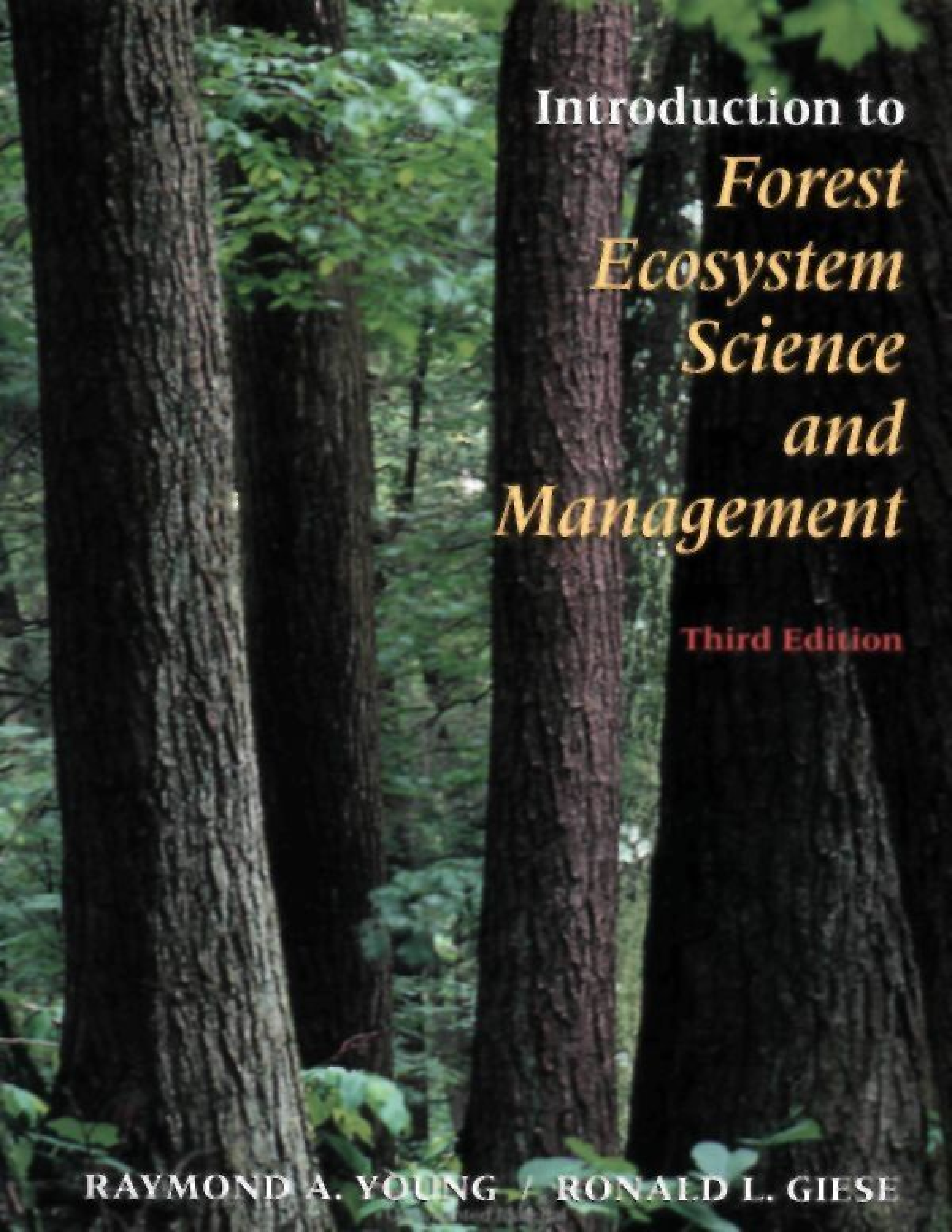


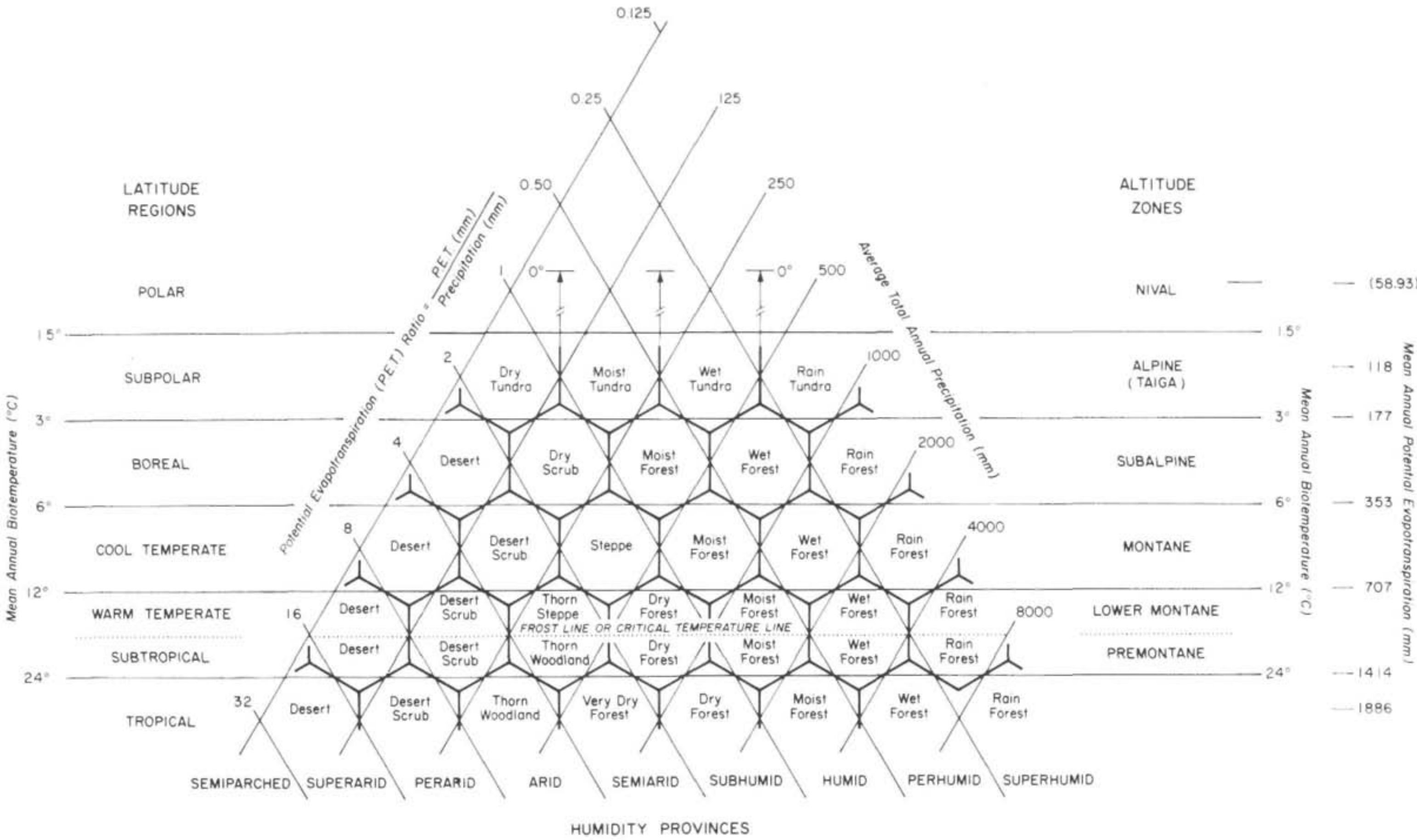
Introduction to *Forest Ecosystem Science and Management*

Third Edition

RAYMOND A. YOUNG / RONALD L. GIESE

FOREST REGIONS OF NORTH AMERICA

DIAGRAM FOR THE CLASSIFICATION OF WORLD LIFE ZONES OR PLANT FORMATIONS



Redrawn from L. R. Holdridge, *Life Zone Ecology*, Tropical Science Center, San Jose, Costa Rica

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THIRD EDITION

RAYMOND A. YOUNG
RONALD L. GIESE
Editors
University of Wisconsin-Madison

WILEY

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Preface

The science of forestry is a complex amalgamation of the biological, physical, managerial, social, and political sciences. Few, if any, forestry professionals are able to treat all aspects of forest science with complete authority. An edited book on forestry is thus the best method for conveying the science of forestry in one text. This third edition, formerly titled *Introduction to Forest Science,* reflects the many changes and approaches to forestry that have occurred in the field of forestry during the past 12 years, and we therefore decided, with reviewer input, to title this new edition *Introduction to Forest Ecosystem Science and Management.* The book is intended to provide beginning and intermediate students with a comprehensive introduction to the important aspects of the field of forestry. It represents a collective effort by a number of authors to present a broad view of the field. The authors give general coverage of their specialized fields within forestry and emphasize how decisions made by forest managers affect the forest ecosystem. References to other works that explore certain aspects of forest ecosystem science and management are provided for the student interested in greater depth.

It seems that there are as many approaches to the organization of a book in forestry as there are forestry professionals. In this third edition of the book, we attempt to maintain a flow from the basic cell and individual trees to the forest stand, followed by management of the forest stand, and then to acquisition of goods and services from the forest. In this new edition, we have added a new section, Forests and Society, to reflect the increasing role of human influences in forestry.

The book is arranged in four major parts. In the two chapters in the Introduction (Part 1), the development of American forest policy and the forestry profession are described. Important events that have shaped forest policy, such as the environmental movement, are treated in the first chapter and important aspects of forestry employment opportunities are discussed in Chapter 2.

Part 2, Forest Biology and Ecology, contains information on factors affecting individual tree growth through growth of the forest stand. The first chapter in the section (Chapter 3) describes the location and composition of forests around the world as biomes. Biotic and abiotic influences on forest growth are discussed in detail in this section, and many agents affecting the complex forest ecosystem are analyzed in separate chapters on tree ecophysiology, soils, insects, and diseases. A new chapter on Landscape Ecology (Chapter 7) has been added to this third edition to emphasize the increasing importance of this subject area.

The management of the forest ecosystem for multiple uses is treated in Part 3, Forest Management—Multiple Uses. An overview of Forest Management and Stewardship is given in Chapter 9 and the significant role of private nonindustrial forests (NIPFs) is given special treatment in Chapter 10, because these forests constitute about 60 percent of all commercial forests. This is followed by two chapters emphasizing measurement and monitoring of the forest through land-based and satellite technology. Biological aspects of management are given thorough treatment in Chapter 13, Silviculture and Ecosystem Management. Separate chapters are devoted to management of forest wildlife, rangeland, watersheds, recreation, and fires in the forest. After a description of timber harvesting in Chapter 19, the last two chapters in the Management section deal with the conversion of forests to usable commodities and their valuation. In Chapter 20, the structure and properties of wood are described, and the methods for conversion to lumber, reconstituted products such as particleboard, paper, chemicals, and energy are outlined. The economics and management of the forest for wood and amenity values are analyzed in Chapter 21. An attempt is made in this chapter to assign monetary values to the amenities ascribed by humans to the forest. This chapter puts into perspective the relative value of the multiple uses we make of forests.

As already mentioned, the last section, Part 4, is devoted to Forests and Society. The increased interaction of humans with the forest, and the expectation of further intense interactions, both in urban and rural settings, has mandated specialized treatment of this subject matter. The unique situation of Urban Forests is described in Chapter 22. Social Forestry is described in detail in Chapter 23 through a discussion of community-based management of natural resources. Both regional and global emphasis are given in this important new chapter for the third edition of *Introduction to Forest Ecosystem Science and Management.*

In reality, the field of forestry cannot be separated into these four distinct sections, because of the interdependence of the many factors affecting the forest. Therefore, the reader is encouraged to refer to other sections or chapters where appropriate. Cross-references in the text designate when a specific subject is given more detailed treatment in another chapter. A glossary is also included to aid readers who are not familiar with the specialized terminology used in forestry.

As noted, a considerable number of changes have been incorporated into this third edition of *Introduction to Forest Ecosystem Science and Management* in response to changing societal needs and constructive criticism from students, colleagues, and reviewers. Fourteen of the 23 chapters, or over 60 percent of the book, have been totally rewritten by new authors and the other chapters have been extensively revised. Thus, this third edition of *Introduction to Forest Ecosystem Science and Management* provides many new perspectives tuned to the changing values of the new millennium, especially in terms of human-forest interactions.

Also new to this third edition is the inclusion of chapter sidebars and a full-color insert. Many of the chapters contain sidebars with detailed, specialized information pertinent to the discussion in the text. The sidebars also provide additional information for the interested reader. The full-color insert has been included in this third edition to better illustrate the features of some of the more complicated figures in the book.

Students are encouraged to use the glossary for technical words that are unfamiliar. Also, the appendixes include taxonomy of forest trees as well as common and scientific names for trees and animals mentioned in the text.

As with the previous editions, the third edition of *Introduction to Forest Ecosystem Science and Management* was designed to give students a broad overview of the field of forestry but with sufficient detail that they will be able to assess their specific role as practicing forestry professionals. The book is intended to be the most advanced introductory text available. Indeed, current forestry professionals would find the text a convenient method for updating their knowledge of forest science. Certainly the book conveys the broad scope of forestry and the great challenges that lie ahead.

Raymond A. Young
Ronald L. Giese
November, 2002

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Appendixes

Acknowledgments

The chapter authors and we have received many constructive comments on the chapters and the book from both our colleagues and outside reviewers. We are grateful to the departmental secretaries, Nancy Nehring, Marilyn McDole, and Sandy Fowler for clerical assistance along the way. Our wives, Kathryn and Maureen, deserve special thanks for their love and assistance throughout the editing process.

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R.A.Y.
R.L.G.

PART 1

Introduction

RAYMOND A. YOUNG

Throughout history, forests have been important to human beings. Forests provided shelter and protection, and trees provided many products such as food, medicine, fuel, and tools. For example, the bark of the willow tree, when chewed, was used as a painkiller in early Greece and was the precursor of present-day aspirin; acorns from oak trees were an important food base to the American Indian. Wood served as the primary fuel in the United States until about the turn of the nineteenth century; indeed, over one-half of the wood now harvested in the world is used for heating fuel. Today over 10,000 products are made from wood.

Forests provide many other benefits, such as control of erosion and flooding and reduction of wind erosion. In addition to many utilitarian uses, the forest provides many aesthetic features to which quantitative values are difficult to assign. The amenities include forest wildlife such as songbirds, fall coloration, wildflowers, and beautiful landscapes (Figure Pl.l). Urbanized society has placed increasing emphasis on preserving the natural qualities of the forest for recreational purposes, escape, and solace. This has led to the designation of "Wilderness Areas" intended to be unaltered by humans.

Figure Pl.l A majestic, mature stand of western redcedar in western Washington State. Lichens clothing the dead branches attest to a humid climate. (Courtesy of U.S.D.A. Forest Service.)

Because of the many different viewpoints, conflicts of interest have arisen over what is considered to be the proper use of the forest in modern American society. What a member of a preservationist group such as the Sierra Club defines as proper management of the forest may be in conflict with how a paper industry executive views as proper use of the forest. The forest manager, although recognizing this conflict, must understand both views and develop a management plan that reflects the values involved in both points of view.

We can now define forestry as the art, science, and practice of managing the natural resources that occur on and in association with forestland for human benefit. This definition necessitates that the forest manager consider not only the trees in the forest, but also such things as protecting wildlife and preserving water systems for drinking and aquatic life. Foresters are often involved with the control of fire, insect pests, and diseases in the forest, and they can also assume the broad role of protecting the forest environment. The forester is a land manager responsible for all the goods, benefits, and services that flow from the forest (1).

The Multiple Use-Sustained Yield Act of 1960 recognized the many benefits derived from the forest: outdoor recreation, rangeland, timber, watershed protection, and wildlife and fish habitat. All need not be available at every location, but the value of each should be given equivalent recognition on a nationwide basis. Thus a clearcut for timber in a national forest should in some way be balanced by opportunities for wilderness-type experience at another location. The importance of the legislative process is further discussed in Chapter 1, Forest Policy Development in the United States.

In order to conform with legislation, managers of forests on public lands must strive to maintain a continual supply of the products, services, and amenities available from the forest. To do this, they must have a solid knowledge of science and society, a broad background in physical, biological, and social sciences, as well as administrative skills and an element of diplomacy for resolving conflicts. Clearly the task of the forest manager is a complex one requiring insight and many learned skills (2). Further discussion concerning the profession of forestry is given in Chapter 2, Forestry: The Profession and Career Opportunities.

The Forest

The forest is a biological community of plants and animals existing in a complex interaction with the nonliving environment, which includes such factors as the soil, climate, and physiography. A continuous canopy of large trees usually distinguishes forests from other types of communities. Forests are widespread, representing almost 30 percent of the earth's land surface, and typically have a predominant species composition; thus there are many forest types. The distribution of forest types or "biomes" around the world is discussed in Chapter 3, Forest Biomes of the World. The remainder of the land surface is composed of desert (31 percent), grasslands (21 percent), polar ice caps and wasteland (11 percent), and croplands (9 percent) (1).

Although trees are the predominant woody vegetation in terms of biomass,[1] trees represent only a small proportion of the total number of species present in the forest. There are thousands, perhaps millions, of different types of plants and animals in the forest. Shrubs, herbs, ferns, mosses, lichens, and fungi are present beneath the forest canopy and in the gaps of the forest cover. Large animals such as deer and bears coexist with smaller birds, insects, and tiny microorganisms. Each component makes a contribution to the flow of energy and materials through the system.

The forest is thus a dynamic ecosystem dominated by trees that is continually changing in structure and composition. Disturbances such as fire, windfall, and harvesting produce sites where new communities of trees, plants, and animals can exist and differ from the original forest. Fallen leaves and woody material that reach the forest floor decay and continue the cycling of energy and nutrients through the system. The forest community is a complex unit divided into many areas of study; these areas are treated in specific chapters in the text.

Tree Classification

Although forest ecosystems are composed of many plant and animal species, the dominant vegetation that foresters study and manipulate is the variety of tree species in the forest. Trees are generally

[1] Terms that may be unfamiliar to the reader are defined in the Glossary.

classified into two categories as seed plants: angiosperms with encased seeds and gymnosperms with naked seeds (Figure P1.2). The angiosperms are the dominant plant life of this geological area. They are products of a long line of evolutionary development that has culminated in the highly specialized organ of reproduction known as the flower. The seeds of angiosperms are enclosed in the matured ovary (fruit).

Two classes exist for the angiosperms, the Monocotyledones and the Dicotyledones (Table Pl.l). Palms are classified as monocots, and the woody dicots are what we usually refer to as broad-leaved trees. Because the broad-leaved trees typically lose their leaves each fall, they are also often referred to as deciduous trees. However, a number of exceptions occur, such as southern magnolia or Pacific madrone, both of which retain their leaves all year. The broad-leaved or deciduous trees are also often referred to as hardwood trees, although this is a misnomer and does not refer to wood texture. Many broad-leaved trees such as basswood (linden) have soft-textured wood.

The other major class of trees is the gymnosperms, which bear their seeds in cones. The majority of the trees in this classification fall into the division Coniferophyta or conifers. A notable exception is the ginkgo tree, the only living species in the division Gingophyta. Some of the last living ginkgo trees were located by a botanical expedition in China in 1690. Subsequently, seeds from the mature tree have been planted worldwide (Figure PI.3). In recent years, extracts from the seeds and leaves have been touted for their medicinal values.

The conifers generally do not lose their needle-like leaves annually in the fall and therefore are termed evergreens. Again, there are exceptions such as larch and bald cypress, conifers that lose their needles each year like the broad-leaved trees. The conifers are also referred to as softwoods, but, like the hardwoods, the designation does not refer to the texture of the wood but to the class of tree. The terminology of hardwoods and softwoods probably originated in the early sawmills when most of the conifers used for timber were soft-textured pines, whereas most of the broad-leaved

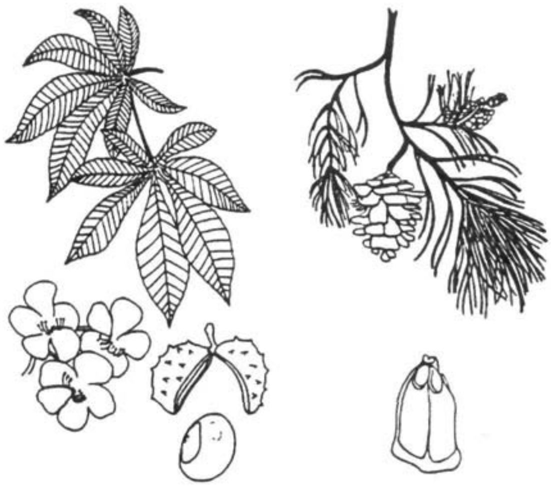

Figure P1.2 Depiction of angiosperms (encased seed) and gymnosperms (naked seed).

Figure P1.3 The ancient ginkgo tree thrives in polluted urban environments and is planted as an ornamental worldwide. (Photograph by R. A. Young.)

Table Pl.l Scientific and Common Terms for Trees

Angiosperms (Magnoliophyta; Encased Seeds)	Gymnosperms (Naked Seeds)
Liliopsida (monocots; parallel-veined leaves)	Cycadophyta
Palms and palmettos (Palmaceae)	Cycads
Yucca (Liliaceae)	Ginkgophyta
Magnoliopsida (dicots; net-veined leaves)	Ginkgo
Common terms for trees in this class:[2]	Coniferophyta
Hardwoods	Common terms for trees in this class:
Deciduous trees	Softwoods
Broad-leaved trees	Evergreens
	Needle- (or scale-) leaved
	Conifers

[a]These terms are considered synonymous in common usage, but it is important to remember that many exceptions occur as described in the text.

trees used were hard-textured maples and oaks. It is important to recognize the synonymous terms listed in Table Pl.l, since they are used interchangeably in both the literature and the common language.

Trees are referred to both by their common and scientific names. Common names are often utilized since the tree name is more recognizable in English than the Latin-based scientific names. In the text we have generally utilized the common names in reference to specific trees or stands of trees, with the scientific name sometimes in parentheses. However, it is important to recognize that common names can vary in different localities and refer to totally different trees. For example, the common name "Black Pine" is utilized for Ponderosa Pine (*Pinus ponderosa*) in the Rocky Mountain regions of the United States, while in the eastern United States, the common name "Black Pine" usually refers to Austrian Pine (*Pinus nigra*) introduced from Europe. The use of binomial scientific names, developed by the Swedish botanist Linnaeus in the mid-eighteenth century, avoids this confusion. Common and scientific names of tree species mentioned in the text are given in Appendix I.

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1. R. D. NYLAND, C. C. LARSON, AND H. L. SHIRLEY, *Forestry and Its Career Opportunities,* Fourth Edition, McGraw-Hill, New York, 1983.
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CHAPTER 1

Forest Policy Development in the United States

THOMAS M. BONNICKSEN AND
DIANA M. BURTON

All U.S. residents derive benefits from forests, either indirectly as forest product consumers or directly as participants in forest outdoor activities. Americans are making increasingly heavy and varied demands on forests. Although forest resources are renewable, there is limited land on which to produce forests. As demand rises, competition for resources also rises. Competition leads to formation of interest groups to influence elected officials and government agencies on forest resource allocation and management issues. The policy-making process resolves these differences. Understanding this process and the forest policy it generates is the principal focus of this chapter.

According to Boulding, a policy "generally refers to the principles that govern action directed toward given ends" (1). However, policies are much more. They are also hypotheses about what will happen if certain actions are taken. Whether a policy will achieve its specified ends is always in question until policy implementation results are realized. If a policy does not perform as expected, the whole policy process might be reinitiated. Thus, policy making is a continuous process that constantly attacks both new problems and those generated by past policies (2).

A society's history, philosophy, beliefs, attitudes, values, contemporary problems, and hopes are woven into its policy-making process. Thus, what is acceptable forest policy to one society in a given context may be inconceivable to another society in the same setting. Although U.S. forest policy incorporates many European forestry principles, it is a unique blend of approaches and goals tailored to American needs and circumstances. U.S. forest policy is also continually developing to accommodate change. Thus, forest policies adopted in the late 1800s differ significantly from those of a century later. Which policies are better at one time cannot be judged using standards of another time, just as forest policies appropriate to a given society cannot be judged according to another society's values.

Profile of Forest Policy Development

Throughout this chapter, the policy process is used as a framework for visualizing U.S. forest policy historical development. We look at broad periods that characterize major shifts in policies toward forests. In addition, we describe the environmental context and goals of the policy process within each period and evaluate policy results in terms of these goals. Because American forest policy is a vast topic, the scope of this text is necessarily limited. We emphasize the federal government's role and national forest management. We focus on policies stated as legislative statutes, executive orders and decrees, administrative rules and regulations, and court opinions.

Native Americans and Forests (to 1607)

The relationship between American Indians and forests varied. Forests provided building materials, food, or both. Forests were often seen as an obstacle to cultivation. For instance, the pre-Columbian northwestern coast of North America was heavily forested and occupied by seafaring people who were highly skilled woodworkers (3, 4). Although many native peoples of the eastern deciduous forests also obtained wood from forests, the forest was principally an obstacle to the cultivation of maize, beans, and squash (5).

American Indians at times consciously favored certain tree species. In California, abundant oak trees produced acorns that were the staff of life for the Indian. The Miwok in Yosemite Valley burned grass under black oak trees in the fall to prevent growth of other trees that might shade the black oak. They also burned to clear the ground so that acorns could be easily gathered.

American Indians abided by certain rules while deriving their livelihoods from the land. These rules or guidelines were handed down from one generation to the next by word and action. Such an agreed-upon pattern of behavior, designed to accomplish a specified goal, fits the definition of a policy. Consequently, although native peoples did not have forest policies that were explicitly recognized as such, they did have rules that governed their relationships to forests. Whether modern people agree with these rules is unimportant. What is important is that American Indians had the equivalent of forest policies that enhanced their survival.

Colonial Settlers and Forests (1607-1783)

Although the world known to Europe expanded to include North America in 1492, it was not until 1607 that Europeans successfully colonized what is now the United States. The Virginia Company of London founded Jamestown, on the wooded banks of the James River, in what is now Virginia. Forests were the colonial landscape's dominant feature and a valued resource. Forests surrounding Jamestown were used to construct the town and as fuel for a thriving glass industry. However, the thick forests hid unfriendly Indians, so forests were cleared to make the area safe. Forests were also cleared for farms and roads. Thus, two attitudes toward forests developed that profoundly influenced forest policies for generations. First, forests were nuisances

Sidebar 1.1

Questions About Future Forests

America's forests have undergone pronounced changes since first seen by European explorers. Many older forests disappeared because a growing nation needed wood for fuel and construction. Clearing for agriculture and towns took the greatest toll. Even so, reforestation on federal and private lands and planting on abandoned agricultural lands have replaced much of the lost forest.

Forests now cover one-third of the United States, but they differ significantly from the original ancient forests. There are fewer old trees in today's forests than there were in ancient times, and forests are less patchy and diverse. Some change is caused by timber management, but also results from efforts to protect against lightning fires, insects, diseases, and development. The elimination of traditional burning by American Indians may have caused the most widespread changes. The lack of Indian fires and suppression of lightning fires allow debris to accumulate in today's forests. They are choked with thickets of young trees, which is slowing tree growth, increasing mortality and reducing stream flows. Thicker and more uniform forests also have less wildlife habitat. In addition, trees that grow in the shade replace trees that grow in the sun, such as Douglas fir and pine. Even more disturbing is that increasing fuels make wildfires more severe and dangerous.

Many scientists and resource managers believe that forest restoration provides the best hope for reversing American forest decline. Some predicted the forest health crisis coming several decades ago. One of the first was Aldo Leopold, who promoted forest restoration as early as 1934. Forest restoration involves using ancient or pre-European settlement forests as models for creating sustainable forests. Restoration does not apply to forests that are dedicated to growing wood fiber. Ancient forests provided many of the things that people want from today's forests, including large trees, scenic vistas, abundant wildlife, and wildflowers. However, people also want forest products. Management that includes controlled burning and cutting can mimic processes that created and sustained the ancient forest beauty and diversity and generate forest products as well. Since ancient forests were sustainable, future forests that use them as models should also be sustainable.

Managers can produce what we want from forests by engineering new forests using modern tools and scientific principles. They do not need ancient forests as models. This is already happening in forests that are being manipulated to favor certain wildlife species, particularly endangered and threatened species, or to maximize timber production. However, are these artifical forests necessary or even desirable, and will they be sustainable? Do we really want to invent new forests, or do we want forests to look as beautiful and diverse as they did when explorers first saw them? Can we have both historic forests and engineered forests? Can the same forest serve both purposes or must they be separated? Even more intriguing, do we want forests to look the way they might look now if Europeans had not settled the continent and American Indians were still the only inhabitants? On the other hand, do we want forests to look as if no one, including Native Americans, had ever lived on the land? These are just some of the policy questions that should be

(continues)

Sidebar 1.1 *(continued)*

pondered. The future of America's forests depends on the answers. An in-depth description of North America's ancient forests is found in *America's Ancient Forests: From the Ice Age to the Age of Discovery* (1).

Source;

1. T. M. BONNICKSEN, *America's Ancient Forests: From the Ice Age to the Age of Discovery,* John Wiley & Sons, New York, 2000.

and citizens made great improvements to the land by cutting trees. Second, the seemingly unending supply of trees led to acceptance of waste and a view that American forests were inexhaustible.

Wood was the primary fuel and energy source for colonial America and remained so until 1870. Because the colonists lacked transportation, wood for fuel and building material was cut near settlements. As forests receded from settlements, it became increasingly difficult to haul wood. Although forests as a whole seemed inexhaustible, local timber supplies were limited. As a result, the first American forest policy on record was established on March 29, 1626, by Plymouth Colony. The policy forbade transport of any timber out of the colony without the governor's and council's consent. Similar policies were adopted by Rhode Island, New Hampshire, and New Jersey. In addition, William Penn directed in 1681 that in Pennsylvania ("Penn's woodland") 1 acre (0.4 hectare) of forest be left for every 5 acres (2 hectares) cleared.

Colonial policy making included political rule by a distant monarchy. Thus, forest policies reflected the perceived wants of a distant society as well as the colonists' immediate needs. The tension between these two interests seriously limited England's forest policies for the New World.

The abundance of large trees made a colonial shipbuilding industry possible. The *Blessing of the Bay,* a ship launched at Medford, Massachusetts in 1631, marked the beginning of both this industry (6) and a direct conflict with British interests in America's forests. As early as 1609, the first shipment of masts was sent from Virginia to England (6) (Figure 1.1). Trees of sufficient size were scarce and hostile countries could easily disrupt supply lines from northern and central Europe. Great Britain was competing for European masts, so America became its principal source of supply. In order to protect its interests, Great Britain in 1691 granted a new charter to the Province of Massachusetts Bay that reserved for the crown all trees 24 inches (6l centimeters) or more in diameter growing on lands not in private ownership. This was known as the Broad Arrow policy because reserved trees were marked with a broad arrow blaze—the symbol of the British Navy. By 1721, this policy covered all colonial lands from Nova Scotia to New Jersey. The British did obtain a relatively steady supply of naval timbers under the Broad Arrow policy, which had to be enforced with large fines because colonists vigorously opposed it. In 1772, for instance, in Weare, New Hampshire, Sheriff Benjamin Whiting arrested Ebenezer Mudgett for cutting the king's white pine. The colonists reacted by seizing the sheriff in the night, beating him with rods, and forcing him to ride out of town. This event was known as the "Pine Tree Riot" (6). The Broad Arrow policy likely contributed to the American Revolution.

Building and Defending the Republic (1783-1830)

The British formally recognized United States independence in the Treaty of Paris in 1783. America

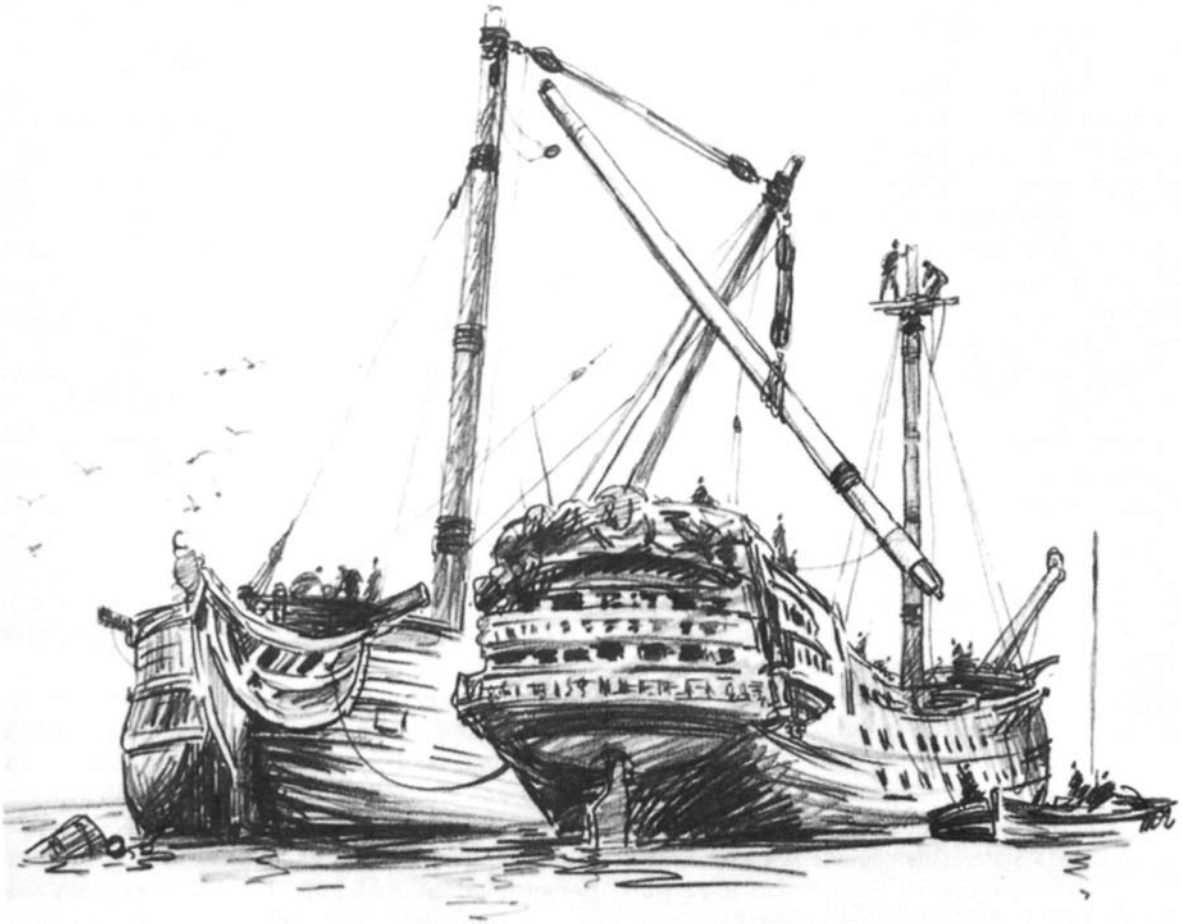

Figure 1.1 A sheer hulk stepping a mainmast. (Courtesy of Mr. Jack Coggins and Stackpole Books.)

then controlled her own forests. The social and economic problems of the new nation were exacerbated by the old belief that American forests were inexhaustible. The most significant change in the forest policy process that occurred at this time was establishing the first American government. The new government was based on the Articles of Confederation, a document designed to preserve the states as free and independent sovereignties while granting Congress limited authority. Thus, the Articles denied Congress the authority to levy taxes and to regulate commerce.

The Articles of Confederation required unanimous consent of all thirteen states. Six states were reluctant to sign because they did not have claims to large tracts of unsettled western lands. States with such lands had an advantage because land could be sold to defray Revolutionary War debts. Maryland, without western land, refused to sign the Articles of Confederation unless other states abandoned their claims. Maryland held out until March 1781, when New York surrendered its western land claims to the federal government and Virginia appeared ready to do so. Thus, ratification of the confederation also marked the beginning of the public domain. (The public domain included all lands that were at any time owned by the United States government and subject to sale or transfer of ownership under the laws of the federal government.) Congress pledged to dispose of the public domain for the "common benefit," partly to create new states and partly to make good on its promise to grant land to Revolutionary War veterans. Since Congress could not levy taxes, it used the public domain as a revenue source to discharge national debt and run the government.

Although Congress was weak under the Articles of Confederation, it managed to pass two laws that affect the landscape to this day. The first is the Land Ordinance of 1785. It provided that the Old Northwest, a territory lying between the Ohio and Mississippi rivers and the Great Lakes southern shores, should be sold to help defray national debt. The land was surveyed before sale using the now-familiar rectangular grid system of townships and sections. Only the thirteen original states and later Texas, whose admission to the union was contingent on state ownership of public lands, were not subjected to this survey system. The Northwest Ordinance of 1787 further provided that when a territory could claim 60,000 residents, it could be admitted as a state. This scheme worked so well that it was carried over to other areas of the public domain.

One problem facing the new Congress was the need for a strong navy. Congress authorized construction of six frigates in 1794, established a Department of the Navy in 1798 (6), and appropriated $200,000 to purchase timber and lands growing timber suitable for naval construction. Thus, Congress bought two islands supporting live oak off the Georgia coast. At the outbreak of the War of 1812, the United States still had only sixteen ships in its entire navy against the 800 men-of-war in the British navy. By war's end, the United States had only two or three ships left (7). Congress reacted in 1817 by authorizing the Secretary of the Navy to reserve from sale, with presidential approval, public-domain lands that supported live oak and red cedar to rebuild the navy. An 1828 act appropriated an additional $10,000 for land purchases. These timber reserves received no more public support than had the earlier British Broad Arrow policy. Looting, or timber trespass, was common. In 1821, the General Land Office commissioner instructed his agents to stop illegal cutting on the reserves (6), but officials responsible were political appointees with little interest in confronting timber thieves. Therefore, in 1822, Congress authorized use of the army and navy to prevent timber depredations in Florida, but there was little improvement.

Important Features of the Period 1783-1830
Forest policies adopted between 1783 and 1830 produced mixed results. First, revenues derived from public land sales did not reach expected amounts. The Land Ordinance of 1785 provided that lands should be sold in blocks of at least 640 acres (259 hectares) to the highest bidder at not less than $1 per acre. Unfortunately, land could be purchased elsewhere at lower prices, and the $640 required as a minimum purchase price proved too high for most people. As a result, people in need of land "squatted" on the public domain in increasing numbers, and efforts to remove them met with little success. Naval timber reserve policies faced similar results because forests were regarded as inexhaustible. In addition, the public domain was expanding as the nation added to its land holdings through the Louisiana Purchase and like transactions, and interest in forest reserves gradually declined. However, the policy of reserving forestlands as a source of timber set an important policy precedent. Congress's right to control public lands use in the national interest was firmly established.

The Erosion of a Myth (1830-1891)

In 1830, Andrew Jackson was elected U.S. President with the support of common people. Many in the upper classes sneered at this "New Democracy," referring to "coonskin congressmen" and enfranchised "bipeds of the forest" (7). Nevertheless, politicians who could boast of birth in a log cabin had a real advantage in an election. The sturdy pioneer and forest settler were clearly in command. By the 1867 Alaska purchase, the public domain had grown by more than one billion acres (405 million hectares) and there was a need to fill these lands with settlers to protect them and make them productive. During this period more than any other, the nation's policy was to transfer land into private ownership and rely on market forces as a primary means for allocating natural resources.

Exploitation of the Forests With seemingly inexhaustible forests, and a government dominated by western settlement and economic expansion interests, rapid resource exploitation was inevitable. Pressure on timberlands increased as wood was used to build on the treeless Great Plains, to construct railroads, to fight the Civil War and repair what it destroyed, and to rebuild four square miles (10.4 square kilometers) of Chicago burned in the Great Fire of 1871. Settlers occupying lands on the Great Plains had to import timber. Tree planting was thought to be a reasonable solution that might also increase rainfall. In 1866, General Land Office Commissioner Joseph S. Wilson recommended that homesteaders be required to plant trees in areas lacking timber (6). Therefore, Congress enacted the Timber Culture Act in 1873- Under the law, settlers received 160 acres (65 hectares) of public land by planting 40 acres (16 hectares) with trees and maintaining them for a given period.

With the exception of railroad land grants, most policies enacted during this period focused on agricultural development. However, by 1878 it was clear that large areas of public domain were more suited to timber than agriculture and that no provision existed for timber or timberland acquisition by the public. Congress offered a remedy in 1878: the Free Timber Act and the Timber and Stone Act. The Free Timber Act stipulated that residents of nine western states could cut timber for building, mining, and other purposes without charge to aid in farms and mineral claims development (Figure 1.2). While this act was well intentioned and undoubtedly provided substantial aid to deserving settlers, it was widely abused, as enforcement was nearly impossible. The Timber and Stone Act provided that unoccupied, surveyed land principally valuable for timber or

Figure 1.2 Native Americans used wood under provisions of the Free Timber Act, Black Hills National Forest, South Dakota, in 1931. (Courtesy of U.S.D.A. Forest Service.)

stone, but not agriculture, could be purchased in 160 acre (65 hectare) tracts for $2.50 per acre in Washington, Oregon, California, and Nevada. The purchaser had to swear that the land was for personal use and not for speculation.

Throughout this period, two major forest policy problems existed. First, speculation and fraud in public land sales and transfers were rampant. Speculators and lumber executives accumulated large timberland holdings and abused public domain disposal policies. Most laws were designed to encourage small owner-operator farms, but there was little control over what the landowner did after purchase. For example, military land bounties granted to soldiers for their service and to encourage enlistment were sold to land speculators and large companies. The sales became so common that bounty warrants were quoted on the New York Stock Exchange (6). Second, some timber operators made no pretense of purchasing timberlands but simply set up lumber mills on the public domain and cut trees. In other cases, they purchased 40-acre (16 hectare) plots and proceeded to cut timber on surrounding public lots. These were known as "round forties" or "rubber forties" because of the flexibility of the boundaries.

The end of timber stealing began in 1877 with the appointment of Secretary of the Interior Carl Schurz. He immigrated from Germany where scarce forest resources were carefully husbanded. Schurz advocated a similar approach in the United States. He took exception to the popular belief of inexhaustible timber resources. In his first annual report, Schurz predicted that the timber supply would not meet national needs in 20 years (8). Schurz vigorously enforced laws against timber theft (6). He based his authority on the March 1831 Timber Trespass Law, which imposed fines and imprisonment on those who cut timber from public lands without authorization. In 1850, the U.S. Supreme Court upheld the act and extended it to include any trespass on public lands.

Conservation and Preservation of the Forests

Rapid disposal and exploitation of the public domain characterized the period from 1830 to 1891. However, the myth that timber and other resources were inexhaustible gradually eroded, while a concern for conservation and preservation grew. As early as 1801, publications by Andre Michaux and his son, after their travels through U.S. forests, noted "an alarming destruction of the trees" and warned that increasing population would make timber scarce (6). By 1849, the commissioner of patents was also warning of timber shortages (6). In 1864, George Perkins Marsh published his famous book *Man and Nature,* pointing out undesirable consequences of forest destruction. Beginning about 1866, annual reports from the Secretary of the Interior and the commissioner of the General Land Office regularly included an expression of concern about the exhaustion of forest resources.

In 1867, this concern translated into state action when legislatures in both Michigan and Wisconsin appointed committees to investigate potential long-term consequences of deforestation. More dramatic action was taken in 1885 by New York when it created a "forest preserve" on state-owned lands in the Adirondack and Catskill mountains. In 1894, the new state constitution of New York forbade timber cutting on the preserve. In addition, in 1885, California established a State Board of Forestry and granted it police powers two years later.

Federal action aimed at forest conservation began about the same time. In 1874, an American Association for the Advancement of Science (AAAS) committee prevailed on President Ulysses S. Grant to ask Congress to create a commission of forestry (6). Congress attached an amendment to the Sundry Civil Appropriations Bill of 1876, providing $2000 to hire someone to study U.S. forest problems. This act established such a position in the Department of Agriculture and henceforth federal forest management would be primarily performed by this department. Franklin B. Hough, who had chaired the AAAS committee, was appointed to the job. He published three monumental reports containing most of what was known about forestry in the United States at that time. Later, he became chief of the Division of Forestry, which was subsequently given statutory permanence in the Department of

Agriculture on June 30, 1886. This division was the precursor of what is now the U.S.D.A. Forest Service. Also in 1886, Bernard E. Fernow, who had studied forestry in western Prussia, succeeded Hough as chief of the division.

The preservation movement had a profound effect on forest policy. In 1832, George Catlin, a painter and explorer of the American West, called for establishment of "a nation's park" in the Great Plains "containing man and beast, in all the wild and freshness of their nature's beauty!" (9). Catlin's plea for preservation was echoed by Henry David Thoreau in 1858 when he asked, in an article in the *Atlantic Monthly,* "why should not we . . . have our national preserves . . . for inspiration and our true re-creation?" (10). Other well-known preservationists such as Frederick Law Olmsted and John Muir followed Catlin and Thoreau. Together they helped to found our present system of national parks and monuments, beginning with Yellowstone National Park, which was set aside in 1872 "as a public park or pleasuring-ground for the benefit and enjoyment of the people." Yosemite Valley and the Mariposa Big Tree Grove were set aside in 1864 for public recreation, to be managed by the state of California. They became part of Yosemite National Park in 1890. Sequoia and General Grant (now Kings Canyon) became national parks that same year.

Important Features of the Period 1830-1891 The period from 1830 to 1891 saw three separate movements. One, an exploitive movement, was to dispose of the public domain and cut forests extensively. At the same time—and partly in response—two other movements encouraged scientific resource management and natural scenery preservation. One major success stands out. About one billion acres (405 million hectares), nearly the same amount of land as entered the public domain during this period, were sold to private owners (6). However, much land did not end up with small farmers but added to large corporate holdings. Another major success was the encouragement of western expansion and settlement, but the benefits were mixed with problems. A quarter-section of land, which would have been an adequate size for a farm in the East where water was plentiful, was completely inadequate for sustaining a farmer in the arid West, and therefore many farms in the West were abandoned. Finally, prodigious amounts of timber products were produced, but subsequent generations inherited a legacy of cutover and deteriorated forestland. Nevertheless, this period ended with a rapidly growing and prosperous nation that had already taken major steps toward improving the use of its forests.

Crystallizing a Philosophy (1891-1911)

The circumstances affecting U.S. forest policy between 1891 and 1911 were different from those of any previous period. The shift from rural to urban life was accelerating. In 1790, only 2.8 percent of the population lived in cities with 10,000 or more people; by 1900, 31.8 percent did (7). An urban population often perceives natural resources differently than a rural population, whose livelihood is directly and visibly land-dependent. Thus, the conflict between the strong desire for preservation of Eastern seaboard urban residents, and the expansionist views of Western rural residents became marked.

This was the first period without a geographic frontier. In 1890, the superintendent of the census in Washington announced that a frontier line no longer existed (3). All of the United States and its territories contained settlements. The myth of inexhaustible resources had been eroding for decades. However, the loss of the frontier and the presence of large tracts of cutover land in the once heavily forested East made it obvious that something had to be done to conserve forests and other resources. People saw a "timber famine" as a real possibility. Three societal goals emerged that strongly affected forest policy: defend the rights of the people, maintain a continuous supply of timber, and prevent waste in natural resource use, particularly timber.

Creation of Forest Reserves Perhaps the most important forest policy enacted in the United States was the General Revision Act of 1891. Provisions

Sidebar 1.2

The Legacy of George Perkins Marsh

Born in Woodstock, Vermont, in 1801, Marsh grew up on America's frontier. As the fifth of eight children of the local district attorney, Marsh read intensively and ran free in the great outdoors. Graduating at the top of his Dartmouth class, Marsh taught Greek and Latin for a time at a military academy. He became a lawyer, a politician, and eventually was appointed as ambassador to Italy by President Abraham Lincoln (1). His most famous work, *Man and Nature, or Physical Geography Modified by Human Action* (1) was written during his tenure in Italy and published in 1864.

Marsh's claim that man was modifying nature was not remarkable at the time. Forests were being removed for agriculture, canals were being constructed, and a spreading population erected new towns. However, his notion that man should consider his impact on the natural environment, in part because a changed natural environment would have an impact on man, was almost radical. Marsh's thoughts anticipate by more than a century the now widely accepted idea of an integrated ecosystem:

> **... the trout feeds on the larvae of the May fly, which is itself very destructive to the spawn of salmon, and hence, by a sort of house-that-Jack-built, the destruction of the mosquito, that feeds the trout that preys on the May fly that destroys the eggs that hatch the salmon that pampers the epicure, may occasion a scarcity of this latter fish in waters where he would otherwise be abundant. Thus all nature is linked together by invisible bonds, and every organic creature, however low, however feeble, however dependent, is necessary to the well-being of some other among the myriad forms of life with which the Creator has peopled the earth (1, p. 96).**

One of the main messages in *Man and Nature* is that man ought to consider fully the impacts of his actions, not that nature should not be modified.

Marsh's ideas were taken up by many who read his works. As science progressed, the complexity of natural ecosystems became more apparent. Writers such as Rachel Carson, who published *Silent Spring* in 1962 (2), pointed out that agricultural pesticides were killing eagles through their food chain, as well as the intended crop bug targets. The Environmental Impact Statement, required by NEPA, is modern society's attempt to do what Marsh suggested: act, but act with maximum possible knowledge of consequences.

Sources:

1. G. P. MARSH, *Man and Nature,* The Belknap Press of Harvard University Press, Cambridge, Mass., 1967 (originally published 1864).
2. R. CARSON, *Silent Spring,* Houghton Mifflin, Boston, 1962.

included repeal of the Timber Culture Act of 1878 and Preemption Act of 1841, as well as imposition of restrictions on the 1862 Homestead Act to discourage speculation and fraud. What made this act so important to forestry was Section 24. It provided that "the President of the United States may, from time to time, set apart and reserve any part of the public lands wholly or in part covered with timber or undergrowth, whether of commercial value or not." The authority granted to the president by Section 24 (also known as the Forest Reserve Act) to set aside forest reserves from the public domain served as the basis for the U.S. national forest system. Less than a month later, President Benjamin Harrison established Yellowstone Park Forest Reservation. Over two years, he proclaimed an additional fourteen forest reserves, bringing the total to over 13 million acres (5.3 million hectares). A storm of protests from western interests followed, in part because the Forest Reserve Act did not include a provision for using the reserves. Consequently, the westerners' argument that forest reserves were "locked up" and could not be used was correct. Logging, mining, and other activities were illegal on the reserves. However, there was little law enforcement, so timber theft proceeded unobstructed.

A few months before passage of the Forest Reserve Act, Gifford Pinchot, who became the most famous person in American forestry history, returned from Europe where he had been studying forestry under Dr. Dietrich Brandis in France. Pinchot's motto, from the beginning of his career until the end, was "forestry is tree farming" (11). He did not believe in preserving forests but in using them "wisely."

Pinchot emerged on the national forest policy scene when he joined a National Academy of Sciences forest commission formed at the request of Secretary of the Interior Hoke Smith. The commission studied the forest reserves and their administration and made legislative recommendations that would break the Congressional deadlock over forest reserve management. The commission submitted a list of proposed forest reserves to President Grover Cleveland without a plan for their management. Pinchot argued, without success, that a plan should accompany the list so that western congressional representatives would know that the commission wanted to use the forests and not simply lock them up. President Cleveland had only ten days left in office, so he was forced to act on the commission's recommendation. On February 22, 1897, he set aside an additional 21.3 million acres (8.6 million hectares) of forest reserves.

Once again, a storm of criticism arose in Congress and legislation was introduced to nullify President Cleveland's actions. In June 1897, Congress passed the Sundry Civil Appropriations Act with an amendment (known as the Organic Administration Act). Senator Richard Pettigrew of South Dakota introduced the amendment. It provided that "no public forest reservation shall be established except to improve and protect the forest . . . for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber." The act excluded lands principally valuable for mining and agriculture and authorized the Secretary of the Interior to make rules for the reserves "to regulate their occupancy and use, and to preserve the forests thereon from destruction." This language dated from 1893 when Representative Thomas C. McRae introduced the first of many bills for forest reserve management. Early opposition came from western senators whose constituents were accustomed to obtaining timber from public lands without paying a fee. When a compromise was reached to handle western criticism, eastern senators continued to block passage of the bill because they feared that opening up the reserves would lead to more abuses. President Cleveland's bold action in setting aside reserves served as the catalyst to overcome the impasse. Enough votes were obtained to pass the Organic Administration Act because even some eastern senators thought the new reserves created a hardship for people in the West.

The General Land Office administered the forest reserves, an agency that Pinchot said was governed by "paper work, politics, and patronage" (11). Reform seemed impossible, so when Pinchot became head of the Division of Forestry in July 1898, he immediately set out to gain control of the reserves. His good friend Theodore Roosevelt, who became president in September 1901, after President William McKinley's assassination, aided Pinchot. Roosevelt and Pinchot were both master politicians—persuasive, dedicated, and equipped with boundless energy (Figure 1.3). The same ideas about the meaning of conservation, epitomized by such words and phrases as *efficiency, wise use, for the public good*, and *the lasting good of men*, drove them. To Roosevelt and Pinchot, conservation was the "antithesis of monopoly" and, though wealthy

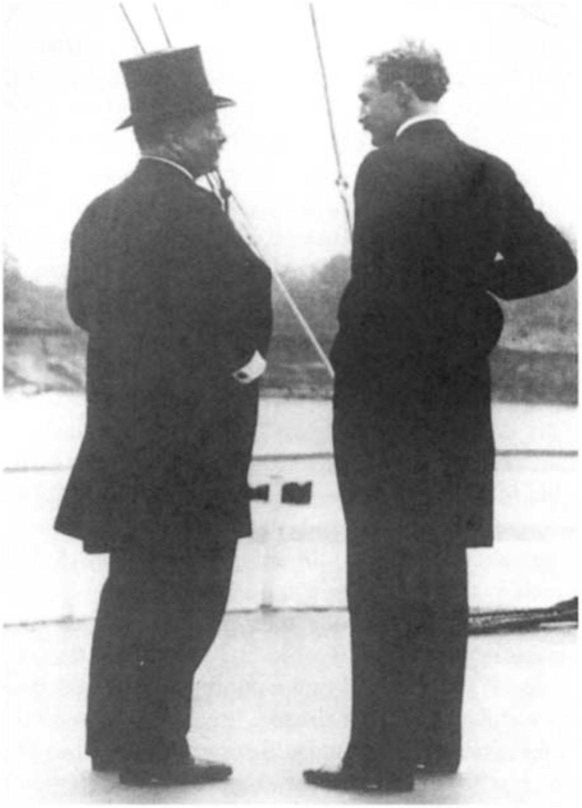

Figure 1.3 Chief forester Gifford Pinchot (right) with President Theodore Roosevelt on the riverboat *Mississippi* in 1907. (Courtesy of U.S.D.A. Forest Service.)

themselves, they both abhorred "concentrated wealth," which they viewed as "freedom to use and abuse the common man" (11). With President Roosevelt's help, Pinchot accomplished his goal to gain custody of the forest reserves. The Transfer Act of 1905 moved their administration from the Department of the Interior to the Department of Agriculture. One month later, Pinchot's agency became the Forest Service. In 1907, forest reserves were renamed national forests.

Management of forest reserves changed dramatically under the new regime. On the day the Transfer Act was signed, Secretary of Agriculture James Wilson sent a letter to Pinchot outlining the general policies to follow in managing the reserves. Pinchot wrote the letter (6). In keeping with the philosophy of the time, the letter required that the reserves be used "for the permanent good of the whole and not for the temporary benefit of individuals or companies." It also stipulated that "all the resources of the reserves are for use" and "where conflicting interests must be reconciled the question will always be decided from the standpoint of the greatest good of the greatest number in the long run" (6). These lofty, although somewhat ambiguous, goals still guide Forest Service administration.

Many landmark policies affecting U.S. forests were enacted during this period. The Forest Reserve Act's precedent was copied in the American Antiquities Act of 1906, which authorized the president "to declare by proclamation . . . objects of historic or scientific interest" on the public lands "to be national monuments." The lands had protection against commercial utilization and were open for scientific, educational, and recreation purposes. President Roosevelt used the act to set aside eighteen national monuments, including what later became Grand Canyon, Lassen Volcanic, and Olympic National Parks. Roosevelt also enlarged the forest reserves more than any other president did. When he came to office, there were 41 reserves totaling 46.5 million acres (18.8 million hectares) and by 1907, he had increased the reserves (now called national forests) to 159 and their total area to 150.7 million acres (6l million hectares) (12). Roosevelt's zealous expansion moved Congress, in March 1907, to revoke his authority to establish reserves in six western states. Roosevelt left the act unsigned until after he had reserved an additional 16 million acres (6.5 million hectares) of forestland (12).

The end of this period is marked by a controversy between Pinchot and Secretary of the Interior Richard A. Ballinger that led President William Howard Taft to fire Pinchot as chief of the Forest Service in January 1910. Actually, Pinchot had decided several months earlier to "make the boss fire him" (12). Taft's policies upset Pinchot, because, in his view, they did not carry on the traditions of President Roosevelt and the philosophy of conservation.

Sidebar 1.3

The Father of American Forestry

You may describe a Forester from the standpoint of his specialized education and his application of technical knowledge to the protection and management of the forest, but you can not stop there. There is another concept that is equally important. Every Forester is a public servant, no matter by whom employed. It makes no difference whether a Forester is engaged in private work or in public work, whether he is working for a lumber company, an association of lumbermen, a group of small forest owners, the proprietor of a great estate, or whether he is a forest officer of State or Nation. By virtue of his profession a Forester is always and everywhere a public servant (1, p. 27).

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The father of American Forestry.

Sidebar 1.3 *(continued)*

Gifford Pinchot firmly believed that the forester owed his allegiance to the forest, to the land, and to the profession of forestry. Pinchot is known as the Father of American Forestry because he gave so much to the establishment of professional forestry in the United States. Long respected and practiced in France and Germany, where Pinchot went to study, the forestry profession made its debut in the United States about 100 years ago. When he took over the country's national forests in 1905, Pinchot established the Forest Service as a highly trained group of professional forest managers. On the occasion of the 1905 Transfer Act, he set forth, in the famous Pinchot letter, the decentralized management philosophy by which the Forest Service operated for most of the twentieth century.

Pinchot was a founding member of the Society of American Foresters (SAF). Founded in November 1900 in Pinchot's office, membership was limited to trained foresters. Enthusiasts such as President Roosevelt were relegated to associate member status (2). Today, the SAF remains the premier professional forestry organization.

Pinchot was instrumental in establishing the nation's first forestry school at Yale University and taught there after he left government. He wrote much, including textbooks like *The Training of a Forester* from which the previous quote is taken. This text outlines in detail all the disciplines that a forester must study in addition to silviculture, such as soil science, economics and zoology, to properly manage forest complexities. First published in 1914, the book discusses what a forester does on the job, how, and why.

Much of what modern forestry professionals learn and practice today has roots in European traditions brought to this country by Gifford Pinchot. His life of dedication to the profession, and the courage and foresight he displayed, truly make him worthy of the title Father of American Forestry.

Sources:

1. G. PINCHOT, *The Training of a Forester*, J. B. Lippincott Company, New York, 1937 (originally published 1914).
2. T. M. BONNICKSEN, *Politics and the Life Sciences, 15,* 23-34 (1996).

Important Features of the Period 1891-1911 The period from 1891 to 1911 was one of the most colorful and active in American forest policy history. Specific goals guided forest policy throughout the period. Nevertheless, eliminating waste and bringing the management of national forests up to the standard hoped for by Pinchot and Roosevelt constituted too great a task given meager funding and little time. Creation of the Forest Service, establishment of a national forest system, and crystallization of a utilitarian conservation philosophy to guide their management represented the greatest forest policy accomplishments.

Organization, Action, and Conflict (1911-1952)

The United States faced enormous difficulties and hardships from 1911 to 1952. The world went to war twice, taking a frightening toll in human lives and property, and underwent the agonies of the Great Depression. In the United States, disastrous floods regularly ripped through settled valleys. At the same time, drought cycles and improper farming practices on the Great Plains drove farmers off the land as the soil and their livelihoods blew away during the Dust Bowl era. Intolerable working conditions and low wages also drove urban laborers to protest in the streets.

These were difficult years, but also relatively simple years, in that forest problems were clearly understood by most people and goals, though always controversial, were also clear. These goals included: 1) keeping watersheds of navigable streams and rivers covered with vegetation to reduce flooding and sedimentation, 2) keeping sufficient wood flowing out of forests to meet the nation's requirements for building its industries and successfully ending its wars, 3) protecting the nation's forests from overexploitation and losses from insects, diseases, and fire, and 4) using forest resource production from public lands to reduce unemployment during the Great Depression and to stabilize the economies of communities dependent on local forests. In addition, a small but influential segment of society inspired the public to preserve tangible parts of the United States' cultural and natural heritage.

Conservation versus Preservation By 1910, the conservation philosophy of Catlin, Thoreau, and Muir was gaining ground as private organizations formed to represent this view. These "aesthetic conservationists," or preservationists, differed significantly from "Pinchot" or "utilitarian conservationists." Preservationists concentrated their efforts on protecting natural beauty and scenic attractions from the lumberjack's axe and miner's pick by placing them within national parks. Utilitarian conservationists' philosophy was rooted in the idea that resources must be "used." They referred to preservationists as "misinformed nature lovers" (12). This difference of opinion finally led preservationists to break away from the organized conservation movement because it was dominated by utilitarian philosophy. When conservationists and preservationists ceased to be allies, conflict over public lands disposition and management was inevitable. This conflict has grown in intensity. By the 1960s and 1970s, it dominated American forest policy.

In the early 1900s, conflict between preservationists and conservationists centered on partitioning public lands. At first, preservationists focused on creating a separate agency to manage national parks. Pinchot countered by trying to consolidate national parks with national forests. Although preservationists succeeded in gaining support from Taft and Ballinger, Pinchot argued that such an agency was "no more needed than two tails to a cat" (12). He carried enough influence in Congress to block the proposal. However, Secretary of the Interior Franklin K. Lane rescued the preservationists by placing all national parks and monuments under the jurisdiction of an assistant to the secretary. He filled the post with Steven T. Mather, a wealthy preservationist who helped usher the National Park Act of 1916 through Congress and was named first director of the National Park Service. Preservationists thus obtained an administrative home in the Department of the Interior and a champion to expand and protect the national park system.

Pinchot was no longer chief of the Forest Service, but his successors, Henry S. Graves (1910-1920) and William B. Greeley (1920-1928), were utilitarian conservationists. Furthermore, Pinchot continued to be influential with Congress, both as an individual and through the National Conservation Association. Thus, the adversaries were firmly entrenched in two separate agencies within two separate federal departments, each with its own constituency. Their first contest centered on the fact that the national forests contained most of the public land suitable for national parks, and the National Park Service was anxious to take these lands away from the Forest Service. The Forest Service was not hostile toward national parks, but as Chief Forester Graves said, "the parks should comprise only areas which are not forested or areas covered only with protective forest which would not ordinarily be cut" (8). The problem was philosophical as well as territorial. The Forest Service did not want to give up land it was already managing and therefore countered Park Service advances by vigorously resisting withdrawal of national forestland for park purposes. The Forest Service also continued its efforts to develop a recreation program that it hoped would make new national parks unnecessary.

Forest Recreation The Forest Service recreation program represented a response to a technological innovation—the automobile—and expansion of roads pleasure-seekers used to gain access to national forests. In 1907, there were about 4,971 miles (8,000 kilometers) of roads in all national forests. The need for roads increased with automobile use, and between 1916 and 1991 over $33 million was spent on roads in and near national forests (10). These roads brought in so many recreationists that rangers, concerned about fire hazards and other conflicts with commodity uses, sought to discourage them by concealing entrances to new trails and leaving roads unposted (10). The tide of recreationists could not be turned, however, and the Forest Service reluctantly began providing for their needs.

One of the celebrated accomplishments in national forest recreation was establishment of the nation's first designated wilderness area. In 1918, a road was proposed that would cut through the Gila River watershed in New Mexico. Aldo Leopold, an assistant district forester for the Forest Service, protested against the road, claiming, "the Gila is the last typical wilderness in the southwestern mountains" (10). He then proposed designating the watershed as a "wilderness" without roads or recreational developments. No action was taken on his proposal. Then, in 1921, when an appropriation of $13.9 million for developing forest roads and highways passed Congress, he publicly expressed his proposal for wilderness protection. He defined wilderness as "a continuous stretch of country preserved in its natural state, open to lawful hunting and fishing, big enough to absorb a two weeks pack trip, and kept devoid of roads, artificial trails, cottages or the works of man" (10). This definition has remained relatively unchanged until the present. It took nearly three years for Leopold to convince the district forester of New Mexico and Arizona to approve the Gila Wilderness plan. While this was a local decision, criticism of the Forest Service by preservationists mounted and the Park Service increased its acquisition of national forests, leading Forest Service Chief Greeley to establish a national wilderness system in 1926.

The Forest Service was still a popular and aggressive agency even though it spent part of its time defending against incursions from the Park Service. The momentum of the Roosevelt-Pinchot era had slowed somewhat, but the Forest Service maintained a strong sense of mission. It advanced on four fronts: expanding national forests in the East, promoting forest research, developing the national forests, and regulating forest practices on private land.

Preservationists lobbied to add lands to the national forest system in the East. As early as 1901, the Appalachian National Park Association joined with other private organizations to petition Congress to preserve southern Appalachian forests. However, most public lands in the East had already passed into private ownership, so additional national forests would have to be purchased. Congress authorized studies but no purchases. A few years later, the Society for the Protection of New Hampshire Forests joined forces with the Appalachian group, and together they succeeded in securing passage of the Weeks Act of 1911 (11). The Weeks Act specified that the federal government could purchase lands on the headwaters of navigable streams and appropriated funds. This restrictive language reflected a congressional view that the government had the power to buy land for national forests only if the purchase would aid navigation. Naturally, advocates of eastern reserves, including Pinchot, shifted their arguments from an emphasis on forests themselves to the role of forests in preventing floods and reducing sedimentation. These arguments worked and, influenced by the great Mississippi flood of 1927, Congress accelerated acquisition of forestland when it passed the Woodruff-McNary Act of 1928 (13). By 1961, over 20 million acres (8.1 million hectares) of forestland, mostly in the East, had been purchased (8).

Forestry Research The second major task of the Forest Service was expanding efforts in forest research. Documenting relationships between forests and streamflow accelerated forest research activity. However, reforesting cutover lands, increasing yields, and reducing waste through greater utilization of trees were also important research goals. Raphael Zon deserves much credit for the Forest Service research organization. He emphasized applied research, stating that "science . . . must serve mankind" (13). In 1908, he presented a plan to Pinchot to establish forest experiment stations on key national forests. Pinchot, recalling his response, said that "I had seen forest experiment stations abroad and I knew their value. The plan, therefore, was approved at once" (11). When Pinchot left office in 1910, he had established two forest experiment stations and authorized the construction of the Forest Products Laboratory in Madison, Wisconsin.

Congress was tightfisted with research funding over the next fifteen years. A big boost came in 1925, when enough funds were appropriated to add six new experiment stations. Yet funding was haphazard, severely limiting research activities. With Greeley's enthusiastic support, the Forest Service obtained assistance from private groups to lobby Congress for long-term research funding. Their efforts paid off in 1928 with passage of the McSweeney-McNary Act. This act raised research to the same importance as other Forest Service functions such as timber and grazing. Furthermore, the act increased appropriations for forest research and authorized a periodic nationwide survey of timber resources in the United States.

Civilian Conservation Corps Development of national forests received increased attention when President Franklin D. Roosevelt established the Civilian Conservation Corps (CCC) by executive order on April 5, 1933, as part of his New Deal. In a March 21, 1933, document asking Congress for its support, Roosevelt detailed his goals as not only "unemployment relief during the Great Depression but also advanced work in "forestry, the prevention of soil erosion, flood control, and similar projects." He thought of the CCC as an investment "creating future national wealth" (9). Between 1933 and 1942, when the CCC started to disband because of World War II, over two million people worked in the program with as many as a half million enrolled at one time (Figure 1.4). The Forest Service received nearly half the projects, but the Park Service and other federal agencies also received substantial aid from the program (8). Although some people criticized the CCC for hiring enrollees from lists of Democrats (8), its accomplishments

Figure 1.4 Civilian Conservation Corps camp in the territory of Alaska. (Courtesy of U.S.D.A. Forest Service.)

outweighed its problems. Young people built trails, thinned forests, fought fires, planted trees, and constructed campgrounds and other facilities. Their efforts substantially advanced the development of the national forests.

Regulation and Control of the Forests The most controversial action by the Forest Service during the period was its attempt to regulate private forest management. The agency had played an advisory role in private timber management until passage of the Transfer Act of 1905, when much of its attention shifted to managing the newly acquired national forests. Cooperation with private owners was generally accepted as beneficial to all concerned at the time. However, Pinchot later recalled that he had been "misled" into thinking that timber owners were interested in "practicing forestry" (11).

Regulation created a split in professional forester ranks. A Pinchot-led faction favored federal control, and Forest Service chiefs Graves and Greeley led the state control fight. Pinchot argued that "forest devastation will not be stopped through persuasion" but by "compulsory nation-wide legislation" (6). Pinchot believed that the lumber industry could control state legislatures. In his view, only the federal government had the power to enforce regulations. The Forest Service argued that federal regulation was unconstitutional and the federal role should focus on cooperation rather than direct intervention in private forest management. The line was drawn and Congress became the battlefield. Bills favored each position, and both sides stood firm. Pinchot said it was "a question of National control or no control at all" (8). The bills stalled. Greeley then proposed a compromise measure that dropped regulation entirely and emphasized fire control. After all, he contended, timber cutting was "insignificant" in comparison to wildfires as a cause of deforestation (8). Pinchot agreed (8), and Congress passed the Clarke-McNary Act of 1924.

Although the Weeks Act previously authorized state and federal cooperation in fire control, Clarke-McNary expanded cooperation into other areas. It enabled the Secretary of Agriculture to assist states in growing and distributing planting stock and in providing aid to private owners in forest management. These two acts stimulated the establishment of state forestry organizations throughout the country. The Clarke-McNary Act also expanded the Weeks Act provisions for land purchases. Clarke-McNary set a precedent by authorizing purchase of land in the watersheds of navigable streams for timber production as well as streamflow protection. Purchase of timberland, particularly after it had been logged, was one approach to solving the deforestation problem on which most parties could agree. Overall, the Clarke-McNary Act is one of the most important pieces of legislation in American forest policy.

World War II increased the nation's timber appetite. Great quantities of timber were harvested from both public and private lands, and certain important tree species were in short supply. For example, loggers almost cut in Olympic National Park because of the need for Sitka spruce to build warplanes. Rapid cutting to satisfy wartime timber requirements also intensified the public-regulation controversy. Timber executives mounted a major publicity campaign to thwart further federal regulation. They were particularly concerned about attaching conditions to cooperative funds allocated under the Clarke-McNary Act.

Heightened pressure on forest resources induced by war and by proposed federal regulations motivated passage of forestry legislation at the state level. For example, the continued threat of federal control helped lumber interests decide to support state laws as the least offensive alternative. By 1939, five states had enacted legislation to curtail destructive cutting practices, but they were ineffective. The Oregon Forest Conservation Act of 1941 set a precedent for more effective state action, aimed primarily at securing and protecting tree reproduction, including several specific and quantitative guidelines. Landowners had to obtain an approved, alternative timber management plan to deviate from practices specified in the law. Likewise, the state forester could correct problems on timberlands caused by violating the law and charge the owners. Similar acts passed in Maryland (1943), Mississippi (1944), Washington (1945), California (1945), and Virginia (1948). Other states, such as Massachusetts (1943), Vermont (1945), New York (1946), and New Hampshire (1949), relied on incentives and voluntary control of cutting on private land (6).

At the federal level, Congress enacted two major forest policies in 1944. Congress amended federal income tax laws to allow timber owners to declare net revenue from timber sales as capital gains instead of as ordinary income. This law reduced taxes and helped to encourage timber owners to retain forestland in timber production. It also helped to discourage them from abandoning land to avoid paying delinquent taxes.

Congress also passed the Sustained Yield Forest Management Act of 1944. Sustained yield, in a general sense, means that an area is managed to produce roughly equal annual or regular periodic, yields of a resource such as timber. This concept can be traced back centuries in Europe where timber resources were scarce, and predictable, steady yields were essential. The U.S. frontier economy made this approach politically difficult until war-induced shortages helped to make the idea more acceptable. However, the Sustained Yield Forest Management Act focused on safeguarding forest-dependent communities from local timber shortages rather than national needs. The act authorized the Secretaries of Interior and Agriculture to establish sustained-yield units of either federal timberland or a mixture of private and public timberland. Thus, the secretaries could enter into long-term agreements with private forest owners to pool their resources with the government to supply timber to local mills. Opposition from small companies and labor unions prevented the establishment of more than one cooperative sustained-yield unit. However, the Forest Service did establish five federal sustained-yield units on national forests (8).

In 1946, President Truman signed an executive order to create the Bureau of Land Management (BLM) (22). This order combined the lands in the Department of the Interior held by the Grazing Service and those still held and managed by the General Land Office, which was established in 1812 to survey lands and manage the transfer of territory to private hands. The BLM owns great tracts of timberland in the western United States, most acquired through default of original grantees of federal lands.

The rapid and destructive cutting practices associated with the war left behind millions of acres that were not producing timber. Equally troubling was the fact that timber harvests exceeded forest growth. The Forest Service laid blame squarely on the shoulders of private timberland owners. The debate became acrimonious and technical arguments were set aside as the issue degenerated into an emotional squabble. One timber industry representative accused the Forest Service of leading the country into "totalitarian government and ultimately socialism," and even called the Assistant Chief of the Forest Service, Edward C. Crafts, a "dangerous man" because Crafts felt the public had the right to protect its interests in private land (8). Dwight D. Eisenhower settled the debate when, during his campaign, he said that he was against "federal domination of the people through federal domination of their natural resources" (8). Eisenhower became president in 1952. He appointed Governor Sherman Adams of New Hampshire, a fomer lumberman, as his presidential assistant. Adams stated earlier that natural resources could be conserved and distributed "without succumbing either to dictatorship or national socialism" (8). The Forest Service, sensing that the election might bring a philosophical change, moved to have Richard E. McArdle appointed chief, in part because he was not identified with the regulation issue (14). The decision proved sound. McArdle dropped the Forest Service regulation campaign and retained his position through the change of administrations.

Important Features of the Period 1911-1952 An evaluation of forest policies between 1911 and 1952 shows the usual mixture of success and failure. The goal of preventing forest resource overexploitation conflicted with that of furnishing wood needed to fight World Wars I and II. Maintaining forest cover in the headwaters of navigable streams was only partially accomplished. The government could not purchase all such watersheds, and purchased cutover lands were not always reforested. Technological constraints and shortages of money and workers during much of the period made it difficult to protect forests adequately from insects, diseases, and fire.

Nevertheless, the period produced at least four major accomplishments, although none of them represented a major societal goal when the period began. First, the National Park System grew in size to include the nation's most scenic areas and a new agency was established to coordinate their management. Second, the Forest Service established a wilderness system. Third, cooperative arrangements in forest management developed among state, federal, and private timberland owners. Finally, the CCC converted the adversity of the Great Depression into a significant contribution to the development of U.S. forests.

Adjusting to Complexity (1952-present)

Although the forest policy problems of previous periods were never simple, they still seem more comprehensible then the problems faced by contemporary society. Since World War II, the United States has experienced unparalleled material affluence and technological advances. A burgeoning population has heightened competition for essential natural resources. After World War II came a rapid growth in timber demand, particularly for housing construction, that resulted in a continuation of destructive logging practices. Timber needs were too great to be satisfied from private lands alone, so heavy logging reached into the national forests. At the same time, prosperity, supported by rapid exploitation of natural resources, made it possible for people to spend more of their leisure time in the nation's forests, leading to "mass recreation." The numbers of people visiting the nation's wildlands increased tremendously and the nature of those visits changed to include more ' cars and developed recreational sites (22). Extractive use and intensive recreational use, other than hunting, generally conflict with each other. Therefore, issues in the 1950s and 1960s were broader than issues that divided preservationists and utilitarian conservationists in previous periods.

Global events such as the Cold War, the wars in Korea and Vietnam, and the Watergate scandal played an important role in the development of forest policy. The Government's lack of candor concerning these events caused a large segment of society to become suspicious of many public officials and, consequently, distrustful of those in authority, including professional foresters. Public demands for citizen participation in resource management decisions were largely a result of this lack of trust. Professional foresters were unprepared for this intense public scrutiny.

Most forest policy goals from 1911 through 1952 carried over into the current period. The end of Forest Service efforts to impose federal regulation on private forest management in 1952 was a major turning point for the forestry profession. Foresters accustomed to strong public support for the way they managed forests now became defensive. They also faced the challenges of reducing conflicts over resource uses, and providing a growing nation with more goods and services from a fixed land base. Achieving these goals had become more difficult in the political and economic complexity of the period and the resulting uncertainty. In 1981, tax cuts and recession created a $200 billion annual federal deficit, followed by major budget reductions in federal forestry programs (15). Then, in 1982, stumpage prices fell 60 percent because housing construction declined sharply. Consequently, the timber industry began selling timberland and cutting back on personnel and operations.

Multiple Uses of the Forests Recreational use of national forests grew steadily during the pre-World War II years, but never reached parity with timber production as an objective of forest management. Recreation achieved formal recognition as an objective in 1935 when the Division of Recreation and Lands was created in the Forest Service. However, much recreation spending was on campgrounds and other facilities to keep recreationists confined and out of the way of commodity users. Fire prevention was also an important reason for concentrating people in campgrounds (16), particularly in southern California.

Following WWII, a huge demand for forest products dominated the attention of professional foresters, but they overlooked the equally enormous growth in recreation. For example, recreation visits to national forests climbed from fewer than 30 million in 1950 to about 233 million in 1982 (17, 18). The explosive increase in recreational use revived the idea, prevalent in the 1930s, that the Park Service should administer recreation. This spuned competition between the National Park Service and the Forest Service over authority to administer recreational use of public lands.

In 1956, the National Park Service received funding for its "Mission 66," a ten-year plan to expand and upgrade recreational facilities in national parks. The Forest Service, not to be left out, responded with Operation Outdoors in 1957 to garner funds for recreation on national forests, with a focus on the more "primitive" recreation available in national forests as opposed to the more developed opportunities found in national parks. Operation Outdoors laid a critical foundation for the first Forest Service effort to emphasize nontimber uses. On the other hand, the BLM also tried for recreation dollars with its Project 2012 (to celebrate the 200th anniversary of the creation of the General Land Office), but it was less successful.

While getting funding for Operation Outdoors, Forest Service attempts to increase other recreation funding met with limited success because of a lack of statutory responsibility to provide recreational facilities on national forests (16). The Forest Service had to find a way to increase its recreational budget and at the same time protect itself from what it viewed as unacceptable demands from the timber industry, the grazing industry, and the Park Service for exclusive use of certain national forest lands. The concept adopted for defending the agency was "multiple use." In other words, the Forest Service felt that obtaining congressional endorsement to manage lands for several uses, including grazing, wildlife, recreation, watershed, and timber, would both legitimate the agency's management of all resources and enhance its funding position in Congress. The legal vehicle was the Multiple Use-Sustained Yield Act (MUSY) of 1960, through which Congress directed that national forests be managed for outdoor recreation, range, timber, watershed, and wildlife and fish purposes.

Although Edward C. Crafts said, "the bill contained a little something for everyone" (19); it was nevertheless opposed by the timber industry, the Sierra Club (a preservationist group), and the Park Service. The lumber industry thought that timber had always been given the highest priority in national forest management and that the bill would eliminate this preferential treatment by placing all resources on an equal level. Their opposition to the bill turned into mild support when the bill was amended to include the following phrase: "The purposes of this Act are declared to be supplemental to, but not in derogation of, the purposes for which the national forests were established as set forth in the Act of June 4, 1897" (10). In other words, since the Organic Administration Act of 1897 specified timber and water as the resources that forest reserves were meant to protect, they felt that these resources would be given a higher priority than other resources. However, it is generally agreed this ranking covers the establishment of national forests and does not extend to forest management (19, 20).

The Sierra Club opposed the multiple-use bill for two reasons. First, members wanted wilderness added to the resource list so that wilderness would recieve equal but separate recognition from recreation. This issue was partially resolved when the bill was amended at the request of the Wilderness Society to state that wilderness was "consistent with the purposes and provisions" of the bill (21). Second, the Sierra Club and the Park Service believed the real purpose of multiple-use was to stop the Park Service from taking national forest lands to make national parks. However, they failed to include an amendment stating that the bill would not affect creation of new national parks (19). President Eisenhower signed the Multiple Use-Sustained Yield Act of 1960 even though it did not fully satisfy the Sierra Club and the Park Service.

The Multiple Use-Sustained Yield Act has been successful in accomplishing the Forest Service's goals. The Forest Service preserved its broad constituency, its political flexibility, and its varied responsibilities. However, the boost in congressional funding for nontimber resources that was expected to follow passage of the act did not materialize. Only wildlife management received a significant average increase in funding relative to Forest Service requests (20) (Figure 1.5).

One unresolved multiple-use issue involves priorities for allocation among uses. The Multiple Use-Sustained Yield Act evades priorities entirely. It mandates that all uses mentioned are appropriate for national forest management; that all uses will be given equal consideration; that all uses will be managed according to sustained-yield principles; and that land productivity will not be impaired. Now the broader concept of "ecosystem management" integrates multiple-use management within the higher priority of sustaining an ecological system. The Forest Service adopted this concept by an administrative decision. However, this decision creates new issues because it raises the standard of sustaining an ambiguous, and possibly undefinable, ecological system above all other purposes for national forests specified in existing law.

The Wilderness System MUSY did not eliminate Forest Service problems with single-use advocates.

Figure 1.5 Bull moose in the Gallatin National Forest, Montana. (Courtesy of U.S.D.A. Forest Service.)

The wilderness issue remained. Creation of a wilderness system aided the agency in defending its boundaries, but also created a preservation-oriented constituency that wanted to protect scenic and roadless areas against Forest Service commodity use programs.

Over the years, the Forest Service added to its wilderness system and refined administrative regulations. The agency developed a classification scheme including a continuum of protection levels from primitive areas, which permitted some roads and logging, to wild and wilderness areas that prohibited these activities. In 1940, the Forest Service extended greater protection to primitive areas as well (10). However, wilderness enthusiasts watched as the Forest Service gradually reduced the size of wilderness, wild, and primitive areas. Logging roads advanced and technology increased timber utilization in remote areas, so pressures to open protected lands to harvesting increased. Because the Forest Service could change wilderness boundaries, preservationists sought increased security from congressional action for wilderness designation. In addition, they wanted to establish wilderness on other federal lands, particularly within national parks and monuments. After eight years of debate and eighteen public hearings, Congress passed the Wilderness Act of 1964 (Figure 1.6).

The wilderness system created by the Wilderness Act set aside 9.1 million acres (3.7 million hectares) of land in fifty-four areas that the Forest Service originally identified as wilderness and wild areas. Some existing uses of the land, like grazing, could continue. Similarly, mineral prospecting could continue until 1983 (22). National Park Service lands were not included in the original wilderness areas, but Congress designated some lands for study and many wilderness areas now exist in national parks. Bureau of Land Management lands were not included under the Wilderness Act until passage of the 1976 Federal Land Policy and Management Act (22). This act legislatively authorized

Figure 1.6 Packing into the Pecos Wilderness Area of the Santa Fe National Forest, New Mexico. (Photograph by Harold Walter, courtesy of U.S.D.A. Forest Service.)

the BLM, defining a land management mission more than thirty years after executive reorganization established the Bureau (22).

One of the more interesting debates concerned the renewability of wilderness as a resource. The Forest Service stated that wilderness could not be renewed. In other words, land used for other purposes could not be restored to its original wilderness character. On the other hand, preservation groups contended that "certain areas not wilderness ... if given proper protection and management can be restored and regain wilderness qualities" (23). This was an important issue in the eastern United States because timber production and agriculture had already affected much public land. The Forest Service felt that most of these lands no longer retained their original character, so it resisted attempts to classify wilderness areas in the East. Instead, it proposed a new eastern roadless area system that would be less restrictive and separate from the national wilderness preservation system. Preservationists refused to accept this alternative and succeeded in pressuring Congress to pass the Eastern Wilderness Act of 1975. The act added sixteen new areas to the wilderness system totaling nearly 207,000 acres (83,772 hectares). An additional 125,000 acres (50,587 hectares) in seventeen areas in national forests were set aside for the Secretary of Agriculture to evaluate for possible inclusion in the wilderness system.

Wilderness advocates could not satisfy their appetite for land. Their sights included all national forest roadless areas as well as congressionally designated wilderness study areas. The Forest Service responded in 1967 by conducting a nationwide inventory and evaluation of roadless lands within national forests for wilderness suitability. The procedure known as RARE (Roadless Area Review and Evaluation) identified 1,449 sites containing approximately 56.21 million acres (22.7 million hectares). In 1973, the chief of the Forest Service designated 235 of these sites for further study as possible wilderness areas.

Many people criticized the RARE process, so a new RARE II process began in 1977. In January 1979, Secretary of Agriculture Bob Bergland made public the results and recommended to Congress that 15.1 million acres (6.1 million hectares) of national forests be added to the wilderness system, and that an additional 11.2 million acres (4.5 million hectares) be held for "further planning" because of a need for more reliable information on mineral deposits. There was hope that this recommendation would bring resolution to the wilderness question. However, preservationists reacted with "acute disappointment" to the recommendation, feeling that it fell short, while the timber industry argued that it was excessive (24).

Advocates were still demanding more wilderness twenty years after passage of the Wilderness Act. Therefore, the Ninety-eighth Congress added 6.9 million acres (2.8 million hectares) of wilderness to the system, bringing the total to 32.4 million acres (13.1 million hectares). The Eastern Wilderness Act and subsequent congressional actions led to a gradual change in the standards used to judge wilderness quality. Today, many groups use wilderness designation as a way to preserve areas that would not have qualified as wilderness under provisions of the Wilderness Act of 1964. In Wisconsin, for example, one wilderness area contains a red pine plantation. Likewise, current forests in many western wilderness areas are growing so thick that wildfires often burn hotter than would have occurred in the historic forests. These extremely hot fires threaten local communities and devastate the wilderness character of the land. Thus, wilderness is gradually losing its distinction as the repository of the last remnants of the historic American landscape. Clearly, wilderness issues will be around for some time.

The Clearcutting Issue Wood consumption increased in the 1970s at the same time that environmental constraints, such as air and water pollution control and restrictions on the use of pesticides and herbicides, were limiting timber production. Furthermore, net losses of timberland in all ownerships to nontimber purposes averaged about 4.9 million acres (2 million hectares) per decade. Consequently, foresters believed that wood shortages could develop at some point in the future. Although their apprehensions have not been borne out, preservationists and land managers still disagree over which methods are best for producing timber.

The focal point of the debate is clearcutting, which is a regeneration method in which all the trees on a certain area of land are cut and the site regenerated by natural seeding, seeding from aircraft, or replanting of pioneer tree species that grow in openings. Preservationists claimed that clearcutting has "an enormously devastating environmental effect which includes soil destruction, stream siltation, and a stinging blow to the aesthetic sense" (25). Where properly applied, clearcutting is less damaging than wildfire but, like a wildfire, little can be done to reduce the unpleasant appearance of a recent clearcut.

Concern over national forest management practices erupted in November 1970, when Senator Lee Metcalf of Montana released the Bolle Report, titled *A University View of the Forest Service,* and put it into the Congressional Record. Scientists from the University of Montana prepared the report at Metcalf's request. The report not only criticized Forest Service management practices, but it also uncovered a deep division within professional forester ranks. The problem began in 1968 when residents of Montana's Bitterroot Valley complained that clearcuts damaged the national forest surrounding them. Most disturbing to local residents was the Forest Service's practice of terracing steep mountain slopes to prevent erosion and improve timber reproduction. The Forest Service received a torrent of letters demanding that these practices be stopped. The Forest Service responded by appointing a task force to conduct an impartial analysis of management practices in the Bitterroot National Forest. The task force released its findings in April 1970, a full six months before the Bolle committee, and was remarkably candid. Task force members found, for example, that the attitude of many national forest staff was "that resource production goals come first and that land management considerations take second place" (26). The Bolle committee concurred with many of the findings in the task force report, but also found that "the Forest Service is primarily oriented toward timber harvest as the dominant use of national forests" (26). In sum, the Forest Service did an outstanding job of producing timber, but it failed to adjust to changing social values.

The Forest Service modified forest management policies on the Bitterroot National Forest, but disregarded national implications of public concerns over clearcutting. A few months after the Bolle committee report was released, the Subcommittee on Public Lands of the Senate Interior and Insular Affairs Committee, chaired by Senator Frank Church of Idaho, held hearings on public lands management practices, focusing on clearcutting in the national forests, especially in Montana, West Virginia, Wyoming, and Alaska. The subcommittee concluded that clearcutting had to be regulated and found that the Forest Service "had difficulty communicating effectively with its critics, and its image has suffered" (27). Although the Forest Service had taken some actions to adjust to public concerns over clearcutting, the subcommittee felt they "have made little impact" (27). The Forest Service lost the opportunity to make forward-looking revisions in management policies and instead had to accept the Church guidelines.

The clearcutting of hardwood forests in the Monongahela National Forest in West Virginia further increased the controversy, and the issue remains unresolved to this day (Figure 1.7). Clearcutting replaced selective cutting in the Monongahela National Forest in 1964, and the reaction was almost immediate. Concerned citizens pressured the West Virginia legislature to pass resolutions in 1964, 1967, and 1970, requesting investigations of Forest Service timber management practices. A Forest Service special review committee confirmed that abuses had occurred (28). As a result, timber management policies were changed to encourage a variety of harvesting techniques. In addition, clearcuts were limited to 25 acres (10 hectares) or less, and distances between clearcuts were regulated. Since many timber sales were under contract using the old 80-acre (32-hectare) limit, Forest Service reforms could not bring immediate results (29).

These reforms failed to satisfy preservationists. They wanted all clearcutting stopped immediately.

Figure 1.7 Clearcuts (background) on the Monongahela National Forest (Gauley District), West Virginia. (Photograph by R. L. Giese.)

In May 1973, the Izaak Walton League of America and other preservation organizations filed suit alleging that clearcutting violated a provision in the 1897 Organic Administration Act stating that only "dead, matured, or large growth of trees" could be cut and sold from a national forest. In December 1973, Judge Robert Maxwell of the Northern District Federal Court of West Virginia accepted this interpretation. His ruling effectively banned clearcutting on national forests. The Fourth Circuit Court of Appeals unanimously upheld the lower court's decision in 1975, and the Forest Service halted all timber sales on national forests within the jurisdiction of the court. In 1976, the U.S. District Court of Alaska used the same reasoning to issue a permanent injunction against timber harvesting on a large area of Prince of Wales Island. These and similar lawsuits halted timber sales on national forests in six states (30).

The Monongahela decision produced a number of bills in Congress to overcome the timber production bottleneck. For example, a preservationist-sponsored bill would have instituted legislative prescriptions on timber harvesting. Acting with unusual speed, Congress passed an alternative bill titled the National Forest Management Act (NFMA). It was signed into law on October 22, 1976. The act contained many important provisions. Together with the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) (see "Additional Legislation" later in this chapter), the NFMA requires the Forest Service to prepare comprehensive interdisciplinary forest plans for all administrative units at ten-year intervals. By 1986, twenty-five national forest plans were in final form, but most were challenged by interest groups. By the mid-1990s, all forest plans had been finalized and approved by the Forest Service Chief, though court challenges to some plans remain. The NFMA repealed the section of the Organic Administration Act of 1897 that served as the basis for lawsuits that stopped national forest clearcutting. It allows clearcutting when it is found to be the "optimal" (left undefined) silvicultural treatment. Clearcuts today are less extensive and nontimber values, such as wildlife and recreation, have a greater role in decisions about regeneration methods. While the NFMA did not completely resolve the clearcutting controversy, it did make foresters more alert and sensitive to public opinion. The act also brought forest management closer to the multiple-use ideal.

Judicial Involvement in Resource Policy Making The Monongahela decision illustrates the growing importance of courts in forest policy development. In 1978, for example, the U.S. Supreme Court further complicated management of the national forests by handing down the Rio Mimbres decision. The Rio Mimbres flows through the Gila National Forest in New Mexico. The dispute centered on the legal right of the Forest Service to have enough water to manage the multiple uses of a national forest versus the rights of upstream water users who wanted water for irrigation and other purposes. As in the Monongahela decision, the Organic Administration Act of 1897 was used against the Forest Service. The Court interpreted the act to mean that forest reserves were set aside to maintain timber supplies and favorable waterflows. The act did not mention rights to water for other purposes. In essence, the Court ruled that the Forest Service had no legal right to Rio Mimbres water and that it would have to satisfy water needs through state water rights procedures (15). Thus, courts dramatically increased the complexities and uncertainties of national forest management.

The courts normally limit the number and scope of their reviews of administrative decisions. The judiciary gradually became more involved with administrative review as preservationists, frustrated in their dealings with administrators, turned to the courts for relief. The number of suits increased dramatically after the "Scenic Hudson" case of 1965, in which the court decided that an organization whose principal interest is scenic beauty could sue government agencies (31). This decision opened the door to the courts and ushered in judicial involvement in resource policy-making, including the Monongahela case. Lawsuits are expensive, time-consuming, and often embarrassing to the agency involved. Thus, just the threat of a lawsuit can increase participation by citizens in formulating agency policy. Preservationists also use lawsuits as a delaying tactic.

Passage of the National Environmental Policy Act of 1969 (NEPA) and similar legislation enacted by various states greatly expanded opportunities to file lawsuits. NEPA established a detailed procedure for assessing environmental consequences of federal actions significantly affecting the quality of the human environment. These procedures require that agencies consider so many potential effects that it is difficult to fully comply with the law, which invites litigation on procedural grounds alone. Furthermore, NEPA is one of the first environmental policies using "sunshine provisions," which require that decision-making be open to public view and comment. Thus, the public is more aware of regulatory decisions and can quickly respond with legal challenges. This delays decisions and, in many cases, brings about changes in forest policy. The large volume of environmental legislation passed by Congress and the states during the late 1960s and 1970s also provided increased opportunities for lawsuits, in part because the laws included citizen suit provisions that permitted individuals to sue an agency to mandate enforcement of the law.

Additional Legislation The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) was perhaps the most far-reaching forest policy enacted during this period. The RPA was part of a congressional effort to gain greater control of the budgetary process. Congress was reacting to what it perceived as a decline in its authority relative to the executive branch (32). Furthermore, Congress had always shown greater support for resource programs than the executive branch, particularly the Office of Management and Budget (OMB), and RPA was one means of pressuring the president to raise budget requests for natural resources management.

RPA initiated a procedure for setting goals and formulating forest policies. The act requires the Secretary of Agriculture to make periodic assessments of national needs for forest and rangeland resources. Then the Secretary must make recommendations for long-range programs that the Forest Service must carry out to meet those needs. The act required the Secretary to tramsmit the assessment and program to Congress in 1976 and again in 1980. A new assessment was required every ten years thereafter, and the program is to be revised every five years. Subsequent assessments included comprehensive analyses of the forestry and forest products sectors in the United States and worldwide, pointing to a need for improved information to better manage forests under all ownerships. In addition, the president is required to submit a statement to Congress with each annual budget explaining why funding requests differ from the program approved by Congress.

The Forest Service took advantage of the opportunity provided by RPA. In its first budget request under RPA, the agency asked for substantial increases in funds. Congress responded favorably, and President Jimmy Carter signed the appropriations bill for the 1978 fiscal year. The Forest Service budget was raised $275 million over the funding level of the previous fiscal year (33). Subsequent budgets did not do as well. Massive federal deficits forced budget reductions that resulted in a 30 percent decline in national forest funding between 1978 and 1986 (34). While recent federal budgets have not had the sizable deficits of the past, Forest Service budgets have been largely flat or declining in both real and nominal terms as entitlement spending grows.

Although many important policies dealing with forest resources developed during this period, a series of laws adopted for other purposes profoundly affected forest management as well. These policies include enactment of NEPA (already discussed), Clean Air Act of 1970, Federal Water Pollution Control Act of 1972, Federal Environmental Pesticide Control Act of 1922, Endangered Species Act of 1973, Toxic Substances Control Act of 1976, and Clean Water Act of 1977. Two major attributes of these policies are particularly important. First, they rely on complex and detailed federal and state regulation procedures and the exercise of federal police powers. They also mandate public involvement in the regulatory process, including public hearings and comment periods on proposed regulations. Second, they focus on broad environmental goals rather than forestry, yet they influence forest policy. For example, Section 208 of the 1972 Federal Water Quality Act amendments required the establishment of enforceable best management practices to control water pollution. These practices apply to timber harvesting and silvicultural treatments on public and private forestlands, and they further complicate the forest policy process (35).

The 1980s saw much litigation concerning forestry move through the courts and relatively little legislation move through Congress. The idea of "conflict resolution" became a natural resource management specialty because lawsuits proved too cumbersome and time-consuming for use in resolving disputes over resource use. Mediation and stakeholder meetings to collect information, assure that all viewpoints are aired, and hammer out possible solutions were hailed as the future of public natural resource management, as indeed they have become. Those most closely involved in an issue come together to work out a solution that is acceptable to everyone.

After more than a decade of litigation over the adequacy of national forest plans in meeting all of the requirements imposed by RPA, NFMA, NEPA, and various other laws, and squabbles over wilderness, the Endangered Species Act of 1973 (ESA) moved to center stage in the 1980s, 1990s, and 2000s. It may be the most important law affecting forest policy development in the United States. Although not originally controversial, the ESA became more onerous to many agencies and landowners as the U.S. Fish and Wildlife Service became more aggressive in carrying out its provisions. Thus, subsequent amendments attempted to ease the burden on affected interests, but with limited affect. For example, the 1978 amendments created the "God Squad," a presidentially appointed cabinet-level committee convened to evaluate situations where a species' critical habitat designation and recovery measures have a profound economic or other impact. Subsequent amendments allowed private landowners to be issued "incidental take permits" in return for developing a habitat conservation plan for the at-risk species where the critical habitat involves private land.

Perhaps the most well known ESA impact on forestry stems from listing the northern spotted owl as a threatened species in northern California, Oregon, and Washington. This decision curtailed harvesting of old growth forests (generally more than 200 years old) by court injunctions in 1989. Hundreds of sawmills and other processing facilities utilizing this timber shut down, causing economic depression in the myriad small towns in which these facilities were major employers. The loss of public timber also shifted the burden of meeting the nation's wood fiber needs to private forest landowners and it dramatically increased reliance on foreign imports. Since most of the remaining old growth forests in this region are on federal lands (Forest Service or BLM), government appeared on all sides of the debate: as land manager, as enforcer of the ESA, and as states and counties which stood to lose substantial revenues because so much timber harvesting had ceased. The rhetoric surrounding this issue was extreme, some local economic losses were severe, and emotions remain high. Matters reached such a level that the God Squad was convened under the ESA to determine whether some timber sales in process on BLM lands would be allowed to continue.

In the South, the red-cockaded woodpecker (RCW) was listed as endangered in 1970. The effects on Southern forestry have been much smaller than in the Pacific Northwest, in large part because remaining RCW habitat is mostly on public land, which is a small part of commercial forestland in this region.

The U.S. Supreme Court ruled on many of the issues surrounding the presence of endangered species on forested lands. In particular, the Court clarified how the ESA applies to private lands. Private property rights are a precious part of America's cultural heritage, so balancing the rights of landowners against the public interest remains a legal issue. A 1995 Supreme Court decision in *Babbitt v. Sweet Home, et al.* affirmed that the ESA applies to private lands and that a habitat conservation plan is the remedy for landowners. However, these plans are expensive to prepare and difficult to implement. Consequently, efforts are underway to find workable alternatives for small landowners. "Safe Harbor" is one proposed remedy under which small landowners can agree, as part of a statewide habitat conservation plan, to maintain some habitat on their lands for a given number of animals (36). Under "Safe Harbor," small landowners can work together by trading agreements. It is possible for one landowner to maintain all needed habitat in an area. Then other landowners compensate the owner who accepts responsibility for maintaining the habitat so that they are free to harvest timber on their lands.

A group of concerned citizens in Quincy, California, pioneered another innovative alternative to public forest management. They are known as the Quincy Library Group because they met in the town library. They succeeded in forging a compromise plan to protect their community from two interrelated problems. First, they needed a way to revitalize the local economy that had suffered from reduced timber harvests on public lands. In addition, the lack of forest management allowed trees to become denser and dead fuel began piling up underneath them. Therefore, their community also faced a growing threat from wildfires. After several years in development, their plan to resolve these issues became law in The Herger-Feinstein Quincy Library Group Forest Recovery Act of 1999, which passed in Congress as an amendment to the Omnibus Appropriations Bill. Similar programs for local participation in forest management exist in several communities, such as the Applegate Partnership in southwestern Oregon. However, the Canadian government has gone farther than any other country's in creating opportunities for local participation. They launched their Model Forests

Sidebar 1.4

Rediscovering the Local Community

Today's forest management issues frequently involve vast areas of land and national interests. Local communities that must live with decisions to resolve such issues often become victims of the policy process rather than participants. Furthermore, the grand scale of these issues makes relationships within them highly complex, which increases uncertainty about the consequences of actions designed to resolve the issues. National interest groups, who lack detailed firsthand knowledge of local conditions, further complicate such problems by ignoring uncertainties, and oversimplifying issues so that they can prescribe simple solutions. Decisions reached in this manner often generate unanticipated and undesireable social and ecological side effects. Many of these side effects are so serious that they ignite further conflict. Keeping decision making centralized at the national level cannot break the cycle of conflict, simplistic solutions, and new conflicts that such decisions inevitably generate.

Conflict can be a constructive force in an open society, but it has limits. Conflict often focuses on the outcome of a decision. The process that leads to a decision may not be as important to interest groups as winning. Further conflict then develops because the needs of losers in the process remain unfulfilled. This is another reason why conflict often fails to deliver acceptable or sustainable decisions.

Cooperation focuses on the process that leads to a decision. It represents recognition by the participants that there are no right or wrong answers, only acceptable solutions. People who work together for their individual and common interests develop a better understanding of each other and the issue being addressed. Thus, cooperation usually leads to mutual respect and it increases the likelihood of achieving a durable consensus (1).

Decades of conflicts over forest management have led to weariness with endless lawsuits and acrimonious debates. Decisions that resulted from these debates tended to ignore some groups and favor others, which led to frustration and a search for new ways to reduce conflict by promoting cooperation. What has emerged is the rediscovery of the local community. In the United States, the two best-known local groups working to resolve forest management issues are the Quincy Library Group and the Applegate Partnership. They both developed from efforts by local community leaders, loggers,

Program in 1992 through the Canadian Forest Service. Now the program is international, with ten forests in Canada, three in the United States, including the Applegate Partnership, and seven more in such countries as Chile, Russia, Mexico, and Japan.

Small Private Forestry Landowners who do not have a wood-processing facility are called nonindustrial private forest (NIPF) landowners (also see Chapter 10 on NIPFs). Much forest policy focuses on NIPF landowners because they own about 60 percent of the commercial timberland in the United States. For example, the Clarke-McNary Act of 1924 targets NIPFs of less than 1,000 acres (404.7 hectares). These NIPF landowners can obtain cost sharing for reforestation and technical assistance if they meet certain criteria. The Forestry Incentives Program of 1973 provided further assistance to small landowners. States administer many of these cooperative programs.

farmers, ranchers, and environmentalists who came together because conflict was damaging their communities. They are all striving to achieve the same goal: a sustainable balance between human well-being and healthy and productive forests.

The Applegate Partnership deals with issues involving all forest ownerships in the Applegate River watershed in southwestern Oregon. There is no hierarchy, nor are there officers, and the chair position rotates at each meeting. Thus, all participants have equal status and the meetings are open to everyone. Public and donated funds support the organization, and members work to ensure that all interests are respected and fairly considered in decisons.

The Quincy Library Group concentrates on national forests around the town of Quincy, California. Anyone who shows up at a meeting can join, and decisions are made by consensus, because each member has a veto. They reached a consensus on a forest management plan for the surrounding forests that was rejected by national environmental groups and the Forest Service, so the Quincy Library Group went to Congress. The result was the passage of the Herger-Feinstein Quincy Library Group Forest Recovery Act of 1999 that requires the Forest Service to carry out a national forest management plan similar to the one proposed by the group.

Canada has taken a different path to cooperation. The government, through the Canadian Forest Service, created a Model Forest Program. It encourages stakeholders, scientists, and public and private landowners to work together to develop sustainable forests that incorporate a broad range of values. The program began with ten Model Forests, but the idea is so popular that it is now part of the International Model Forest Network. To date, there are Model Forests in six countries and the list is expanding. Thus, rediscovering the local community could change the future of forest management worldwide.

Rediscovering the local community.

Source:

1. T. M. BONNICKSEN, *Politics and the Life Sciences, 15,* 23-34 (1996).

Congress passed the Forest Stewardship Act in 1990 in response to growing concerns about the management of small private forestlands. The act includes three main provisions. First, the Forest Stewardship provision renders technical assistance, but it requires that a forest stewardship plan be prepared by a professional forester and approved by the state forestry agency. The stewardship plan must include land management objectives and strategies for multiple-use management, though the landowner need not manage for all potential uses. The second major provision is the Stewardship Incentives Program, which provides technical assistance and cost sharing to those who have an approved ten-year stewardship plan. The third major provision is the Forest Legacy Program. This program permits landowners to retire lands of special character or lands that are environmentally sensitive in return for payments from the state. Small landowners will increasingly be required to plan with the assistance of resource professionals and demonstrate how their efforts benefit society in order to receive public monies.

Important Features of the Period 1952 to the Present An evaluation of American forest policy since 1952 shows a gradual transition to a more balanced and environmentally aware approach to resources management. The growing strength of nontimber interest groups fostered this change, but timber production remains critically important to the nation's economy and forest management. Citizen participation in local decision-making increased, and will likely continue to do so, although the traditional legislative and judicial processes continued to play an important role in forest policy development. Much work remains to achieve equity and harmony among affected interests. In spite of conflicts, and with the exception of many small communities in the West, most groups received substantially more forest resources from all ownerships, including timber products, than they obtained in any previous period.

Concluding Statement

In this chapter, we traced the history of forest policy development in the United States as seen through the policy process. This approach necessarily simplifies history, but certain general principles about forest resource policy making emerge, principles that will remain unaltered into the foreseeable future.

First, the forest policy process is inherently subjective. The preferred forest policy of one group may be seen as disastrous by another group. The search for objective measures to set goals and resolve forest policy issues has proved futile. No single criterion can ensure agreement among all contending interests as each group uses different standards to judge forest policies. Therefore, converting the forest policy process to science is not likely, nor will scientists and professionals be delegated authority to make the decisions. Active citizen participation will remain an essential part of the forest policy process.

Second, both the lack of objective criteria for assessing policies and citizen participation ensure that debate and compromise will continue to be the central means for making forest policy decisions. A professional forester or natural resource manager must be prepared not only to engage in these debates but also to compromise. The time when professional judgment was accepted without question has passed. (The following chapter discusses the forestry profession, and its responsibilities and career opportunities.)

Finally, the forest policy process is growing more complex. As demand for forest resources increases and diversity among interest groups widens, providing for society's needs in an equitable and cost-effective manner becomes more difficult. Important strides have been made in resolving forestry issues, but the unending search for creative answers remains the challenge of American forest policy.

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CHAPTER 2

Forestry: The Profession and Career Opportunities

RONALD L. GIESE

Forestry provides a diverse set of opportunities, which can lead to a challenging and fulfilling career. Many people are attracted to forestry by their outdoor orientation or environmental concerns, others by the mathematical and engineering applications so important in modern forestry; still others find the biological aspects of forestry to their liking. Some people find rewarding the elements of social studies in forestry such as economics, sociology, and political science. Still others are taken with applications of new technologies such as global positioning systems and satellites, or new disciplines like landscape ecology and geographic information systems in forestry. Whatever the motivation, a sense of stewardship and an appreciation of natural relationships are common denominators among those who pursue forestry as a professional career.

Events in recent decades have created momentous changes in the forestry profession. Passage of the National Environmental Policy Act and the establishment of the Environmental Protection Agency, along with various state versions of environmental and forest practices acts, require assessment of the environmental consequences of forest management decisions. The Forest and Rangeland Renewable Resources Planning Act of 1974 and the National Forest Management Act (NFMA) of 1976, and the Federal Land Policy and Management Act of 1976 provided new opportunities to set national goals and formulate forest policies. Legal challenges to timber management practices on federal lands, like those arising from the Monongahela clearcutting issue, have led to changes in timber-management policies. In 1999, after 20 years of experience under the forest land management planning rules of the NFMA, the Forest Service issued new planning regulations.

The net result of these changes has been to create an institutional setting for forestry that is very different and more complex than ever before. As a society, we are now more concerned with ecosystem management and resource planning, which must deal with issues relating to diversity and biological conservation, wilderness, endangered species and the right of the people to influence the direction of resource management. Modern foresters are challenged, interested, and motivated by the complexities of their profession in a milieu of biological, quantitative and social sciences.

During a forestry career, a person usually encounters a progression of duties and expectations. Early on, foresters are very dependent on technical field skills (Figure 2.1). As they move up the career ladder into the broader aspects of land management, economics and decision-making skills become more pertinent to their professional performance. The next stage of the career often places foresters in the role of people managers who must draw broadly on a background of technology and experience in land management, as well as cope with the challenges generated by people both inside and outside their sphere of control. That such an evolution happens is evident by the fact that of over 12,000 Society of American Foresters members who reported the level of their jobs, 52 percent of these active professionals are in management, administrative, or staff specialist positions (1). The general direction of a forestry career is therefore from exercising technical forestry skills to employing business and management practices. However, the ability to communicate well and to work effectively on multidisciplinary teams is an asset at all stages of a person's career.

Paths to the Profession

Career Decisions

For students making tentative career choices, forestry is sometimes a mystery. Their perception

Figure 2.1 Students learn technical forestry skills in the field during the required summer camp experience.

of forestry may focus on operating sawmills, cutting trees, or outdoor recreation. However, as will be evident over the course of this chapter, modern forestry positions emphasize business approaches, computer science, social science, mathematics and engineering skills, as well as the life sciences. Careers in forestry can provide a variety of stimulating challenges in areas that students not primarily interested in biology usually do not consider seriously.

In planning for careers, students must use testing and classification services with caution. To a large extent the counseling services at the high school and college levels are usually out of date with respect to forestry. Vocational tests often suffer from biases and outdated bases of information. Typically, current automated testing systems picture a firefighter wearing a hard-hat or a logger with a chainsaw as characterizing forestry. These outmoded perceptions fail to do justice to the skills and education of the modern forestry professional whose background embraces computer science, ecology, operations research, business, policy, resource planning and management, engineering, and communications.

Vocational tests are widely available and generally fall into three categories: aptitude, interests, and personality. The outcomes of some of these tests are clearly wrong (based on outdated information), and others are incomplete. The Holland Classification, for example, takes interests, values and skills of individuals and combines them into six personality types (2). A combination of R (realistic), S (social), and I (investigative) types leads to forester in the Holland Code of occupations. If you undergo an analysis under this system using terms such as business management, taking risks, organizing, computing, writing, or decision-making as inputs, you will not be led, for example, to the following important aspects of forestry: planning, trade, paper processing, systems analysis, managerial activities, marketing, technical writing, or administration. Moreover, the concepts of artificial intelligence and expert systems, landscape ecology, biotechnology, and geographic information systems—each a component of forestry—have not yet found their way into the repertoire of the occupational codes or counseling services.

Some counselors and their subjects place too much credence and emphasis on test results. If taken as an end point rather than a beginning, test results are likely to lead to incorrect conclusions. This is so because the popular *Strong vocational interest* approach incorporates the Holland codes. Self-directed career searches and the *Holland Dictionary* (2) provide required educational development. However, the educational preparation specified does not include advanced mathematics or the ability to read technical literature—such a background would not even qualify a forestry program for accreditation. If you have interests or background in advanced mathematics, computer science, or statistics, an aptitude survey or vocational interest test will erroneously declare that you are overqualified for forestry. Because of the interdependency of these counseling tools, incorrect information in one of the components automatically creates flaws in the others.

If you wish to choose career possibilities with an open mind and an eye to future satisfaction, you should use testing information as only one of several sources of input. The informed person will develop a mixed strategy for choosing a career. Testing can provide some direction, but it should also stimulate questions. Interviews with counselors may help interpret the outcome of testing (Figure 2.2). Armed with vocational testing information, you can greatly enhance decisions on careers or academic majors by looking into careers, talking with advisors in college forestry departments, interviewing professionals engaged in fields that interest you, and taking a summer job to gain firsthand experience.

Never before have opportunities for exploring forestry issues been so easy and widespread. In this book, we help you to capitalize on this rich resource of information by interspersing references to websites globally. By using computers, you can expand on specialized information as interested.

Figure 2.2 Interactions with knowledgeable counselors can help in career choices. (Photo by W. Hoffman, UW-Madison.)

Forestry Curricula

The Society of American Foresters (SAF) defines forestry as "the science and art of attaining desired forest conditions and benefits. As professionals, foresters develop, use and communicate their knowledge for one purpose: to sustain and enhance forest resources for diverse benefits in perpetuity. To fulfill this purpose, foresters need to understand the many demands now and in the future" (3). Within this context, the SAF prescribes the curricula upon which professional forestry is built. The general requirements specified by the SAF fall into two categories, and a brief description will serve to show the diversity and strength of a forestry education.

General Education This component must provide coverage and competency in the following areas:

1. **Communications.** Oral and written competencies of communication must be demonstrated. Programs reinforce these skills throughout the entire curriculum.
2. **Science, Mathematics and Computer Literacy.** Competency is required in:
   Biological Science—understanding (a) patterns and processes of biological and ecological systems across space and time, and (b) molecular biology, cells, organisms, populations, species, communities and ecosystems.
   Physical sciences—understanding of physical and chemical properties, measurements, structure, and states of matter.
   Mathematics—understanding and using basic approaches and applications of algebra, trigonometry and statistics for analysis and problem solving.
   Computer Literacy—using computers and other electronic technologies in professional life.
3. **Social Sciences and Humanities.** Competency is required as an understanding of:
   Moral and ethical questions and using critical reasoning skills,
   Human behavior and social and economic structures, and
   Dimensions of the human experience.

Professional Education Competencies are required in the following major areas:

1. **Ecology and Biology**—understanding taxonomy, distribution and ecological characteristics of trees and their associated vegetation and wildlife; physiology of trees; genetics; ecological principles including structure and function of ecosystems; soil formation, classification and properties; silviculture including control of composition, growth and quality of forest stands, and fire ecology and use; entomology and pathology, and integrated pest management. Ability must be shown to conduct forest and stand assessments and to create silvicultural prescriptions.
2. **Measurement of Forest Resources**—identifying and measuring land areas and conducting spatial analysis; designing and implementing comprehensive forest inventory; and analyzing inventory information to project future forest conditions.
3. **Management of Forest Resources**—analyzing economic, environmental and social consequences of resource management strategies and

decisions; developing management plans with specific multiple objectives and constraints; understanding harvesting methods, wood properties, products manufacturing and utilization; and understanding administration, ownership and organization of forest enterprises.

4. **Forest Resource Policy and Administration**—understanding forest policy, processes of how local and federal laws and regulations govern forestry, professional ethics and ethical responsibility, and integrating technical, financial, human resources and legal aspects of public and private enterprises.

The mission of the Society of American Foresters is "to advance the science, education, technology, and practice of forestry; to enhance the competency of its members; to establish professional excellence; and to use the knowledge, skills, and conservation ethic of the profession to ensure the continued health and use of forest ecosystems and the present and future availability of forest resources to benefit society" (3). An important function of the SAF is the study and development of standards in forestry education and accreditation of forestry schools, and these processes further the objectives in its mission. The SAF is recognized by the federal government as the official accrediting agency for forestry programs in the United States. A current listing of forestry schools in the United States and descriptions of their programs are available on SAF's website (4).

Forestry is atypical among professions because of the high percentage of baccalaureate-trained professionals and the small fraction of self-employed professionals, the highest percentage being employed in the public and private sectors (Table 2.1).

Although the majority of students terminate their formal education at the bachelor's level, increasing numbers are proceeding to advanced graduate degree programs, which they enter either from a forestry undergraduate curriculum, or from any number of other undergraduate majors, including mathematics, engineering, botany, and economics or other social sciences. Students who enter from another major are eligible to pursue the first professional degree at the master's level. According to the *Occupational Outlook Handbook* (5), the increasingly complex nature of forestry has led some employers to prefer graduates with advanced degrees.

Table 2.1 Employment Distribution of Society of American Foresters Membership (1)

Employer Sector	Number[a]	Percent
Government		
Federal	2,196	17
State or local	1,917	15
Other than U.S.	64	<1
Private industry	3,728	28
Self-employed		
Consulting	2,116	16
Other self-employed	705	5
College/university	1,350	10
Association/foundation	252	2
Other	341	3
Unemployed	93	<1
Not indicated	429	3
Total	13,191	100

[a]This table excludes, compared to the original information base, retirees and students (constituting over 5,000 other Society of American Foresters members) who would not normally be seeking full-time professional employment.

The relative balance among educational levels in recent forestry recruitment provides a good idea of opportunities. A 1998 report (6) noted that for entry-level forestry hirings over a two-year period, 75 percent were filled at the bachelor's level, 18 percent at the associate degree level, and slightly over 2 percent were at the master's level. A year later, another analysis was completed (7) indicating that for the previous five-year duration, 70 percent of the forestry recruitment was at the bachelor's level. Respondents to the 1998 study revealed their intentions, for the foreseeable future, to recruit people at the bachelor's level for about three-fourths of all forestry positions.

The Bureau of Labor Statistics has its *Occupational Handbook* available electronically. Information about "Foresters and Conservation Scientists" can be found at their website (5). Nature of the work, working conditions, employment, training, job outlook, and sources of information are included in the descriptive material. The handbook is updated and republished periodically so interested people can find reasonably current information in this source.

Career Opportunities

New careers in forestry continually emerge as general technology advances. Today, computer applications in forestry have become important in virtually all aspects of the field. As an example, expert systems based on principles of artificial intelligence promise exciting methods for assessing and diagnosing forestry problems in much the same way these systems are used in the medical field. Remote sensing of the environment and geographic information systems have become invaluable tools in managing forest resources. Biotechnology and genetic engineering show potential for application to forestry, especially for improving the yield and value of forest products. Scientists are modifying species to increase resistance to diseases and herbicides. There is now a greater emphasis on international forestry, and for filling these worldwide positions, skills in foreign languages and knowledge of agroforestry practices are especially important. For an expanded discussion on the variety of specialties available in the profession, the interested reader is referred to *Opportunities in Forestry Careers* (8).

Students often fail to realize that a degree in forestry provides an excellent general education, one that can be viewed similarly to the liberal arts bachelor's degree programs offered at many institutions. Students undecided on an academic major should not miss the opportunity to explore forestry, either as a major emphasis or as a minor field to serve as a companion to a degree in statistics, mathematics, engineering, or environmental science. A forestry education provides a background for a broad variety of jobs in management, business, or computer science and students pursuing forestry degrees should not constrain their job searches just to forest management positions, especially if their interests are broader.

Though the emphasis of this book is on forestry, a group of related programs also offer coursework leading to rewarding careers. Wood science and technology and pulp and paper science majors, available at many forestry schools and colleges, typically have high placement rates for graduates.

Sources of Employment

Public Forestry in Federal Agencies

With 5,000 foresters, agencies within the federal government constitute a large employment base of professional foresters; 17 percent of the active SAF foresters in the United States fall within this group. The Forest Service (U.S.D.A.) has a total permanent work force of 29,000 people. This department is the largest federal employer of foresters. In 1999, there were about 4,000 professional foresters and 7,000 forestry technicians working in the Forest Service. This group of professionals is entrusted with managing large and widely dispersed holdings in numerous national forests comprising 191 million acres. In addition, the Forest Service works cooperatively with state and private enterprises and conducts research at its forest and range experiment stations, at the Institute of Tropical Forestry, and at the Forest Products Laboratory (Figure 2.3). An employment overview of this agency is available online and also provides links to other sites of potential interest (9).

An administrative perspective of new hires in the Forest Service is that:

> **Today's forestry professionals entering the federal workforce still need the technical skills and understanding of ecosystem functions that their predecessors possessed. However, they face a full array of new challenges in managing natural resources. The Forest Service is changing, much as the society we serve is changing. Our job is one of stewardship of public lands with lots of collaboration from the public we serve. We must all understand the concept of customer service. Our daily jobs involve satisfying many internal and external customers. How effectively we do so figures largely in our professional success. The new forester must keep in mind the long-term nature of resource management. Whereas most of our customers may look to the productivity and beauty of a forest for a decade, or for their lifetime, the forester must ensure the needs of future generations and the health of forest ecosystems far into the future (10).**

Other agencies in the U.S.D.A. that employ forestry graduates include the Natural Resources Conservation Service, Cooperative Agricultural Extension Service and the Agricultural Research Service. Elsewhere in the federal government, professional foresters are found in the U.S. Department of Interior (Bureaus of Land Management, Outdoor Recreation, and Indian Affairs, as well as the National Park Service and the Fish and Wildlife Service), Tennessee Valley Authority, and an assorted smaller number in the Departments of Defense and Commerce, the Office of Management and Budget and the Environmental Protection Agency. Hirings in federal agencies are made through the U.S. Office of Personnel Management.

Public Forestry in State Settings

Most of the states, through their departments of natural resources (or some similar title), maintain a staff of forestry professionals to carry out state policies in managing their forest resources. There are over 5,000 foresters in the state natural resource departments and they represent 15 percent of the active practicing foresters who hold membership in the

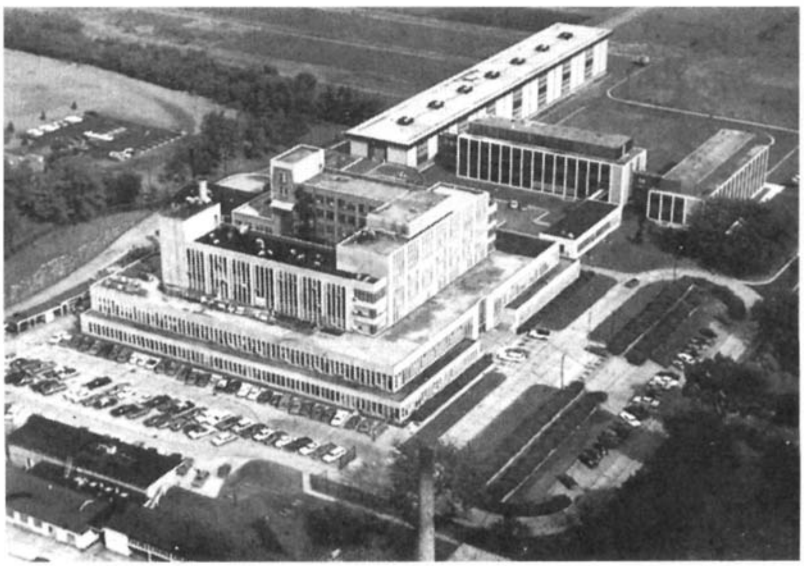

Figure 2.3 The U.S. Forest Products Laboratory in Madison, Wisconsin, is a research and development laboratory and is part of the Forest Service. (Courtesy of U.S.D.A. Forest Service.)

SAF. This represents a large pool of positions, and collectively the states now have a larger work force than the Forest Service, a condition that was the reverse until the early 1990s. In addition, the state agencies hire over 7,000 seasonal or temporary employees each year; with a wide variety of seasonal positions across the country, the states offer excellent opportunities for pre-professional experience. Together, the states also employ over 9,000 technicians; these positions are supportive in nature, normally do not require a 4-year degree, and typically the salaries in the category are lower than those for professional foresters. For the most part the forestry programs and employees are administered by the state forester, usually located in the capitol city. The National Association of State Foresters maintains a website (11) with current employment opportunities listed as well as links to each of the states' department of natural resources where local employment and program information are available.

One chief state forestry administrator summarized the setting for this sector as follows:

> **Foresters working in a state forestry agency are faced with the need to be proficient in a broad range of functions, from the biophysical aspects of forest resource management to complex social interactions with people and groups that have diverse interests and strongly held values relating to forests and natural resources and how they should be managed. Forestry professionals require broad-based knowledge of forest science with an integrated natural resources management perspective. They must be able to use that knowledge to develop, interpret, and implement policies and procedures to sustain and enhance functioning forest ecosystems; provide a sustainable supply of forest resources to meet human needs (material, economic, and social); protect lives and property from wildfire; and provide an economic return to citizens and corporate organizations. It is essential that graduates leave school with that basic knowledge and an initial development of those abilities (10).**

Other state agencies employing foresters, though to a lesser extent, include the park services, fish and game divisions, and in some states, departments of highways and taxation, and commissions of public lands. At about 8 million acres nationally, community forests represent an important component of public forests at the state level. Some were established over 100 years ago. Many are owned and managed by municipalities, but others may be operated by counties, schools, or other public institutions largely for multiple-use. The school forests often serve an important role in the environmental education programs of local districts.

The increasing importance of forests and trees in the urban setting has given rise to a new emphasis on urban forestry (see Chapter 22, devoted entirely to urban forestry). This emerging area requires integration of traditional forestry and arboriculture.

Forestry in Private Industry

By far the largest amount of commercial forest area in the United States is privately owned. An important part of this is held by forest products companies to provide a supply of wood for production of lumber, pulp and paper, and other wood products. "Whereas federal and state resource agencies primarily manage forests, industrial firms both produce timber and utilize it to manufacture products. Thus, industry also offers a diverse set of opportunities for foresters. Industrial foresters may be involved in wood procurement as well as the management of forests. Private industry also promotes modern forestry practices through formal "tree farm" programs. The total number of professional foresters in this category is elusive; however, Wille (8) reports that about 10,000 foresters are employed by private industry. Electronic access to a large number of forest products industries can be gained through the American Forest and Paper Association (12), where an extensive roster of URLs is maintained for individual member firms nationwide and for related associations dealing with, for example, recycling, international trade, pulp, paper, plywood, veneer, and hardwoods.

From a corporate perspective, industrial forestry firms:

> **... seek foresters who are technically sound but also educated. New contributions from the fields of ecology and biotechnology rapidly increase the demands for an even more basic understanding of forest science and art—and social interaction with diverse stakeholders requires professionals who are broad in their thinking, who understand people, and who demonstrate clear leadership in their decisions and actions. Forestry leaders must integrate forest science, social, and business skills ... We need not just a deep scientific and technical education, not just a how-to education of forestry on the ground, but the broad professional understanding of the science, the sociology, the economics, and the politics associated with the management of complex natural resources that are important to the public ... (10).**

International Forestry

One of the greatest challenges for the forestry profession is the wise use of tropical forests. Spurred by population growth and the pressure to gain foreign exchange, developing countries are experiencing depletion of vital forest resources. Nearly half of the world's population depends on wood for fuel; in fact, about 60 percent of the total production of the world's forests is consumed as fuel. An interesting paradox is that in the developed world 80 percent of the wood produced is used for industrial purposes, and in the developing countries 80 percent of the wood produced is used for energy. The Food and Agriculture Organization of the United Nations (FAO) regards the dependence of developing nations on dwindling supplies of fuelwood as a crisis. Over and above the pervasive fuelwood shortage, tropical forests are being whittled away by resettlement programs, development projects, clearing for agricultural purposes and ranching, and logging without attendant forest management. Tropical forests decline each year by an area equivalent to Austria and Switzerland (13). This rate of destruction is a major social issue of our time—so crucial that every nation has a stake in its solution. FAO is partitioned into eight departments, one of which is Forestry and Sustainable Development. The forestry program, headquartered in Rome has a website (14) with excellent global information put together with a neutral approach in a factual format.

International forestry activities are conducted along three general fronts. *Community forestry* functions in rural development, improving work opportunities and consumable goods and enhancing the environment. With the participation of local people, the community forestry approach takes into consideration the importance of forestry in land use planning and its strong relationship to watershed management, arid-zone reclamation, soil fertility, and integrating forestry and agriculture. Among the techniques available for community approaches are: *multiple-product forestry,* the use of forests for wood, edibles, and other products; *small-scale forestry,* cultivating village woodlots for the production of fuelwood; *agroforestry,* combining of forest and agricultural crops; and *silvi-pastoral systems,* controlled grazing of forest vegetation. Forest-based industries are being established, but they can benefit the country only if sustainable development of carefully managed forests is achieved. Required are intensified management and reforestation, development of appropriate harvesting, transportation and marketing systems and intelligent use of residues. The *conservation of forest ecosystems* is recognized as an important emerging area. Tropical forests help to maintain a stable global environment, provide a major genetic reservoir, and offer a source of new forest products and medicines. Wise use of these ecosystems is a high priority among international strategists.

There are numerous opportunities for contributing to the international forestry effort. The Peace Corps supports forestry projects in many parts of the developing world. Staffed primarily by volunteers, it provides excellent opportunities for professional and personal development. Nongovernmental organizations such as CARE play an important role in international forestry. The Food and Agriculture Organization collects and analyzes information on forestry, serves as a major source of technical assistance, and helps to identify investment opportunities in the forestry sector.

The U.S. Agency for International Development (USAID) pursues two strategic goals relevant to environmental protection: 1) reducing long-term threats to the global environment, particularly loss of biodiversity and climate change, and 2) promoting sustainable economic growth locally, nationally, and regionally. Forest and other natural resource management practices form a key element of many USAID assistance efforts in the agency's major spheres of action, notably sub-Saharan Africa; Asia and the Near East; Latin America and the Caribbean; and Europe. In addition to its permanent staff, USAID accomplishes forestry work by employing people for varying periods of time, for short-term consultancies as well as long-term assignment overseas. To this end the Office of International Programs within the Forest Service-U.S.D.A. maintains a large roster of individuals competent in tropical forestry. The Office of International Programs also offers technical assistance and training in forest management and forest conservation to a wide variety of international partners. In addition to its usual governmental partners, this program has recently expanded its array of cooperators to include more nongovernmental and international research organizations.

Research and Teaching

There are over 1,300 people involved as forestry faculty in educational programs at the colleges and universities in the United States. The primary functions of faculty positions are distributed approximately as follows: instruction—45 percent; research—45 percent; and extension (outreach)—10 percent. The largest number of faculty are in forest management, although well represented are the areas of: forest biology; wood science, technology, and industry; biometry; forest hydrology; forest engineering; and urban forestry. All faculty positions require advanced graduate education and, for the most part, a doctorate. Another group of over 600 foresters serves in professional staff roles in forestry departments at universities, while others teach in instructional programs at community colleges or technical schools.

An active and comprehensive organization known as the National Association of Professional Forestry Schools and Colleges serves to advance the science, practice and art of forest resource management through the encouragement and support of forest resource education, research, extension and international programs at the university level.

Some of the larger forest products firms conduct substantial research and development programs, although the number of scientists involved is unknown. The Forest Service plays a major role in research activities, and to a lesser extent, some of the major forested states also support research efforts.

Embracing forestry research on a global scale is the International Union of Forestry Research Organizations (IUFRO). Its lead office is located in Vienna, Austria; this organization is over 100 years old. IUFRO is a nonprofit, nongovernmental international network of 700 member institutions involving 15,000 participating forest scientists. The main purpose of IUFRO is to promote international cooperation in scientific studies embracing the entire field of research related to forestry. Each year over 50 conferences and symposia are sponsored around the world, and every fifth year IUFRO holds a World Congress. Like FAO, IUFRO hosts an online reference library where literature searches may be done at its website (15).

Consulting Forestry

Some professionals choose a private consulting practice. Most of the consultants operate as sole proprietors, and except for a small number of partnerships, the rest are organized as consulting firms. There are over 2,000 consulting foresters in the United States. Consultants provide advice and assistance related to forest management, marketing, and sale of forest products. Timber marking and sales, timber inventory and appraisal, timber volume estimates, timber management plans and harvesting, damage appraisal, and investment advice constitute most of the work collectively conducted by consultants. Sometimes consulting firms deal with large-scale assessments for public agencies and industry.

Over and above technical forestry understanding, from a consulting perspective, "the real key to success—for the individual forester, the consulting firm, and perhaps also for the profession—is the ability to communicate well both in writing and speaking. Opportunity in consulting is unlimited for foresters who understand the technical basics, gain field experience, see forestry in the perspective of nature and society, and can communicate ideas" (10).

Many consultants hold membership in the Association of Consulting Foresters of America. One requirement for membership is a forestry degree from an accredited university program.

Other Areas

According to the roster of members of the SAF, the remaining foresters are self-employed or involved with organizations such as the American Forest Foundation, American Forest and Paper Association, American Pulpwood Association, National Woodland Owners Association, National Hardwood Lumber Association, or various state forestry associations.

Employment

Expectations of Employers

Changes in the public's understanding of sustainability and developments in science, communications, and global markets have created a recent evolution in the practice of forestry (7). Consequently, employers now seek an expanded set of skills and competencies when hiring graduates of professional forest programs.

Table 2.2 provides an overview of technical competencies sought by employers. Based on a strategic assessment conducted by the Pinchot Institute (7) involving employers who had recently hired forestry graduates, the surveys covered all forestry sectors, with federal and state agency, industrial, and consultant participants making up 93 percent of the survey participants. The table, ranked according to importance value, shows the twenty competencies which are most important to employers and which the majority of employers expect to be acquired at the undergraduate level. Certainly the scientific foundation of forestry forms a strong basis of the competencies, but a very high premium is placed on ethics, communications, and teamwork. This is in accord with another nationwide analysis published a year earlier by Brown and Lassoie (6) who found that the application of sound ethical principles is the attribute with the highest desirability regardless of employer category—in fact, 95 percent of the respondents said it is a requirement. This study too, showed that communication and group interaction processes are competencies required for most entry-level positions (Figure 2.4).

Also important to employers hiring professional foresters is a set of broader skills. The Pinchot Institute study (7) identified the skills most critical to hiring agencies and, at the same time, those that entry-level practicing professionals find they need for long-term success in forestry (Table 2.3). Think of these skills as the synthesis and application of certain clusters of competencies seen before in Table 2.2. For example, the ability to listen to and address public questions and concerns—the second skill listed in Table 2.3—would draw not only on specific subject matter knowledge, but would be integrated with ethics, communication, and collaborative problem-solving competencies as well.

Our society is still evolving from a somewhat autocratic mode of management to more of a shared governance model. Thus, there are gaps between how importantly a skill is perceived by employer groups and their rating of performance for the foresters they have recruited. The biggest gaps are reflected in the top two skills, teamwork and public concerns. However, positive changes have transpired in this regard during the last decade, and continued improvement will occur to narrow the gap between importance and performance.

Most forestry employers expect the undergraduate educational experience to primarily provide a sound foundation of technical competency (Table 2.2), with the development of broader integrative skills (Table 2.3) coming largely with experience,

Table 2.2 Technical Competencies Employers Expect to be Achieved at the Undergraduate Level and Their Importance (7)

Technical Competency[a]	% of employers expecting the item by end of undergraduate education	Importance to employers (1-10 scale)
Ethics	79	9.3
Written communication	86	9.2
Oral communication	78	9.1
Silvicultural systems	85	8.4
Collaborative problem solving	53	8.2
Resource management	62	8.0
Forest ecology	63	8.0
Forest inventory and biometry	86	7.8
Landscape analysis-GIS	55	7.7
Tree and plant species identification	93	7.7
Watershed management	64	7.6
Resource economics	70	7.5
Fire dynamics	67	7.3
Forest soils	80	7.2
Resource policy, law	57	7.0
Wildlife biology	78	7.0
Forest pathology	79	6.8
Conservation biology	57	6.8
Forest engineering, transportation systems	64	6.3
Wildland and protected areas management	60	5.8

[a] Terms listed only for which 50% or more of the employers expected the competency to be gained during the undergraduate experience and for which they attached an importance value greater than 5.0 on a scale of 1-10.

graduate education, and continuing education. You may notice a strong correlation between employer's expectations and curricular requirements for a degree from an accredited program discussed earlier.

Seeking Employment

Application for employment is an art and how to do it most effectively differs by industry. In the forest products industry, applicants should develop some knowledge of the company and should not set employment goals that are too narrow. Work experience, a vision of the potential employee's future, and direct contact with the company are desirable. All this requires homework. Do not

Figure 2.4 The ability to work with others is an important component of a forestry career. (Courtesy of U.S.D.A. Forest Service.)

Table 2.3 Skills Identified as Necessary for Success in Forestry, and Their Fatings of Importance and Performance by Employers [Scale of 1-10] (7)

Needed Skill	Importance	Performance
Ability to work in teams that include individuals with a variety of perspectives, both within and outside the organization.	9.0	7.3
Ability to listen to and address public questions and concerns and to explain the principles of environmentally responsible forest management practices.	8.2	6.5
Understanding of the requirements of a healthy forest ecosystem and the full variety of silvicultural and other tools available to manage that system.	8.0	7.4
An innovative approach to forest management that includes critical thinking and willingness to test new and nontraditional approaches.	8.0	7.2
An innovative approach to working with the public to address forest management problems.	7.7	6.6
Ability to evaluate and synthesize information from a variety of specialists when developing resource management plans.	7.5	7.1
Understanding of landscape-level planning of forest ecosystems and how to manage them to meet ecological, economic, and social needs.	7.3	6.9

expect most companies to interview on campus; they usually rely on resumes submitted by people seeking employment, and they purposely look for people from various geographic areas, different universities, and from diverse backgrounds.

Concluding Statement

The field of forestry offers a vast diversity of career opportunities that range from policy and social issues to highly technical, quantitative processes. Career seekers can pursue interests in conservation or timber management. The variety of organizations involved in the many aspects of forestry echoes the breadth of the field itself. Governmental agencies have active programs in forestry, and industrial firms are major players in the production of forest products. Different forestry programs span a geographic area that may be local, national or international. Regardless of agency or firm goals, the majority of forestry professionals deal with ecosystems, a theme that flows through this book.

Students with interests in forestry education should explore careers with several universities to understand curricular requirements and employment prospects. Sufficient website locations are included which, along with related sites included at each address, will provide a breadth of useful forestry information. Descriptions of, and questions regarding specific positions are best achieved by visiting with forestry-related agencies, industries, or consulting firms.

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PART 2

Forest Biology and Ecology

Trees are the largest and oldest of the known living plant species in the world today (Figure P2.1). Starting as a minute seed, they can grow to heights over 120 meters (394 ft) and accumulate as much as 1500 cubic meters (5.3×10^4 ft^3) of wood in the process. In addition, trees possess a water-transporting system so powerful that it can raise water about a hundred times as efficiently as the best suction pump ever made by human beings (1). Trees are truly remarkable mechanisms of nature.

Like all other plants, trees are constructed solely of cells, the basic units of life. However, the cells in a leaf, for example, are quite different from those in the trunk and different again from those in the root. Each kind of cell is usually found in association with similar cells; groups of similar cells make up tissue and tissues combine into even more complex groups know as organs (1). Clearly the specialized organs serve different purposes in the tree. The complex functions of the tree and its component parts are treated in detail in Chapter 4, Forest Ecophysiology.

Figure P2.1 One of the oldest known living plants in the world: a 3000-year-old bristlecone pine sculptured by the wind, sand, and ice of the White Mountains in eastern California. (Courtesy of U.S.D.A. Forest Service.)

The growth and vigor of trees are a function of many factors. In addition to genetic variations, environmental factors can have a profound influence on tree growth. Minerals in the soil, water shortages, wind and climate, the availability of sunlight, and attack by insects and disease all affect the patterns of tree growth (Figure P2.2). The impact of these influences and human interaction for control of tree growth and vigor are examined in this section. The distribution of forests around the world are discussed in Chapter 3, Forest Biomes of the World. A biome is a broad classification of plant communities characterized by climate and soil. Within a biome there are numerous ecosystems. A further description of forest ecosystems and integration of the many factors that affect tree and stand growth are discussed in Chapter 6, Forest Ecosystem Ecology. The importance of ecological relationships across landscapes is then discussed Chapter 7, Landscape Ecology. Not only do landscape patterns affect organisms, but organisms can also create landscape patterns.

A forest community is a dynamic structure that responds to the laws of cause and effect, one in which all organisms intertwine to form a harmonic ecosystem (2). The classic ecological concept is that forests evolve through plant succession, the orderly replacement of one plant community or

Figure P2.2 Twisted aspens on the Grand Canyon's northern rim in Arizona are called "The Crooked Forest." The resilient trees were probably bent as saplings by deep snowdrifts, a phenomenon referred to as snow creep. (Courtesy of Life Picture Service.)

forest stand with another. Generally a temporary plant community is replaced by a relatively more stable community until a dynamic equilibrium is attained between the plants and the environment. However, the behavior of forests frequently does not follow this classical concept. Many tree species, rather than arising during predicted periods of succession, often play a more opportunistic role. For example, red maple, which is usually considered to be a climax or final successional stage species, has light wind-borne seeds that can invade open areas and thus function as an early successional species (3). Disturbances such as those described below can also affect forest succession. The many factors affecting vegetation distribution and succession of forests are described in several chapters in this section.

Disturbances in the forest can be either natural (wind, fire, insect and disease outbreaks) or caused by human beings (forest harvesting and fire) and can result in destruction of small or large segments of the forest. The effect of disturbance is to produce sites where new communities of the trees, plants, and animals can exist. These new communities may differ from those of the native forest (Figure P2.3). The effect of disturbances are treated in several chapters in this section while the specific effects of disease and insects on forests are described in Chapter 8.

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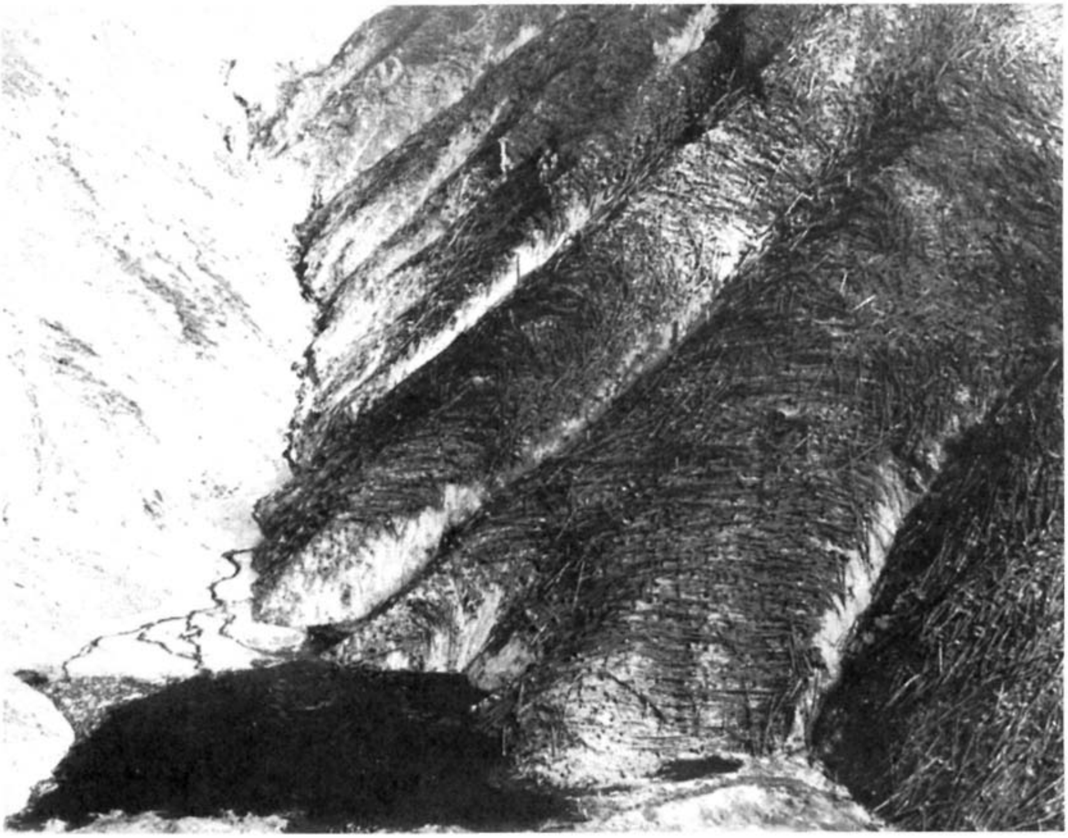


Figure P2.3 The blast from the eruption of Mount Saint Helens in the state of Washington flattened previously lush, green forests. Ecologists are closely monitoring the return of plant and animal life. (Photograph by R. L. Giese.)

CHAPTER 3

Forest Biomes of the World

STITH T. GOWER, JOE J. LANDSBERG,
AND KARI E. BISBEE

Forests provide many ecosystem services to humans and other organisms. Forests provide timber that is used for a myriad of wood and paper products (Chapter 20). Millions of species of flora and fauna, some of which have gone, or will go, extinct before they are documented, live in forests. Forests protect the soils from erosion, minimize sedimentation in adjacent wetlands and aquatic ecosystems, mitigate flooding, and remove toxic heavy metals and organics (Chapters 5 and 16). Forests also provide recreational opportunities and have inherent aesthetic value to society (Chapter 17). Lastly, forests play an important role in global carbon budget.

The contribution of a forest biome to each of the ecosystem services and functions varies among biomes, and ecosystems within the major forest biomes. Therefore, sustainable management of forests of the world requires a fundamental understanding of the effects of environmental factors on distribution and growth of forests (Chapters 4-8), and properly matching forest management practices to the silvics of the trees (Chapters 9 and 13). Structural characteristics such as height, density, the amount of leaf area, leaf habit (e.g., evergreen versus deciduous) are important factors that differ among forest biomes, and forest ecosystems within a biome. The climate and soils of forests also influence the ecosystem services and function. Therefore, it is essential to understand how important characteristics such as species composition, climate, soils, disturbance and structural characteristics differ among major forest types. This knowledge can be used to ensure which forest should be managed for timber production, devise management plans that ensure forests are managed on a sustainable basis, identify forests that should be preserved for services other than timber production, and determine how global change may affect world forests.

The objective of this chapter is to describe briefly each of the major forest biomes. The first section describes the major factors that influence the geographic distribution of forest biomes of the world. The second section highlights the major forest biomes of the world. We describe the extent and distribution, climate, soils, important structural and functional characteristics, and management and mismanagement issues for each biome. The third section summarizes some of the major conservation concerns for forests and the susceptibility of forest biomes to global change. The treatment of each forest biome is cursory because of space limitations. The text is intended to provide the necessary background for the more detailed treatments of various aspects of forest/environment interaction in the following chapters.

Factors Affecting Vegetation Distribution

The distribution of the major forest biomes, and terrestrial biomes in general, is strongly influenced by climatic, geologic, ecological, and anthropogenic factors. Plant geographers first noted the influence of climate on the distribution of vegetation; they observed that similar climates, regardless of continent, produced vegetation with similar appearance or physiognomy. Plants require solar radiation, water, nutrients and adequate temperatures to germinate, grow, and reproduce (see Chapters 4-7). The relative amount of these essential resources and the ecophysiology of the plants determine the species composition and structure of the forests. Climate directly and indirectly affects the distribution of biomes. Temperature and moisture availability directly affect the growth of plants. Climate also strongly influences soil development (Chapter 5), which also influences plant distribution.

The major control on climate at the global scale is solar radiation. The amount of solar radiation reaching the forest canopy is greatest near the equator and decreases toward the poles. The causes for the variation in solar radiation are two-fold: the angle at which the sun's radiation strikes the earth's surface and the length of the pathway that solar radiation must pass to reach the canopy (Figure 3.1). Solar radiation strikes the Earth's surface at a less direct angle at higher latitudes than near the equator, resulting in the radiation being distributed over a greater area—or a smaller intensity per unit land

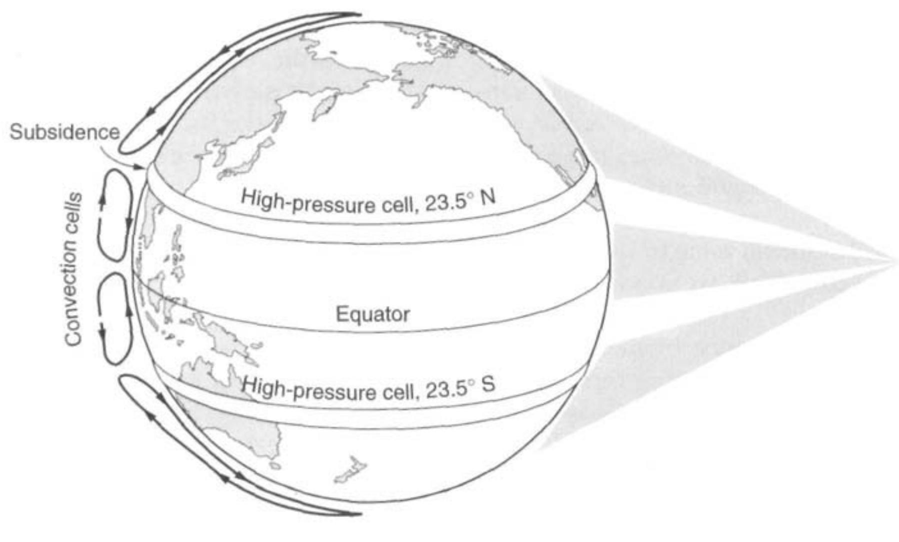


Figure 3.1 A schematic diagram contrasting the solar radiation path length at the equator and high latitude. The global precipitation patterns are determined by the convergence of air masses. Collectively, the solar radiation and precipitation patterns determine the distribution of terrestrial biomes. Adapted from Bailey (22).

surface area. Also, solar radiation travels through a greater distance of the atmosphere, increasing the reflection of solar radiation away from the earth's surface. As a result, the temperature is warmer near the equator than at higher latitudes.

Within a similar latitudinal zone, seasonal variation in temperature is much greater for a continental than for a coastal location. The pronounced differences in climate are because water has a greater thermal capacity than land. Examples of the effects of large water bodies on climate are shown in Figure 3-2. The latitude of Portland, Maine and Madison, Wisconsin are similar, but the winters are colder, the growing season is shorter and the summers are hotter in Madison than Portland. Similarly, for a similar latitude and elevation, the climate is milder and more equitable in the Southern than Northern Hemisphere. Continents are smaller in the Southern Hemisphere than Northern Hemisphere, and as a result, the mesoscale climate of the Southern Hemisphere is buffered by the greater thermal capacity of the oceans. The large thermal buffering capacity of oceans has a pronounced effect on the distribution of forest biomes. In the Southern Hemisphere, temperate forests occur from 30° to 55° S, and within this zone broad-leaved evergreen species dominate the forest landscape. In the Northern Hemisphere, broad-leaved deciduous tree species are the dominant forest type in the lower latitudes, and boreal forests can occur as far south as 50-55° N. Axelrod (1) concluded that the temperate climates, ample rainfall evenly distributed throughout the year, and rarity of frost, favored the evolution of broad-leaved evergreen rather than deciduous forests in the temperate regions of the Southern Hemisphere.

Water availability, a function of both precipitation and drying power of the air, also influences the distribution of vegetation biomes. Near the equator, moisture-saturated trade winds rise and produce abundant precipitation (Figure 3.1). The dry subtropical high-pressure air masses centered

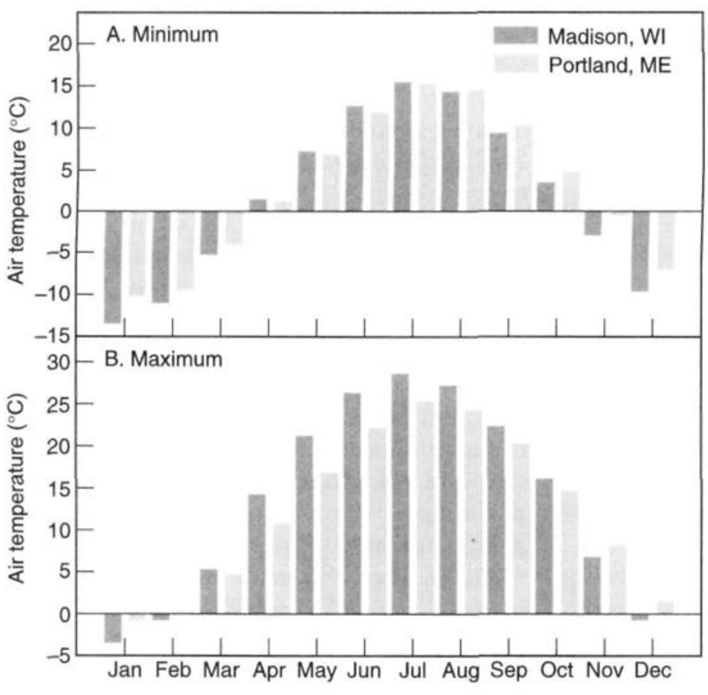


Figure 3.2 Comparison of the long-term monthly average of the maximum and minimum air temperature for Madison, Wisconsin (continental climate), and Portland, Maine (coastal climate). The two locations have approximately the same latitude. Data obtained from *http://www.worldclimate.com.*

on the Tropics of Cancer and Capricorn (23.5° N and S, respectively) produce bands that are too dry to support forests. Precipitation pattern is also influenced by continental position. Warm air passing over large bodies of water (oceans) collects water vapor. As the warm, moisture laden air mass goes over a large land mass it loses its ability to hold the water vapor, especially if the air mass must rise over a coastal mountain range. Rainfall is typically very high for these coastal regions. Forests growing on windward slopes of mountains near oceans can receive from 3.5 to 6.5 meters of rain—some of the largest annual amounts of precipitation in the world!

Soil fertility also influences distribution of vegetation. In general, evergreen plants occupy the more infertile soils while deciduous forests occur on more fertile soils. Parent material and climate influence soil fertility (Chapter 5). Hot and moist climates, such as subtropical and tropical regions increase soil weathering, causing nutrients to be removed from the soil on the time scale of millions of years. Conversely, milder climates have more fertile soils. Extremely young soils, such as those that developed since recent glacial advances, tend to be nitrogen-limited. The type of parent material that the soils develop from also influences soil fertility.

Disturbance intensity, frequency, and type of disturbance also influence biome distribution and species composition within a biome. The disturbance can be natural, such as fire, wind, or drought, or related to human activity (e.g., land clearing, harvesting, and fire suppression). Fire suppression in the midwestern United States has hastened the invasion of woody and tree species into prairies.

Forest Biomes

Vegetation Classification Systems

There are many vegetation classification systems used, although all of them use climate, physiognomy (the general appearance of the vegetation, e.g., desert, grassland, forest) and leaf habit (evergreen or deciduous) to classify vegetation. The broadest level of classification is the biome—vegetation with a similar climate and physiognomy. Within a biome there are numerous ecosystems. For example, the temperate needle-leaved evergreen forest biome includes the coastal Douglas fir (*Pseudotsuga menziesii*) forests in the Pacific Northwest, the jack pine (*Pinus banksiand*) forests in the Lake States, and loblolly pine (*Pinus taeda*) forests in the southeastern United States. Classification systems differ in the level of detail, ranging from a simple system that has eight vegetation cover types to 30 vegetation associations. In this chapter, we provide an overview of the main forest biomes in the world. We briefly characterize the extent and distribution, the climate and dominant soils (readers are suggested to refer to Chapter 5, Forest Soils, for a detailed explanation of the different soil orders), a general description of the vegetation including some of the dominant forest genera (or families for the extremely diverse tropical forests), unique structural and functional characteristics that influence the ecology and management, and management of the major forest biomes.

For the purpose of this book, we used the vegetation classification system used by Melillo, et al. (2), because it is a reasonable compromise between complex and simple schemes. Forest biomes are based on major climatic zones (tropical, temperate, and boreal) and the physiognomy (broad-leaved evergreen, broad-leaved deciduous, and needle-leaved evergreen conifer) of the vegetation. Figure 3.3 (see color insert) shows the regions where biomes could occur, although it is unlikely that the areas concerned are completely covered by those vegetation types. The impact of humans has resulted in vegetation loss and change across very large areas of the globe.

The description of the major forest biomes is brief, but provides a general overview of the distribution, climate, soils, species composition, structure, and function, and management characteristics of the major forest biomes. The amount of information available for each forest biome varies substantially. The information provided for each forest biome is intended to provide a framework for thinking about the ecology and management of forests, as discussed in the following chapter.

Boreal Forests

Distribution and Extent Boreal forests cover about 15.7 x 10^8 hectares and occur only in the Northern Hemisphere (Table 3-1). The greatest single area of boreal forests is in Eurasia, where they extend from Scandinavia to eastern Siberia. The second largest boreal forest region occurs as a 500-600 km wide band from eastern Canada and the northeastern United States westward into northern British Columbia and Alaska. Boreal forests give way to arctic woodland or tundra to the north, while the vegetation to the south of the southern boundary varies. In some regions, such as eastern Canada, boreal forests transition to cold temperate evergreen needle-leaved or broad-leaved deciduous forests. In central Canada, the southern boreal forests give rise to prairies, and in Eurasia boreal forests often transition into cold steppe or shrubland.

Climate The climate of the boreal forests is one of the harshest in which trees occur. The boreal forest regions, represented by climatic data from The Pas, Manitoba, in Canada (Figure 3-4a), are characterized by long cold winters. The mean daily minimum temperature at The Pas is below 0°C for more than seven months of the year, and during the period when temperatures remain above zero, there are significant water deficits. There may be fewer than 50 frost-free days in summer (Figure 3.4a). Permafrost, a buried frozen soil layer, is common in many boreal forests. Woodward (3) suggests that the northern limit of boreal forests may be crudely defined by the number of months in which the air temperature is greater than 10°C. The length of growing season must be sufficient for evergreen conifers to construct an adequate cuticle to protect needles from winter desiccation, and mycorrhizae (root-fungus association) to facilitate nutrient and water uptake.

Soils Soil development is slow in boreal forests because of the cold temperatures; therefore soils tend to be nutrient-poor. Poorly drained soils accumulate large amounts of peat—undecomposed mosses and sphagnum. The soils are young and derived from parent material left by retreating glaciers. Permafrost, which can be less than one meter below the surface, restricts root zones and impedes soil water drainage. Few major soil taxonomic groups occur in boreal forests. Histisols, or organic soils, are common to poorly drained forests. Entisols have little or no horizon development and are typically associated with early successional riparian forests (*Populus*, *Betula*) and coarse-textured,

Table 3.1 Area (hectares x 10^8) and Average Net Primary Production (NPP, tC ha^{-1} yr^{-1}) of the Forest Biomes of the World [Adapted from Landsberg and Gower (4) and Gower, et al. (6)]

Forest Biome	Area (ha x 10^8)	% of total	Average NPP (tC ha^{-1} yr^{-1})
Boreal	15.7	30	4.2
Deciduous	—	—	—
Evergreen	—	—	—
Temperate	14.2	27	—
Coniferous	2.4	5	6.6
Deciduous	3.5	7	6.6
Mixed	5.1	10	—
Evergreen (Broad-leaf)	3.2	6	10.0
Tropical	22.0	43	—
Evergreen	17.4	34	8.2
Deciduous	4.6	9	8.0

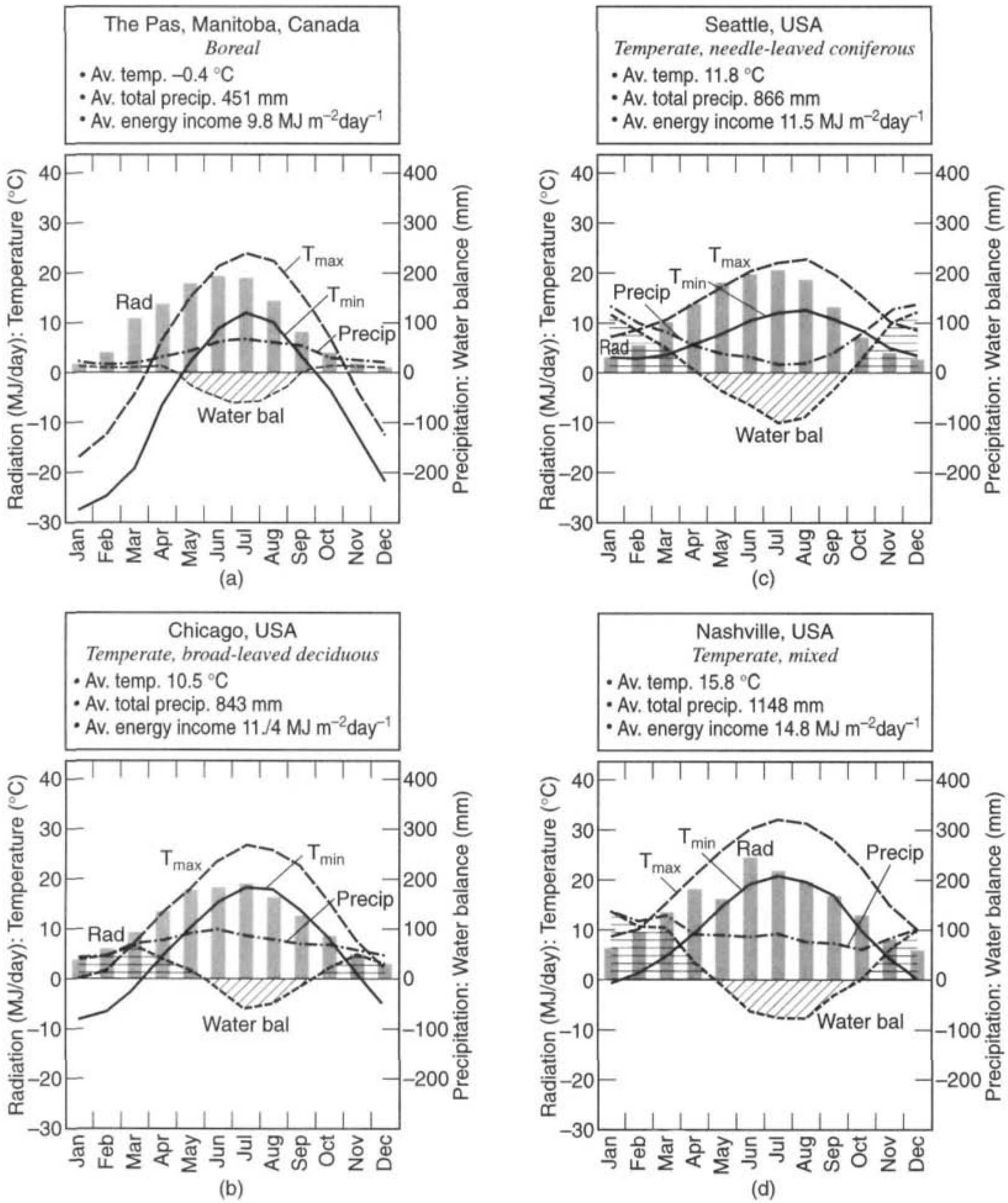
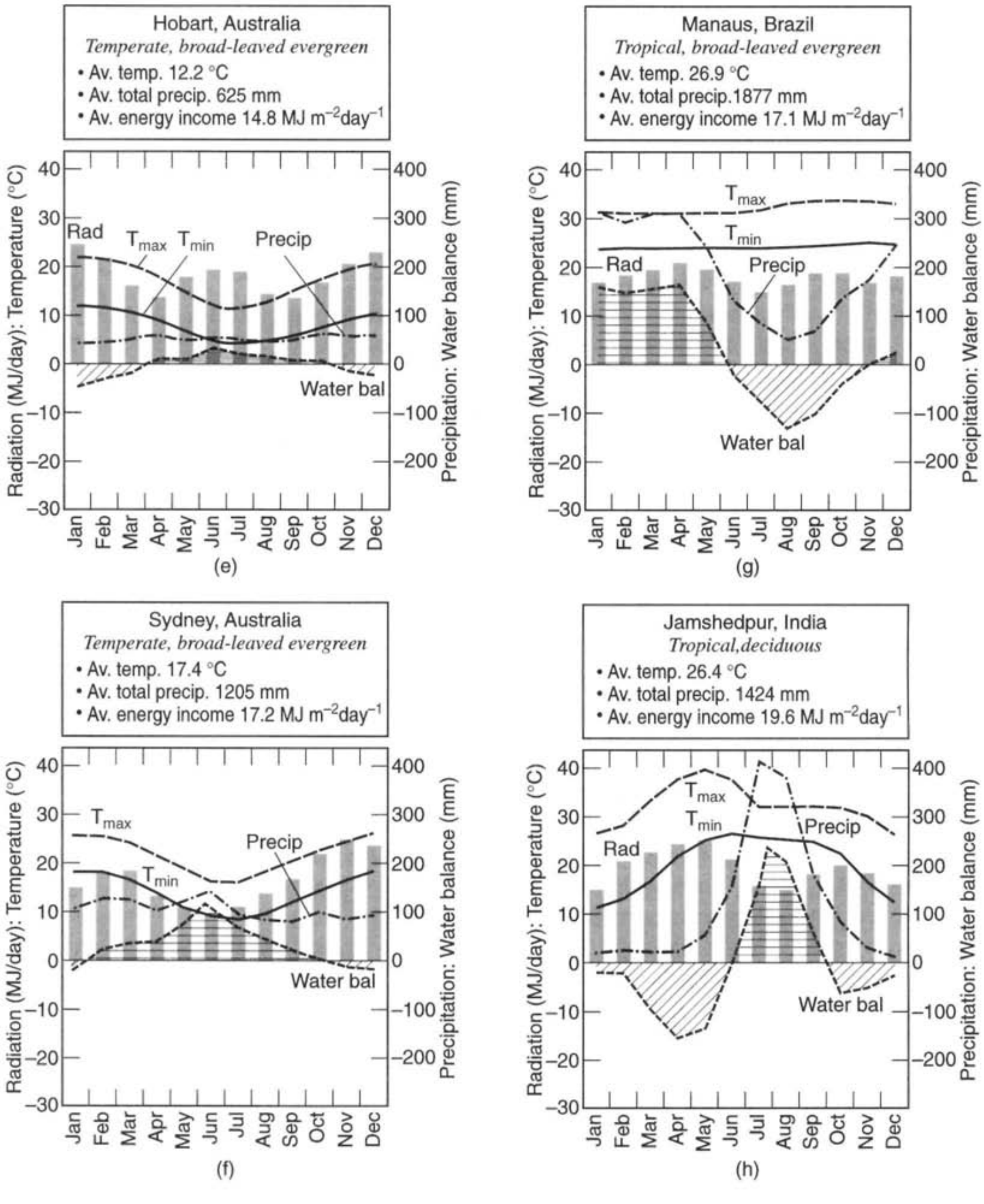


Figure 3.4 Climate diagrams illustrating the conditions in which we can expect to find: a) boreal forests; b) temperate deciduous forests; c) temperate coniferous forests; d) temperate mixed forests; e) and f) temperate evergreen forests; g) tropical evergreen forests; h) tropical deciduous forests. The diagrams show long-term monthly averages of maximum (Tmax) and minimum (Tmin) temperatures (°C), precipitation (mm) radiation (MJ $m^{-2}day^{-1}$) and the water balance, calculated as the difference between precipitation and evaporation using the Thornthwaite (23) equation. The diagrams were produced from data presented by Muller (24). Radiation data were not available for every station (they were missing for The Pas, Hobart, Manaus and Jamshedpur); where this



was the case, data from other stations at similar latitiudes, that closely matched these in terms of sunshine hours, temperature and rainfall patterns, were used. The water balance data (precipitation-evaporation) were derived from the monthly potential evaporation figures provided by Muller (24), which were calculated from the evapotranspiration formula derived by Thornthwaite (23). This formula is based on temperature and is unlikely to provide accurate values for the water use of tropical forests. However, as Muller points out, the Thornthwaite equation is the only one that gave comparable values for every station, and it does provide a reasonable indication of evapotranspiration regimes and hence the overall water balance.

excessively drained pine forests (*P. banksiana* in Canada and *P. sylvestris* in Eurasia). Some Spodosols can be found in the wetter regions of boreal forests.

Species Composition Tree species diversity is very poor in the boreal forests. There are only nine dominant tree species in North America, and 14 in Fennoscandinavia and the former Soviet Union (4). The low species diversity is attributed to the recent development of boreal forests following the retreat of glaciers and the harsh climate (3). In general, boreal species arrived in this region less than 2000 years ago. The distribution of species, and the species composition of stands are strongly influenced by topography and soils. Important genera include fir *(Abies)*, birch *(Betula)*, larches *(Larix)*, spruce *(Picea)*, aspen *(Populus)*, and willow *(Salix)*. *Picea* and *Larix* commonly occur on poorly drained lowland soils. Pines commonly occupy well-drained upland soils, while *Populus*, *Abies*, *Salix*, and certain species of *Picea* occur on the finer-textured upland soils. In North America and Europe, needle-leaved evergreen conifers tend to dominate the boreal landscape, especially at northern latitudes. However, *Larix*, a deciduous conifer, increases in importance in Eurasia and dominates the boreal treeline in Siberia (5). Ericaceous shrubs commonly dominate the understory of boreal forests. In no other forest biome do bryophytes play such an important role. Lichens *(Cladina* spp.) occur on the excessively drained sandy soils, feathermoss *(Pleurozium* spp.) forms a continuous ground layer in many spruce and pine forests of intermediate drainage and sphagnum *(Sphagnum* spp.) are the most common bryophyte on poorly drained soils.

Structure and Function Boreal forests have low leaf area index (LAI, the amount of leaf area per unit ground surface area) and the conifer trees have very pronounced spiral canopies. The spiral canopies help shed the snow and maximize light interception when the sun is low in the horizon. Boreal forests have a low LAI because the extremely short growing season and very nutrient poor soils limit the amount of foliage area a stand supports (Chapter 6). Aboveground net primary production (ANPP, the annual amount of organic matter or biomass trees accumulate in stem, branches, and foliage) is low, averaging 4.2 and 3.2 tC $ha^{-1}yr^{-1}$ for evergreen and deciduous forests, respectively (6). Although live bryophytes constitute less than 1 percent of the total aboveground biomass of boreal forests, they have a profound effect on the structure and function of boreal forests. Bryophytes insulate the soil, which strongly affects the thermal regime and hence overall nutrient cycling and productivity patterns of boreal forests. Also, the productivity of bryophytes can equal or exceed that of the stem growth of trees (7).

Fire is an important natural disturbance in boreal forests. Fires, ignited by lightning, tend to cover large areas and may burn as much as 25,000 to 50,000 hectares (8). Fire frequency in the boreal forests in North America ranges from 30 to 200 years, depending on species composition and topographic position. Fire strongly influences species composition, nutrient availability and forest productivity (8). Insect damage can be important in boreal forests in some regions. Damaging summer storms are rare, and severe winter weather is unlikely to cause damage to trees.

Management Boreal forests are one of the least managed forest biomes of the world because of the low growth rates, the extremely cold and dry climate, and inaccessibility. However, there are areas—for example, along the southern edges of the forests in Canada, Scandinavia, and in Siberia—where commercial logging occurs. A concern with harvesting boreal forests is that the rate of vegetation regrowth is very slow because of the extremely cold winters and infertile soils. Timber companies are interested in harvesting boreal forests, especially in Siberia, because of the large areas of mature forests (Table 3.1). The political instability and poor infrastructure in Siberia may be the only factor stopping large-scale harvesting of this fragile ecosystem. Plantation forests are scarce in the boreal regions. Management of natural and plantation boreal forests in the Nordic countries (Denmark, Sweden, Finland and Norway) can approach the intensity of plantation forestry, but are probably the best example of sustainable management of boreal forests. Another serious environmental threat to boreal forests is the unchecked air pollution from some of the world's largest iron ore, and nickel mines.

Temperate Broad-leaved Deciduous Forests

Distribution and Extent Temperate broad-leaved deciduous forests cover 3.5 x 10^8 hectares (Table 3.1) and occur primarily between 30° to 50° N latitude (Figure 3.3). Large tracts of these forests occur in the eastern United States, Europe, western Turkey and eastern border areas of Iran, western China and Japan. The noticeable absence of deciduous forests in the Southern Hemisphere, except for the western coast of southern Chile, is because the year-round mild climate favors the evergreen over deciduous leaf habit.

Climate In the temperate deciduous forest zone of the northern United States (represented by Chicago, Illinois, Figure 3.4b), minimum temperatures are well below freezing for at least four months of the year. The best period for growth is in the spring, when temperature and water are adequate. During the summer high, evaporation may equal or exceed precipitation, resulting in water deficits that restrict growth.

Further south, in the temperate mixed (evergreen, needle-leaved conifers and broad-leaved deciduous) region, represented by the climate at Nashville, Tennessee (Figure 3.4d), higher rainfall is not enough to prevent summer water deficits, but early-season temperatures are significantly higher than in the deciduous and coniferous areas. The deciduous trees lose their leaves during the winter, but the period when temperatures are low enough to prevent growth of evergreen conifers is relatively short.

Soils Temperate forest soils are highly variable. Many of the mountain soils in temperate regions are Entisols, Inceptisols, or Alfisols, with the former being young and infertile and the latter being moderately weathered, but fertile. In warmer climates (e.g., southeastern United States, southern Europe) the soils have undergone greater weathering and the dominant soil order is Ultisols; these soils can be productive, especially if nitrogen and phosphorus fertilizer is applied.

Species Composition Both tree and understory diversity are greater in temperate deciduous than temperate conifer and boreal forests; approximately 30 plant families and 65 genera occur in the overstory canopy of temperate deciduous forests (9). Species diversity of deciduous forests is highest in North America, China and Japan, where refugia for temperate forests are hypothesized to have existed during the most recent glacial periods. Species diversity is lower in Europe, perhaps because the predominantly east-west mountain ranges prevented species from retreating south to warmer climates during the most recent glacial advance. Species composition varies according to topography, soil fertility, and successional status. A few important temperate deciduous tree genera and species include maple (*Acer*), birch (*Betula*), hickory (*Carya*), beech (*Fagus*), ash (*Fraxinus*), walnut (*Juglans*), tulip tree (*Liriodendron*), *Magnolia*, aspen (*Populus*), oak (*Quercus*), basswood (*Tilia*), tree of heaven (*Ailanthus*), silktree (*Albizzia*), *Castanopsis*, and *Zelkova*. Except for stands of *Populus*, pure stands of one species are uncommon.

Structure and Function The growing season ranges from 4 months in northern forests to 8 months in southern forests. The leaf area index of temperate broad-leaved deciduous forests tends to be higher than that of temperate evergreen forests because the evergreen conifer forests often occur on the more infertile, drought-prone soils. Net primary productivity of temperate broad-leaved deciduous forests averages 6.6 tC ha^{-1} yr^{-1}. The riparian broad-leaved temperate forests in the southeastern United States are some of the most productive forests in the world and NPP can exceed 10 tC ha^{-1} yr^{-1}. Riparian forests are also important in flood prevention, maintaining water quality, filtering harmful chemicals and sediments, and habitat for aquatic flora and fauna. A large percentage of the original temperate deciduous forests have been cleared for agriculture because these soils tend to be fertile. The drainage and conversion of riparian forests to agriculture threatens regional watersheds.

Management Present-day temperate deciduous forests do not usually occur in extensive tracts because of large-scale human activities (e.g., clearing and conversion to agriculture, pasture, and urban areas). Management may range from periodic selective tree removal to short-rotation plantations for fiber or fuel production—the most intensive form of forest management. Species commonly used in short-rotation plantations include poplars, sweetgum, willows, and sycamore. Depending upon the species, life history, and ecophysiology, both even-aged and uneven-aged management practices can be sustainable. Even-aged management is most prevalent for shade-intolerant and coppicing—regrowth of aboveground vegetation from the root stock of the trees that were harvested—species (aspen), while uneven-aged management is commonly used for shade-tolerant species. Uneven-aged management is becoming increasingly popular because managed uneven-aged forests retain many of the desirable characteristics (e.g., canopy gaps, multilayer canopies, biodiversity) of old-growth forests.

Temperate Needle-leaved Evergreen Forests

Distribution and Extent Temperate evergreen coniferous forests are largely restricted to the Northern Hemisphere and cover approximately 2.4×10^8 hectares (Table 3.1). Conifers dominate the montane forests in North America, Europe, and China and smaller areas of temperate conifers are located in montane regions of Korea, Japan, and Central America. Pines species have been planted extensively in the Southern Hemisphere. Natural temperate conifer forests tend to occur on droughty or infertile soils that cannot supply the greater water and nutrient demands of deciduous species. Evergreen conifers are the most common trees in the Pacific Northwestern United States, where dry summers and mild winters provide a more favorable environment for evergreens than conifers (10).

Climate Temperate evergreen conifers occur in a wide range of climates, such as sub-tropical, woodland, boreal forests and temperate rainforests (Figure 3.3). However, an area notable for such forests is the northwest coast of the United States, represented by Seattle, Washington (Figure 3.4c), which has cooler summers than the temperate deciduous zone, warmer winters (the average minimum temperature for any month is never below zero) and a different precipitation pattern. The largest amount of precipitation occurs in the winter months, with very little during the period of highest evaporation. As a result, significant water deficits occur and reduce tree growth during the summer. Fire can be an important cause of ecosystem disturbance, especially in exceptionally dry summers when the normal summer drought (Figure 3.4c) is extended and exacerbated by unusually hot weather and lack of precipitation.

Soils It is also difficult to generalize about temperate needle-leaved forest soils because they are extremely variable over the wide range of climatic and parent materials where these forests occur. The more common forest soil orders include: Inceptisols, Alfisols, and Ultisols. Spodosols are primarily restricted to cool to cold-temperate conifer forests that receive abundant rainfall. Many of the temperate needle-leaved conifer forests occurring on Ultisols and Spodisols respond positively to nitrogen and phosphorus fertilization treatments.

Species Composition Common genera in the temperate coniferous forests in the northern latitudes include fir (*Abies*), spruce (*Picea*), Douglas fir (*Pseudotsuga menziesii*), while hemlock (*Tsuga*) occur over a much broader range of environmental conditions. Pine, an important genera from both an economic and ecological perspective, occur in a wide variety of environments ranging from hot, arid southwestern United States to cold temperate regions of Scandinavia and Eurasia.

Structure and Function Given the diverse environments in which temperate conifers occur, it is not surprising that the ecophysiology and structure of these forests also vary. For example, needle longevity can range from less than 2 years for loblolly pine (*P. taeda*) to greater than 40 years for bristlecone pine (*P. longaeva*). Above ground biomass of mature forests can range from a low of about 100 t ha^{-1} for *Pinus* forests in the southwestern United States to 3300 t ha^{-1} for giant redwood *{Sequoia sempervirens)* forests in northern California (11). Some of the lowest leaf area index < 1 occur in temperate conifer forests, while the highest measured leaf area index 12 was for a western hemlock *(Tsuga heterophylld*) forest in coastal Oregon (4). Aboveground net production is also quite variable, ranging from about 2 to 20 t ha^{-1} yr^{-1}, averaging 6.6 tC ha^{-1} yr^{-1} (Table 3.1).

Management Management practices in temperate coniferous forests vary greatly; the intensity of management tends to be strongly correlated to the suitability of environmental conditions for tree growth. At one extreme these forests are allowed to regenerate naturally following disturbance such as fire or harvesting. Biomass accumulation can be substantial over several centuries, but the annual accumulation rate is very slow. The harvesting of mature, slow growing forests is controversial, because these forests provide many other valuable ecosystem services such as wilderness areas extensively used for recreation, wildlife refuges, and valuable watersheds. Because of the long growth cycle and the destruction of many of these values, harvesting these "old growth" forests more closely resembles resource mining than sustainable forest management.

Management practices of intermediate intensity are becoming more common because there is increasing pressure from society to manage mature forests on an uneven-aged basis. Managed uneven-aged stands retain structural characteristics that are similar to "old-growth" or pristine forests. At the other extreme, temperate conifers are managed at a level of intensity that rivals or exceeds agriculture. Intensive management includes mechanized site preparation and planting, use of genetically superior seedlings, application of herbicides and fertilizers during the rotation, pruning (the removal of low branches to increase wood quality), and mechanised harvesting, which can include the complete removal of all above ground biomass.

Major needle-leaved temperate conifer species used in plantations include Sitka spruce (*Picea sitchensis*) in Britain, extensive plantations of loblolly and slash pine (*P. taeda* and *P. elliotti*, respectively) in the southern United States, Douglas fir (*Pseudotsuga menziesii*) in the Pacific northwestern United States and Canada, and Monterey pine (*P. radiatd*) in Australia, New Zealand, Chile and South Africa (although South Africa also uses several other softwood species).

Temperate Mixed Forests

Temperate mixed (deciduous plus evergreen) forests occur throughout the temperate evergreen and deciduous regions—particularly the southeastern United States, Europe through northern Iraq and Iran, and China—where the climates are the same as those described for temperate deciduous and coniferous forests. Mixed forests have been studied less than pure deciduous or evergreen forests. Their occurrence reflects past land use change, successional status and local variations in edaphic conditions. In the southeastern United States, conifers dominant early successional forests, mixed forests are common for mid-successional forests, and broad-leaved hardwoods dominate late successional forests. In the Lake States, needle-leaved evergreen forests dominate the xeric, infertile soils, mixed forests are most common on the soils of intermediate edaphic conditions, and broad-leaved hardwood forests occur on the mesic fine-textured soils (12). A wide range of species combinations is found in mixed forests: evergreen conifers and deciduous broad-leaved species: for example, oak and loblolly pine, Douglas fir, red alder and western hemlock, Sitka spruce and alder, larch, fir and pine, eucalyptus, and acacias.

Temperate Broad-leaved Evergreen Forests

Distribution and Extent The potential area of temperate broad-leaved evergreen forests is 5.1 x 10^8 km^2 (Table 3.1). Two categories of temperate broad-leaved evergreen forests are recognized: broad-leaved sclerophyll and broad-leaved rain forests (4). The broad-leaved sclerophyll forests occur in areas with a Mediterranean-type climate: winter rain and summer drought. The temperate broad-leaved rainforests are found in humid, frost-free climates, usually along coastal areas. The sclerophyll forests occur in scattered areas of the United States, around the Mediterranean, and over large areas of Asia from northern India through southern China. The greatest continuous areas still existing are the eucalyptus forests of Australia. Temperate broad-leaved evergreen rain forests occur in Japan, Chile, New Zealand, Australia (Tasmania), and in scattered, remnant patches in Asia.

Climate The climate at Hobart, Tasmania, Australia (Figure 3.4e) is not dissimilar to that of the west coast of South Island, New Zealand, and both areas are characterized by broad-leaved evergreen forests. The annual rainfall in Hobart is not high, but it is evenly distributed through the year and evaporation is low. Therefore, trees only experience mild water deficits during the summer. Average minimum monthly temperatures are rarely below zero, so tree growth occurs throughout the year. The climates of Sydney and Tasmania, Australia are similar (Figure 3.4e-f), although the average annual temperature for Sydney is higher (17.4°C versus 12.2°C). Higher rainfall (1200 mm or 47 inches) compensates for the higher temperatures and evaporation, so environmental conditions are good for growth throughout the year.

Soils Less is known about the temperate broad-leaved evergreen forest soils compared to other temperate forest soils. The soils of schlerophylous forests of Australia and Mediterranean areas are composed of Inceptisols and Ultisols, while the forests in Tasmania, New Zealand and South America are dominated by Alfisols and Inceptisols.

Species Composition The sclerophyll—a term that describes the thick, tough foliage of many of these tree species—forests in the Mediterranean area and the United States are dominated by oaks (*Quercus*), while the broad-leaved temperate forests of Australia are dominated by Eucalyptus. In Tasmania and Victoria, there are relatively small areas of *Nothofagus* forests; these are extensive in New Zealand and Chile. Temperate broad-leaved evergreen forests in New Zealand vary from multi-storied, mixed-species coastal forests, with tall conifers (*Podocarpus, Dacrycarpus, Agathis*), to the pure, dense-canopied montane and subalpine stands of beech (*Nothofagus*). The evergreen beech forests should not be confused with the deciduous beech forests that are native to the eastern United States. Many of the trees species have chemical compounds in the foliage that make them much more flammable than other tree species, and are therefore much more prone to catastrophic wildfires (see below).

Structure and Function The characteristic sclerophyll foliage is advantageous because it deters herbivory, helps avoid drought, and is believed to be an important adaptation to help plants cope with nutrient infertile soils. The natural structure of the sclerophyllous oak forests is a dense, often continuous canopy, less than 20 m tall. Eucalyptus canopies may vary from tall (up to 60 m in height) closed forest to shorter closed forest and woodland. The LAI of eucalyptus forests is low, especially relative to the high productivity of these forests. The forests have relatively dense shrub understory, presumably because there is adequate light and reduced evaporative demand. The NPP averages 10.0 tC ha^{-1} yr^{-1}, the highest of all the forest biomes, but this average is based on very few data. Nonetheless, temperate broad-leaved forest can be very productive when moisture and nutrient availability are high.

Management Forests in the Mediterranean area have been used by humans for thousands of years, and in the United States cutting and clearance for agriculture and various other forms of development have been rapid. The forest industry in Australia has been based on native forests for more than 100 years. During this time, the mature forests have been either clearcut or selectively logged. Most Eucalyptus species are tolerant of fire, and the forest ecosystems are adapted to it. The native people of Australia used fire for thousands of years in a manner that appeared to be consistent with natural regimes (fires caused by lightning strikes). Since European settlement, fire has been excluded, as much as possible, from the remaining forests. The result has been fuel buildup, so that when fires do occur, they are likely to be much more intense than was normal historically (Chapter 18).

Large areas of the native Eucalyptus forests in Australia have been cleared and replaced by softwood Monterey pine (*P. radiata*) plantations. The establishment of hardwood plantations has been slow, largely because of economic and sociological reasons. Many lowland Podocarp forests have been harvested for their exotic timber. There are still large areas of beech forest. New Zealand has now virtually halted native forest logging.

The South American temperate broad-leaved evergreen forests include a range of types, from lowland to Andean slopes. The dominant species is generally *Nothofagus.* These forests have all been heavily exploited for timber. Like Australia and New Zealand, Chile now has extensive *P. radiata* plantations, which may serve to slow the destruction of native *Nothofagus* forests.

Tropical Broad-leaved Evergreen Forests

Distribution and Extent Tropical broad-leaved evergreen forests, or rainforests, comprise the largest single forest biome in the world (see Table 3.1). The greatest single area of tropical evergreen forest is in the Amazon Basin, in the northern half of South America. Similar forests are found on the isthmus of Panama and into southern Mexico, the Congo Basin in equatorial Africa, and the southern fringe of West Africa. In Asia, tropical rainforests occur along the southeast coast of India, in Sri Lanka, the Malaysian Peninsula, the Indonesian archipelago, Borneo, Sarawak, and Papua New Guinea (collectively called Melanesia). A small remnant strip of tropical rainforest also occurs along the northeast coast of Australia. Rainfall is generally greater than 1500 mm per year and relative humidity is uniformly high. There is a broad range of subtypes within tropical forests, ranging from lowland to montane types. The large differences in climate and parent material have a pronounced impact on the structure and function of tropical forests (13), and it is difficult to make generalizations about such a large forest biome.

Climate The tropical evergreen forests are generally considered to be wet at all times, but Figure 3.4g indicates there are periods when evaporation may exceed rainfall in the Amazon rainforests. This pattern also occurs in the African tropical rainforests, but in many of the southeast Asian areas rainfall exceeds evaporation in every month of the year. In general, diurnal variation in temperature exceeds seasonal variation in temperature.

Soils Tropical forest soils are highly variable. An excellent summary of tropical soil distribution, extent, and key pedogenic processes that control soil fertility is provided by Sanchez (14). Oxisols and Ultisols, the two dominant soil orders in the tropics, are highly weathered and are typically infertile. Phosphorus and base cations are commonly the most deficient nutrients. They have extremely low cation exchange capacity, base saturation, and pH. Alfisols, more fertile than Oxisols and Ultisols, occur in regions with lower precipitation (e.g., tropical deciduous forest regions) than lowland wet tropical forests. Because of their higher fertility, the forests on these soils are often cleared and used for agriculture.

Species Composition Tropical evergreen forests are the most diverse terrestrial ecosystems on earth, with the greatest number of species per unit area.

The Amazonian forests contain more than 2500 different tree species, with thousands more in the African and Asian forests. Dipterocarps are common trees in many tropical forests in the world. Eastern South America tropical rainforests contain conifers such as *Dacrydium, Podocarpus, Agathis,* and *Araucaria* (15). The African rainforests appear to be relatively poor in species compared to those of America and Asia. Characteristic species are *Lophira alata, Turraeanthus africana, Tarrieta utilis* and *Uapaca* spp. The most important commercial tree species of the evergreen forests of Africa belong to the *Meliaceae* family (16).

Structure and Function Rainforest canopies are characterized by layered architecture. The canopy includes an upper layer of emergent trees, a main canopy layer and a subcanopy of smaller trees and shrubs. The varied canopy structure is caused by gaps of different sizes, created at different times. The aboveground biomass of tropical rainforests varies with topography, soil type, stage of development and other factors. Aboveground biomass ranges from 100 to 1500 t ha^{-1} (4). NPP averages 8.2 tC ha^{-1} yr^{-1}. The most recent summaries of NPP for different forest biomes suggest that differences in NPP between tropical and temperate forests are smaller than reported in earlier studies (17).

Millions of canopy-dwelling insects reside in wet tropical forests. These insects are part of an ecosystem in which predator-prey relationships are extremely complex. Vast numbers of these organisms consume large quantities of foliage, bark and wood.

Natural disturbances in tropical forests include cyclonic storms, wildfires and volcanic eruptions. Inland forests, in the Amazon and Congo basins, are not subject to hurricanes and appear to be at very little risk from environmental hazards, but the hazard is significant through much of the southeast Asian area, particularly in the Indonesian archipelago and Malaysia. Hurricanes are a common form of disturbance for coastal tropical rainforests.

Management Tropical rainforests are under increasing pressure from human activities. During the 1980s (1981-90) 4.6 million hectares—or approximately 0.6 percent of all lowland tropical rainforest—were harvested or cleared. An additional 2.5 million hectares of tropical montane forests are destroyed each year. Indonesia and Brazil accounted for 45 percent of the total. Degradation and fragmentation of the remaining forests result in the loss of large tracts of unmanaged forests substantially greater than the clearing rates suggest. The causes for deforestation are numerous, and the remedies are complex. In Africa, expanding populations and constant clearance for agriculture are the primary causes of deforestation. Shifting cultivation and cattle ranching are major causes of deforestation in South America. In Asia, deforestation is caused by burgeoning human populations and poorly regulated logging. Solutions must be found for these problems—perhaps the most important will be control of human populations. Agroforestry may be a sustainable system for tropical areas. The development of viable tropical forest management systems and procedures for preserving the forests and utilizing them on a sustainable basis will require much better ecological and physiological information for the dominant tree species.

With the exception of the widely grown Eucalyptus plantations, most tropical plantations are softwoods, although hardwood plantations are beginning to gain popularity in the tropics. However, a great deal of research is necessary before the problems of managing tropical plantations to produce acceptable timber growth rates are solved.

Tropical Broad-leaved Deciduous Forests

Distribution and Extent Tropical deciduous forests occupy 4.6 x 10^8 hectares (Table 3.1) and comprise 42 percent of tropical and subtropical regions (18). Tropical broad-leaved deciduous forests replace tropical broad-leaved evergreen trees as annual rainfall decreases and interseasonal differences in precipitation increase. Drought induces leaf shedding and the deciduous growth habit in trees. Deciduous tropical forests occur on the borders of evergreen forests in South America and

Africa, where the mountain forests of central Africa may be included in the deciduous category. The largest areas of tropical deciduous forests are the monsoonal forests of southern and southeastern Asia, in India, the Himalayan countries and Bangladesh, stretching through to Burma, Thailand, Laos, Cambodia, and Vietnam (16).

Climate Jamshedpur, in India (Figure 3.4h) is a monsoon climate, characterized by heavy rains for 4-6 months of the year, with high water deficits developing after the monsoon season. Temperatures are high throughout the year. A very similar climate is found in Central and South America; Managua, Nicaragua has a mean annual temperature of 27.3°C (cf. 26.4°C at Jamshedpur), and total annual precipitation of 1142 mm, most of which falls in five months.

Soils Major soils orders of tropical broad-leaved deciduous forests are Alfisols and Inceptisols. Highly weathered soils (e.g., Ultisols and Oxisols) are rare because lower precipitation prevents excessive weathering of the soil. Many of these soils are rich in base cations.

Species Composition Species diversity is typically less in tropical deciduous than in tropical evergreen forests (18). Dominant species in Africa include *Antiarus africana*, *Ceiba pentandra*, *Triplochiton scleroxolon*, and others, while important species in America are *Andira*, *Dalbergia*, and *Tabebuia* genera, with conifers represented by Caribbean Pine (*P. caribaea*) and *P. oocarpa* (16). Important tropical deciduous tree species in Central America include *Calcophyllum candidissimum* and *Licania arborea* in lowland forests, *Luehea seemannii* and *Guarea excelsa* in lowland riparian areas and an oak, *Quercus oleoides*, which occurs in scattered populations over a wide area (19). Deciduous tropical forests in Asia include *Tectona grandis* (teak), *Shorea robusta*, and species of *Dalbergia* and *Terminalia* (16).

Structure and Function The canopies of deciduous tropical forests tend to be shorter, less layered, and characterized by more open structure than tropical evergreen forests. Dense shrubs often occur as the second layer, presumably because of the better light environment and reduced evaporative demand at lower levels in the canopy. The productivity of tropical deciduous forests is influenced by the periods for which the trees have leaves and water relations are such that the trees can utilize radiant energy and grow relatively unchecked by water stress (see Chapter 4 on water relations and Chapter 13 on ecosytem models). Average NPP for tropical broad-leaved deciduous forests is 8.0 tC ha^{-1} yr^{-1} (Table 3.1). Fire is an important natural ecological component of tropical broad-leaved deciduous forests, and human disturbance has greatly reduced the amount and quality of these forests (4).

Management Tropical deciduous forests in all continents have been subject, over long periods, to burning and clearing for grazing and arable agriculture. Annual deforestation rates during the 1980s was 6.6 million hectares, and like the tropical broad-leaved evergreen forests, the greatest rates of deforestation are occurring in Brazil and Indonesia; human population growth in these areas will lead to continued destruction of the few remnants, with progression towards degraded forests, woodland and savannah. Soil erosion is among the many serious effects of forest destruction and degradation. Protection of these forests is an unattainable goal in many regions of the world because of rapidly growing population. The future objective should be to preserve existing pristine forests and develop sustainable management plans for disturbed ecosystems. Where damaged forests can be protected, their recovery depends heavily on the state of the soils, in terms of organic matter content, structure, and nutrient status.

Global Change and Forests

Forests are an important component of the biosphere. Forest and woodland soils contain 45 percent of the total soil carbon of terrestrial ecosystems, forest and woodland vegetation contain 84 percent of the total terrestrial vegetation carbon, and forests annually assimilate 61 percent of the total carbon dioxide removed from the atmosphere by terrestrial ecosystems (17). The role of forests in the biosphere is changing because of land use change and climate and atmospheric chemistry change. Altering the extent and spatial distribution of forests can cause feedbacks between the atmosphere and vegetation.

Habitat Protection and Land Use Change

Habitat protection is a necessary management practice to maintain or improve biodiversity—an important component of sustainable forestry. The practice is more difficult because of the need to protect large tracts of threatened ecosystems. The World Conservation Union, an independent international organization that oversees conserving biodiversity established a goal of protecting a minimum of 10 percent of each of the world's major biomes. Few of the forest biomes has the minimum 10 percent of the area protected (Figure 3.5). The temperate forest biomes have the smallest area in protected forests (2.9 to 3.2 percent). Tropical broad-leaved deciduous forests also have less than 5 percent of the total area in protected forests. Perhaps even more disturbing is there are very few temperate broad-leaved deciduous and broad-leaved evergreen forests of "low human disturbance" available for protection.

A second, and more complicated consideration, is the spatial arrangement of the protected forests. The spatial arrangement of vegetation communities is important for the survival of certain species and proper ecosystem function. For example, assuming the edge effect of harvest extends one kilometer into the intact forest, a 10 x 10 km clearcut would affect 143 km^2 of forest. However, if 100 km^2 is deforested as 10 strips, each 1 x 10 km (e.g., logging adjacent to new roads in remote forests) the affected area would be about 350 km^2. Skoles and Tucker (20), using repeated satellite imagery, estimated an annual deforestation rate for the entire Amazon Basin of 280,000 km^2 yr^{-1}, but using the assumption outlined earlier, the area affected by clearing—the so-called rate of fragmentation—would be 380,000 km^2 yr^{-1}. Although the assumption made by Skoles and Tucker about the magnitude of the edge effect is controversial, they raise a valid concern, particularly for animals that require large tracts of natural forests.

An increasing percentage of timber products used in the world today, particularly pulpwood but, increasingly, sawn timber products, come from plantations rather than from natural forests. Plantations have many advantages over natural forests. Plantations can be established on prepared land, using genetically improved and uniform material at standardized spacings that allow optimum growth rates of individual trees. It is economically feasible to control weeds and use fertilizers to ameliorate problems of soil nutrition in plantations. Plantations should be used to increase the production of wood products, thereby alleviating the need to harvest the remaining native forests.

Climate Change

Changes in atmospheric chemistry also threaten the health of forest ecosystems. The concentration of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O_X) and chloroflorocarbons (CFCs) have all greatly increased and the consensus of world experts is that the increased concentration of greenhouse gases will cause the climate to change (21). One major concern is that the predicted increase in temperature is far faster than changes in climate in the geologic past and some forest ecosystems tree species may experience future climates that do not currently occur in their present-day range. There is great interest in understanding how anticipated climate change will affect the distribution and extent of future forests. Model simulations suggest that the extent of boreal forests will decrease and tropical forests will increase, although the magnitude of the change differs among the models (4).

Ozone is another atmospheric pollutant that is harmful to plant growth. Ozone is the product of complex chemical reactions in the atmosphere that

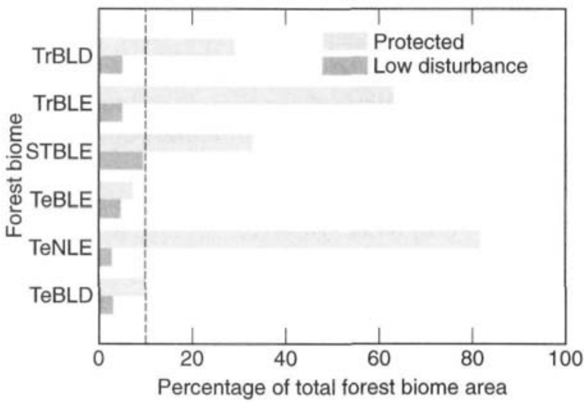


Figure 3.5 Percentage of each major forest biome area that is protected or subject to low human disturbance. The dashed line represents the goal of designating 10% of the total area of each forest biome as protected preserves. TrBLD = Tropical broad-leaved deciduous; TrBLE = Tropical broad-leaved evergreen; STBLE = Subtropical broad-leaved evergreen; TeBLE = Temperate broad-leaved evergreen; TeNLE = Temperate needle-leaved evergreen; TeBLD = Temperate broad-leaved deciduous.

involve pollutants from the combustion of fossil fuel. Reductions in the growth of agriculture crops and trees from elevated ozone concentrations are well documented (Chapter 4). A second atmospheric pollutant that is gaining worldwide attention is atmospheric nitrogen deposition. Although many forest ecosystems are nitrogen limited, chronic deposition of moderate to high amounts of nitrogen may cause forest ecosystems to function improperly, causing forest dieback and contamination of adjacent watersheds. The susceptibility of forests to nitrogen deposition is strongly dependent upon forest species, and soil type. Forest dieback attributed to stress induced from climatic change has already been suspected in many heavily industrialized areas in the temperate forests (4).

Concluding Statement

Humans have exerted a large influence on forest ecosystems of the world, and will continue to do so as the world population increases. Preserving large areas of (relatively) undisturbed forest ecosystems should be pursued wherever possible, but it is equally important to be realistic about the fact that forests must be used. The most pressing objective in forestry is to manage ecosystems on a sustainable basis. To achieve this goal, managers, politicians, and scientists must work together to develop management plans that are consistent with the ecology of each of the forest ecosystems comprising all the major forest biomes. Obtaining this goal will occur only if forest management is based on a sound understanding of forest biology (Chapters 4-8), forest fire ecology (Chapter 18), plant-animal interactions and protection (Chapters 14 and 18), and forest hydrology (Chapter 16).

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CHAPTER 4

Forest Ecophysiology

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Ecophysiology is a marriage of ecology and physiology in which the functions and activities of organisms are studied in the context of their environment. Implicit in this description is a quest to identify adaptive traits that organisms possess to cope with their often harsh and variable surroundings. Forest ecophysiology explores many of the questions and issues that emerge in related disciplines, including forest ecology, genetics, silviculture, pathology, and entomology. A good example of such an issue is forest succession, a fascinating and important ecological process involving the orderly replacement of certain plant species or communities by others through time (see Chapter 13). Ecophysiologists continue to pursue a mechanistic understanding of this phenomenon and the species adaptations that drive it. Another current focus is the generation of accurate predictions as to how forests will respond to changes in the global environment. There is currently a pressing need for these forecasts as society faces the seemingly imminent specter of marked shifts in global climate and atmospheric chemistry.

As the discipline of ecophysiology has evolved, it has expanded in scope, addressing issues at an increasingly wide range of scales. For instance, ecophysiologists have recently been studying how forest responses to changes in atmospheric chemistry will affect continental rainfall patterns, and the explanation links molecular behavior in certain leaf cells with landscape-level changes in vegetation water use. Conceptually, ecophysiology relies heavily on basic sciences such as chemistry and physics. However, it has also developed ties with ostensibly unrelated disciplines, such as economics. This has occurred because the ability of organisms to flourish in a given environment depends in part on such aspects as the efficiency in which a particular resource is used, or how effectively it is scavenged from the environment. These are critical considerations in the life of a tree, as essential resources exist in dilute concentrations in most forest ecosystems.

So where does one begin in tackling issues in forest ecophysiology? The first step is to garner a basic understanding of how trees "make a living." This step necessarily entails a coupling of tree structure and function, and there this chapter begins. From there, one can pursue any number of different paths. Here we will explore various aspects of tree response to environment, highlighting our knowledge (or lack thereof) about mechanisms underlying these behaviors. Armed with this background, we will then take a brief look at global-scale issues facing forests at present and in the future.

Coupling Tree Structure and Function

Leaves—The Tree's Solar Panels

Like all other plants, trees are made mostly from sugars as the basic building blocks. Sugars are the primary raw material from which all tree tissues (wood, bark, leaves, fine roots, flowers, etc.) are constructed. They are also the source of fuel used by enzymes and associated biochemical machinery in building and maintaining the tree. Tree leaves are sugar factories producing glucose, an organic (carbon-based) compound, by way of photosynthesis, the process of "trapping" the sun's energy. A large tree typically displays thousands of leaves that absorb sunlight and transfer its energy (by way of electrons) to carbon dioxide (CO_2), a relatively scarce gas in our atmosphere (currently ~0.037% by volume). The electron-rich carbon is then assembled to make either a disaccharide sugar, sucrose, or the closely related storage polysaccharide, starch (the general formula of both is $[C_6H_{12}O_6]_x$). A glance at the simplified chemical formula for photosynthesis, $CO_2 + H_2O \xrightarrow{light} CH_2O + O_2$, reveals that it also produces life-sustaining oxygen (O_2) when it strips electrons from water (H_2O) (see also Chapter 20, Wood Products).

This elegant process occurs in layers of leaf cells (Figure 4.1) collectively referred to as mesophyll (meaning middle of the leaf). A leaf is green because these cells contain bacterium-sized organelles called chloroplasts, which are laden with the pigment chlorophyll. The green color of chlorophyll stems from its preferential absorption of red (600-700 nm) and blue (400-500 nm) light. Thus, when looking at a leaf, we see the small amount (typically <10%) of visible light that is reflected or transmitted rather than absorbed and utilized for photosynthesis.

Chlorophyll is one of several pigments, proteins, and other components of chloroplast machinery that absorbs and converts light energy into what is essentially electric current. The energy in this current is then stored in chemical fuels that are used

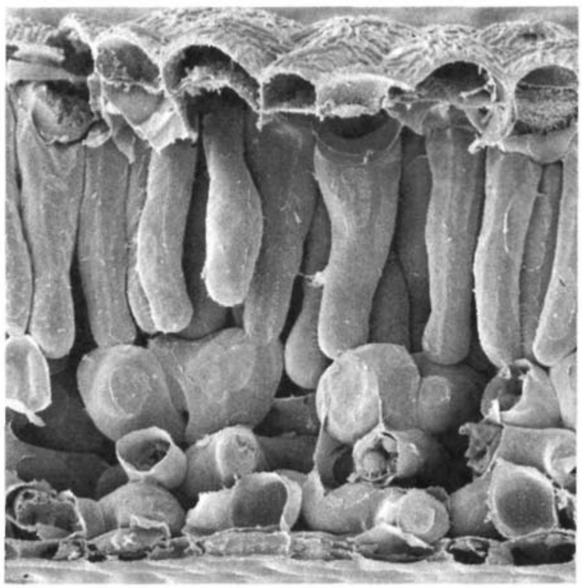


Figure 4.1 Cross-section of a Norway maple (*Acerplatanoides*) leaf. The wax-coated epidermis encloses several cell types, including columnar chloroplast-laden cells called *palisade parenchyma*, amorphous spongy mesophyll (beneath the palisade cells) and vascular bundles containing xylem and phloem (not shown). All of this is packed in an envelope less than one millimeter thick.

to "fix" or assimilate carbon dioxide (CO_2) molecules into sugar. The first step in CO_2 assimilation is performed in the chloroplast by one of the most abundant and important enzymes on earth, known by the acronym "rubisco" (short for ribulose bisphosphate carboxylase-oxygenase). Rubisco, which can constitute nearly one-half of the protein in a leaf, is responsible for producing an estimated 200 billion tons of sugar around the world each year. As a frame of reference, humanity currently consumes the equivalent of roughly 10 percent of that energy, including portions of the enormous fossil fuel reservoirs that were generated by rubisco millions of years ago.

Water is a critical factor in the design of a leaf. Living cells such as the mesophyll must bathe in water, and to ensure that this is always the case, mesophyll is wrapped in the epidermis, a largely water-impermeable skin (Figure 4.1). The epidermis is impermeable because it deposits a thin wax (hydrophobic) cuticle on its exterior. However, the photosynthetic requirement for CO_2 necessitates that the mesophyll has access to the atmosphere, and therefore the epidermis has holes in it called stomates. Tens of thousands of these tiny pores typically dot a square centimeter of leaf surface. An important implication of this arrangement is that, in order to photosynthesize, the leaf must lose water, which diffuses from the moist leaf interior through the stomates to the relatively dry atmosphere. As water is generally the most limiting resource for trees and other terrestrial plants, it is essential that water loss, otherwise known as transpiration, is carefully controlled. To achieve this, stomatal pores are lined with a pair of guard cells (Figure 4.2).

Figure 4.2 Close-up of a pair of guard cells lining a stomatal pore in the leaf epidermis. When guard cells absorb water, the stomate opens (upper photo), and when they lose water, it closes (lower photo).

Guard cells maintain a balance between photosynthesis and transpiration by opening and closing the stomatal pore in response to key environmental factors, including light, relative humidity, and even CO_2 concentration. Stomates open in response to increasing light intensity, and they close in response to dry air or high CO_2 concentrations inside the leaf. Stomates also close in response to soil drying, and this is often mediated by a chemical message from the root system. Collectively, these behaviors tend to minimize the amount of water lost per molecule of CO_2 assimilated.

Another essential component of leaves is the "plumbing"—the conduits through which materials are transported to and from the leaf. Water is delivered from the roots to the leaf mesophyll through a set of pipes known as the xylem. Sugar is delivered from the mesophyll to the rest of the tree through a different system called the phloem. The xylem and phloem lie adjacent to each other in vascular bundles that are imbedded in the veins pervading the leaf.

Woody Stem—The Distinctive Feature of Trees

The key feature distinguishing trees from other plants is the perennial woody stem, generally a single column that, in the case of species such as coastal redwood *{Sequoia sempervirens),* can reach massive proportions. Through the ages, arboreal forms have arisen repeatedly in unrelated plant families around the world. Why such a convergence in design? It may simply boil down to the enhanced light capture and competitive ability afforded by a tall stem.

Wood, which affords the stem sufficient strength to support a massive canopy, is essentially a matrix of lignified water conduits (Figure 4.3) that extend from the tips of the roots to the tips of the leaves. Wood (or xylem, derived from the Greek word for wood) actually owes most of its strength and density to lignin, an amorphous polymer deposited in cell walls (see Chapter 20). Much of the wood of conifers and other gymnosperms (often referred to as softwoods) is a honeycomb-like aggregate of conduits called tracheids. In dicot angiosperms (often referred to as hardwoods), the pipes, called vessels, are interspersed with thick-walled fibers that make the wood strong and dense. With few exceptions, the cross-sectional diameter of tracheids and vessels ranges from 10—500 micrometers, and only the widest of them (such as the large vessels of many oaks) are visible to the naked eye when viewing a stem cross-section.

Technically, most of the wood is dead. That is, tracheids, vessels, and fibers consist of nothing more than cell walls at functional maturity. However, in the outer band of wood, known as sapwood, there is a network of living cells, called parenchyma, which permeates the otherwise inert matrix. These cells serve as storage reservoirs for the tree's foodstuffs (mainly starch), and they help maintain the

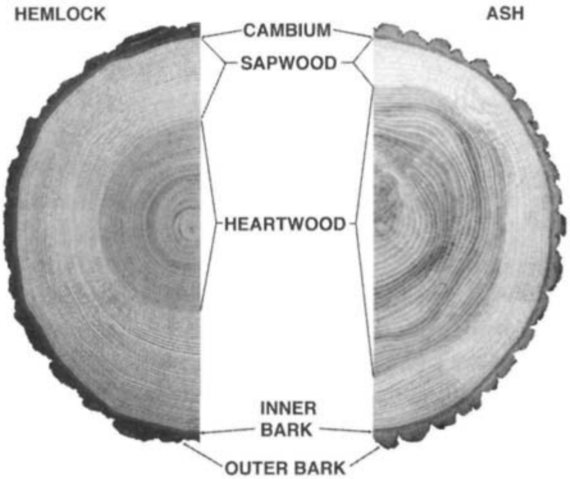


Figure 4.3 Cross-section of the stem of eastern hemlock *(Tsuga canadensis,* a gymnosperm) and white ash *(Fraxinus americana,* an angiosperm). Note in both stems the conspicuous heartwood core surrounded by sapwood and bark. Between the sapwood and inner bark (phloem) lies the meristimatic band of cells known as the vascular cambium.

integrity of the wood, by responding to injury and defending against stem-boring insects and fungi (Figure 4.4). They also participate in a coordinated abandonment of older wood as the tree stem increases in girth. This core of completely dead tissue is the heartwood, which, during the transition from sapwood, is often infused with organic chemicals (e.g., resins, gums, and oils) that deter wood-decay organisms (see Chapter 20). This imparts much of the durability and color that characterizes highly valued lumber from species such as redwood, cedar, and oak.

While water is transported through the stem sapwood from roots to transpiring foliage, a solution of carbohydrates (mostly sugar) flows from the canopy down the stem by way of the phloem, which is a thin band of cells often referred to as the inner bark (Figure 4.3). Unlike the tracheids or vessels of xylem, the plumbing in phloem tissue, consisting primarily of sieve cells (gymnosperms) or sieve tube members (angiosperms),

Sidebar 4.1

Trees are remarkable organisms.

Trees are remarkable for their size, longevity, and ability to thrive in a wide range of habitats. As for size, there are coastal redwood and giant sequoia (*Sequoiadendron giganteum*) trees in California that exceed 110 meters (360 feet) in height and 30 meters (100 feet) in basal circumference, respectively. But none of these methuselan trees has been crowned the largest organism on Earth. Instead, the current record holder is a clone of trembling aspen (*Populus tremuloides*), nick-named "Pando," in the Wasatch Mountains of Utah. This single organism, composed of some 47,000 interconnected and genetically identical tree stems, covers about 43 hectares (106 acres) and is estimated to weigh about 6,000 tons. (The former record holder was also a forest organism—the giant shoestring fungus, *Armillaria bulbosa*, found in Michigan). Not only is this aspen stand the largest organism ever measured, it may also be the longest-lived. It is thought that the clone may have been established before the end of the Pleistocene (last glacial epoch) some 10,000 years ago. If that estimate holds true, it smashes the previous record among trees, which was held by a tenacious, 4,900 year-old bristlecone pine (*Pinus longaevd*) growing in the cold, high-elevation deserts in the western United States. Yet from the standpoint of an ecophysiologist, the most impressive feature of trees is the broad range of habitats in which they can survive. There are species, such as bristlecone pine, that can eke out an existence in some of the driest and coldest areas on earth. And there are others, such as bald cypress (*Taxodium distichum*), that successfully inhabit the warmest and wettest places.

Figure 4.4 In many gymnosperms, parenchyma called epitheleal cells line a network of resin ducts in the wood. When the stem is injured, these cells produce copious amounts of resin to repel the intruder and plug the wound. The presence of pitch tubes on this lodgepole pine (*Pinus contorta*) indicates that the tree has been attacked by mountain pine beetles. Sometimes the intruder is entombed in resin (like the beetle on the right). (Photo at right courtesy of Ken Raffa, copyright of Plenum Press.)

is alive at functional maturity. This contrast underscores a key difference in the mechanism of material transport between the two juxtaposed tissues. Leaf transpiration generates a tension that pulls water through the tiny capillaries of the entire xylem, which is essentially an open or porous system. On the other hand, the sugary solution in the phloem is transported by the buildup of pressure at one end of the system (e.g., the leaf). This occurs within an interconnected plasma membrane that lines all the individual sieve elements, creating something akin to a very long dialysis tube through which the pressurized fluid moves from leaves all the way to root tips.

It may seem counterintuitive that the plasma membrane, which is essential for the creation as well as maintenance of phloem hydraulic pressure, is inherently leaky. Like all cell membranes, it is semipermeable, meaning that certain substances, including water, pass easily across it while others, such as sugar, do not. The key here is that sieve elements have mechanisms to accumulate sugar from surrounding cells. In response to this sugar loading, water flows into the sieve elements from the adjacent xylem. This phenomenon, known as osmosis, is made possible by the unique properties of the plasma membrane. Pressures exceeding ten atmospheres will commonly develop as water fills the confines of the phloem cells. Downstream, sugar is offloaded to needy tissues, and this lessens the strength with which the phloem can hold water. Consequently, water leaks out and pressure declines, creating the gradient in pressure from leaves to roots that drives phloem transport.

When one examines the cross-section of a stem (Figure 4.3), it may be a bit puzzling as to how the tree coordinates the production of new xylem and phloem tissues as the stem increases in girth. It turns out that the stem has a thin layer of meristematic cells, known as the vascular cambium, positioned between the xylem and phloem (or wood and inner bark). Each year throughout the life of the tree, the cells in this cylinder undergo innumerable divisions, producing new xylem in an inward direction, and at the same time new phloem in the outward direction.

Meanwhile, new cells are being produced in yet another meristematic cylinder that lies outside of the phloem, the cork cambium (or phellogen). The cork cambium is responsible for maintaining the protective outer bark of the tree. As the name implies, much of the tissue manufactured by this perennial cambium is cork, which is dead at maturity and has suberin, a waxy waterproof polymer, incorporated in its cell walls. This creates a barrier to water loss from the inner stem, as well as a tough guard against potential intruders. In some species, such as paper birch (*Betula papyrifera*), this skin remains fairly thin throughout the life of the tree, whereas in others, such as cork oak (*Quercus suber*), it can exceed 30 cm in thickness. (*Quercus suber* is the source of wine bottle corks.) Most of the variation in bark design that distinguishes different tree species derives from the wide array of peculiar behaviors of the cork cambium.

Until they begin to senesce, trees continuously increase in height as well as girth, and the former is accomplished by meristems at the tips of branches. These apical zones of cell division, which number in the thousands on a large tree, give rise to new stems and leaves, as well as the reproductive structures (flowers and fruits). All stem tissues originate in the apical meristem, including the vascular and cork cambia: hence, there is a continuous network of interconnected apical and lateral meristems that forms a sheath around the entire stem.

Roots—Anchorage and Access to Soil Resources

The meristematic sheath around the stem also extends below ground, surrounding the tissues of a massive root system that at times can rival the tree crown in weight and volume. Large subterranean branches, and in many species a deep-running taproot, serve to anchor the tree in the soil. From these woody "coarse roots" grows a network of ever smaller laterals, which eventually terminate in a labyrinth of fine roots. The latter, typically light brown- or cream-colored and no more than a few millimeters in diameter, are typically confined to the upper 20 cm of the soil profile. They are the primary means with which the tree absorbs water and an array of soil elements (nitrogen, phosphorus, potassium, and at least 11 others) essential for normal growth and vigor.

While woody coarse roots resemble branches in structure, fine roots have a distinctive architecture reflecting their absorptive function (Figure 4.5). As in the case of a twig in the tree crown, the fine root terminates in an apical meristem, which lies beneath a protective root cap. Unlike a twig, the fine root's plumbing (xylem and phloem) is located in its core, which is surrounded by a band of parenchyma called the cortex. All of this is enclosed in an epidermis, from which a plethora of root hairs typically emanate. These elongated epidermal cells

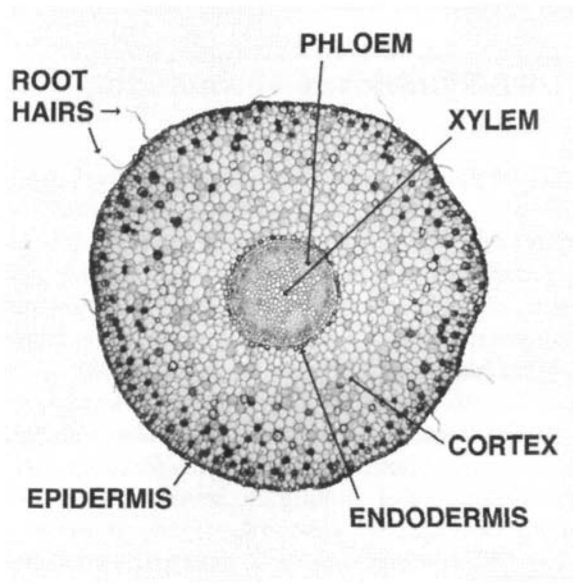


Figure 4.5 Most of the water and nutrients acquired by a tree are absorbed through fine roots with a cross-sectional structure like that shown here. Just outside of the stele (core of xylem and phloem) lies the endodermis. This acts as a barrier to unwanted materials flowing inwardly through the cortex. Primary roots such as this are short-lived; within a few months they will either die or initiate secondary growth, becoming a perennial woody root. (Photograph by Richard Dickson.)

greatly enhance the effective surface area and absorptive capacity of a root system.

One of the key functions of a fine root is to prevent the tree from accumulating potentially harmful—yet often prevalent—substances in the soil. A common example of this is aluminum, which is one of the most abundant elements in soil, and which can be toxic when in a soluble form. Between the stele (core of xylem and phloem) and the cortex lies an important cell layer, called the endodermis, which allows the fine root to discriminate between beneficial and harmful materials. The radial walls of these cells are impregnated with a plastic-like polymer (called a casparian strip) that acts as a barrier to the movement of water and anything floating in it. Consequently all materials that enter the stele must first cross the endodermal cell membranes, which are very effective filters.

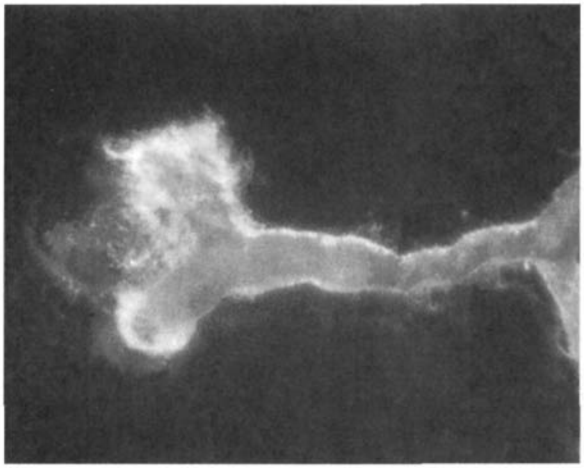


Figure 4.6 A mutualistic partnership, or symbiosis, between terrestrial plants and mycorrhizal fungi has existed for at least 400 million years. Pictured here is a fine root of red pine (*Pinus resinosa*) that has been colonized by an ectomycorrhizal basidiomycete (mushroom fungus). The telltale feature of ectomycorrhizae is the coralloid and/or bifurcated appearance of the root. The "fuzz" around this root is a matrix of fungal hyphae that permeate the soil, greatly enhancing the absorptive surface of the root. (Photograph by Glen Stanosz.)

Root Symbioses—Enhancing Nutrient Acquisition

One of the most intriguing aspects of root structure and function is the mutualistic partnership, or symbiosis, that fine roots of trees and virtually all other terrestrial plants form with certain fungi and in many cases bacteria as well. These ancient liaisons have been shown to enhance many facets of root function and appear to be critical for plant survival in most environments. The symbiosis between a fine root and a fungus is called a mycorrhiza (derived from the Greek words for fungus and root) (Figure 4.6). Among the several major types of mycorrhizae, two are commonly found on trees, ecto- and endomycorrhizae. These types involve different taxa of fungi and are readily distinguished from one another by general contrasts in the structure of the fungus-fine root complex. Overall, the chief benefit of this symbiosis for the host tree is an increased ability to scavenge typically scarce nutrients, such as phosphorus and nitrogen, from the soil. Much of the benefit is conferred by the network of gossamer fungal hyphae that radiate from and deliver absorbed nutrients to the mycorrhizal root, often expanding the effective size of the root system by manyfold. In return, the fungus absorbs food, primarily in the form of sugars, from the host tree root.

Hundreds of tree species belong to an important group of plants that form a symbiosis with nitrogen-fixing bacteria (Figure 4.7). Nitrogen fixation is the energy-demanding process of converting atmospheric nitrogen (N_2) into a form that plants and other organisms can use—namely, ammonium (NH_4^+). (Fertilizer manufacturers currently use a tremendous amount of fossil fuel to accomplish this feat.) Typically, most of the usable nitrogen in an ecosystem is generated through this mechanism by free-living soil bacteria and blue-green algae. However, particularly in environments where soil or climatic factors limit bacterial activity, many plant species have evolved the capability of harboring certain nitrogen-fixing bacteria in

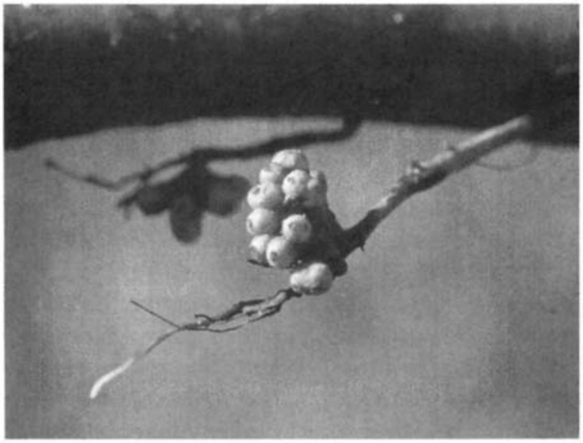


Figure 4.7 Here is yet another root symbiosis, this time involving nitrogen-fixing bacteria. These berry-like structures are root nodules of speckled alder (*Alnus rugosa*), which house actinomycete bacteria. Another group of leguminous tree species form nodules containing *Rhizobia*. Both symbioses reduce (add electrons to) large quantities of nitrogen gas (N_2) and convert it into ammonium (NH_4^+), which is a form that plants can absorb and use.

their roots (and sometimes elsewhere), in specialized structures called nitrogen-fixing nodules.

In these nodules, the host tree provides energy (small carbohydrates derived from sugar) and a favorable environment for the bacteria, and in return it assimilates the NH_4^+ that its prokaryotic guests manufacture. This partnership often allows the host tree to grow relatively well in dry, nutrient-poor and/or cold environments. Indeed, N-fixing species commonly dominate these habitats, where they exert a strong influence on the ecosystem nitrogen cycle.

Flowers, Fruits, and Seeds

Tree reproductive biology plays an important role in the ecology of forests. For example, reproductive strategies, whether sexual (seed-producing) or vegetative, often govern the distributions of different tree species in space and time. Several aspects of sexual reproduction are critical to this role, including the timing and mode of flowering and pollination, fruit structure and chemistry, as well as seed ripening, dispersal, and germination physiology. Perhaps the most effective way to examine some of these aspects is by highlighting the reproductive characteristics of individual species.

A comparison of the flowers of northern Catalpa (*Catalpa speciosa*) and northern pin oak (*Quercus ellipsoidalis*) illustrates the key connection between flower structure and mode of pollination (Figure 4.8). The flowers of catalpa trees are "complete," in that they possess all the major flower parts, including sepals, petals, pistils, and stamens. Oak, on the other hand, has separate male (staminate) and female (pistillate) flowers, each of which is incomplete—not only because one of the sexes is lacking, but also because petals are absent. Consequently these flowers are fairly inconspicuous.

It turns out that these two species rely on different pollinators. The "showy" flowers of catalpa attract not only our attention, but that of insect pollinators as well. Insects inadvertently transfer pollen from flower to flower in their quest for sugar-rich nectar, which is secreted from tiny nectaries located in various places such as the base of the pistil. In contrast, the relatively drab flowers of oak rely exclusively on wind pollination. Thus they have no need for visual attractants such as brightly colored petals. Rather, the structure of both male and female flowers facilitates wind pollination. The female stigma is located in an exposed position, while the male anthers are born on a long catkin, which flops around in the wind, promoting pollen dispersal.

Although there are numerous exceptions, wind-pollinated species tend to flower in the spring in temperate and boreal forests, when the air is less humid (aiding pollen dispersal) and too cool for many flying insects. On the other hand, many insect-pollinated trees flower in the early summer months, when the climate is generally more favorable for insect activity. Perhaps for similar reasons, wind tends to be the dominant pollination mode in the cooler, drier climes at high latitudes and altitudes, whereas insect pollination is most common in the warm moist tropics.

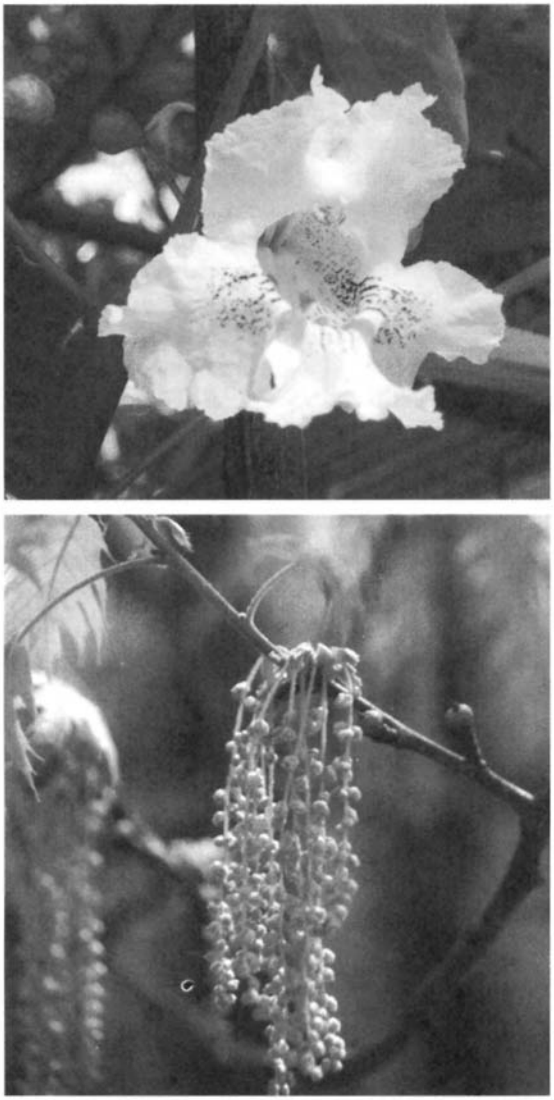


Figure 4.8 With these flowers, form certainly follows function. The showy corolla (collection of petals) of northern catalpa (*Catalpa speciosa,* top) is an effective attractant for insect pollinators. The relatively drab male catkins and inconspicuous female flowers (in leaf axils) of northern pin oak (*Quercus ellipsoidalis,* bottom) rely instead on wind pollination. Results of the previous year's flowering, a developing acorn, can be seen farther back on the oak twig. Acorns of this and associated species in the red oak subgenus require two growing seasons for full development.

The seasonality of flowering and pollination is not necessarily linked to that of seed ripening and dispersal. For example, many early-flowering species common to upland temperate forests do not disperse their seeds until the fall. In contrast, most bottomland or floodplain hardwoods, such as silver maple (*Acer saccharinum*), not only flower early but also ripen and disperse their seeds in early or midsummer. These seeds germinate immediately, as it is an opportune time for seedling establishment in the newly deposited alluvium on recently flooded sites. Fall is generally not a safe time to germinate in temperate forests, and thus the seeds of most upland trees are dormant at the time of fall dispersal. These dormant seeds must be exposed to a fairly specific set of environmental cues before they germinate. The most common requirement is exposure to a period of near-freezing temperatures (typically 2-5°C), which must last for weeks to months depending on the species. This helps to ensure that seeds do not germinate before the onset of consistently warm temperatures in the spring.

Seeds of angiosperm trees are imbedded in a fruit that develops from the ovary and at times other flower parts. The chemistry and architecture of the fruit has important implications for the manner in which the seed is dispersed. The role of architecture is apparent when one observes the tiny seeds of trembling aspen floating from their capsules with the aid of a parachute-like appendage, or the winged samaras of sugar maple (*Acer saccharum*) whirling away from their parent like helicopter blades. Water is also an important mode of dispersal for many species with floating fruit, such as the coconuts of palms, which can wash up on a beach thousands of kilometers from their parents, and the acorn of overcup oak (*Quercus lyrata*), which has enough cork in its outer wall to buoy a heavy seed. Yet some other propagules are designed to avoid the vagaries of travel. A good example of this is the seed of red mangrove (*Rhizophora mangle*) (Figure 4.9).

Around the world, tree seeds and/or their fruits serve as important dietary staples for a wide array of mammals, birds, insects, amphibians, reptiles, and even fish. A fine example of this is an oak acorn,

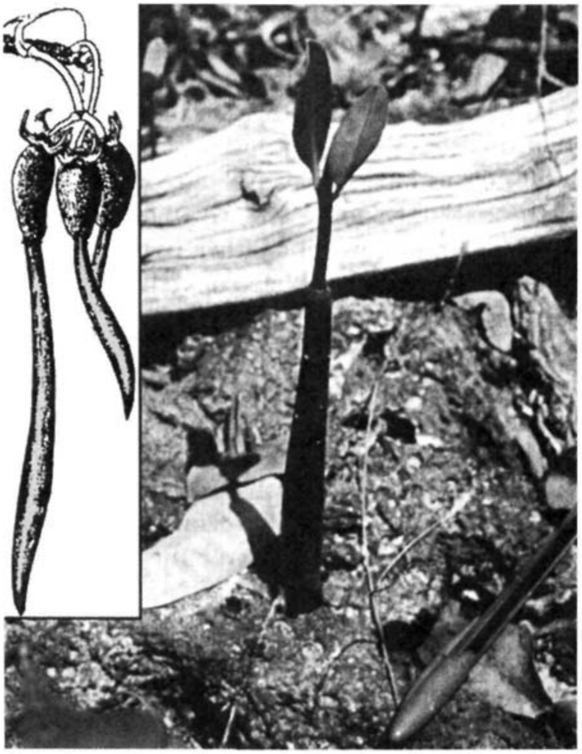


Figure 4.9 This dagger-like structure is a red mangrove *(Rhizophora mangle)* seed. The "blade" is really a root radical that grows while the seed is still attached to the tree. This uncommon circumstance, where the seed germinates before dispersal, is called vivipary. The structure of mangrove seed is critical to its establishment in favored habitat, the muddy flats or shallows along tropical or subtropical ocean coasts. The germinant literally drops from the parent and embeds itself firmly in the mud beneath. (Photograph copyright W.H. Freeman and Company.)

which is eaten by everything from an acorn weevil to a chipmunk to a black bear. It is also an important food source in many human cultures. A number of animals hoard or cash acorns, and in the process they are often unwitting agents of acorn dispersal. For example, migrating blue jays will carry an acorn in their crops for hundreds of kilometers, dropping the seed as they attempt to consume it and the accompanying cargo.

Many animals will ingest an entire fruit, such as the drupe of a cherry tree, and subsequently excrete the intact seed after traveling long distances from the parent. In fact, some tree species have become dependent on this process as a means of promoting seed germination. Among the most famous examples of this is the large seed of the Calvaria tree, which lives on the island of Mauritius in the Indian Ocean (1). In order to germinate, the seed's tough outer coat must be softened and cracked. This used to occur when the seed was ingested and excreted by a flightless, turkey-sized bird known as the dodo. Unfortunately, dodos were extirpated from the island during the 19th century. Consequently, this tree species has not regenerated itself for many decades and is now threatened with extinction. Other species have evolved traits that deter fruit and seed predation. During development, for instance, the fleshy fruits of certain tree species, such as persimmon (*Diospyros virginiana*), contain high levels of bitter, mouth-puckering astringents, which disappear when the fruits are ripe. This trait discourages fruit consumption before the seed is mature and ready to be dispersed.

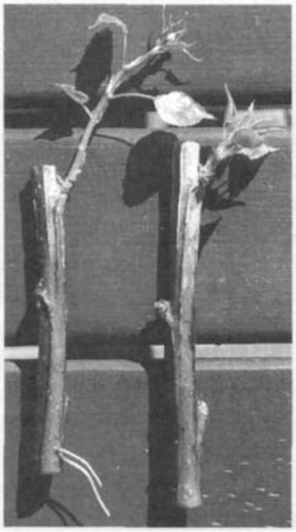
Coping with Environmental Stress

Effect of Seasonal Variation in Climate

Since they have no means of escape, trees and other sessile organisms have evolved strategies to deal with extreme seasonal variation in climate. This capability is most obvious in deciduous forests of temperate, boreal, and montane biomes around the world, where trees drop their leaves in preparation for the annual onset of potentially lethal winter temperatures. By shedding foliage, deciduous trees also avoid excessive buildup of snow or ice on their branches, which can topple the crown. On the other hand, deciduous tree species can be found in dry tropical and subtropical environments where the threat of cold temperatures is minimal. In these biomes, there are regular annual cycles of wet and dry

Sidebar 4.2

Trees don't always rely on sex.



In addition to seed production, various modes of vegetative reproduction are employed by many tree species. Perhaps the most common means of reproducing vegetatively is sprouting from the tree stump. This capability is common among angiosperms and rare among gymnosperms. A new shoot will typically emerge from underneath the bark on the stump of a tree that has been severely damaged or decapitated for any of a number of reasons. The origin of this new shoot is often, but not always, a perennial bud that remained dormant until the stem was killed. A number of angiosperms are also capable of forming new shoots from their root systems. The list of species that root sprout (often referred to as "suckering") includes trembling aspen, American beech (*Fagus grandifolid*), and several other hardwoods. Although relatively few gymnosperms can sprout from the stump or root system, many are capable of yet another trick called layering. Layering is the rooting of a living tree branch that has come into contact with the soil or some other rooting medium, such as a rotting deadfall. Eventually, that branch separates from the parent tree and becomes a whole new entity. Dense, genetically uniform stands of firs, spruces and cedars can form in this manner from just one "founder" tree. Many angiosperm trees are also able to layer, and this trait has been exploited in the vegetative propagation, or cloning, of individual trees with desirable qualities. Stem cuttings are often used to propagate poplars.

periods, and accordingly many species will minimize untimely water loss by dropping their foliage before or during the drought.

In many deciduous forests, an aesthetic consequence of leaf senescence and abscission each fall is the brief appearance of brilliant leaf colors. This is a byproduct of an essential recycling process that precedes leaf abandonment. The nitrogen-rich green pigment (chlorophyll) and associated photosynthetic chemicals in leaves are broken down, withdrawn and stored by the tree for use in next year's foliage. Chlorophyll degradation unmasks yellow, orange, and red pigments called carotenoids, which are actually present all summer in the green leaf. Pinks and purples, on the other hand, are anthocyanins produced by foliage largely during senescence.

In seasonally cold climates, leaf senescence is just one of many steps that trees take to prepare for winter. A number of biochemical transformations occur throughout the tree's living tissues, and collectively they allow the tree to become "cold hardy." In evergreen species, such as most of the needle-leaved conifers, cold hardiness develops in foliage as well as other tissues (Figure 4.10). The process of cold hardening may include tissue dehydration, changes in the chemical makeup of cell membranes, increases in cell sugar concentrations, and the appearance of certain dormancy proteins. These changes are quite effective, as is evident in

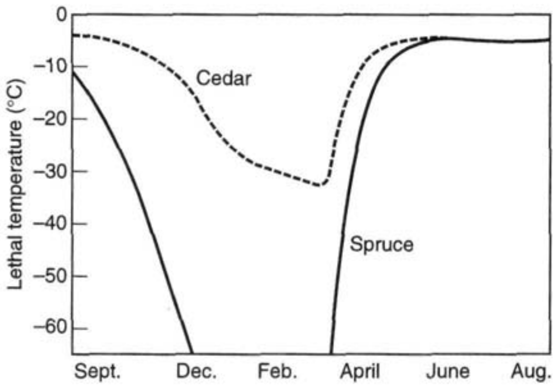


Figure 4.10 Tree species can differ markedly in cold hardiness, which is measured here as the temperature that kills 50% of the needle tissue. The relatively tolerant white spruce (*Picea glauca*) is a boreal forest species in North America. The less tolerant yellow cedar (*Chamaecyparis nootkatensis*) inhabits low-elevation sites along the northwest coast of Canada and Alaska. Note the wide seasonal oscillation in lethal temperature. Tissues are quite vulnerable to frost during the growing season, whereas during mid-winter spruce needles withstand the minimum temperature used in the study, -65°C. (Figure redrawn from Silim and Lavender, 1994, *Can. J. Bot.*, vol. 72, pages 309-316; copyright of NRC Press.)

the recent finding that needles of some evergreen conifers, such as red pine (*Pinus resinosa*), can withstand immersion in liquid nitrogen (—196°C) during the winter (2).

Trees appear to use at least two environmental cues to time the onset not only of winter dormancy but also the subsequent reawakening in the following spring. This timing of behavior is referred to as phenology. Studies have indicated that most temperate and boreal trees enter winter dormancy in response to the combination of shortened day lengths and colder temperatures. These same species break bud in the spring following the onset of warm weather. However, for temperate species in particular, there is a clever twist in this response. These trees require a period of chilling (exposure to near-freezing temperatures) before they will respond to spring warming. Just as it does in the case of seeds, this prechilling requirement, which varies in duration from 30-120 days, prevents a tree from being fooled by spells of warm winter weather and waking up too early.

Effect of Chronic Resource Shortages

In order to persist in many ecosystems, trees and other plants must make a living in the presence of chronic shortages in resources such as light or nutrients. Tree species vary considerably in their ability to tolerate these shortfalls, and that variation leads to the differentiation of species niches (suitable positions) along environmental gradients. The litany of acclimations (short-term adjustments by individuals) and adaptations (evolutionary changes in populations) to resource limitation is too large to explore here. Instead, we will focus on the ways in which trees cope with a common stress, the minimal light availability often endured by seedlings and saplings (and mature individuals of certain species) in the forest understory. As for acclimation, most tree species exhibit light-dependent plasticity in leaf structural and biochemical properties, and this plasticity allows the tree to construct leaves that maximize photosynthetic efficiency in a given light environment (Figure 4.11). However, because both shade-tolerant and -intolerant species possess this capability, it does not afford much insight into the true nature of shade tolerance.

The amount of light reaching the regeneration layer in an undisturbed forest is typically less than 5 percent of that in an open habitat. Differences among tree species in the ability to tolerate this level of shading create the driving force for forest succession. Generally, fast-growing, shade-intolerant species, such as tulip poplar (*Liriodendron tulipifera*), are the first to colonize and dominate a site following disturbance. However, largely because of their intolerance, these early-successional species do not regenerate under themselves. Instead, they are gradually replaced by slower-growing, shade-tolerant species, such as sugar maple. While this sequence of events is predictable, the underlying physiological basis remains somewhat of an

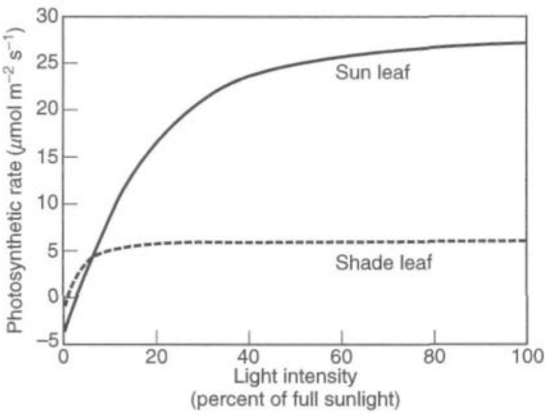


Figure 4.11 Response of leaf photosynthesis to variation in light intensity. Examples shown are leaves that have developed in sun and shade. Compared to sun leaves, shade leaves are thinner and have less photosynthetic machinery per unit leaf area. Correspondingly, they have a lower photosynthetic capacity and rate of dark respiration (when light intensity is 0). These traits allow shade leaves to be more photosynthetically efficient in low light (less than 5% of full light in this example).

enigma. Despite a considerable amount of research, there is no consensus as to why seedlings and saplings of one species are necessarily more tolerant of shade than those of another.

One prevailing hypothesis is that persistence in shade is linked with the ability to conserve valuable resources, especially carbohydrate reserves. Starch is one form of reserve that is commonly stored in trees and is available for use when photosynthesis cannot meet the demand for energy or building materials. This circumstance is likely the rule rather than the exception in dimly lit understories. Intolerant species may not maintain adequate carbohydrate reserves for two reasons. First, because they are geared for rapid growth, intolerants tend to allocate most of the photosynthate they earn to new tissue construction in lieu of reserve accumulation.

Second, and of equal importance, intolerants tend to have higher rates of dark respiration than do tolerant species. Whereas photosynthesis utilizes light energy to make sugar, dark respiration (operating in the absence of light) generates usable chemical energy, called ATP, by breaking down a portion of that same sugar. (The chemical formula describing respiration is $CH_2O + O_2 \longrightarrow ATP + CO_2 + H_2O$, which mirrors that of photosynthesis.) This catabolism (enzymatic breakdown) occurs in all living tissues and is essential because ATP powers the tree's biochemical machinery. But, high rates of respiration can deplete sugar supplies and ultimately the starch reserves from which they originate. Overall, there is an intriguing correspondence between tolerance of shade and other chronic stresses, inherently slow growth, and low rates of tissue metabolism. But the mechanistic underpinnings of this relationship remain elusive.

Effect of Variation in Resource Availability

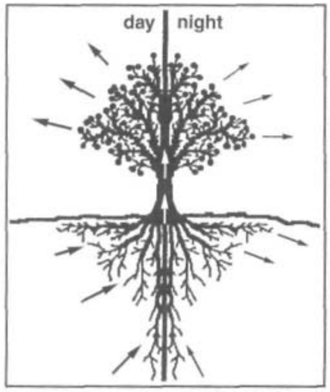
Trees must also endure stochastic and often life-threatening variation in the availability of resources, especially water. Drought is common to most forest ecosystems around the world, and excesses of water are also problematic, particularly in lowland or flood plain forests. Trees possess a number of attributes that allow them to survive drought and flooding, and some species are much better than others at coping with water stress. Indeed these differences constitute much of the basis for the presence or absence of a given species in a particular ecosystem, and for the broad patterns of vegetation we see at the biome and continental scales.

Scientists that study drought adaptations distinguish between two general resistance strategies, drought avoidance versus drought tolerance. With few exceptions, trees and other terrestrial plants respond to the onset of soil drying by closing their stomates to conserve existing water supplies. As mentioned previously, this response originates in the root system. When the surface soil begins to dry, fine roots in that soil manufacture a small chemical messenger called abscisic acid. This hormone travels to the leaves through the transpiration stream, whereupon it triggers a set of biochemical

Sidebar 4.3

Trees can supply water to the forest.

It turns out that the role of trees in forest hydrology is not always confined to water use (evapotranspiration). Recent studies (3, 4) have revealed the importance of certain tree species as suppliers of water to the forest ecosystem. For instance, the architecture of needles, branches, and crowns of coastal redwood trees in California creates an effective collector of fog and mist, which then drips to the forest floor. Calculations of ecosystem water budgets indicate that this process is responsible for as much as 30 percent of the water input to the soil. Equally noteworthy is the phenomenon of hydraulic lift carried out by deep-rooted tree species. In this case, trees with taproots that penetrate the groundwater table are capable not only of absorbing that deep water supply, but also of



sharing it with less deeply rooted species. The mechanism of hydraulic lift works as follows: The water tension that forms during leaf transpiration allows the tree to pull groundwater through its taproot up into the tree crown (shown at right). However, especially when the surface soil of a forest is dry, some of that groundwater is pulled out of the tree's surface roots at night by the strong water tension in the soil. It is thought that during drought, this mechanism may facilitate the survival of understory herbs and shrubs located near these deeply rooted "nurse" trees.

events that lead to stomatal closure. The importance of this nearly ubiquitous response has been highlighted in studies of certain genotypes of black Cottonwood (*Populus trichocarpa*) that do not close their stomates in response to soil water depletion. Needless to say, these trees perish during drought and thus are confined to riparian and other habitats where water is continuously in ample supply.

Perhaps the next most common characteristic is structural in nature. Many species effectively avoid internal drought (maintain adequate tissue water content) by constructing a deep-running taproot to access the ground water supply, which during drought may lie many meters below the soil surface. Species that are adapted to inherently dry (xeric) ecosystems, such as jack pine (*Pinus banksiana*), have these deeply penetrating taproot systems. Some species from these environments are also capable of competing for scarce water through a mechanism known as "osmotic adjustment." In essence, soil drying induces these trees to accumulate unusually high amounts of sugars and other organic solutes in their living tissues. This buildup creates a large osmotic force (like that used in phloem functioning), which allows the tree to absorb (and retain) the scarce supplies of tightly held water in dry soil.

Ultimately, if drought persists there will be no way for most trees to avoid eventual dehydration. It is at this point that many species will succumb.

A few, however, possess the seemingly miraculous ability to tolerate tissue desiccation. In these cases, the cells of living tissues enter a sort of dormancy, which entails a number of membrane alterations and other biochemical changes that allow them to retain their integrity until adequate levels of moisture return. The most remarkable examples of this capability are found not in trees but in certain ferns and mosses. These plants are often referred to as "resurrection plants," because they can withstand extended dry periods, in which their tissue water contents equilibrate with that of the atmosphere, and quickly regain their original vigor following rewatering.

The ability of certain tree species to endure prolonged periods of flooding is another matter entirely. Several serious problems arise when the roots and lower stems (and at times the crown as well) are inundated for more than a few days. The most critical of these is a shortage of oxygen (O_2), the concentration of which is quite low in water as opposed to an aerated soil. A lack of O_2, known as anoxia, impairs the metabolism of plant cells and eventually kills them. But trees and other plants have a few mechanisms that delay this fate, the most important being fermentation. One might recognize this as the process used to generate ethanol (an alcohol), and that is precisely what happens in an anoxic plant cell. Fermentation is an alternative type of respiration that requires no O_2, and under anoxia it maintains a certain, albeit minimal, level of metabolism (ATP production).

This shift in metabolism is not, however, a long-term solution, and trees that survive protracted inundation undergo a number of additional changes, including the production of hypertrophied lenticels and aerenchyma in stems and root systems (Figure 4.12). These modifications can greatly enhance the diffusion of O_2 from aerial portions of the tree to the flooded roots. The development of adventitious roots is also a common flood response (Figure 4.12). These new fine roots often form on the tree stem near the water surface, presumably so that they have access to enough O_2 to allow for normal functioning. There is currently no clear understanding as to why some species, such as river birch (*Betula nigra*) can make these necessary changes while others, such as the closely related paper birch (*Betulapapyrifera*), cannot. About all that appears certain is that the origin of this difference lies primarily within the root system.

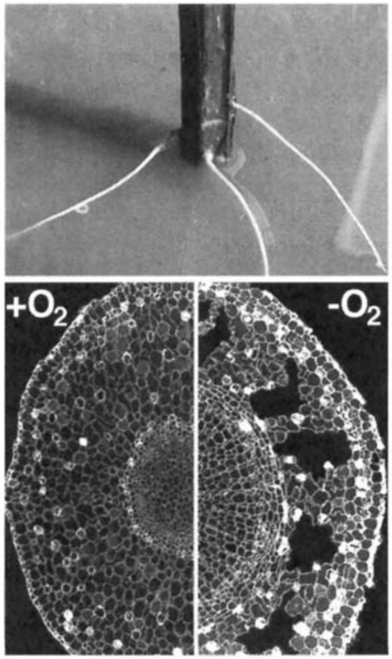


Figure 4.12 Trees that endure prolonged flooding will typically produce adventitious roots and hypertrophied lenticels (upper photo) at or near the water line on the stem. The lenticels look like little cotton balls dotting the stem. Adventitious roots, which help the tree restore its water and nutrient uptake, often have an altered structure that includes aerenchyma (lower-right photo of root cross-section), large openings in the cortex that facilitate oxygen transport to the root. (Lower images provided by Richard Dickson.)

Global Issues in Forest Ecophysiology

Effect of Anticipated Global Warming

At the outset of this chapter, I cited forest response to global change as one of the prominent contemporary issues addressed by forest ecophysiologists. Global change embodies two related environmental phenomena, changes in climate and atmospheric chemistry. The two are closely linked because climate is governed in part by atmospheric chemistry and vice versa. Atmospheric scientists have been utilizing global circulation models (GCMs) to derive estimates of future climates, and such calculations are influenced strongly by current and predicted future increases in atmospheric concentrations of "greenhouse gases" such as CO_2 and methane (CH_4). These and other atmospheric constituents are effective absorbers of infrared radiation, or heat, that would otherwise escape from the earth's atmosphere.

Depending primarily on future patterns of human behavior (e.g., fossil fuel consumption, land use), concentrations of CO_2 may nearly double during the 21st century (from 0.037% to ~0.07%). Consequently, the global mean for surface temperature could rise by as much as 3°C (5). GCM output also indicates that warming might be most pronounced at higher latitudes and during the winter rather than summer (in the Northern Hemisphere).

One of the charges to physiological ecologists is to generate credible predictions regarding the impact of these dynamics on the world's forests. However, the challenge of forecasting these consequences is daunting in its complexity. First of all, the effects of warming will be mediated through changes in the metabolism not only of trees, but of all life forms. Also, the nature of this change will vary depending on the manner in which climate warming is manifested. For example, a rise in the annual average for surface temperature can be brought about by a variety of changes in temperature patterns, including increases in the minimum or maximum temperatures during either the summer or winter. That these different scenarios have varying implications becomes apparent when we begin exploring the possible effects of climate warming on the spatial distribution of individual tree species and forest communities around the world. A basic assumption in ecology is that the geographic range of most plant species is governed primarily by climate and soil characteristics. In light of this, and given that the predicted magnitude of warming is equivalent to shifting isotherms (imaginary lines connecting areas with the same average temperature) by 300-400 kilometers northward, it appears likely that warming will lead to widespread species migrations.

The U.S. Forest Service has recently published some provocative forecasts (6) of possible tree species migrations in North America (Figure 4.13). In the northern United States, they include a mass exodus of keystone northern species and an invasion by southerners. But how credible are such predictions? As with any modeling effort, they are only as good as their underlying assumptions. In this case it is fair to question the presumed link between a species' current geographic and climatic boundaries.

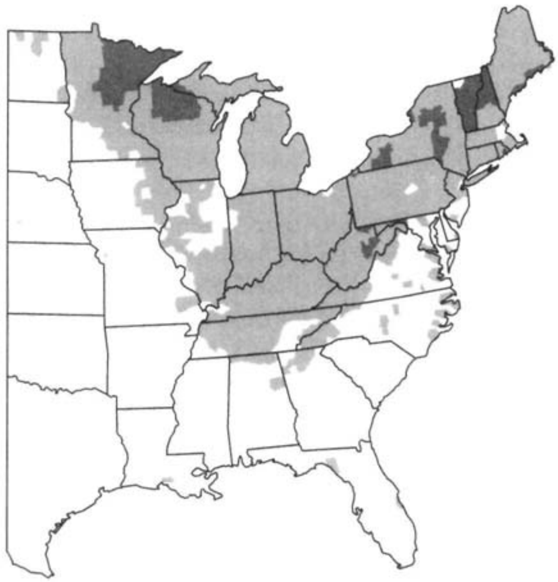


Figure 4.13 Recent predictions by scientists from the U.S. Forest Service (6) indicate that the anticipated extent of climate warming could lead to long-distance, northward migrations by certain tree species in North America. Illustrated here is the potential response of sugar maple. The light shade represents its current range, while the dark areas represent the overlap between current and predicted future ranges. (Illustration courtesy of the U.S. Forest Service.)

In fact, there are many instances where a given tree species thrives in areas where conditions are quite different from those associated with its native range. In other words, there is no certainty that a species' realized niche (the range of habitats in which it is found) matches its fundamental niche (the range of habitats that it can colonize). Moreover, there are few, if any, tree or other plant species for which scientists have identified the specific suite of environmental factors defining their fundamental niches. Further complicating this issue is the fact that these environmental factors are biotic as well as abiotic, and the former, including insects and fungi, may be very sensitive to changes in climate.

What effects will climate warming have on forest growth? Once again this is a complex issue requiring consideration of all facets of tree metabolism. Initially, it is probably most useful to focus on the balance between photosynthesis and its chief counterpart, dark respiration (Figure 4.14). Because enzymes carry out key steps in photosynthesis and dark respiration, the rate at which both processes occur is inherently sensitive to temperature. Yet, at least under current atmospheric conditions, dark respiration is relatively more responsive than photosynthesis. The net result is that increases in temperature tend to stimulate dark respiration more than photosynthesis, and thus lessen the amount of sugar produced per unit sugar consumed in fuel production. That balance equates with growth (biomass accumulation), which accordingly may decrease in response to higher growing season temperatures.

Alternatively, the most important consequence of climate warming may be an increase in the length of the growing season. Interestingly, there is a growing body of evidence, based largely on plant and animal phenologies, indicating that this is already happening (7). Such a trend would simply increase the annual duration of photosynthetic activity and growth by trees. Support for this prediction is found in a comparison of annual tree growth along latitudinal gradients in the midwestern United States. (For example, both the length of the growing season and annual rate of tree growth in Mississippi are at least twice those in Minnesota.) The upshot of all this is that there is much to be learned before the scientific community can confidently embrace any broad-scale prediction of global warming impact on forest structure or function.

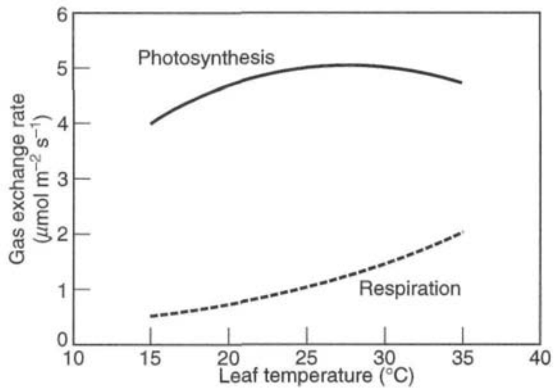


Figure 4.14 Comparison of the sensitivities of leaf photosynthesis and dark respiration to variation in leaf temperature. Rates are expressed in terms of CO_2 influx or efflux per unit leaf area per second. The example shown is a leaf from a sugar maple sapling. Under current levels of atmospheric CO_2, photosynthesis is not very responsive to changes in temperature between 20°C and 30°C. In contrast, dark respiration roughly doubles for every 10°C increase in temperature.

Effect of Changes in Atmospheric Chemistry

The potential influences of fossil fuel combustion on forests are not restricted to alterations of global climate. Based on a wealth of evidence from laboratory and field experiments, along with some alarming trends in forest health, it appears that our emissions of CO_2 and a suite of other atmospheric pollutants may already be having direct, widespread impacts on forests and other ecosystems, especially in the Northern Hemisphere.

The burning of fossil fuels or any other organic matter results in the volatilization (conversion to gaseous forms) not only of carbon, but several other elements, including nitrogen and sulfur. These gases (mostly oxides of N, C, and S) are considered to be primary pollutants because we emit them into the atmosphere. Ironically, they do not necessarily pose a direct threat to forests, at least in the concentrations at which they presently occur. Rather, it is their subsequent conversion into secondary pollutants, namely ozone (O_3) and nitric and sulfuric acids (HNO_3, H_2SO_4), that generally causes the most concern. The latter two are constituents of acid precipitation ("acid rain"), which has been the focus of much public attention in recent decades. This stems primarily from its postulated (but not necessarily proven) role in the widespread decline in health of high-elevation conifer forests in Europe and North America that first caught the attention of the media during the 1970s.

Nitric and sulfuric acids form in the atmosphere when nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) are oxidized (altered by chemical interaction with oxygen) and subsequently combined with water vapor. These acids are carried aloft in clouds and eventually deposited on the earth's surface as precipitation (rain, snow, or, especially at high elevations, fog). The acidity of this precipitation, which is expressed in terms of pH ($-\log_{10}$ of solution H^+ concentration), varies markedly among regions and elevations. For example, in pristine areas remote from major pollution sources, rain pH is about 5.6, whereas in industrialized regions of North America and Europe, rain pH often falls below 4.5. Within these regions, the extremes of exposure occur at high elevations, where clouds with a pH as low as that of vinegar (pH = 3.3) can envelop the vegetation.

Studies have revealed numerous potential threats to forests posed by chronic exposure to acid precipitation. These are typically separated into two major types, direct and indirect. Direct effects occur as a result of acid deposition on the forest canopy, and the possible consequences include destruction of leaf cuticles (waxy protective coverings), leaching of nutrients (especially potassium) from foliage, and disruption of pollination. There are potential benefits as well, including a direct fertilization of tree foliage with the essential elements N and S, when nitric and sulfuric acids are absorbed through leaf stomates.

While these impacts could be important in certain ecosystems, it is the group of indirect effects, resulting from acid deposition to the forest soil, which may prove to be most damaging in the long run. Several key properties of forest soils are sensitive to acidity and to balances of elements such as N and S. Inputs of acidity per se can accelerate leaching of valuable base cations (such as K, Mg, and Ca) from the soil profile, inhibit microbial activity (and thus nutrient cycling) and increase the solubility of toxic compounds, such as aluminum, that are naturally abundant but mostly inert in soil clay fractions. Once again, however, it is worth noting that some indirect effects, such as soil N fertilization, may be beneficial. However, even this benefit has a downside. There is increasing concern that chronically high rates of N deposition will cause detrimental nutrient imbalances in many forests, which may result in declining tree health, shifts in species composition, and disruption of ecosystem nutrient cycling. This postulated threat, coined the "nitrogen saturation hypothesis," has received much attention in the eastern United States (8).

The overall concern surrounding O_3 can be somewhat confusing, in that it involves both shortage and excess. Part of the earth's stratosphere (upper atmosphere) contains relatively high concentrations of O_3, which forms an effective barrier to much of the harmful ultraviolet light that would would otherwise strike the earth's surface (O_3 absorbs ultraviolet radiation with wavelengths between 250 and 320 nanometers). High intensities of ultraviolet radiation threaten all life forms. It appears that "ozone holes," areas of dangerously low stratospheric O_3 concentration, have been enlarging during the last few decades, perhaps because of our use and release of chlorofluorocarbons into the atmosphere.

On the other hand, concentrations of O_3 in the troposphere (~ lower ten kilometers above Earth's surface) are too high in many regions. The extra O_3, which is a potent oxidant, is produced through a complex chemical interaction among oxides of nitrogen (e.g., NO_2), oxygen and volatile organic compounds (primary pollutants resulting from incomplete fuel combustion). Notably, the process is catalyzed by ultraviolet radiation, and thus the rate of O_3 production in the troposphere is accelerated when it is sunny. Although the problem arises chiefly in urban and industrial areas, it is not confined to them; transportation, power generation, and industry pump the air full of O_3 precursors, and, while O_3 is accumulating, the polluted air mass flows into rural areas, over O_3-sensitive croplands and forests.

The threat that O_3 poses to trees and other vegetation is essentially the same as that faced by all organisms; O_3 is a strong oxidant, and as such it can damage and destroy the living tissues with which it comes in contact. (For that reason, O_3 is used to kill microbes in some municipal water supplies.) In forests, it is the canopy foliage that normally bears the brunt of this assault. Correspondingly, forest canopies are excellent "filters" of O_3 and other gaseous or particulate pollution in the atmosphere. Leaves are vulnerable to O_3 primarily because of their stomates, through which O_3 can diffuse and subsequently damage the leaf interior. One may recall that the interior, or mesophyll, houses photosynthetic machinery. Hence a loss of photosynthetic capacity is often the first functional symptom of O_3 exposure. Eventually, continued exposure will cause the death of leaf mesophyll cells, and it is at this point that O_3 damage becomes visually apparent (Figure 4.15).

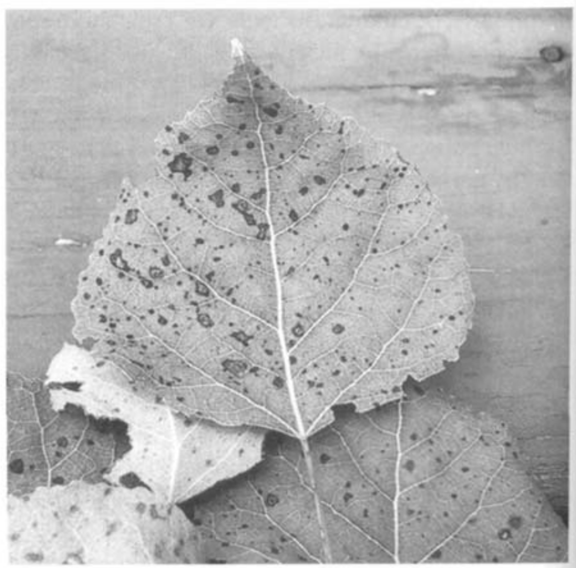


Figure 4.15 Necrotic spots on the upper surface of this trembling aspen (*Populus tremuloides*) leaf resulted from chronic exposure to moderately high ozone (O_3) concentrations (e.g., 60 ppb).

Through its inhibiting effects on photosynthesis, O_3 exposure can cause large losses in growth and vigor, and thus predispose trees to other biotic and abiotic stresses such as fungal pathogens, high temperatures, and other forms of pollution. Also, it doesn't take much O_3 to cause trouble. Based on controlled laboratory and field exposures, these problems can arise when trees are chronically exposed to atmospheric concentrations of O_3 exceeding 50-60 ppb (parts per billion). In many areas of the eastern United States, concentrations commonly rise much higher than that threshold on sunny days during the growing season. Although less common, O_3 levels routinely exceed 100 ppb in some areas, and these episodes can result in acute damage to foliage.

As mentioned earlier, not all atmospheric pollution necessarily has negative consequences for forests. For example, the gas emitted in greatest quantity, CO_2, is a primary substrate in the dark reactions of photosynthesis. Thus the recent and anticipated future increases in atmospheric CO_2 concentrations are likely to stimulate photosynthesis and growth in most terrestrial plant species. However, by what magnitude will growth be stimulated? This is a critical uncertainty in predictions of future climate (based on global circulation models), because the overall increase in atmospheric CO_2, a pivotal greenhouse gas, may be tempered substantially by the increased absorption of CO_2, and subsequent incorporation into wood, by the world's forests. This issue is viewed by the U.S. government to be sufficiently important to warrant considerable investment in research on forest responses to atmospheric CO_2 enrichment. As a result, three FACE (free-air CO_2 enrichment) facilities have been constructed in the eastern United States specifically to monitor the long-term behavior of tree stands exposed to CO_2-enriched atmospheres (Figure 4.16).

Potential Impacts of Atmospheric Pollution

To answer this question, one has only to fly over any of the infamous ore processors in North America. Consider, for instance, the large iron sinterer near Wawa, Ontario. Directly downwind from its smokestack lies a zone that is essentially denuded of vegetation. Beyond that one can see concentric bands of improving forest health and vigor as the distance from the stack increases. The total impact of that stack's emissions on its immediate surroundings extends for hundreds of square kilometers. The nearby forest quite clearly is not able to cope with the chronic exposure to a cocktail of sulfuric acid and a host of heavy metals (such as zinc and copper), which together not only kill vegetation, but also leave a legacy of soil toxicity. The impacts of this type of point-source pollution are so obvious that they require little discussion and debate.

It has proven much more difficult, however, to indict atmospheric pollution as a cause of the widespread declines of forest health and vigor that have been observed with increasing frequency during the last several decades. The most notorious of these have occurred in montane spruce forests of Germany (largely Norway spruce, *Picea abies*) and the northeastern United States (primarily red spruce, *Picea rubens*). Beginning in the 1960s, widespread episodes of crown damage, growth loss and mortality have been documented in these forests (9). No one can ignore the disturbing coincidence between these epidemics and high rates of pollutant deposition. As was mentioned previously, high elevations in polluted regions receive especially severe loadings of acid precipitation as well as O_3. Yet, to the dismay of many, decades of careful

Sidebar 4.4

Tree species differ in their tolerance of gaseous oxidants.

A survey of trees in urban or other polluted landscapes often reveals a great deal of variation, within as well as among species, in vulnerability to gaseous oxidants such as ozone. Norway maple (*Acer platanoides*), for example, is widely planted in urban settings partly because of its comparative pollution tolerance. Why does the foliage of one species or genotype differ from that of another in pollution tolerance? There are at least two reasons. The first is that leaves of some species do not open their stomates as widely as others (the measure of openness is stomatal conductance). Consequently, leaves with a lower stomatal conductance absorb less of the gaseous pollutant per unit time. The tradeoff for this decrease in exposure is an opportunity cost, as leaves with wide-open stomates tend to have higher rates of photosynthesis. However, stomatal behavior is only part of the story. Another mechanism for dealing with gaseous pollution is the maintenance of a large pool of antioxidants and associated enzymes in leaf tissues. Species have been shown to vary considerably in foliar levels of antioxidants, such as ascorbate (vitamin C) and alpha-tocopherol (vitamin E), as well as key enzymes such as superoxide dismutase and glutathione reductase, which together quench the oxidative power of ozone and other gases before they injure vital plant components. We require a constant supply of vitamin C for the same general purpose; however, since we do not produce it, we have to eat vitamin-rich vegetables and fruit.

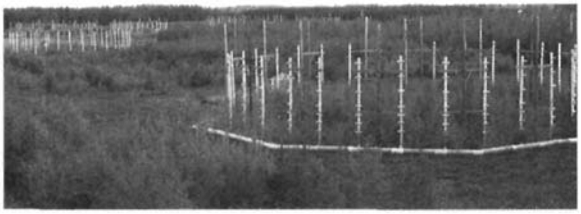


Figure 4.16 In an effort to generate accurate predictions of forest response to atmospheric CO, enrichment, scientists have constructed three FACE (free-air CO_2 enrichment) facilities in the eastern U.S. Each facility consists of several large rings of vertical pipes surrounding stands of trees. Based on measures of meteorology and atmospheric chemistry inside the ring, CO_2 is released from vents in a subset of the pipes. Using this approach, stands of trees can be continuously exposed to a target CO_2 concentration with otherwise minimal perturbation of their environment. The rings shown here enclose stands of trembling aspen (*Populus tremuloides*), white birch (*Betula papyriferd*) and sugar maple (*Acer saccharuni*) at a facility in northern Wisconsin. (Photograph by Evan McDonald.)

experimentation and monitoring have not resulted in a consensus among scientists regarding the real culprit in these declines.

Some of the most compelling detective work in recent years has been the deciphering and synthesis of an array of data to characterize past trends in climate and atmospheric chemistry. For example, CO_2 concentrations in air bubbles trapped in cores taken from the Greenland Ice Sheet indicate that atmospheric CO_2 levels have risen more than 30 percent since the middle of the 19th century. Correspondingly, there is circumstantial evidence that at least some forests around the world may be growing faster as a result of this "CO_2 fertilization." The evidence exists primarily in the form of tree rings, the concentric layers of wood that a tree will build each year. There is a discipline, called dendrochronology, which studies historical patterns in tree ring widths to draw inferences about past climates. Wide rings usually correspond with growing seasons wherein temperatures and patterns of rainfall are most favorable. In certain cases, steady increases in ring width have occurred during the last several decades in the absence of discernible trends in monitored climatic variables (11). Many scientists implicate rising CO_2 concentration as the only remaining explanation for these growth stimulations.

Concluding Statement—Future Directions in Forest Ecophysiology

After reading this chapter, it should be apparent that some of the most interesting and important questions in forest biology remain largely unresolved. For example, ecophysiologists still do not know exactly why certain tree species are more shade-tolerant than others, and perhaps to the surprise of many, we lack sufficient information to determine how forests will respond to predicted changes in global climate. A variety of new tools are emerging to help us address these issues. Interestingly, these new frontiers promise to further expand the scale of inquiry. Exploration of biological mechanisms at very fine scales is increasingly feasible as new techniques evolve in molecular biology. This has already created new insight in plant physiology. For instance, much information has recently been generated as to how different plant hormones modify a fundamental process underlying all aspects of plant behavior, gene expression and consequent protein metabolism in plant cells. And at the other end of the scale, a number of satellites are now equipped with an array of different electro-optical sensors monitoring reflectance by vegetation in critical portions of the radiation spectrum, such as visible and infrared wavelengths. Increased availability of these remotely sensed data, along with advances in our ability to couple them with particular aspects of tree physiology, hold considerable promise in allowing scientists to monitor forest structure and function at the stand and landscape scales (see Chapter 7 and 12).

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CHAPTER 5

Forest Soils

JAMES G. BOCKHEIM

Forest-soil science is a broad field involving chemistry, physics, geology, forestry, and other disciplines. Because soils have a profound influence on both the composition and productivity of a forest, it is important that persons dealing with the forest ecosystem understand the basic character of soils.

Concept of Forest Soil

There are at least four concepts of the forest soil (1). The forest soil may be viewed as a medium for plant growth. Indeed, soils are important to trees because they offer mechanical support and supply moisture and nutrients. The forest soil differs from the agricultural soil or soils under natural grassland or desert vegetation in that it contains a forest floor, tree roots, and specific organisms whose existence depends solely on the presence of forest vegetation. Soil also has been defined as a natural body with physical, chemical, and biological properties governed by the interaction of five soil-forming factors: initial material (geologic substratum), climate, organisms, and topography, all acting over a period of time. A third (hydrologic) view (see Chapter 16) holds that the forest soil is a vegetated, water-transmitting mantle. Finally, the soil may be recognized as a component of the forest ecosystem where materials are added, transformed, translocated, and lost because of natural cycling mechanisms (ecologic view). Each of these views has value in understanding the role of the soil in forest science.

Properties of Forest Soils

Forest soils may be characterized in terms of their morphological and physical properties, their organic matter and moisture contents, their populations of organisms, and their chemical properties.

Soil Morphology

A *soil profile* is a two-dimensional section or lateral view of a soil excavation. The soil profile is divided into a number of sections termed *soil horizons,* that are distinct, more or less parallel, genetic layers in the soil (Figure 5.1).

The capital letters O, A, E, B, C, and R represent the master horizons and layers of soils. The forest floor (O *horizon)* is a layer of relatively fresh and partially decomposed organic matter that overlies a series of mineral horizons. The forest floor is important as a "slow-release" source of nutrients, as an energy source for organisms, and as a covering for protecting the soil against runoff, erosion, and temperature extremes. *A horizons* are mineral horizons formed at the surface or below an O

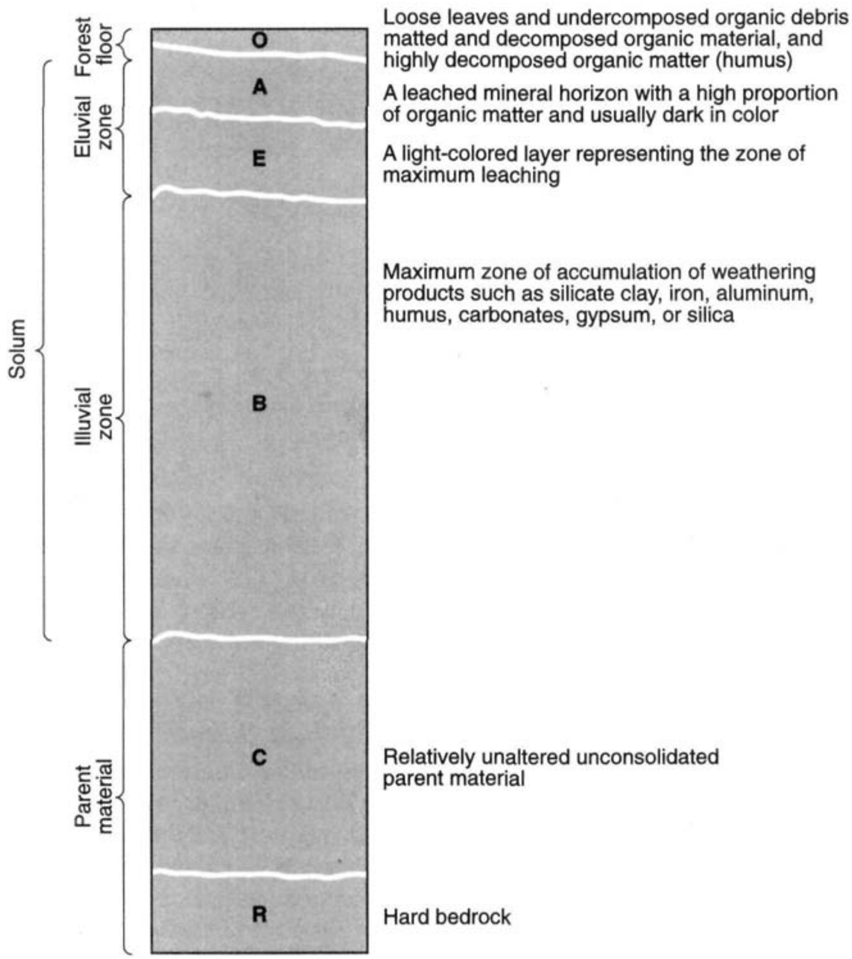

Figure 5.1 A hypothetical soil profile showing the principal soil horizons.

horizon that contain humified organic matter intimately mixed with the mineral fraction or have properties resulting from cultivation or similar kinds of disturbance. *E horizons* are mineral horizons that have lost silicate clay, iron, and aluminum, leaving a concentration of sand and silt particles of quartz or other resistant minerals. *B horizons* contain weathering products, such as silicate clay, iron, aluminum, and humus, that have either been translocated from A, E, or O horizons above or have developed *in situ.* A key property of the B horizon is that all or much of any original rock structure has been obliterated by soil-forming processes. *C horizons* are horizons or layers, excluding hard bedrock, that are little affected by soil-forming processes and lack properties of horizons described earlier. R layers represent hard bedrock that can be investigated only with heavy power equipment.

Lowercase letters are used as suffixes to designate specific kinds of master horizons and layers. For example, Figure 5.2 shows two contrasting soil profiles, along with their horizons, beneath northern hardwoods and red pine in northern Wisconsin. The soil under northern hardwoods is derived from wind-blown, silty sediments *(loess)* over an unsorted, medium-textured glacial till. The soil beneath red pine is derived from stratified, sandy glacial outwash. The profiles differ in at least two respects: (i) the profile featuring northern hardwoods contains a thick A horizon reflecting mixing of organic matter by earthworms, and the profile supporting red pine has a distinct O horizon and no A horizon; and (ii) the soil beneath northern hardwoods has a clay-enriched B horizon, designated as Bt (t = clay accumulation), and the soil under red pine has an iron-enriched B horizon, designated at Bs (s = accumulation of translocated iron and aluminum oxides and hydroxides and organic matter). In *Soil Taxonomy,* these soils beneath northern hardwoods and red pine are designated as an Alfisol and Spodosol, respectively (see section on "Soil Survey and Classification" in this chapter).

An example of a soil profile occurring beneath a northern hardwoods forest in Upper Michigan is shown in Figure 5.3. This soil contains a thin O horizon, followed by a dark-colored, organic-enriched A horizon, a bleached E horizon, an iron-enriched Bs horizon, and a relatively unaltered sandy C horizon.

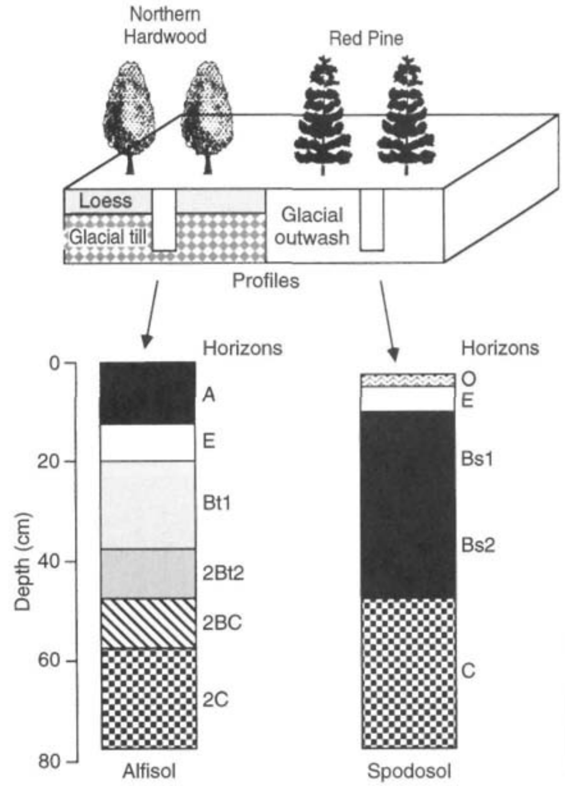

Figure 5.2 Contrasting soil profiles beneath northern hardwoods and red pine in northern Wisconsin.

Physical Soil Properties

Soils can be differentiated according to a range of physical properties. These properties are discussed fully in forest soils textbooks (2); therefore, only three such properties will be discussed here: soil color, texture, and structure.

Soil Color Soils display a wide array of colors. This has been recognized by landscape artists who have

Figure 5.3 A soil profile occurring beneath a northern hardwoods forest in the Upper Peninsula of Michigan. The profile contains a thin forest floor followed by an organic-enriched A horizon, a bleached E horizon, an iron-enriched Bs horizon, and a relatively unaltered sandy C horizon.(Photograph by J. Bockheim).

depicted soil profiles in their paintings. Soil color is dependent upon (i) mineral composition, (ii) organic matter content, and (iii) drainage class, among other factors. For example, red colors are caused by the presence of iron oxides, and native cultures have used red soils to prepare paints. Black or dark brown colors are typical of soils enriched in organic matter. Blue and green colors may exist in soils that are poorly aerated. Soil color may be measured in the field by comparing samples of the soil to standardized soil-color charts.

Soil Texture *Soil texture* refers to the relative proportion of the various mineral particles, such as sand, silt, and clay in the soil. The U.S. Department of Agriculture developed a classification system where the particle-size fraction of sand ranges between 2 and 0.05 millimeters; silt particles range between 0.05 and 0.002 millimeters; and clay particles are less than 0.002 millimeters in diameter. Soil texture may be estimated in the field by trained people by simply feeling the soil in moist and dry states. However, soil texture is measured in the laboratory using sedimentation, centrifugation, and sieving techniques. After such analyses are completed, particle-size data often are plotted on a soil-textural triangle, as shown in Figure 5.4. Thus, for example, a soil that contains 60 percent sand, 30 percent silt, and 10 percent clay by weight is termed a sandy loam. Texture is important because it influences other soil properties such as structure and aeration, water retention and drainage, ability of the soil to supply nutrients, root penetrability, and seedling emergence.

Sandy forest soils often support pines, hemlocks, scrub oaks, and other trees with low moisture and nutrient requirements. In contrast, silt- and clay-enriched soils usually support trees of high moisture and nutrient requirements, including Douglas fir, maple, hickory, ash, basswood, oak, elm, spruce, fir, tulip poplar, and black walnut. Soil texture is thus an important consideration in reforestation, in selection of silvicultural treatment and system (Chapter 13), and in establishment of forest nurseries.

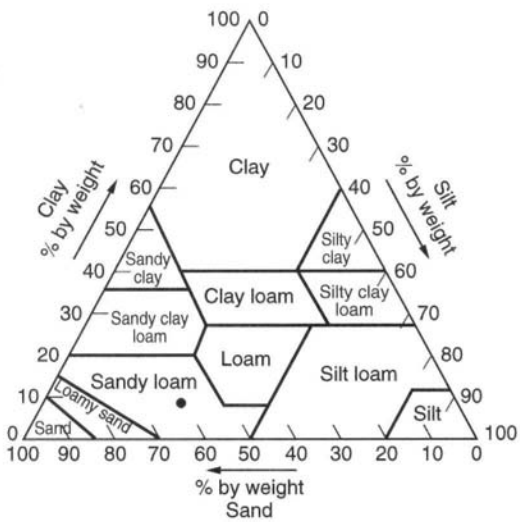

Figure 5.4 A soil textural triangle using the classification scheme of the U.S. Department of Agriculture. A soil with 60 percent sand, 30 percent silt, and 10 percent clay (designated by the point within the triangle) is classified as a sandy loam. (Courtesy of U.S. Department of Agriculture.)

Soil Structure *Soil structure* refers to the arrangement of primary soil particles into secondary units that are characterized on the basis of size, shape, and degree of distinction. Common shapes include prisms, columns, angular or subangular blocks, plates, and granules (Figure 5.5). The major causes for such differences in soil structure are chemical reactions, the presence of organic matter and organisms, and wetting and drying or freezing and thawing cycles. A well-structured soil is able to retain and transmit water and provide nutrients more effectively than a soil lacking structure.

Organic Matter

Organic matter in the forest soil serves several important functions. It improves soil structure by binding mineral grains and increases soil porosity and aeration. In addition, organic matter moderates soil temperature fluctuations, serves as a source of energy for soil microbes, and increases the moisture-holding capacity of forest soils. Upon decomposition, soil organic matter is an important source of plant nutrients.

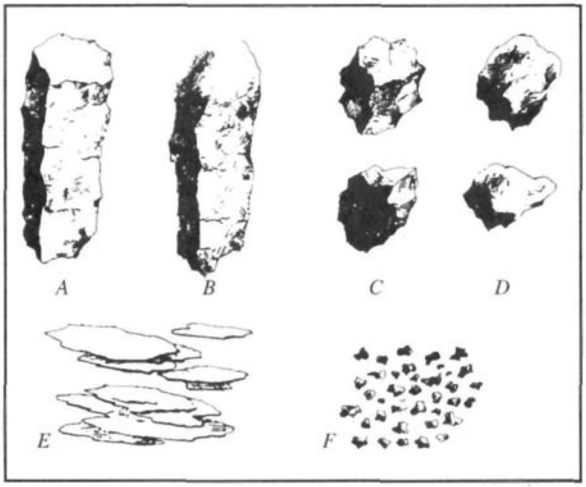

Figure 5.5 Examples of several types of structure commonly found in soils: (A) prismatic; (B) columnar; (C) angular blocky; (D) subangular blocky; (E) platy; (F) granular. (From U.S. Department of Agriculture.)

Most organic matter is added to the forest soil in the form of *litter*, which includes freshly fallen leaves, twigs, stems, bark, cones, and flowers. Many factors influence litter production. Annual production in temperate latitudes is 1000 to 4000 kilograms per hectare. Litter is composed predominantly of cellulose and hemicelluloses (which are carbohydrates), lignins, proteins, and tannins, the characteristics of which are treated in more detail in Chapter 20. Many nutrient elements are supplied by litter, including calcium, nitrogen, potassium, and magnesium, in descending order of abundance.

Once litter reaches the forest floor, a host of macro- and microrganisms act on it. As litter is decomposed, carbon dioxide, water, and energy are released. A byproduct of litter decomposition is *humus*, which is a dark mass of complex amorphous organic matter. Organic matter may be produced below ground by the annual turnover of small roots. The organic-matter content of an undisturbed, mature forest soil represents the equilibrium between agencies supplying fresh organic debris and those leading to its decomposition. The ratio of carbon (C) to nitrogen (N) is stable in soils where this equilibrium exists. Whereas the C:N ratio of agricultural soils commonly ranges from 8:1 to 15:1, the ratio is wider in the surface mineral horizon of forest soils, usually 15:1 to 30:1.

Organic matter may be regulated in the forest soil by careful selection of a silvicultural system (i.e., shelterwood versus clearcutting) and of a utilization practice (i.e., harvesting of only the merchantable stem versus the entire aboveground portion of the tree), and by leaving the slash on the ground following pruning or thinning (see Chapter 13). Burning may be prescribed in some areas for release of nutrients from thick, undecomposed humus and slash.

Soil Water

Moisture supplies in the forest soil are rarely at optimum levels during the growing season, as described in Chapter 4. Studies with forest trees invariably have shown growth responses to changes in soil moisture. Not only does soil water influence the distribution and growth of forest vegetation, but it also acts as a solvent for transporting nutrients to the tree root. Soil-water content influences *soil consistency* (i.e., resistance to deformation or rupture), soil aeration, soil temperature, the degree of microbial activity, the concentration of toxic substances, and the amounts of runoff and soil erosion.

The ability of the soil to retain water is influenced by adhesive and cohesive forces associated with the soil matrix and by attraction of water molecules for ions produced by soluble salts in the soil. Often soil scientists speak of "available" water—the proportion of water in a soil that can be readily absorbed by tree roots. Many factors influence the amount of "available" water in soils, including the amount and frequency of precipitation, runoff, soil storage and leaching, and the demand placed on water by the vegetation.

Water moves in forest soils under saturated and unsaturated conditions and as water vapor. Saturated flow occurs predominantly in old root channels, along living roots, in animal burrows, and in other macropores of the subsoil. Saturated flow also occurs in smaller soil pores in the surface soil during and immediately following heavy rainstorms. Unsaturated flow occurs by capillarity at the upper fringe of the water table, from the soil matrix to the tree root, and in small to medium pores in the soil matrix whenever moisture gradients exist in the available-water range.

A mode of water loss from the soil is through *transpiration.* In a humid temperate environment, trees transpire nearly as much water as will be evaporated from an open body of water. Agricultural crops transpire less than a forest because of lower leaf area indexes and a shorter growing period. However, during the peak period of growth, agricultural crops may consume more water than a forest. A measure of the efficiency of water consumption is the *transpiration ratio,* which is the grams of transpired water required to produce a gram of dry matter. While the transpiration ratio of trees commonly ranges between 150 and 350, the transpiration ratio of agricultural crops generally ranges between 400 and 800. Therefore, trees, particularly conifers, are more efficient in their use of water than are agricultural crops.

Excessive amounts of soil water may be controlled by ditching, ridging, or bedding, mechanical breakup of barriers such as a hardpan, and underplanting with species requiring high amounts of moisture. Wilde (3) described a situation where Trappist monks were able to reduce standing water and the incidence of malaria by planting eucalyptus trees. Flooding and irrigation have been used on a limited scale in areas where water deficiencies exist. Silvicultural treatments, such as thinning and herbicide application to control weed growth, may be an economical way to increase the amount of moisture available to trees in some areas.

Soil Organisms

Soil organisms play an important role in forest soils and tree growth. Soil organisms decompose organic matter and release nutrients for consumption by trees. They incorporate organic matter into the soil, thereby improving soil physical properties, soil moisture, temperature, and aeration. Soil organisms also influence soil profile development, particularly the nature of the forest floor.

Perhaps the most important organisms in the forest soil are the roots of higher plants. These roots do the following: (i) add organic matter to the soil, (ii) stimulate microorganisms via root exudates, (iii) produce organic acids that solubilize certain compounds that are relatively insoluble in pure water, (iv) hold and exchange nutrients within the soil, (v) give off toxic compounds that inhibit the establishment and growth of other plants, (vi) act as an important soil-forming agent, and (vii) protect against soil creep and erosion.

Another group of important soil organisms are *mycorrhizae* ("fungus root"), which are associations, usually symbiotic, of specific fungi with the roots of higher plants. Mycorrhizae increase the absorbing surface area of tree roots, and roots infected with mycorrhizal fungi usually live longer than uninfected roots. Mycorrhizae may also increase the ability of trees to take up nutrients, particularly nitrogen, phosphorus, potassium, calcium, and magnesium. Other types of fungi also are important in forest soils; for example, saprophytic-type fungi decompose forest litter, and parasitic fungi may cause "damping off or may kill young seedlings by decay of the stem or roots. The influence of certain fungi on growth of forest trees is discussed further in Chapter 8.

Bacteria, microscopic unicellular organisms of different forms, are also important soil organisms. Some types of bacteria break down organic matter and others utilize nitrogen directly from the atmosphere or mutually with higher plants. A variety of other organisms occur in forest soils, such as protozoa, algae, nematodes, earthworms, insects, and small invertebrates. In terms of soil organisms, forest soils tend to contain an abundance of fungi, while agricultural soils often have a greater number of bacteria. This is mainly because fungi are favored by the more acidic forest soils, while bacteria respond more favorably to the mildly acidic or neutral agricultural soils (see section on Soil Reaction).

Chemical Soil Properties

As in the case of physical properties, soils can be differentiated according to a range of chemical properties. Since detailed discussions are provided in forest soils textbooks (2), only three chemical properties will be discussed here: soil reaction, cation-exchange capacity, and essential soil nutrients.

Soil Reaction (pH) The acidity or alkalinity of a soil solution is measured according to the pH; a pH of less than 7 indicates an acidic solution, while a pH between 7 and 14 indicates an alkaline solution. pH is extremely important in forest soils, because it influences the microbial population of the soil, the availability of phosphorus, calcium, magnesium, and trace elements, and the rate of nitrification—that is, biological oxidation of ammonium to nitrate. Forest soils are often more acidic than grassland or agricultural soils. This is because tree litter commonly is acidic and releases hydrogen ions upon decomposition. In addition, trees may naturally acidify the soil by taking up and storing in woody tissues calcium, magnesium, and other elements that tend to form bases in the soil. Atmospheric deposition in areas receiving pollution ("acid rain") may also acidify soils. Liming (i.e., replacing hydrogen with calcium or magnesium) commonly is used to raise the pH in agricultural ecosystems. Because of cost limitations, this practice seldomly is used in forest ecosystems, except in forest nurseries. Soil pH may decrease following fertilizer application and increase following burning of litter and slash.

Cation-Exchange Capacity *Cation exchange* is the ability of the soil to hold and exchange positively charged forms of plant nutrients. These positively charged ions, or cations, are held on "exchange sites" on the surfaces of clay particles and humus. Dominant cations in most forest soils are hydrogen ion (H^+), aluminum (Al^{3+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), ammonium (NH_4^+), and sodium (Na^+), in descending order of abundance. Cation-exchange capacity (CEC) is dependent on the amount of organic matter, the amount and types of clays, and pH. Cation-exchange capacity is low in sandy soils but higher in finer-textured soils.

Essential Soil Nutrients In addition to carbon, hydrogen, and oxygen, which constitute the bulk of the dry matter of plants, thirteen chemical elements are considered essential for normal growth and development of trees. Nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur are absorbed in relatively large amounts by trees and are referred to as *macronutrients.* Iron, manganese, boron, copper, molybdenum, zinc, and chlorine are called trace elements or *micronutrients,* because they are taken up in comparatively small but important quantities. Macro and micronutrients need to be present in the necessary forms, in sufficient quantities, and in the proper balance for normal tree growth.

The sources and available forms of the macro- and micronutrients are shown in Table 5.1. Nitrogen is present largely in the organic form in forest soils. Trees utilize nitrogen in inorganic forms, as ammonium (NH_4^+) or as nitrate (NO_3^-). Bacte-

Table 5.1 Sources and Ionic Forms of Nutrients Taken Up by Trees

Nutrient	Source	Ionic form taken up by tree
	Macronutrients	
Nitrogen	Organic matter (proteins, amino acids)	NH_4^+, NO_3^-
Phosphorus	Organic matter (phytin, nucleic acids), apatite, secondary Ca, Al, Fe phosphates	HPO_4^{2-}, $H_2PO_4^-$
Potassium	Feldspars, phyllosilicates	K^+
Calcium	Feldspars, hornblende, calcite, dolomite	Ca^{2+}
Magnesium	Mica, hornblende, dolomite, serpentinite, phyllosilicates	Mg^{2+}
Sulfur	Organic matter, pyrite, gypsum	SO_4^{2-}
	Micronutrients	
Iron	Oxides, sulfides, silicates	Fe^{2+}, Fe^{3+}
Manganese	Oxides, silicates, carbonates	Mn^{2+}
Boron	Borosilicates, borates	BO_3^{3-}
Copper	Sulfides, hydroxy carbonates	Cu^+, Cu^{2+}
Molybdenum	Sulfides, molybdates	MoO_4^{2-}
Zinc	Sulfides, oxides, silicates	Zn^{2+}
Chlorine	Chlorides	Cl^-

ria are able to convert organic nitrogen to ammonium and nitrate, a series of processes called *nitrogen mineralization.* Recent studies suggest that trees may be able to take up some organic forms of nitrogen.

Phosphorus is present in organic forms and also as secondary inorganic phosphate compounds in combination with calcium, iron, and aluminum; $H_2PO_4^-$ and HPO_4^{2-} are soluble forms taken up by trees. Phosphorus is most available under near-neutral pH conditions.

Potassium, calcium, and magnesium are contributed mainly by weathering of soil minerals. Potassium is present largely in minerals such as micas and orthoclase feldspar. Calcium and magnesium exist in dolomite, olivines, pyroxenes, and amphibole minerals. These chemical elements are available to trees as exchangeable and as water-soluble mono- and divalent cations.

Sulfur is present in organic and mineral forms and can be taken up by trees as exchangeable and as water-soluble sulfate, SO_4^{2-}. In addition, sulfur dioxide (SO_2) gas may be taken up directly by trees through their stomata (see Figure 4.2).

Micronutrients are present in mineral forms and as complexes with organic matter. Acid sandy soils, organic soils, and intensively cropped soils, such as those in forest nurseries, may be depleted in micronutrients.

Nutrient Distribution and Cycling in Forest Ecosystems

The behavior of nutrients in forest ecosystems is characterized in terms of abundance and migration. Nutrient abundance refers to the amount (mass per unit area) of an element in various compartments of the ecosystem. In forest ecosystems, these compartments generally include the atmospheric compartment, the organic compartment, the extractable or exchangeable ("available") soil compartment, and the soil and rock mineral compartment (Figure 5.6).

The distribution of nutrients within forest ecosystems is dependent on climatic zone or ecosystem type, forest type, successional stage, and site quality. Table 5.2 shows the distribution and cycling of

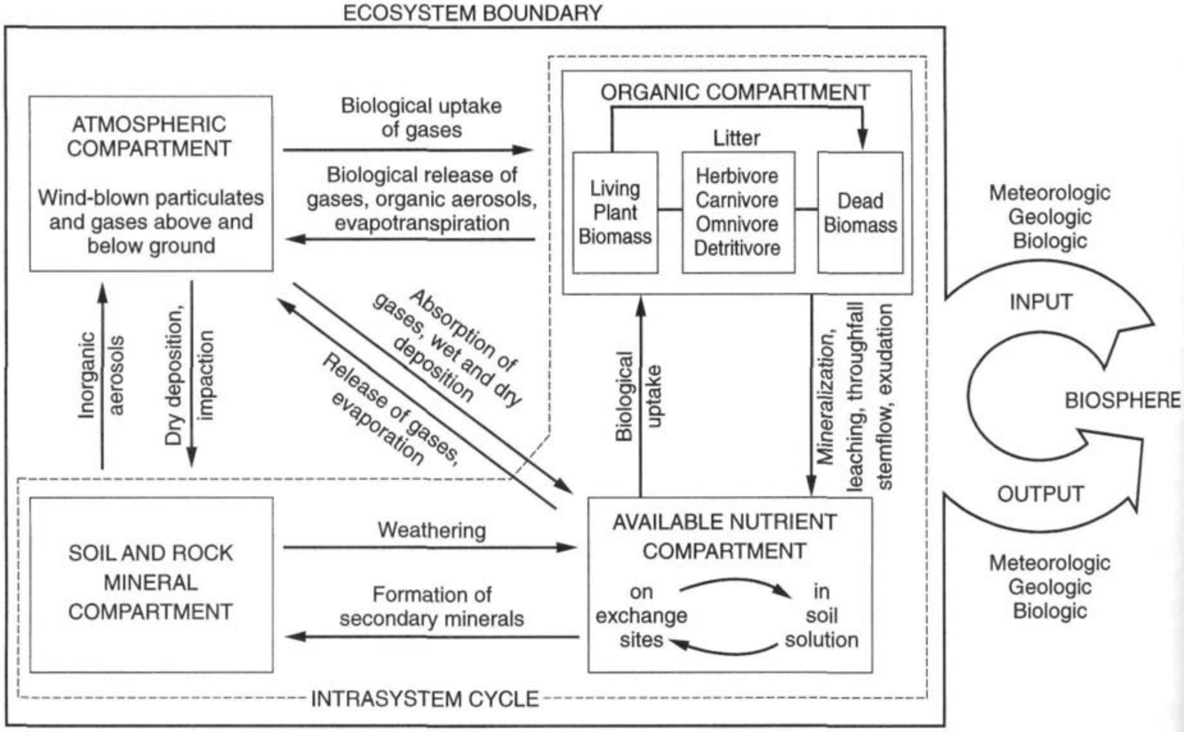

Figure 5.6 Nutrient distribution and cycling in forest ecosystems (from reference 15, Likens and Bormann).

nutrients in a 65-year-old aspen-mixed-hardwood ecosystem in northern Wisconsin. The living vegetation contains 69 percent of the dry matter in the ecosystem and from 11 percent (nitrogen) to 76 percent (potassium) of the ecosystem nutrients. The forest floor contains less than 4 percent of the dry matter and nutrients in the ecosystem.

To understand the behavior of chemical elements in terrestrial ecosystems, a knowledge of nutrient cycling is needed. Three kinds of nutrient cycles have been identified in forest ecosystems (4). The geochemical, or external cycle, refers to the balance between precipitation inputs and streamwater or leaching-loss outputs from the system. The biogeochemical cycle refers to the circulation of nutrients between the vegetation and soil compartments. The biochemical, or internal cycle, encompasses the translocation of nutrients within individual trees. To understand these cycles, measurements of inputs, transfers, transformations, and outputs of chemical elements are necessary.

Atmospheric deposition is the major source (input) of nutrients in forest ecosystems, in the form of liquids (rain, fog, etc.), solids (dust), and gases. An additional input in the case of nitrogen is N fixation by free-living or symbiotic (rhizospheric) organisms. In managed forest ecosystems, chemicals may be applied as fertilizers, lime, and other additives.

There are five ways in which nutrients are lost from forest ecosystems: erosion, runoff, drainage beyond the rooting zone (leaching), gaseous losses, and product removal. Erosion and runoff contribute minimal nutrient losses in undisturbed or well-managed forest ecosystems. Gaseous losses occur primarily with regard to nitrogen in the form of ammonia volatilization and denitrification. The major source of nutrient loss in unmanaged forest , ecosystems is leaching beyond the rooting zone (i.e., streamwater output.) For example, the aspen-mixed hardwood ecosystem lost between 0.047 kg/ha/yr (nitrogen) and 2.5 kg/ha/yr (calcium) because of leaching (Table 5.2). In managed forest ecosystems, product removal may constitute a major loss of nutrients. For example, if the aboveground biomass (all but roots) were to be removed in the example from northern Wisconsin (Table 5.2), 818 kg/ha of Ca and 329 kg/ha of N would be removed from the site, averaging 12 and 5.1 kg/ha/yr for Ca and N, respectively (i.e., aboveground vegetation nutrient pool, divided by stand age), which exceeds the annual leaching losses for these elements.

Nutrient transfers involve movement from one compartment to another. For example, litterfall is the primary pathway by which most elements are returned to the forest floor (Table 5.2). Throughfall (the solution that passes through the forest canopy) and stemflow (the solution that moves along the bole of the tree) may return large proportions of the potassium and sulfur taken up by trees (Table 5.2).

Table 5.2 Distribution and Cycling of Nutrients in a 65-year-old Aspen-mixed Hardwood-Spodosol Ecosystem in Northern Wisconsin

Compartment or Flux	Organic Matter	N	P	K	Ca	Mg	S
Nutrient distribution	**mg/ha**			**kg/ha**			
Vegetation							
Roots	20	70	17	77	190	24	10
Bolewood	124	97	13	190	160	25	15
Bolebark	24	86	11	83	400	17	8.0
Branches	23	92	14	78	220	17	6.0
Leaves	3.4	54	7.0	26	38	5.0	5.0
Total	194	399	62	454	1008	88	44
Forest Floor	4.1	41	2.9	3.3	62	3.2	3.0
Mineral soil (0-30 cm)	84	3200	100	140	840	110	
Ecosystem total	283	3640	165	597	1910	201	
Nutrient cycling				**kg/ha/yr**			
Inputs							
Precipitation		5.6		2.4	5.2	0.6	4.65
Transfers							
Litterfall	4800	43	6.5	18	75	7.7	5.0
Throughfall + stemflow		3.6		20	10.7	2.0	6.35
Uptake*		59	10	60	126	13	15
Accum. in perennial tissues		26	4.1	25	6.3	5.4	9.4
Transformations							
Mineral weathering**				24	60	5.6	
Net mineralization***		69	1.8	2.4	14	2.0	
Outputs							
Leaching loss		0.047		1.1	2.5	0.8	2.6
Input-output****		5.6		1.3	2.7	-0.2	2.1

*Uptake - return in leaf litterfall + net leaching from canopy + annual accumulation in perennial tissues.

**Mineral weathering = leaching loss output - precipitation input + annual accumulation in perennial tissues of trees.

***Net mineralization - assumes release of 2.5% of mineral soil pool, 0-20 cm.

****Precipitation input - leaching loss output.

Nutrient transformations involve a change in chemical form. For example, mineral weathering releases a large amounts of calcium to the soil solution in northern Wisconsin (Table 5.2). Similarly, mineralization of soil organic matter releases large amounts of nitrogen—that can be taken up by trees.

Forest Soils and Tree Nutrition

Soil-Site Factors Related to Tree Growth

Soil-site evaluation involves the use of soil properties (as discussed earlier in this chapter) and of other site factors, such as topographic and climatic features, to predict tree growth. The ability to predict tree growth is of great value to the forester and for planning in the forest-products industry. To use the method, plots are located in stands representing the range of sites and soils found within a particular region. Measurements of tree growth and soil properties are then taken and correlated using statistical methods. The resulting equations can be used to predict site quality of stands that are heavily cut or too young for traditional site-index measurements.

Soil features important in soil-tree growth studies usually include depth, texture, and drainage (5). Site factors other than soils that are important to tree growth include slope position, orientation (aspect), and steepness. These factors influence soil moisture and temperature relations and the degree of erosion. Elevation and rainfall vary considerably in western North America and influence productivity of western conifers.

Diagnosis and Correction of Nutrient Deficiencies

Three methods are commonly used to diagnose nutrient deficiencies in forest ecosystems: 1) visual tree symptoms, 2) soil analysis, and 3) plant-tissue analysis (2, 6). Visual nutrient-deficiency symptoms include chlorosis and necrosis of foliage, unusual leaf structure, deformation or rosetting of branches, and tree stunting. Although many of these symptoms are relatively easy to recognize, nutrient-deficiency symptoms of trees may be difficult to isolate from those caused by disease, insects, or other site limitations, such as a moisture deficiency. Thus, it is important to combine visual techniques with soil or plant analysis.

Soil testing involves determining the "available" nutrient content of the soil and relating it to productivity of a particular tree species. Two problems with this technique include: 1) selecting a chemical that will extract that portion of the nutrients available to the plant, and 2) establishing optimum levels of soil nutrients for the various tree species. Soil testing is available through most land-grant universities and from private laboratories.

The third method for identifying nutrient deficiencies is tissue analysis, which is the determination of the nutrient content of a particular plant tissue, usually the foliage, and relating it to visual deficiency symptoms and tree growth.

Nutrient deficiencies may be corrected through the use of fertilizers. Forest fertilization is generally used where the following three conditions exist: 1) forests respond to fertilization with significant increases in growth rates, 2) high demand in the region makes the price of raw wood expensive, and 3) the infrastructure for buying, transporting, and applying fertilizers exists. The practice of forest fertilization is becoming widely used especially in parts of North America. Volume gains from nitrogen average 16 percent to 26 percent in the Pacific Northwest. In a regional study employing nitrogen and phosphorus in a factorial design, volume growth of loblolly pine averaged 25 percent greater for treated than controls (7). Forest fertilization may increase not only fiber yield but also insect and disease resistance and aesthetic quality of the vegetation. However, use of fertilizers in the forest constitutes use of a nonrenewable resource for perpetuating a renewable resource. Fertilization is also expensive and may contribute to environmental pollution when not applied judiciously.

Rate of fertilizer application depends on: 1) initial soil fertility level, 2) tree species, 3) age of stand, and 4) type of fertilizer. The nutrient most commonly applied to forests is nitrogen. Nitrogen is applied at rates of 100 to 400 kilograms per hectare to stands of Douglas fir in the Pacific Northwest and at rates of 5 to 100 kilograms per hectare to pines in southeastern United States. Phosphorus is applied to pines in the southeast at rates of 30 to 100 kilograms per hectare. Fertilizer generally is applied to open land or young plantations using mechanical spreaders. In established stands and those occupying large land areas, aerial application may be used. Municipal and industrial effluents and sludges ("bio-solids") may be applied as a fertilizer substitute in some forested areas.

Soil Survey and Classification

A *soil survey* involves the systematic examination, description, classification, and mapping of soils in a particular area. Mapping of soils requires a knowledge of the interaction of five soil-forming factors: climate, initial material, relief, organisms, and time.

A soil-survey report contains soil maps at scales commonly ranging from 1:10,000 to 1:60,000 and the following information: descriptions, use and management, formation and classification of soils, laboratory data, and general information pertaining to the area. The resulting soil surveys provide the forester with valuable information for planning forest activities. For example, soil surveys can be used to locate roads and landing areas, to match harvesting systems with soil conditions for minimizing site degradation, and to match tree species with soil type during reforestation for increasing yield. These soil surveys also enable the forester to plan silvicultural treatments, such as thinning and fertilization, more efficiently. Finally, soil surveys are useful for planning recreational facilities, for evaluating potential impacts of mining, grazing, and waste disposal, and for predicting water yield and quality in forested areas.

Numerous schemes have been used to classify forest land and to predict site quality. *Multiple-factor systems* have been used extensively especially in western North America (8). These systems differentiate and classify ecologically significant segments of the landscape using landform, soil initial material, forest cover type, and soil taxonomic unit.

Single-factor systems are used to map and/or classify individual components of the ecosystem, such as vegetation or soils. The *habitat system* is an example of a single-factor system and is based on climax plant associations that can be used to predict site/successional relationships and site quality (9).

Soil Taxonomy (10) is an example of a single-factor (soil) system used to classify forest land. There are seven categories of classification in the system: 1) order (broadest category), 2) suborder, 3) great group, 4) subgroup, 5) family, 6) series, and 7) type.

Of the 12 soil orders in *Soil Taxonomy,* four are of particular importance in world forests: Ultisols, Alfisols, Spodosols, and Oxisols. *Ultisols* are forest soils with less than 35 percent of the exchange sites containing calcium, magnesium, potassium, and sodium. These soils occur in areas with moist, warm to tropical climates, with an average annual temperature of more than 8°C. Ultisols contain a yellow E horizon and a reddish, iron and clay-enriched B horizon. These soils support loblolly and shortleaf pine in the southeastern United States and oak-hickory and oak-pine in the south-central United States and tropical rainforest in central South America, equatorial Africa, southeast Asia and Oceania, and eastern Australia.

Alfisols are forest soils with greater than 35 percent of the exchange sites containing calcium, magesium, potassium, and sodium. They contain a gray E horizon and a brown, clay-enriched B horizon. These soils feature oak-hickory in the central United States, northern hardwoods in northern New York, aspen-birch in the northern Great Lakes states, and ponderosa and lodgepole pines in western North America. Alfisols are common in drought-deciduous forest and central broad-leaved forests worldwide (see Chapter 3).

Spodosols contain a grayish E horizon and dark reddish-brown B horizons that are enriched in organic matter and/or iron and aluminum oxides

(Figure 5.3). These soils develop from coarse-textured, acid initial materials under cold humid climates. Major forest cover types are spruce-fir, eastern white pine, and northern hardwoods in New England and eastern Canada, and northern hardwoods and aspen-birch in the Great Lakes region. In southwest Alaska, Spodosols support western hemlock—Sitka spruce, and in Florida poorly drained Spodosols support longleaf and slash pines. Spodosols are common in the taiga of northern Eurasia.

Oxisols are intensively weathered soils enriched in iron oxides and depleted in weatherable minerals. They occur in tropical areas, especially in equatorial South America and Africa.

Forest Soils and Environmental Quality

Forest Health, Sustainability, and Ecosystem Management

With the advent of "Ecosystem Management" (Chapters 6 and 13), a number of terms have arisen that are intended to address the long-term productivity of forest ecosystems. Because of the importance of soils in supplying nutrients to sustain productivity, it is appropriate to consider these terms in this chapter. A healthy forest ecosystem has the following characteristics (11):

- the physical environment, biotic resources, and trophic networks to support productive forests during at least some serai stages;
- resistance to catastrophic change and/or the ability to recover from catastrophic change at the landscape level;
- a functional equilibrium between supply and demand of essential resources (water, nutrients, light, growing space) for major portions of the vegetation; and
- a diversity of serai stages and stand structures that provide habitat for many native species and all essential ecosystem processes. Basically, forest health is a condition of forest ecosystems that sustains their complexity while providing for human needs.

Forest sustainability is the continued ability of the forest ecosystem to provide a number of valued goods and services and involves 1) intergenerational responsibility; 2) maintenance of ecosystem processes and scales; and 3) use of management practices that reflect ecological conditions (12).

Timber Harvesting and Long-Term Soil Productivity

The Long-Term Soil Productivity (LTSP) program was established to address U.S. National Forest Management Act of 1976 concerns over possible losses in soil productivity on National Forest lands. Following an extensive review of the world's literature on productivity decline, authors of the cooperative LTSP concluded that soil porosity and site organic matter are the key properties most influenced by management and most related to forest health and growth within the constraints of climate and topography (Figure 5.7). The LTSP program follows standard format throughout North America with some modifications for local conditions (13). Steps consist of site selection, pretreatment measurements, treatment installation, and post-treatment measurements. About 50 experiments have been established in major commercial forest types on public and private land in North America. The treatments generally include different levels of organic matter removal and different levels of compaction. Among the important findings to date are those concerning the effects of treatment on soil physical properties affecting site productivity. For example, retaining the forest floor or logging slash keeps soils cooler in the summer and improves plant water availability by reducing evaporative losses. Another key finding is that a slight amount of compaction may actually improve the available water-holding capacity of coarse-textured, sandy soils.

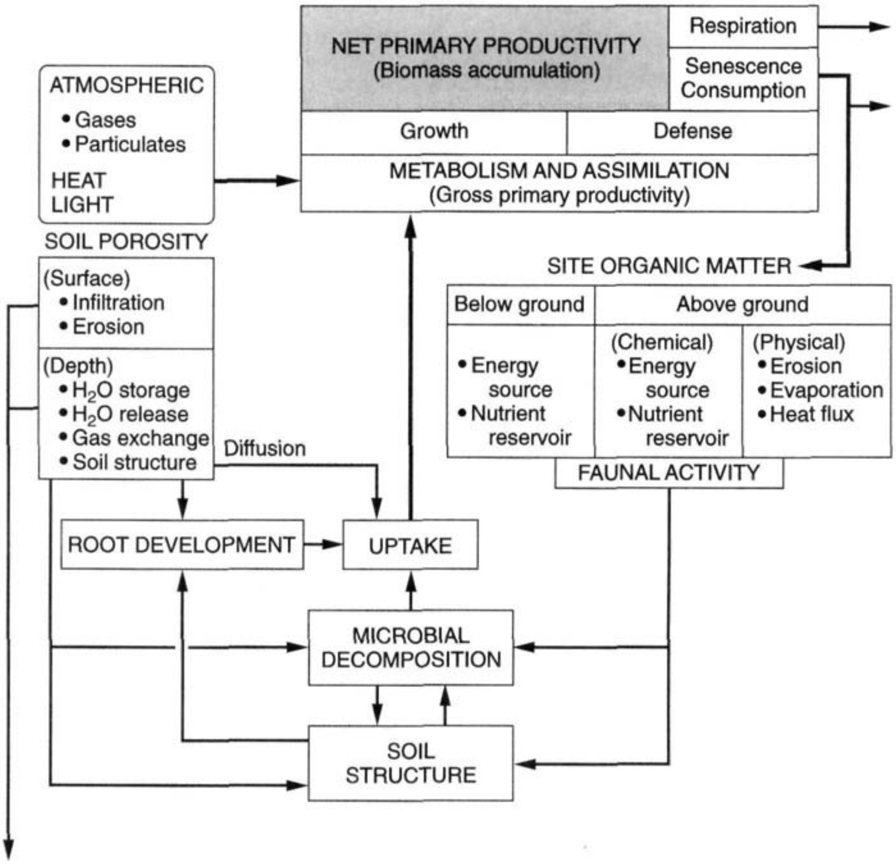

Figure 5.7 Conceptual model of how soil porosity and site organic matter regulate the processes controlling forest growth and site productivity (from reference 13, Powers et al.).

Nutrient Budgets and Forest Management

Nutrient budget and balance sheets enable the forest manager to assess the consequences of alternative management practices on long-term site quality. For example, based on data in Table 5.2, a bolewood harvest in aspen-mixed hardwoods in northern Wisconsin would remove 64 percent of the dry matter in the tree but less than 42 percent of the macronutrients (N, P, K, Ca, Mg, and S) present in the vegetation. A conventional stem harvest (bolewood + bolebark) would remove 76 percent of the dry matter but from 38 percent (P) to 60 percent (K) of the nutrients in the tree. Therefore, if feasible, leaving the bark along with the branches, foliage and roots would conserve nutrients in this ecosystem. A more accurate estimate of the long-term sustainability of the site can be obtained by comparing the annual needs of the tree ("Accumulation of nutrients in perennial tissues," Table 5.2) with the net gain or loss of nutrients. The net gain or loss is determined by summing "Mineral weathering," "Net mineralization," and "Input-Outputs." Based on this analysis, all of the nutrients are in good supply, except possibly, phosphorus.

Concluding Statement

As the demand for forest products continues to increase, forest soils will be more intensively used. The following forest management practices may have profound effects on soil and water quality: 1) shortened rotations; 2) close utilization; 3) use of fast-growing hybrid species; and 4) mechanical and chemical site preparation.

Industrial foresters have expressed interest in *short-rotation intensive culture* (SRIC), which has also been called fiber farming or "puckerbrushing." This practice uses fast-growing hybrid cuttings that are grown at close spacings and are harvested every few years. This practice may require fertilization to supply an adequate supply of nutrients.

Site preparation refers to soil manipulation techniques designed to 1) rid areas of logging slash, 2) reduce weed competition, 3) prepare a mineral seedbed, 4) reduce compaction or improve drainage, 5) create more favorable microsites for tree planting, and 6) control diseases (14). Site preparation involves use of prescribed burning, chemical applications, mechanical techniques, and combinations of these practices. Where injudiciously applied, these practies may lead to increased erosion and runoff and an overall decline in site quality.

Improper road-building practices are often cited as a major cause of sedimentation in forest environments, particularly in steep mountainous areas. Timber removal may also contribute to sedimentation of streams, lakes, and reservoirs by exposing the surface soil, particularly during skidding and yarding operations (see Chapter 19 for methods of timber harvesting). Skidding of logs with tractors and rubber-wheeled vehicles is more likely to cause soil erosion and mass-wasting than when high-lead cable, skyline cable, balloon, or helicopter systems are employed. Wet-weather logging is especially detrimental to soils and should be avoided if at all possible.

A major concern in recent years has been the potential effects of widespread deforestation in tropical and boreal forests on carbon dioxide accumulation in the atmosphere. The accumulation of CO_2 in the atmosphere has been related to climate warming (i.e., the "greenhouse effect") and is discussed further in Chapter 4, Forest Ecophysiology.

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CHAPTER 6

Forest Ecosystem Ecology

STITH T. GOWER

Ecology is the study of the interactions between organisms and the environment. The study of the relationship of a species to the environment is referred to as *autecology.* An ecosystem includes the vegetation, the soil, the organisms, as well as complex interaction of the three components. Forest ecosystem ecology is the study of the interactions between forest vegetation and organisms and the environment. The subdiscipline of ecology that focuses on all organisms and their complex interactions with each other and the environment is referred to as *synecology.*

Foresters must be well versed in both autecology and synecology to manage forests to ensure adequate regeneration, growth, and reproduction of the desirable forest tree species. In essence, forest management, or applied forest ecology, is the application of theoretical forest ecology, including topics such as species dynamics, succession, nutrient cycling, and production ecology, to achieve the forest management objectives. This chapter provides an introduction to the topics of succession, nutrient cycling, and production ecology as they relate to forest management. It is essential to understand how forest ecosystems are affected by natural disturbances and harvesting, because very few forests remain unaffected by humans.

The first section of the chapter focuses on the processes that determine the species distribution in a stand. Tolerance and competition are two key processes that affect species composition. The life history patterns and associated ecological attributes affect the tolerance, and hence competitiveness, of species in a stand. The second section introduces the carbon cycle, of which plant growth, or net primary production, is one component. Plant growth is strongly influenced by the quantity and quality of organic matter in the soil, and in turn, the growth rate of the vegetation influences the quantity and quality of organic matter that is returned to the soil (also see Chapter 5, Forest Soils).

Tree growth is often limited by nutrient availability, which is affected by the amount of organic matter that returns the soil. The third section provides a brief introduction to nutrient cycles. Nutrient inputs, losses, and internal cycling of nutrients are discussed and the strong linkage between the carbon, or organic matter cycle, and nutrient cycles is emphasized.

The fourth section reviews the basic concepts of succession. Forests are not static; species composition, structure and function of forests change in response to internal and external factors. One of the most important external factors is disturbance; particularly, forest harvesting. Forests provide many services to humans, such as wood, and other organisms. The last section of the chapter reviews how forest harvesting affects the long-term sustainability of forests and adjacent aquatic ecosystems.

Forest Tree Species Distribution

Tolerance and Competition

What determines the distribution of species? In Chapter 3, Forest Biomes of the World, you learned that climate, soil, and disturbance regime influence the distribution of the major forest biomes. These same factors influence the distribution of species at the local (within a stand) scale. Tree species are ranked according to their tolerance to varying environmental conditions. Tolerance to light is the ecophysiological characteristic most commonly used to classify tree species. Although the classification of species can be subjective, it has a physiological basis, and is a useful concept to guide forest managers. Table 6.1 summarizes some common forest tree species for different forest regions in the United States and their relative tolerance to light. The physiological basis for the classification is leaf photosynthesis versus light relationship. Figure 6.1 illustrates the relationship

Table 6.1 Examples of Commercially Important Tree Species for Different Forest Regions in the United States that Vary in Shade Tolerance (Adapted from Hocker [1])

Shade Tolerance Class	Forest Region			
	Eastern Deciduous	Lake States	Rocky Mountain	Pacific Northwest
Very Intolerant to Intolerant	pin cherry willow tulip poplar river birch	trembling aspen jack pine tamarack	trembling aspen lodgepole pine ponderosa pine	Douglas fir red alder western larch
Intermediate Tolerant	ash spp. oak spp. American elm sweetgum	basswood ash spp. oaks spp. red maple	blue spruce Douglas fir — —	sugar pine western white pine noble fir giant sequoia
Tolerant to Very Tolerant	sugar maple American beech hickory spp. Eastern hemlock	sugar maple yellow birch eastern hemlock	Englemann spruce subalpine fir	western hemlock Pacific silver fir western red cedar grand fir redwood

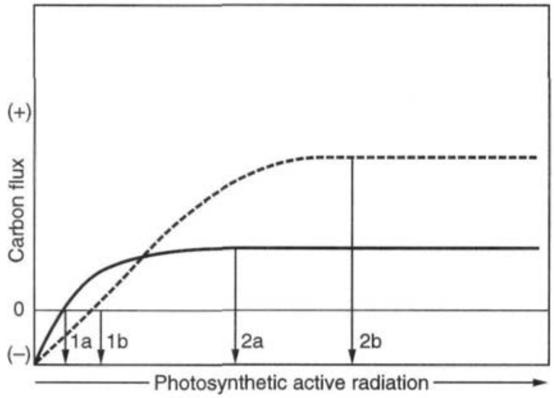

Figure 6.1 Hypothetical response curve illustrating the relationship between net leaf photosynthesis and photosynthetic active radiation, or visible light, for shade-intolerant and shade-tolerant tree species. The light compensation point, or the light intensity at which net carbon reaches zero, is lower for shade tolerant (la) than shade intolerant (lb) species. Light saturation point, the light intensity at which net leaf photosynthesis no longer increases with increasing light, is greater for shade intolerant (2b) than shade tolerant (2a) species. (solid line—shade tolerant species; dashed line—shade intolerant species)

between net carbon balance and increasing photosynthetic active radiation (PAR)—the wavelengths of light that plants use in photosynthesis—for a shade-intolerant versus shade-tolerant tree for increasing light. The light level at which the leaf carbon balance is zero (photosynthesis equals respiration) is refened to as the *light compensation point* (LCP). The LCP is lower for shade-tolerant than shade-intolerant trees, allowing shade-tolerant plants to maintain a positive carbon budget (photosynthesis exceeds respiration) at much lower light level than shade-intolerant plants. The light level at which photosynthesis no longer increases with increasing light is refened to as the *light saturation point* (LSP). The LSP is greater for shade-intolerant than shade-tolerant tree species, demonstrating that shade-intolerant trees will outgrow shade-tolerant tree in high light environments because they can more fully utilize the higher light levels.

Despite the emphasis placed on the relationship between light availability and plant tolerance, other resources such as water and nutrients affect the ability of plants to compete and survive, and ultimately affect the distribution of plants. Plants range in tolerance to nutrient and water availability, temperature, pollution, and so forth. *Niche* is the physical environment where a species occurs. The *physiological niche* is the environment that a species can tolerate when grown in isolation and is used to infer that species can grow and reproduce successfully (Figure 6.2). Ecological niche is the environment that a species can tolerate when grown with naturally co-occurring or sympatric species. The ecological niche of species A is more restricted than its physiological niche because species B and C are better adapted than species A at edges of the physiological niche of species A. Why are species B and C better adapted than species A at edges of the physiological niche of species A? The answer to this question is not straightforward, but a partial explanation is related to the morphological or physiological adaptations of plants that enable them to more effectively compete for growth-limiting resources. This is the topic of the next section.

Life History Patterns

Numerous classification schemes have been devised to categorize plants based on the ecological niche they commonly occupy. Some classification schemes emphasize successional status, while others emphasize tolerance to light, resource limitations, and so forth. J. Grimes (2) proposed a very useful classification scheme that was based on the general life history patterns of plants. The life history refers to the ecological niche and disturbance regime that plants occupy. The Grime's life history classification scheme recognizes three categories: ruderals, competitors, and stress-tolerants. *Ruderals* are plants that occupy niches with high resource (water, nutrients, and light) availability and frequent disturbance. Many of the invasive weedy plants found along roadside cuts, railroad right-of-ways, and forest tree species that occur in recently disturbed forests are good examples of ruderals.

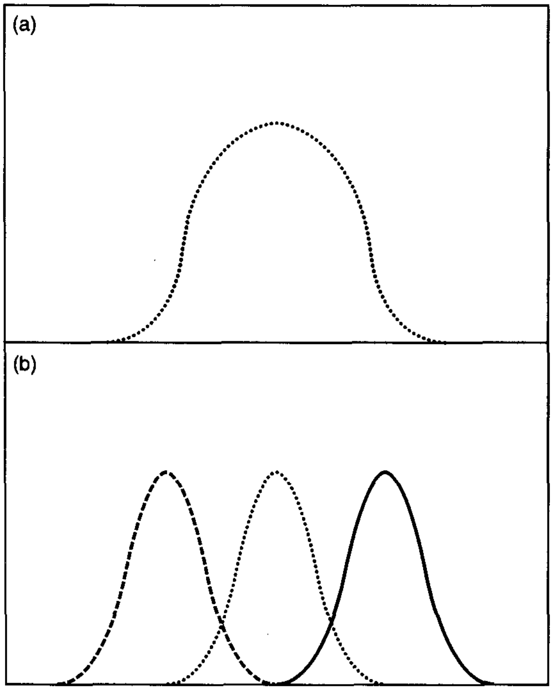

Figure 6.2 Comparison of the physiological niche (a) and ecological niche (b) for three species of varying tolerance to the availability of an essential resource required for plant growth. Note that the physiological niche is always greater than the ecological niche; the unique suite of ecophysiological and structural characteristics make species better competitors for aquiring limiting, but essential, resources for plant growth.

Table 6.2 summarizes some of the general characteristics and tree species of each of the three life history categories. Ruderal plants are characterized by rapid growth rates, prolific reproduction, and high shoot:root ratios. Competitors occupy a niche that experiences less frequent disturbance than ruderals, and competition for resources is high. Many commercially desirable forest tree species fall into this category. Stress-tolerant plants occur in the most resource-limited environments and the disturbance frequency is low. Stress-tolerant species have the slowest growth rates because resource availability is very low. Stress-tolerant species typically have a greater root:shoot ratio than ruderals or competitors to increase uptake of limiting nutrients and water. Competitors have life history characteristics that are intermediate to ruderals and stress-tolerant species.

The unique suite of morphological and physiological characteristics of each of the life history patterns makes each plant species best adapted to different environments. The different life history patterns of commercially valuable trees species require different forest management practices to promote the growth of desirable tree species and retard the growth of unwanted tree or weed species. Ruderal tree species, such as aspen, are more common to early successional forests originating from natural disturbance or timber harvesting. Stress-tolerant tree species are poor competitors in recent clearcut because of their intrinsic slow growth rates and greater allocation of biomass to roots. However, the availability of light, nutrients, and water

Table 6.2 General Life History Characteristics of Ruderal, Competitor, and Stress-tolerant Tree Species

Characteristic	Ruderal	Competitor	Stress-tolerant
Life longevity	short	intermediate	long
Leaf longevity	short	intermediate	long
% NPP allocated to reproduction	large	intermediate	small
Maximum growth potential	rapid	intermediate	slow

Adapted from Table 5-3 in Barbour, Burk, and Pitts (3)
NPP = Net Photosynthetic Productivity

changes during succession. Conversely, ruderals are poorly adapted to harsh environments, such as drought-prone, nutrient-poor soils where stress-tolerant plants occur. The boundaries between the three life history categories are not discrete, but are a continuous gradient. Nonetheless, the classification scheme is useful for categorizing tree species for both ecological and management purposes.

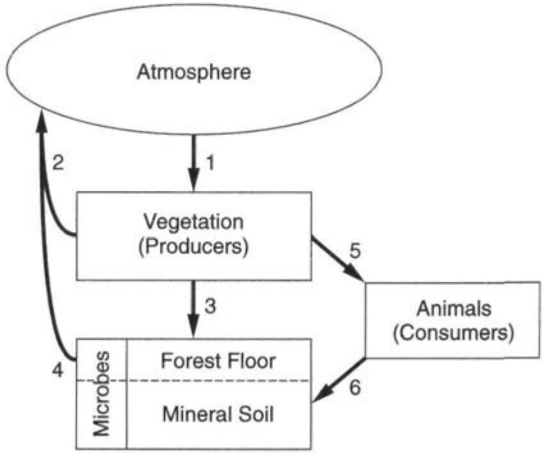

Figure 6.3 Schematic diagram of the carbon cycle. The boxes represent pools, or containers of carbon, while each arrow depicts a transfer of a fraction of carbon between pools. The corresponding names of the numbered fluxes are as follows: 1 = gross primary production (GPP); 2 = autotrophic respiration; 3 = detritus production; 4 = heterotrophic respiration; 5 = herbivory; 6 = animal mortality.

The Carbon Cycle and Forest Growth

The Carbon Cycle

The cycle or budget of elements such as carbon can be described by the size of the various pools, or reservoirs of the elements in the ecosystem, and the fluxes, or rates of movement of the element between the different pools. The carbon, or organic matter, cycle is composed of five major pools and the transfer of carbon among the pools. The five pools are: the atmosphere, forest biomass, animal biomass, microbial biomass, and the various forms of soil organic matter (Figure 6.3). The uptake of carbon dioxide (CO_2) from the atmosphere by the vegetation is referred to as *gross primary production* (arrow #1). The vegetation, or *photoautotrophs,* use the solar radiation (Figure 6.4) to produce their own carbohydrates that are used to build new organic matter *(autotrophs).* A portion of the atmospheric carbon dioxide taken up by the plant is released back to the atmosphere; this process is referred to as autotrophic respiration (arrow #2). *Net primary production,* the net difference between gross primary production and *autotrophic respiration,* is closely related to forest growth. Stated slightly differently, net primary production is the sum of all the new biomass (stem, branches, foliage, roots, mycorrhizae, and reproductive tissues) produced each year. A fraction of the living organic matter dies each year, and returns to the soil surface as detritus (arrow #3). There are millions of fungi and bacteria that derive their energy by decomposing dead organic matter. These organisms are referred to as *heterotrophs* because they are dependent upon other organisms to produce the organic matter that they consume for energy. Carbon dioxide is released back into the atmosphere as heterotrophs decompose the soil organic matter; this process is referred to as *heterotrophic respiration* (arrow *#4).* The net difference between the total organic matter inputs and loss of organic matter from the soil determines whether the soil organic matter is increasing or decreasing.

Understanding the carbon cycle is important for several reasons. First, an imbalance between the exchange of carbon dioxide between the atmosphere and terrestrial ecosystems increases the concentration of carbon dioxide in the atmosphere. This is important because carbon dioxide is a greenhouse gas and is suspected of being responsible for climate warming as described in Chapter 4, Forest Ecophysiology. Soil organic matter is important because of its large water and nutrient holding capacity. Maintaining the soil organic matter is an essential component of sustainable forest man-

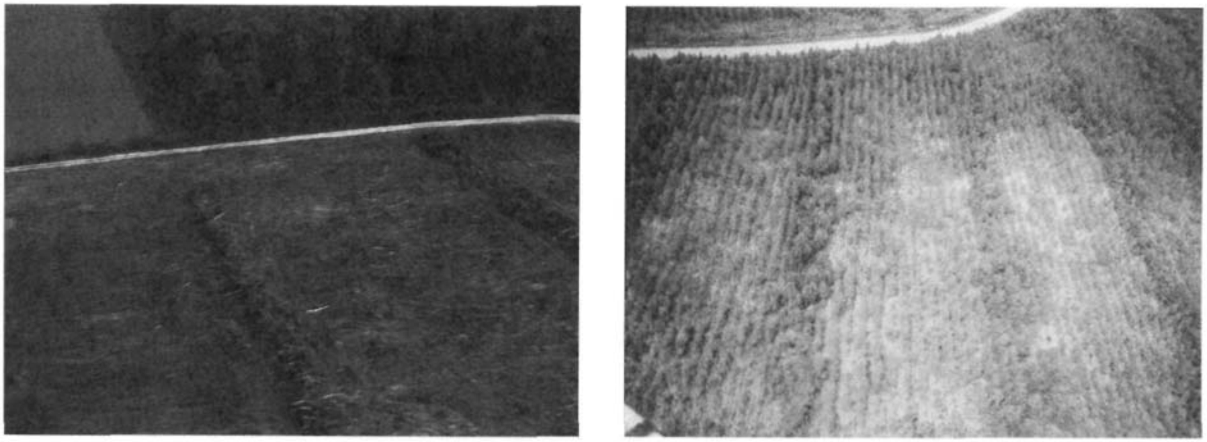

Figure 6.4 Aerial view of a regenerating southern pine forest several years after planting (right). The location of old windrows (left) are still apparent because the nutrients in the windrows and displaced nutrients from the upper soil horizons of the surrounding area stimulated growth. Conversely, the excessive displacement of nutrients that can occur during site preparation appears to have decreased the soil fertility of the areas between the windrows.

agement. Third, the net uptake of carbon dioxide from the atmosphere by the vegetation determines the growth rate of the forest, or the ability of the forest to provide forest products for human use. A more detailed discussion of the factors that influence forest structure and growth, and soil carbon dynamics is discussed next.

Environmental Constraints on Leaf Photosynthesis

There are numerous environmental and biological factors that influence the growth rate of forests, but for simplicity, this chapter focuses on the fundamental factors that influence growth rate of forests. Where appropriate, the reader is referred to other relevant sections in the book that provide more detail. The growth rate of forests is controlled by two major groups of constraints: environmental constraints on leaf-level photosynthesis, and environmental constraints on leaf area index—an important canopy structural characteristic of terrestrial ecosystems.

Photosynthesis is the biochemical process by which carbon dioxide (CO_2) from the atmosphere, and water (H_2O), in the presence of light, are converted to carbohydrates (CH_2O) as described in Chapter 4. Air and soil temperature, solar radiation, vapor pressure deficit (or how dry the air is) and foliage nutrient status are the major environmental factors that affect leaf-level rates of photosynthesis. The climate diagrams presented in Chapter 3 (Forest Biomes of the World) illustrate that the relative importance of the environmental constraints on leaf photosynthesis varies among forest biomes. Liebig's "Law of the Minimum" states that the rate of a process—photosynthesis, for example—is controlled by the most limiting resource. A useful analogy is imaging each stave of a wooden barrel as an environmental constraint (Figure 6.5). The water level in the barrel, or photosynthesis rate, can be only as high as the shortest stave, or the most limiting resource. The precise relationship between each of the above-mentioned environmental variables and leaf photosynthesis varies among species, but a general relationship exists that fits most tree species.

Extreme cold air and soil temperatures restrict photosynthesis; therefore, trees do not grow during the winter periods when temperatures drop below freezing for several days in a row. Photosynthesis increases linearly with temperature above

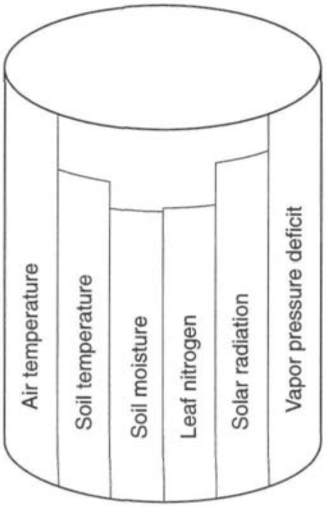

Figure 6.5 Conceptual model of Liebig's Law of the Minimum. The top of the barrel represents the theoretical maximum of a rate—in this case, leaf photosynthesis. However, the maximum rate is determined by the most limiting resource, or the greatest environmental constraint on leaf photosynthesis, which is depicted by the shortest staves in the barrel—soil moisture and leaf nitrogen, in this hypothetical example.

freezing, levels off at some optimum temperature, and declines rapidly if lethal temperatures occur (Figure 6.6a). The optimum temperature for photosynthesis for temperate and boreal tree species ranges from 15 to 20°C, and can be as high as 25°C for some tropical tree species (4). Even if air temperature is above freezing, roots cannot absorb water from frozen soil, making it impossible for trees to replace water lost by transpiration. The growing season, defined as the period of the year when environmental conditions are suitable for trees to grow, of continental boreal forests is reduced by three to four weeks in the spring because the soils remain frozen when all other environmental conditions are suitable for tree growth.

Soil moisture availability, or, more accurately, the internal water status of the plant, limits leaf photosynthesis (Figure 6.6b). The concept of internal plant water status and pre-dawn xylem water potential as a useful index of plant water status was discussed in Chapter 4 (Forest Ecophysiology). When plants open their stomates to absorb CO_2, water vapor is lost, because the ambient air surrounding the leaf is drier than the near-saturated mesophyll inside the leaf. Extremely hot, dry days cause stomata to close because the water uptake by the roots cannot keep pace with the rapid water loss. The large vapor pressure gradient causes a rapid loss of water from high to low vapor pressure gradient until plants close their stomata. Plants, therefore, must optimize the duration and rate of stomatal conductance to maximize CO_2 uptake and minimize water loss from photosynthesis and transpiration, respectively. When soil moisture is plentiful, plants keep the stomata open for most of the day, but as the soil moisture decreases, plants will keep the stomata open during the early morning and partially or completely close the stomata during midday to avoid large water losses. During extreme droughts, plants experience severe water stress and will close stomata for days until soil moisture is replenished.

Many of the essential elements are required to construct the biochemical constituents involved in photosynthesis. As a result, photosynthesis is positively correlated to nutrient concentration, especially nitrogen over a moderately broad range of leaf nitrogen concentration (Figure 6.6d). Nitrogen is required to construct chlorophyll. Nitrogen is commonly limiting in many forests, and foliage nitrogen concentrations are typically on the linear portion of the curve.

Environmental Constraints on Canopy Structure and Forest Growth

Many of the same environmental constraints that influence photosynthesis at the leaf level also influence stand-level growth of forests by altering the biomass allocation patterns of trees. Trees use the current photosynthate to construct stems, branches, coarse and fine roots (including mycorrhizae, a symbiotic fungus—see Chapter 4), and reproduc-

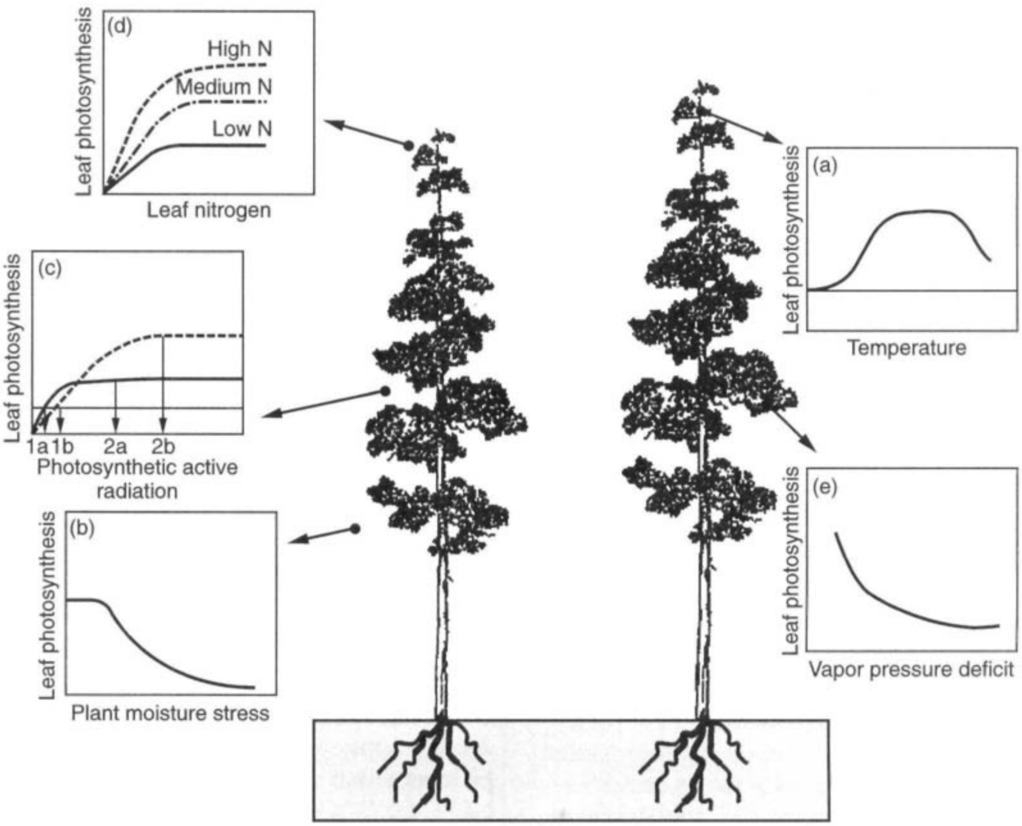

Figure 6.6 Canopy photosynthesis is limited by five major environmental constraints: (a) air and soil temperature, (b) soil moisture, (c) photosynthetic active radiation, (d) leaf nitrogen, and (e) vapor pressure deficit. Each of the environmental constraints has a different influence on leaf photosynthesis.

tive tissues, as well as storage and defense compounds. In general, trees allocate more biomass to construct tissues that will increase the availability of the most limiting resource (5). For example, trees grow fewer fine roots and mycorrhizae and more foliage when they are fertilized, because nutrients are less limiting (Figure 6.7). The increased nutrient availability often stimulates an absolute increase in foliage production. The remarkable process by which trees control the growth of different tissues is not fully understood. However, it appears that the environmental stimuli (such as drought, high vapor pressure deficit, etc.) cause plants to increase or decrease the production of different plant growth regulators, or chemical compounds, that control the growth of different plant parts.

Water availability also influences the allocation of biomass to trees. As we have seen in Chapter 3, global patterns of precipitation, solar radiation, and temperature vary among the forests biomes of the world. Collectively, these environmental factors influence the water budget, and hence water available for plant uptake (see Chapter 16, Watershed Management).

Figure 6.8 illustrates the strong influence the hydrologic budget has on canopy structure—specifically, leaf area index (LAI)—and the positive relationship between leaf area index and forest

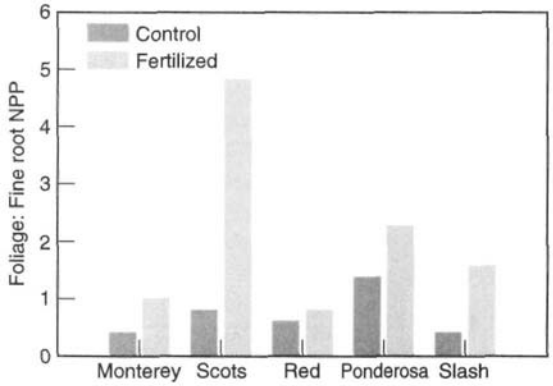

Figure 6.7 The fine root:foliage production ratio for control and fertilized conifer forests growing in contrasting environments. In all cases, fertilization caused a relative shift in priority of new growth of decreased fine root growth and increased foliage growth. Figure was adapted from Landsberg and Gower (5).

growth. The data are from forests along a precipitation gradient caused by the orographic rainfall pattern[1] as moisture from the Pacific Ocean crosses the Coastal Range and then the Cascade Mountains in Oregon. Forests that receive more precipitation have a more favorable site water balance. The average water balance of a forest is determined by the amount of precipitation minus the losses such as evapotranspiration, overland flow, and deep drainage (see Chapter 16). A large leaf area index is beneficial because there is more photosynthetic surface area to absorb carbon dioxide from the atmosphere. The amount of solar radiation absorbed and converted into carbohydrates for tree growth is directly proportional to the leaf area index.

One question that should come to mind then is: Why don't all forests support a large leaf area index to absorb all the solar radiation? The answer to this question can be found by revisiting the carbon budget of forests. Recall that a fraction of gross primary production is used to repair and maintain tissues, such as foliage. Autotrophic respiration costs occur each day regardless of whether the stomates are open and photosynthesis is occurring. In other words, supporting a large leaf area index increases the large carbon cost each day, regardless of whether environmental constraints are prohibiting photosynthesis (Figure *6.6).* Consequently, plants support a leaf area index that optimizes the potential for net primary production. Excessive amounts of foliage cause excessive autotrophic respiration costs, while less than optimum amounts of foliage result in an incomplete use of light and canopy photosynthesis.

The Nutrient Cycle

Figure 6.9 summarizes the important components of the nutrient cycle for a hypothetical forest. The figure includes only the major nutrient pools and fluxes. Readers interested in a more detailed treatment of terrestrial nutrient cycles should refer to Schlesinger (8). Most of the processes shown in Figure 6.9 apply to all nutrients, but there are a few processes that are applicable only to the nitrogen cycle.

Why do we need to understand the nutrient cycles of forest? The answer to this question has both an applied and theoretical basis. From an applied or management point of view, it is important to understand how forest management affects soil fertility, because nutrients often limit forest growth. For example, can forests be harvested repeatedly without decreasing the long-term productivity of the site? If so, how frequently can they be harvested without depleting the nutrients in the soil? Also large losses of nutrients from the forest ecosystem into adjacent aquatic ecosystems can severely decrease water quality and threaten human health. Are there some forest types that are more likely to experience greater nutrient losses to groundwater following disturbance? Answers to these questions are needed if forests are to be man-

[1] Rainfall patterns in mountainous regions.

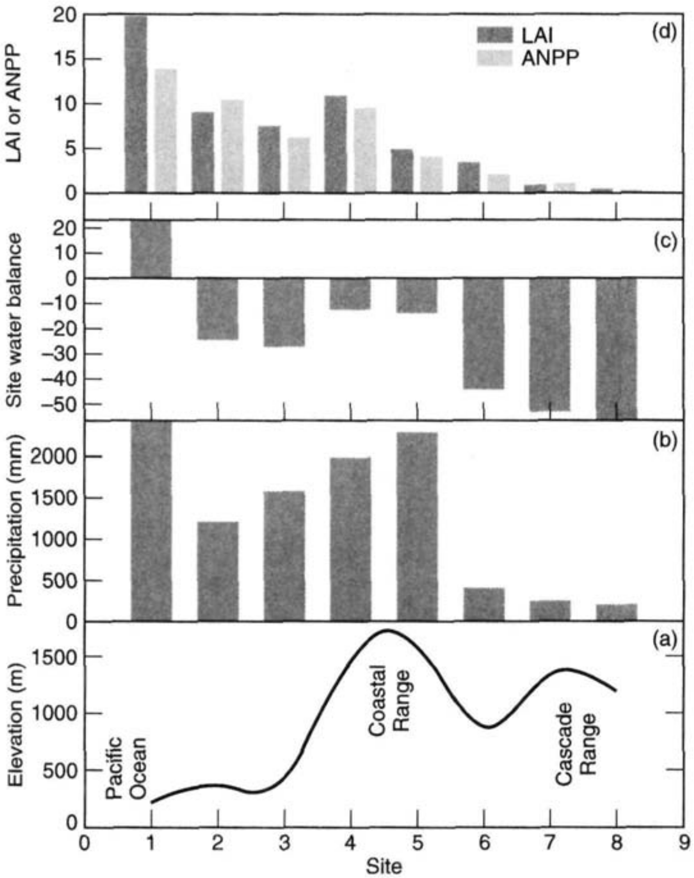

Figure 6.8 Relationship between site water balance, leaf area index (LAI), and forest growth. The data were obtained for forests in Oregon that occur along a pronounced orographic precipitation gradient along the Coastal Range and the further inland Cascade Mountains. Leaf area index is positively correlated to precipitation and available soil water, and in turn, aboveground net primary production (ANPP) is positively correlated to leaf area index. Similar relationships between the hydrologic budget and forest growth have been reported for other forest regions of the world. Data from Grier and Running (6) and Gholz (7).

aged on a sustainable basis. The effects of natural and human disturbance on nutrient cycle are discussed later in the chapter after a general introduction to the nutrient cycle is presented. From a basic point of view, there is great interest in understanding the processes that control nutrient cycling rates and nutrient accumulation in the various components of forest ecosystems.

Nutrient Distribution

Nutrients are generally not distributed equally within forest ecosystems. Figure 6.10 is a graphical illustration of the relative distribution of nitrogen (N), phosphorus (P), and calcium (Ca) in the foliage, wood, and soil (forest floor + mineral soil) for four contrasting forest ecosystems. The soil contains the greatest fraction (80-99%) of the total nutrient content of forest ecosystems. It is important to note that although a large fraction of the nutrients are in the soil, only a very small percentage of the elements occur in a form that plants can absorb. The distributions of nutrients shown in Figure 6.10 are representative of many forest ecosystems of the world, although there are several notable exceptions. Extremely infertile forests, such as the tropical forests that occur on nutrient poor Oxisols and Spodosols, contain a higher percentage of the total nutrients in the vegetation than the soil.

Nutrient Inputs

Atmospheric deposition and weathering are two primary pathways by which nutrients enter forest

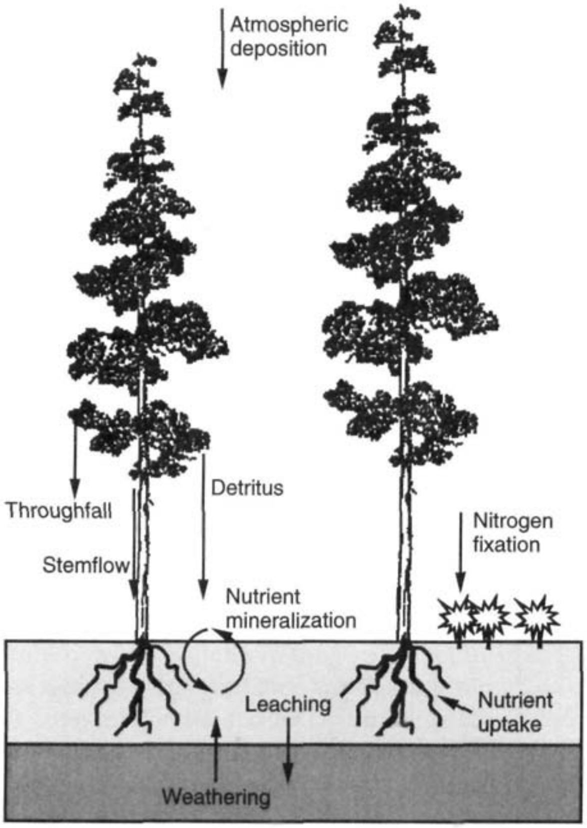

Figure 6.9 Diagram of a nutrient cycle for a hypothetical forest. The diagram illustrates the major pools and fluxes of nutrients. A complete treatment of the major terrestrial nutrient cycles is provided by Schlesinger (8).

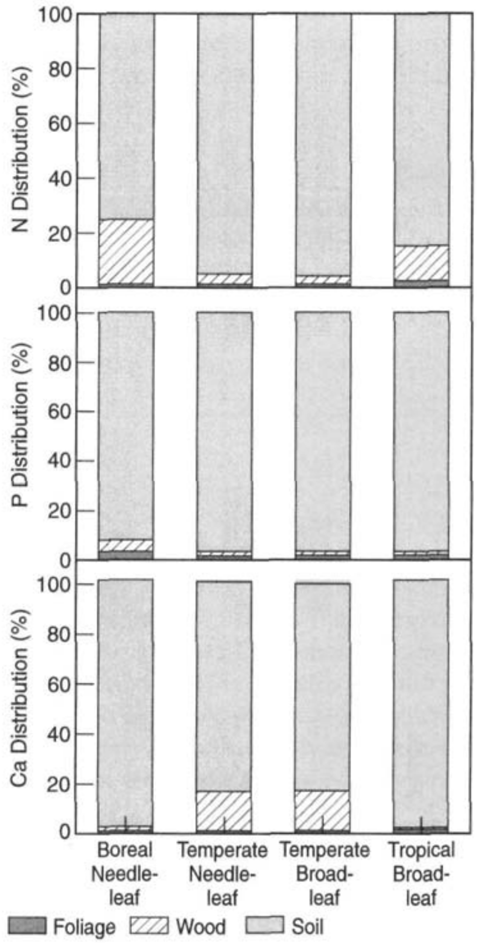

Figure 6.10 Relative distribution of nitrogen (N), phosphorus (P), and calcium (Ca) in foliage, wood tissue, and soil (forest floor and mineral soil) for forests in four contrasting biomes. By far the greatest fraction of the total nutrient content in an ecosystem is contained in the soil, but only a small fraction of this pool is available for plant uptake. Adapted from Landsberg and Gower (5).

ecosystems, although nitrogen can enter via biological fixation (see Sidebar 6.1—Nitrogen Fixation). The amounts and types of nutrients that are present in atmospheric deposition are strongly dependent upon geographic location. Large amounts of nitrogen and sulfur deposition occur in highly industrialized areas such as the northeastern United States and Europe. Sodium and chlorine, originating from sea spray aerosols, are important nutrient inputs in forests that occur along the coast. The amounts and types of nutrients that become available for plant uptake from weathering are strongly dependent upon climate and parent material—or the type of rock beneath the soil (see Chapter 5, Forest Soils). Chemical weathering of limestone produces calcium, feldspars and micas release potassium when they weather, and dolomite releases calcium and magnesium when it weathers. Nitrogen is not contained in rock near the earth's surface; therefore, nitrogen is not released from weathering. As a result, nitrogen is almost always limiting in new soils derived from volcanic activity, or from unconsolidated rocks from glacial deposits.

Nutrient mineralization is the primary source of nutrients for trees in many forests. Unlike atmospheric deposition and weathering, nutrient mineralization is not a new input, but is derived from recycled nutrients contained in decaying organic matter and detritus input. Sources of decaying organic matter include dead leaves, branches, stems, and roots, as well as dead animal matter. The annual input of nutrients to the soil from detritus decreases in the order of tropical > temperate > boreal forests (5). Dead leaves and fine roots comprise the majority of the annual nutrient input in forest ecosystems. The chemical composition of the tissues and the physical environment determine the rate that the organic matter will decompose and that nutrients are released back to the soil. Leaves and fine roots have higher nutrient concentrations and lower concentrations of chemicals, and therefore decompose faster than woody tissue.

Nutrient Losses

Erosion, leaching, volatilization, and harvesting are the primary pathways for nutrient loss from forest ecosystems. The loss of nutrients via erosion is generally not a concern for intact forests because the multilayers of foliage and the forest floor reduce the physical impact of raindrops on the soil. The forest floor increases water infiltration into the soil which also helps minimize erosion. The *erosion* of the surface soil can be a large source for nutrient loss in highly disturbed forests (i.e., the canopy

Sidebar 6.1

Biological Nitrogen Fixation

A unique source of nitrogen input to terrestrial ecosystems is biological fixation of nitrogen. It is ironic that many forests are limited by nitrogen, despite the chemical composition of the atmosphere, which is 70 percent nitrogen. However, there are a small number of free-living organisms and organisms that have evolved a symbiotic relationship that can convert atmospheric nitrogen into an organic form of nitrogen that can be used by the plant or organism. There are two types of biological nitrogen fixation: symbiotic or asymbiotic fixation. *Symbiotic fixation* involves a mutualistic relationship between a plant and, often, a bacteria. Examples of symbiotic nitrogen fixation include the agriculture crop, alfalfa, and the bacteria *Rhizobium;* or black locust, a common early successional tree species in the southeastern United States, and the bacteria *Rhizobium.* Some of the highest biological nitrogen fixation rates, ranging from 100 to 300 kgN ha^{-1} yr^{-1}, have been reported for the tree species red alder (*Alnus rubra*) and the actinomycete, *Frankia,* in the Pacific Northwest. Shrubs such as *Ceanothus* in the western United States and alder in the boreal forest can also fix nitrogen. There are also many ground and tree dwelling lichens that are capable of biological nitrogen fixation. *Asymbiotic nitrogen* fixation involves only free-living microorganisms, and the rates of nitrogen fixation are much smaller than those for symbiotic nitrogen fixation. Typical rates of asymbiotic nitrogen fixation range from 5-10 kg N ha^{-1} yr^{-1}.

and/or forest floor are removed) because a large percentage of the total nutrient content of the soil is in the upper soil horizons.

Nutrient leaching below the rooting zone is a second potential pathway of nutrient loss. Nutrient leaching is detrimental because it is a permanent loss of nutrients from the soil and decreases the water quality of adjacent aquatic ecosystems. The leaching of nitrate (NO_3^-) is a common concern in agricultural ecosystems. Nitrate is derived from animal waste and excessive use of nitrogen fertilizer, and is a serious health concern. Ironically, nitrate leachate levels can exceed government standards in some natural forest ecosystems that are dominated by nitrogen-fixing trees, such as red alder. A more detailed discussion of the effects of timber harvesting on nutrient leaching is provided later in this chapter. Measurement and modeling the leaching of nutrients in forested watersheds requires a biological understanding of the cycling of nutrients and the flow of water in the soils (see Forest Hydrology, in Chapter 16).

Volatilization is the conversion of an element from the ionic form to a gas that is subsequently lost to the atmosphere. Volatilization of nutrients occurs during wildfires when the temperatures exceed the threshold for an element. Denitrification is a process similar to volatilization in that an ionic form of nitrogen is converted to a gas, but the mechanisms and environmental conditions necessary for denitrification to occur are very different. Chemoautotrophic bacteria, or soil microorganisms that derive their energy from breaking chemical bonds, are responsible for denitrification. These bacteria require anaerobic conditions and an abundant source of nitrogen. These conditions are not common in most upland forest soils, but can be important in fertile lowland soils. Denitrification is the source of large nitrogen losses in cattle and pig feedlots, because the soils are typically poorly drained and nitrogen is abundant from urine and feces. A complete treatment of the factors controlling nutrient losses in harvested forests, and the potential implications for sustainable forest management, are discussed later in the chapter.

Nutrient Transfers Within Forest Ecosystems

Nutrients intercepted by the forest canopy are either absorbed by the vegetation, drip from the canopy to the soil surface (*throughfall*), or flow down the stem (*stemflow*) (Figure 6.9). Nutrients entering the soil follow one of several pathways. Nutrients are either stored on the exchange sites of the soil, absorbed by the roots and mycorrhizae and reused by the vegetation, temporarily immobilized by soil microorganisms, which require nutrients similar to vegetation, or lost. Nutrients taken up by the vegetation are stored in the perennial tissue of the vegetation or returned to the soil surface at the end of the growing season as detritus, primarily as leaf litterfall or fine root turnover. Nutrients return to the soil as litterfall or fine root turnover (Figure 6.9). Decomposition of the organic matter releases the nutrients, completing the nutrient cycle. The amount of nutrients returned to the soil each year varies among and within the major forest biomes, but in general litterfall nutrient content decreases from tropical forests to boreal forests (5).

The mean residence time of nutrients is calculated as the total nutrient content of the compartment divided by the sum of all the inputs to an ecosystem compartment. For example, the mean residence time of nutrients in the forest floor is calculated as the nutrient content of the forest floor divided by the sum of nutrient content of litterfall (leaves and woody tissues) and fine root turnover. The nutrient residence time is a useful index of the rate that organic matter or nutrients cycle through a forest. In general, nutrient availability is inversely proportional to mean residence time. What factors influence the residence time of nutrients in forests? Warm moist climates stimulate the activity of soil microorganisms that decompose litterfall, while cold, dry climates restrict the activity of decomposers. Consequently, the organic matter and nutrient content of the forest floor is lowest in the tropical forests and highest for boreal forests (Figure 6.11). It should be of little surprise then that

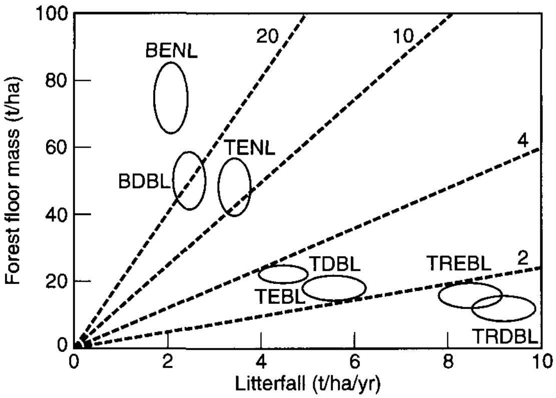

Figure 6.11 A generalized relationship for organic matter or nutrient content in the forest floor and annual litterfall organic matter or nutrient content. The mean residence times for the organic matter and nutrients in the forest floor, depicted by the dashed lines, illustrate that the time it takes for organic matter and nutrients to decompose and mineralize decreases in the order of boreal forests > temperate forests > tropical forests. The abbreviations are as follows: BENL = boreal evergreen needle-leaf; BDBL = boreal deciduous broad-leaf; TENL = temperate evergreen needle-leaf; TEBL = temperate evergreen broad-leaf; TDBL = temperate deciduous broad-leaf; TREBL = tropical evergreen broad-leaf; and TRDBL = tropical deciduous broad-leaf. The figure was adapted from organic matter data summarized by Landsberg and Gower (5).

organic matter and nutrient residence times are shortest for tropical forests, intermediate for temperate forests, and longest for boreal forests (Figure 6.11).

Forest Succession

Succession is the continuous change in the species composition, structure, and function of a forest through time following disturbance. The early stage of succession is referred to as a *successional sere.* The final stage or sere of succession, which is generally self-replacing, is referred to as the *climax sere.* There are two major types of succession: primary and secondary. Primary succession is the establishment of vegetation on bare rocks or severely disturbed soil. Secondary succession is the reestablishment of vegetation following a disturbance that killed or removed the vegetation but did not greatly affect the soil. Volcanic eruptions, retreating glaciers and colonization of bare sand dunes are examples of primary succession, while clearcutting of forests, wildfires, and hurricanes are examples of secondary succession. Hundreds to thousands of years are required for primary succession to reach climax, compared to decades to hundreds of years for secondary succession. The longer time to reach the climax sere for primary than secondary succession is because soil development must take place in primary succession. The rate of succession is dependent upon the severity of the disturbance, and the availability of seeds for recolonization. Tree species that have small, light seeds that are dispersed by wind or transported by animals recolonize a disturbed area quicker than a species with large seeds.

What morphological and ecophysiological characteristics determine the species composition and abundance in succession? In general, nitrogen fixing plants are important early succession species in primary succession because nitrogen is not derived from weathering, and little or no soil organic matter is present. Ruderals are common early successional species because of their rapid growth rates, while stress-tolerant species are common late successional species.

The structure of a forest changes during succession as well (5). Depending upon the type and severity of the disturbance, a moderate to large amount of dead organic matter from the previous forest remains on the site immediately after disturbance. The leaf area of the forest is at a minimum and slowly increases as new vegetation occupies the site. Following a stand-reinitiating disturbance, such as a blow-down or fire, the new canopy is largely composed of similar-aged, or even-aged, trees. Light, nutrient and water availability are highest during the early successional sere because the vegetation has not completely occupied the site. Canopy closure, or maximum leaf area can occur within several years after disturbance in some tropical forests, but may take 3 to 50 years in boreal forests.

The second stage of stand development is referred to as the stem exclusion stage because of the tree mortality caused by competition for light, nutrients, and water. The intense intraspecies (within a species) and inter-species (between species) competition for light, nutrient and water induces mortality of plants that are shaded or have one or more life history characteristics that are not well-adapted to the changing environment. The third stage of stand development, referred to as understory reinitiation, is characterized by openings in the overstory canopy, caused by tree mortality, and the renewed growth of understory and suppressed sub-story trees in response to increased light reaching the forest floor. Consequently, the forest canopy becomes more complex, or multilayered. The final stage of stand development, climax or old-growth stage, is characterized by a species composition that in theory will continue to replace itself until a catastrophic disturbance takes place. Unique characteristics of old-growth forests include the largest accumulation of standing and fallen dead trees—referred to as coarse woody debris. Also, the annual input of litter is dominated by coarse woody debris compared to the earlier stages of stand development where leaf and fine root detritus were the dominant sources of nutrient and organic matter input to the soil.

Some vegetation ecosystems may never reach the latter stages of succession if natural disturbances (fire, flooding, hurricanes, etc.) are frequent. A pyric climax refers to an ecosystem that never reaches the potential climax vegetation defined by climate because of frequent fires. The ecotone, or boundary, between grasslands and forests is a *pyric climax,* and only with fire suppression have woodlands and forest begun to advance into these regions.

Effects of Timber Harvesting on Forest Ecosystems

The effects of timber harvesting on the long-term site productivity of forests are of great interest to land mangers and the general public. The issues surrounding timber harvesting and sustainability have many facets: deleterious effects on the physical properties of forest soils, altered microclimate, increased nutrient leaching loss, and excessive nutrient removal in the biomass. The effects of forest management on wildlife is beyond the scope of this chapter, but is discussed in Chapter 14.

Maintaining the physical properties of forest soils is essential for sustainable forest management. Increased bulk density can restrict fine root growth, thereby decreasing water and nutrient availability to trees. The use of heavy equipment for harvesting or site preparation is primarily responsible for soil compaction. Soil compaction can often be avoided or minimized by restricting heavy equipment to designated areas (logging trails and deck), the use of high flotation tires, hi-lead cable logging, or helicopter logging. Harvesting wet areas when the soil is frozen is also a management option in cold temperate boreal forests.

A second form of physical abuse of the soil is soil displacement. Soil displacement can take on several different forms, but all are deleterious to the soil. Operating heavy equipment on wet soils often results in long-term damage to the soil structure, which reduces water infiltration and water available for plant uptake. Decreased water infiltration increases overland flow and the likelihood of severe erosion. Soil displacement can also occur during site preparation if the operator of the equipment is not careful to minimize disturbance of the forest floor and upper soil horizons. The debris remaining from the harvesting is often pushed into long rows referred to as *windrows.* Significant removal of the forest floor and mineral soil to the windrows drastically decreases nutrients in the field except for where the windrows occur (Figure 6.4).

The removal of the forest canopy in some harsh climates, such as hot and dry forests, sufficiently changes the microclimate to restrict adequate regeneration. Greater extremes in temperature occur in clearcut than control forests, and even greater extremes occur in forests that are burned because the black surface decreases the albedo[2] (Figure 6.12). Small changes in the microclimate maybe insignificant for many forests, but the changes may be deleterious for hot, drought-prone forests such as those found in the Rocky Mountains and eastern slopes of the Cascades in the western United States.

Much of the discussions surrounding the potential adverse effects of timber harvesting have focused on nutrient leaching losses following harvesting and nutrient removal. Nutrient leaching is the loss of nutrients, in solution, below the rooting zone. Recall from Chapter 5 (Forest Soils) most temperate forests soils lack an anion exchange capacity, meaning that unless plants or soil microorganisms take up anions (e.g., NO_3^-, Cl^-, HCO_3^-, HSO_4^-), the anions in the soil will be leached if there is sufficient water draining below the tree roots. A cation of similar charge to the anion will also be leached because electroneutrality must be maintained. Nutrient leaching decreases the amount of nutrients available for plant uptake and decreases water quality in the groundwater or adjacent aquatic ecosystems.

Concern for the potential nutrient leaching associated with timber harvesting gained worldwide attention with the Hubbard Brook study by Likens, et al. (9). The Hubbard Brook watershed experiment involved a control (uncut) and a clearcut plus herbicide-treated watershed. The objective of the study was to better understand the natural mechanisms in a forest ecosystem that controls nutrient cycling, including nitrate leaching. To do this, the investigators removed the hypothesized primary mechanism that prevents nutrient leaching—plant uptake of nutrients. It is important to note that the objective of this experiment was not to simulate a typical forest harvest. The removal of the trees (harvest) and continued suppression of vegetation re-growth (herbicide treatment) allowed decomposition and nutrient mineralization to occur, but there were few plants to take up the mineralized nutrients. Eventually the microbial demand for nutrients was exceeded and large nutrient leaching losses occurred (Figure 6.13).

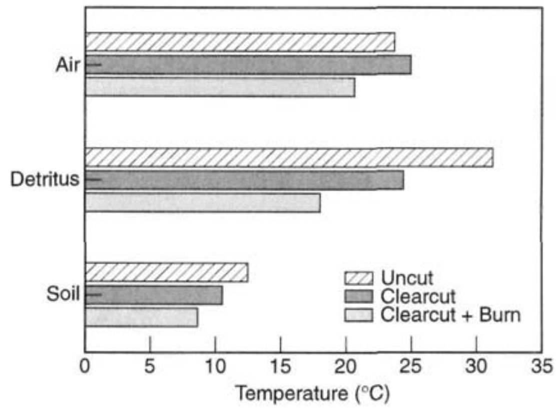

Figure 6.12 Comparison of the temperature of the air 10 cm above the forest floor surface, the forest floor, and mineral soil at a 10 cm depth for an uncut, clearcut, and clearcut and burned forest.

How representative are the results in the Hubbard Brook study to normal forest harvesting practices? This was a question asked by both foresters and environmentalists alike after the Hubbard Brook results were published. Control and harvested paired watershed studies were conducted in the United States to quantify potential nutrient leaching losses and to better understand the mechanisms that govern nutrient leaching losses. A wide range of nutrient leaching losses were observed by Vitousek, et al. (10). Nutrient leaching losses were insignificant in some forests, but exceeded 50-100 kg N ha^{-1} yr^{-1} for other forests (Figure 6.14). In general, high nitrogen leaching losses occurred in

[2] The ratio of light reflected to that received.

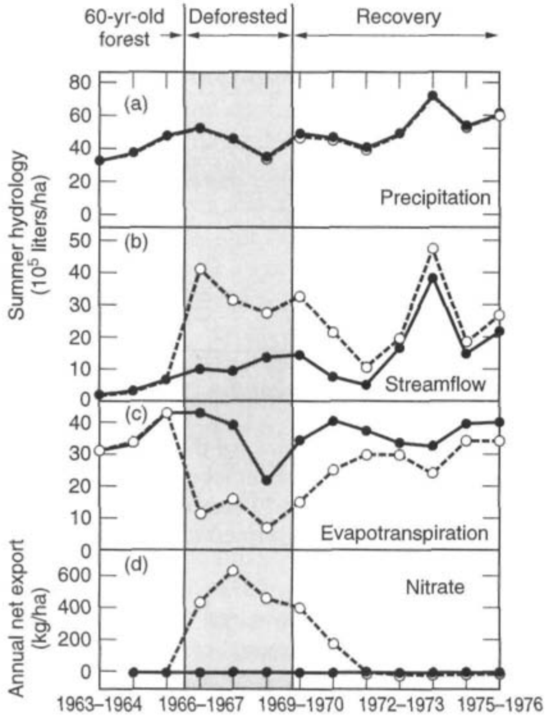

Figure 6.13 Comparison of the nutrient leaching losses from the uncut control (solid line) and harvested + herbicide (dashed line) forest. Copyright permission provided by Springer-Verlag (9).

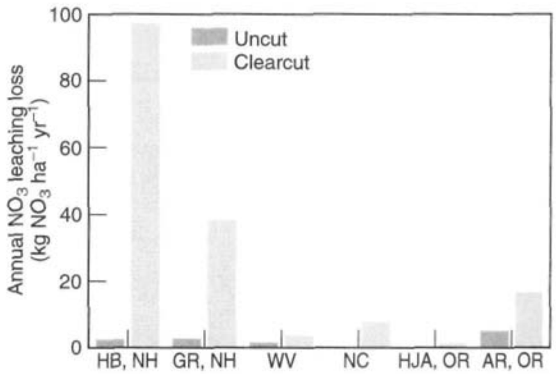

Figure 6.14 Comparison of annual nitrate leaching losses for paired control and clearcut watersheds. Abbreviations for the sites are as follows: HB, NH is Hubbard Brook, New Hampshire; GR, NH is Green River, New Hampshire; WV is West Virginia; NC is Coweeta Hydrologic Laboratory, North Carolina; HJA, OR is the H.J. Andrews Experimental Forest, Oregon; and AR, OR is Oregon. Figure was prepared from data presented in Vitousek, et al. (10).

forests that had large nitrogen mineralization rates or experienced chronic atmospheric nitrogen deposition. Conversely, forests with low nitrogen mineralization rates or small nitrogen deposition rates experienced small to non-significant nitrogen leaching losses in the clearcut forest.

Concluding Statement

Sustainable forest ecosystem management requires a fundamental understanding of the principles of forest management and forest ecosystem ecology. I hope this chapter has provided the reader a better appreciation of the challenges of forest ecosystem ecology—a discipline in ecology that draws upon ecophysiology, soil science, micrometeorology, and hydrology. Although, conceptual understanding of forest ecosystem ecology is required, all too often, economical, political, or social issues take precedence over ecological principles. These situations often result in mismanagement and deleterious effects to the forest. This chapter attempted to illustrate the interconnection of the water, nutrient, and carbon cycles, and how alteration of a process in one of the cycles, resulting from natural of human disturbance, affects the structure and function of the forest.

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CHAPTER 7

Landscape Ecology

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Introduction

Ecologists recognized early the effect of the surrounding landscape on a given ecosystem. For example, a pond located within a forest will have very different ecological characteristics from a pond located among agricultural fields, even if both ponds are of the same size and depth. The forest pond is likely to be cooler because of the shade from nearby trees, and the surrounding forests provide habitat for amphibians that will lay their eggs in it. The agricultural field pond is likely to contain more nutrients from fertilizer runoff, and may be a stopover site for waterfowl during migration. These two examples illustrate how landscape patterns affect organisms (1).

However, not only do landscape patterns affect organisms, but organisms can also create certain landscape patterns. For instance, beaver create ponds in forests by building dams on creeks or small rivers. Trees that are flooded die, and beaver cut down more trees for food, thus opening the forest canopy. Once their food supply is depleted, the beaver abandon their pond, their dam breaks down and an open, nutrient-rich wet meadow remains that will gradually be recolonized by trees. Landscape ecologists study both the effects of landscape patterns and the processes that create them (2-4). The aim of this chapter is to provide an introduction to the science of landscape ecology and its application to forest management.

Definition and History

Ecology is the study of relationships between organisms and their environment. Landscape ecology is the subdiscipline of ecology that focuses on spatial relationships usually over broad areas or "landscapes" (2-4).

The importance of examining ecological relationships across landscapes was recognized in the early 20th century. Carl Troll, a German geographer, coined the term *landscape ecology* in 1939 after he had studied aerial photographs of various landscapes around the globe. Aldo Leopold, an American wildlife ecologist, noted the importance of landscape patterns for game animal populations in 1933, and Alexander Watt, an English botanist, studied the relationships between patterns and processes in plant communities in 1947 (4).

Despite these early roots, landscape ecology did not gain widespread recognition in North America until the 1980s. The increasing availability of computerized spatial data (e.g., satellite images, soil maps, forest inventories) and computer programs that have the ability to analyze mapped information (e.g., Geographical Information Systems or GIS), fostered new research and applications (5). At the beginning of the 21st century, landscape ecology has become a well-established scientific discipline, and an increasingly important aspect of forest management.

Landscape Patterns and How They Are Generated

In the previous sections, we introduced the concept of landscape patterns and landscape processes. In this section, we will examine various forms of characteristic landscape patterns, and discuss how they originate. The different types of processes that cause landscape patterns are the organizing principle for this section.

Effects of Topography, Surface Geology, and Geomorphological Processes on Landscape Patterns

One of the most basic causes of landscape patterns is topography. Alpine tundra, for example, occurs in the Rocky Mountains only at the highest elevations. A map of alpine tundra therefore shows only relatively small patches of tundra that are isolated from each other (Figure 7.1).

Surface geology has a strong effect on soils as parent material and thereby on the distribution of different types of forest patches. A good example of this effect exists in northern Wisconsin, a landscape that was glaciated until about 10,000 years ago. When the glaciers retreated north, the features they left were large sandy outwash plains, moraines, and former lakebeds. Jack pine is a tree species that is well adapted to sandy soils, and the outwash plains are the only places in Wisconsin where jack pine is common, whereas the moraines, with heavier, loamy soils, are dominated by hardwoods and hemlock.

Geomorphological processes that shape landscape patterns include landslides, erosion, sand dune development, and pattern formation over permafrost. We will discuss here only one process, the fluvial dynamics that are typical of meandering

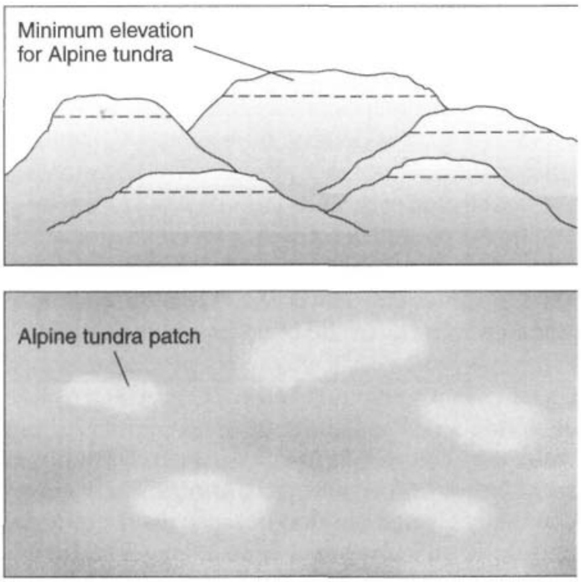

Figure 7.1 Panoramic view of a mountain range with alpine tundra at highest elevations, and a corresponding map with isolated patches of alpine tundra.

Sidebar 7.1

Key Concepts

Several concepts and terms are central to landscape ecology. The first of these are *patch* and *matrix.* A patch is a reasonably homogeneous area identifiable within a landscape. Patches are often delineated based on their vegetation. Patches are embedded in the landscape matrix (1). For example, in a forested landscape with scattered, small bogs, the bogs can be regarded as patches, whereas the forest forms the matrix.

The second important concept is the relationship of *landscape patterns* and *landscape processes* (2). The spatial arrangement of patches and matrix forms the landscape patterns of a given area. Landscape processes are dynamic processes that operate over large areas. An example of a landscape process is forest fire. In boreal forests, fires occur naturally and one fire can cover a very large area (10,000 to 100,000 hectares). After a fire, the forests regenerate and form very large patches of even-aged trees (3).

The third important issue is that of *landscape scale,* which is defined by landscape *grain* and *extent* (4). The landscape grain is the smallest spatial unit of a landscape or map representation, also termed the *resolution.* The size of the smallest patches usually determines the landscape grain. The landscape extent comprises the entire area within the boundaries of a landscape.

Scale is also very important conceptually. Different landscape processes occur at a certain scales, and need to be studied at their appropriate scale (1). For example, fires in the boreal forest operate at a very broad scale, and one has to analyze several 100,000 hectares at once to capture the dynamics of these large fire dynamics. Forest management, on the other hand, operates at a smaller scale, and a study area that captures several thousand hectares will usually be sufficient to study the effects of different forest management activities on landscape patterns (3).

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rivers (see Figure 7.2a in color insert). These rivers are characterized by numerous curves. These curves constantly change position because rivers erode the outside of the curves and deposit gravel and sands on the inside of the curve. When the river course forms the shape of a horseshoe, it may eventually break through, leaving an oxbow lake. Such oxbows can persist as open water bodies for quite a while, but will gradually fill in, first with aquatic vegetation, and later with shrubs and trees. The shapes of the oxbows, however, remain, and form a very characteristic landscape pattern.

Effects of Natural Disturbance Processes on Landscape Patterns

The previous examples described how geological and geomorphological processes affect landscape pattern. One may not think of mountain ranges as a process, but underlying their development are plate tectonics and erosional forces that operate over millions of years. Glacial landscapes are shaped by 10,000-100,000 year cycles of glaciation, and rivers change their paths over centuries or decades. In contrast, the landscape processes that we focus on in this section operate at much shorter time scales. These processes are collectively referred to as "disturbances" or "disturbance regimes," because they alter the vegetation rather abruptly (6). However, the term "disturbance" is somewhat misleading because it implies that the disturbance process is not part of the natural ecosystem. On the contrary, disturbances are inherent parts of many ecoystems and are forces that often create characteristic landscape patterns and cyclic alterations in ecosystems.

A typical disturbance that was previously mentioned is fire in boreal forests (7). The boreal forest zone occurs in the Northern Hemisphere across Canada, Alaska, Siberia, and Scandinavia and reaches to the treeline, the northernmost extent where trees can grow. Fires are a natural part of the boreal forest ecoystem; they are necessary to initiate forest regeneration, and they create important habitat for many wildlife species. A single fire may last only a few days or weeks, and may cover hundreds, up to more than 100,000 hectares. The vegetation type in these landscapes depends on the time since the last fire. Recently burned patches are open, and contain only grasses and shrubs. Tree regeneration, especially by aspen and pine, soon follows, and even-aged young forests characterize a patch 20-30 years after a fire. As more time passes, the forests of the patch grow older until a new fire occurs. Fires are fairly frequent in the boreal zone, and most forests burn on average about every 100 years. The landscape pattern that is typical of boreal forests is a very large mosaic of large patches (see Figure 13.2). This landscape pattern is called a "shifting mosaic," because the landscape always exhibits a mosaic of patches of different ages, but their location shifts over time.

Quite different landscape patterns result from hurricanes, tornadoes and other winds. Wind damage to forests can also be fairly extensive, but does not typically reach a contiguous extent comparable to boreal forest fires. Wind disturbance patches occur in very variable shapes. For example, tornadoes may cause narrow, elongated patches of windthrow, and hurricanes may cause damage across a much larger area, with very variable effects. Another unique aspect of wind disturbance is that it can blow down all or only a portion of the trees in an area. Forests that are particularly prone to wind damage include tropical forests in the Carribean, Central America, and the forests in the southeastern United States, because of the higher likelihood of hurricanes in these regions. Windthrow that can have extensive damage also occurs in north temperate regions, such as central North America, that are affected by large low pressure storms and thunderstorms. However, the frequency of wind damage even in these regions is generally much lower than the frequency of fires in the boreal zone.

The different disturbance processes of boreal and Central American forest landscapes result in a much smaller grain for the Central American forest landscape compared with the boreal landscape. An even smaller grain is typical of some temperate forests, such as the eastern United States, or tropical rain forest in Amazonia, that typically experience fire and wind damage less frequently than the regions mentioned earlier. The dominant landscape patterns of these forests are often the result of single tree gaps, caused by the death of an old tree with a large crown. Such gaps are usually not larger than 0.1 ha. An interesting case of gap disturbance is the European beech forest ecosystem. Gaps in beech forests are often 1-2 ha in size and elongated in a north-to-south direction. The reason for this is that mature beech trees often die after a few years when their trunk is exposed to sunlight. Once a single old beech tree dies, the trunks of its neighbors to the north are exposed to sunlight, and their death causes the northward expansion of the gap.

Effects of Animals on Landscape Patterns

Physical processes, such as wind, fire, and sunlight are powerful forces that shape the landscape pattern of many ecosystems, but animals also leave their mark in the landscape (1). We will again present three examples of processes that create distinctive landscape pattern, all of them being related to animal activities.

Forest insects can shape forest landscapes at large scales (8). Outbreaks of defoliating insects can occur simultaneously over many hundreds of thousands of hectares. One result of these outbreaks is that the tree species composition in the landscape is changed. For example, a spruce budworm outbreak in boreal forests will kill mainly fir and spruce thereby giving hardwoods such as aspen a competitive advantage. Spruce budworm outbreaks can also increase fire fuel loads by leaving large areas of dead trees, which may make fires more intense and/or likely.

We briefly mentioned the effect of beaver on landscape patterns in stream valleys. Beaver create dams along creeks where trees, especially young hardwood trees, are common. They maintain their dam over many years until food sources in the vicinity are depleted. Sediments accumulate on the bottom of their ponds during this period. Once a dam is abandoned, it will eventually break, thus draining the pond. What remains are nutrient-rich sediments that quickly revegetate, first by grasses and forbs, and later by tree species such as aspen. Once a new forest has formed the cycle may start again with the establishment of a new beaver dam.

Our last example for the effects of animal activity on landscape patterns is certainly not a disturbance. Jays are birds that feed on acorns among other things. One aspect of their feeding behavior is that they carry acorns, sometimes over several kilometers, and bury them in the ground. They do not recover all of these buried acorns, and some of them will germinate. This makes jays very effective seed dispersers (Figure 7.3). Trees with heavy seeds, such as acorns, are otherwise limited in that their seeds cannot travel far from the parent tree. However, activities by jays may ensure that oaks can spread relatively quickly into areas where they do not occur. This is an important advantage after a disturbance such as fire has killed the canopy across a large area. At larger spatial and temporal scales, after glaciations, seed dispersal capability determines how quickly tree species can follow the retreating glaciers and migrate northwards. The activity of jays and other seed dispersers is one of the major processes that shape the spatial pattern of plant occurrence.

Effects of Human Activities on Landscape Patterns

All the processes described above have shaped landscape patterns for many millions of years, but during the last few thousand years, human activities have increasingly affected landscape pattern. It is important to note that humans have altered the landscape for a long time. For example, indigenous peoples in Australia and North America set fires in forests and grasslands to promote young regrowth, and thus provide better habitat for the animals they hunted. However, the impact of human activities has greatly increased with the advent of agriculture, cities, the industrial revolution, and growing world population and resource use in the 20th century.

One of the most distinct patterns of landscapes is the pattern of human settlements. These patterns are particularly striking when forested areas are being settled and often follow the patterns of transportation networks and legal boundaries. For example, in the Amazonian province of Rondonia (Brazil), roads are the most important means of transportation (see Figure 7.2b in color insert). Major roads form the backbone of what has been called "fishbone patterns." Early settlers clear land adjacent to the major roads, but soon numerous minor roads develop that run perpendicularly to the major roads. Farmers continue to clear land in the vicinity of the minor roads thus leaving only small strips of forest in the middle between them. This process of breaking up the intact forest is called *forest fragmentation,* which encompasses both the loss of the majority of the forest and a resulting pattern where forests occur only in small patches that are isolated (9). Forest fragmentation by settlement has occurred in many parts of the world over time. Most recently, it has occurred during the last 300 years in areas that were colonized by European immigrants such as the eastern United

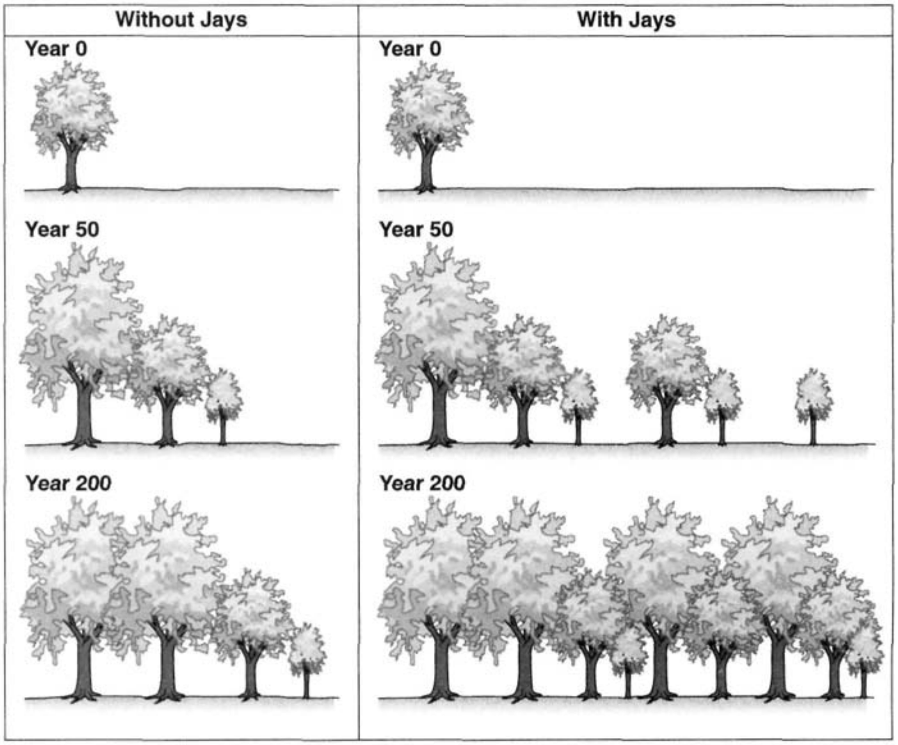


Figure 7.3 Diagram of oak encroachment with short-range seed dispersal caused by wind and squirrels (on the left) and long-range seed dispersal by jays (on the right).

States, Western Australia, and in tropical regions with rapidly growing populations.

Even where forests remain, human management will often have a strong influence on their patterns. Forest harvesting—especially clearcutting—creates very distinct landscape patterns (10-13). The actual pattern will depend on three factors, the size of the dearcuts, the rotation length (i.e., how often each forest is harvested), and how cutting units are allocated across the landscape spatially.

Both management objectives and legal restrictions determine the size of clearcuts. For instance, the state of Baden-Württemberg in Germany allows clearcuts no larger than 1 ha. Currently, the National Forests in the United States observe a 16 ha limit, whereas some clearcuts in Canada can occupy hundreds of hectares. Clearcut size will also vary with topography, usually being larger in flat terrain, and depending on the tree species and purpose of forest management.

Rotation length determines how much of the landscape is open at any given point in time. For instance, a rotation length of 50 years translates into 20 percent of the landscape area being younger than 10 years and thus probably not containing a closed forest canopy. A rotation length of 100 years reduces the area of open patches to 10 percent of the landscape area.

The allocation of clearcuts also has a strong effect on landscape patterns. In the recent past, the most common management practice in the United States has been to disperse clearcuts as much as possible. The result is a pattern characterized by many small, open patches with narrow stands of intervening forest, creating a highly fragmented matrix (Figure 7.4). A very different approach is to allocate new clearcuts in the vicinity of previous harvests. This creates larger openings, but it also leaves large areas of continuous and undisturbed forest, and regenerates large, future patches of forest.

Subtler patterns that humans impose on landscapes are the road networks (14). Forests can be fragmented even without any forest cutting, because roads form barriers to movement of some animals. It is obvious that major highways have a strong effect even on large mammals. Highways not only cause wildlife accidents and deaths, they can also prevent migration between areas, leading to the isolation of populations and a higher potential for local extinctions (9). However, even small roads impair the movements of insects, small mammals and amphibians (15). In experiments, pedestrian beetles only once crossed a six-meter-wide, two-lane road and even single-lane roads were only rarely successfully crossed (Figure 7.5). The main reason is that the gravel makes it very easy for predators to spot their prey. This finding demonstrates that even small, rarely traveled logging roads can fragment forests.

Figure 7.4 Clearcuts on U.S. National Forest land (on the left) adjacent to Yellowstone National Park (on the right). (Photo courtesy of J. Rotella, Montana State University.)

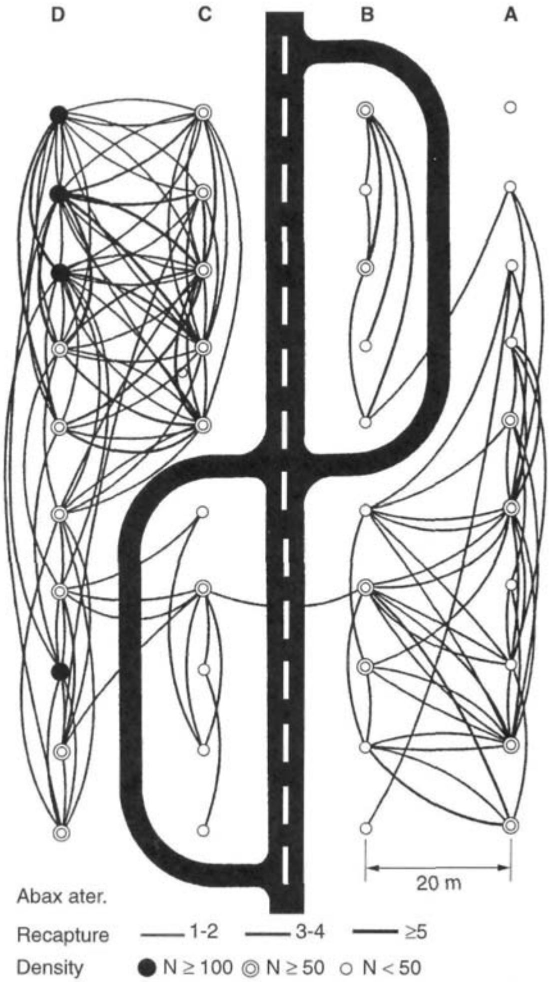


Figure 7.5 Number of beetle crossings over a major and two minor roads, A-D represent trap rows; circles represent live traps. Curved lines represent the movement of a marked beetle between capture and recapture.

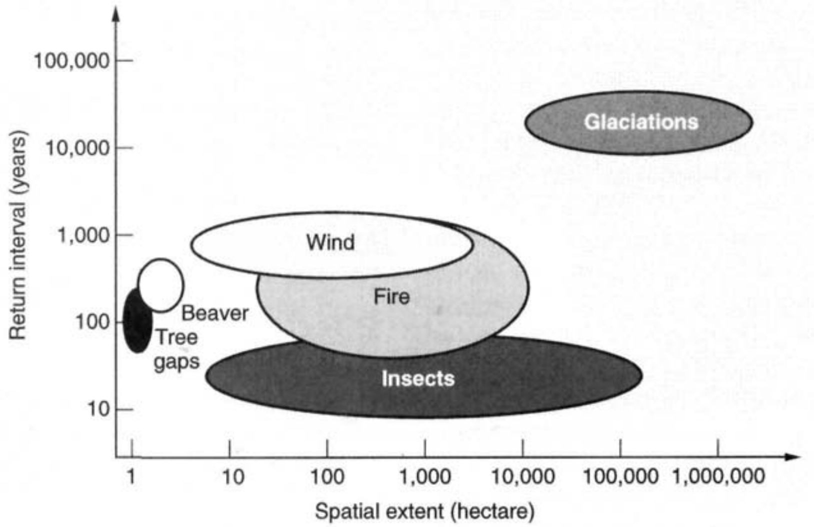
How Landscape Patterns Affect Forest Ecosystems

In the previous section, we outlined causes for different landscape patterns. In this section, we will examine how different landscape patterns affect forests. This includes not only direct effects on trees,

Sidebar 7.2

Temporal and Spatial Scales of Processes That Affect Landscape Patterns

It is useful to stratify landscape processes that alter forest landscape pattern according to two criteria; their return interval (i.e., how much time passes, on average, until a location is affected a second time by a process), and their spatial extent. These two aspects are somewhat correlated (i.e., processes that operate on smaller areas tend to occur more frequently). On the other hand, processes that affect very large areas, such as plate tectonics and glaciations have very long return intervals. However, there are notable exceptions to this rule, and they indicate how disturbance-prone a landscape is. For example, boreal forest fires extend over large areas, and occur relatively often. This indicates that boreal forests are particularly prone to disturbance.



but also on other aspects of forest ecosystems. The organizing principles of this section are the different basic patterns, first, of single patches, and second, of the arrangement of multiple patches in a landscape.

Effects of Individual Patch Size and Shape

The most obvious spatial attribute of a single patch is its size. Patch size has a strong influence on many ecological processes. For example, a large forest opening, perhaps caused by a fire or a clearcut, will often experience different natural regeneration than a small one. The reason is that the ability to invade open areas differs among plant species. Tree species such as aspen have light wind-dispersed seeds. They can disperse their seeds into the center of even a very large opening. Other species, such as maple, have seeds that are heavier. Seeds such as these are not dispersed great distances and may reach only the center of small openings, but fail to colonize the center of large openings. The result is that aspen will be more dominant in larger openings than species such as maple, even if stand history, soil conditions, and climate are the same. Also, the size of an opening will affect its microclimate. For example, wind will be less pronounced in small openings, and very small openings might be partially shaded by the adjacent forest canopy.

Patch size can also determine if a patch is suitable habitat for an animal species. For example, a pair of northern spotted owls requires a patch of at least 450 ha of continuous, mature forest to successfully raise their young. The reason is that the density of their prey is relatively low. Smaller patches do not provide the necessary amount of food. The minimum value of 450 ha increases to up to 1700 ha in areas where prey is particularly sparse. However, this value is only the habitat requirement of a single pair of spotted owls. If an owl pair is isolated from other owl pairs it is unlikely that owls will persist in that location. The forest patch size required to maintain an entire population of northern spotted owls is much larger. A strong relationship between patch size and likelihood of extinction occurs not only in owls, but in many species. The size of a patch (i.e., the total amount of suitable habitat), affects the number of species it is likely to contain. This is the first law of island biogeography: larger patches (or islands) of the same habitat type are likely to contain more species than smaller ones.

Another spatial attribute of single patches is the shape of its boundary. This can be defined by how long its perimeter is compared to its area. A circular patch has the lowest perimeter compared to its area. This value increases when patches are more elongated or have complex boundaries (Figure 7.6). Patch shape is important because the forest along the edges of a patch functions differently from the forest in the interior. For example, sunlight and wind can penetrate onto the forest floor along the edges, thereby creating a different microclimate and more favorable conditions for sun-loving tree seedlings or groundlayer plants. These plant species will have an advantage in this environment over species that compete better in total shade.

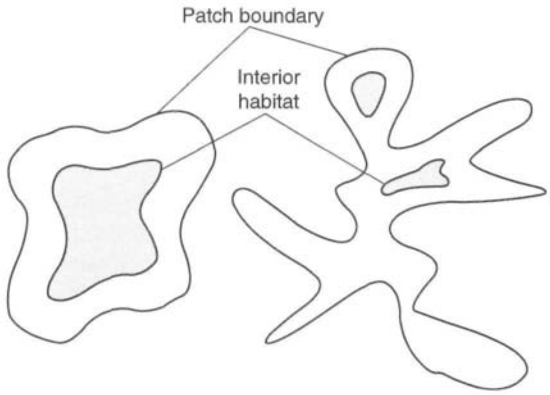


Figure 7.6 Two patches of different complexity and amount of interior habitat.

Plants or animals that survive best under intact forest are often called *interior species*, because they are usually only found in the interior of forests. Edge effects may persist up to 200-300 meter into a patch, making small woodlots often unsuitable for interior species.

Effects of Landscape Patterns

In order to understand landscape pattern fully, it is necessary to look not only at the size and shape of single patches, but also at the spatial arrangement of multiple patches on a landscape. Distances between patches or connectivity are an important attribute of patches of the same type. For example, amphibians that live in forests may be able to traverse agricultural fields up to 300 meters, and thus colonize forest patches that are less than 300 meters apart. This means that a forest patch that is devoid of amphibians is only likely to be recolonized if it is less than 300 meters away from the next forest patch. The maximum distance for recolonization varies among different species. It may be very small for ground beetles, and much larger for wide-ranging mammals or birds. The result of this pattern is that the further a forest patch is from another forest, the fewer species it is likely to contain. This is the second law of island biogeography. The combination of the first law (island size), and the second law (distance to mainland) can be used to calculate a rough estimate about the likely biodiversity (i.e., the number of species) of an island or an isolated forest patch. However, the actual number of species in a given patch is not only affected by patch size and distance to the next patch, but also by habitat heterogeneity and disturbance history, among other factors.

Most landscapes contain not only one type of patch but many. Forest landscapes are commonly a mosaic of patches of old-growth, maturing and regenerating forest, wetlands, lakes, and other vegetation types. Such landscapes exhibit a high diversity of patch or ecosystem types, exhibiting landscape heterogeneity. A diverse landscape usually provides habitat for more species than a landscape that is composed of only one vegetation type. However, biodiversity alone is not necessarily a good indicator for assessing landscapes or quantifying management effects. For example, in a region of largely young, managed forests, a large continuous block of forest may contain relatively few, but regionally rare or even endangered forest interior species. Fragmentation of this block may cause the extinction of these species in this area (9). However, the biodiversity of this area may increase at the same time, because habitat for common, open habitat species was created. Thus, it should not be a management goal to maximize biodiversity for a given forest stand, but to ensure that viable populations of all species are maintained in the landscape.

A heterogeneous landscape will also respond differently to disturbance. For example, wetlands and lakes are natural firebreaks that will limit the size of a burn. Furthermore, these areas can be important refuges during fires, where some mature trees can survive and provide seed sources for tree regeneration on the burned upland patch. A landscape that contains many wetlands will therefore regenerate differently after fires than one that contains only upland forest.

Forest management that regenerates only a limited number of tree species and age classes can reduce landscape diversity in terms of tree species. Such management can have unexpected consequences because landscapes are complex systems, and reducing this complexity may make them less resilient to stressors. For example, insect defoliation is often more intense when tree species diversity across the landscape is low. This is because insects disperse during an outbreak into areas that are not yet infested. A landscape that is homogeneous, where host species are abundant, may result in a more rapid spread of a disturbance. In this case a high percentage of insect dispersal attempts are successful, which means that the number of insects on each tree is higher, and tree mortality may increase.

Interactions Between Landscape Patterns and Processes

In the previous sections, we discussed the origin and effects of landscape patterns. Our examples described comparatively simple one-way relationships; we discussed how a process creates a landscape pattern or how a pattern affects a process. In reality, much more complex relationships are common. This section will provide examples of feedbacks and indirect relationships that can be important but difficult to predict.

We will return in our first example of complex interactions between pattern and process to the effects of human settlements. In the European Alps, most settlements, agricultural fields and roads are located in the valley bottoms. These valley bottoms were historically the wintering grounds for red deer. Because of habitat alterations and human disturbance, red deer today remain in the forests at higher elevations during winter. Food availability is limited in these forests, and hunters often provide supplemental forage to prevent a reduction of the deer herd from starvation. High deer densities in the forest result in widespread damage to tree regeneration, both by browsing tree buds, and by peeling of the bark. This damage severely limits the regeneration of many alpine forests and threatens human settlements because forests are an important protection from avalanches. Many alpine forests have been protected from cutting for centuries to ensure that they can form a barrier against avalanches. Current landscape changes and the chain of effects described previously threaten this historic protection system and thus some of the human settlements in the European Alps themselves.

Another example of unexpected changes is related to an alteration of a landscape process. For the last half century, fires have been actively suppressed in many parts of North America, Australia, and Eurasia. This has changed many ecosystems, especially where fire was part of the natural regeneration cycle. For example, under natural conditions, ponderosa pine forests of the American West are kept open by very frequent, but low-intensity surface fires. Fire suppression altered this cycle and permitted in some areas less fire-tolerant species, such as Douglas fir, to invade ponderosa pine stands. This young Douglas fir in the understory is typically much denser than the ponderosa pine. The change in species composition and forest structure has several consequences. First, Douglas fir forests are susceptible to spruce budworm defoliation, and their outbreaks are becoming more frequent as their food source becomes more abundant in the landscape. Second, ponderosa pine seedlings are not very shade-tolerant; they can grow only under an open canopy. Dense Douglas fir prevents ponderosa pine regeneration. Third, a fire in a dense Douglas fir stand can be very intense. Ponderosa pine is adapted to light surface fires, but it cannot survive a crown fire. This means that mature ponderosa pine will disappear from the tree species mix. Once the mature trees are gone, seed sources are lacking in the landscape and the ecosystem is even less likely to revert to its original state.

Most of our examples have focused on terrestrial systems, but interactions also occur between terrestrial and aquatic systems. Our last example on complex interactions between landscape patterns and processes will address the relationship of forests and streams in the Pacific northwest. Forest management and the salmon fisheries are two major environmental issues, and these issues are widely discussed among the public and studied by scientists. What emerges is a picture of an intricate web of relationships between these two resources.

Most of the landscape in the Pacific northwest is mountainous and the forest cover is largely composed of conifers, most notably Douglas fir. The common forest harvesting practice has been to clearcut. The steep slopes are often prone to erosion once the forest cover is removed, and forest road building further increases the likelihood of landslides. This has detrimental effects on stream habitat because the silt load increases. Furthermore, water temperature rises once trees no longer shade the streams. Forest management has partly adapted to these problems, and riparian zones are often left standing during harvesting. Nevertheless, forest harvesting has been one important factor causing the decline of the salmon populations in the Pacific northwest. Other factors include commercial harvesting of salmon, and the hydroelectric power dams along the major rivers. The combined effect of all these factors is that current salmon runs represent only a fraction of their historic levels. Salmon runs comprised an important food source for many predators and scavengers, such as gulls, eagles, and bears. However, salmon not only affect the numbers of these predators along rivers, they also represent an important source for nutrient input for the forest as well as the river. Forest soils in the Pacific northwest are often limited in phosphorus, and it has been estimated that a good salmon run can result in as much as 6.7 kg/ha of phosphorus input in a forest strip of 100 meters along both sides of a stream. The effect is strongest close to the river because this is where bears leave most of the carcasses. This level of phosphorus input is comparable to the amount that is applied commercially when fertilizing evergreens. Forest harvesting thus affects not only the salmon populations, and the populations of those predators that depend on them, but also indirectly the nutrient dynamics of the forests themselves.

Methods in Landscape Ecology

The importance of landscape ecology was recognized early, but major progress has been made largely since the 1980s, when new sources of spa-

Sidebar 7.3

Critical Thresholds of Landscape Patterns

The effects of landscape pattern on process are often nonlinear, and landscape context is very important. For example, forest cutting on 10 percent of a landscape area may have very little effect if the landscape is still 90 percent forested. However, a landscape with only 10 percent forest left will change dramatically when this last 10 percent is cut.

Critical thresholds are a special case of nonlinear relationships. Systems that reach a critical threshold will change abruptly. For example, when water is heated up it does not change its properties much until reaching 100°C, at which point it starts boiling, turning to water vapor. There is growing evidence that landscapes also exhibit critical thresholds. Studies of forest fragmentation indicate that as more forest cover is cut, reducing forest cover below certain thresholds can cause landscape connectivity to break down suddenly (1). The exact percentage of forest cover at which direct connectivity is lost varies somewhat among landscapes, but usually occurs with between 20-40 percent remaining forest cover. Knowledge of critical thresholds is crucial for predicting the results of management actions, but can be difficult to ascertain. Also, thresholds will vary for different species because habitat requirements differ among them, and because they have differing abilities to cross unsuitable habitat.

Source:

1. J. A. BISSONETTE, *Wildlife and Landscape Ecology—Effects of Pattern and Scale,* Springer-Verlag, New York, 1997.

tial data, and new techniques to analyze them, became available. Other chapters in this book provide an introduction to remote sensing, and geographical information systems (GIS). We will not duplicate the material covered there, but rather outline specifically some of the applications of these tools and methods in landscape ecology (5).

Data Collection and Analysis

Landscape ecology originated with the advent of aerial photography in the 1930s, which provided the means to accurately map large areas consistently and at comparatively low costs. Aerial photography remains an important data source for landscape ecology. Its main advantage is that it provides a spatially detailed picture. Also, for many areas historical aerial photographs have been available since the 1930s. This provides an opportunity to study long-term changes. Air photos are commonly interpreted by outlining the boundaries of identifiable patches on them, either manually on paper prints, or digitally on scanned and computerized versions. This requires that the study purpose, land classification, and resolution be determined in advance of the mapping. Attributes, such as tree species composition, age, stocking density, or habitat values, are entered into the GIS database for each patch or polygon identified.

In the mid-1970s, satellite images of the earth's surface became available, and they have fundamentally changed the way we see and study very large landscapes. The main advantages of satellite images are that they 1) cover very large areas, 2) can be automatically classified by computer, 3) provide information for remote areas, and 4) permit the examination of changes where images from different dates are available for a given area.

Digital maps derived from aerial photography or satellite imagery can be analyzed in a Geographical Information System (GIS). A GIS is a computer system designed to retrieve, store, manipulate, analyze, and reproduce spatial data. This definition may sound dry, but the long list of attributes indicates that a GIS is a very powerful tool to work with all the information that was traditionally stored on paper maps. The vast amounts of data provided by satellites, the increasing abundance of widely available digital data, such as elevation models, forest inventories, ecosystem and habitat attributes, and climate measurements, and the need to analyze large areas, make GIS an essential tool for most landscape ecologists.

Landscape Indexes

The importance of landscape patterns for the functioning of forest ecosystems necessitates being able to describe them quantitatively. Numerous landscape indexes have been proposed to measure various spatial attributes of individual patches (Figure 7.6), and of entire landscapes. These landscape metrics help to predict the habitat suitability or other ecosystem properties of a given landscape, provide a framework for comparing different landscapes, and allow quantifying landscape change over time. Specific landscape metrics have been designed, for example, to measure patch area, the ratio of patch perimeter to patch area, and diversity of habitat types in a landscape, among many other spatial attributes. The following three examples illustrate the use of landscape metrics.

The *mean patch area index* is calculated as the average size of all patches. We discussed earlier that certain species require habitat to occur in patches of a certain minimum size in order to utilize it. Computing the mean patch area is a good way to compare landscape and to evaluate if habitat is clumped or dispersed.

The *mean perimeter-area ratio* estimates the shape of patches. Again, it is an average of a value that is first derived for every single patch. Among patches of equal area but different shape, circles exhibit the lowest perimeter-area ratio. Among patches of the same shape, the mean perimeter-area ratio is smaller when patches are larger. There is no upper limit of the mean perimeter-area ratio.

The *Shannon Weaver Diversity Index* cannot be calculated for single patches but only for an entire landscape. It combines an estimate of the number of different ecosystems that are present in a landscape (richness) with a measurement of how much area each ecosystem type occupies (evenness). Richness is higher where more ecosystem types occur. Evenness is highest when all ecosystems occur in equal portions in the landscape.

We will not discuss these mathematical formulas of these indexes in detail, but rather point to three excellent reviews of landscape metrics and their use (16-18). Scientists have developed dozens of landscape indexes. Specialized computer software is now available to calculate landscape metrics for any type of digital data and their use is becoming more widespread. For example, scientists investigate how animals respond to landscape pattern by correlating animal censuses with landscape indexes. Forest managers use landscape indexes to examine if their management actions alter landscape pattern drastically. Also, governments use landscape indexes as indicators of ecosystem health. Landscape indexes offer a simple, objective and cost-effective way to summarize landscape characteristics for large areas. However, the relationship between the ecological question at hand, and the landscape index in use has to be kept in mind in order to attain meaningful results.

Simulation Models

Computers provide not only the means to analyze large amounts of data and to synthesize the information using landscape indexes, they also allow the use of simulation models. Landscape simulation models are unique in that they are spatially explicit; that is, they simulate processes, such as fires or animal movements, at actual locations in a landscape (19, 20). Traditional, nonspatial, forest models included processes such as fire, but they model fire only as an event that may affect any given location with a certain likelihood. What is unique about spatial landscape models is that they can incorporate neighborhood effects. For example, a fire is much more likely to spread and burn a stand that adjoins the fire than one that is far away. Only spatially explicit models can incorporate such aspects of landscape processes.

Landscape ecology and management face a challenge, because the scale of analysis required to study landscapes usually precludes the use of experiments as a tool for scientific investigation. Landscapes are in many cases simply too large to be altered for a scientific experiment. Also, there are many cases where a landscape may be unique, such as the Florida Everglades. Experimenting with such a landscape would not only be unfeasible, but also a major risk for the survival of the ecosystem under investigation. Also, a scientific experiment traditionally requires the use of controls (i.e., similar experimental units that are not altered in the experiments) and replicates (i.e., a number of similar units in which the experiment is conducted). The use of controls and replicates is obviously not feasible when a unique landscape is studied. Furthermore, landscape processes may operate over large time scales. For example, changes in fire frequency may not translate into altered landscape patterns until many decades have passed, because natural fire regimes contain high degree of variability, and broadscale ecological processes often operate slowly.

All these factors have resulted in the extensive use of simulation models in landscape ecology. Models are used for many different purposes. Some models are fairly simple and mainly used to test scientific understanding. For example, scientists built simple models simulating forest fire and regrowth to examine which fire frequency would result in the landscape pattern observed in boreal forests. Other models incorporate many processes simultaneously and are currently being tested as tools to improve complex forest management decisions (see Figure 7.7 in color insert). The results of forest management are difficult to predict over large areas. Foresters have good tools to manage single stands, but struggle to manage landscapes as a whole. This may change by using landscape simulation models, to test, for example, the effects of different forest harvesting regimes on a landscape over a century or more. Such an approach allows predicting changes in landscape pattern that result from certain management practices. It would also allow predicting, for instance, which wildlife species may increase in the landscape and which are likely to decrease. Such information allows proactive management decisions, and might help avoid ecological problems before they arise. However, these uses of simulation models are only now being explored, and time will tell if they become a widely used tool.

Concluding Statement—Management Rules

Landscape ecology is a young subdiscipline of ecology but attention to pattern and process at the landscape scale is increasing, both in forest science and forest management. Landscape ecologists recognized early the importance of the landscape context on ecosystems. Forest managers are becoming increasingly aware that ecosystem management requires looking beyond the stand level at the entire landscape and managing for all its components. The importance of landscape patterns and processes for the management of a forest will vary for different ecosystems, but a few general rules for forest managers emerge.

The first rule is to take the landscape context into account when managing an area. Questions that are important to consider before making management decisions include: Does this management area contain unique habitat types, or key resources for certain wildlife species? How important is the management area as a corridor for animal dispersal? What is the effect of management actions on neighboring ecosystems?

The second rule is to carefully choose the spatial unit of management. Traditionally, forests were managed one stand at a time. This chapter provided numerous examples of interactions between patterns and processes in forests that operate at much larger scales. Management can take these interactions into account only when it adapts the scale of management to the scale at which the most important pattern and processes of an ecosystem occur. In mountainous areas, entire watersheds are often managed as a whole, and this appears to be a successful way to define boundaries of management units based on ecological properties.

The third rule is to use natural disturbance processes as a guideline for forest management (12,21). For example, ecosystems previously shaped by extensive crown fires may be more resilient to large clearcuts than forests that exhibit only gap dynamics. The comparison of landscape pattern in managed and unmanaged forests can assist forest managers in their harvest planning.

Landscapes are inherently complex and dynamic, and much is still to be learned about the relationships between patterns and processes. Our current understanding suggests certain changes in forest management practices. However, more research is needed, and we hope that the way we manage forested landscapes will evolve with increasing knowledge about them. Landscape scale management is challenging and not all attempts will succeed. Because of the development of tools and methods that can be applied to large spatial data sets we are better equipped today than ever before to rise to the challenge. Landscape ecology as a science, and forest management as an application of the science, will have succeeded when we find ways to integrate the utilization and the conservation of forested landscapes.

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CHAPTER 8

Forest Trees: Disease and Insect Interactions

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Like all plants, forest trees are subject to injury and disease caused by adverse environmental influences, including other organisms. They may be affected at all stages in their life cycle, from seed to mature tree. Diseases and insects produce a variety of effects and can cause losses in economic, environmental, recreational, and aesthetic values produced by the forest. *Forest pathology* and *forest entomology* involve study and management of the influences of diseases and insects, respectively, on trees, forests, and forest products. Practitioners of these biological disciplines also are interested in the effects of forest management activities on the occurrence and development of diseases and insects. In the broadest sense, forest pathology and forest entomology include study of diseases and insects affecting trees in nurseries and the landscape, as well as plantations and forests. Although not discussed here, the degradation of wood products such as lumber by microorganisms and insects often is included. Thus, forest pathology and forest entomology literature is vast. Current texts and reference books emphasize the nature of damaging agents, as well as the principles and practices that are employed in their management (1-8).

Introduction

Origins and Roles of Microorganisms and Insects in Forests

Although the destructive activities of some forest microorganisms and insects are well known and often dramatic, most are beneficial to trees and forest ecosystems. The periodic epidemic or outbreak, and even the sudden, severe, and long-lasting damage resulting from introduction of exotic organisms, are exceptions rather than the rule in forests. The vast majority of microorganisms and insects have long evolved with the tree species comprising the forests they inhabit, and only a relatively small proportion of these are capable of causing severe damage.

Many activities of microorganisms and insects are of direct benefit to plants, animals, and other organisms that comprise forest communities. As pollinators, certain insects are necessary for reproduction of some forest tree species (e.g., maples and willows). A diverse group of fungi and the feeder roots of trees form mutually beneficial symbioses called *mycorrhizae* that function in uptake of both water and nutrients (9). Both microorganisms and insects are important sources of food or substrate for similar organisms and for a vast array of wildlife, including birds and mammals. In addition, many microorganisms and insects are parasites or predators of other species that can damage forest trees. They can play a major role in suppressing pest populations and reducing the damage they cause.

Microorganisms and insects, although damaging to individual trees, also have important roles in the function of forest ecosystems and in the development of forest stands. Insects deteriorate leaves, bark, and wood, which microorganisms ultimately decompose. Fungi, in particular, are essential and unique in their ability to decompose complex substrates such as wood. This process is essential in the cycling of nutrients necessary to sustain all other life. Decomposition of killed trees also reduces accumulation of fuel in forests, and therefore decreases the risk and intensity of wildfires. As microorganisms and insects kill some trees or cause damage that leads to stem breakage or "windthrow," they provide disturbance that alters forest structure. For example, mineral soil may be exposed and a gap may open in the canopy to provide light, allowing new seedlings to become established or releasing other trees from the effects of competition. Particular pathogens and insects also can exhibit host preferences or even very narrow host specificity. As they damage certain plant species and leave others unharmed, they can influence individual species distribution and the composition of the plant community. Similarly, in removing shorter-lived or intolerant "pioneer" species, pathogens and insects may be powerful forces in driving or directing the succession of forest plant communities.

Losses Caused by Forest Tree Diseases and Insects

When they interfere with the objectives of owners and managers of forest lands, both microorganisms and insects might be considered forest "pests." Activity of forest pests can inhibit production of a diversity of benefits, including aesthetic, recreational, environmental, and economic values. Although more emphasis is being placed on noneconomic values of forests, estimates of the damage caused by forest pests usually are associated with their impact on the quality or quantity of forest products such as fiber and lumber. Indeed, development of the disciplines of forest pathology and forest entomology, and continued research in these fields, is very much motivated by the potential for reducing the tremendous economic losses caused by forest pests.

A sudden and unpredictable destruction of forest trees resulting from an event of dramatic proportions can be referred to as a *catastrophe.* Examples of catastrophic events include massive ice or windstorms, wildfires, and extensive outbreaks of insects such as the mountain pine beetle or epidemics of diseases such as chestnut blight. It has been estimated that during the 20th century, almost 300 million cubic meters of timber were destroyed during catastrophes (10). Almost half of this catastrophic loss is attributed to the activity of insects.

Less spectacular but actually more important than catastrophe, is total *growth impact,* which is a continuous and pervasive feature of forests. *Growth impact* is the result of all the various effects resulting from damaging agents, or the sum of both tree *mortality* and tree *growth loss* (10). Mortality refers simply to death from natural causes. Growth loss includes reduced rates of terminal or diameter growth, losses of accumulated growth (e.g., by decay), losses of efficiency in utilizing a site, and losses in quality.

Our knowledge of the losses caused by forest tree diseases and insects is grossly inadequate, and for lack of better figures, we continue to quote the estimates made at the time the concept of growth impact was derived in 1952, as shown in Table 8.1 (10). These estimates do, however, give some idea of the enormous annual magnitude of total growth impact. In addition, differences are apparent in the relative proportions of mortality and growth loss that are caused by diseases, insects, and other destructive agents. The growth impact resulting from diseases and insects, for example, is far greater than that resulting from fire. The majority of growth impact attributed to diseases is the result of growth loss, whereas insects cause greater losses due to mortality. More recent reports of mortality (11) and pest activity (12) confirm the enormity of losses resulting from forest tree pests, and identify the numerous and diverse diseases and insects that continue to affect the health of forest trees.

Table 8.1 Estimated Single-Year Losses Caused by Destructive Agents to Forests

Loss Factor		Total Volume Reduction*	Insects	Diseases	Fire	All Other**
Mortality						
	Growing stock	99.4	28	22	7	43
	Sawtimber	29.9	40	18	6	36
Growth loss						
	Growing stock	217.7	10	56	19	15
	Sawtimber	73.5	11	57	21	11

*Million cubic meters.

**Includes weather, animals, suppression, logging damage.

Source: Timber resources for America's future, U.S.D.A. For. Serv. Res. Rpt. 14, 1958

Diseases and Insects Affecting Forest Trees

The health of forest trees is affected by numerous factors, including diseases and insects, that subject them to stress. At any point in time, several factors may be operating concurrently, so that the general state of health of a tree may be determined by the total effect of all stresses (13). For convenience in study and understanding, however, we separate the treatment of these factors into various disciplines, such as pathology and entomology. In each of these fields of study, damage may be classified in several ways, for example, according to the causal agent, the portion of the tree affected, the process or function disrupted, or the stage of development of the tree.

The Causes of Forest Tree Diseases

Plant *disease* can be defined as: a malfunction of a metabolic process or a disturbance of normal structure of a plant, that is caused by some abiotic *agent* or biotic *pathogen,* is influenced by the environment in which they exist, and results from continuous irritation. Abiotic agents are noninfectious and nonparasitic; biotic pathogens (e.g., a bacterium or fungus) usually are infectious and parasitic. *Injury,* as opposed to disease, also may impair vital functions or disrupt the normal structure, but it is caused by an agent such as fire, insects, or animals that affects the plant only once, briefly, or intermittently, and the irritation is discontinuous or temporary. *Damage* is sometimes used as a synonym for injury, but it usually connotes a decrease in quantity or quality of a product that decreases its economic value. A reaction (often visible) of the plant to disease is called a *symptom,* and any structure of the pathogen on or in the affected plant is called a *sign.* Symptoms and signs are used to characterize and diagnose diseases.

Abiotic or Noninfectious Agents A number of abiotic agents cause disease in trees, including extremes of moisture and temperature, nutrient excess or deficiency, and toxic substances in the air or soil (3, 6-8). Mechanical injury may be inflicted by hail, ice, snow, and windstorms; lightning damage may kill individual trees or even trees in groups. Diseases caused by abiotic agents are often difficult to diagnose because the causal agent is no longer present or active, or because the cause and effect relationship is difficult to establish.

Temperature or moisture extremes may cause direct damage to trees or so weaken them that they are predisposed to attack by microorganisms. Sunscald canker of thin-barked trees often follows upon a sudden exposure to direct summer sun, for example, after thinning. Days and nights of high and low temperatures during late winter or early spring may cause a similar injury to bark, exposing it to sun and then freezing it again by a rapid drop in temperature at night. When warm winds in winter cause excessive transpiration, and roots in frozen ground cannot replace the water, the foliage of conifers may suffer winter injury or winter drying.

Physical and chemical characteristics of soils may have profound effects on tree growth and tree species differ greatly in their tolerance of various soil properties. Soil texture, for example, influences root development, aeration, moisture penetration, and water holding capacity. Forest tree species vary in the range of soil pH in which each may thrive, and soil must provide a balance of macro- and micronutrients within limits that also vary among species. Soil conditions in which nutrients or other chemicals are deficient or in excess may be encountered in local areas, especially in nurseries and forest plantations. As forest management becomes more intensive, forest fertilization may become almost routine, but there is also the likelihood of damage from a variety of chemicals such as fertilizers, fungicides, insecticides, and herbicides, if they are applied at excessive rates or under improper conditions.

In recent decades, air pollution has reached such high levels that forest and urban trees in industrialized regions of the world have been damaged (Figure 8.1). Many chemicals toxic to plants are introduced into the atmosphere, especially by transportation vehicles, industrial processes, and power plants. Sulfur dioxide, produced in coal combus- {

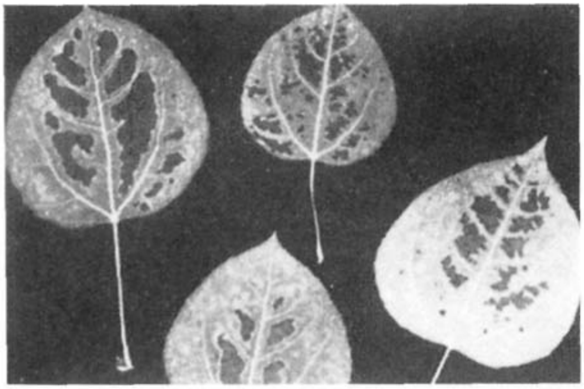

Figure 8.1 Symptoms produced by aspen exposed to sulfur dioxide. (Courtesy of U.S. Department of Agriculture.)

tion and other industrial processes, and the photochemical pollutants ozone and peroxyacetyl nitrate, the main components of urban smog, are major causes of damage to conifers in particular. Eastern white pine has suffered damage from sulfur dioxide and ozone, and disease of ponderosa pine in southern California is attributed to prolonged exposure to aerial oxidants, mainly ozone. Fluorides have caused local damage to forest and orchard trees when released into the atmosphere from ore reduction, fertilizer, and ceramics installations. The potential for both wet and dry deposition of acidic substances to influence plant growth, especially that of forest trees, also is attracting considerable attention. At present, however, the effects of acidic deposition on forest trees remain unknown and the subject of continuing investigation. There are no research results indicating that acid precipitation has a direct damaging effect on forest vegetation, but the complexity of forest ecosystems makes it difficult to document such effects conclusively.

Biotic or Infectious Agents Most diseases of forest trees are caused by biotic agents, usually referred to as pathogens. These include viruses, bacteria (including phytoplasmas), fungi, parasitic higher plants, and nematodes. Of these, fungi cause the largest number of diseases as well as the greatest total loss. Examples of diseases caused by these pathogens are described in the following sections.

Diseases Caused by Fungi

The most numerous and destructive agents causing tree diseases are fungi. The basic structural unit of fungi is the *hypha,* a microscopic threadlike filament or tube that contains the cytoplasm. Collectively, many hyphae make up *mycelium,* which comprises the vegetative body of the fungus. Mycelium is seen in the growth of the common bread mold or the white mycelial fans beneath the bark of a tree root attacked by the root rot fungi in the genus *Armillaria.* Fungi reproduce by spores produced on fruiting structures that vary in complexity from a simple hypha to complex bodies, such as the mushroom that emerges from the soil or the shelflike bracket or "conk" on the trunk of a tree with heartrot. Some fungus spores are disseminated by wind, but fungi are also distributed by rain, insects, birds and other animals, and even human beings. On a suitable substrate the spore germinates to form a simple hypha or germ tube, which then elongates and branches to form another mycelium.

Fungi are heterotrophic, requiring complex compounds that are synthesized by autotrophic organisms such as chlorophyll-containing plants. They secrete enzymes that degrade their substrates and allow absorption of nutrients from organic matter, either as *saprophytes* on dead material or as *parasites* on living plants or animals. Most fungi are saprophytes, and the deterioration of dead organic material by saprophytic fungi is often designated as rot or decay. The activities of parasitic fungi disrupt the structures or life processes of their hosts, and disease results. These diseases vary enormously in the species and parts of the tree affected, in symptoms, and in the type of damage they cause. Therefore, the effects of diseases on the production of various values of the forest and their significance to forest management are also variable; some may be inconsequential, but others may be limiting factors in growth and management of a species.

Foliage Diseases A large number of fungi cause foliage diseases that can vary greatly in both the symptoms produced and in their ultimate effects on tree health (3, 6-8). Growth and vigor may be reduced, but the time of year of the attack and the shoot and foliage characteristics of the tree greatly influence the amount of damage caused. In wet years that favor spread of spores and repeated infection by many leaf pathogens, complete defoliation can result. Young seedlings with relatively few leaves can be severely damaged, but diseases that damage most of the leaves of even very large trees can have great and prolonged impacts on tree health.

A variety of leaf spot and anthracnose pathogens are among the most damaging fungi to broadleaved tree species. Large numbers of small leaf spots, each resulting from an individual infection, can cause leaves to drop. Defoliation of black cherry seedlings, caused by *Blumeriella jaapii,* can greatly reduce their growth or even lead to death. Anthracnose symptoms are characterized by dark discoloration and a collapse of affected leaf tissue sometimes referred to as watersoaking. As the pathogen grows through the leaf, the areas killed progressively enlarge and coalesce. The effects of sycamore anthracnose, caused by *Apiognomonia veneta,* are compounded as it also colonizes and kills buds, succulent shoots, and twigs.

Radial growth of conifers is often reduced in proportion to the degree of defoliation, and there is usually an accompanying reduction in vigor. Cosmetic damage that reduces quality also is important in ornamentals, especially in Christmas trees; a single year of attack may completely destroy marketability. The brown spot needle blight, caused by *Mycosphaerella dearnessii,* (Figure 8.2), has extensively damaged Christmas tree plantations of Scots pine, especially in the Great Lakes region. The same disease affects production of longleaf pine in the South, where it defoliates seedlings and kills young trees or greatly delays their height growth, keeping them in the "grass stage" for unacceptably long periods. In the western United States, *Elytroderma deformans,* causes a serious needle disease of ponderosa, Jeffrey, and lodgepole pines. The fungus initially infects needles, but can grow into the bark of branches and persist for years in western forests at a low, endemic level. Under conditions that are not yet well understood, however, repeated defoliation may occur and result in mortality.

Figure 8.2 Growth of a germ tube from a spore of the brown spot fungus, *Mycosphaerella dearnessii,* on a needle of Scots pine, and development in the stomatal antechamber as seen with the scanning electron microscope.

Rust Diseases The rust fungi, so called because of the orange color of many of their spores, constitute a group of highly specialized parasites with complex life cycles. Both hardwoods and conifers are hosts of various rusts that may attack fruits or cones, leaves, and stems (Figure 8.3) (3, 6-8). Most rust fungi produce five different spore stages appearing in a definite sequence, although some species have only two. Although rust fungi often have very narrow host ranges, many require two different and widely unrelated host plants to complete their life cycle. Their different spore stages have specific functions in dissemination, survival, and reproduction. *Cronartium ribicola,* the cause of the white pine blister rust disease, produces sper-

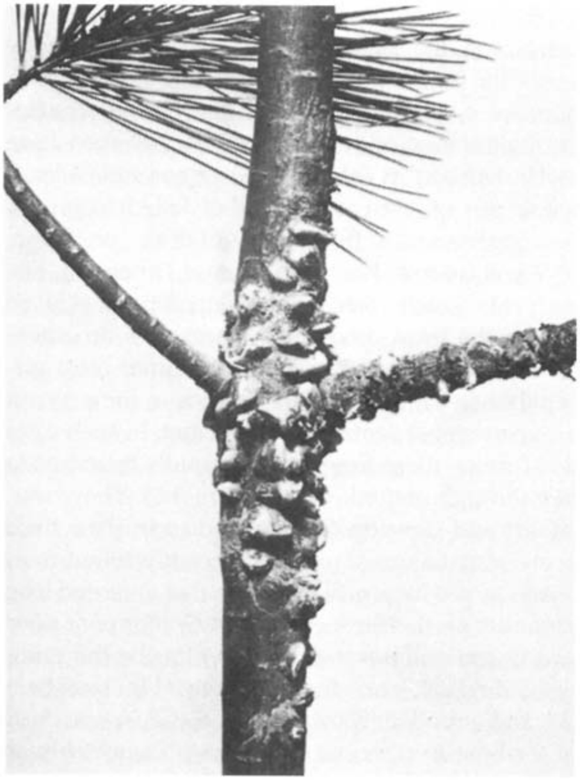

Figure 8.3 Aecial pustules or "blisters" containing orange masses of aeciospores on a branch canker of white pine blister rust.

matia (pycniospores) and aeciospores on white pines, and three other spore forms (urediniospores, teliospores, and basidiospores) on the alternate host plants including currants and gooseberries in the genus *Ribes.*

Stem rusts of conifers are diseases of major impact in natural forests and plantations. The white pine blister rust, a native of Asia, spread to Europe and from there was introduced to North America on imported white pine planting stock in about 1900. On this continent it found a number of highly susceptible hosts in the white (five-needle) pines and it has spread to become one of the limiting factors in growth and management of these commercially important trees. The fungus produces branch and stem cankers that girdle and may kill trees of all ages and sizes, although the disease is most important as a killer of seedlings and young trees. The fusiform rust pathogen, *Cronartium quercuum* f. sp. *fusiforme,* alternates between southern pines and oaks. Although many loblolly and slash pines are killed by development of the elongated fusiform (spindle-shaped) stem galls, longleaf pine and shortleaf pines are relatively resistant (Figure 8.4). This fungus is native to North America, but has become more damaging as management of susceptible pine species has become more widespread and intensive (24).

Figure 8.4 Spindle-shaped gall on the main stem of a loblolly pine, induced by *Cronartium quercuum* f. sp. *fusiforme.* (Courtesy of U.S.D.A. Forest Service.)

Both conifers and hardwoods are affected by a large number of foliage rust diseases. The *Melampsora* rusts of poplars are receiving increased attention as clonal plantations of hybrid poplars and cottonwoods are being established in the Pacific Northwest and the southern United States. Premature defoliation reduces growth rates, and increases susceptibility of defoliated trees to damage from other agents including cold temperatures and stem canker pathogens.

Vascular Wilt Diseases and Stain Fungi Vascular wilts are among the most publicized tree diseases, probably because some are not relegated to the forest, but rather kill trees along city streets and in suburban yards. Vascular wilt pathogens colonize xylem vessels. Their activity reduces or inhibits normal water conduction in stems, resulting in permanent wilting of leaves and death of branches or entire trees. Dutch elm disease, oak wilt, and Verticillium wilt each can cause sudden death, killing susceptible hosts in a single growing season. The notoriety of wilt disease fungi is enhanced by their particular adaptations enabling survival and spread.

The Verticillium wilt pathogen can persist in resistant structures called *sclerotia* in the soil for many years. Sclerotia can be moved in soil with nursery stock or already be present in soil when trees are planted in the landscape. When the opportunity arises, the fungus grows from sclerotia to infect roots of maples, ashes, elms, and many other species through natural or artificial wounds. Sclerotia form in the debris of its colonized hosts, so careless landscape use of untreated chips of killed trees is a potential means of further spread of the pathogen.

The introduced fungi that cause Dutch elm disease (14) and the native oak wilt pathogen (15) are among the most destructive diseases of ornamental and shade trees. The American elm is most susceptible to the former, and species in the red oak group are most damaged by the latter. In both cities and forests, these fungi spread rapidly from tree to tree through grafted roots (Figure 8.5). They overwinter and develop fruiting bodies in their dead hosts, and failure to remove recently killed trees results in production of inoculum that is carried long distances by their insect vectors. *Ophiostoma ulmi* and *O. novo-ulmi* are carried to elms by the European elm bark beetle and the native elm bark beetle, and introduced to trees as these insects feed on or bore into stems. *Ceratocystis fagacearum* is carried to fresh wounds on oaks, such as those resulting from pruning, by beetles including some members of the family Nitidulidae. Costs for con-

Figure 8.5 Large oak wilt "pocket" in an oak forest continues to enlarge by marginal spread through root grafts.

trol of these diseases, removal of the many trees killed, and planting of replacements total millions of dollars annually.

Many other similar fungi colonize the vascular tissues of trees, imparting discolorations referred to as "stain," ranging from brown to blue to black. Although many of these pathogens are not highly aggressive, and when acting alone may have limited affects on tree health, some stain fungi are very damaging when interacting with insects in complexes or in decline diseases (described later in this chapter). In addition, discoloration of wood in standing trees or stain developing after harvest can reduce the value of pulpwood and be a cause of serious reduction in lumber grade.

Canker Diseases Cankers result when areas of the bark and vascular cambium of stems, branches, and twigs are infected and killed by a variety of fungi. There is often a discrete canker margin between the healthy and the colonized tissues, which may be discolored and deformed, sunken or swollen, and surrounded by a layer of healthy *callus* tissue. Ends of branches may be killed as they are "girdled" by cankers that coalesce or expand around their circumference, and stems weakened by cankers or subsequent decay often break. The variety of canker diseases that affect a wide range of hosts are categorized according to the duration of the association and the relative balance in the host-pathogen interaction (6).

Canker diseases may be annual or perennial. Annual canker pathogens, such as *Fusarium solani* (which affects maples and several other hardwoods), apparently are active at a particular location in the stem during a single growing season. Usually only a small area is killed, and as the tree grows it may become enclosed to form a permanent defect in the wood. A perennial canker disease usually involves a longer-term relationship between the pathogen and its host. Year after year the pathogen gradually enlarges the area it has colonized, and the host responds by development of a new layer of callus. The resulting concentric ridges or layers of callus characterize these "target cankers" such as *Eutypella* canker of maple and *Nectria* canker of various hardwoods.

The relative balance in the host-pathogen interaction also may be used to categorize canker diseases. A high level of host resistance normally dominates many interactions. Factors that induce tree stress, however, may allow relatively weak pathogens to become more aggressive and cause saprobic canker diseases. *Cytospora* canker of blue spruce, which damages older trees grown outside of their native geographic range, and some *Fusicoccum, Diplodia,* and *Sphaeropsis* cankers of drought-stressed trees are examples. Diffuse canker diseases are characterized by rapid growth of the pathogen through host bark with little or no callus development. Resulting from interactions that are dominated by aggressiveness of the pathogen, such diffuse cankers may girdle and kill even large trees in a single year. Damage caused by *Hypoxylon* canker of aspens, the most important disease of these species in the Great Lakes area, can decimate entire stands in just a few years (Figure 8.6).

Stem Decay When wood is used as food by fungi, cell walls are degraded to result in changes in the physical and chemical properties of wood. This process, and the resulting altered wood, are known as decay or rot. Most decay occurs in the central core or "heartwood" of nonliving wood inside trees, and may be referred to as heartrot (Figure 8.7). Decay of heartwood, which reduces harvestable volume and wood quality, has been estimated to

Figure 8.6 Stem breakage and cankering (arrows) in a stand of aspen trees severely affected by *Hypoxylon* canker.

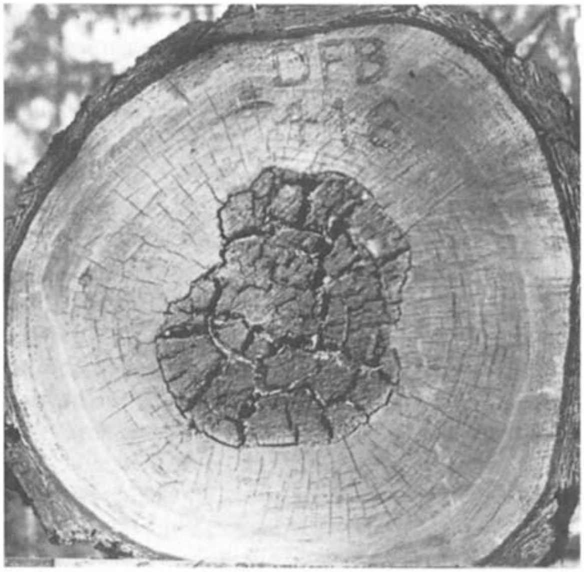

Figure 8.7 Typical brown cubical heartrot in a log of Douglas fir. (Courtesy of Canadian Forest Service.)

be responsible for the majority of growth impact attributed to forest tree diseases. Because the effect of heartrot is largely on deadwood, it is not a major influence of tree vigor or mortality unless structural weakness leads to breakage. In contrast, decay of sapwood, which is living and has important functions in tree growth and maintenance, can strongly affect tree health. Although sapwood is relatively resistant to decay in many living trees, it can be decayed by some fungi.

Wood rots produced by fungi are commonly grouped into two main types, brown and white rots, referring to color changes characteristic of different decay processes. Brown-rot fungi decompose wood by using primarily the carbohydrates (cellulose) of the cell walls, whereas white-rot fungi utilize both the carbohydrate and lignin components of the cell wall. Chapter 20 contains further discussion of the chemical nature of wood. These differences in the mechanism of decay are important in that they can affect the utilization of decayed wood. Both types of decay weaken wood, and even partially rotted wood may be unsatisfactory for construction. Pulp yields from partially white-rotted wood may be relatively high (much of the cellulose will remain, however, whereas brown-rotted wood cannot be used for pulp). Because of changes in texture that accompany the decay process, various adjectives, including laminated, spongy, stringy, and cubical are used to describe different wood rots.

Many different species of fungi cause stem decay, but each has its own distinctive characteristics (3, 6-8). *Phellinus pini* is among the most damaging stem decay pathogens across North America. Decay columns may extend for many meters, destroying the economic value of entire stems of conifers including Douglas fir, pines, spruces, larches, hemlocks, and western red cedar. A related species, *Phellinus tremulae,* is restricted to aspens, but is the greatest cause of decay in its host species and again decay columns are often extensive. Fruiting bodies of *Oxyporus populinus* commonly are observed in old wounds, cracks, or cankers of sugar and red maples, and some other hardwoods. The decay of both heartwood and sapwood caused by this fungus often is restricted to within a meter of the conk, and therefore most of the wood in affected trees may be usable.

Although the number of trees decayed and the volume of rot generally increase as trees age, the total amount of decay in forest stands is extremely variable. The associated decay fungi, as well as the rate of decay, vary greatly among tree species. Events in the history of the stand also strongly influence decay, especially those such as fires, severe storms, and past silvicultural practices which have resulted in broken branches or trunk wounds through which many decay fungi enter trees. Determining the amount of decay in given forest stands, however, is important for the preparation of accurate inventories of present and potential growing stock upon which estimates of yield and allowable cuts are made in forests managed for wood production (see Chapters 9 and 13). Foresters can estimate the amount of decay in a stand with information from sample plot measurements and by examining trees for external indicators of decay, such as fruiting bodies or "conks" (Figure 8.8), swollen knots, and branch stubs.

Root Diseases A large group of very different fungi causes root diseases that reduce vigor, growth, and even kill trees from every stage of development from seedling to mature tree (3, 6-8). Some attack only young, succulent roots such as the feeder roots, essentially causing tree health to deteriorate through starvation. Other fungi are root sapwood colonists, and some first kill roots by parasitic attack and then decay them. Some root pathogens also cause butt rot (decay of the basal portion of the stem) causing a loss of growth and reduction in both volume and quality. Trees with root and butt rots also are subject to windthrow (Figure 8.9), providing gaps in the forest canopy. Development of symptoms on seedlings in clusters in nurseries and large openings in forests (sometimes called root rot "centers") may result from underground spread of root pathogens.

Many devastating root diseases are widely distributed in temperate forests throughout the world. The genus *Armillaria* (16) contains some species known as aggressive tree killers, and others that appear to be opportunistic pathogens of trees under stress. Spores disseminated from mushrooms (Figure 8.10) may be responsible for initiation of new

Figure 8.8 Fruiting bodies ("conks") of a stem decay fungus on white ash. (Courtesy of U.S.D.A. Forest Service.)

Figure 8.9 Wind-thrown trees in a *Phellinus weirii* infection center of a 50-year-old stand of Douglas fir. (Courtesy of G. W. Wallis and Canadian Forest Service.)

Figure 8.10 Clump of mushroom fruiting bodies of the root disease fungus in the genus *Armillaria* at the base of a white pine sapling killed by the fungus. Notice the white mycelial fan on the stem and the characteristic resin-infiltrated mass of soil around the root collar.

disease centers, but these fungi spread locally from colonized dead tree or stump "food bases" by black, shoestringlike strands of mycelium. Called rhizomorphs, these strands penetrate the bark of living roots to colonize new substrate as far as several meters from the original food base. *Armillaria* species and *Heterobasidion annosum* (17), another important root pathogen of conifers in much of North America and northern Europe, also can spread by root-to-root contact. Annosum root disease centers commonly begin when wind-borne spores germinate on freshly cut stump surfaces, such as those produced by thinning or other harvest of intensively managed plantations. *H. annosum* continues to spread through roots of cut or killed trees, infecting residual trees and natural or planted regeneration that contact diseased roots. Similarly, *Phellinus weirii* is especially damaging to Douglas fir in the Pacific Northwest and British Columbia, persists in decaying roots of the previous stand, and infects the roots of young trees through root contact (18). Management of relatively extensive areas occupied by root pathogens for decades, or even centuries, is among the greatest challenges facing foresters today.

Other Pathogens that Cause Diseases of Trees

Viruses, Phytoplasmas, and Bacteria Viruses are extremely small and simple infectious agents visible only with the use of the electron microscope. Composed of nucleic acid and proteins, viruses utilize molecules produced by the living cells of the plants they inhabit for their own replication. Although plant viruses cause many major diseases of agricultural crops, the pathological importance of virus diseases of forest trees such as elm mosaic, birch line pattern, or locust witches'-broom is much less certain (19). As the incidence and effects of the many characterized (and many more as yet unknown) viruses of trees become better understood, perhaps they will be considered of greater significance. Moreover, because vegetative propagation perpetuates viruses, trends toward plantation forestry and vegetative reproduction of some species (e.g., poplars) might increase the threat and extent of virus diseases in commercial forest plantings.

A few tree diseases are caused by phytoplasmas that colonize the phloem of tree roots, stems, and leaves. These were previously referred to as mycoplasma-like organisms or MLOs. Phytoplasmas lack a cell wall, but possess a distinct flexible membrane and are often smaller than bacteria. Because chlorosis (yellowing) of foliage is a common symptom, these are commonly referred to as "yellows" diseases. Ash yellows is characterized by slow deterioration and eventual death of affected trees many years after initial infection (20). In contrast, elm yellows has very rapidly killed many elms in the eastern and central United States. Susceptibility of American elm to the elm yellows phytoplasma also complicates efforts to control Dutch elm disease by breeding for resistance to the introduced fungi that cause the latter.

Bacteria are known to cause relatively few diseases of forest and shade trees, but some can be serious and result in a variety of symptoms (7). Xylem-inhabiting bacteria can cause elm, oak, and sycamore leaf scorches. The bacterial canker of poplar is a serious disease in Europe, but so far is unknown in North America. No new poplar clones are released in European countries without intensive selection and testing for resistance to this disease. Presence of the bacterial canker pathogen in Europe also has led to restrictions on importation of poplars into the United States. In many species of trees a water-soaked condition of the heartwood, called "wetwood," along with discoloration and production of gas (principally methane), is associated with bacteria. The maintenance of an anaerobic situation and the presence of anaerobic bacteria, especially *Clostridium* spp. and *Methanobacterium* spp., are key factors in the production of wetwood rather than normal heartwood. Ring shake (a crack formed in the tree along an annual ring), lumber checking, and the abnormally long time required to dry lumber are problems associated with products from trees with wetwood. Bacteria also are involved in the processes causing discoloration and decay in the wood of trees.

Nematodes Plant-parasitic nematodes are microscopic roundworms of great importance as pests of agricultural and ornamental crops, yet few nematode diseases of forest trees have attracted great attention or have been well studied. Severe damage, however, has occurred in some seedling nurseries and plantations established on abandoned farmlands (21). Plant-parasitic nematodes feed by piercing cells with a needlelike stylet. Their attacks on fine feeder roots of trees can lead to browning, deformity, and death of roots or the production of root galls. Repeated and prolonged injury caused by nematodes gradually decreases the water- and nutrient-absorbing area of feeder roots. Affected seedlings may be stunted (Figure 8.11) or killed, and the growth rates and vigor of larger trees may gradually decrease.

Much more dramatic damage, including rapid death, results from pine wilt disease caused by the pine wood nematode, *Bursaphelenchus xylophilus* (22). This nematode is lethal to Japanese red pine and black pine in East Asia and has been epidemic in Japan for decades. Juvenile pine wood nematodes are vectored by wood boring beetles in the genus *Monochamus,* and enter trees through beetle feeding wounds. The nematodes feed and complete their development within tree stems. Since its identification in the United States in 1979, the pine

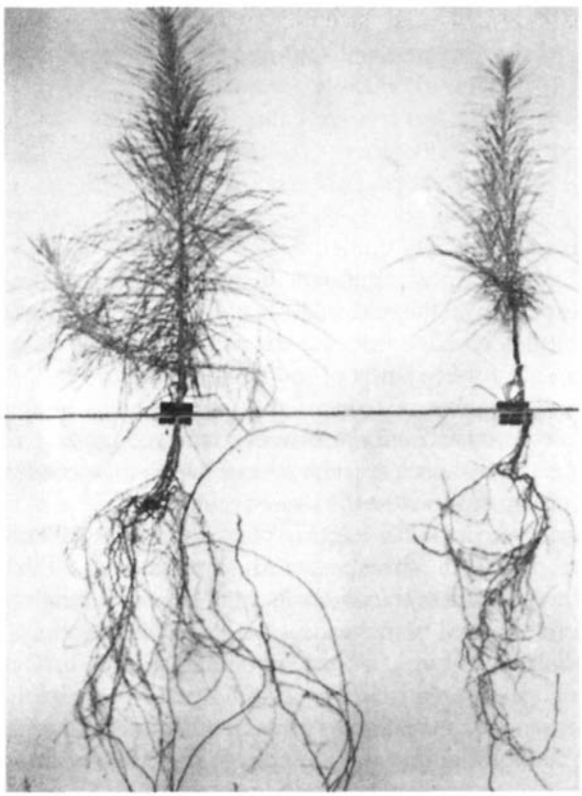

Figure 8.11 Healthy sand pine on left and seedling injured by lance nematodes on right. (Courtesy of U.S.D.A. Forest Service.)

wood nematode has attracted much attention and concern that it could be a serious menace to our pines. Local epidemics have appeared on two exotic pines, Austrian pine and Scots pine, and some native pines in warm regions, but the nematode does not appear to pose a threat to most conifer forests of North America. Discovery of the pine wood nematode in wood chips exported from the southern United States has had an impact on international trade. Embargoes have been enacted to prevent movement of some wood products, and heat treatment to kill nematodes has been required before shipment of lumber to countries where the nematode is not present.

Mistletoes Mistletoes are perennial evergreen seed plants that are parasitic on stems or branches of trees or shrubs. Mistletoe seeds germinate on the surfaces of their host plants. Rootlike structures emerge and penetrate through bark and into vascular tissues to obtain water and nutrients from their hosts. The leafy, or so-called true, mistletoes are well known for their ornamental and sentimental uses during the Christmas holidays. They occur chiefly on hardwoods, but some grow on a few conifer species, juniper, cypress, and incense cedar. They are most abundant in warmer regions and especially in the arid southwest. In general, the leafy mistletoes have not caused major economic damage in forest stands of the United States.

The numerous dwarf mistletoe species in the genus *Arceuthobium,* however, are recognized as the single most important disease problem in conifer forests of the western United States (23). The parasitic growth of these tiny plants (Figure 8.12) can stunt growth of the host to an extreme extent. Host tree responses to colonization include proliferation of abnormal branches in clusters called "brooms," dieback of branches, and eventual tree death. The parasite spreads in the stand by sticky, forcibly ejected seeds that may "shoot" many meters through the air to land in the crowns of other trees. In this way, large radially expanding "infection centers" develop, in which all susceptible trees may be damaged. New, distant infection centers are established when seeds are carried by birds.

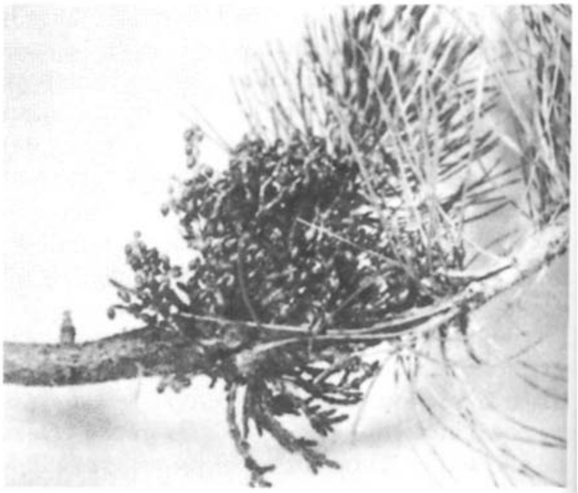

Figure 8.12 Shoots of dwarf mistletoe emerging from a colonized branch of ponderosa pine. (Courtesy of U.S.D.A. Forest Service.)

Insects that Damage Forest Trees

Although often unnoticed, ignored, or unappreciated, insects can be the most numerous, diverse, and damaging animals inhabiting forests. As arthropods, insects have rigid, external *exoskeletons* and jointed appendages. The adult insect body is segmented, composed of a head, thorax (bearing three pairs of legs), and abdomen. Whether they initially hatch from eggs or are borne live, insects must periodically shed their exoskeletons to allow growth in size. Thus, as insects develop, they pass through several immature stages. These might be nymphs, that resemble the adult insect they will ultimately become, or larvae (such as caterpillars) that completely change in appearance while undergoing rather dramatic *metamorphosis* into adults. Insects "breathe" through body openings called spiracles and have decentralized, well-developed nervous systems. Their visual and chemical sensory systems often are extremely sensitive and like other animals, insects exhibit sophisticated behaviors. In I either immature or adult stages, various insects may be relatively sedentary or highly mobile. Some complete their entire life cycle on a single plant; oth-1 ers are dispersed widely by wind or fly long distances in search of food or mates.

Insect damage to forest trees results directly from ingestion or destruction of plant parts that are fed upon, from colonization (such as tunneling or boring) of trees during feeding and reproduction, or from toxins they egest. The degree of damage that results from these activities vary widely among insect species, their various immature and mature stages, and the tree species and its stage of development from seedling to mature tree. The size of the insect population often strongly influences the degree of damage that results. Because the part of the tree that is damaged also influences whether the damage is merely cosmetic or serious, the different locations of feeding and breeding on and in trees is a convenient way to categorize groups of insects that damage forest trees.

Defoliators Defoliators eat needles and leaves. They include caterpillars, sawflies, leaf beetles, and walkingsticks (Figures 8.13 and 8.14). Some defoliators consume entire needles or leaves; others mine tunnels between the epidermal layers of the tree's foliage. Skeletonizers feed on leaf tissue between the veins. Leaf tiers attach portions of leaves to each other with silk, thereby creating a curled effect.

Insect defoliators vary greatly in their seasonal histories, biologies, and methods of feeding (1, 2, 4, 5). Some species, such as the gypsy moth are polyphagous and include many tree species in their host range. Others are oligophagous and feed only on a few hosts; examples include the European pine sawfly, which feeds on about half a dozen pine species. Defoliators that feed on a single host species such as the larch casebearer, are monophagous.

Tree response to defoliation varies greatly, depending on the individual characteristics of the tree and insect species, time of year, intensity of defoliation, and additional stresses prior to and after the defoliation event. Among conifers, complete defoliation in one growing season can cause immediate tree death (Figure 8.15). Two exceptions include the annually deciduous larch and bald cypress, which can tolerate nearly complete defoliation for several years with little or no mortality, and several southern pines (shortleaf and longleaf pines), which can be completely defoliated and refoliate with only rare mortality.

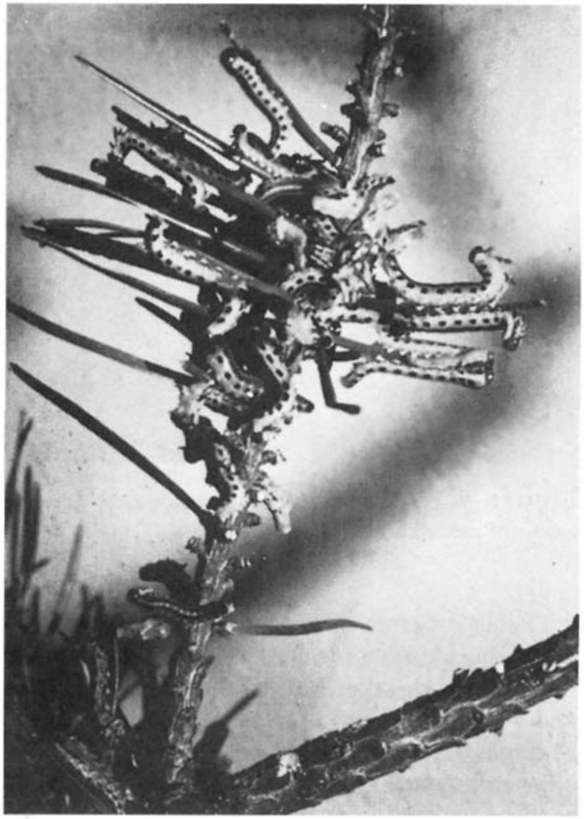

Figure 8.13 Red pine sawfly larvae are defoliators that must feed gregariously if they are to grow and develop normally.

A single defoliation, such as that resulting from feeding of gypsy moth larvae (24), rarely causes mortality among the broad-leaved trees. Exceptions are hard maple and yellow birch, which may die if completely defoliated during mid-July to mid-August (25). As a general rule, partial defoliation (50 to 90 percent) of broad-leaved and coniferous trees reduces terminal radial growth. Tree branches rarely die until after several seasons of severe defoliation.

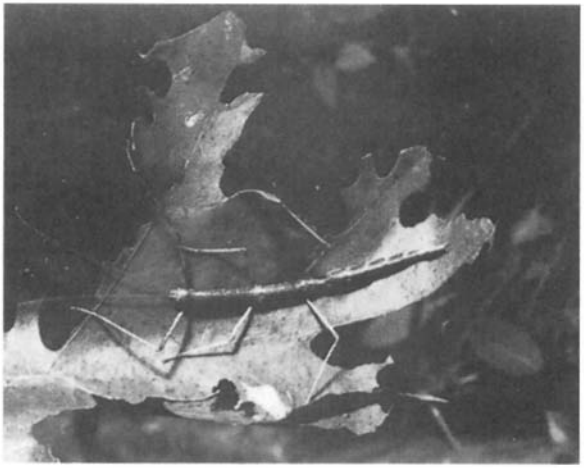

Figure 8.14 The walkingstick belongs to the group of pests known as defoliators.

Defoliators often cause indirect damage by weakening their hosts and rendering them susceptible to invasions by other insects, such as bark beetles and borers, that can kill trees. For example, defoliation by budworms may predispose spruces and pines to the attacks of *Ips* and *Dendroctonus* bark beetles. Cankerworms can weaken oaks so that the two-lined chestnut borer can colonize and kill these otherwise resistant trees.

Defoliator outbreaks may cover many thousands of hectares of forest. For example outbreaks of the forest tent caterpillar have encompassed most of the aspen type of north-central North America. Likewise budworm outbreaks have occurred in spruce-fir forests across the continent. Most defoliator outbreaks, however, are more locally distributed.

Bark Beetles Bark beetles are among the most devastating forest insects in the world (26). They have been responsible for the stunting and killing trees in vast areas of forests (Figure 8.16). Most species attack and kill trees that are old, or under environmental stress. However, some species infest healthy, vigorously growing trees, and often inflict serious damage. Bark beetles also have important interactions with fungi (26-28) as vectors, in pathogen—insect complexes, and as factors in the development of decline diseases, which will be discussed later.

Bark beetle adults bore through the bark and produce tunnels called "galleries" in the relatively thin area composed of the vascular cambium and adjacent phloem and xylem. After mating, females lay their eggs between the bark and the wood, either along their galleries or in special niches (Figure 8.17). After hatching, larvae feed in this area,

Figure 8.15 Jack pine mortality resulting from defoliation by the pine tussock moth.

Figure 8.16 Tree mortality on a Colorado mountainside resulting from tunneling activity of the Douglas fir beetle. (Courtesy of W. E. Waters.)

eventually extending their tunnels throughout the circumference of the trunk or branch. This girdling interrupts the translocation of nutrients and moisture, and the tree may soon wilt and die. Trees that are growing vigorously often "pitch out" or intoxify the adult bark beetles in resin. Trees possess an additional means of active defense, consisting of very high levels of toxic compounds that accumulate at the attack site. However, decadent trees and those weakened by drought or insect defoliators may not be able to repel the mining adults or larvae.

Ambrosia beetles (Figure 8.18) infest their galleries with fungi that serve as food for their larvae. Although ambrosia beetles rarely attack healthy trees, they are very significant pests of logs, stored lumber, and wood products (29). In addition to the galleries that may extend deep into the wood, economic value is reduced because of discoloration produced by the associated fungi.

Still another group of bark beetle species infests cones and seeds of pines. Many of these are in the genus *Conopthorus.* Because the activity of cone and seed beetles can cause nearly complete destruction of seed crops, they can be major seed orchard pests.

Wood Borers Wood borers, like bark beetles, bore through the outer bark of trees, but these insects tunnel deep into the sapwood (30). A variety of different types of insects, including beetles, moths, and wasps, comprise this group (1, 2, 4, 5). Many wood borers, such as the two-lined chestnut borer (31), attack trees that are old, dying, or suffering from environmental stress. They may also invade cut pulpwood, logs, and fire-scarred trees. A few species attack healthy, vigorous trees. This is especially true of species that have been accidentally introduced into new regions in which native trees have not evolved appropriate defenses. Devastating losses have occurred in Japan (32) and New Zealand (33) by introduced wood boring species that are much less damaging in their native range. The Asian long-horned beetle has recently been introduced into North America, and is causing serious damage to highly valued urban trees. Its potential impact on North American forests is unknown.

Two major groups of wood-destroying beetles include the long-horned or round-headed borers (Figure 8.19), and the short-horned or flat-headed borers. Females of both groups lay eggs in notches cut into the bark, and the new larvae mine for a period in the phloem. They then turn inward to feed in the wood, where they construct large and damaging tunnels. Some examples of long-horned

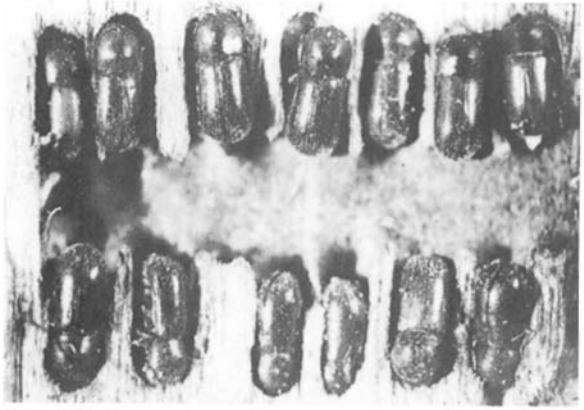

Figure 8.18 Adult stage of the ambrosia beetle, *Xyloterrinus politus.* These individuals have recently emerged from their pupal cases and will soon disperse to infest other trees.

Figure 8.17 Galleries excavated by larvae of the smaller European elm bark beetle. Not only does this beetle inflict damage by its feeding activities, but it is also a vector of the Dutch elm disease fungus.

Figure 8.19 Larval (left) and pupal (right) stages of the poplar borer.

beetles include the pine sawyer and the locust borer. Examples of short-horned beetles include the two-lined chestnut borer (which now primarily attacks oaks) and the bronze birch borer (which can be a particularly damaging pest of ornamental trees).

Sucking Insects Sucking insects have modified mouth parts that enable them to pierce the foliage, tender twigs, or roots of trees and suck the sap or resin as food. These pests drain the vitality of healthy trees, and, if their numbers are great enough, can cause serious stunting or death of their hosts. Both coniferous and deciduous trees are attacked by sucking insects such as aphids, scales, and spittle bugs (Figure 8.20). Feeding by pine spittle bugs results in necrotic areas on stems or branches, and can cause stunting or death of many coniferous species in the eastern United States (34). Sucking insects can also introduce pathogens into trees or cause hypersensitive reactions. Some of the most damaging exotic insects pests in North America are sucking insects, such as introduced beech scale, the balsam woolly adelgid, and the hemlock woolly adelgid (35-37).

Aphids or plant lice usually attack a tree's tender new foliage or twigs, withdrawing sap and producing sugary secretions commonly referred to as "honeydew." Honeydew serves as a substrate for proliferation of superficial, nonparasitic fungi known as "sooty molds." Sooty mold, therefore, can be used as an indicator of the presence of sucking insects.

Figure 8.20 Spittle masses formed by immature stages (nymphs) of the pine spittle bug help the insect maintain a high-humidity environment while feeding on sap extracted from the tree.

Shoot and Bud Insects Insect feeding on the growing meristem can lead to distortion and stunting of shoots and even forking of the main bole. The pine tip moths, the best known of these pests, occur throughout the world. They are especially damaging in even-aged forests, in plantations, and in ornamental beautification plantings.

The white pine weevil is the most injurious pest of white pine in northeastern North America, and one of the most damaging pests of spruce in northwestern North America (Figure 8.21). Infestation may cause permanent forking of the main bole and render the tree less marketable. Although affected trees are not killed, the recoverable volume often is of low quality.

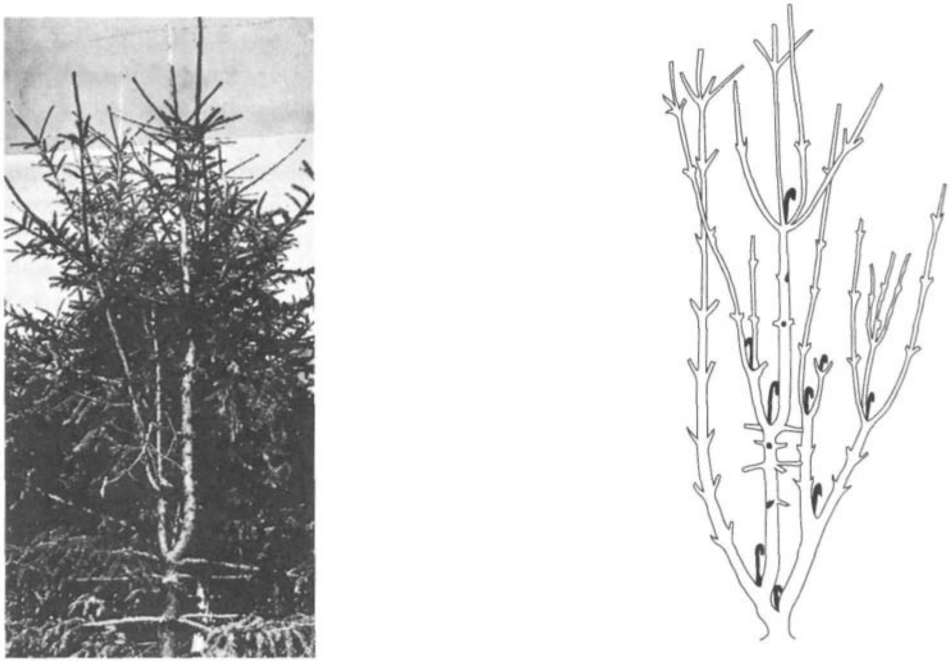

Figure 8.21 A 13-year-old spruce tree with evidence of numerous white pine weevil attacks. The weevil kills the terminal shoot, causing lateral shoots to assume dominance. The attack history is shown schematically on the right. Dead leaders appear as black crooks.

The pine shoot beetle, a bark beetle introduced from Europe, can cause significant damage to Scots pine Christmas trees. Its discovery in the United States led to imposition of quarantine restrictions that add to growers' costs and limit export opportunities.

Root Insects Root insects cause tree stunting and death by infesting the roots and root collar regions of trees, often of planted conifers. Habits of these pests vary greatly, depending on the host species, age, and mode of attack (1, 2, 4, 5).

Female pales weevils lay their eggs in stumps of harvested trees, and the emerging adults debark newly replanted seedlings (38). Entire young plantations can be killed. The pine root collar weevil infests the trunks of living hard pines from 3 to 20 years old. Feeding by the larvae causes stunting, and severely injured trees often break off at the soil surface or die suddenly during windy periods. Several species of caterpillars, such as the swift moth in spruce, exhibit similar behavior.

White grubs, the larvae of May and June beetles, pose serious problems to forest nurseries and new plantings. The adults feed mainly on broad-leaved trees nearby and lay eggs in areas of heavy grass and sod. Larvae feed on the roots and stunt or kill seedlings.

Tree, Pathogen, and Insect Interactions

Microorganisms and insects interact in many interesting ways and participate in unique relationships in the forest ecosystem. Some of these result in very significant damage to the health of individual trees and to forest stands that interfere with production of a variety of forest values. Insects may be *vectors,* responsible for dissemination of a variety of tree pathogens. Trees also may be affected by a fungus-insect *complex,* in which partners each play important roles in development of damage. Finally, both pathogens and insects, along with abiotic agents, can be among multiple interacting factors involved in initiation and progression of a particular syndrome recognized as a *decline disease.*

Vector-Pathogen Relationships

An insect that transfers or transmits a pathogen from one plant to another is referred to as a *vector.* Although some pathogens may grow through soil or in roots from a diseased plant to a healthy neighbor, and many are disseminated in wind or water, still other pathogens are typically carried by vectors. While other methods allow local spread, vector transmission may facilitate long-distance dissemination. Vectors also may cause physical damage (such as the wounds created during feeding) that pathogens exploit for entry into trees.

Some vector-pathogen relationships are relatively accidental, with propagules of pathogens carried externally on the bodies of the vectors. Nectar feeding and pollinating insects, such as bees, frequent rosaceous hosts including trees in *Prunus* and *Malus.* During such visits they sometimes contact oozing cankers caused by the fire blight bacterium, *Erwinia amylovora.* Bacteria contained in the ooze will stick to insect bodies, and be carried to sites of infection, including blossoms on new host trees. Similarly, fungus- and sapfeeding insects including beetles in the family Nitidulidae can vector the oak wilt fungus, *Ceratocystis fagacearum* (15). Aromatic mats of *C.fagacearum* mycelium and its fruiting bodies develop under the bark of trees colonized and killed during the previous year. Nitidulid beetles are attracted to these mats, and as they feed they also acquire spores of the fungus that are carried on their bodies. These beetles subsequently may be attracted to fresh wounds on oak trees where spores are deposited and infection occurs.

Other pathogens are internally borne by their insect vectors. Some sucking insects (including species of aphids, leafhoppers, and spittlebugs) acquire viruses, phytoplasmas, or bacteria as they penetrate and feed from the xylem or phloem of diseased trees. Infection of healthy trees occurs when these pathogens are deposited in vascular tissues during feeding. In a very special relationship, the insect vector of a tree-invading virus may also become a "host" of that virus, supporting replication within its body. An insect vector of such a "propagative virus" can remain a source of that pathogen for long periods and may even transmit the virus through its eggs to the next generation.

Insect-Pathogen Complexes

Although the previous sections emphasize the effects that individual pathogens and insects can have on trees, these agents often act in concert. In insect-pathogen *complexes* each member contributes directly and significantly to the development of damage. Attempts to minimize the impacts of such complexes on trees are challenging, because the factors influencing each member, and their interaction, must be carefully considered. A small sample of the many insect-pathogen complexes follows.

Red Pine Pocket Mortality One commonly encountered complex that affects tree health includes bark beetles and/or root-feeding insects interacting with stain fungi. An example occurs in plantations of red pines in the northcentral United States that sometimes exhibit mortality of trees in distinct clusters or "pockets" (27). Dead and dying trees in the center of the pocket are surrounded by a zone of slowly growing trees with thin crowns of chlorotic needles. Each year the affected area expands, as trees within this zone die and as previously healthy trees immediately surrounding the pocket develop symptoms. Death ultimately results from effects of both insects and pathogens. Bark beetles, such as the pine engraver, infest and girdle the main stems of these trees. Simultaneously, trees are colonized by beetle-associated blue-stain fungi in the genus *Ophiostoma.* Although metabolites of these fungi can interfere with the tree's ability to respond to bark beetle attack, healthy red pine trees normally resist both the pine engravers and the stain fungi they vector. In these plantations, however, root weevils, other bark beetles, and their associated fungi in the genus *Leptographium* often colonize the root collars and lateral roots of these trees in advance of the stem colonizing bark beetles and fungi. Red pines can normally tolerate colonization by these root insects and black-staining fungi, but this root infestation reduces the ability of trees to mobilize defenses against the pine engraver-*Ophiostoma* complex. Expansion of the pocket is perpetuated by maintenance of populations of the insect vectors of the *Leptographium* fungi and growth of these pathogens through interconnecting root grafts into trees surrounding the pocket. The circumstances that most strongly affect root insect populations are not well understood, but appear to include factors such as very sandy soils at sites where this complex occurs.

Dutch Elm Disease The very close association of insects and fungal pathogens is illustrated by the complex of bark beetles and the Dutch elm disease pathogen (14). The aggressive, exotic fungi *Ophiostoma ulmi* and *O. novo-ulmi* quickly kill even vigorous American elms. These pathogens, however, possess neither a means of long-distance dispersal nor can they penetrate intact trees. The European elm bark beetle undergoes maturation feeding in elm twig crotches and native elm bark beetles bore into elm branches. This crown feeding does not elicit strong defensive responses, and beetles can feed in healthy as well as stressed trees. During feeding, beetles introduce spores of the pathogens, which germinate to colonize and proliferate in xylem through which the tree transports water and nutrients. Rapid wilting is induced followed by death, usually in the same year as initial infection. Dying and dead trees then provide the substrate for breeding and overwintering of the beetles. Because the fungi also overwinter in dead elms, colonizing and sporulating in beetle galleries, continued association of the beetles and the pathogens is assured. A similar relationship occurs between wood borers such as the white spotted sawyer and the pine wilt nematodes introduced into healthy pines during maturation feeding. These nematodes can kill nonadapted hosts, and the dead trees provide the breeding material for these normally secondary beetles.

Sirex Wasps—Amylostereum Fungi Another intimate association of insects and fungi is that of *Sirex* wood wasps and their *Amylostereum* fungal symbionts, which together cause damage and death of trees in the genus *Pinus* (33). In all species of *Sirex* investigated, adult females carry a symbiotic fungus, either *Amylostereum areolatum* or *A. chailletii,* in a pair of intersegmental sacs. Spores of the fungus are inserted into the wood when eggs are deposited by female wood wasps. The fungus proliferates in tunnels produced by the feeding larvae. *Sirex* wood wasp larvae also obtain some nutrition from the fungus, and the fungus benefits from dispersal by the insect and inoculation into its host. Although wood wasps are known in many parts of the world, the *Sirex—Amylostereum* complex has caused major damage only to exotic plantations of Monterey pine in New Zealand and Australia. Attacks by *Sirex noctilio* in these plantations occurred most frequently on trees under stress.

Defoliating Insects—Opportunistic Pathogens and Insects Insects do not always act as vectors for pathogens or provide a means of entry into trees, but they also may be important in altering a tree's interaction with a pathogen or other insects. Defoliation by insects such as the gypsy moth or forest tent caterpillar often is tolerated by deciduous trees. Defoliation, however, may be followed by an increase in root disease caused by fungi in the genus *Armillaria* (16). Some *Armillaria* species are commonly found as rhizomorphs on root surfaces or in restricted lesions in roots, but colonization of vigorous trees may be limited. Defoliation causes chemical changes in root tissue, however, including alteration of the concentrations of carbohydrates and the relative abundance of certain amino acids. The increased aggressiveness of *Armillaria* fungi has been associated with these changes, and these pathogens can rapidly invade and kill previously healthy trees that have been stressed by severe or repeated defoliation. Defoliation also reduces resistance against normally "secondary" insects such as the two-lined chestnut borer, which typically does not extensively infest healthy trees. Colonization of defoliated or otherwise stressed trees can result in dieback of limbs and even whole trees. Similar relations occur among defoliators and opportunistic wood-boring insects and pathogens in conifers.

The Beech Scale-Nectria Complex Another interaction in which insects alter the susceptibility of a tree to a fungal pathogen is the beech *scale-Nectria* complex. Feeding of the introduced scale insect, *Cryptococcus fagisuga,* on the bark of beech trees results in cellular proliferation, hypertrophy and bark cracking. This provides an infection court and reduces resistance of the bark tissues to *Nectria* fungi. The principal pathogen is *Nectria coccinea var.faginata,* although native species *of Nectria* also can be involved. These fungi colonize large areas of insect-altered bark on the trunks of some trees, quickly girdling and killing stems, whereas on other trees narrow strips of bark are infected, parts of the crown become chlorotic and die, and the tree survives in a weakened state for many years. Little injury is caused by each organism attacking separately.

This complex has caused massive mortality of American beech in the maritime provinces of Canada and in parts of the northeastern United States. The effects on forests last long after this complex is first observed, however. Beech root systems are not killed by this complex and sprout to produce new stems as susceptible to scale and *Nectria* as those previously present. Highly defective beech sprout thickets, therefore, can dominate stands that develop following the passage of an initial killing front. These interfere with attempts to regenerate other tree species. Beech stands in the "aftermath forest" are neither economically valuable, nor can they adequately support wildlife that depend on beechnuts produced by healthy trees.

Decline Diseases

In addition to acting alone or in particular complexes (as described earlier), it has been proposed that abiotic agents, pathogens, and insects may interact in the development of *decline diseases* (6). Decline disease does not merely refer to any gradual loss of tree health, or to any malady resulting from interaction of an agent or pathogen and an insect. Rather, a particular tree decline disease is produced by interaction of multiple, interchangeable, and ordered factors, which result in a gradual, general, and progressive deterioration in tree condition, often ending in death. Although not universally accepted, the decline disease concept can be a useful model for the study of complicated or incompletely understood phenomena affecting tree health.

Trees affected by different decline diseases often develop similar symptoms. They display reduced growth in diameter and by reduction of shoot elongation. Leaves may be chlorotic (yellow), reduced in size, and crowns may prematurely exhibit fall coloration. Symptoms of roots may include reduced carbohydrate reserves, degeneration of fine roots and mycorrhizae, and root decay fungi are often active. Twig and branch death results in crown "dieback," and epicormic shoots are common. Affected trees usually are randomly dispersed, and not aggregated (as might result from the spread of a single agent). Characteristically, symptoms and signs of pathogens and insect activity intensify over many years.

The abiotic agents, pathogens, and insects that interact to produce a decline disease are categorized as *predisposing, inciting,* and *contributing* factors (39). Predisposing factors diminish tree vigor from its potential optimum. Their effects may not be noticeable and they affect the tree over a long period of time (many years). Predisposing factors may include inherent attributes of the tree or characteristics of the physical environment. Inciting factors are especially damaging to trees that are already predisposed. They are relatively short-term, acting quickly and often producing very noticeable effects. Inciting factors include features of either the physical or biotic environment. Contributing factors perpetuate deterioration of trees already altered by predisposing and inciting factors. These last factors to affect trees in a decline disease typically occur over many years, and effects are very noticeable. Contributing factors often include "opportunistic" insects and pathogens, including many described earlier in this chapter. Predisposing, inciting, and contributing factors are incorporated into the decline disease spiral proposed by Manion (6), one model for the interaction of different abiotic agents, pathogens, and insects in tree decline. Though not common to all decline diseases, both insects and pathogens are thought to play important roles in development of each of the three syndromes described below.

Maple Decline At least two different syndromes affecting sugar maples, in urban areas and in forest stands, are considered to be examples of decline diseases. In cities and especially along streets, maples may be predisposed by old age, heat associated with the urban environment, and soil factors such as compaction, poor aeration and drainage, and salt accumulation. Construction damage, especially to roots, is a common inciting factor. Contributing factors may include chronic effects of *Verticillium* wilt, opportunistic canker fungi, sugar maple borer, and *Armillaria* root disease. Decline of sugar maples in forests has been observed since the early 1900s. There this species also may be predisposed by site factors, such as shallow soils. Important inciting factors may include defoliation by moth species including the saddled prominent, forest tent caterpillar, and loopers, root damage resulting from soil freezing during winters lacking normal snow accumulation, and intense droughts. A vascular pathogen of forest maples, *Ceratocystis coerulescens,* and again, sugar maple borer, canker fungi, and *Armillaria* species are the contributing factors that are often associated with visibly deteriorating and dying trees.

Birch Dieback The decline disease known as "birch dieback" has occurred episodically across the northeastern United States and eastern Canada. Most recently, forests of the northern Great Lakes region were affected, with mortality of millions of yellow and white birch trees during the early 1990s. Tree age appears to be the primary predisposing factor associated with birch dieback, but site factors also are suspected. Inciting factors include defoliation, caused either by insects such as the birch leaf miner or by late spring frosts. Stand opening and warmer than usual summers also are inciting factors. Resulting elevations in soil temperatures can lead to massive birch rootlet mortality. The bronze birch borer, which invades and kills branches and stems of stressed trees, and *Armillaria* root rot fungi are commonly observed contributing factors of birch dieback.

Oak Decline Oak forests in the eastern and southern United States are periodically affected by declines. Characteristics of the site including both poorly and excessively drained soils, and tree age are predisposing factors. Inciting factors that have been important in the past include drought, frost, and defoliating insects and diseases. As the range of gypsy moth extends farther and farther, it is gaining in importance as an inciting factor. A large number of contributing factors have been associated with oak decline. These include the two-lined chestnut borer, canker pathogens that become aggressive on stressed trees, and several root and stem decay fungi.

Tree Disease and Insect Management

Despite beneficial activities that include important roles in forest ecosystems, diseases and insects can interfere with achievement of objectives established by forest landowners, resource managers, government agencies, and the public. These include production of the diversity of aesthetic, recreational, environmental, or economic benefits for which forests are valued. After careful consideration of factors that influence disease and insect occurrence and development, specialists in forest health protection employ pest management principles and select from a variety of diverse practices to prevent or suppress damage caused by diseases and insects.

Influences on Disease and Insect Occurrence and Development

Tree and Stand Attributes Attributes of both individual trees and the stands they comprise have important influences on frequency and intensity of damage resulting from diseases and insects. Tree species vary widely in their inherent resistance to particular diseases and insects. Five-needled pines (e.g., eastern white pine) are rarely damaged by the pine shoot blight and canker pathogen *Sphaeropsis sapinea,* which frequently and severely damages several species of two- and three-needled pines (e.g., Austrian pine). Oaks and poplars are highly favored feeding hosts of the gypsy moth, and thus often are severely defoliated. Other tree species, including ashes and tulip tree are not favored, and may suffer relatively little defoliation during outbreaks of this insect. Considerable variation in the damage among trees of a single species often is an indication of genetically controlled resistance, which has sometimes been exploited in attempts to manage pest impacts. Hosts also may vary widely in their ability to support both reproduction and survival of microorganisms and insects. Thus, both maintenance and growth of pest populations may be influenced strongly by tree attributes.

Size and age, and a variety of factors that influence "vigor," may affect the relative susceptibility of individual trees to pests. Young trees, such as seedlings and saplings may be severely damaged by a disease or insect that is a relatively minor pest of mature trees. Some pests exploit smaller, suppressed understory trees and very old or slowly growing trees can be particularly damaged. Thus, the ability of trees to express resistance to many pests is diminished by environmental factors that alter physiological processes of the host. An example is provided by the integrated defense system of conifers, including oleoresin exudation (40). Sticky oleoresin, or "pitch," exudes from sapwood and can flood wounds such as those produced by boring beetles. Oleoresin exudation pressure (OEP), with other preformed and induced defenses, varies by the season, time of day, weather conditions, the age of the tree, and history of other pest activity, and is closely correlated with the water balance in the tree. Trees with an impaired defense system (including low OEP) may succumb to attack by bark beetles, while those with more rapid and extensive responses are more resistant. For this reason, large and damaging infestations of conifer bark beetles are associated with older trees or stands subjected to drought or defoliation. It is important to note, however, that many pathogens and insects require no assistance from stress-inducing factors to successfully attack their hosts. Even the most vigorously growing trees are subject to damage by some pests.

Stand attributes, which can be strongly influenced by past forest management practices, also influence development of diseases and the activity of insects. As a general rule, forests with the greatest diversity of tree species are less frequently and less severely subjected to epidemics and outbreaks. Uniform age distribution functions much like species composition, in that even-aged stands may be more vulnerable to damage by some pests than those composed of a mixture of ages. More diverse stands of trees can host a greater diversity of microorganisms and insects, but usually support fewer individuals of each of these species. Thus, diversity often is associated with low levels of pest activity and stability of forest ecosystems.

Site and Weather Attributes Abiotic environmental factors associated with particular forested locations, including those of the weather or climate, directly influence disease and insect development. For example, hatch of insect eggs is influenced by temperature. These might occur earlier on warmer, south facing slopes or in areas where penetration of sunlight has increased because of opening of the stand. The generation time of insects can be reduced at higher temperatures, so that more generations of some insects might occur during an unusually warm summer. Conversely, extreme cold could adversely affect survival of overwintering eggs, larvae, or adults.

Dissemination of many pathogens, processes involved in infection, and the extent of subsequent colonization are strongly affected by conditions of both temperature and moisture. The formation and germination of basidiospores of the white pine blister rust fungus, for example, require a period of at least 18 hours of high moisture and temperatures above freezing but below 20°C. Hot, dry weather unfavorably affects development of the fungus, and chances for pine to escape infection are increased. White pines in valleys or depressions where cool, moist air collects, on sites with north-facing slopes where dew persists, and in proximity to bodies of water providing high humidity, therefore, might be considered to be at a higher risk for development of white pine blister rust.

Other site attributes, especially soil factors, have strong indirect effects on susceptibility of trees to damage by diseases or insects. Each tree species is adapted to grow within a particular range in fertility, pH, and moisture-holding capacity. At the extremes or outside of these ranges, even native tree species that are planted "off site" may be very susceptible to pests that exploit their less than optimal condition.

Pathogen and Insect Attributes Much of the research undertaken by forest pathologists and forest entomologists is directed toward gaining fundamental knowledge of pest biology. The ability of different pathogens and insects to cause damage to trees is heavily dependent on inherent characteristics of these organisms, expressed at different times during their life cycles while interacting with their hosts. Knowledge of how organisms that can be pests survive during periods unfavorable for their growth, reproduce, disseminate, recognize their hosts, and of how their activities produce damage are critical for selection of biologically rational strategies for their management (1-8, 41, 42).

Both pathogens and insects can vary greatly in their "host range," or the variety of different host species that they exploit. Some are very host specific, and a single host species might be required for life cycle completion. Others are generalists, utilizing a wide range of hosts, often in many different plant genera or even diverse plant families. Particular insects and pathogens have life cycles that include stages that alternate between host plants. For example, feeding of the Cooley spruce gall adelgid on needles can heavily damage Douglas fir. Immature females of the Cooley spruce gall adelgid, however, overwinter on spruce. In spring they mature and oviposit. Eggs hatch to produce young insects that also initially utilize spruce, feeding within galls formed on shoot tips. In midsummer, however, winged females migrate to Douglas fir, where they lay eggs to produce another generation. As mentioned previously, many rust fungi also alternate between angiosperm and gymnosperms, with presence of both hosts necessary to allow disease development.

Forest pests also vary in important aspects of population biology, including the number of generations or cycles that can be produced each year. For organisms that can only complete a single cycle each year, population growth may be relatively slower, building for many years until epidemic or outbreak levels are achieved. In contrast, the Cottonwood leaf beetle *(Chrysomela scripta)* is *multivoltine.* In the southern United States, it can complete up to seven cycles from adult to egg to adult per year. Even in the northern United States, especially during prolonged warm summers when weather conditions are conducive to beetle development, rapid population growth can lead to massive and repeated defoliation of intensively, managed poplar plantations. Similarly, fungi such as the dogwood anthracnose pathogen (*Discula destructives*) are capable of multiple cycles in a single growing season. New, sporulating lesions develop within just one to two weeks after infection. Particularly during moist weather, repeated cycles of spore dissemination, infection, lesion development, and production of additional spores are responsible for defoliation and initiation of cankers that eventually kill stems of flowering dogwood.

Forest Pest Management Principles and Practices

Knowledge of the biology of particular tree and insect or pathogen interactions may suggest one or more appropriate pest management principles.

These principles can be considered "strategies," or general approaches to minimizing the effects of damaging agents on trees and forests. Six strategies that are employed in forest pest management, including attempts to control pests of nursery seedlings and landscape trees, are:

Resistance: utilization of trees with inherent, genetically controlled characteristics that minimize pest impacts, or use of practices to increase the ability of trees to defend themselves;

Exclusion: prevention of the introduction of a pathogen or insect to an area where it is not already present;

Protection: placement of a barrier or other material (usually chemical) that interferes with interaction of the pest and the tree;

Eradication: removal or destruction of pathogen or insect life stages to reduce or eliminate pest populations;

Avoidance: utilization of locations, conditions, or practices that do not favor, or even suppress, development of disease and/or insect infestations;

Therapy: treatment to cure already diseased or infested trees (may involve employment of one or more of the other strategies listed above).

For each of these strategies, a variety of practices may be applied in managing forest pests. Different types of practices can be categorized as regulatory, physical, chemical, cultural, or biological. Selection of particular practices depends not just on availability, cost, and effectiveness, but on compatibility of the practice with forest management objectives, and environmental impacts, and societal constraints. Examples of practices that might be appropriate for each forest pest management strategy are listed in Table 8.2.

Integrated Pest Management

Integrated pest management (IPM) refers to an approach to pest control that is based on an understanding of host and pest biology, knowledge of ecological principles, and integration of methodologies from several disciplines (43). IPM plans are designed to be effective, practical, economical, and protective of human health and the environment. Both basic and applied forest research results support development and refinement of integrated pest management efforts that contribute to sustainable management of forests.

In the past, scientists in different disciplines—entomology, plant pathology, soils, forestry, and chemistry—often approached a pest problem with minimal communication with their colleagues in other fields. Sometimes methods proposed to deal with one pest were in conflict with those used to manage another, or had other undesirable effects on the forest community, including beneficial organisms. For example, thinning lodgepole pine stands to improve vigor and resistance to bark beetle attack favors spread of dwarf mistletoe and development of epidemics by this pathogen. Use of broad spectrum insecticides to kill defoliating insects also can diminish populations of parasites, parasitoids, and predators that help hold pest populations in check. It finally has been realized that it is not only feasible, but necessary to integrate pest control strategies and practices, and in so doing consider simultaneously the effects on a multitude of other factors, including other organisms, other forest management activities, and all benefits produced by the forest ecosystem.

A key element of the IPM concept is pest population monitoring. Information provided by surveys to detect and quantify insect pests and pathogen occurrence is used as a tool for decision making. Based on previous population biology and forest ecology research, numbers of insect life stages (such as egg masses) or the symptoms and signs of disease associated with unacceptable effects are determined. These are used to establish a "damage threshold" representing the population level at which attainment of desired forest values is compromised (Figure 8.22). The goal of the IPM program is to prevent pest activity from reaching this damage threshold. Therefore, a lower population level, or "action threshold" is established. Successful implementation of an appropriate pest management practice at the point when the action threshold is reached leads to the eventual decline in insect num-

Table 8.2 Examples of Practices Applied to Implement Different Pest Management Strategies

Strategy	Type of Practice	Examples
Resistance	Biological	Plant loblolly pines bred for resistance to fusiform rust
	Biological	Maintain favorable moisture regime to enhance resistance to bark beetles
Exclusion	Regulatory	Quarantine to prevent untreated wood products that could harbor insects or fungal pathogens from entering the United States
	Regulatory	Inspect nursery stock for insect egg masses before shipment
Protection	Chemical	Spray Christmas trees with fungicide to prevent infection and subsequent defoliation by needlecast fungi
	Biological	Apply the fungus *Phlebiopsis gigantea* to freshly cut conifer stumps to prevent infection by root rot pathogen *Heterobasidion annosum*
	Chemical	Treat foliage with insect feeding deterrent to reduce defoliation
	Physical	Cut root grafts to prevent spread of fungal pathogens to healthy trees through interconnected root systems
Eradication	Biological	Release insect parasites, parasitoids, and predators in infested areas
	Physical	Flood or heat treat nursery soils to reduce populations of insects, nematodes, and fungal pathogens
	Chemical	Aerially apply insecticide to kill feeding larvae of eastern tent caterpillar
	Physical	Pull gooseberry and current bushes (alternate host of white pine blister rust) in white pine production areas
Avoidance	Cultural	Increase proportion of nonfavored hosts by manipulating stands in areas subject to gypsy moth defoliation
	Cultural	Prevent logging injuries and shorten rotations to minimize losses from decay
	Cultural	Maintain diversity of stand age structure to avoid population explosions of spruce budworm
	Cultural	Utilize even-aged management in red pine to prevent dissemination of *Sirococcus* shoot blight fungus inoculum from overstory to understory trees
Therapy	Chemical	Inject systemic insecticides to kill developing wood borers
	Physical	Prune cankered branches from trees

bers or pathogen occurrence, and unacceptable damage is prevented.

Concluding Statement

Studies of diseases and insects continue to yield information that is fundamental to understanding and managing these influences on trees and forests. By definition, integrated management of forest pests brings together old knowledge, novel ideas, policy considerations, management strategies, treatment practices, monitoring, and decision making in new ways. The characteristics of trees and forest stands, site and climatic factors, and the biology of pathogens and insects discussed in this chapter are

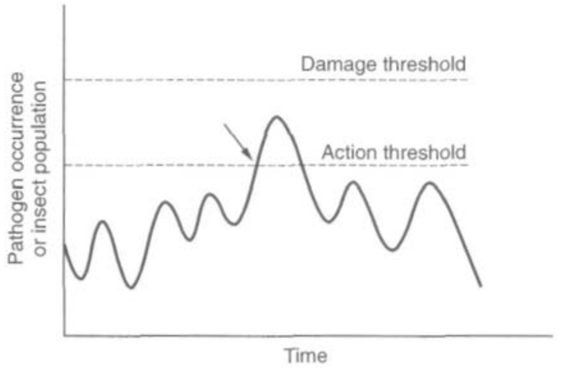

Figure 8.22 Relationship between insect population or disease occurrence, action threshold, and damage threshold. Application of an appropriate forest pest management practice at the action threshold (arrow) should prevent development of unacceptable damage.

all considered in evaluating forest pest management needs. The challenge and opportunity of forest pest managers is to employ strategies and practices so they work in concert, not in conflict, in maintaining and enhancing aesthetic, recreational, environmental, and economic benefits provided by healthy trees and forests.

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PART 3

Forest Management—Multiple Uses

The forests make up one of the earth's greatest reservoirs of renewable natural resources. Managed properly, they can provide us with essential products indefinitely and at the same time can remain a home for wildlife and a vital source of water supplies (Figure P3.1). However, the management of the forests for each of the many products, services and benefits presents a complex problem. This section presents the methods and practices by which the successful forest manager obtains these benefits from the forest without adversely affecting the environment.

In Chapter 9 an overview of forest management and stewardship is given; the approaches to management of public and private organizations, the interests of ownership, and the planning of operations are discussed. This is followed in Chapter 10 by a more in-depth treatment of small nonindustrial private forests because these forests hold a major share of the future for forest derived benefits. Almost 60 percent of commercial forestland is owned by the private nonindustrial sector.

Specific procedures for assessment of forest and timber resources are provided in Chapters 11 (Measuring and Monitoring Forest Resources) and 12 (Remote Sensing and Geographic Information Systems for Natural Resource Management). The various methods available for determining individual tree sizes and volumes and those for estimating the volume of timber in forest stands are presented. The chapter on remote sensing describes methods for evaluating stand composition, density, and the health of forests from aerial photographs and satellite data.

Chapter 13, Silviculture and Forest Ecosystem Management, describes the biological management of the forest—how forest regeneration, species composition, and growth are regulated by biological means. Forests are used by wildlife and for

Figure P3.1 Our forests make up one of the earth's great reservoirs of renewable resources. Properly managed, they can provide us with essential products indefinitely and at the same time remain a home for wildlife and a vital source of water supplies. (Courtesy of U.S.D.A. Forest Service) rangeland, watersheds, recreation, and timber. Chapters 14 through 17 describe the important aspects of forest management for nontimber uses of the forest. Methods of integrating management decisions for protection of all the natural resources provided by the forest are described in these chapters. Extraction of timber from forests does not necessarily diminish the other benefits derived from the forest. A moderate size clearcut, for example, provides additional habitats for wildlife, and selection cutting in the forest creates areas suitable for aesthetics and recreational activities.

Although human beings cause most forest fires today, fires have always occurred in the forest due to lightning storms. The importance of fires in shaping the forest landscape is discussed in Chapter 18, Behavior and Management of Forest Fires. The use of fire as a management tool (i.e., "prescribed burns") is also described in this chapter.

A primary product of great economic importance derived from the forest is wood, and to obtain wood, the forest must be harvested. Chapter 19 shows the variety of approaches available for timber harvesting. In Chapter 20 an overview is provided of the many uses that are made of wood, from lumber and plywood to paper and chemicals. The unique characteristics and comparative abundance of wood have made it a desirable natural material for homes and other structures, furniture, tools, vehicles, and decorative objects. The structure and chief attributes that give wood these special properties are discussed in this chapter. A large percentage of harvested wood is also used for production of pulp and paper. Thousands of paper supplies are produced every year for household and industrial use. Since smaller-size logs are suitable for pulp production, the second growth timber in the United States is very suitable for production of these important commodities (Figure P3.2). Use of wood for paper and for energy and chemicals are also described in Chapter 20.

Figure P3.2 Log drivers wrestling Douglas fir logs on Oregon's Coos River, using long pike poles and a short peavey. These logs will roar downstream to be processed in a pulpwood mill. (Courtesy of Life Picture Service.)

The final chapter in this section, Chapter 21, provides a valuable discussion of the economics and management of forests for both wood and amenity values. A thought-provoking comparison is made of the economics of forest products markets versus other forest amenities based on economic theories. The chapter demonstrates how economic reasoning can help in the wise management of forest resources.

CHAPTER 9

Forest Management and Stewardship

JAMES M. GULDIN AND
RICHARD W. GULDIN

Why manage forests? Many reasons might come to mind, but they all turn on one point—managed forests are better able to provide for the needs of society than unmanaged forests. Management of forests becomes especially important as human populations increase and forest lands decrease, and as society demands more and a wider variety of forest resources. A common thread in the history of civilization is that the practice of forestry has evolved in response to society's concerns about the scarcity of forest resources (1).

Forests do not require management to maintain their structure and function. For eons, trees have used energy from the sun to convert water, atmospheric carbon dioxide, and a handful of mineral resources into the sugars and metabolic by-products required for growth, and they have done so in a way that collectively confers productivity to the forest ecosystem. Thus, it is perhaps arrogant to discuss the value of forest resources under human administration. Forest ecosystems will be rich in natural resources even if human beings do not tamper with them. But they may not be the resources that humans want, and they may not be produced in the length of time that humans want them to be. Also, there may be unacceptable ecological and economic effects if humans use forest resources in a careless and unregulated manner.

Society has had its greatest influences on the natural patterns and processes of forests since the Industrial Revolution. One prominent influence has been the suppression of natural processes that humans find damaging or dangerous. For example, in North America, lightning has historically been, and still is, responsible for igniting wildfires annually. Before European settlement, those wildfires would have run their natural course; today, they are aggressively suppressed by firefighters. As a result, many fire-dependent forest ecosystems no longer burn as frequently as in the past. Without fire, these ecosystems can become degraded or lost. When fires do strike, the results can be catastrophic, as happened during the great Yellowstone fires of 1988 (2). (A further discussion of the behavior and management of forest fires is given in Chapter 18.)

A second prominent influence of society on forests has been the introduction of exotic species from other continents. Chestnut blight, a European fungal disease, got its start in North America when diseased chestnut logs were imported from Europe to New York in 1904. In two decades, the blight virtually wiped out the American chestnut and thereby dramatically changed the species composition of hardwood forests across the East (3). The gypsy moth, an Asian lepidopteran insect, was introduced to North America to develop a domestic silk trade. In 1898, a handful of moths escaped into a nearby forest. Today, gypsy moth causes millions of dollars of loss in oak-hickory forests in the East (3). Without advances in control technology to slow its spread, it will be found in every state east of the 100th meridian early in this century (4).

However, perhaps the single most prominent influence of society has been the deforestation of North America following European colonization. Since 1630, about a third of the forest area in the United States has been cut and converted to nonforest uses, primarily agriculture (Figure 9.1). Nearly all the rest has supported some form of timber harvesting. Two hundred years ago, forests were considered a barrier to agriculture and an inhibition to westward expansion. Today, forest resources are scarce relative to society's demand for them.

Figure 9.1 Agricultural fields taken from the forest land base in post-European settlement in North America; view looking north from Hawk Mountain Sanctuary in eastern Pennsylvania. (James M. Guldin)

A century ago timber was unquestionably the most valuable resource in the forest. Although today's society still ascribes high monetary value to timber resources, we increasingly find important nontimber values in forest resources. For example, a stand of black walnut trees growing along a stream in northern Missouri has value on many levels. It can serve as a source of beautiful cabinet lumber, as a prime squirrel habitat, and in a protective capacity by helping to maintain water quality and reduce soil erosion. It is easy to ascribe a monetary value to the lumber from a black walnut tree; it is more difficult to place a dollar value on each squirrel, each cubic foot of uneroded soil, and each unit of clarity in the stream water. Yet, society desires all these resources, and no one can dispute that maintaining squirrel habitat and water quality would be difficult if all the black walnut trees were harvested for lumber.

Moreover, the productivity and distribution of resources in any ecosystem are variable and complex. Some natural resources, such as wood fiber in a Mississippi riverfront Cottonwood stand, are produced very quickly (Figure 9.2). Others are produced in very small quantities over longer periods of time. For example, the endangered red-cockaded woodpecker in east Texas constructs its nest only in the decayed heartwood of pine trees that are generally over 100 years old (5). Some natural resources require such an extended period of development that they might be considered essentially nonrenewable. The awe that many feel toward a grove of stately redwood trees in northern California is heightened by the realization that the trees are over a thousand years old.

Figure 9.2 A short-rotation cottonwood plantation on forest industry land adjacent to the Mississippi River in northwest Mississippi; the stand will be harvested at age 11, by which time the trees exceed 30 cm (12 inches) in diameter and 25 m (80 feet) in height. (James M. Guldin)

This scarcity and complexity of forest resources, coupled with society's demand for them, is what confers value to the forests of today. Fundamental economic concepts of supply and demand, and noneconomic considerations, such as concern for preserving endangered species and maintaining environmental quality, affect the value of forest resources. Sorting out these conflicting demands, resources, and values is the domain of forest management.

Forest Management

Forest management is the process of organizing a collection of forest stands so that they produce the resources that the landowner wants from that forest. The landowner might be a forest industry, a private individual or family, or the public (represented by federal, state, county, or municipal governments). The resources might be timber products, wildlife, awe-inspiring aesthetics, or any conceivable combination of these. The task of the forest management specialist is to organize the production of such resources in a sustainable manner so that they will always be available to meet the needs of the landowner. The management techniques for accomplishing these purposes vary from the simple to the exceedingly complex.

Common goals for forest management are to produce the resources demanded by the landowner and society, to maintain a sustainable supply of resources over time, and to minimize conflicting ecological, economic, or social demands in resource use. Management typically begins with a *forest management plan* that identifies the objectives of the landowner, outlines the treatments and timetables required for each stand over the entire forest, and describes a program of resource evaluation to ensure that the ownership objectives are attained.

Forest management would be simple if all forest resources were readily renewable and if it were possible to use one resource without affecting other resources. However, nearly every practice that a forester uses to manage a particular resource also affects other resources in the forest. The more resources that are desired from a given area, the greater the likelihood that the management and use of one resource will affect another. Also, there is often a fine line between careless exploitation of a resource and a conservation-based use that ensures resource renewability.

Broadly speaking, the forest management plan is implemented using the principles of forest administration. These actions include supervising personnel, developing operational budgets, prescribing and conducting stand-level treatments, and reviewing treatments after they are completed to ensure that the outcomes desired are attained.

The degree of planning and the resources allocated for administration often depend on the size of the forest being managed and the number of resources being managed. Plans are usually more detailed if the resources of interest have high intrinsic or monetary value, because of the financial incentive to ensure that management does not adversely affect current resource quality or future resource availability. Plans also increase in complexity if a forest has multiple owners; the greater the number of owners of a particular forest, the more difficult it is to identify ownership objectives and to manage for them. Federal agencies, forest industry companies, and other large organizations have complicated management organizations that reflect their complex objectives. Conversely, small entities such as a specialized wood products plant, a cross-country ski resort, or a farm woodlot have correspondingly smaller management infrastructures. Regardless of size, forest management generally consists of two stages, each of varying complexity: planning and administration.

To develop a forest management plan, the manager assesses the landowner's objectives and evaluates the resources available to satisfy those objectives. The manager then reviews the options available for satisfying the owner's objectives. Each option must be examined from a number of aspects, including the likely desirable and undesirable effects, the financial cost compared to the budget available, and any regulatory consequences, such as permits needed and taxes imposed. The manager then selects the options that best fit the situation and summarizes them in a written plan. The plan details the methodology and treatment schedules needed to manage each stand, and demonstrates how all the stands, when combined, will provide the resources needed to meet the owner's objectives. The manager and owner then review the manager's recommendations, as well as the options not chosen and reasons why. Once accepted by the owner, the plan is finalized and becomes the basis for future action by the manager or owner.

A management plan prepared by a consulting forester for 400 acres of family-owned land in southern Arkansas may be quite simple. A management plan for the Mountain Pine Division of Weyerhaeuser Company in west-central Arkansas will be more complicated because of the value of the wood products involved, and the mills and jobs that the woodlands must support. A management plan for a national forest, such as the Amended Land and Resource Management Plan for the Ozark National Forest in northwest Arkansas, includes detailed provisions for managing all the multiple uses required by law, and reflects the diverse interests of the national forest's landowners—the citizens of the United States.

Multiple Uses

A forest has an infinite variety of uses. Trees can be used for lumber, wooden baskets, split-bark hickory chairs, maple syrup, or supports for a hammock. An outdoor enthusiast can enjoy forest fauna by hunting deer with a rifle, rainbow trout with a fly rod, or butterflies with a camera. This inherent variety of forest resources and uses reveal the challenge to modern forest management, both in choosing which resources should be used and in giving society access to them.

In the practical sense, however, the forestry profession recognizes a standard broad categorization of resources. Easy, convenient, and commonly accepted categories are those that appear in the Multiple Use-Sustained Yield Act of 1960.

> **The national forests are established and shall be administered for outdoor recreation, range, timber, watershed, and wildlife and fish purposes.**

The Act's five categories have come to be known as *multiple uses.* The degree to which forestlands are managed for any one or more of them depends on the goals of ownership. However, because federal land is owned by the American people, the multiple uses essentially constitute a statement of the ownership objectives for the national forests. Each national forest must expressly provide an adequate supply of each of these multiple uses over a 50-year period of management.

The most dominant objective of ownership in the past has been to manage forests for timber. Timber management is often used to finance forest ownership, to support other uses more difficult to administer, or for which a financial value is more difficult to assess. In most regions of the country, trees of sawlog size bring a fairly high monetary return (Figure 9.3). Markets for smaller trees are more variable and usually depend on the species and the distance to processing facilities. These markets, if they exist, provide an opportunity to conduct treatments in young stands that improve stand condition. Finally, because trees are the dominant ecological component of a forest ecosystem, the value of nontimber resources can increase with the judicious manipulation of the timber component—or decrease by injudicious operations.

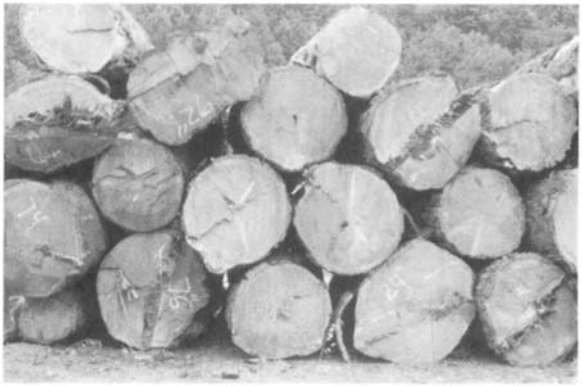

Figure 9.3 Redwood sawlogs await manufacturing into lumber at a mill in northern California. (James M. Guldin)

In certain situations, of course, the values of other resources far outweigh the value of timber. For example, the annual gate receipts at a 100-unit campground on nearly any national forest will exceed the value of the annual growth of the timber within the campground. Timber production is not economically feasible on sites that have low productivity or difficult access, such as ridge tops or swamps. On some sites, management for timber is at odds with management that requires an undisturbed or unharvested ecosystem, such as wilderness areas, national recreational trails, or wild and scenic rivers.

Forest ecosystems provide an important watershed value by serving as living filters for precipitation. Many cities and towns throughout the United States rely on forested watersheds for abundant, clean surface waters for municipal water supplies (Figure 9.4). In many arid western states, the yield of water from high-altitude forests is increased by forest management techniques that gather more snow in the winter and prolong the snowmelt period into early summer (see also Chapter 16, Watershed Management).

Federal laws require landowners to control nonpoint sources of water pollution, such as the nutrient discharges and sedimentation associated with forest management and harvesting. The most likely source of water pollution in forestry, erosion from roads, can be minimized by proper engineering practices. Erosion of soil can also occur from stream banks or skid roads if harvesting equipment crosses permanent or ephemeral streams. An effective way to minimize streamside erosion is to retain a buffer strip of trees (called a "streamside management

Figure 9.4 The Quabbin Reservoir in central Massachusetts, source of drinking water for the Boston metropolitan area. (James M. Guldin)

zone") and to exclude forest operations from this zone.

Virtually all timber management practices affect the wildlife and fish in forest ecosystems. Wildlife species tend to be associated with certain successional stages in the forest, and practices that favor one stage of forest succession are likely to favor the wildlife that thrive in that particular stage (Figure 9.5). Forest industry landowners often manage early-successional forest ecosystems that are favorable to white-tailed deer, ruffed grouse, bobwhite quail, and other species that prefer the brushy habitat mosaic. As a result, the popularity of hunting on forest industry lands has increased tremendously in certain parts of the country. Some forest industry landowners have taken advantage of this; the hunting leases in the bottomland hardwood stands along the Mississippi River in Tennessee and Mississippi provide higher annual returns per acre than the timber. Even companies that lease their land to hunters for a nominal fee can expect significant nontimber income from their forest property. Game management has always been a by-product of timber management, but these recent trends demonstrate the increasing value of nontimber uses in the marketplace.

Figure 9.5 Elk grazing in a mixed conifer stand in the Canadian Rockies. (James M. Guldin)

Forest management can also favor nongame species. It is common practice on industry and government forestlands to leave dead standing trees (called "snags") on a harvested site. In addition to the nesting habitat provided by these snags, the insect fauna that use them for food and shelter provide forage for nongame bird species.

The protection of populations and habitat for species found on the federal list of endangered and threatened species is common on public land, and growing in importance on private lands. For example, the endangered red-cockaded woodpecker, which under natural conditions requires old pines with heart rot for nesting, has not prospered under intensive sawtimber management regimes. Such regimes have a rotation age of 35 to 50 years, and few sawmills can produce good lumber from old pines with heart rot. A landowner who wants to manage for woodpecker populations must be willing to accept reduced timber income, or apply innovative approaches such as artificial nest box cavities in younger trees. Forest-wildlife management is treated further in Chapter 14.

A productive fish resource is generally achieved by promoting good water quality. Many of the practices that prevent turbidity, siltation, and excessive eutrophication of a stream will obviously benefit fish. An aquatic habitat can be quickly degraded by sudden changes in stream temperature. If the trees adjacent to a stream are cut, direct solar radiation on the water surface will increase stream temperature significantly, and may be detrimental to fish. For this reason, the use of streamside buffer strips of trees is beneficial for fish populations.

Range resources consist of the grasses commonly found within forest ecosystems. Grazing for domestic livestock, the primary use of rangeland resources, is prevalent in western forests (Figure 9.6). For example, ponderosa pine forests in the Southwest are sufficiently open for sunlight to reach the forest floor and promote development of grasses. The number of cattle that such forests can support is determined by research and practical experience. This number can be managed using rangeland allotments, which specify the number of animals allowed in specific areas during a given season. Using these methods, the range manager can balance the quality and quantity of forage with the grazing intensity, both for a given area and forest-wide. Rangeland management is given further treatment in Chapter 15.

A dramatically increasing use of forestland in the United States is for outdoor recreation. Recreational use of forest resources varies, and requires different kinds of facilities and resources (Figure 97). Examples range from organized bus tours of national parks to solo backpacking trips in the wilderness, or from a three-week transcontinental journey to a fifteen-minute stroll in the woods. Forest recreation typically centers on the ecosystem-based resources of the forest. The challenge to the

Figure 9.6 Livestock on a national forest grazing allotment in a New Mexico ponderosa pine stand. (James M. Guldin)

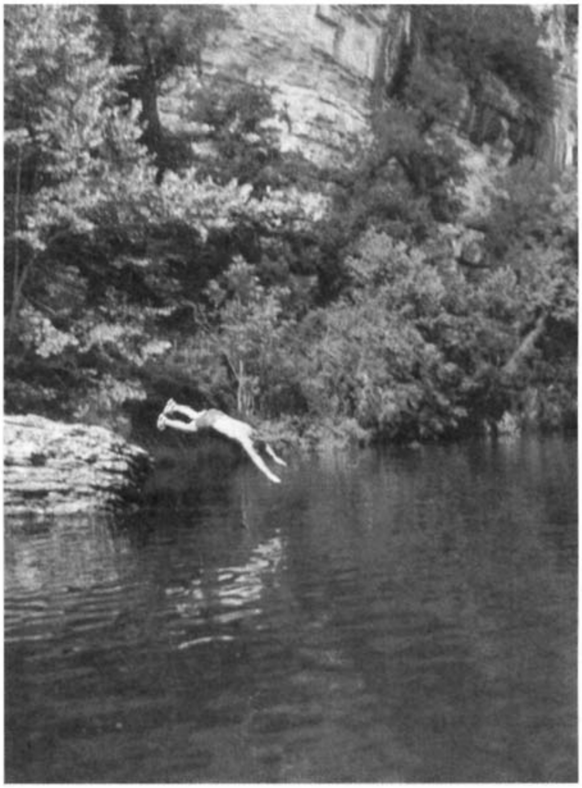

Figure 9.7 Outdoor recreational activity on the Buffalo National River in the Arkansas Ozarks. (James M. Guldin)

manager is simultaneously to maintain or enhance the quality of the forest resource, and to promote conditions that satisfy the expectations of the resource user. The factors involved in managing recreation behavior are discussed in Chapter 17.

Interactions Among Competing Uses

The concept of multiple use implies that on any given acre of forestland, the opportunity exists to utilize more than one forest resource. Forest management would be simple if the owner of the forest was interested in a single resource such as timber or recreation. Multiple use is the philosophy that a forest can support the socially desirable utilization of many different resources. This is an easy philosophy to espouse, but it can be difficult to implement.

A given pair of uses can interact in one of three ways. The interaction can be *neutral,* in that one use does not particularly affect another; a wildflower enthusiast is not likely to be affected by a nearby fisherman. The interaction may be *compatible,* such as the beneficial effects of small clearcuts on wildlife species that inhabit early-successional ecosystems. Finally, the interaction may be *incompatible:* a genuine wilderness experience is impossible in an area under intensive timber management. Clawson (6) developed a qualitative model to assess the degree of compatibility of a variety of uses. The model requires specific information about the resources being used, the manner in which they will be used, and the specific forest ecosystem constraints that apply.

Conflicts may result if multiple uses of the forest are incompatible. The conflict may be between the resources themselves, as between healthy pine trees and red-cockaded woodpeckers. When incompatibility occurs, it is necessary to separate directly conflicting resources either in space, allocating resources to different areas, or in time, allocating resources to a given area in different seasons, years, or decades. The concept of *dominant use* (7), in which one use of the forest is given relative priority over others, can be implemented with techniques such as zoning specific areas (8) and instituting seasonal controls over resources and users.

Some conflicts can occur when the techniques used to manage a particular resource are different. For example, a hiker who dislikes the visual impact of a two-year-old clearcut may not even notice a recent timber harvest in an uneven-aged stand. Under these conditions the solution may be to evaluate the range of alternative practices available for the management of the resource. The forest manager can refine or modify practices to create compatibility, such as by converting all trailside forests to an uneven-aged condition. Should this fail, it may be necessary to partition resource uses either spatially or temporally, such as by rerouting the trail or temporarily withdrawing the area from timber management.

As human populations increase, the demand for the multiple-use resources available from the forest will also increase. The challenge to forest managers is to provide a supply of forest resources that meet these projected demands and to increasingly implement the multiple-use concept on lands not restricted to a dominant or single use. Management in each of the three major ownership categories—the public forests, industry forests, and forests of the nonindustrial private landowner—must broaden its objectives. The private sector will play a key role in future resource supply, since the majority of forest land in the United States is in private hands.

Sustainability and Ecosystem Management

For most of the 20th century, forest management emphasized the timber resource. The reason is simple—pulpwood and sawlogs have been generally the highest-value products a forest can produce. Only in unusual instances do other resources rival the value of timber on a per acre basis. As a result, foresters in North America have been concerned about sustainability of timber since the rise of the profession at the turn of the century.

In the early 1900s, efforts to promote forest management were a response to concerns about widespread misuse of timber resources—abusive timber cutting practices, inadequate or no reforestation, and uncontrolled wildfire. Early attempts at forest management targeted those three issues by establishing scientific methods of timber harvest, ensuring reforestation, and controlling wildfires.

However, early forest management only ensured the sustainability of the timber resource; they did not address sustainability of other forest resources. Even if trees are properly cared for, other resources of the forests may suffer. For example, removing all the hollow trees in a stand managed for timber production would affect only a few individuals of a wildlife species that likes hollow trees; they would just look for other hollow trees in nearby stands. On the other hand, if removal of hollow trees were the standard policy for all foresters working in a large timber company or public agency, this policy would affect the numbers and distribution of the species on a much larger scale.

Research is needed on how forest management can include both the sustainability of the timber resource and the sustainability of other major resources that forests provide. However, far less is known about the needs of nontimber forest resources, because their relative value has only recently begun to be understood. This is an unfortunate byproduct of the value of timber resources relative to nontimber resources.

Many different organizations support changes in traditional approaches to forest management (9). Both public and private forestry interests have responded to this call. The National Forest System has adopted the concept of "ecosystem management," and the American Forest and Paper Association has established the "Sustainable Forestry Initiative" for managing forest industry lands. The concepts differ in some fundamental ways, but both reflect a commitment to enhance the scope of forest management beyond the usual concern with commodity production.

Ecosystem Management In 1992, the Chief of the U.S.D.A. Forest Service, F. Dale Robertson, defined ecosystem management as:

> ... **using an ecological approach to achieve the multiple-use management of national forests and grasslands by blending the needs of people and environmental values in such a way that national forests and grasslands represent diverse, healthy, productive, and sustainable ecosystems. (10)**

By this statement, the Forest Service embraced a new conceptual model for implementing the Multiple Use-Sustained Yield Act of 1960 and the National Forest Management Act of 1976.

The key to Robertson's statement is the importance given to the ecological basis for management of National Forest System lands. Traditionally, economic measures such as present net value, benefit/cost ratio, or return on investment guided forest management decisions on federal lands. Under ecosystem management, decisions are based on the ecological value they produce or sustain. Such decisions might have a secondary value economically, but the economic value is less important than whether the proposed action improves the ecological condition of the area being managed.

The most important change that underlies ecosystem management on national forest lands involves how the forester views timber production. Under ecosystem management, the focus is more on what is retained in the forest stand than on what is removed (11). The primary goal is not production of timber under optimal economic regimes, but to produce conditions in the forested landscape through stand-level actions that will maintain or restore forest health, diversity, productivity, and sustainability. Rather than harvesting simply to cut timber, harvesting is designed to achieve specified attributes in the forest that remains. These stand-level actions may produce timber as a byproduct, but the intent that underlies a practice is an ecological one.

Forest health is a key aspect of ecosystem management. If the concept of ecosystem management started anywhere, it was during the Yellowstone National Park fires of 1988. More than any recent forest event, the Yellowstone fires revealed that continued efforts to suppress fire in fire-adapted ecosystems were doomed to fail, and

Sidebar 9.1

Ecosystem Management in Action

A good example of ecosystem management in action is the restoration of shortleaf pine-bluestem in the Ouachita Mountains of western Arkansas. Consider an 80-year-old shortleaf pine stand on national forest land in west-central Arkansas. Traditional economic analyses would suggest the stand is economically mature, and should be subject to reproduction cutting. However, under ecosystem management, a district ranger might consider a different decision—to restore the pine savanna community described in early reports from the region.

Silvicultural tactics for pine savanna restoration include: 1) extending the rotation for pine sawtimber to 120+ years, 2) thinning the stand from below so as to reduce susceptibility to southern pine beetle, 3) undertaking a program of midstory hardwood control to eliminate the understory hardwoods that have sprung up in the 60-year period during which fires have been excluded from these sites, 4) reintroducing periodic prescribed fires to reestablish the native prairie flora such as the big bluestem grass and purple coneflower, and 5) installing artificial cavities in some of the pines for use by the endangered red-cockaded woodpecker. Through this decision, the ecological goal of restoring the pine-bluestem habitat, an underrepresented plant community in the area, is achieved, while still providing timber from the thinning to the local forest products economy, bobwhite quail for local hunters, and red-cockaded woodpeckers for local birdwatching enthusiasts.

A typical stand of shortleaf pine in Arkansas, prior to shortleaf pine-bluestem habitat restoration treatments.

The practice has the benefit of creating nesting and foraging habitat ideal for the endangered red-cockaded woodpecker. Yet, the area remains a place where an active program of timber production can still have a place, through periodic thinning and, ultimately, reproduction cutting in the shortleaf pine overstory. The project has elements of forest health, diversity, productivity, and sustainability, and the implementation of creative management tactics to achieve restoration. However, even in such restoration work, the immediate needs of habitat restoration and

A different stand of shortleaf pine, which has been treated by midstory removal and restoration of a regular cycle of prescribed fire. (James M. Guldin)

recovery must include provisions to ensure a sustainable supply of those habitats over the long term. For example, the endangered woodpecker requires an adequate area in stands of suitable age and structure to provide nesting habitat, roughly defined as from 90 to 120 years old. Suitable foraging habitat for the bird can be obtained in stands from 30 to 120 years old. However, these stands do not remain static in age; over time, they will grow and mature. Young stands between 0 and 30 years in age must be established and managed as the replacement stands to fulfill future foraging needs in three to nine decades, and future nesting needs 9 to 12 decades down the road.

Thus, for long-term sustainability of the shortleaf pine-bluestem habitat, plans must be made to keep about 25 percent of the area in suitable nesting habitat, and an additional 50 percent in suitable foraging habitat. The last 25 percent in stands must be managed as very young stands between 0 and 30 years in age—a continuous supply of replacement stands for future foraging and nesting needs.

in a spectacular manner. Today, considerable effort is being made in the West and South to restore fire to fire-adapted ecosystems, either by deliberately setting understory burns (called "prescribed fires") or by allowing natural ignitions such as isolated lightning strikes to burn under controlled conditions (Figure 9.8). In both instances, foresters will limit fires to a specified area under manageable weather conditions.

Concerns about forest health in the context of ecosystem management include situations where past management practices have a negative effect on current forest conditions. For example, some managed forests in the West consist of dense, overstocked young stands of pine. Trees in such stands have low vigor, and as a result are highly susceptible to attack by insects such as the mountain pine beetle. Forest managers must choose either to develop tactics to reduce overstocking, or to allow the mountain pine beetle to do so in a way that may have unacceptable impacts within the given watershed.

Figure 9.8 Prescribed fire in a loblolly pine stand on forest industry land in southern Arkansas. (James M. Guldin)

Ecosystem management is a framework for emphasizing species diversity through habitat restoration, using methods such as thinning and prescribed fire to restore patterns and processes that have been absent in a given habitat. The target is not one specific habitat, but a spectrum of conditions that would result from varying the intensity and timing of prescribed fires and would reflect the range of naturally occurring variation in ecosystem structure and function.

Finally, sustainability is as important under an ecosystem management scenario as it is under a more traditional timber-oriented approach to forest management. Timber sustainability can be defined as a function of the species composition and age of stands, and the cumulative area occupied by stands of different ages. These factors can also define the desired ecological habitats and conditions under ecosystem management. Thus, development of a balance of habitat conditions is as important a goal under ecosystem management as it is when timber production is a primary goal of management. Incorporating precise, quantitative descriptions of forest conditions is necessary to determine sustainability, whatever the goal of management.

Foresters working under ecosystem management are likely to face greater challenges than were faced by traditional timber-oriented forest managers. Many of these challenges are beyond the forester's control. The past 40 years have been marked by detailed Congressional legislation and by the actions of different presidential administrations, as illustrated by Robertson's ecosystem management letter in 1992 and the changes in national forest planning regulations proposed by President Clinton in 1999. These Congressional and administrative shifts in forest management policy and process reflect society's shifting attitudes toward forest management. While 40 years constitutes a long professional career for a human being and a period of 10 presidential administrations in our constitutional democracy, it is just a third of the time required to develop a regulated shortleaf pine-bluestem habitat over a large area.

As a result, it is best not to think of ecosystem management as a replacement for more traditional forms of timber-oriented forest management, but rather as the next step in the evolution of the overall theory of forest management on federal lands over time. Society, Congress, or some future administration may well come up with ways to refine or replace ecosystem management. The most realistic perspective may well be to consider ecosystem management as the latest in a long line of philosophical views that have been and will be developed to better capture society's goals for the nation's forests.

Sustainable Forestry Initiative In the 1990s, forest industry landowners sought to play a leadership role in forest conservation on the lands that they own or manage. The result was a program called the Sustainable Forestry Initiative, which was established in 1994 by the American Forest and Paper Association (AF&PA), the nation's most influential forest industry trade association.

Under the principles of sustainable forestry, AF&PA members agree to use responsible forestry practices, maintain forest health and productivity, protect special sites, and continuously improve the practice of forest management (Figure 9.9). The guidelines that member companies follow on their own lands, and encourage landowners from whom they buy timber to follow on their lands as well, include requirements for an independent expert review of compliance, public reporting of compliance, and support of public forest policy goals for sustainable forestry

Central to the program are eight public policy goals for sustainable forestry on private and public lands. These goals include increasing growth and timber quality of forest lands, implementing appropriate ecosystem management on federal lands, reducing the risk and occurrence of wildfires, practicing integrated pest management, encouraging research on forest health and productivity, promoting continuing education in forest resources, recognizing members and others who practice sustainable forestry, and working to help all private landowners manage forests in a sustainable manner.

Figure 9.9 A streamside management zone separates pine plantations of different age classes on forest industry land in central Arkansas. 0ames M. Guldin)

It is difficult to say as yet how the Sustainable Forestry Initiative will change the practice of sustainable forestry on private lands. For example, one specific objective of the Initiative is for loggers to enroll in training courses on how to prevent erosion, stream sedimentation, and other adverse ecological effects. However, it is not clear whether this training actually leads to the desired on-the-ground improvement in harvesting practices. Similarly, member companies can agree to independent monitoring to ensure that company lands are being promptly reforested. Initiative guidelines cannot be required on outside lands that a company harvests but does not own; that decision must be made by the landowner. Like public forest managers, AF&PA members face challenges that are beyond their immediate control. Time will tell how much of an influence the Sustainable Forestry Initiative and similar efforts will have on the management practices of private landowners.

Forest Owners and Ownership

The most fundamental tenet in the practice of forestry is this: the landowner, not the forester, determines the objectives of management. The task of the forester is to implement the landowner's objectives by developing and administering a forest management plan. Foresters can and should use their professional expertise to suggest management objectives and alternatives to the landowner. At times, foresters may even be called upon to convene and facilitate discussions among landowners or with the public about land management objectives. However, the ultimate decision-making authority on forest management objectives generally rests with the landowner.

By no means does every forest landowner have or want every multiple use on his or her forest land. Owners of forest industry lands often accommodate hunting and other nontimber uses as long as they have no worse than a neutral effect on timber production. Conversely, the nonindustrial private landowner may have objectives that are not clearly defined, and that may be oriented either to a specific single use or to a specific subset of the multiple uses. Lands managed by the Forest Service are expected to provide for multiple uses at the ranger district level (generally between 50,000 and 200,000 acres) through land and resource management plans for each national forest. Thus, ownership patterns often define the uses of forests in each region of the country.

Land Ownership and Distribution

About a third of the United States is forest land—302 million hectares (747 million acres) (Table 9.1). The rest is either rangeland or other land, which includes farmland and urban and suburban areas. The 302 million hectares of forest today is about two-thirds of the land area that was forested in 1630, leaving some 123 million hectares (304 million acres) that has since been converted to agriculture and other uses. About 75 percent of the land conversion from forests to agriculture occurred in the 19th century. Between 1850 and 1910, American farmers cleared more forest than had been cleared in the previous 250 years of settlement—about 77 million hectares (190 million acres). By the 1920s, the clearing of forests for agriculture had largely ceased (12). The 1930s to 1950s saw a considerable reversion of agricultural land to forestland, especially in the South. However, those gains in forestland were largely offset by suburban expansion and other developments.

Forestland is subdivided into three categories. *Timberland* is defined as forestland that is 1) capable of producing more than 1.4 cubic meters per hectare per year (20 cubic feet or 0.25 cords per acre per year) of industrial wood under natural-stand conditions, and 2) that is not allocated to nontimber single uses. The land may or may not be under any program of forest management, but would exceed the indicated volume growth if it were. Today, about 204 million hectares (504 million acres) are classified as timberland. The northern and southern regions contain about 69 percent of the total forestland, and about 75 percent of the timberland in the United States (Table 9.2). Within these regions timberland constitutes more than 90 percent of the total forestland base.

Reserved forestland is sufficiently productive to be timberland, but it has been allocated to specific nontimber uses such as wilderness areas, wildlife sanctuaries, and national parks. About 21 million hectares (52 million acres) of timberland (7 percent of total forestland; 9 percent of total timberland) are classified as reserved forestland, a significant resource legacy for future generations.

Other forestlands consist of slow-growing forests that are not capable of producing 1.4 cubic meters per hectare per year. Although these lands are not productive for timber, they are valuable to society for many other uses, including watershed protection, wildlife habitat, grazing, and recreation. About

Table 9.1 Land Area in the United States, 1997 (12)

Type of Land	Total Area *(million hectares)*	Proportion *(percent)*
Timberland	204	22
Reserved Forestland	21	2
Other Forestland	77	8
Total Forestland	302	33
Other Land	614	67
Total Land Area in U.S.	916	100

Table 9.2 Land Area in the United States, by Section and Type of Land, 1997 (12)

Type of Land	Total *(million hectares)*	North *(million hectares)*	South *(million hectares)*	Rocky Mountains *(million hectares)*	Pacific Coast *(million hectares)*
Timberland	204	64	81	29	29
Reserved Forestland	21	3	2	7	9
Other Forestland	77	1	4	22	51
All Forestland	302	69	87	58	89
Other Land	614	98	130	242	143
Total Land Area in U.S.	916	167	217	300	232

77 million hectares (26 percent of forestland) fall in this category. More than half is in Alaska and most of the rest is west of the Great Plains, ranging from arid lowland pinyon-juniper forests to high-altitude, slow-growing coniferous forests.

The National Forest System manages 19 percent of the nation's timberland, three-quarters of which is located west of the Great Plains. When national forests were created from unclaimed public lands 100 years ago, much of the lower elevation, more accessible, and productive land had already been claimed by railroads, settlers, and sawmills. Consequently, national forests tend to be on steeper terrain, at higher elevations, and have lower productivity than private timberland (12).

Although timberland on national forests is important to the economies of many communities, the timberland in private ownership plays a much larger role in meeting America's wood and fiber needs. Only 13 percent of the nation's timberland and 12 percent of the softwood growing stock is owned by forest industry, while industry timberlands provided 30 percent of the volume harvested in 1996. More than half these industry timberlands—53 percent—are located in the South, an important region in the timber economy of the nation. Most of the timberland in the United States—almost 60 percent—is owned by private individuals whose major source of income is not from their forestland. These nonindustrial private forest owners, to whom special attention is given in Chapter 10, own 71 percent of the timberland in both the heavily populated North and the timber-dependent South.

Volume, Productivity, Growth, Mortality, and Removals

In 1997, America's timberland contained an estimated 25.3 billion cubic meters (905 billion cubic feet) of timber, of which 92 percent is in growing stock—live, sound trees suited for roundwood products (12). Coniferous softwoods account for 58 percent of growing stock. Softwood volume is up 12 percent since 1953, 7 percent since 1987. Western forests contain 68 percent of the nation's softwood growing stock, primarily because conifers comprise 90 percent of the growing stock in western forests. Three-quarters of these western coniferous forests are on federal lands. In contrast, more than 90 percent of the hardwood growing stock in the United States is found in the northern and southern regions. Most of this volume is on nonindustrial private land, and it varies greatly in quality.

Productivity is measured by the mean annual growth obtainable from fully stocked natural stands, a definition that varies depending on the species and site condition. Of the 302 million hectares of forestland in the United States, 73 million hectares (24 percent) are capable of producing in excess of 5.95 cubic meters per hectare (85 cubic feet per acre) annually. Half of this most productive land is in the South. Another 131 million hectares (43

Sidebar 9.2

Forest Inventory and Analysis Web Site

The power of the Internet is increasingly apparent in the federal forestry research program. No better example can be given than the National Forest Inventory and Analysis web site of the Forest Service. This web site (www.srsfia.usfs.msstate.edu) gives access to the national data base upon which Forest Inventory and Analysis state reports are prepared.

The advantage of this web page is that it enables users to customize their requests for data. For example, suppose the user is interested in building a wood-processing facility, and needs data on the availability of conifers on private lands within a given radius of the proposed location. The data entry provisions on the web page would produce the standard set of 25 tables typically found in a state report, but the tables would contain only the data specified in the parameters selected by the user. The summary tables are automatically opened in the web browser and can then be printed locally by the user.

An easier way to access inventory data—and to do so with ability to specify the area, variables, and constraints in which the user is interested—has long been a desired product from Forest Service research. This web page goes a long way toward fulfilling that promise.

percent) of forestland are capable of producing between 1.40 and 5.95 cubic meters per hectare (20 to 85 cubic feet per acre) annually. About 73 percent of this medium productivity land lies east of the Great Plains. On the 77 million hectares classified as Other Forestland, productivity is less than 1.40 cubic meters per hectare annually. Over 90 percent of these lands are west of the Great Plains and comprise over half of western forests. Reserved forestlands are not classified for productivity.

Growth has exceeded harvest in America since the 1950s, so the volume of growing stock on U.S. timberland has increased considerably the past 5 decades. Between 1953 and 1997, the net volume of hardwood growing stock increased 90 percent to 9.9 billion cubic meters (350 billion cubic feet). The hardwood volume in trees greater than 48 centimeters (19 inches) in diameter more than doubled, from 74 million cubic meters to 158 million cubic meters. For softwoods, the net volume increased 35 percent to 13.7 billion cubic meters (484 billion cubic feet), but the softwood volume in trees larger than 48 centimeters in diameter declined 6 percent. Combining both hardwoods and softwoods, net per-hectare volume rose in the 1953-1997 period in all regions—doubling in the North, increasing 76 percent in the South, rising 27 percent in the Rocky Mountains, and up 2 percent in the Pacific Coast region. Western increases were lower than the East because much of the timberland stocked with high volumes of mature or overmature timber was either harvested and regenerated with young stands, or it was shifted to the reserved forestland category (12).

Mortality is the growing stock volume that dies annually from natural causes, such as insect and disease attacks, suppression beneath the forest canopy, forest fires, windthrow, and catastrophic events. Mortality is a part of every ecosystem. In otherwise healthy stands, mortality normally ranges from 0.61 to 0.85 percent of growing stock volume. Individual dead trees are usually left standing because they are widely scattered and cannot be economically removed. Occasionally, hurricanes and other catastrophic events result in a high mortality in a localized area. In Table 9.3, mortality has already been subtracted from gross growth to obtain net growth.

Removals, which measure the growing stock volume removed from timberland, include volume removed during forest operations such as precommercial thinnings or commercial harvests, as

Table 9.3 Net Annual Growth and Removals from Growing Stock in the United States, 1996 (12)

Section and Item	All Species (million cubic meters)	Softwoods (million cubic meters)	Hardwoods (million cubic meters)
North:			
Net growth	152	33	118
Removals	79	19	60
Growth-removal ratio	1.93	1.75	1.99
South:			
Net growth	303	167	137
Removals	288	183	105
Growth-removal ratio	1.05	0.91	1.30
Rocky Mountains:			
Net growth	70	57	14
Removals	15	14	0.8
Growth-removal ratio	4.69	4.00	16.03
Pacific Coast:			
Net growth	144	126	18
Removals	72	68	3
Growth-removal ratio	2.01	1.84	5.64
United States:			
Net growth	670	383	287
Removals	454	285	167
Growth-removal ratio	1.48	1.34	1.70

well as wood removed during conversion from forest to nonforest land uses. In 1996, timber removals in the United States totaled 454 million cubic meters in comparison to total net growth of 670 million cubic meters (Table 9.3). Put another way, American forests grew 34 percent more softwood volume and 70 percent more hardwood volume than was harvested.

The South, with 64 percent of the total volume removed, has been the preeminent timber supply region in the United States for the past two decades. Its share has grown even larger with recent declines in harvesting on the public forests in the West. In several southern states, such as Louisiana, the economic value of the timber harvest exceeds the value of any other agricultural crop. But the softwood resource in the South, where removals exceeded net growth by 10 percent in 1996, will not be sustainable unless productivity increases or harvesting decreases.

Timber harvest on nonindustrial private forest lands increased by about 17 percent between 1986 and 1996, largely in response to continuing pressure to reduce harvests on national forests and other public lands (12). Nonindustrial private forest lands provided 59 percent of all timber volume harvested in 1996 compared to 30 percent from forest industry lands. The national forests accounted for only 5 percent of timber harvested in 1996, down from 13 percent in 1987. Other public lands—primarily state and county forests and Bureau of Land Management lands—accounted for the remaining 6 percent of removals.

As America's population grows in the 21st century, the nation's ability to meet its increasing wood and fiber needs depends on increasing the productivity of privately owned forestlands. Forest industry firms are investing substantial sums in increasing the productivity of their own lands and managing them on a sustainable basis. Nonindustrial private forestland owners usually need financial assistance to make equivalent investments, and professional advice on the latest scientific findings and technologies available for increasing productivity and managing as sustainably as industrial forest enterprises.

These statistics illustrate the challenge to sustainable forest management over the next several decades. Projections indicate that the forest resources desired by society, including timber, will surely increase as our country's population grows. Despite making major increases in productivity and putting increased emphasis on sustainable forest management, forest industry lands will be hard-pressed to meet projected increases in demand for softwoods two to three decades from now. Recent declines in softwood harvests on public lands have increased the pressure on nonindustrial private forestland owners to harvest available softwoods, and on forest industry to import softwoods from other countries. Further, access to nonindustrial private forestlands, also home to two-thirds of the hardwood growing stock, is becoming more difficult as the number of owners proliferates, and average tract size shrinks. Also, the pressures for access to forestlands for timber production are increasingly in conflict with forest values that arise from non-timber forestland uses.

These are the conflicts facing American forests, their owners, and their managers in the 21st century. The challenges have spawned an intense national debate over the future of both public and private forests. Two examples are the 1998 report by the National Academy of Sciences on prospects and opportunities for sustainable management of America's nonfederal forests (13) and the 1999 report by a committee of scientists who issued recommendations for stewardship of the national forests and grasslands (14). The recommendations in these two reports have helped define the forms of stewardship that should be provided for America's forests in the 21st century.

Stewardship of Public Lands

Approximately 30 percent of the nation's 302 million hectares of timberland is controlled by public owners. Four federal agencies have land management as their primary responsibility: the Forest Service of the Department of Agriculture, the Bureau of Land Management (BLM), the Fish and Wildlife Service, and the National Park Service of the Department of the Interior. Of these four agencies, the Forest Service manages 25 percent of the federally controlled forest and rangeland and the BLM 62 percent. However, the Forest Service is responsible for approximately 80 percent of the federal commercial timberland. All the BLM lands are located in the thirteen western states, mostly in the two states of Alaska and Oregon. These agencies all have other responsibilities as part of their mission. These may include educating the public about resource management options, or assisting and encouraging good management practices on private lands.

Two other federal agencies play a lesser role in land management. The Natural Resources Conservation Service (formerly the Soil Conservation Service) within the Department of Agriculture is the lead federal conservation agency for private forest land. The Department of Defense manages forestland on military reservations; although activities such as grazing, timber production, and wildlife management are permitted on some of these lands, they are primarily managed for defense purposes. It also supports the U.S. Army Corps of Engineers, which provides extremely important recreation opportunities on the nation's inland waterways.

Several other federal agencies directly administer forestlands and rangelands for various purposes, depending on the agency's particular responsibilities. Approximately 10 percent of the public forestland and rangeland is administered by federal agencies for which forestry functions are generally minor or incidental to their major responsibilities. They include the Departments of Commerce and Treasury, the State Department, the Environmental Protection Agency, the U.S. Agency for International Development, the Agriculture Research Service, the Natural Resources Conservation Service, and the Cooperative State Research Education and Extension Service.

Finally, at the state level, forest management is generally coordinated through an appropriate department or commission. At local levels, county commissions or municipal authorities manage forests within their jurisdiction, such as those affiliated with public schools.

Figure 9.10 A wilderness area overlook on the Ouachita National Forest in eastern Oklahoma. (U.S.D.A. Forest Service)

Forest Service

The USDA Forest Service is the major forest management agency within the federal government. Its origins lie in the Department of Agriculture, which established a Division of Forestry in 1876, and the Department of the Interior, which managed the nation's system of forest reserves through its Forestry Division of the General Land Office. In 1905, under the administration of Theodore Roosevelt, these agencies were combined to form the Forest Service, within the Department of Agriculture. Gifford Pinchot—a professional forester, conservationist, and associate of Roosevelt—was appointed to be the first Chief.

Today, the Forest Service manages 155 national forests, 20 national grasslands, and a variety of smaller holdings in the National Forest System, totaling over 77 million hectares (192 million acres) of land—roughly 8.4 percent of the land area of the United States, and 34 percent of the land area in the United States managed by the federal government.

The mission of the Forest Service is "Caring for the land and serving people," and reflects the longstanding commitment of the agency to conserve natural resources while providing for the needs of society (Figure 9.10). To fulfill its mission, the Forest Service takes an ecological approach to the management of national forests and grasslands, to ensure a sustainable supply of timber, wildlife, water, recreation, and forage resources. This is done by developing and implementing Land and Resource Management Plans, which outline the exact goals and means by which any given national forest or grassland will be managed.

The Forest Service has a number of other important responsibilities. Its Research and Development program—the largest forestry research organization in the world—conducts research in forest resource management and conservation. State and Private Forestry is responsible for working with state forestry agencies and private landowners to enhance management of private forest lands in the nation, including support for forest health protection, rural economic development, and assistance with improved management practices on nonindustrial private forest lands. International Forestry is responsible for working cooperatively with foreign governments to promote forest resource conservation in the United States and abroad.

The Forest Service has the most advanced system of planning and administration of virtually any public or private forest management agency in the United States. This is not surprising, given the federal mandate for multiple use and the varied clientele inherent in public ownership. Guidance

Sidebar 9.3

Committee of Scientists Report

The National Forest Management Act of 1976 (NFMA) requires the Secretary of Agriculture to develop, maintain, and revise land and resource management plans for the National Forest System. Acts like this are implemented through federal regulations and internal agency directives. The regulations and directives provide guidance to planners and decision makers. The original regulation implementing NFMA was published in 1979 and revised in 1982. That regulation guided the first round of forest planning. In 1998, the Secretary of Agriculture decided to appoint a Committee of Scientists to offer recommendations on how to revise and update the federal regulation.

The Committee spent a year reviewing innovative examples of natural resource planning and management throughout the Forest Service and meeting with citizens, state and local government officials, leaders of Indian tribes, and employees of the Forest Service and other federal agencies. In their report, the Committee recommended a new vision for the Forest Service. They called for making sustainability—ecological, social, and economic—the foundation for planning and decision making. They reaffirmed that only through collaborative problem solving, where all interests are at the table and all viewpoints considered, could complex natural resource issues be resolved. They proclaimed that the best available scientific information should be used in the planning process, and they called for more involvement of the scientific community. Finally, they envisioned forest plans as "living" documents that are easy to amend and revise.

for current management of the National Forest System can be found in the Multiple Use-Sustained Yield Act of 1960, the Renewable Resources Planning Act (RPA) of 1974, and the National Forest Management Act (NFMA) of 1976. The RPA charges the Forest Service to conduct an economically based assessment that allocates forest resources among their many conflicting uses (15), and the NFMA ensures a scientific basis for management and for both scientific and public input into the planning process (16).

Planning within the Forest Service occurs at national, regional, and local levels. The Chief of the Forest Service develops long-term national goals, programs, and production levels for management of the national forests based on data generated by the RPA assessment. Regional contributions to national goals are based on regional supply of and demand for resources. Within each region, standards and guidelines are formulated on the basis of regional RPA assessments; these standards and guidelines are expressed as long-range program objectives and production levels for individual national forests within the region. At individual national forests, the planning team summarizes the management situation, establishes long-term goals and objectives, specifies in detail a plan of activities that will be conducted throughout the 10-year planning horizon for each alternative proposed, selects the desired alternative through public input and consideration of associated environmental impacts, and establishes a program to monitor plan implementation. The management plan for a national forest typically provides general directions for forestwide management and specific directions for implementing the selected alternative.

National Park Service

National Park management is probably the oldest federal forest management program. In 1872, Congress established Yellowstone National Park by withdrawing it from the public-domain lands that had been open to entry for homesteading. The early Parks were under the protection and administration of the Department of the Army. The National

Park Service (NPS) was established in 1916 within the Department of the Interior, and was given responsibility for management for the network of National Parks and Monuments.

Today, the National Park System consists of 378 areas covering more than 32 million hectares (80 million acres) in the United States and its territories. The mission of the National Park Service is to conserve the scenery and the natural and historic objects and values of the lands under its administration, and to ensure their conservation for future generations (Figure 9.11). They are not used for production of forest products, as are national forest lands. Lands in the National Park System are of such national significance as to justify special recognition and protection in accordance with various acts of Congress. The system includes not only the large National Parks such as Grand Canyon and Yellowstone, but also National Monuments, Preserves, Historic Sites, Historic Parks, Memorials, Battlefields, Cemeteries, Recreation Areas, Seashores, Lakeshores, Rivers, Parkways, and Trails.

Additions to the National Park System are generally made through acts of Congress or by executive order of the President. Under the Antiquities Act of 1906, the President has the authority to proclaim an area as a National Monument without the support of Congress, and many areas now famous within the National Park System were initially protected under this Act by Theodore Roosevelt. In the last year of his administration, President Bill Clinton used this act to set aside many additional natural areas. However, the power to establish a new National Park resides with Congress, in collaboration with the Secretary of the Interior.

Lands in the National Park System are maintained in an essentially intact condition. The challenge in this approach is that forests do not remain static. For example, the decision to suppress forest fires in western forests results in the accumulation of woody debris on the forest floor, which can lead to catastrophic wildfires. As a result, land managers are increasingly using ecological practices such as prescribed burning, fuel reduction, and habitat restoration to better manage the successional dynamics of forest stands—and thereby to maintain the health, diversity, and beauty of forest ecosystems in the National Park System.

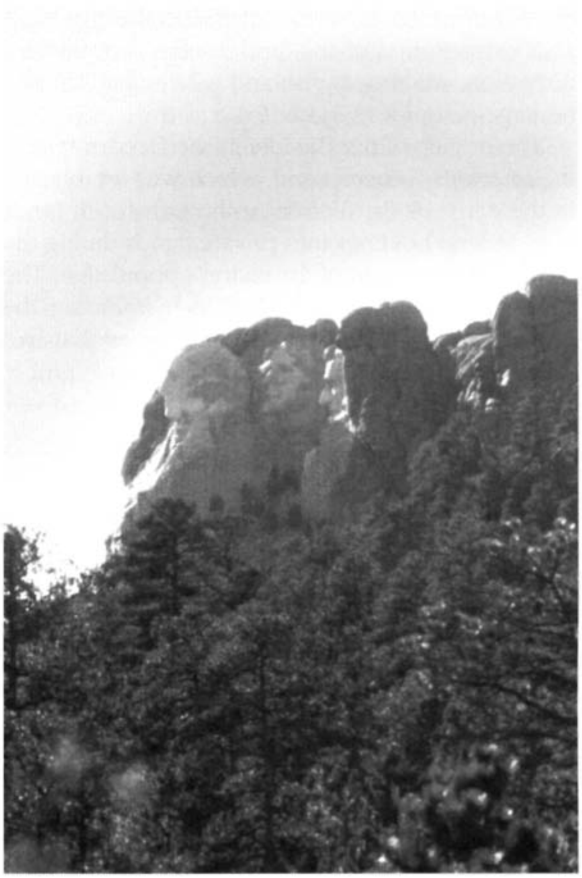

Figure 9.11 The mission of the National Park Service includes conserving both the natural and historic objects under its care, illustrated by this view of Mount Rushmore and the surrounding forest. 0ames M. Guldin)

Bureau of Land Management

The Bureau of Land Management (BLM) is responsible for managing 107 million hectares (264 million acres) of land in the United States. Major BLM holdings are in the extensive grasslands and noncommercial forestland in the West. Management practices on BLM lands include mineral exploration and extraction, grazing and timber production, recreation, wilderness, fish and wildlife habitat, and heritage resources (Figure 9.12).

The origins of the BLM lie in the Department of the Interior's General Land, which was established in the early 1800s to oversee the transfer of lands from federal holdings into private hands during the westward expansion of the nation's population. The BLM was established in 1946 by combining the General Land Office with other agencies that had responsibilities for managing the remaining federal land base in the West.

The BLM mission is to manage the lands it administers under a multiple-use framework. This mission is complicated by the increasing value that society places on recreation, conservation, and non-consumptive resources. Mining, grazing, and timber production continue to be important, but these objectives must now be integrated with the other multiple uses that do not involve extraction of resources.

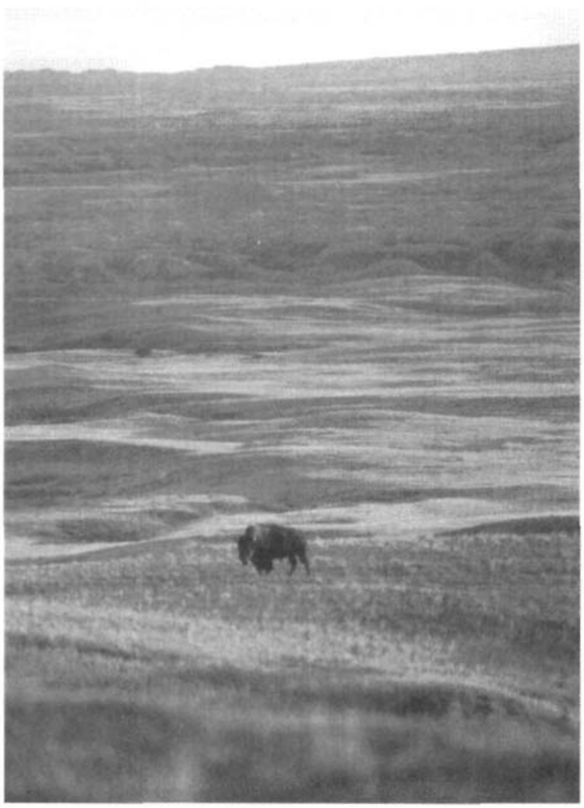

Figure 9.12 Buffalo on grasslands managed by the Bureau of Land Management in western South Dakota. (James M. Guldin)

U.S. Fish and Wildlife Service

The U.S. Fish and Wildlife Service, under the Department of the Interior, is responsible for managing and conserving fish and wildlife and their habitats for the benefit of present and future generations. The agency has important program responsibilities for migratory birds, endangered species, some marine mammals, and both freshwater and anadromous fish species,[1] either through direct management or through leadership in international conservation programs for migratory waterfowl and fish.

The agency manages a network of over 520 National Wildlife Refuges, encompassing over 37 million hectares (93 million acres). The majority of these are located in Alaska, but there is at least one National Wildlife Refuge in each of the 50 states. The refuges provide critical habitat for native species of plants, animals, and fish, especially for endangered and threatened species. However, the refuges are also important for recreation and conservation education, as shown by the 25 million people who visit annually.

A major program of the agency is to identify, protect, and restore the roughly 700 plant and animal species that have been identified as endangered or threatened under the provisions of the Endangered Species Act. The listing or de-listing of a species is conducted under rigorous scientific scrutiny, with

[1] Anadromous fish species—those ascending upriver from the sea to spawn, such as salmon.

opportunities for public comment. When a species is listed, the agency works with landowners to develop management plans for population and habitat conservation.

Natural Resources Conservation Service

The Natural Resources Conservation Service (NRCS), formerly known as the Soil Conservation Service, is the primary federal agency responsible for conservation leadership on private lands in the United States. The NRCS has no land of its own to manage, but provides advice and program access for use in managing forests on private and nonfederal government lands. The agency traces its roots back to 1935, when the SCS was established to support conservation on private lands during the difficult years of the Depression.

The NRCS is responsible for the Forestry Incentives Program (FIP), the Conservation Reserve Program (CRP), and the Wetland Reserve Program (WRP). Each of these programs is administered and funded in slightly different ways, but they share a common goal—to assist private landowners in forest management and conservation through technical advice and financial assistance. The technical advice is usually in the form of guidance about forestry practices that qualify for federal support. If a site qualifies for assistance, management plans are prepared by foresters with NRCS or state forestry and wildlife agencies; funds are then provided to help support the financial costs of implementation, usually through some form of cost-sharing.

For example, reforestation of erosion-prone agricultural fields was a priority in the late 1990s. To determine if a particular field or pasture qualifies for assistance, a farmer might contact a county NRCS employee, county forester or state extension agent. That professional would check the site, prepare the management plan, and submit it to the NRCS for approval. If approved, federal funds will be provided to support some percentage, typically half, of the cost of the tree planting.

The NRCS works closely with state forestry and conservation agencies and private landowners to communicate the availability of program funds, to identify areas that would be of high priority for support, and to advise landowners on the conservation practices that would benefit their land. Thus, the agency best achieves its mission by providing support to landowners who want to learn more about the conservation of their land.

U.S. Army Corps of Engineers

It may seem unusual to include the U.S. Army Corps of Engineers in the list of organizations responsible for forest management on federal lands. However, most forest recreation activities involve water, and the Corps of Engineers manages over 450 manmade lakes covering nearly 5 million hectares (12 million acres). Specific legislation authorizes the Corps of Engineers to provide public outdoor recreation opportunities at these facilities (Figure 9.13).

The Corps of Engineers is the largest provider of water-based recreation in the nation. It supports over 4300 developed recreation sites, approximately 30 percent of the total found on federal lands. Annually, Corps recreation facilities support 350 million visits; about 10 percent of the population of the United States makes at least one visit per year to a Corps of Engineers recreation site.

Figure 9.13 Lake Ouachita, a U.S. Army Corps of Engineers impoundment in west-central Arkansas. (U.S.D.A. Forest Service)

Nationally, there is growing awareness that the Corps of Engineers serves a large user population and makes a significant contribution to the U.S. economy. Coupled with this is the awareness that increased support is needed to improve facilities, maintain the waterways, and manage forests adjacent to these bodies of water to enhance forest health and watershed values.

State Agencies and Other Organizations

State forestry and wildlife agencies are responsible for managing state-owned forest resources such as state parks, forests, and wildlife areas. The organization of state agencies depends largely on the amount of forestland and the importance of forestry within the individual state. States that have extensive state forest lands, such as California, Oregon, and Washington, have large forestry agencies and comprehensive procedures for management of state forest lands (Figure 9.14). In other states, activities emphasize control of wildfires, which is a major responsibility in the South. Most states also provide advice on forest management to owners of nonindustrial private forestlands.

Figure 9.14 Redwoods in Humboldt Redwoods State Park, northern California. (James M. Guldin)

Stewardship of Private Lands

Forest ownership in the United States is dominated by the private sector, which includes both forest industry and owners of nonindustrial private forest (NIPF) lands. Because of their importance, the NIPF sector is discussed in a separate chapter (Chapter 10).

Forest Industry

Forest industry lands are those lands owned by companies or individuals that also operate wood processing plants (17). The mission of a typical forest industry is to satisfy company goals and provide favorable economic returns to the company owners or stockholders. Their size may range from a small open sawmill with a few thousand hectares of land to multinational, multiproduct conglomerates operating several dozen mills, employing thousands of people, and owning millions of hectares of productive forestland. As a result, management of lands owned by forest industry differs greatly from that of public lands.

The organization of administrative efforts also varies. Some companies employ a chief forester and staff to implement production quotas and forest management programs. Others are organized within a woodlands division, generally headed by a vice-president and subdivided into management districts (about 20,000-50,000 hectares in size), each managed by one or two foresters and a crew of technicians.

Within the company the woodlands division may exist as a separate profit center, required to show acceptable returns on all its investments from stand establishment through harvest, or the woodlands division may be part of a vertically integrated profit center, in which financial losses are acceptable if they create profit-making opportunities elsewhere or otherwise contribute to the company's goals.

A hallmark of management on forest industry lands is keen attention to productivity and growth. Practices commonly found on industry lands include the establishment of plantations using genetically improved seedlings that are bred for traits such as rapid growth and disease resistance. Seedlings are planted at precise spacing to optimize growth. The use of fertilizers to enhance early seedling growth, and herbicides to control competing vegetation (Figure 9.15), is also common. As stands mature, thinnings maintain proper spacing between trees and optimize stand volume growth (Figure 9.16). Harvests are scheduled so that the size and volume of harvested trees meet mill requirements.

A major goal of the woodlands division of the typical forest industry is to provide an even flow of wood products to the mill. Shutting down a mill for want of raw material is enormously expensive, so industry foresters develop detailed plans to ensure a continuous flow of timber from the forest to the mill. A company's mill managers and foresters occasionally disagree about harvesting priorities in the forest, if events such as unusually wet weather or labor difficulties require logging during marginal conditions of operability, access, or when stands are not yet of optimal rotation age.

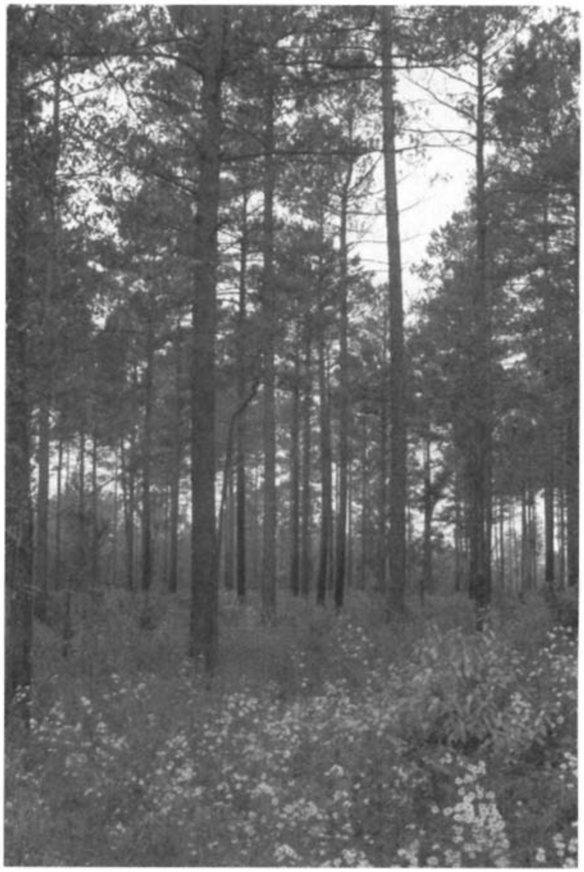

Figure 9.16 A thinned stand of loblolly pine sawtimber nearing its rotation age on forest industry land in south Arkansas. (James M. Guldin)

Figure 9.15 Applying herbicides to control competing vegetation in a loblolly pine plantation on forest industry land in central Arkansas. (James M. Guldin)

For the 21st century, managers of forest industry lands are increasingly aware of the value of resources other than timber on their lands. In response, they are pursuing opportunities to profit from managing wildlife, fish, or recreational facilities, as illustrated by the common practice of leasing forest industry lands for hunting. Nontimber resource specialists increasingly find employment with forest products companies, and their responsibilities range from encouraging hunting strategies that reduce browsing damage on seedlings to advocating for compliance with nonpoint pollution standards. In addition, the public goodwill that results from producing and accommodating nontimber resources is not lost on industrial forest managers. Even the preservation of endangered species and the protection of their habitat are increasingly viewed as a mark of good corporate stewardship.

Nonindustrial Corporate Holdings

It has become increasingly common for forest lands to be held and managed by corporations that do not own their own processing facilities but that nevertheless practice intensive management. Common examples of these are life insurance companies, real estate trusts, and other firms that look on forest management as an investment opportunity.

Similarly, a forest industry may divest its woodlands from its mills, and establish the woodlands division as a separate real estate trust. In this arrangement, the woodlands real estate trust becomes independent of the mill and responsible for making a profit. One effect of this is for the real estate trust to sell timber on the open market, where the high bidder may not necessarily be the mill that it served exclusively before the divestiture.

Generally, land or real estate trusts manage their holdings to ensure that the timber they put on the market is in demand by the manufacturing facilities in the area. Since the investment companies do not own their own processing facilities, they must produce timber with attributes—species composition, quality, volume, and operability—that are highly desirable to the forest industries that will bid on the products when they are made available for sale (Figure 9.17).

Investment firms often seek to achieve the same standards of forest management as the major forest industries. As a result, several of the largest and most prominent investment firms also subscribe to the principles of the Sustainable Forestry Initiative of the AF&PA. Doing so commits the investment trust to manage its lands according to the mandatory guidelines of compliance stated in the Initiative's forest management principles.

Figure 9.17 Cull tree removal in a sawtimber-sized stand of bottomland hardwoods on real estate trust land in western Tennessee. (James M. Guldin)

Private Conservation Groups

A relatively new player in the field of forest management is the private conservation group. The most notable example is The Nature Conservancy, an organization dedicated to the preservation of plants, animals, and natural communities representative of the diversity of life on earth. The Nature

Sidebar 9.4

Private Conservation Groups in Action

The original forested wetland ecosystem of the lower Mississippi River Valley covered 8.5 million hectares (21 million acres) of bottomland hardwood forests. By 1991, only 2 million hectares (4.9 million acres) remained. The Big Woods of Arkansas consists of 200,000 hectares (500,000 acres) of bottomland hardwoods along the Cache, White, and lower Arkansas Rivers in eastern Arkansas, and is one of the largest remaining contiguous blocks of this vanishing forest type. Because of its rarity and the unique conservation opportunity the area represents, interest has been growing among federal and state natural resource agencies, private conservation groups, and others in developing a plan to conserve and protect the ecological diversity and promote compatible use of natural resources in the Big Woods.

The Arkansas Field Office of The Nature Conservancy (TNC) is spearheading efforts to conserve the Big Woods as a functioning ecosystem that preserves biologically significant areas. Implicit in TNC goals are mandates to connect and expand remaining forest patches and corridors, to restore natural patterns of hydrology when possible, to promote compatible human use, to conduct and encourage ecosystem research, and to reach out to local communities.

Bald-cypress in a minor stream bottom in the Big Woods of eastern Arkansas. (James M. Guldin)

To achieve these goals, TNC has and will continue to acquire property in the area. It is working with existing landowners on afforestation and reforestation projects, and with its own scientists and others in academia to develop ecological research and monitoring in the region. Key partners include the U.S. Fish and Wildlife Service, the Arkansas Land and Development Corporation (a minority farm organization), the Natural Resource Conservation Service, Arkansas Forestry Commission, Arkansas Game and Fish Commission, Arkansas Natural Heritage Commission, Potlatch Corporation, Anderson-Tully Company, Ducks Unlimited, the Arkansas Wildlife Federation, and the Arkansas Audubon Society.

(continues)

Sidebar 9.4 *(continued)*

Ecologically, the conservation actions taken by the Conservancy represent a new direction in resource management—the conservation of significant areas through private action and development of coalitions of interested agencies, forest industry, and private citizens.

Conservancy has extended conservation protection to more than *4.4* million hectares (11 million acres) in the United States and 24 million hectares (60 million acres) elsewhere in the world.

The Nature Conservancy (TNC) achieves its results through a nonconfrontational, apolitical approach in its activities, unlike many conservation groups. If TNC identifies property as having significance for a species or habitat of interest, it will acquire it either through purchase on the open market, through donation, or through working with the landowner for a permanent conservation easement. All of these tactics have prominent tax advantages to the landowner.

After acquisition, TNC arranges for transfer of the property to the best available conservator, typically a state or federal agency. In some properties, TNC retains partial or complete ownership. The organization does not simply draw a line around its properties, though it will do so if dictated by the best science for managing a given species or habitat. However, it is common to see TNC crews engaged in active programs of forest or grassland management, especially in an ecosystem restoration context. For example, the prescribed burning crews of TNC are equal to the best of any federal or state agency, given their experience in burning prairie and woodland habitats for ecological restoration.

Stewardship Across Ownerships

If one major advance in forest stewardship can be identified in the early 21st century, it is the concept of promoting forest stewardship across ownerships. It is not that public agencies, forest industry, and private nonindustrial forest landowners cannot work alone or independently of one another; they can, and will continue to do so. However, increasingly, these three ownership sectors are finding more opportunities by working together across ownership boundaries than they would by working alone.

The collaboration starts by sharing knowledge. Forest landowners do not operate in a vacuum. They blend their personal knowledge and experience with information from many difference sources. Some of this information is scientific, such as the latest research results. Some is market-driven, such as the monthly stumpage price reports for local forest products. The local experience of forestry professionals should not be overlooked, although it tends to be more value-laden, including personal preferences, opinions, and beliefs.

Collaboration across sectors can extend to informal or formal cooperative relationships. A simple example occurs when a forest industry company buys timber from a nonindustrial private landowner on the open market. However, this simple example can extend to a formal contract for long-term management services between the company, or a private consulting forester, and the landowner. It can include partnerships between government agencies and private landowners for advice on managing special sites, or for help in preserving habitat for endangered and threatened species.

Over the past several decades, private nonindustrial forest lands have been a special concern to professional foresters. Nearly 60 percent of the timberland in the United States is in farm and other private nonindustrial ownership; these lands produce a significant share of the nation's timber, they support livestock herds, they contain unique ecological habitats, and they provide recreational opportunities for many people. Most of these forest owners hold small parcels under 400 hectares (1000 acres). Some give little thought to the management of their natural resources. Much is known about the extent of private nonindustrial forest ownership and about the resource production capabilities of their lands, but little is known about the landowners themselves.

Four types of programs provide information to forest land managers and forest landowners. *Cooperative programs* provide management and financial assistance. *Forest protection programs* deal with problems, such as wildfires or insect attacks, which commonly cross property boundaries and affect all lands irrespective of ownership. *Research programs* in various federal and state organizations exist to discover and develop new ways of applying scientific information. *Advocacy programs* exist to foster interest in specific areas and mobilize public and political support.

Cooperative Forestry Programs

Millions of hectares of forestlands are in the hands of forest industries, states, local governments, and small landowners. In recent years state agencies have become stronger and federal funds have dwindled. This situation has spawned a national effort to focus federal assistance on cooperative forestry activities that require a federal role, have multistate implications, and will provide for long-term improvements (18).

Several formal programs under the *cooperative forestry* umbrella facilitate forest management on nonfederal ownerships. Some programs provide forestry assistance to landowners, primarily nonindustrial owners of small parcels of land. Others coordinate the activities of managers of large land parcels, primarily public agencies and forest industries. The underlying premise of these programs is the need for additional financial or technical assistance to promote desirable stewardship activities. Most cooperative programs are aimed at private lands, either by direct assistance to private landowners or by supporting programs of state forestry agencies. Cooperative programs provide technical assistance and financial assistance, often both simultaneously.

The Department of Agriculture cooperates with land grant colleges and universities to support the nationwide system of county extension agents. Some county agents provide technical advice in forestry, with the help of district or state forestry extension specialists. They focus on sharing new scientific information and technologies with landowners, consultants, and land managers. They often organize demonstration projects, teach short courses, help develop land management plans, answer questions, and may even provide a day or two of consulting to an individual private landowner who seeks their assistance.

Financial assistance includes cost-sharing incentives programs to assist nonindustrial private landowners in implementing a variety of conservation measures. It can take the form of special laws providing favorable treatment for forests, such as the capital gains provisions of the federal income tax code that use lower tax rates for income from forestry than for ordinary income. Some state property tax codes contain provisions to defer annual property taxes until the parcel generates income, usually through a timber harvest. Others require counties to assess private forest land based on its current use value rather than its value if converted to agricultural cropland, suburban housing development, or other "highest and best use" from a land value standpoint.

Finally, conservation education programs are an effective way to translate technical expertise as well. The Smokey Bear and Woodsy Owl programs are cooperative programs between the Forest Service and participating state and local agencies. Programs supported by forestry industry and state and federal agencies include Project Learning Tree (emphasizing forests), Project Wild (emphasizing wildlife), and Project Wet (emphasizing aquatic ecology). These programs use the talents of resource professionals to train primary and secondary teachers, who then use their own talents to bring environmental education to the classroom.

Forest Protection Programs

For some landowners, concerns about forest management only begin when their property is threatened. Forest protection programs are special cooperative programs set up to help public and private landowners deal with wildfires and pest outbreaks.

Wildfire policies and practices have evolved significantly in the past decade. The aggressive suppression policies of the 1950s and 1960s were encapsulated by the goal of extinguishing every wildfire fire by 10:00 a.m. the morning after the fire was detected. These policies dramatically reduced the number of hectares burned each year. However, they had some unintended outcomes that have led to a rethinking about the role of fire in ecosystems.

For those fires where suppression is appropriate, a well-coordinated initial attack framework has been established that involves federal and state forestland management agencies, Native American tribal governments and forest industry landowners. All participants have teams of employees who are trained in specific firefighting or support tasks and can be called upon to fight fires anywhere on public or private lands. The Forest Service developed a management framework, called the "Incident Command Team," through which teams and individuals from all partner agencies can quickly, cooperatively, and cost-efficiently blend their skills and resources to suppress the fire.

Pest outbreaks also call for cooperative action between federal, state, and private organizations. Like fires, pest outbreaks can occur suddenly and threaten multiple landowners. The Forest Health Monitoring Program is a joint effort by the Forest Service State and Private Forestry and participating state forestry agencies to track long-term trends in forest conditions, identify changes in health status, and evaluate causes. When pest outbreaks are identified, cooperative programs involving federal agencies, states, and municipal governments are launched to bring the pest under control. Particularly vexing are outbreaks caused by invasive species not indigenous to North America such as the gypsy moth, Dutch elm disease, and Asian longhorned beetle.

Cooperative programs are also in place to encourage land management practices that reduce the risk of infestations. For example, research has demonstrated that thinning the basal area of southern pine stands to below 17 square meters per hectare (75 square feet per acre) greatly reduces the likelihood of southern pine beetle outbreaks. Cooperative research between the Forest Service and land grant universities has led to innovative methods for controlling pest outbreaks. Chemicals that confuse insect behavior, such as artificial sex pheromones that disrupt mating, often can be used in lower doses and with fewer adverse ecological effects than pesticides. Biological controls, such as growing and releasing sterile males or natural predators of the invasive species have also been proven effective by researchers. Blending all these management tools together—silvicultural techniques, biological controls, effective chemicals, outreach activities providing technical assistance and targeted financial assistance to those in need-is called *integrated pest management (1PM).* Because so many partners and cooperative elements are involved in integrated pest management, it is the epitome of a cooperative program for protection of forests from pest outbreaks. IPM is discussed in detail in Chapter 8 on forest diseases and insects.

Research and Development Programs

Research and development aims to discover new knowledge about ecological, economic, and social systems and to develop new ways of applying the knowledge to solve problems. In the United States, the primary research and development organizations are the Research and Development program of the Forest Service, colleges and universities, forest industry firms, and private institutes and interest groups.

The mission of the Research and Development program of the Forest Service is to "discover and develop credible new knowledge and exciting new technologies that help to sustain the health, productivity, and diversity of America's forests and rangelands and meet the needs of present and future generations." Sustainable development—meeting the needs of the present generation without compromising the ability of future generations to meet their needs—is a fundamental objective of all agency activities. They focus on sustainable development at multiple geographic scales—site, landscape, regional, national, and global.

Research is conducted through six regional Research Stations located throughout the United States, and the national Forest Products Laboratory. The core of the program is a network of 160 *research work units,* each consisting of one or more scientists holding advanced degrees as well as technicians and support staff (Figure 9.18). Unit research specialties include the spectrum of multiple uses and resources in the forest, such as silviculture, forest ecology, wood products, economics, wildlife, recreation, range science, hydrology, forest pests, and fire. Each unit has a charter that describes its mission, and that lists three or four problem areas to achieve the mission. Frequently, the problem areas are so complex that they require a number of studies focused on specific elements of a problem. The unit mission and assigned problems are reviewed every five years to assess progress and, if warranted, to adjust the mission and redirect the resources into higher priority lines of research. During these periodic reviews, research collaborators, users of the research, and members of the public at large are invited to comment on and influence the priorities of the work assigned.

Figure 9.18 Classic uneven-aged structure in a loblolly-shortleaf pine stand after 56 years of management on the Good Farm Forestry Forty demonstration area. The stand is located on the Crossett Experimental Forest, which is managed by the Monticello-Crossett Research Work Unit of the Southern Research Station, U.S.D.A. Forest Service. (U.S.D.A. Forest Service)

Cooperation with others is a hallmark of Forest Service research activities. Every research work unit cooperates with researchers in other organizations. This cooperation is formalized in over 1000 active agreements that provide funding to partners, typically university colleagues, for collaborative research. Many of these are cooperative agreements in which university colleagues and Forest Service scientists work together to complete the studies described in the agreement.

One major Forest Service research program that depends on cooperation for its success is the Forest Inventory and Analysis (FIA) program. The FIA program has been collecting information about America's forests since the 1930s. The program uses a combination of images from remote sensing and data collected by field crews on 13,000 field plots annually to evaluate the status, condition, health, and productivity of America's forests. Without the cooperation of private landowners, state forestry agencies, and advocacy groups, the FIA program could not be successful.

Universities are the second major source of new research and development activities supporting public land managers and private landowners. Funding for university faculty involved in research comes from many sources—endowments, federal and state appropriations, cooperative agreements, and research grants from forest industry, private foundations, and government agencies. The U.S.D.A. Cooperative State Research, Education, and Extension Service provides funding to land grant institutions through formula grant funds and competitive grants. Formula grant funds are allocated according to a set of criteria, such as the acreage of forestland in a state, and support both land-grant university research (Mclntire-Stennis program) and extension (Smith-Lever program) activities. Competitive grants are offered through the National Research Initiative.

The typical competitive grants process begins with the funding organization issuing a *request for proposals* (RFP) that describes in detail the particular research problem to be addressed, and the requirements for eligibility. A group of scientific peers reviews the proposals that are submitted and ranks them in order of merit. The highest ranked proposals are awarded funding. Generally, faculty who obtain grant funding will be asked to submit progress reports to the funding organization as the research is being conducted, and a final report when the research is competed.

Forest industry funds research in three categories. The first is research on the development of new products and manufacturing methods. This work is usually proprietary, often conducted by company employees, and is intended for use inside the company. A second category is for nonproprietary research available to any and all users. A few companies have their own internal research organizations that solve problems and develop improved technology for application on the firm's lands and lands of cooperating nonindustrial private forest landowners. Others conduct research activities through grants to external research partners such as Forest Service or university scientists. The third category is through alliances formed by companies to solve larger problems through industry associations or university cooperatives; member companies pool their contributions, award grants to research faculty and graduate students, and share the research results among the members. One example is Agenda 2020, a competitive grants program sponsored by the American Forest and Paper Association; another is the Southern Forest Tree Nursery Cooperative, organized by Auburn University.

Like their government and university counterparts, industry researchers and industry grant recipients usually submit nonproprietary research findings for publication in professional journals, which makes them available to the general public. Research funded by industry tends to be carefully focused on industry objectives. Thus, it sometimes tends to be of narrower scope and applicability than publicly funded research.

Advocacy groups also conduct limited forestry research. Their research usually focuses very precisely on the group's interests. It is often aimed at filling gaps in research results conducted by others, at tailoring previous results to specific sites, and at corroborating or denying previous results. The Appalachian Mountain Club, The Nature Conservancy, and the Wilderness Society are examples of advocacy groups that conduct research studies.

Advocacy Programs

Advocacy programs are run by groups of people with common interests who pool their energy and resources to create change or preserve a status quo aligned with their shared values. Advocacy programs concentrate their efforts on communications and representation activities. Working with print, broadcast, and electronic media, they gather, package, and disseminate information that describes their position management policies and options. They also contact elected and appointed officials and landowners to represent their members' interests and build support. Advocacy programs contribute to stewardship by assuring that a broad range of options are considered and that minority viewpoints get aired in the political process of making natural resource policies and management decisions. Most of the positive changes in natural resource management that occurred during the 20th century owed their success, at least in part, to support from advocacy groups and their programs.

Advocacy groups can be classified into four general categories: 1) the commodity user group, 2) the noncommodity user group, 3) the professional group, and 4) the special-issue group. It is important to recognize that a specific advocacy group may have activities in more than one category.

The commodity and noncommodity groups are both forest users. Both groups try to promote forest policies and budgets that favor their interests. A *commodity group* is composed of businesses associated with an industry that produces a marketable product such as paper, lumber, or beef. Examples are the American Forest and Paper Association and the National Cattleman's Association. A *noncommodity group* is composed of businesses or private individuals that also use the forest, but their use does not involve a marketable forest product. Rather, the primary focus of the use is enjoyment of the forest. Examples of noncommodity advocacy groups are the National Wildlife Federation, the Sierra Club, and the All-Terrain Vehicle Association. Other groups, such as the Sporting Goods Manufacturing Association, bridge this distinction.

The third category is *professional groups.* They consist of organizations whose primary purpose is to maintain and advance the technical and scientific practice and ethics of the forestry and related professions and sciences. This group includes such organizations as the Society of American Foresters, Ecological Society of America, The Wildlife Society, and the Society for Range Management.

The final category is the *special-issue group.* These are organizations that formally support or oppose a single issue. Their existence is usually limited to the duration of the issue or focused on a place having extraordinary value to the group members. However, on occasion, they take on new issues and evolve into organizations with broader interests. Examples of special-issue groups are Citizens Against Toxic Substances and Friends of the Boundary Waters Wilderness.

All these advocacy groups contribute to the stewardship of America's forests. However, the Society of American Foresters (SAF) plays an additional, very significant role as representing the forestry profession.

The SAF was founded in 1900 with the objectives of advancing the science, technology, education, and practice of professional forestry in America and of using the knowledge and skill of the profession to benefit society. The SAF publishes the *Journal of Forestry* and a newsletter, *The Forestry Forum,* each month; *Forest Science,* a quarterly research journal; and three quarterly journals with regional focus—the *Northern, Southern, and Western Journals of Applied Forestry.* In addition to serving as the voice of the forestry profession during national and regional policy discussions, SAF also maintains a code of professional ethics for foresters, accredits schools providing undergraduate or graduate forestry education, promotes continuing forestry education, strengthens international relations with foresters and forestry organizations in other countries, provides insurance for members, and develops standard references for the profession, such as a forestry dictionary and descriptions of forest cover types.

Forestry at the National Level

At first glance, the link between the practice of forestry in the woods and the nation's capital seems obscure. Other than the aesthetic appeal of the Japanese cherry blossoms during springtime on the National Mall, one does not usually think of Washington when one thinks of forestry and trees. However, in the government buildings that line the Mall—the White House, the Capitol, the Departments of Agriculture and Interior, and others—more key decisions are made about how forestry will be practiced and financially supported than anywhere else in the nation.

The balance of power is shared among three separate but equal branches of the U.S. government. Both Congress and the executive branch have active roles in forestry, and the judicial branch is often called upon for solutions to forestry issues and interests. Moreover, many people and interest groups focus their demands on forestry at the national level. The international implications of forestry cannot be ignored in Washington; many of the forests in developing nations are under public management, and the management practices of the United States are often used as the model for other countries. This diversity of interests means that the nation's policy on forestry is actually a collection of policies addressing many concerns and springing from any number of interests.

The Federal Government Role

Leadership for establishing the debate on forestry issues lies in the executive branch, and specifically in the Forest Service. Within an agency such as the Forest Service, many different staff units work together to formulate agency policy. When these staff units have different concepts about what forestry policy should be, they must work together to hammer out a policy direction for the agency's management program and the budget allocations needed to support that program. They are constrained by the limitations of the resources to be managed, the laws and regulations in effect, agency traditions, and executive orders from the president. This process goes on within a legal framework established by Congress in a single charter act or by a series of acts for different components of the agency's program.

However, the management program and budget of an agency such as the Forest Service is just a small part of the overall executive program and budget that the president seeks to enact. Forestry programs, and the budget to support them, must be balanced with other national programs such as health care, transportation systems, and defense. The central issue is the amount of federal funding to allocate to forestry programs in relation to other programs in a way that serves the American public most effectively.

The unenviable task of recommending to the president how to slice the pie falls to the Office of Management and Budget (OMB). The OMB takes all agency and department budget proposals and fits them into one or more cohesive packages. This office operates under the president's direction and with no allegiance to any one agency or department. Generally, staff members at OMB referred to as "examiners" are assigned responsibility for one agency (at most three or four). The examiner analyzes the agency's budget proposal for use in program-balancing deliberations. The agency must provide its examiner with full information, including justifications, analyses, and assessments with each program request. If support seems inadequate, the examiner may challenge or even recommend dropping a specific program. Effective interaction with its examiner and support by the secretary and departmental staff are critical to an agency's ability to maintain its position within an administration budget.

Implementation of any part of the president's budget must await congressional action to approve the activity and its funding. Congress can of course vote to increase, decrease, or otherwise change the president's budget proposal. Congressional interest in forestry issues is evident both by members of Congress individually and by staff members of forestry-related committees or subcommittees. No single committee or subcommittee has overall jurisdiction over forestry matters. For example, committees on foreign trade consider log export issues, and committees on energy issues may consider wood fiber as an alternative energy source.

A member of Congress or a congressional staff member may have expertise in forestry matters, or may rely on an agency for such knowledge. Although most members of Congress have little background in forestry, they still may take a strong interest in particular forestry issues. The Forest Service manages land in many states and congressional districts. As a result, it is not unusual for legislators to represent the interests of their constituents in specific forestry issues during the annual congressional budget review process.

The overall role of Congress in forestry issues is somewhat similar to that of a local forest manager. Congress tries to resolve disputes over conflicting uses, but on a broader scale—that of forestry in a national context. The role of Congress is threefold. First, Congress reviews and revises the president's program budget requests, providing direction through its annual appropriation committee reports. The budget review process provides an overview of an agency's plans and policies as specified in existing laws.

Sidebar 9.5

Joint Roles in Action on the National Level

The role of the federal government, Congress, citizens, and the courts in establishing forest policy can, in very general terms, be shown by the evolution of forestry management policy for the Forest Service.

In the 1860s and 1870s, public opinion grew to favor federal management of forests. In 1879, the American Forestry Association (AFA) and the American Association for the Advancement of Science (AAAS) petitioned Congress to reserve or set aside forested lands from public entry or disposal. In 1891, Congress passed a bill for general revision of the public land laws. When the bill emerged from House-Senate conference, a Section 24 had been added that provided authority for a president to reserve forestlands for public ownership. A month later, President Harrison set aside the Yellowstone Park Forest Reserve, south of Yellowstone Park. He proclaimed it an Executive Reserve but gave no specific direction on how or for what purpose it was to be managed.

In 1896, the president asked the National Academy of Sciences to study what had become known as the 'Forest Reserves." Congress incorporated the concepts of forestry management resulting from the study into an amendment to an appropriation bill. This 1897 action, called the Organic Act, laid the groundwork for how the reserved federal forestland would be managed and used.

In 1905, the president, with congressional approval, merged the Forestry Division of the General Land Office in the Department of the Interior, which until that time had custody of the forest reserves, with the Bureau of Forestry in the Department of Agriculture. The new agency was named the Forest Service, and it was placed in the Department of Agriculture. Two years later, the former forest reserves became known as national forests. Throughout the 1900s the Forest Service managed the national forests and set specific policy based primarily on the Organic Act and the annual budget review.

In 1960, Congress stepped back into center stage by passing a new law, the Multiple Use-Sustained Yield Act, to ensure that national forests would be managed for multiple uses at levels providing a sustained yield for the future. This was a codification of policies already followed by the Forest Service.

In the early 1970s, several groups of people became concerned about how forestry was being practiced in some national forests. The citizens' groups petitioned the courts in 1975. The courts ruled that forestry practices were not in accordance with the law of 1897. More or less concurrently, Congress reentered the scene in 1974 with the Renewable Resources Planning Act (RPA). This bill requires the Secretary of Agriculture to assess natural resources periodically and to submit a five-year renewable-resources program to Congress, based on this assessment of future supplies and demands. In 1976, Congress amended the RPA legislation and enacted the National Forest Management Act (NFMA), also in response to the 1975 court action. This bill provides general guidelines for the agency by establishing the general content and process to be followed in developing national forest plans.

Thus, from the 19th century to the present day, forest policy has moved into the spotlight several times, and has been scrutinized and reshaped by public interest, the executive branch, the legislature, and the judiciary. The changes in forest policy that will occur in the future will be no less representative of these public deliberations.

Secondly, Congress affects national policy matters by enacting legislation. Laws define, redefine, or clarify the context within which agencies administer policy. Congress tends to legislate infrequently on forestry issues (although the 1970s were an exception). Legislation usually sets broad guidelines or frameworks, but defers to the agencies for the development and implementation of specific forestry policy. More specific direction is inappropriate for several reasons, including the diversity and changing demands on American forests, the size and diverse membership of Congress, and the reluctance of members to legislate on professional forestry matters. The result is that Congress usually supports and relies on the agencies that are staffed and run by professional resource managers.

A final but important role performed by Congress is monitoring and reviewing the day-to-day activities and occasional crises that occur during agency operations. These tasks are performed by two legislative branch offices, the General Accounting Office and the Congressional Budget Office, and occasionally through congressional oversight hearings. Their findings take the form of reports to or from Congress.

The executive and legislative branches sometimes employ subtle methods of reaching an agreement when establishing programs and setting program direction. The executive branch may omit from its budget recommendation programs that are enthusiastically supported by members of Congress, because the executive branch considers them lower priority. Then, in return for congressional compromise on another issue, the executive branch will include a portion of or the entire omitted program. This process may also work in reverse. Often, the key national issues of compromise often are not forestry matters, but other matters of domestic or foreign policy. Thus, professional foresters generally participate at the fringes of this process. Their role is to provide factual information on forestry opportunities and the consequences of various proposals for the forest resources and for the people who rely on these resources.

The judicial branch of the federal government is concerned with forestry issues only at the request of interested parties. Its role is to interpret and clarify actions and policies in terms of existing law and to offer redress to petitioners. The courts can either approve or prohibit specific activities and policies according to legal interpretation. They can only initiate new direction if supported by an existing legal basis, in which case an agency's operating policies may need to be changed in order to comply with the court's decision. If a law is overly broad or unclear or if controversy touches on constitutional matters, the courts may, in fact, provide considerable direction that the agency must follow. Each time a law is tested in court, new case law or precedent is established. If the law or action being tested is confirmed as being appropriate, the law or action takes on new support or strength for similar future actions.

The Public Interest

Among the most important influences on the role of the federal government are the diverse opinions of the people of the United States. Forestry at the national level cannot be understood without considering how people express their common interests and how those interests become input for forestry policy. People can make themselves heard by policymakers in many ways, from contacting management agencies and their congressional representatives, or engaging in some form of public expression.

Concern with the integration of diverse public interests into the formulation of public policy is not new to our political scene. In 1789, James Madison discussed the role and importance of what we call *public interest* or *pressure groups* in the *Federalist Papers* (19), arguing that a major function of the governmental process is to integrate opposing interests and reconcile conflicting views. Almost 50 years later, Alexis de Tocqueville, the eminent French publicist, commented on the tendency of U.S. citizens to form and join organizations, that in turn often had agendas for political action, in his book *Democracy in America,* (20).

In more recent times political scientists have suggested the "group basis of politics" as one fundamental characteristic of U.S. government. Economists have recognized "countervailing power" and interactive forces as important elements in public-policy decision making. Matters of the environment, natural resources, and forestry are presented by interest groups for consideration in developing public policy.

Several related developments in recent years have intensified both individual and group involvement in questions of forestry policy and management. One of these is a widespread and growing concern for the environment. Another is the introduction of new statutory requirements governing forestry practices, and their reinforcement by court decisions; agency responses to public views and comments are the other development.

Numerous court challenges to government agency actions have been mounted by permanent or ad hoc groups. The National Environmental Policy Act (NEPA) of 1969 provides the basis for legal challenges by requiring federal agencies to prepare environmental impact statements assessing the consequences of alternative actions. If dissatisfied with the content and rationale of such statements, citizens and groups can file suits challenging findings and other aspects of agency decisions.

Public involvement has considerably sharpened the awareness of decision makers to the consequences and alternatives of action and, in many cases, has stopped or delayed actions. Many feel that these delays have contributed to wiser decisions. Most would agree that this emphasis on impact analysis has been helped by the willingness of federal courts to give "standing to sue" to a variety of interest groups. One result has been that federal agencies have taken the requirements of the NEPA and other statutes more seriously than they might otherwise have done.

However, on any issue or set of issues, neither the involved groups nor the individual participants represent all people or all possible interest configurations. In part, the problem is one of span of attention. People cannot possibly get involved in all the issues that will affect them, nor is it clear that the decision to become involved is always rational or deliberate. Such variables as personality, friendship, and presence—as well as preferences—may determine both the existence and the degree of involvement. Getting involved sometimes requires too much money, commitment, time, or understanding. Thus, it is important to recognize that less vocal citizens might be reluctant to offer their opinion before a decision is made—though they might not remain silent if a wrong decision is reached. By exercising informed judgments on what they perceive are the interests of the expressed and the silent publics, professionals and their agencies must begin to approximate the overall public interest.

In forest management, as in many resource and environmental decisions, the articulation of the public interests is often complicated by the fact that decisions made today have very long-term consequences. The responsible professional public servant must attempt to consider the future. To be sure, the crystal ball is always clouded, and there is a tendency to address the immediate crisis. Hence, analysis must substitute for prophecy and foreknowledge as much as possible. If public agencies respond only to current public outcry, the real potential public welfare may be overlooked.

The very multiplicity of interests in forestry at the national level ensures a high degree of conflict and controversy. In many situations, one set of interests will run counter to another. A major challenge to Congress and agencies is conflict resolution, that is, seeking to reconcile and choose the appropriate solution from a wide range of possible outcomes.

International Forestry

Washington, D.C., is not only a hub for national forest policy, it is also one of the world's major centers for international forestry. Headquartered in Washington are a number of U.S. government agencies, international organizations, and nongovernmental entities with international programs in forestry or natural resources.

Among the U.S. agencies, the largest international forestry program is managed by the U.S. Agency for International Development (USAID), which contributes to forestry projects in some 36 tropical countries at an annual cost of about $135 million. Assistance projects sponsored by USAID include training, disaster relief, and private-sector development efforts. The largest U.S. employer of foresters overseas, however, is the Peace Corps, which now has 550 foresters in 46 countries. The Forest Service also manages an active international program that represents the U.S. government on major world forestry issues, promotes scientific exchange and cooperative research among countries, works directly with various countries on mutually beneficial technical programs, and provides technical support to USAID (Figure 9.19). Other government agencies with international forestry or natural resource programs include the State Department, National Park Service, Fish and Wildlife Service, U.S. Geological Survey, and the Smithsonian Institution. On tropical matters, informal coordination of activities is achieved through the Interagency Task Force on Tropical Forestry.

International organizations with home offices in Washington are the World Bank, Inter-American Development Bank, and the Organization of American States (OAS). Each is active in international forestry and natural resources. The World Bank is the largest with annual forestry disbursements of about $150 million in seven countries. From 1985 to 2000, it invested approximately $1.5 billion in forestry development in 55 countries. The World Bank's policy and lending strategy on forestry emphasizes a balanced program of small-scale tree farming, institution building, and industrial projects. Activities include village forestry, environmental protection, and rural development. Some of these activities are further described in Chapter 23, Social Forestry. The Inter-American Development Bank has a growing forestry portfolio limited to the Western Hemisphere. The OAS supports forestry, agricultural research, information exchange, and training in tropical America.

Figure 9.19 The main entrance to San Juan Tetla Experimental Forest, managed by the Central Region of the National Institute of Forestry and Agriculture Research (NIFAP), the federal forestry research branch of the Government of Mexico; here, as in many other experimental forests around the globe, university and government research scientists collaborate on studies of mutual interest. (James M. Guldin).

Although headquartered in Rome, Italy, the Food and Agricultural Organization (FAO) of the United Nations also maintains a Liaison Office for North America in Washington. Since its creation in the early 1940s, the FAO has directed the world's leading international forestry program. The FAO convenes ad hoc meetings to coordinate the activities of the world's major forestry donor agencies. Through technical meetings and publications, its Rome office facilitates the worldwide exchange of forestry information and provides assistance to developing countries. Its office in Washington coordinates policy and administrative ties to North America.

Nongovernmental organizations are playing an increasingly important role in international forestry. Many are located in Washington, such as the World Resources Institute, the International Institute for Environment and Development, and the Pan American Development Foundation. The World Resources Institute demonstrated leadership in tropical forestry by publishing a major report entitled, "Tropical Forestry: A Call for Action," which outlines problems, successful experiences, and financial resources needed to stem the rampant deforestation of tropical forests (21). The International Institute for Environment and Development emphasizes natural-resources policy and planning and often works closely with USAID on development projects.

Two major professional societies concerned with international forestry issues, the Society of American Foresters (SAF) and the International Society of American Tropical Foresters (ISTF), are also headquartered in Washington. Through its International Forestry Working Group and Committee on World Forestry, the SAF keeps its members abreast of international forestry concerns. Communication among the world's tropical foresters is facilitated by the ISTF, especially through its quarterly newsletter.

As can be seen, international forestry is a growth area for the profession. As awareness of world forestry problems grows, so will opportunities and responsibilities for the professional forester.

The Role of Forestry Research

Advocacy for research has long been a part of the national concern for forest resource management. The need for research is not a recent phenomenon. Before 1890, reports and recommendations on the nation's forests specifically called for national research initiatives. The Reverend Frederick Starr, Jr., called for "extensive, protracted, and scientific experiments in the propagation and cultivation of forest trees" in 1865. The "Report on Forestry" by Franklin B. Hough in 1882 called for research on the effect of forests on climate and for the establishment of experiment stations.

Forest management benefits from a blend of basic and applied research investigations, as well as the experience of the professional tempered through trial and error. Research projects are initiated to examine particular management questions, often at the request of resource administrators. Thus, forestry research at the national level has three functions: 1) to assist in identifying areas of major concern that require research, 2) to establish and maintain continuity between research and evolving management policy, and 3) to provide coordination and management of the nation's research programs.

National forestry policy and direction change with fluctuating social conditions and needs. Quite often, management policy options depend on new ways of monitoring uses and impacts, new methods of doing old jobs, and new means of incorporating and balancing resource needs. National forestry policy and the national research agenda are closely related; national forestry policies must be based on sound scientific information, and on occasion research findings indicate a need to change national policy.

Representatives of different research communities at the national level maintain the links between needed research and current policy. The link to policy helps determine which areas of study have high priority. High-priority research is not simply a matter of which forest problem is the greatest, but rather research that has applicability beyond a particular problem in a particular area. The other area of national responsibility for research is coordination. It is often easiest to coordinate research across agencies at the national level rather than regional or state levels, which can help avoid duplication and research voids.

Many agencies and groups have national interests in forestry research. The Fish and Wildlife Service studies the protection and management of animal resources. The National Park Service studies how to protect and manage park resources. The Environmental Protection Agency sponsors research on environmental protection and the consequences of forest activities on air and water quality. Forest Service research covers a wide spectrum of ecological, economic, engineering, and social problems related to forest and rangeland management. They emphasize opportunities for taking products from the forest; how to protect and enhance noncommodity values; and how to improve forest products.

Several special-interest groups also support research. They often do not have a national program of study but concentrate on the interests of the organization. The National Wildlife Federation has a program of grants to sponsor research by university students. The National Forest Products Association sponsors research of interest to its members. Organizations such as these study forest technology, the resource base, changing social needs, and interactions between social demands and renewable resources. Several national organizations such as Resources for the Future and the Society of American Foresters seek to focus and direct research to specific areas of concern and, when appropriate, to develop a greater understanding of the present state of the art.

University studies often depend more on an individual investigator's interests and funding sources than on overall department programs. Studies may range from social demands and needs to methods for improving product utilization. National research coordination is much more difficult to achieve among agencies, organizations, and universities than within an agency or organization. Some umbrella groups formally link federal and state research organizations, and facilitate the communication needed to set national priorities. For example, the Joint Council on Food and Agriculture Sciences fosters planning and coordination of research, extension, and higher education between U.S.D.A. agencies and the private sector. A related U.S.D.A. organization, the User's Advisory Board for National Agriculture Research and Extension, provides input into policy and program development by identifying research and extension priorities from the view of the citizen user. If formal connections do not provide a national network between scientists, informal ones often spring up among individual scientists.

People use forest environments in many ways. New knowledge is continually needed to manage the complex and changing relationships between people and forests. Research provides this knowledge.

Concluding Statement

From the resource perspective, a forest ecosystem can be viewed either as a valuable whole or as a sum of valuable parts. Multiple-use forestry is a philosophy of resource utilization that provides a theoretical basis for developing qualitative and quantitative predictions of resource interrelationships. Ecosystem management and the Sustainable Forestry Initiative provide blueprints for incorporating those multiple uses into an ecological context with sustainability as a goal.

In some instances, the valuable whole receives priority, such as in the preservation of wilderness areas and of the ecological habitats for rare or endangered species. In other instances the valuable components of a forest ecosystem, such as timber or wildlife species, receive management emphasis. However, contemporary forestry on both public and private lands must increasingly provide for the health, diversity, productivity, and sustainability of forest ecosystems.

The management of specific forest ownerships depends on many factors. First and foremost are the unique attributes of the ecosystem itself, which determine both the availability of specific resources and the degree to which management can develop the resources for economical use. The methods by which management is planned and administered affect the economic efficiency of resource utilization, which may or may not be important in bringing forest products into the market place. The objectives of the owner of the forest land—whether an individual, a corporation, or society—are another critical factor. It is the owner who decides the patterns of resource management, if any, that are implemented by the forest manager. As populations grow, demands for a diverse array of forest resources increase; but the area of timberland will probably decline through the 21st century. The centennial of forestry in North America is characterized by both redoubtable management challenges and gratifying professional rewards.

Forestry at the national level is different from that practiced at the field or technical level. It focuses on forestry issues as components of many diverse national policies. Many groups, agencies, and individuals are involved in shaping national policy; some groups are interested only in certain aspects of forestry. However, forestry is only a small part of the national agenda, and it must be viewed in a context of larger, national concerns such as employment, housing, energy, and international relations. Much effort goes into identifying how forestry can address these major national concerns.

It might be helpful in concluding this chapter to look ahead to the future of forestry from a national perspective. Because forests are renewable, they will increasingly provide some resources more economically than nonrenewable sources. The ways in which forestry issues are important to national policies will become even more complex and diverse in the coming decades as we increase our knowledge of forest ecosystems.

The complexity of forestry issues and opportunities will require agencies and other organizations to work more closely together. Such important subjects, as acid rain, global warming, and tropical deforestation require the formation of new and exciting partnerships.

Increasing public interest in and access to forestry issues will lead to questions about the roles of resource professionals and interested citizens. Forestry professionals will need to develop better ways of analyzing alternative actions and giving the public access to the decision-making process. People with little forestry background whose interests may be narrowly defined must be able to understand these processes. An increased awareness of international forestry will create new demands and will result in a broader range of issues and problems for foresters to address.

People will increasingly employ available means of influence, through all three branches of government, as they become more involved with national forestry issues. Competing interests and uses for forest resources will require new approaches to balance social needs and resource capabilities. This is the future realm of forestry at the national, regional, and local levels. The possibilities are challenging and intriguing. To serve the public in this future, foresters will need to:

- Grow more trees.
- Use more reconstituted wood products.
- Conserve more species and habitats at risk
- Improve public understanding and management of the ecosystem.
- Learn to accommodate additional segments of society in managing forests.

The future of forestry issues in national and international policies promises to be active and controversial. The coming decades will be perplexing and frustrating for professionals who continue to focus solely on the application of technical forestry principles. On the other hand, the coming decades can be a time of challenge and excitement for professionals who adopt a national perspective. For them, the future offers opportunities to make valuable contributions to forestry in the tradition of Bernhard Fernow, Franklin Hough, and Gifford Pinchot.

The following chapters in this section provide more detailed treatment of the different multiple uses made of the forests, including management approaches for different aspects of forestry endeavors.

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CHAPTER 10

Nonindustrial Private Forests

JOHN C. BLISS AND A. JEFF MARTIN

Introduction

Whose woods these are I think I know
His house is in the village, though
He will not mind our stopping here
To watch his woods fill up with snow

—From "Stopping by Woods on a Snowy Evening" by Robert Frost (1)

Robert Frost's poem, "Stopping by Woods on a Snowy Evening," conjures up a wonderful image: a quiet winter's night, the deep silence of a forest under snow, the joy of a horse-drawn sleigh ride. The writer draws from the snowy woods comfort, solitude, and inspiration.

The values that Frost's narrator enjoyed are provided by millions of forest owners all across the United States (Figure 10.1). A private forest whose owner does not own or operate wood processing facilities (such as saw, paper, or plywood mills) is known as a *nonindustrial private forest* (NIPF). NIPF owners include individuals, families, farmers, and retirees. Hunting clubs, churches, schools, and other associations may also be NIPF owners. Even banks, insurance companies, real estate companies, pension fund companies, and other corporations are classified as NIPF owners if they own forest land but not wood-processing facilities. NIPFs range in size from one wooded acre to many tens of thousands of acres, and from sparsely vegetated tracts

Figure 10.1 The farm woodlot, so common when Frost penned his lines, is still common but no longer the dominant NIPF ownership type. As Frost hints in his poem, absentee landowners now control one-third of the NIPF ownerships. White-collar workers and retired individuals now own 58% of the NIPF land.

to lush, productive forests. Some NIPFs are intensively managed for production of forest products, some are held primarily for recreation and enjoyment. Many are models of forest stewardship, still others are neglected or exploited.

This chapter presents a brief overview of the nonindustrial private forest resource. We start by describing the significance of the resource and quantifying its dimensions. A section on the history of NIPF forestry sets the stage for discussion of current policies and programs. The chapter closes with a summary of emerging trends and issues affecting NIPF resources.

Significance of NIPFs

Economic Value Comprising almost 60 percent of the United State's productive forestland, NIPFs are of enormous economic, environmental, and social significance to the United States. As key suppliers of wood to the country's forest products industries, NIPFs economic significance has long been recognized. Even in the American South, where the country's industrial forests are concentrated, NIPFs supply most of the wood used by industry. In the West, the region with the least NIPF ownership, the dramatic decline of timber harvesting on National Forests has forced industry to increasingly look to NIPF sources of timber. The economic importance of NIPFs is not limited to the timber they supply to industry, however. Timber production employs people: loggers, truckers, tree planters, foresters, mill workers, gas station attendants, and grocery clerks. Moreover, the economic importance of nontimber products such as recreation, floral greens, mushrooms, and maple syrup is growing. Thus, NIPFs are vital to the economies of forest-dependent communities and regions.

Environmental Value The environmental value of NIPFs is gaining recognition as the United States becomes more urbanized, and clean air, clean water, green landscapes, and open space become scarcer. In many parts of the heavily populated East, NIPFs provide most of the available supply of such amenities. In the South, small private woodlands add diversity to landscapes dominated by large industrial and nonindustrial forest plantations. In the West, NIPFs typically occupy riparian zones alongside waterways, areas that are ecologically sensitive and that provide significant environmental values. Because of the diverse objectives of their owners, NIPFs add ecological diversity to the landscape wherever they occur.

Human Value Less recognized than the economic and environmental value of NIPFs are the associated *human* resources. The great diversity of NIPF owners and the objectives they hold for their forests lead to the existing diversity of forest types, ages, and conditions. Many NIPF owners are vital members of rural neighborhoods and communities. Others are urban dwellers who retreat to their rural forestlands to work and recreate. They provide important links of experience and communication between urban and rural populations. As NIPF owners shape their forests through use and management, they humanize the landscape, imbuing it with human history, meaning, and values.

Dynamics Underlying NIPF Issues

Population growth, increasing urbanization, changing social values, and changes in ethnic, age, and income distribution drive two dynamics influencing NIPFs: increasing demands for forest products, values, and services, and an increasingly dynamic policy environment.

Increasing Demand NIPF lands are under increasing pressure to produce an ever-widening array of products, services, amenities, and values. Major policy changes have led to steep declines in timber harvest levels from public lands. This in turn has resulted in increasing pressure on private forest resources to meet growing demands for forest products. In many areas, population growth is creating growing pressure for residential and commercial development of urban fringe areas, and recreational development of rural areas. Everywhere, the environmental, recreational, and spiritual values provided by forests—including nonindustrial private forests—are in high demand. These increasing demands occur at a time of unprecedented public concern over the management and condition of forest ecosystems. In other words, society is demanding more from private forests, and greater accountability from private forest owners.

Dynamic Policy Environment The policy environment within which forest owners must make management and investment decisions is one of increasing flux. Public support continues to grow for increasingly stringent management regulations for all ownership categories. In addition to such federal laws as the Endangered Species Act and the Clean Water Act, many states have forest practices acts which regulate how forests are managed. Even counties and municipalities in some states have enacted controls over land use in their jurisdictions. Policies are dynamic, not static, which adds to the complexity of these layers of regulations. The resulting regulatory uncertainty compounds the natural and market uncertainty with which NIPF owners must contend. Indeed, regulatory insecurity may be more distressing to many NIPF owners than any possible regulations.

Moreover, new and innovative policy instruments, both governmental and nongovernmental, further complicate each forest owner's management decisions. Examples include local voluntary watershed councils, safe harbor agreements for protecting endangered species habitat, conservation easements for a wide range of conservation goals, and forest certification programs for producing and marketing forest products. Although many of these changes may prove to be positive for NIPF owners in the long run, they can be challenging, unsettling, and confusing in the short term.

The Forest Resource

Size and Distribution

About one-third of the total U.S. land area is forestland, and two-thirds of that is designated timberland, that is, forestland capable of and available for producing commercial wood crops (Figure 10.2) (2). Fifty-eight percent of all forestland and 73 percent of timberland is in private ownership. Forest products manufacturing companies own about 14 percent of the timberland. The majority of the country's private timberland (59 percent) is owned by NIPF owners, defined as private individuals, farmers, businesses, and other private groups that do not own or operate wood processing facilities (Figure 10.3).

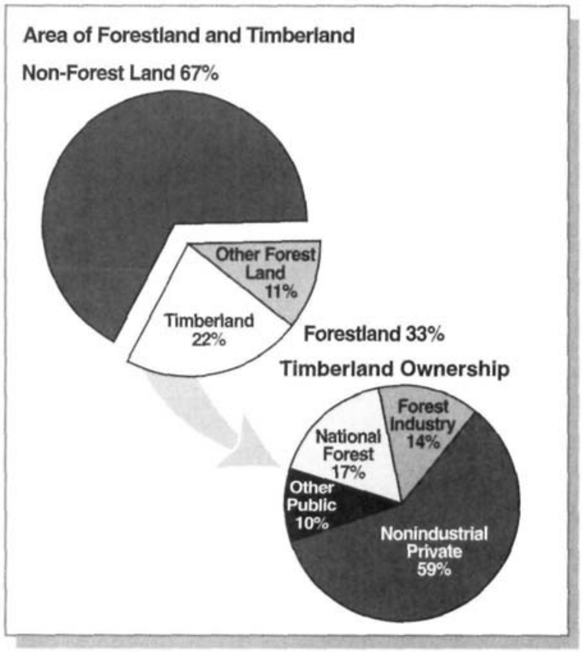


Figure 10.2 Land area and ownership of timberland in the United States, 1992 (Powell et al., 1993).

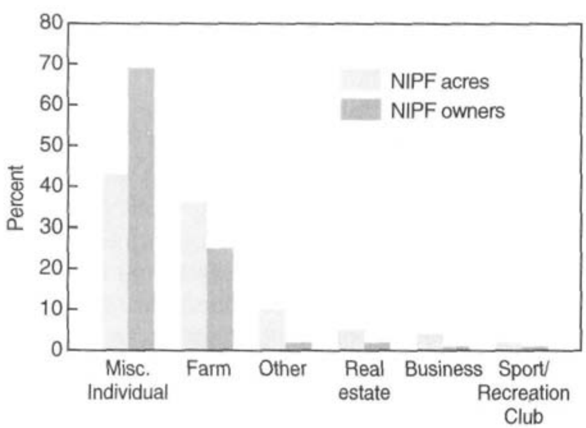


Figure 10.3 Distribution of nonindustrial private forestland ownership in the United States, 1994 (Birch, 1996).

NIPFs occur in every region of the country (Figure 10.4). About 88 percent of the NIPF timberland is in the North and South, and 12 percent is in the West. NIPFs comprise 70 percent of all timberland in the North and South, and 28 percent in the West. Total NIPF timberland declined 5.5 percent in the forty-year period between 1952 and 1992, either as a result of conversion of forest to other uses (such as urban growth) or because of changing ownership (i.e., purchase by forest industry).

Forest Productivity, Growth, and Removal

Nonindustrial private forests are an indispensable component of the nation's wood supply. NIPF lands contain 72 percent of the nation's hardwood growing stock inventory (mostly in the North and South), and 30 percent of the softwood inventory (mostly in the south and West) (2). These inventories have grown dramatically in the decades 1952 to 1992 (Table 10.1). Hardwood growing stock volume on NIPF lands increased 81 percent during the period, less than the increase on national forests, but more than that of industrial lands. Softwood growing stock volume rose 51 percent on NIPF lands in the 40 years, while other ownership groups experienced a slight decline. NIPF growing stock volume suitable for lumber manufacture increased 98 percent for hardwoods and 57 percent for softwoods. As a result of these growing inventories, NIPFs have become increasingly important as sources of wood for the nation's forest products industries.

In 1992, average net annual growth for all growing stock trees on NIPF timberland was 42 cubic feet per acre. This was less than forest industry's average of 61 cubic feet per acre but matched that on national forests and other public lands, which averaged 39 and 42 cubic feet per acre respectively,

The percentage of the national annual harvest taken from NIPF lands is about equal to the percentage of growing stock inventory that these lands contain. In 1992, for example, 67 percent of the nation's hardwood harvest came from NIPF lands-lands that contained 72 percent of the hardwood

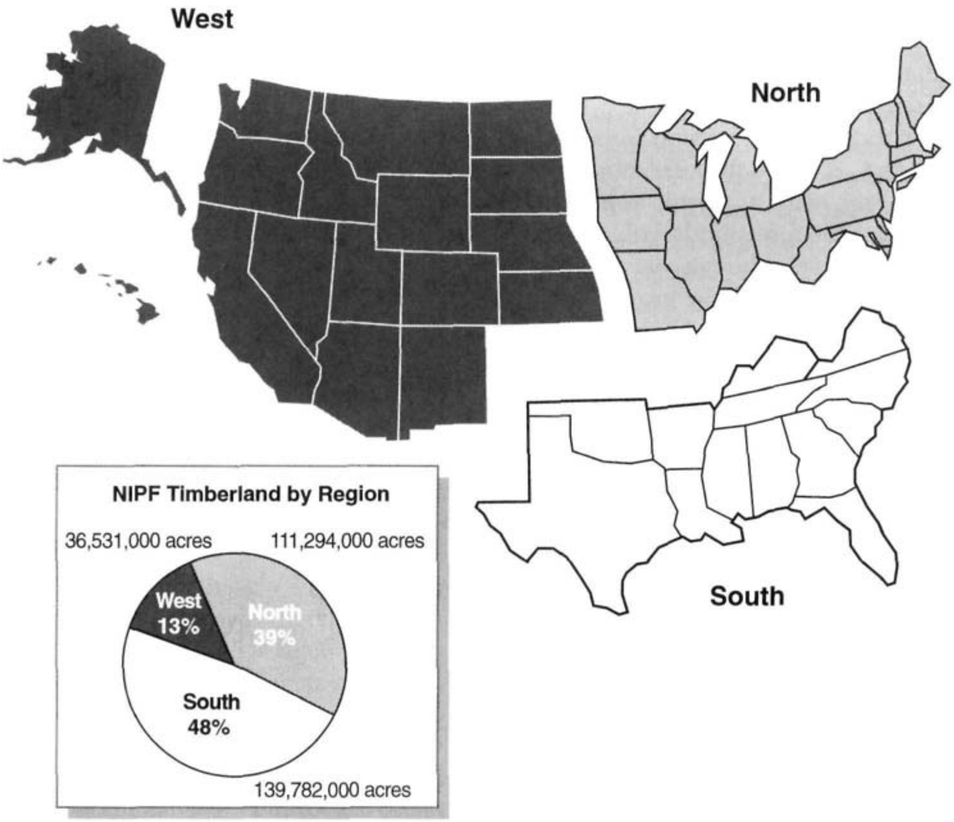


Figure 10.4 Distribution of NIPF timberland by region, 1992 (Powell et al., 1993).

Table 10.1 Net Volume of Growing Stock and Sawtimber on NIPF Timberland, 1952 and 1992

		Growing Stock (1 million cubic feet)		Sawtimber (1 million board feet, Int. 1/4-inch Rule)	
Region	Year	Softwood	Hardwood	Softwood	Hardwood
North	1992	28,514	114,967	79,133	301,272
	1952	16,048	57,054	34,163	128,880
South	1992	64,391	112,279	244,818	340,498
	1952	36,360	69,985	111,823	197,853
West	1992	50,456	15,052	236,925	41,412
	1952	42,341	6,649	211,955	18,812
U.S.	1992	143,361	242,298	560,876	683,181
	1952	94,749	133,688	357,941	345,545

Source: Powell, et al., 1993 (2)

inventory. In contrast, NIPF lands contained about 32 percent of the softwood growing stock volume, yet supplied 40 percent of the softwood harvest.

One criterion often used to indicate the productivity and condition of forestland is the ratio of net growth (that is, growth less mortality) to removals (harvests). With a growth/removal ratio greater than one, the forest adds volume to the existing inventory, even though harvests occur. Over the 1952 to 1992 period, the growth/removal ratio for NIPF lands averaged 1.5, indicating they were growing more wood volume than was being harvested. The growth/removal rate for national forests was also about 1.5, for other public lands it was about 2.0, and forest industry lands it was slightly below 1.0, indicating removals exceeded growth. From the perspective of growth/removal rates, then, NIPFs compared quite favorably with other ownerships over the 40-year period.

The Human Resource

What distinguishes NIPFs from industrial and public forests is the diversity of NIPF owners, their management objectives, capabilities, and constraints. We focus here on the 94 percent of private forest ownerships that are held by individuals and families and that collectively account for 59 percent of all privately owned forest land. Who are these people, and why do they own forest land?

Who Are the NIPF Owners?

There were 9-9 million owners of private forest land in 1994, up from 7.8 million in 1978, and their number is growing (3). Nearly 100 percent were NIPF ownerships. Why? A relatively small number of industry holders own a lot of land. Thus, although they own about 20 percent of the private forest land, they comprise less than 1 percent of the number of ownerships. About 90 percent of the NIPF ownerships are in the northern and southern regions of the United States. In 1994, the North had about 18 percent more private forest landowners than in 1978; the South experienced a 26 percent increase, whereas the West saw a jump of nearly 67 percent.

The growing number of NIPF ownerships indicates that the NIPF resource is being divided between more and more owners. This is particularly true at the urban-rural interface, where land parcelization and urbanization are formidable trends. *Fragmentation*—large ownerships being divided into smaller ones—is also taking place in rural areas, as urbanites seek rural retreats. One estimate is that the number of NIPF tracts of 10 acres or less increased 52 percent between 1978 and 1995 (4). Fragmentation undoubtedly has contributed to the dramatic increase in numbers of NIPF owners in the West over the past two decades.

In contrast to the national trend toward fragmentation of forest ownerships, some parts of the country are experiencing land concentration, wherein large ownerships become even larger through purchase of adjacent land. This is especially evident in areas dominated by large industrial ownerships, such as parts of the deep South (5).

The demographic profile of NIPF owners is changing. The proportion of older NIPF owners is increasing: about 45 percent of NIPF owners are 45 to *64* years of age, and about 20 percent are 65 years or over. Farm ownership of NIPFs has declined from 57 percent of the NIPF timberland in 1952 to 29 percent in 1992. Today, white collar and retired woodland owners are the most prevalent occupations, together comprising over half of all private ownerships (Figure 10.5). New purchasers of NIPF land, however, tend to be younger, more highly educated, and have higher incomes than the NIPF owners of j earlier decades (3).

Although 67 percent of woodland owners live on, or within one mile of, their woodlands, they tend to own their forestland for less time than did earlier generations: 40 percent of the private landowners have owned their lands for 15 years or less. Less than 10 percent of private forestland has been in the same ownership for over 45 years. This presents serious obstacles to long-term management.

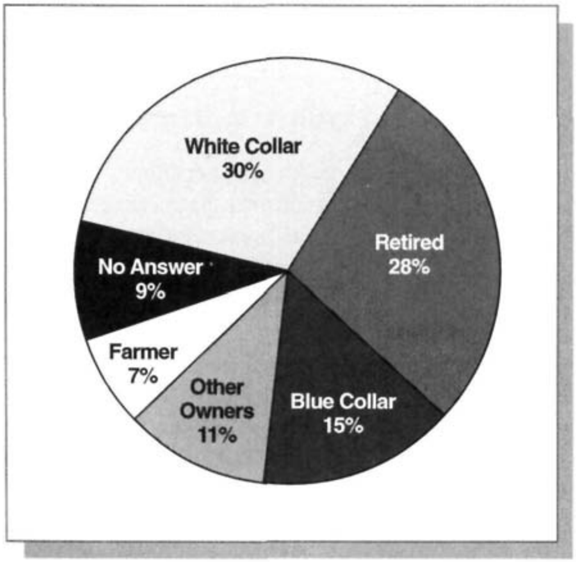


Figure 10.5 Distribution of private forestland by owner occupation, 1994 (Birch, 1996).

Several long-standing myths about NIPF owners have only recently begun to be challenged by social science research (7). Based upon generalizations that may have had more validity in the 1950s, many foresters have thought of NIPF owners as rural folks with strong family ties to the land. As such, they were assumed to be oriented toward timber production, and somewhat antagonistic toward environmentalism. They were thought to value private property rights above and beyond any other considerations, including ecological health or the public good. These truisms were thought to be especially true for owners of large tracts of forestland.

Recent research in the American South and elsewhere puts the lie to these myths. NIPF owners look increasingly like the rest of the American population and share the same values. They are more urban, better off financially, and more educated than in the past. They share the environmental values of mainstream society in the same proportions as do other U.S. citizens. And large tract owners are not nearly as different from small tract owners as formerly believed (see sidebars).

Why Do They Own Forest Land?

NIPF owners own forestland for many reasons. Some inherit forestland, or acquire it incidentally with farm or residential land. Others deliberately purchase forestland for recreation or as an investment. Most NIPF owners have a variety of reasons for owning forestland, only some of which may dominate their management decisions at particular times. In surveys, most report the following as primary reasons for owning forestland: 1) the forest is part of their residence or farm, 2) forest ownership provides aesthetic enjoyment, 3) forest ownership is a good financial investment, and 4) they enjoy forest recreation.

Relatively few NIPF owners—5 percent in a recent survey (3)—report timber production as a primary reason for owning forestland. Nonetheless, over time, most commercial timber on NIPFs is harvested—46 percent of those surveyed in 1994 had harvested timber. This is particularly true of larger NIPF ownerships, which typically receive more intensive management for timber crops.

In-depth interviews with NIPF owners (8) suggest that forest-related values and behaviors may be components of forest owners' ethnic or cultural heritage. Forest ownership and forest management provide families with opportunities to be and work together, enhancing family cohesiveness and strengthening ties between generations. For many owners, forest ownership is key to personal identity, and management gives expression to personal beliefs and values. The well-managed forest serves as a legacy of those who have been its steward. While these values are less easily quantified than income from timber sales or days spent hunting, they nevertheless help determine NIPF forest conditions.

NIPF Policies and Programs

Historical Overview

Since the 1900s, NIPF owners have received assistance with forest management planning, tree

Sidebar 10.1

A Few Own a Lot, Most Own Only a Little

The highly skewed distribution of private forest acres among owners renders discussion of average ownerships quite misleading (see Figure). Most private owners hold relatively small tracts of forestland: 59 percent have fewer than 10 acres, and 86 percent own less than 50 acres. On the other hand most of the forestland is held in very large tracts by industrial owners and NIPF owners.

Research shows that owners of large tracts are more likely than owners of small tracts to have management plans, be knowledgeable about forestry, be amenable to forest management, and to harvest timber. A 1994 study estimated that fewer than 6 percent of NIPF landowners had a written forest management plan (1). These were typically the owners of larger tracts; these 6 percent of NIPF owners owned 28 percent of the NIPF forest land. A number of studies have demonstrated that the intensity of forest management is positively conelated to the size of forest holding and the landowner's financial position. However, some recent research (2) suggests that large tract owners are not as different from small tract owners in their opinions regarding environmental and forestry issues as has typically been assumed. For example, majorities of both groups agreed that "Private property rights should be limited if necessary to protect the environment."

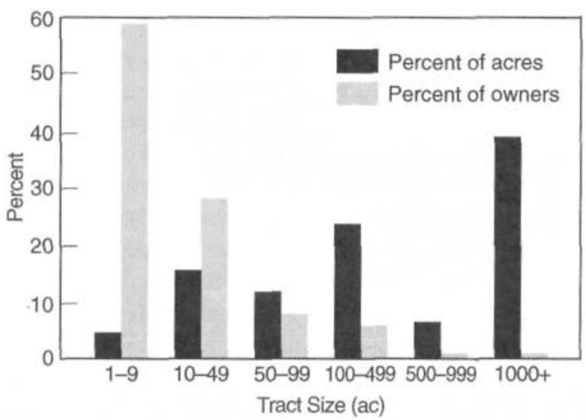
The distribution of NIPF acreage among owners has significant implications for forest policy. Historically, tax-supported forestry assistance programs have favored large ownerships because contacts with only a few landowners could result in treatment of thousands of acres of forestland. However, as a result, owners of smaller tracts—many of whom may be unlikely to hire professional forestry assistance—have received less public assistance.

Sources:

1. T. W. BIRCH, "Private Forest-land owners of the United States, 1994." Resource Bulletin NE-134. Radnor, Penn. U.S.D.A. Forest Service NE Forest Experiment Station, 1996.

2. J. C. Bliss, S. K. NEPAL, R. T. BROOKS, JR., AND M. D. LARSEN. *Southern J. of Applied Forestry, 21(1),* 37 (1997).

Distribution of private forestland among owners, 1994 (Birch, 1996).



Sidebar 10.2

Environmental Values of NIPF Owners

Since the late 1960s, environmentalism has increasingly become part of the American character. Pollsters have documented a steady rise in the proportion of Americans reporting concern over dwindling supplies of clean air and water, open space, and wildlife (1). A majority of Americans support greater efforts by government to guard against environmental degradation and believe that protecting the environment should take precedence over preserving private property rights or fostering economic growth (2).

As owners of most of the country's forestland, nonindustrial private forest owners have much at stake in these policy debates. To what extent do NIPF owners share in the general public's environmental values? Research conducted over the past decade demonstrates that, in their attitudes toward forest management and environmental protection, NIPF owners are similar to the rest of the American public (3, 4). A 1992 survey in the mid-South compared the environmental attitudes of NIPF owners with those of the general public (3). The views of NIPF owners and non-owners were essentially identical on the acceptability of prescribed burning (both groups were evenly split), the use of herbicides (a majority disapproved), and the practice of clearcut harvesting (a majority disapproved on public land). The great majority of owners and non-owners alike favored a balance between environmental protection and private property rights that ensures environmental protection. Three-quarters agreed with the statement, "Private property rights should be limited if necessary to protect the environment." Similarly, both forest owners and non-owners sought a balance between environmental and economic values, but a balance that puts environmental protection first. In sum, the environmental values and opinions of private forest owners mirrored those of the general public.

Source:

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planting, fire control, and other forestry activities from public agencies. Recognizing the crucial contribution NIPF lands make to U.S. timber production, the U.S. Forest Service early in its existence assigned a high priority to improving management of these lands. Government programs in this area have always been controversial. Since the inception of public forestry assistance programs in 1898, proponents of increased government involvement in private forest management have consistently felt that regulation of harvesting on private lands is necessary to protect the public interest, and that subsidies and tax incentives are needed to ensure effective management. Critics have decried governmental interference in private-land management, arguing that the working of the free market will ensure responsible forest management in the long run. This ongoing debate has historically resulted in a mix of regulation, financial incentives, tax policies, education and technical assistance programs.

The U.S. Forest Service role in private forest land management began with Gifford Pinchot's 1898 publication of Circular 21. Pinchot believed that proper management of private forests was in the public interest. Circular 21 offered free forest management advice to farmers and other owners of large tracts of forestland.

The 1924 Clarke-McNary Act authorized a comprehensive study of state forest tax policy that was expected to reveal means of counteracting the "cut-and-get-out" pattern of forest exploitation and land abandonment, which had left behind vast areas of tax-delinquent land. The Act provided the foundation for all subsequent federal assistance to the states for private forest management and became a focal point for debate on the federal role in private forestry. Forest industry leaders lobbied vigorously against government regulation of harvesting practices on private land. A Society of American Foresters committee chaired by Pinchot argued that regulation was needed to protect the public interest. The committee's report, "Forest Devastation: A National Danger and How to Meet It," concluded that "[n]ational legislation to prevent forest devastation should [provide] such control over private forest lands . . . as may be necessary to insure the continuous production of forest crops . . . and to place forest industries on a stable basis in harmony with public interest." Pinchot added some personal comments to those of the committee as follows:

> **Forest devastation will not be stopped through persuasion, a method which has been thoroughly tried for the past twenty years and has failed utterly. Since they will not otherwise do so, private owners of forestland must now be compelled to manage their properties in harmony with the public good. The field is cleared for action and the lines are plainly drawn. He who is not for forestry is against it. The choice lies between the convenience of the lumbermen and the public good (9).**

Despite Pinchot's concern, Congress ultimately shied away from regulation and opted for cooperation between the federal government and the states in a number of programs designed to encourage proper forest management (Figure 10.6). One historian of the Forest Service, William G. Robbins, stressed the influence of forest industries in shaping

Figure 10.6 Service foresters are the primary source of forest management information and assistance for many landowners.

Sidebar 10.3

From "The Small Woodland Problem" to "Sustainable Forestry"

The nation's nonindustrial private forests have been a major concern and research focus of professional foresters since the publication of Gifford Pinchot's Circular 21 in 1898. The profession's dominant view toward private forests has evolved in several distinct, yet overlapping phases corresponding to the concerns of the day. From the beginning, the profession has been obsessed with NIPF timber productivity. *The Small Woodland Problem* mentality arose from the view that NIPF lands were being "devastated" by exploitation and were not producing timber in volumes commensurate with their acreage. Low timber productivity was the "Problem."

From the 1950s into the 1980s this view evolved into *The Small Woodland Owner Problem,* in which the perceived under-productivity of NIPFs was attributed to the diversity of NIPF owners' objectives, their lack of forestry knowledge, and their reluctance to practice what professional foresters considered to be sound forest management. In other words, the NIPF owners themselves were the "Problem." Eventually some within the profession began to realize that "The Problem" was not the owners' problem at all, but the profession's: NIPF owners have what forest industry and the public wants—beautiful forests full of timber and wildlife (1). If foresters wanted to influence NIPF management, they first had to help achieve NIPF owners' goals.

By the early 1990s, yet another perspective on NIPFs was emerging in response to advances made in forest science. As scientists began to recognize the environmental importance of scale, ecological relationsips, and cummulative effects, foresters began considering forest ownerships within a landscape context. Under the paradigm of *ecosystem management,* timber productivity was viewed as one value among many to be managed, including water quality, endangered species recovery, and forest health. Accordingly, emphasis in NIPF research shifted from examining individual owner behavior to exploring how ownership patterns affect ecological processes and values, and how landowners might cooperate to achieve conservation goals for entire landscapes.

This paradigm is, in turn, broadening to include human and social values as well as forest and environmental values, and to concern itself with social systems as well as ecological systems. One expression of this emerging model is that of *sustainable forestry,* which explicitly considers the social, as well as the economic and environmental impacts of forest management. In this model, NIPF owners play key roles not only as resource owners but as members of rural neighborhoods, communities, and economies.

Aspects of each of these paradigms prevail within the forestry profession. The dominant perspective continuously evolves in response to changes in science, social values, and the economic and political climate.

Source:

1. W. D. TICKNOR, "Gloria reminiscences." Unpublished remarks to American Forestry Association Conference, Traverse City, Mich., October, 1985.

public policy toward private forest lands, concluding that "[industrial conditions have determined the kind and quality of federal resource programs" (10). Until the 1990s, industry's need for low-cost wood fiber was the driving force behind most NIPF assistance programs, resulting in their strong focus on timber productivity. More recently, environmental concerns (discussed later in this chapter) have dominated public policy initiatives in the NIPF arena.

The 1950s and 1960s were decades of tremendous growth in federal and state cooperative forestry assistance programs. The Cooperative Forest Management Act of 1950 provided for direct technical forestry services to all classes of private forest ownership, including small, nonfarm tracts.

During the "Environmental Era" of the late 1960s and early 1970s, several states passed legislation to protect environmental quality on private lands from poor timber harvesting practices. While many states relied upon forest taxation programs designed to encourage good stewardship of NIPF lands, other states enacted forest practices legislation to restrict and prescribe management activities. California's 1973 Forest Practice Act included the most comprehensive timber harvest regulations.

The Cooperative Forestry Assistance Act of 1978 enabled the secretary of agriculture to establish requirements for state forest resource programs. As a result of this and other legislation, the role of the federal government in private forestry assistance was largely reduced to an administrative one. In contrast to the intensive federal involvement in Depression era programs, primary responsibility for private forestry assistance was, by the 1980s, on state shoulders (10).

Contemporary Policies and Programs

Since Gifford Pinchot's 1898 publication of Circular 21, the public interest in healthy, productive private forest lands has been pursued through a combination *of financial incentives, regulations, education, technical assistance,* and *partnerships.*

Financial Incentives *Financial Assistance:* At the beginning of the 21st century a number of government programs exist to assist owners of forest, range, or farmland protect environmental values or increase productivity of forest and related resources. Most of these programs involve a cost-share payment (the landowner typically pays 35-50 percent, the government pays the balance) to private landowners for conducting a variety of forest management practices. In addition to federal assistance programs, some states administer assistance programs aimed at enhancing management of NIPF lands (11).

Forest Taxation: Traditional property taxes are based on "highest and best use" of the land and assume production of an annual income. However, unlike agricultural lands, few NIPF ownerships produce annual income, putting forest owners at a disadvantage relative to other landowners. Several states now administer special property tax programs designed to remove such destructive effects of taxation for NIPF landowners. For those states having yield taxes, the land may be taxed annually, but the timber is not taxed until it is harvested.

Federal and state income taxes have a big impact on private forest ownership and management. Tax laws continually change, quickly rendering any summary out of date. However, rules for reporting timber sale income and deducting expenses for forestry activities are always important tax issues for NIPF landowners. Over the years, various modifications to the tax code have attempted to reduce the financial impact of forest management activities on landowners' tax obligation. Generally, timber sale income can be considered a capital gain and is thus taxed at a rate different than that of ordinary income. Forestry expenses are typically deductible from income if the landowner can demonstrate being actively involved in the management activities.

Taxes on estates, above an allowed exclusion, are high, between 37 and 55 percent of the value of the estate. Consequently, federal estate taxes are often blamed for causing landowners to break up and sell their forest lands, or to harvest their timber excessively and prematurely in order to meet their tax obligation. Proposals to lessen the negative impact of estate taxes on private forest owners include increasing the allowable exclusion and

Sidebar 10.4

Forest Products Certification

Green certification—third-party evaluation of sustainable forest management and forest products—is a rapidly growing market-based approach to improving stewardship on private and public forest lands alike. Several organizations are competing for primacy in forestry certification. One of the most established is the Forest Stewardship Council (FSC), an international organization based in Mexico. FSC developed broad principles and criteria for green certification of forest management activities, including principles regarding compliance with existing laws, the rights of indigenous peoples, workers, and local communities; environmental impacts; conservation of environmental and culturally significant resources, and management planning, monitoring, and evaluation. While most of the principles are widely accepted as central to responsible forestry, acceptance is not universal. Debate continues over whether practices such as clearcutting, plantation silviculture, and use of pesticides should be condoned.

FSC-approved foresters inspect forest owners' management plans and lands for compliance with national and regional standards. Timber products that are harvested from certified forests can then be marketed as certified, or "green." The standards of several certifying organizations comply with those of the FSC, including Smartwood, a nonprofit certifier, and Scientific Certification Systems, a for-profit certifier. It remains to be seen whether green-certified wood products will command a higher price in the marketplace and thereby become a real influence on NIPF management (1).

Source:

1. G. J. GRAY, M. J. ENZER, AND J. KUSEL, IDS., *Understanding Community-Based Forest Ecosystem Management*, Food Products Press, New York, 2001.

excluding from taxation the value of forestland placed in a qualified conservation easement.

Regulations Although NIPF owners are affected by many federal regulations, none is of more consequence than those embodied in the Clean Water Act of 1972 and the Endangered Species Act of 1973. Under the Clean Water Act, states have responsibility to monitor and manage impacts of nonpoint sources of water pollution, including forest-related sources. Many states' forest practices acts arose out of state efforts to meet the requirements of the Clean Water Act. Although normal silvicultural practices are exempt from this act, dredging or filling in wetlands (such as might be required in forest road building) requires a permit from the Army Corps of Engineers.

The Endangered Species Act of 1973 set out regulations for conserving endangered and threatened species and their habitat. In the landmark 1995 Sweet Home case, the Supreme Court upheld the government's authority to regulate endangered species habitat on private land. The Endangered Species Act has been invoked to restrain timber harvest activities in northern spotted owl habitat in the Pacific Northwest and in red-cockaded woodpecker habitat in the Southeast. Lawsuits related to this use of the act raise the issue of whether such restraints on forest management activity on private lands constitute an infringement of private property rights, and if so, whether effected landowners should be compensated.

Most states and a growing number of local units of government have passed regulations restricting the forest management practices of private forest owners. In the 1940s, a first wave of regulations covering forestry on private lands was prompted by concern over future timber availability and hence stressed regeneration standards. Subsequent regulations have mandated that forest management activities not adversely affect environmental quality, by setting minimum standards for timber-harvesting, road construction and location, and the use of herbicides and pesticides. Recent regulations have addressed long-term resource sustainability, biodiversity, improving water quality and resource conservation.

By 1997, about one-third of the nation's private timberland was covered by state forest practices acts, and a total of 38 states had at least one program regulating forest practices on private land (12). State forest practices acts typically include standards for road and skid trail construction, stream crossings, timber harvesting, size of clearcuts, slash disposal, reforestation, minimum stocking levels, riparian zones, sensitive wildlife habitat, and wetlands protection (Figure 10.7). Several states are experimenting with contingent or conditional regulations wherein best management practices are voluntary, contingent upon their widespread application. Where established forest practice standards are not followed, the state may levy penalties (12).

Recognizing the limitations of regulations to achieve conservation goals, nongovernmental organizations, state agencies, and others are working together to develop innovative conservation incentives for private land owners. In some cases, agencies and conservation organizations purchase land from private owners in order to protect the special environmental value it contains. In other cases, conservation easements are negotiated with landowners to allow some public uses or to disallow certain practices, such as the harvest of tree species or forest types that are locally threatened. Safe harbor agreements are designed to enhance protection of endangered species habitat without preventing landowners from using their land.

Education and Technical Assistance Much of the research on NIPF owners points to education as the most effective means of influencing NIPF management decisions. A major source of information and education for NIPF owners is the Cooperative

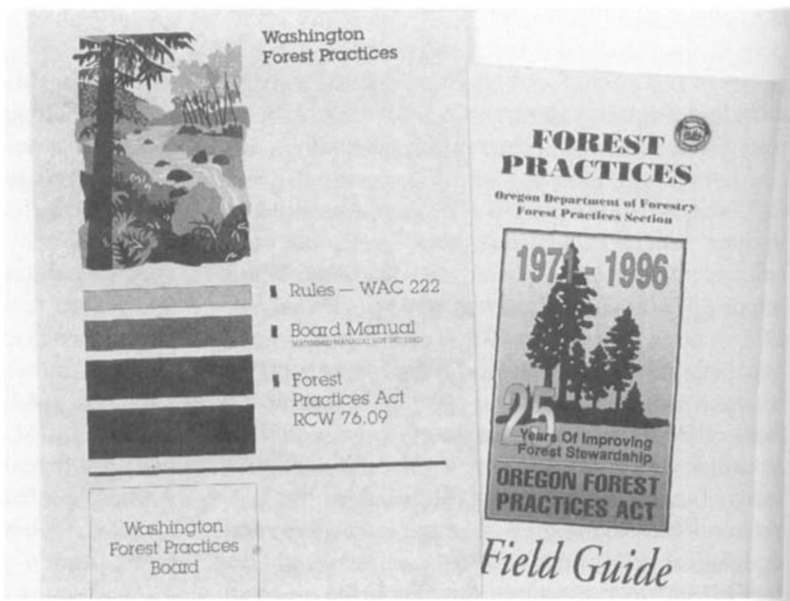

Figure 10.7 Forest Practice regulations covering private forestlands are mandatory in some states. Other states have opted for voluntary best management practices. Most states are seeking a workable balance between regulatory and voluntary forest conservation measures.

Extension Service. The CES provides educational programs and materials to NIPF landowners, professional resource managers, forest products industry personnel, loggers, policymakers, and the general public (Figure 10.8). Usually the educational service is provided through workshops, conferences, field days, TV and radio programs, "how-to" publications, the Internet, videotapes, marketing bulletins, newspaper stories, and computer programs.

As resources shrink, a number of states are adapting a volunteer training model, called the Master Woodland Manager Program, to extend their educational outreach capabilities (13). This program provides participants intensive forestry training, and, in return, each Master Woodland Manager volunteers service to other forest owners. The program aims to stimulate management activity among landowners, provide leadership in woodland management, promote woodland management to nonowners, and assist forestry extension agents in their outreach activities.

Partnerships Some of the oldest partnerships are among NIPF owners themselves, and between owners and forest industry. As of 1998, state forest owner associations existed in 31 states. Ten of these states also had local associations. Total membership in all known state and local forest owner associations was estimated to be 48,000 (14). Although the members of these associations represent a very small portion of the 9.9 million private forest owners in the nation, their influence at local, state, and national levels is growing. Through sponsorship of conferences, tours, workshops, and field days, they educate members and bring them into contact with each other and with agency personnel, researchers, and other natural resource professionals. Some associations sponsor environmental education activities for youth and the general public. Most publish newsletters, magazines, and contribute articles and editorials to local papers. Some provide timber price reporting, marketing, and insurance services to their members. Many are politically active at the state and national levels, participate in policy development, and support lobbyists.

Figure 10.8 Many woodland owners are eager to learn more about managing their lands. Field days, workshops, and conferences covering a wide range of topics are readily available, and publications abound for those seeking up-to-date "how-to" information.

Any NIPF landowner with a minimum of 10 acres of woodland and a commitment to forest management can become a member of the American Forest Foundation's Tree Farm program. As of 1998, the program boasted some 70,000 members (11). Properties meeting program criteria are certified as Tree Farms, and are re-inspected at regular intervals. Every year the program chooses state, regional, and national Outstanding Tree Farmer of the Year recipients (Figure 10.9).

Many forest products companies provide forest owners free assistance with management planning,

Figure 10.9 The Tree Farm Program provides recognition and technical assistance to NIPF owners who wish to manage their woodlands.

tree planting, vegetation management, timber harvesting, and marketing. In return for this assistance, many companies develop written agreements with landowners that guarantee the company first option on the timber crops as they become available for market. In 1994-95, nearly 11,000 landowners participated in landowner assistance programs, many in the Southeast (15).

In the past, when the public interest in private forest lands was primarily defined as one of promoting timber production, programs focused on improving the productivity of individual forest stands. As the public interest has become more broadly understood to include improvement of environmental quality, reclamation of degraded habitats, and restoration of endangered species populations, the focus on individual ownerships has become inadequate. Major conservation goals with strong public support include restoring more natural insect, disease, and fire regimes; maintaining healthy populations of aquatic and terrestrial species; and restoring endangered habitats such as the longleaf pine forests of the Southeast. Each goal requires concerted effort over large landscapes. The understanding that resource conservation requires landscape-scale attention drives current forest management planning and policy.

Achieving conservation goals is challenging in landscapes of mixed ownership where owner objectives, capabilities, and constraints vary widely. Developing partnerships between public and private landowners and land users is one of the distinctive aspects of conservation at the beginning of the 21st century. Finding an effective mix of regulatory and nonregulatory instruments to encourage cross-boundary, cooperative solutions to environmental problems will likely be among the most daunting forest conservation policies of the first decade of the new millenium.

Emerging Trends and Issues

The beginning of the 21st century is both an exciting and frightening time for NIPF owners and for the profession of forestry. The extent and rate of change in every aspect of forestry—forest science, social values and demands, forest policies—have never been greater. This rapid change makes it difficult to predict with certainty what conditions will

Sidebar 10.5

Oregon's Salmon Plan: An Experiment in Public-Private Collaboration

To residents of the Pacific northwest, the salmon symbolizes the region's ideal of living in touch with nature. The dramatic decline in salmon populations is seen as a threat not only to the species, but also to the region's very identity. The 1995 proposal by the National Marine Fisheries Service to list coho salmon as threatened under the Endangered Species Act triggered a major, innovative experiment to avoid listing and restore salmon habitat. In 1997, the Oregon state legislature approved expenditure of $30 million—$13.6 million from a tax on forest products volunteered by forest landowners and industry—to implement what has become known as The Oregon Plan. In essence, the Plan aims to supplement existing regulations (such as the state's forest practices act) with voluntary measures designed not only to prevent "takings" of salmon, but also to restore salmon habitat and increase salmon populations. The Plan made funding available to some 60 existing or newly created watershed councils—voluntary associations of landowners, community residents, environmental organizations, and public agencies—to collaborate in restoration efforts (1). In the first year of the Plan some 1200 restoration activity reports were filed on projects including steam bank stabilization, fencing, riparian habitat restoration, culvert replacement, and "putting to bed" unused logging roads (2).

Monitoring efforts have been a major component of watershed council work. Volunteers have inventoried and mapped culverts, dams, stream crossings, forest roads, and other obstructions affecting fish passage. They have conducted salmon spawning and stream temperature surveys. Instructions for conducting and reporting these surveys are available on the World Wide Web, thereby encouraging wide participation in monitoring. An Independent Multidisciplinary Science Team monitors achievements of watershed councils through an annual audit.

This experiment in bottom-up, voluntary collaboration between state government and local stakeholders is not without controversy and risk. In 1998, a federal magistrate ruled that the National Marine Fisheries Service had violated the Endangered Species Act by not listing the coho, thereby forcing its listing. By prior agreement, that action nullified the dedicated forest products tax, thus putting Plan funding in jeopardy. It remains to be seen what effects the ruling will have on the thousands of volunteer participants in local watershed councils. Conservation groups around the country are watching to see if watershed councils will survive this blow and achieve the potential of this experiment in collaboration (3).

Sources:

1. J. CHRISTENSEN, *American Forests, 103(4),* 17 (1998).
2. Oregon Forest Resources Institute, "Saving the Salmon: Oregonians Working Together to Manage Environmental Change." Special report, Oregon Forest Resources Institute, Portland, Ore. (No date given).
3. G. J. GRAY, M. J. ENZER, AND J. KUSEL, EDS., *Understanding Community-Based Forest Ecosystem Management*, Food Products Press, New York, 2001.

be like for NIPF owners even five years from now. Nonetheless, the following are trends and issues emerging at the birth of the new century that will likely affect ownership and management of NIPFs over the coming decade.

Rights and Responsibilities of NIPF Owners

Finding the appropriate balance between individual and public rights to private land continues to be the defining NIPF issue. Public interest in private forest lands has grown with our new understanding of the importance of these lands for environmental health. NIPF owners find themselves called upon to produce more—more timber, more wildlife, more beauty, more recreational opportunities—while at the same time being subjected to greater scrutiny. Owners in all states are subject to federal laws such as the Endangered Species Act and the Clean Water Act. However, the level of state regulation varies from states with no state regulation whatsoever over forest practices acts, to states in which most forest practices are regulated in great detail. Further complicating the regulatory scene is the profusion of municipal and county ordinances affecting management of forests and related resources. Faced with confusing, sometimes conflicting, and continuously changing rules and regulations, NIPF owners are anxious about their future ability to manage their forests.

Nonregulatory Mechanisms for Environmental Protection

This regulatory maze, together with the growing need to address environmental problems at a landscape scale, is driving a nationwide search for nonregulatory mechanisms for achieving environmental objectives. It is a time of frustration with existing policies, anxiety over the future, and optimistic experimentation with new approaches to forestry. These include promotion of voluntary Best Management Practices, cross-boundary cooperative management arrangements, conservation easements and leases, strategic alliances between environmental, industry, and landowner organizations, and innovative market mechanisms such as green certification.

Changing Forest Ownership Patterns

Forestland at the fringe of many metropolitan areas is being fragmented and converted to nonforest uses at an alarming rate, with an accompanying loss of green space and wildlife habitat. Urban residents decry the resulting erosion of environmental quality, and rural NIPF owners fear they will lose the right to manage their forests as residential neighborhoods proliferate. Clashes between old and new residents and their contrasting forest values are becoming more frequent. A new class of mini-forest owners is being created, with new needs for tree and forest information and management services.

At the same time, smaller NIPF ownerships in some rural areas are being consolidated into large tracts by corporate and industrial entities. Often, this change in ownership results in dramatic changes in forest composition, as the multiple objectives of NIPF owners are replaced by a stronger emphasis on commercial timber production. Loss of ownership diversity also drains a landscape of the human values NIPF owners provide. Changing ownership patterns will present multiple challenges to sustaining economic, social, and ecological health.

Changing Markets

The economic climate within which NIPF owners operate has changed significantly in the past decade, presenting new marketing and forest management challenges. Once, locally owned mills dominated local markets, determining what forest products were marketable and at what price. Such market determinations are now increasingly made in the global marketplace. Forest products produced in the United States compete with imports from Canada, South America, Pacific Rim countries, and elsewhere. U.S. environmental policy influences forestry investment decisions around the world. For example, dramatic reductions in timber harvesting on U.S. National Forests has led both to increasing harvest pressures on NIPF lands and increased imports of wood from Canada and elsewhere. In retail markets, wood and nonwood building materials compete for consumer recognition as being environmentally friendly. Green certification advocates propose to label forest products derived from sustainably managed forests, and achieve higher prices for them. All these factors combine to create dynamic and unpredictable wood markets. NIPF owners will increasingly require marketing savvy to effectively compete in complex global wood markets.

Emerging Forestry Paradigms

The profession of forestry, like all professions, evolves in response to societal changes. During the last two decades of the 20th century, the profession of forestry experienced a period of intense introspection, reevaluation, and testing of new paradigms. First derided as a mere buzzword, *ecosystem management* has become the dominant management paradigm for forestry on private as well as public lands. Ecosystem management focuses on very large geographic areas (watersheds to eco-regions) and very long time frames (up to several centuries), and emphasizes connections, processes, and desired future forest conditions. Many of the alternative policy mechanisms discussed above are attempts to find solutions to problems occurring at the ecosystem scale. Finding effective, equitable, and politically tenable means to achieving ecosystem objectives in mixed-ownership landscapes—especially landscapes dominated by NIPFs—is likely to be among the greatest challenge of natural resource managers and policy makers in the next decade.

Closely associated with ecosystem management, *sustainable forestry* encompasses many of the concepts and principles that are currently emerging within the forestry profession. Sustainable forestry goes beyond the traditional sustained yield model of production forestry to emphasize sustaining all forest values, functions, and outputs. It adds to ecosystem management by explicitly recognizing social and economic, as well as environmental, goals for forestry. People involved in developing sustainable forestry include silviculturalists testing timber harvesting schemes that mimic natural processes, community groups searching for meaningful participation in regional forest resource planning, and forestry companies evaluating markets for green-certified forest products.

Concluding Statement

Nonindustrial private forests are of immense social, economic, and environmental value. They dominate the landscape of vast regions of the United States, are a vital component of the national economy, and play a growing role in international markets. The great diversity of NIPF owners results in a wide variety of objectives, constraints, and capabilities, which in turn create diverse forest types, ages, and conditions. This social and environmental diversity is in itself an important contribution made by NIPFs to the landscape and economy of America.

NIPF owners operate in a rapidly changing environment. Advances in forest science, growing demands for the products and values produced by NIPFs, and a dynamic policy environment all contribute to an atmosphere of instability, unpredictability, and risk. Over the coming years, NIPF owners will face changing markets, regulatory instability, and increasing demands that they cooperate with their neighbors to achieve environmental protection goals.

Each of these issues presents daunting challenges to the profession of forestry as well as to NIPF owners. Some will throw up their hands in frustration and declare the end of the forestry profession. Others will see in these challenges limitless opportunities to solve problems, serve people, improve the condition of the planet, and grow professionally. Enterprising and determined persons of creativity, patience, and energy will find the coming decade to be a wonderful time to work in the field of nonindustrial private forestry.

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CHAPTER 11

Measuring and Monitoring Forest Resources

ALAN R. EK, GEORGE L. MARTIN, AND DANIEL W. GILMORE

There are as many reasons to measure forests as there are uses of forests, and each use has its own specific needs for information. A forest landowner may want to sell some timber, and the determination of a fair price will require information about the species, size, quality, and number of trees to be sold. Forest managers seek to monitor forest conditions and practices and develop long-range plans concerning protection, planting, thinning, harvesting, and other treatments in their forests. These plans in turn require detailed information about the type, size, density, and growth rates of the existing stands, together with information about the location, accessibility, quality, and usage of the forest sites. Increasingly, surveys of on-the-ground silvicultural and harvesting practices are also conducted to understand the character, extent, and effectiveness of such activities, and particularly to assess compliance with practices deemed best for various situations. These and more detailed surveys also provide the data for forest scientists to develop an understanding of how forests grow and interact with their environment and benefit society.

These diverse information needs have led to recognition of a specialized branch of forestry, *forest measurements* (also *forest biometrics),* which focuses on techniques for the efficient measurement of forests, including their growth and response to management practices. The word *efficient* means that the measurement techniques strive to provide accurate information in a short time period at low cost.

This chapter presents an overview of some of the measurement techniques used in forestry. Both English and metric units of measurement are in use today, so both systems are described in this chapter. To help the reader become familiar with both systems, measurements in some tables and examples are in English units, and measurements in others are in metric units. The emphasis is on timber resources, but the measurement of some nontimber resources is also briefly described. Textbooks (1-3) are available for readers who want to learn more about forest measurements.

Measurement of Primary Forest Products

To appreciate how forests are measured, we first need to understand how we measure the primary products derived from forests. These primary products include *sawlogs, bolts,* and *chips.* Sawlogs are logs of sufficient size and quality to produce lumber or veneer. They must be 8 feet or more in length with a minimum small-end diameter of 6 to 8 inches. Bolts are short logs, less than 8 feet in length, and used primarily for manufacture into pulp and paper. Chips are small pieces of wood obtained by cutting up logs and sawmill wastes. They are used as a raw material for manufacturing a variety of forest products and as a source of fuel.

Scaling

The process of measuring the physical quantity of forest products is called *scaling.* During the nineteenth century the practice became established in the United States to scale sawlogs in terms of their board foot contents. Actually, the *board foot* is a unit of sawn lumber equivalent to a plank 1 foot long, 1 foot wide, and 1 inch thick. Estimates of the board foot contents of a log must take into account the portions of a log lost to saw kerf, the saw cuts between the boards, and to slabs, the rounded edges of the log. By 1910, more than forty *log rules* had been devised to estimate the volume of logs in board feet, based on measurements of the diameter inside bark on the small end of the log (Figure 11.1), and the length of the log. Most of these log rules were very inaccurate and are no longer in use; however, a few managed to achieve widespread acceptance and continue to be used today: notably, the Doyle, Scribner, and International log rules.

The *Doyle log rule* was first published in 1825 by Edward Doyle of Rochester, New York. This rule is based on the simple formula:

$$V = (D - 4)^2 L/16$$

where V is the volume of the log in board feet, D is the small-end scaling diameter in inches, and L is the length of the log in feet (after allowing 3 to 4 inches for trim). The Doyle log rule grossly underestimates the volumes of logs less than 20 inches in diameter, but it continues to be used because of its simplicity and because it encourages the delivery of large-diameter logs to mills.

The *Scribner log rule* was published in 1846 by John Marston Scribner, an ordained clergyman and teacher of mathematics in a girls' school. Scribner estimated log volumes from diagrams of boards drawn on circles of various sizes corresponding to the small ends of logs. Boards were drawn with a 1/4-inch allowance for saw kerf and with the

Figure 11.1 First step in scaling: determining the diameter inside the bark on the small end of the log.

assumptions that boards would be 1 inch thick and not less than 8 inches wide. He further assumed that the logs were cylinders, so no adjustments were made for log taper. Scribner published his log rule in the form of a table, but the following formula has since been developed to describe his rule:

$$V = (0.79D^2 - 2D - 4)1/16$$

A variation of the Scribner rule is the *Scribner decimal C rule,* obtained by rounding the former rule to the nearest 10 board feet and then dropping the rightmost zero. For example, a 16-foot log with an 18-inch scale diameter would have 216 board feet according to the Scribner rule and would scale as 22 by the Scribner decimal C rule.

The most accurate log rule in use today is the *International log rule* developed by Judson Clark in 1906. Clark was a professional forester who had been bothered by the inconsistent and radically different estimates that he obtained from the Doyle, Scribner, and other log rules. He concluded that these rules grossly underestimated the volume of long logs because they did not take into account the increased board foot yield caused by log taper. In its basic form, this rule assumes a 1/8-inch saw kerf and estimates the volume of a 4-foot section. The volume of the entire log is estimated by adding the volumes of each 4-foot section and assuming a 1/2-inch increase in diameter for each section. In this way, the International rule allows for an increase in log volume owing to taper. The basic formula for the volume of a 4-foot section is

$$V = 0.22D^2 - 0.71D$$

For a quarter-inch saw kerf, this formula is multiplied by 0.905.

Table 11.1 shows that there are substantial differences between the estimates obtained with the log rules just described, especially for smaller log sizes. A wise buyer or seller will study the differences before completing any agreements.

Sawlogs can be scaled more consistently by simply estimating the volume of solid wood in the log. *Smalian's formula* is often used for this purpose,

$$V = (A_1 + A_2)L/2$$

where V is the volume of solid wood (in cubic feet or cubic meters), A_1 and A_2 are the cross-sectional areas inside bark on the two ends of the log (in square feet or square meters), and L is the length of the log (in feet or meters). Despite numerous attempts to promote cubic-volume scaling in the United States, board foot scaling still prevails.

The sawlog volume obtained with a log rule or cubic-volume formula is called the *gross scale. A net scale* must then be calculated by deducting for *scale defects* that will reduce the usable volume of wood in the log. Scale defects include rot, wormholes, ring shake (separation of wood along annual rings), and splits. In addition, if the log is not sufficiently straight, a scale deduction is made according to the amount of sweep or crook in the log.

Pulpwood and firewood are usually scaled by measuring the dimensions of a stack rather than measuring individual bolts. A *standard cord* of wood is a stack 4 by 4 by 8 feet and contains 128 cubic feet of wood, air, and bark. The number of standard cords in any size stack can be calculated by dividing the product of the stack's width, height, and length (in feet) by 128. Variations of the standard cord include the *short cord or face cord,* a stack 4 feet high and 8 feet wide with individual pieces cut to a length less than 4 feet. The dimensions of various types of cords are illustrated in Figure 11.2.

The amount of solid wood in a standard cord may range from 64 to 96 cubic feet, depending on several factors. Solid-wood content is reduced by thick bark, small-diameter bolts, crooked bolts, and loose piling, so these variables must be assessed when estimating the actual amount of wood in a given stack.

In recent years, much of the pulp and paper industry has adopted weight scaling for stacked pulpwood and wood chips. With this method, a truck carrying a full load of wood is weighed before and after it is unloaded. The difference is the weight of the wood, which can then be converted to volume or dry weight by taking into account the specific gravity and moisture content of the wood. Weight scaling is favored because it is fast and objective, and it encourages delivery of freshly cut wood to the mill.

Table 11.1 Board-Foot Volume of 16-Foot Logs for International Rule and Other Rules in Percentage of the International Rule[a]

Scaling Diameter (in.)	International[b] (bd ft)	Scribner (percent)	Scribner Decimal C (percent)	Doyle (percent)
6	20	90	100	20
8	40	80	75	40
10	65	83	92	55
12	95	83	84	67
14	135	84	81	74
16	180	88	89	80
18	230	93	91	85
20	290	97	97	88
22	355	94	93	91
24	425	95	94	94
26	500	100	100	97
28	585	99	99	98
30	675	97	98	100
32	770	96	96	102
34	875	91	91	103
36	980	94	94	104
38	1095	98	98	106
40	1220	99	98	106

D. L. Williams and W. C. Hopkins, "Converting factors for southern pine products," U.S.D.A. For. Serv., Tech. Bull. 626, South. For. Expt. Sta., New Orleans, 1969.

[a] Terms used in this table are defined in the text.

[b] Quarter-inch kerf (width of cut made by saw).

Figure 11.2 Examples of stacked-wood units, from left to right: standard cord, face cord (pieces 16 inches long), split face cord, and a split face cord piled in a small truck.

Grading

The value of forest products, particularly sawlogs, can be greatly reduced by *grade defects* that lower their strength, take away from their appearance, or otherwise limit their utility. Defects that lower the grade of sawlogs include knots, spiral grain, and stain.

Rules for grading hardwood logs emphasize the number, size, and location of defects, such as knots, that affect the amount of clear lumber that can be sawn from the log. Four classes of log use have been defined for the grading of hardwood logs (4).

1. *Veneer Class.* Logs of very high value as well as some relatively low-value logs that can be utilized for veneer. Logs that qualify as factory lumber grade 1 can often be utilized as veneer logs.
2. *Factory Class.* Boards that later can be remanufactured to remove most defects and obtain the best yields of clear face and sound cuttings. Factory lumber is typically separated into grades 1, 2, and 3-
3. *Construction Class.* Logs suitable for sawing into ties, timbers, and other items to be used in one piece for structural purposes.
4. *Local-Use Class.* In general, logs suitable for products not usually covered by standard specifications. High strength, great durability, and fine appearance are not required for the following types of products: crating, pallet parts, industrial blocking, and so on.

Rules for grading softwood logs emphasize strength and durability. The majority of softwood logs fall into the *veneer class* or the *sawmill class*, which includes logs suited to the production of yard and structural lumber. The number, location, and size of grade defects determine the grade of logs in these two classes.

Land Surveying and Mapping

Land-surveying and land-mapping techniques are used in forestry to locate the boundaries of forest properties and stands of timber, to measure the land areas enclosed within these boundaries, and to locate roads, streams, and other features of importance within the forest. Surveying techniques are also used for locating sample plots as described later in this chapter.

Forest land surveys in the United States are usually conducted with the English system of units. Distance is measured *in feet, chains (1* chain = 66 feet), and *miles* (1 mile = 80 chains); land area is measured in *acres* (1 acre = 10 square chains) and *square miles* (1 square mile = 640 acres). In the metric system, distance is measured in *meters* (1 meter = 3.28084 feet) and *kilometers* (1 kilometer = 1000 meters), and land area is measured in *hectares* (1 hectare = 10,000 square meters) and *square kilometers* (1 square kilometer = 100 hectares). Acres and hectares are both used to describe land areas in the United States, so it is useful to remember that 1 hectare is equal to 2.471 acres or about 2.5 acres. Additional converting factors for units of distance and area can be found in Appendix III.

Distance

There are several methods for measuring distance in forest surveys, and the choice depends on the accuracy required. *Pacing* is often used for locating sample plots and in reconnaissance work where great accuracy is not required. Foresters must first calibrate their individual pace by walking a known distance—say, 10 chains—and counting the number of paces. In forestry, a pace is considered two steps, using a natural walking gait, and should be calibrated for each type of terrain encountered. Having determined the average number of paces per chain, the forester can then measure and keep track of distances by counting paces while walking through the forest. An experienced pacer can achieve an accuracy of 1 part in 80; that is, for every 80 chains traversed the error should be no more than 1 chain.

When greater accuracy is required, steel tapes are used in a technique known as *chaining.* The steel tapes may be 2 chains, 100 feet, or 30 meters in length, depending on the units desired. Chaining requires a minimum of two people to hold each end of the tape. The head chainer usually uses a magnetic compass to determine the direction of the course line while the rear chainer keeps a record of the number of tape lengths traversed. Careful chaining can achieve an accuracy of 1 part in 1000.

There are also a variety of *electronic and optical instruments* for measuring distances. Examples of such tools include laser-based rangefinders. However, these instruments require a line of sight largely free of obstacles such as trees and shrubs. For this reason, they are not well suited for timber surveys in densely wooded areas, but they are used for road and boundary surveys. Additionally, satellite linked global positioning system (GPS) units are increasingly used for establishing locations, travel routes, and boundaries.

Direction

Many of the instruments available are more accurate for measuring direction, but the *magnetic compass* is favored by foresters because of its speed, economy, and simplicity. With a magnetic compass, directions are measured in degrees (0 to 360) clockwise from magnetic north, the direction pointed by the compass needle. These direction angles are called *magnetic azimuths* and must be converted to true *azimuths* by correcting for *magnetic declination;* that is, the angle between true north and magnetic north. Many compasses allow this correction to be made automatically by the instrument. GPS units are also supplanting compass usage where the forest cover allows links to satellites (Figure 11.3).

Land Surveys

Much of the land subdivision in the world is based on the *metes and bounds* system. Under this system, property lines and corners are based on physical features such as streams, ridges, fences, and roads. Locating such legal boundaries is often difficult, especially when descriptions are vague, corners that were once marked have been lost, and lines such as streams have moved over the years. However, most of the United States west of the Mississippi River and north of the Ohio River, plus Alabama, Mississippi, and portions of Florida, have been subdivided according to a *rectangular survey system.* This system was conceived by Thomas Jefferson at the close of the Revolutionary War, and enacted as the Land Ordinance of 1785 "to survey and sell these public lands in the Northwest Territory"

The rectangular survey system uses carefully established *baselines and principal meridians* as references for land location. The baselines run east-west, and the principal meridians run north-south. The intersection of a baseline and principal meridian is called an *initial point* and serves as the origin of a survey system. More than thirty of these systems were established as land was acquired and

Figure 11.3 Examples of GPS (with PDA) usage (left), and laser rangefinder usage (right), in the field.

development progressed westward in the United States.

Figure 11.4 shows how land is subdivided under the rectangular survey system. At intervals of 24 miles north and south of the baseline, *standard parallels are* established in east-west directions. At 24-mile intervals along the baseline and each of the standard parallels, *guide meridians* are run north to the next standard parallel. Because of the earth's curvature, guide meridians converge to the north and the resulting *24-mile tracts* are actually less than 24 miles wide at their northern boundaries.

The 24-mile tracts are then subdivided into sixteen *townships,* each approximately 6 miles square.

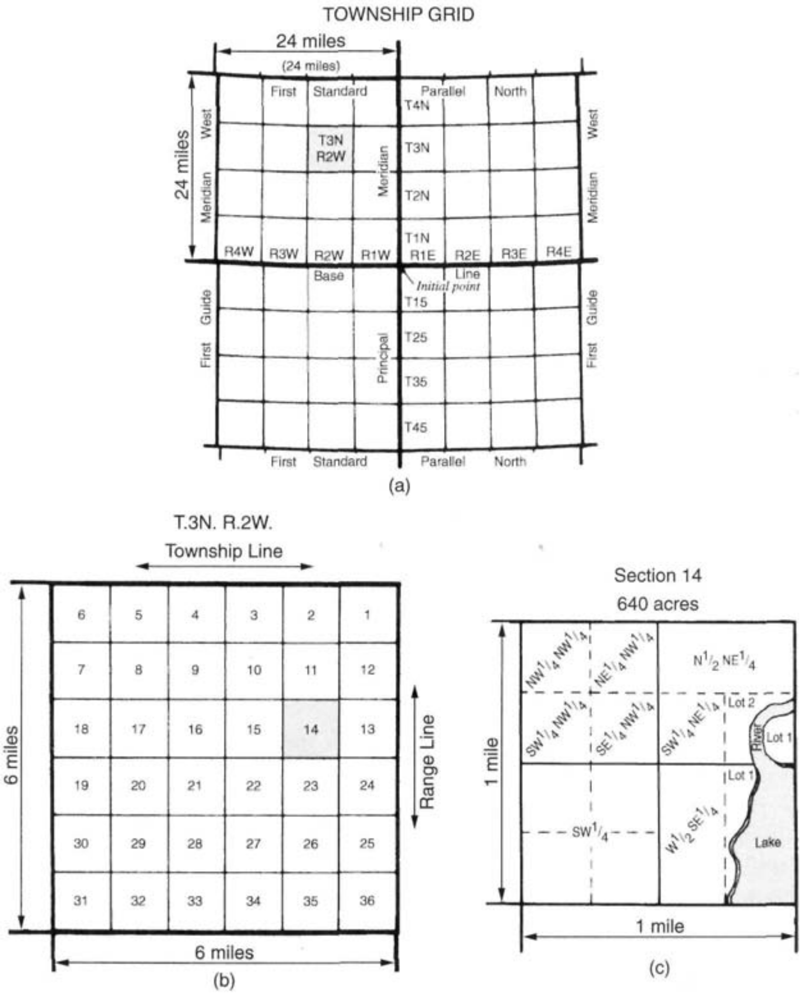


Figure 11.4 Diagram of the U.S. rectangular survey system, (a) Township grid showing initial point, baseline, principal meridian, standard parallels, and guide meridians, along with examples of township and range designations. (b) Subdivision of township into sections and the system of numbering sections from 1 to 36. (c) Subdivision of a section into quarter-sections and forties. (Adapted from the Bureau of Land Management, U.S. Department of Interior.)

Townships are numbered consecutively north and south of the baseline. Township locations east and west of the principal meridian are called *ranges* and are also numbered consecutively. For example, in Figure 11.4a the township labeled T3N, R2W denotes a township that is three townships north of the baseline and two ranges west of the principal meridian.

Townships are subdivided into thirty-six *sections,* each approximately 1 mile square and 640 acres in area. Figure 11.4b illustrates how the sections are numbered within a township. Each section is subdivided into *quarter-sections* of approximately 160 acres, which are further subdivided into 40-acre parcels known as forties. Figure 11.4c illustrates how the subdivisions of a section are identified.

A legal description for a parcel of land begins with the smallest subdivision and progresses to the township designation. For example, the forty in the northwest corner of section 14 (Figure 11.4c) would be described as NW 1/4 NW 1/4 Sl4, T3N, R2W.

Forest Type Mapping and Area Measurement

Forest type maps are very useful to forest managers because they show the locations and boundaries of individual forest stands, that is, areas with similar species, size, and density of trees. These maps also show nonforested areas such as lakes, rivers, and fields. Vertical aerial photographs are extremely useful for preparing forest type maps because they can be viewed with a stereoscope (Figure 11.5) to provide a three-dimensional picture of the forest.

Trained interpreters are able to identify forest stands on the photographs and outline their boundaries (Figure 11.6). Chapter 12 describes the use of aerial photographs and other forms of remote sensing in forestry.

After the forest type maps have been prepared, it is usually necessary to measure the land area within each of the stand boundaries. Forest stands normally have irregular boundaries, so their areas are often determined with a *dot grid,* a sheet of clear plastic covered with uniformly spaced dots. The grid is laid over the map and all the dots falling within the stand boundary are counted. Multiplying this dot count by an appropriate converting factor gives the land area of the stand. For example, the converting factor for a dot grid with sixty-four dots per square inch and a photograph scale of 1:20,000 is 0.996 acres per dot.[1] Suppose the number of dots falling within a given stand boundary is forty-seven; then the estimated area of the stand is

$$47 \times 0.996 = 46.8 \text{ acres}$$

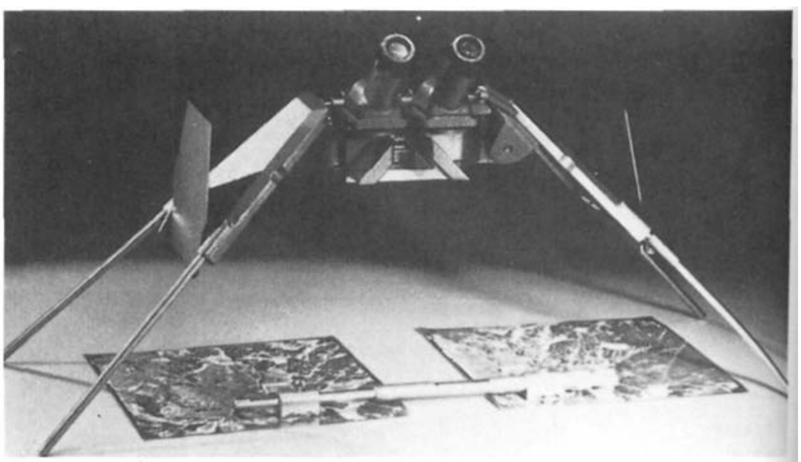


Figure 11.5 Parallax bar oriented over overlapping vertical aerial photographs under a mirror stereoscope. The stereoscope facilitates three-dimensional study of the photographed scene. The parallax bar is used to determine approximate tree heights and terrain elevations. (Courtesy of Wild Herrbrungg, Inc.)

[1] At a photoscale of 1:20,000, one inch on the photograph represents 10,000/12 = 1,667 feet on the ground. Thus one square inch = (1667 X 1667)/43,560 = 63.8 acres. Each of the sixty-four dots then represents 63.8/64 - 0.996 acres.

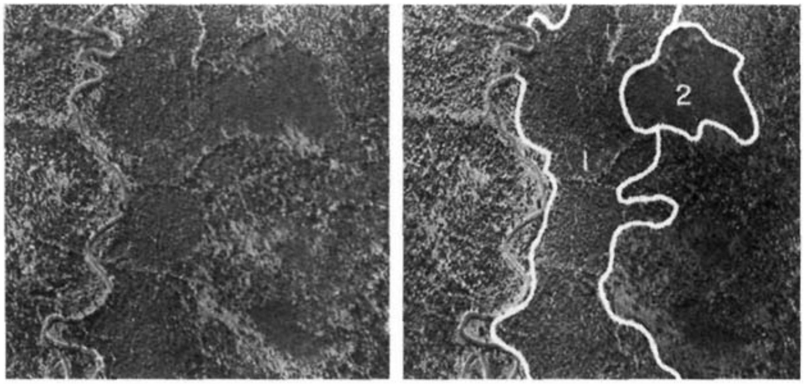


Figure 11.6 Stereogram illustrating cover-type mapping of balsam fir (1) and black spruce (2) stands in Ontario, Canada. (From V. G. Zsilinszky, "Photographic interpretation of tree species in Ontario," Ontario Department of Lands and Forests, 1966.)

Measurement of Forest Resources with a Focus on Timber

There are many variations in the types of timber focused surveys. They range from the precise measurement of individual trees on a woodlot while marking them for a timber sale, to the assessment of the timber supply in the United States, including its rate of growth and consumption. There are several major types of surveys for timber. *Strategic surveys* are used primarily for identifying overall forest conditions and to establish broad protection, management, and use policy. These are also used to determine appropriate levels of investment, both public and private, in forest management. The major example is the state-by-state nationwide Forest Inventory and Monitoring survey led by the U.S.D.A. Forest Service. This survey also measures many nontimber aspects of the forest. *Management-oriented surveys* or *inventories* are used for developing management plans for specific federal, state, private, and other forests. These ownership specific inventories are designed to provide details on the quantity, quality, and location of timber and associate site and use considerations. Typically, these surveys involve the construction of localized maps of individual stands and other important features via aerial photography and geographic information systems usage. Such information is essential to forest managers in their planning and conduct of forest wide and local site management. *Timber appraisals* are used to determine the monetary value of a specific timber or land sale. The objectives of these surveys differ considerably as do the measurement procedures they employ. Additionally, a variety of surveys are used to monitor regeneration development, timber harvesting practices, and so forth, to inform managers about the type, extent, and sometimes the effectiveness of practices and needs as appropriate. These surveys, perhaps best labeled *practices monitoring,* are often part of ongoing management information efforts. The following discussions provide an overview of some of the more common tools and techniques used in assessing the timber aspects of such surveys.

Standing Trees

Most timber surveys require the measurement of individual trees. Standing-tree measurements may be required to estimate the volume or mass (weight) of various products obtainable from the trees, or they may be used to assess the relative sizes of trees to aid in the development of management prescriptions for the forest.

Diameter at Breast Height One of the most useful tree measurements is the diameter at breast height (dbh). This is the diameter, outside bark, of the tree stem at a height of 4.5 feet (or 1.3 meters when the metric system is used), above ground on the uphill side of the tree. The *tree caliper* (Figure 11.7) is one of the most accurate instruments for obtaining this measurement. Another instrument, the *tree diameter tape,* is a steel tape with special calibrations that convert the circumference of the tree to its corresponding diameter, assuming the cross-section of the tree is a perfect circle. Since trees are not usually circular, the diameter tape tends to overestimate tree diameters and, hence, is somewhat less accurate than the caliper. Even less accurate, but very quick and easy to use, is the *Biltmore stick* (Figure 11.8). Invented in 1898 by Carl Schenck for use on the Biltmore Forest in North Carolina, this stick is held horizontally against the tree at arm's length (25 inches), with the left edge in line with the left side of the tree. The diameter is then sighted on the stick in line with the right side of the tree. The Biltmore stick is calibrated according to the principle of similar triangles.

Figure 11.8 Field crew in the process of observing and recording species and tree diameters on a plot. Diameters are being measured with a Biltmore stick held at a fixed distance from the eye. Observations with this instrument are based on the geometric principle of similar triangles.

Figure 11.7 Forester using a caliper to measure a tree diameter at breast height (dbh).

Basal Area The dbh measurement is frequently converted to basal area, that is, the area (in square feet or square meters) of the cross-section of a tree at breast height. The formula for the area of a circle (pi times radius squared), together with appropriate unit-converting factors, is used to calculate tree basal area. If dbh is measured in inches, tree basal area, *b*, in square feet is given by

$$b = 0.005454 \text{ dbh}^2$$

If dbh is measured in centimeters, tree basal area in square meters is given by

$$b = 0.00007854 \text{ dbh}^2$$

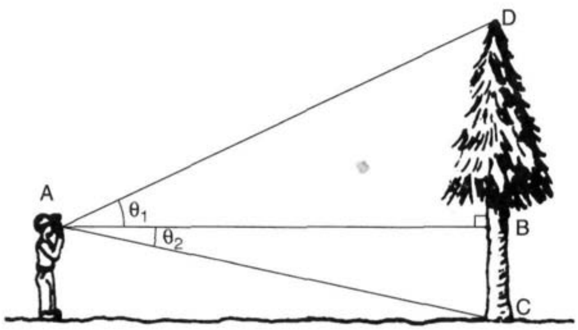
The basal area of a forest stand is expressed as the sum of the tree basal areas divided by the area of the stand, and is expressed in square feet per acre or square meters per hectare. Stand basal area is used by forest managers as a measure of the degree of crowding of trees in a stand (see "Stocking and Density," later in this chapter).

Height There are a number of different instruments for measuring tree height, and the required level of accuracy dictates the instrument of choice. *Height poles* provide very accurate measurements for trees that are not too high. A variety of sectioned, folding, and telescoping poles are available, and they are best suited to trees with branches that allow the poles to pass readily between them but also give the poles lateral support. Height poles become too cumbersome for trees taller than 60 feet, and their use is primarily restricted to research plots for which great accuracy is required.

Tree heights can be measured indirectly with instruments called *hypsometers.* Many types of hypsometers have been devised over the years, but they all work on either trigonometric or geometric principles. Figure 11.9 illustrates the trigonometric principle, which requires knowledge of the horizontal distance between the observer and the tree, and an instrument to measure the angles between this horizontal distance and the top and base of the tree. Most hypsometers employing the trigonometric principle are calibrated in terms of the tangents of the angles, so the observer can read tree heights directly on the instrument's scale. Hypsometers employing the geometric principle must also be used at a fixed horizontal distance from the tree and, in addition, must be held a fixed distance from the observer's eye (Figure 11.10). Laser rangefinders are new tools for height measurement that allow for high accuracy and flexibility as to where the observer may stand in observing the base and top of the tree.

When trees are measured to assess the volume or weight of merchantable products in the tree, the *merchantable height* or *length* is often measured instead of the total height (Figure 11.11). Merchantable length is a measure of the usable portion of the tree above stump height (usually 1 foot) to a point on the stem where the diameter becomes too small or too irregular to be utilized.

Volume and Mass There are at present no instruments that allow the direct measurement of the volume or mass (weight) of a standing tree. Instead, volume and mass must be estimated from other

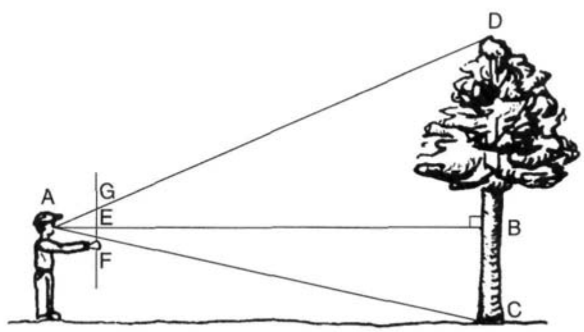


$$\tan\theta_1 = \frac{DB}{AB} \qquad DB = AB\tan\theta_1$$

$$\tan\theta_2 = \frac{BC}{AB} \qquad BC = AB\tan\theta_2$$

$$\text{total tree height} = DB + BC = AB(\tan\theta_1 + \tan\theta_2)$$

Figure 11.9 Three measurements are required to determine the total height of a tree, using *trigonometric* principles: the angle q_1 from horizontal to the top of the tree, the angle q_2 from horizontal to the base of the tree, and the horizontal distance *AB* from the observer to the tree.



$$GF : DC = AE : AB$$

$$\text{total tree height} = DC = \frac{AB \times GF}{AE}$$

Figure 11.10 Measurement of total tree height using *geometric* principles: ratios of distances are constructed using the principle of similar triangles.

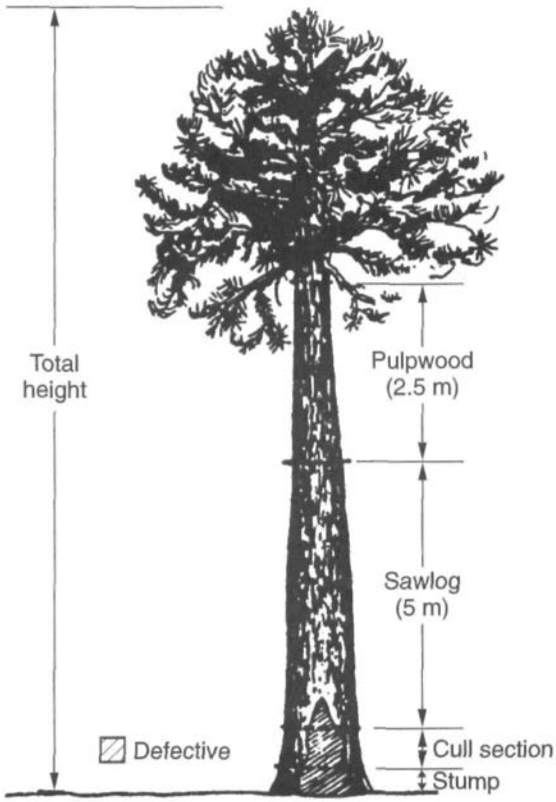


Figure 11.11 Diagram of a tree stem showing the total height of the tree and the length of merchantable sections.

tree dimensions. Tree height and dbh are most frequently used for this purpose, and many *tree volume tables* giving the average volume or mass for trees of different diameters and heights have been developed (Table 11.2).

More accurate estimates of tree volume can be obtained by measuring upper-stem diameters with instruments called *optical dendrometers* (Figure 11.12). With diameter measurements taken at various heights on the tree, volumes may be calculated for individual stem sections (see earlier section on "Scaling") and then summed.

Age and Radial Increment Tree age is defined as the time elapsed since the germination of a seed or initiation of a sprout. Many tree species in the northern temperate region produce annual rings of wood conesponding to light-colored earlywood and darker latewood. This property makes it possible to measure tree age by using an *increment borer* to extract a core of wood and then counting the number of annual rings (Figure 11.13). The age of live trees can be determined through increment cores taken at ground level; however, stem deformaties near the ground and/or decay make it difficult to obtain a core including the tree center and all the annual rings. Consequently, cores are taken at breast height and an estimate of the time to reach that height is added to the core measure to obtain total age. The number of years for a tree to reach breast height is dependent upon the species, early competition, and site quality and can vary from 2 to 17 years (5). Annual rings are easily discernible in most conifers, but difficult to see in hardwoods such as aspen and basswood.

With young conifers having determinate height growth, age can also be estimated by counting the number of growth whorls along the stem. For older, larger trees that have lost their lower branches and evidence of whorls, this method is no longer feasible. Plantation records or records of natural disturbances which have led to new stands are also used to estimate ages. When discernible annual rings, growth whorls, or other records are missing, determination of tree and thus stand age is very difficult.

Increment borers are also used to determine the rate of tree growth by measuring the length of the last several rings in the core. This observation is called a *radial increment* and can be multiplied by 2 to estimate the diameter growth during the period.

Forest Sampling

It is seldom necessary or desirable to measure every tree on a forest property. Sufficiently accurate estimates can be obtained from measurements of a subset or sample of the trees in the forest. The process of selecting a representative sample of trees and obtaining the required estimates is called *forest sampling.*

Table 11.2 Portion of a Tree Volume Table for Approximating Merchantable Volume of Commercial Species in the Great Lakes States[a]

Diameter at Breast Height (cm)	Total height (m)					
	10	15	20	25	30	35
	Volume[b] (m^3)					
10	0.021	0.024		—	—	—
20	0.126	0.186	0.247	0.311	—	—
30	0.292	0.429	0.570	0.718	0.853	—
40	0.524	0.767	1.017	1.281	1.523	—
50	—	1.200	1.592	2.005	2.384	2.783
60	—	1.728	2.294	2.887	3.436	4.010

Source: Adapted from S. R. Gevorkiantz and L. P. Olsen, "Composite volume tables for timber and their application in the Lake States," U.S.D.A. For. Serv., Tech. Bull. 1104, 1955.

[a] As an example of usage, a tree with a measured diameter of 30 centimeters at breast height and a total height of 25 meters would have an estimated usable volume of 0.718 cubic meter).

[b] Volume inside bark from 0.3-meter stump height to limit of merchantability—that is, to a point on the stem where the diameter inside the bark is just equal to 8 centimeters.

Figure 11.12 Observation of the upper-stem diameter with a Wheeler optical caliper.

Sampling Units Sample trees are usually selected in groups at different locations throughout the forest. Each group of trees is called a sampling unit and may be selected in a variety of ways. One approach is to tally (count and measure) all the trees on a plot of fixed area at each location. *Sample plots* may be square, rectangular, or circular and are usually between 0.01 and 0.20 acre in area. Circular plots are often preferred because of their ease of

Figure 11.13 Tree age determination with an increment borer.

installation. All trees (or all trees of merchantable size) with a midpoint at breast height lying within the plot boundary are tallied (Figure 11.14).

Table 11.3 presents an example of a forest sample obtained from 0.10-acre plots at fifteen different locations within a forest stand. Each sample tree was measured to determine its dbh to the nearest inch and its merchantable volume in cubic feet. Columns 1, 2, and 3 in Table 11.3 summarize the number of trees tallied and the total volume tallied for each dbh class. These data can be used to calculate estimates of the average number of trees, basal area, and volume per acre. The average number of trees per acre (column 5) for each dbh class is given by

$$\text{average number of trees per acre} = \frac{\text{number of trees tallied}}{nA}$$

where n is the number of sample plots (fifteen in this example) and A is the area of each sample plot

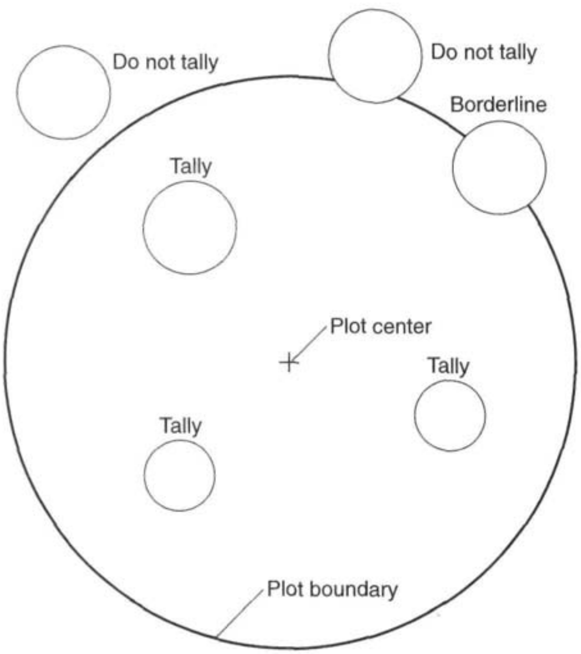


Figure 11.14 In fixed-area plot sampling, field crews tally all trees with a midpoint at breast height lying within the plot boundary.

(0.10 acre in this example). The average basal area per acre (column 6) for each dbh class is given by

$$\text{average basal area} = \frac{(\text{number of trees tallied})b}{nA}$$

where b is the basal area per tree, given in column 4 of Table 11.3 (see earlier section, "Basal Area," for formulas). The average volume per acre (column 7) for each dbh class is given by

$$\text{average volume} = \frac{\text{total volume tallied}}{nA}$$

Another useful type of forest-sampling was devised in 1948 by Walter Bitterlich, an Austrian Forester. This method is known as the *Bitterlich* method, *horizontal point sampling,* or *variable plot sampling.* Observers tally all trees with a dbh larger than the angle projected by a gauge viewed from each sample point (see Figure 11.15).

A variety of *angle gauges* are available for use with Bitterlich's method. Figure 11.16 illustrates the use of a stick-type angle gauge; the observer's eye corresponds to the sample point, and the stick is rotated through a complete circle while the observer views each tree at breast height to determine whether it is "in" or "out."

Instead of tallying every tree on a fixed-area plot, Bitterlich's method is equivalent to tallying each tree on a circular plot with an area proportional to the basal area of the tree. Hence, large-diameter trees are tallied on large plots and small-diameter trees are tallied on small plots. One advantage of this approach lies in the fact that large-diameter trees contribute more to stand basal area and volume than do small-diameter trees; therefore, by including more of the large trees in the sample and fewer of the small trees, more precise estimates of stand basal area and volume can usually be obtained with less effort. The geometry of Bitterlich's method gives it another advantage. If the basal area of a tree is divided by the area of its corresponding sample plot, the result is a constant, BAF, called the *basal-area factor,* and depends only on the angle projected by the gauge. Hence, each tree tallied represents the same basal area per acre regardless of the tree's area per acre and regardless of the

Table 11.3 Example of a Tree Tally and Averages for a Sample of Fifteen 0.1-Acre Plots[a]

1 Diameter at Breast Height (in.)	2 Number of Trees Tallied	3 Total Volume Tallied (ft^3)	4 Basal Area per Tree (ft^2)	5 Average Number of Trees per Acre	6 Average Basal Area (ftVacre)	7 Average Volume (ft^3/acre)
6	89	223	0.1963	59.3	11.6	149
7	54	216	0.2672	36.0	9.6	144
8	34	204	0.3491	22.7	7.9	136
9	21	195	0.4418	14.0	6.2	130
10	15	195	0.5454	10.0	5.5	130
11	12	204	0.6599	8.0	5.3	136
12	8	160	0.7854	5.3	4.2	107
13	6	162	0.9217	4.0	3.7	108
14	3	96	1.0690	2.0	2.1	64
Total	242			161.3	56.1	1104

[a] A procedure for calculating the averages in columns 5, 6, and 7 is explained in the text.

tree's size. Thus, stand basal area can be estimated by simply multiplying the average number of trees tallied per point by the basal-area factor. This result is illustrated in the following example.

Table 11.4 gives an example of a forest sample obtained from Bitterlich points with a basal-area factor of 10 square feet per acre, at fifteen different locations within a forest stand. Each sample tree was measured as in the previous example. Columns 1, 2, and 3 in Table 11.4 summarize the number of trees tallied and the total volume tallied for each dbh class. Again, these data can be used to calculate stand averages, but the formulas are different from those used for fixed-area plots. The average number of trees per acre (column 5) for each dbh class is given by

$$\text{average number of trees per acre} = \frac{\text{BAF (number of trees tallies)}}{nb}$$

where BAF is the basal-area factor of the angle gauge (10 square feet per acre in this example), n is the number of sample points (fifteen in this example), and b is the basal area per tree, given in column 4 of the table (see earlier section, "Basal Area," for formulas). The average basal area per acre (column 6) for each dbh class is given by

$$\text{average basal area} = \frac{\text{BAF (number of trees tallied)}}{n}$$

Notice that this formula can be used even if trees are not tallied by dbh class. For example, if only the total number of trees tallied is known (eighty-five in this example), we can use the formula just given to calculate the total basal area per acre:

$$\text{total basal area} = \frac{\text{BAF (total number of trees tallied)}}{n}$$

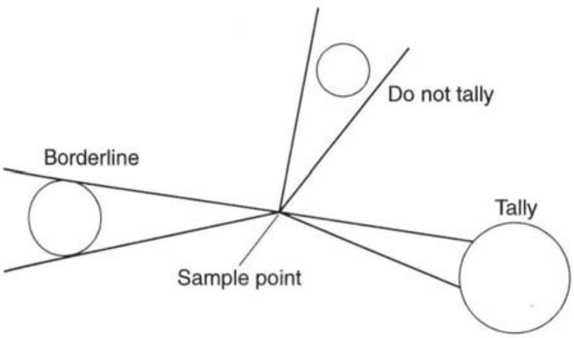


Figure **11.15** In Bitterlich horizontal point sampling, field crews tally all trees with a dbh larger than the angle projected by a gauge.

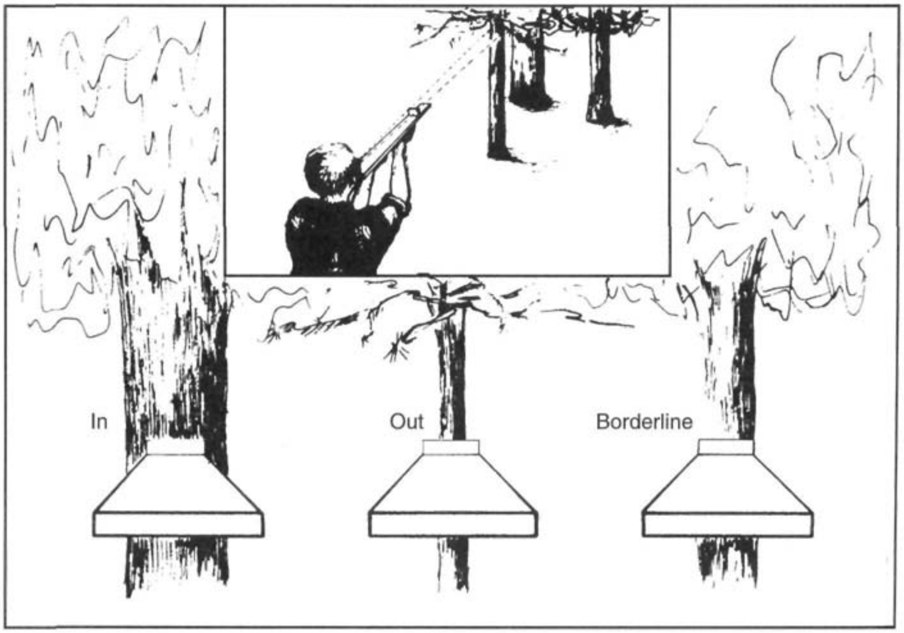


Figure 11.16 Use of stick-type angle gauge to tally trees on a Bitterlich horizontal sample point. Borderline trees are checked with distance tapes and careful measurement of the diameter to determine whether they are "in" or "out."

$$\frac{10 \times 85}{15}$$

$$= 56.7 \text{ ft}^2/\text{acre}$$

This result is in close agreement with the total basal area at the bottom of column 6 in Table 11.4. However, the Bitterlich method required the tally and measurement of only one-third as many trees as were tallied on the 0.1 acre plot. Thus, it can be seen that Bitterlich's method provides a very quick and easy way to obtain basal-area estimates. All one has to do is count the number of "in" trees.

The average volume per acre (column 7) for each dbh class is given by

$$\text{average volume} = \frac{\text{BAF (total volume tallied)}}{nb}$$

One of the important decisions in a forest-sampling design is the size of plot to use, or the basal-area factor of the angle gauge when using Bitterlich's method. Larger plots will include more trees, will be less variable, and will yield more precise estimates. However, if there are too many trees on the plot, the time and cost of tallying them may be excessive and there is a good chance that some trees may be overlooked. A rule of thumb that seems to work well is to use a plot size that gives an average of 15 to 20 trees per plot. For example, a sawtimber stand may have 75 to 100 trees per acre, so a good plot size to use in this stand is 1/5 acre. A poletimber stand with 150 to 200 trees per acre would be sampled with a 1/10 acre plot.

Bitterlich's method works best if an average of 5 to 10 trees are "in" at each sample point. The important thing to remember here is that the larger the basal-area factor of the angle gauge, the fewer the number of trees tallied at each point. If the average basal area of the stand is divided by 10, the result is a good basal-area factor to use. For example, if a large sawtimber stand has a basal area of 200 square feet per acre, a good basal-area factor to use is 20. A poletimber or small sawtimber stand with 100 square feet per acre of basal area would be sampled with a 10-factor angle gauge.

Sampling Methods Once appropriate sampling units have been selected, it is necessary to decide how many units to measure and how they will be located in the forest. The total number of sample

Table 11.4 Example of a Tree Tally and Averages for a Sample of Fifteen Bitterlich Points with a Basal-Area Factor (BAF) of 10 Square Feet per Acre

1 Diameter at Breast Height (in.)	2 Number of Trees Tallied	3 Total Volume Tallied (ft^3)	4 Basal Area per Tree (ft^2)	5 Average Number of Trees per Acre	6 Average Basal Area (ft^2/acre)	7 Average Volume (ft^3/acre)
6	17	43	0.1963	57.7	11.3	146
7	14	56	0.2672	34.9	9.3	140
8	12	72	0.3491	22.9	8.0	137
9	10	93	0.4418	15.1	6.7	140
10	9	117	0.5454	11.0	6.0	143
11	8	136	0.6599	8.1	5.3	137
12	6	120	0.7854	5.1	4.0	102
13	6	162	0.9217	4.3	4.0	117
14	3	96	1.0690	1.9	2.0	60
Total	85			161.0	56.6	1122

[a] A procedure for calculating the averages in columns 5, 6, and 7 is explained in the text.

units is called the *sample size,* and the manner in which they are located is called the *sampling method.*

Random sampling is a method in which sample units are located completely at random within each stand (Figure 11.17a). Random sampling ensures that estimates obtained from the sample are *unbiased;* that is, on the average they will tend toward the true stand values. *Systematic sampling* (Figure 11.17b) is often preferred because it is easier to implement, the time it takes to walk between plots is usually less, and sketching field maps and adjusting type lines on aerial photographs is more easily done while *cruising.*[2] In systematic sampling, also *called line-plot cruising,* sample units are located at specific intervals along straight cruise lines running across the forest property. If appropriate precautions are observed, systematic sampling will not introduce undue bias. In particular, it is important to ensure that cruise lines do not force plots along a line to be in some atypical forest condition. One way, to prevent this type of bias is to run cruise lines up and down slopes, since timber conditions tend to vary, with changes in elevation.

The number of sample units located in a given stand is usually determined by the maximum allowable error that can be tolerated in the final estimates. The more sample units measured, the smaller the errors will be, on the average, in estimates obtained from the sample. Sampling errors are usually expressed as a percentage of the timber volumes or values being estimated. For example, if the objective of sampling is to determine a fair price for a large, valuable stand of sawtimber, the maximum allowable error may be set at 3 to 5 percent. If, however, estimates are desired for the purpose of making long-range management plans, less accuracy is required and allowable errors may be set at 10 to 20 percent.

Foresters can use statistical formulas to determine the minimum number of plots required to achieve a specified sampling error. The actual formula depends on the sampling method. For example, the following formula gives the number, n, of sample

[2] To *cruise* a holding of forestland is to examine and estimate its yield of forest products.

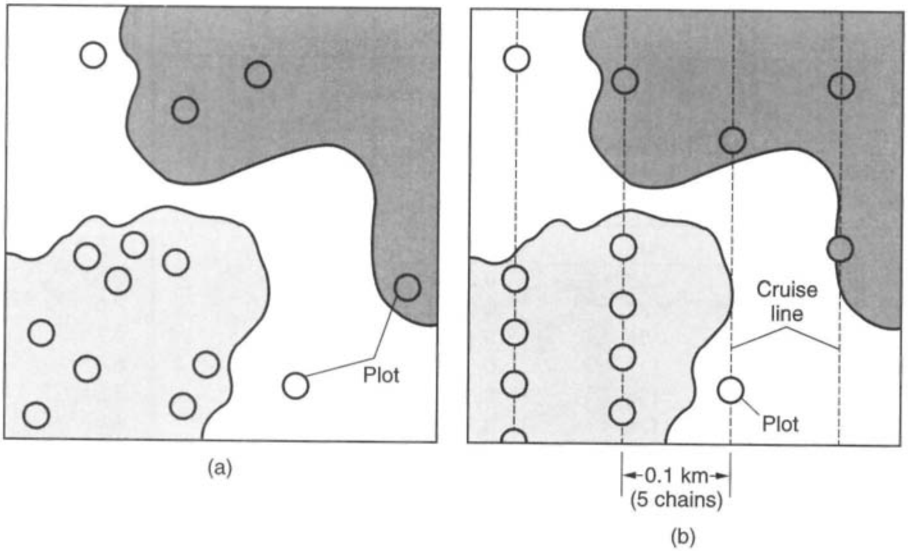


Figure 11.17 Portion of a forest tract illustrating (a) random and (b) systematic allocation of sample plots for three cover types. Sampling intensity (number of plots per unit area) varies by cover type.

units required when using random sampling in a single stand of timber,

$$n = \left(\frac{tCV}{E}\right)^2$$

where E is the allowable percentage of error, CV is the coefficient of variation in the stand, and t is a value obtained from a table of Student's t distribution.[3] The CV is a measure of how variable the size and density of timber are from place to place in the stand. A very uniform stand, like a plantation (Figure 11.18a), will have a relatively low CV. With clustering (Figure 11.18b), which can occur to varying degrees in naturally regenerated stands, CV values are higher.

The CV plays a major role in determining the required number of sample units in a given stand. Suppose the CV in a relatively uniform stand is 20 percent, the maximum allowable error for the timber cruise is set at 5 percent, and the value of t is approximately 2. In this stand, our formula gives a required sample size of

$$n = \left(\frac{2 \times 20}{5}\right)^2 = 8^2 = 64 \text{ units}$$

If the trees in the stand were clustered and the CV were, say, 40 percent, the required sample size would be

$$n = \left(\frac{2 \times 40}{5}\right)^2 = 16^2 = 256 \text{ units}$$

Because the required sample size varies with the square of the CV, a doubling of the CV (as happened in this example) means that four times as many sample units are required to achieve the same sampling error. Careful selection of efficient types and sizes of sampling units helps reduce the CVs in forest sampling designs, and can considerably reduce the required sample size and cost of a forest inventory.

[3] Procedures for calculating CV and determining t are explained in forest measurement textbooks (1-3).

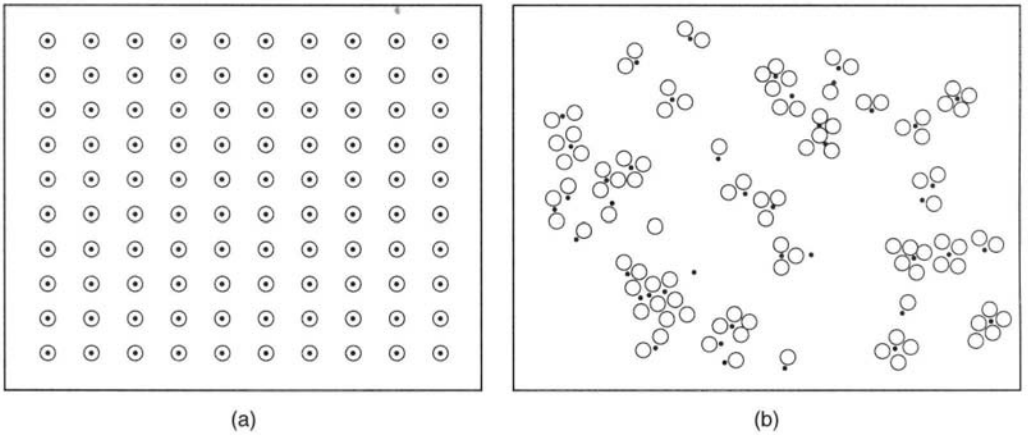


Figure 11.18 The circles in these diagrams illustrate the locations of tree stems in (a) uniform and (b) clustered forest stands.

Forest sampling is generally performed by survey crews of two people each. The crew chief is responsible for locating sample units and recording data. The second crew member is responsible for tree measurements such as dbh, height, age, and quality or condition. Data are often recorded on tally sheets and then entered into an office computer for statistical processing. However, small hand-held computers are increasingly replacing field tally sheets. Such battery operated devices are often quite rugged and may also be integrated (connected to) GPS units and other electronic measuring devices (Figure 11.19). These devices can also be programmed to help reduce the chance of data entry errors and speed subsequent data handling and compilation of results.

Statistics Estimates obtained from forest sampling are called statistics, and they will vary in detail according to the type of timber survey. In general, the most detailed statistics are required for timber appraisals and for scientific research. This level of detail may include stand and stock tables (Table 11.5) for each timber stand in the forest, together with maps showing the boundaries, area, and topography of each stand. Stand and stock tables show a breakdown of the trees and volume of timber in a stand by dbh class and species. They may also tabulate the volume of sawtimber by tree or log grades. These important factors affect the value

Figure 11.19 Sample tree measurements are entered directly into this small, battery-operated computer, which is taken into the forest. The computer is capable of performing all the statistical calculations necessary to prepare a stand and stock table (Table 11.5).

Table 11.5 Stand and Stock Table for a Red Oak Stand in the American Legion State Forest, Oneida County, Wisconsin[a]

Diameter at Breast Height (in.)	Red Oak		White Birch		Sugar Maple		Red Maple		Total	
	Trees	Cords	Trees	Cords	Trees	Cords	Trees	Cords	Trees	Cords
6			76.5	2.2	76.5	2.1			153.0	4.3
8	14.3	1.2	14.3	1.5					28.6	2.7
10	82.5	12.0	18.3	2.2					100.8	14.2
12							6.4	1.3	6.4	1.3
14	4.7	1.3							4.7	1.3
Total	101.5	14.5	109.1	5.9	76.5	2.1	6.4	1.3	293.5	23.8

[a] Values are averages per acre.

of timber, together with accessibility and distance to mills.

Inventories designed for management planning and operations usually do not require as much precision and statistical detail as appraisals. Management oriented inventories are more concerned with estimates of the species composition, average size and age of the trees, and the density and site quality of timber stands. In addition, of particular importance to management planning are the rate of growth of timber and the rate of loss through natural mortality, insects, disease, fire, weather, and harvesting.

Forest Growth and Yield

The volume of timber in a forest at a specific point in time is *called forest yield*, and the change in volume that occurs over an interval of time is called *forest growth*. The forests of North America and particularly those of Europe have been surveyed a number of times. Repeated surveys provide data for assessing the growth of a forest, changes in species composition, and the effectiveness of past management. Such surveys are the basis for regulating forests to provide a sustained, even flow of timber over long periods.

In order to reduce the effects of sampling errors on growth estimates, repeated surveys often rely on permanent sample plots that are carefully monumented so they can be found and remeasured at subsequent points in time, usually at intervals of five to ten years. Permanent sample plots also allow the growth of a forest to be assessed in terms of its basic components.

Components of Forest Growth When a permanent sample plot is remeasured, several distinct components of growth can be observed. There may be new trees on the plot that were not present, or were too small to be tallied, at the previous measurement. The present volume of these new trees is called *ingrowth*. Trees that are alive and tallied at both measurements are called *survivor trees*, and the difference in the volume of these trees at the two measurements is called *survivor growth*. The volume of trees that were alive at the first measurement but died during the growth period is called *mortality* and is usually classified according to the cause of death. Finally, any trees that were harvested during the period can be identified by their stumps. The volume of harvested trees is called *cut*.

The net change in the volume of a forest is equal to ingrowth, plus survivor growth, minus mortality, minus cut. Important factors that affect the rate of forest growth include site quality, stocking, and density.

Site Quality Forest stands are commonly classified according to *site quality,* which indicates the productive capacity of a specific area of forest land for a particular species. Although many species may grow on the same site, they may not grow equally well. The site productivity measure most commonly used is *site index,* the average height of dominant and codominant trees at a specified index age, usually 50 years. The selection of an index age is based on the potential rotation age or timing of harvest for a given species. For example, an index age of 100 years is often used for the longer-lived West Coast species while an index age of 25 years is commonly used for fast-growing southern plantations.

When height and age have been measured, they are used as coordinates for determining site index from a set of curves (Figure 11.20). Site index curves and tables have been developed for most commercial species. Suppose a white pine stand has an average total height of 20 meters at an age of 70 years. Figure 11.20 shows that this point lies on site index curve 15. This means that the expected dominant tree height for this site is 15 meters at the index age of 50 years.

Site index has been found to be correlated with soil factors and topography related to tree growth. For example, when there is no forest stand, the site index can sometimes be predicted from such factors as the depth of surface soil, stone, silt and clay content, and slope steepness. However, the concept of site index is not well suited to uneven-aged stands and areas taken over by mixed species.

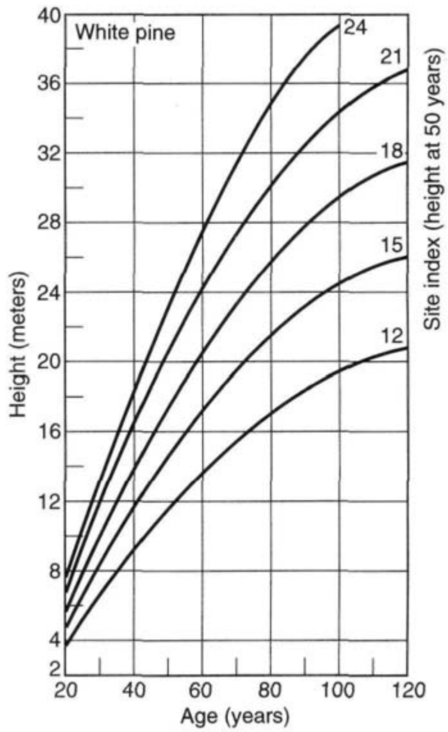


Figure 11.20 White pine site index curves. (From P. R. Laidly, "Metric site index curves for aspen, birch and conifers in the Lake States," U.S.D.A. For. Serv., Gen. Tech. Rept. NC-54, North Cent. For. Expt. Sta., St. Paul, Minn., 1979.)

Stocking and Density The terms forest stocking and density are often used interchangeably, but Avery and Burkhart (2) do not consider them to be synonymous. *Stand density* is a quantitative term indicating the degree of stem crowding within a stand, and *stocking* refers to the adequacy of a given stand density to meet some management objective, for example, maximizing the production of sawtimber. Stands may be referred to as understocked, fully stocked, or overstocked.

Stand basal area is often used as a measure of stand density and stocking charts (Figure 11.21) have been prepared for different species that show acceptable ranges of basal area for stands of different average diameters. To use a stocking chart, the forester must first determine the average basal area and number of trees per acre in the stand, by using one of the forest-sampling procedures previously described. These values are used as coordinates to locate a point in the stocking chart. If this point falls between the curves labeled A and B, the stand is fully stocked. If the point falls below the B curve or above the A curve, the stand is understocked or overstocked, respectively. For example, a red pine stand with 500 trees per acre and a basal area of 200 square feet per acre would be overstocked (Figure 11.21), whereas another red

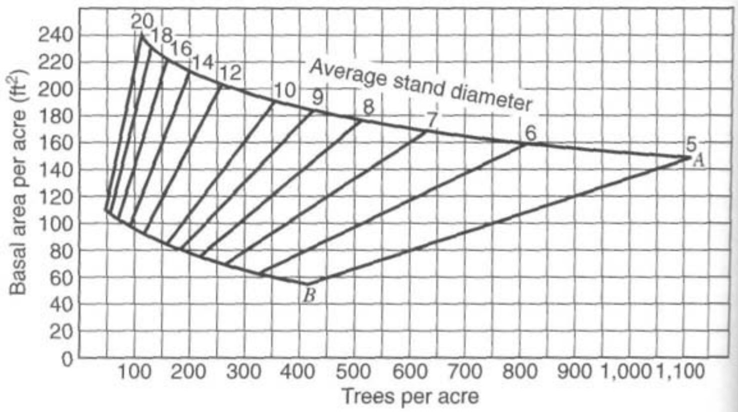


Figure 11.21 Stocking chart for managed red pine stands. (From J. W. Benzie, "Manager's handbook for red pine in the North Central States," U.S.D.A. For. Serv., Gen. Tech. Rept. NC-33, North Cent. For. Expt. Sta., St. Paul, Minn., 1977.)

pine stand with the same basal area but only 150 trees per acre would be fully stocked.

It has been shown that height growth is not greatly affected by stand density. It has also been determined in recent years that there is not as strong a relationship as originally supposed between basal area and site quality. The main reason for the differences in volume on good sites as against poor sites is height. For many practical purposes, therefore, we can assume that basal area varies little with site quality except at the extremes.

Growth and Yield Projection Repeated surveys together with site index assessments provide a basis for projecting future stand conditions and associated yields. Growth projection models may also be used to predict stand yield for specific management practices. Table 11.6 illustrates a yield table constructed for pine stands under a particular set of management alternatives—in this instance, stand density alternatives. Notice that the model on which this table is based provides estimates of both growth and future product yields. It is important to stress that the growth and yield information for this particular forest type represents estimates based on a sample of observations from various study plots.

A variety of models have been developed to characterize growth and dynamics at the individual-tree, stand, and landscape level. *Empirical* models describe tree growth in relation to age, site index, and other easily observed variables or stand treatments such as site preparation and fertilization. These models can be used to predict yields and to determine optimal thinning and rotation ages (typically with the aid of simulation or mathematical programming techniques). Thus these models are widely used in management. In recent decades, researchers have focused on building models that attempt to quantifying growth processes. Such *process* models consider weather, site quality, the physiology of tree growth, and sometimes regeneration and disturbance in detail. These models are used by scientists to understand tree and stand response to potential climate change and increasing atmospheric CO_2, as described in Chapter 4.

Measurement of Nontimber Resources

Measurements are also made on many other resources for multiple-use management of forests. It is not possible in an introductory text to cover all the details for measurement of these resources. Brief descriptions of the rationale and the types of measurements obtained for water, wildlife habitat. recreation, and other resources are given in other chapters in this book addressing those specific i

Table 11.6 Variable-Density Growth and Yield Table for Managed Stands of Natural Slash Pine[a]

Initial Basal Area (m^2)	Age (years) From	Age (years) To	Site Index (m)[b] 20	25	30	Projected Basal Area (m^2/ha)
			Projected Yield (m^3/ha)			
16	20	20	73	106	136	16
		30	134	194	248	22
		40	181	262	336	25
		50	217	315	403	28
	30	30	102	147	189	16
		40	147	213	273	20
		50	184	267	341	23
	40	40	120	174	222	16
		50	156	226	289	19
20	20	20	89	129	166	20
		30	153	222	284	25
		40	200	290	371	28
		50	235	341	436	30
	30	30	124	180	230	20
		40	171	248	318	24
		50	207	301	385	26
	40	40	146	212	272	20
		50	183	265	340	23
24	20	20	105	152	195	24
		30	171	247	316	28
		40	217	315	403	31
		50	251	364	466	33
	30	30	146	212	271	24
		40	193	280	359	27
		50	229	332	425	29
	40	40	172	250	320	24
		50	209	302	387	27

Source: Adapted from equations given by F. A. Bennett, "Variable density yield tables for managed stands of natural slash pine," U.S.D.A. For. Serv., Res. Note SE-141, 1970.

[a] Cubic-meter yields and basal area as projected from various initial ages and basal areas.

[b] Base age of 50 years.

resources. Importantly, the statistical aspects of these sampling, measurement, and modeling processes are fundamentally like those used in this chapter.

With *water*, we are primarily interested in measuring quantity, quality, and timing of the water resource for particular locations. Forest characteristics affect water yield in terms of these variables. Timber harvest operations are one example of a use that could increase water yield and affect stream sediment load and temperature. There is also increasing interest in nonpoint pollution[4] and how it might be controlled by forest management practices. In

[4] *Nonpoint pollution* derives from a dispersed source such as agricultural activity, as compared with *point pollution*, for which a single pollution source can be identified (e.g., a factory drainspout).

this area we may be concerned with sampling and characterizing the forest resource in much the same way as we do the timber resource inventory, but with an emphasis on forest age and size class structure and associated cover, and sampling and measuring streamflow characteristics from a particular watershed. The statistical aspects of this sampling and measurement process are fundamentally like those used for the timber resource. A discussion of watersheds in forest ecosystems was given in Chapter 6 and a further discussion of watershed management is given in Chapter 16.

For measuring *wildlife* resources, management surveys usually employ census techniques to determine animal population levels directly or to develop indexes that are suggestive of relative population levels. Examples of such indexes are pellet counts or flush counts for deer and birds, respectively. There is also increasing interest in relating the forest habitat conditions, often described in large part by the timber inventory, to the population numbers and the health of the wildlife populations inhabiting or potentially inhabiting the area. The forest functions both as a food source and cover, although different features of the forest may vary in importance for either function. For wildlife, data on forest stand species and size class structure are particularly important locally. Over landscapes, forest cover type and age class distributions are fundamental habitat data. A further discussion of the interactions of the forest with wildlife is given in Chapter 14.

Management of *recreation* areas requires surveys that are primarily concerned with the numbers of users and the physical impact they have on particular sites. Thus, we may be sampling a population of users or a population of sites used by people engaged in outdoor recreation. In sampling the resource users, we frequently use questionnaires intended to get at their attitudes and likely responses to various kinds of recreation resource management. Such surveys may consider the forest as a visual resource to be experienced by the visitor. With such concepts it is possible to characterize and subsequently manage the forest environment to provide scenic forest types and opportunities that contribute to user satisfaction. A further discussion of forest recreation management is given in Chapter 17.

Urban forests are receiving much more attention, and many cities now have a forester assigned specifically to this resource. Inventories of the forest in small communities frequently take the form of a complete census of all trees. Typical information collected for each tree includes species, diameter, location (perhaps by block or lot), position (such as parkland, boulevard, or interior lot), ownership, and condition—in terms of vigor and presence of insects, diseases, and hazards. The immediate site or growing conditions are particularly important to urban tree health. For larger cities, a 5 to 10 percent systematic sample of trees or city blocks may be used. This is sometimes combined with classifications of blocks into two or three tree density classes based on aerial photos (e.g., parkland, residential, and industrial areas). Because of the diversity of species in urban areas, the field crews need considerable background in plant identification.

Given this information, the urban forest manager is in a good position to estimate future needs for tree removal and replacement and to develop annual plans for these activities. Urban forestry is further treated in Chapter 22.

Concluding Statement—Future of Measurement and Monitoring

Interest in measuring and monitoring forest resources and their use is increasing. Landowners are seeking the basic information for investments in stewardship. Governments are seeking knowledge of resources available for economic development and ways to assure resource protection. Industry seeks information about timber supply, Special interest groups ask about practices. Questions come from interests as diverse as utilization, productivity, wildlife habitat, fire protection (fuel load measurement), and outdoor recreation. Inventories and monitoring are now conducted more frequently, and long-term predictions of future forest conditions are expected. At the same time we see rapid development in technologies that provide new ways to measure the forest and to make those results readily available, such as new laser measurement tools, precise geographic positioning, satellite based remote sensing tools, and the Internet. Researchers are also gathering detailed plant and environmental data to allow for the construction and use of more sophisticated models for predicting forest conditions and use decades and even centuries ahead. The measurement of forests increasingly demands technology, quantitative skills, and integration capabilities and is likely to become even more challenging. Professionals who specialize in this area are in high demand.

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CHAPTER 12

Remote Sensing and Geographical Information Systems for Natural Resource Management

PAUL V. BOLSTAD

Three spatial data technologies—Geographical Information Systems (GIS), Global Positioning Systems (GPS), and remote sensing—are changing how humans perceive, measure, and manage natural resources. Global positioning systems and remote sensing are aimed at answering two fundamental questions regarding natural resources: "where?" and "how much?" GIS provides a framework for organizing and analyzing this information in efficient and effective ways. These technologies are key in solving our most vexing natural resource problems, and their effectiveness has frequently been demonstrated in the preservation and recovery of endangered plants and animals, in improved planning and management of public lands, and by increased efficiency and profitability of wood production on private forest lands. Spatial data technologies are found in private and public resource management agencies of all types and sizes (1-8).

Geographical information systems consist of software, hardware, and protocols for collecting, managing, analyzing, and displaying spatial data. GIS are computerized systems wherein maps and tabular data are stored in digital formats (3, 7). GIS provides the tools to enter, edit, combine, and output these digital maps in order to solve problems. GPS is a space-based system that allows users to locate positions to within a few centimeters, almost anywhere in the field with modest training and cost. Remote sensing tools provide natural resources managers with aerial photographs and satellite-based images, rapidly providing important data over large areas. GPS and remotely sensed data are useful in their own right, but their value is multiplied many times when they are combined with other data in a GIS.

The widespread adoption of GIS, GPS, and remote sensing is the result of two phenomena. First, a societal pull is driving their use, because many resource management questions require spatial analysis. For example, best forest management practices often require buffer zones around wetlands and water bodies, National Forest plans must entertain alternatives regarding where and how much land should be dedicated to competing uses, and sawmills must be located near a timber supply. Second, there is a technological push. Forest resource managers and scientists have recognized the potential for gains in efficiency and the breadth and depth of analysis through the adoption of new technologies, and many companies and government agencies have been actively developing and funding the use of GIS, GPS, and remote sensing technologies. Managers now have the tools to collect and combine disparate and previously incompatible data in novel ways to solve resource management problems.

Basic Concepts in GIS

A GIS is based on a computer-stored representation of real-world entities or phenomena (3, 6, 7). Typically, the GIS user is interested in studying or managing an area or event, for example, a wildlife refuge, forest landholdings, or the spread of invasive exotic species. These entities are represented in a GIS with cartographic objects, most often in the form of points, lines, polygons, or an array of cells. The objects are defined using a necessarily limited set of variables that are entered and maintained in a GIS. A researcher monitoring colonial nesting birds might define a bounding polygon that contains most of the colony, and count the number of breeding pairs and species. This polygon, species identifier, and count are the variables that represent the real object (colony), and are an abstraction of the real world. Typically, a single type of object or phenomenon is represented in a data layer, with multiple layers used to represent various different types of data. Multiple data layers are often developed for an area, each layer corresponding to a different data theme (Figure 12.1). For example, forest managers may define layers representing vegetation type, soils, elevation, slope, and road location. These layers are then used singly or in combination to perform spatial analyses that aid in managing the forest.

Each data layer typically contains two distinct types of data (Figure 12.2). Geographic coordinate data are used to identify the location, size, and shapes of objects. Objects in a data layer are typically represented as points, lines, or areas. Points are objects which are considered to have no dimension (e.g., wells or feeding stations) while lines are used to represent objects conceived as one dimensional, for example, roads or streams, and areas are used to represent two-dimensional objects, such as forest stands or counties. Attribute data that correspond to the geographic coordinate

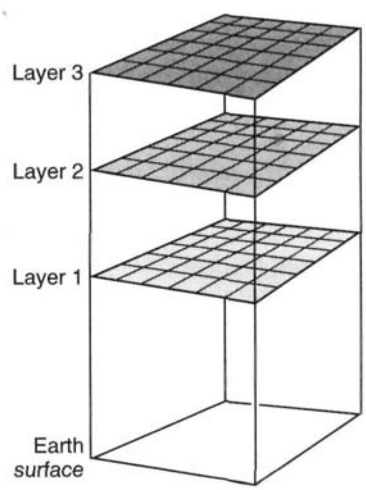

Figure 12.1 Data layers in a GIS. Different themes—for example, roads, vegetation, or political boundaries—are stored in separate, spatially-referenced data layers.

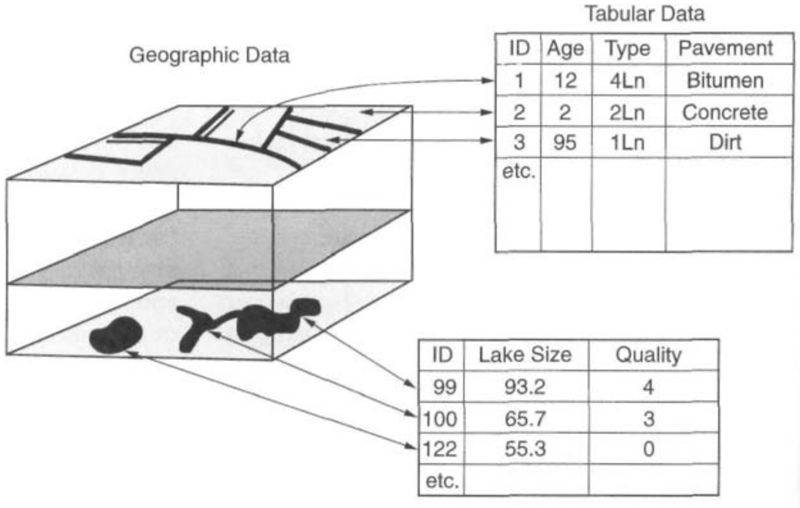

Figure 12.2 Data in a GIS are often organized into linked geographic and tabular components.

data are maintained—for example, the well depth and age, road name and surface type, or forest vegetation type or age. Attribute data are usually stored as tables in a relational database.

There are two common methods of structuring geographic data (Figure 12.3). When a raster data structure is used, a grid, similar to a checkerboard, is defined. Each grid cell has fixed, uniform dimensions, which correspond to the resolution of the data layer. Codes are assigned to each grid cell corresponding to the objects represented. Point objects are typically represented by a single grid cell, line features represented by a sequence of touching grid cells, and area features by a group of adjacent grid cells.

An alternative, "vector" data structure, may be used for geographic data. Features are represented by strings of coordinates. A point is represented as a single X-Y coordinate pair, a line object represented by a set of X-Y coordinate pairs, and an area represented by a closed line or set of lines. Identifiers are assigned to each point, line, or area, and linked to data in the attribute tables.

Earth coordinates are used to tie spatial data to earth locations. Latitude and longitude may be used to uniquely define locations on the surface of the

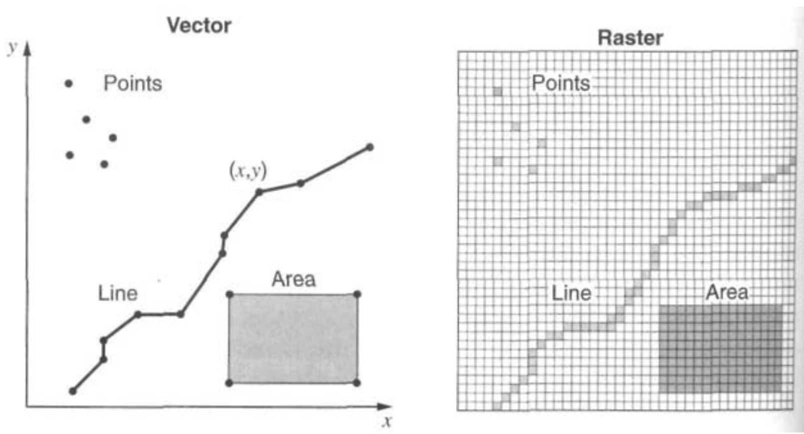

Figure 12.3 Raster and vector representations of point, line, and area features.

earth. However, the latitude/longitude values are unsuitable for many uses, particularly for producing planar maps. Therefore, map projections are used to convert from curved geographic coordinates to right-angle Cartesian coordinate systems. These map projections are typically defined by mathematical formulas that "project" points on the curved earth surface to points on a flat or "developable" surface. For example, a *Mercator* is a common projection type wherein points from the surface of the earth are projected onto a cylinder encompassing the earth (Figure 12.4). This surface is then "developed," in that the mathematical equivalent of cutting and unrolling the cylinder produces a flat map. Cones and planes are also common projection surfaces. Each projection introduces distortion by stretching or compressing the curved geographic coordinates on the flat map; however, this distortion can be controlled by choosing the proper map projection, and by limiting the size of the area mapped. For example the *State-Plane coordinate system* is a standard set of projections defined for each state or portions of states. As it is used for many county-level and property line recording projects, the State-Plane coordinate system is used in GISs maintained by many county governments and other civil authorities. The State-Plane system of map projections is defined such that distance measurements using the projected coordinates do not differ from measurements on the curved earth's surface by more than one part in 10,000, or about 2 feet in a mile.

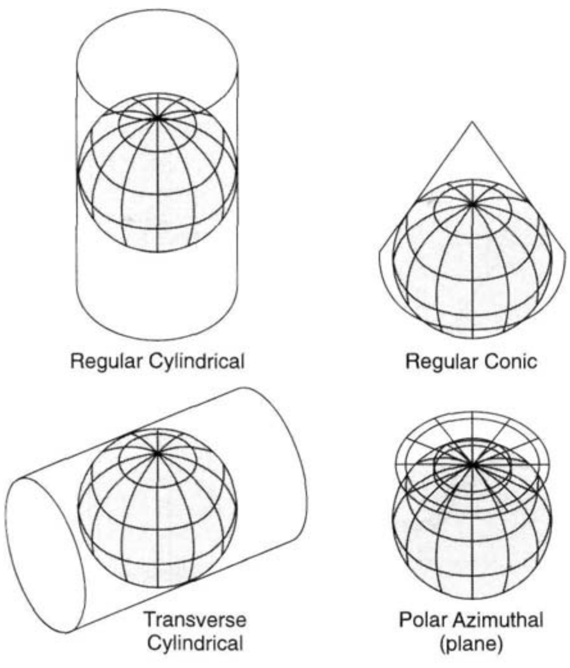

Figure 12.4 Map projection surfaces.

Data Entry—Digitizing

Digitizing is the process of converting data from paper maps or images into a digital data layer. Published maps contain substantial information; however, this information must be converted to digital formats to be used in a GIS. There are several methods to perform this conversion.

Manual digitizing is among the most common techniques because the equipment is relatively inexpensive and easy to learn and use. Manual digitizing requires a coordinate digitizer, typically a flat table with an attached stylus or puck. A map is fixed to the table, and the operator guides a pointer over the feature to be digitized, indicating when to collect coordinates. The coordinate information is stored in the computer, and digitizing and editing tools included in most GIS programs are used to convert these digitized data into a digital data layer. While the equipment can be quite accurate, measuring position to within 0.001 inches, it may also be quite slow and laborious, particularly when recording data from detailed maps.

"Heads-up" digitizing is a variant of manual digitizing. Satellite data or scanned aerial photographs or maps are digital images that may be displayed on a computer screen. Point, line, and area features are identified and their locations recorded by guiding a cursor on the screen. This method has become quite common in recent years, as more image data are provided in digital formats.

Automated scanning is another common digitizing method. While the equipment is typically more expensive than manual digitizers of similar accuracy, it is also much faster, and requires less human input. Maps are placed on a bed or drum of a scanning device, and transmitted or reflected light is used to record the locations of map features. All features on the maps are recorded, including legends, names, and any other annotation or symbols. These unwanted features must be removed, a process which is often aided by specialized software.

Once data are digitized, they must be edited, error-checked, and have attributes added. All digitizing methods may result in errors, caused by operator or equipment imprecision, errors in the source materials, or blunders. Location, consistency, and correctness must be checked, and attribute data entered into the tabular database and referenced to the specific geographic objects.

Global Positioning System

Global positioning system (GPS) technology is another method by which data may be entered into a GIS. GPS provides rapid, accurate positional measurements and has many uses beyond GIS data entry, including mapping, vehicle guidance, pathfinding, automatic aircraft take-off and landing, and precise scientific measurements. This inexpensive technology requires minimal training, and will be used in most future efforts when field data are collected for a GIS.

GPS is a satellite-based system operated by the United States Department of Defense. It was designed for military navigation and positioning, but civilian uses quickly emerged. The system is based on twenty-one satellites orbiting the globe, each satellite transmitting encoded signals. A field receiver measures signals from at least three satellites to determine positions on the surface of the earth. Since there are typically from six to ten satellites above the horizon at any give time, GPS can be used anywhere except under extreme terrain conditions—for example, in deep canyons.

The satellites transmit two types of signals that are commonly used by civilian receivers. One signal, called the *C/A code,* allows positions to be located to within one to a few meters. C/A code receivers are often used for field digitizing, collecting the feature locations to be entered into a GIS data layer. C/A code receivers typically operate well under closed forest canopy, take the required measurements in minutes, and are small, lightweight, and relatively inexpensive. The satellites also transmit a second, *carrier phase signal* that allows more precise position determination, down to sub-centimeter accuracies. However, because carrier-phase receivers often perform poorly under forest canopies, require longer time periods for the most accurate measurements, and are more expensive, heavier and larger, carrier-phase receivers are used primarily where higher accuracies are required, such as in property or geodetic surveys.

GPS is based on combined range measurements (Figure 12.5). A range is a distance from the receiver to the satellite. The code transmitted by the satellite contains timing and satellite position information. The receiver decodes this information to establish the satellite location and the distance to the satellite. Measurement from one satellite places the receiver somewhere on a sphere, a fixed distance away from the satellite. Measurements from two satellites constrain the location to a circle where the two spheres intersect, and measurements from

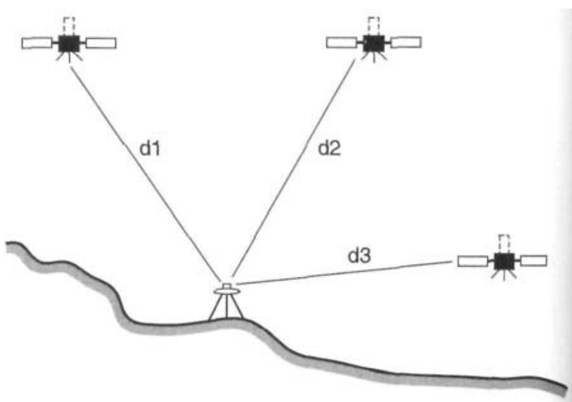

Figure 12.5 Satellite range measurements, d1 through d3, are the basis of GPS position determination.

three satellites constrain the location to two points, one of which can be discarded after a few measurements. Measurements from a fourth satellite are usually used to reduce systematic error, and additional satellites may be used to improve the position measurement. Multiple position fixes are often taken for several minutes, and averaged.

Several sources of error affect GPS measurements and lead to positional uncertainties (Figure 12.6), and the high accuracies mentioned earlier are obtained only after these errors have been removed. System delays, clock errors in range measurements, uncertainty in the satellite location, and ionospheric and atmospheric delays also add uncertainty. These errors are reduced via differential positioning, where two receivers collect data simultaneously. One receiver, a base station, occupies an accurately surveyed point. The difference between the GPS estimate and the known location at the base station can be calculated, and this difference applied to correct data collected by the roving field receiver to correct the errors. The errors are similar when the roving and base station receivers are using the same satellites, and are within a few hundred kilometers so that atmospheric and ionospheric errors are similar. A radio can be used to transmit the differential corrections from the base station receiver to the roving receiver, and accurate positions may be obtained in the field. If a radio link is infeasible, then the data may be downloaded to a computer and post-processed.

Spatial Analysis

Much of the utility of geographic information systems comes from the rich array of spatial-analytical tools they provide. These tools are applied to spatial data layers to provide information and to help solve resource management problems. The

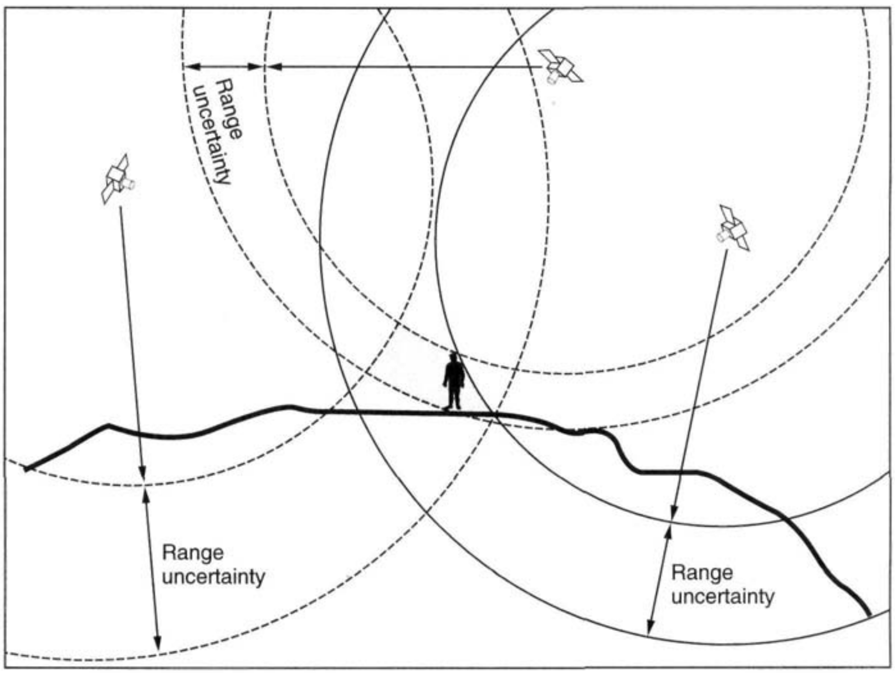

Figure 12.6 GPS signal triangulation and uncertainty caused by range error.

tools may be viewed as functions that are applied to one or more data layers. Tools typically produce summary numbers, tables, or new data layers.

Database Operations

Attribute data in a GIS are usually stored in a database; database functions are often applied to the tabular data associated with a data layer. Each row in a database may contain several variables, and these variables are used to describe each object represented in the data layer. For example, forest stands may be represented by polygons in a forest vegetation data layer. Each polygon is associated with a row in the database that contains information describing the forest stand; for example, tree species, age, average diameter, average tree height, health status, or stand area. Database operations may be applied; for example, selecting all stands over 40 years old.

Sorting, searching, and selecting are among the most common database functions. Database records are selected based on attributes and their values. Compound searches (or queries) are common, for example, selecting all aspen stands that are also greater then 80 acres in size and over 40 years old. Arithmetic or statistical functions are also commonly applied; for example, stand volume may be calculated by multiplying the average diameter, height, and area information contained in the database.

Geographic Operations

Geographic operations provide much of the unique utility found in GIS. These operations use the geometric information in a data layer or layers, and generate additional layers, tables, or summary numbers. These geographic operations may be unary, involving only one input data layer, or they may be binary or higher order, involving multiple data layers.

There are many unary geographic operators. For example, a slope layer is typically derived from an elevation data layer. The slope operation typically uses raster data input, and calculates a slope value for each output grid cell. Slope at each cell is determined from a measure of the change in elevation divided by a change in horizontal position in the neighborhood of each grid cell.

Buffering is one of the most common geographic operations. A buffer layer identifies boundaries at set distances from features in a layer (Figure 12.7). Buffers distances may be defined for point, line, or area features in a data layer. For example, timber harvesting Best Management Practices (BMPs) often exclude activities around streams or wetlands. A buffer operation in a GIS may be used to map these exclusion zones.

Cartographic overlay is another common operation. In an overlay, the geometric and tabular data are combined, and new points, lines, or regions defined that contain geometry and attributes from both source data layers (Figure 12.8). Raster overlay involves comparisons, recoding, and sometimes calculations based on grid cell values. Vector overlay of line or area features involves the intersection

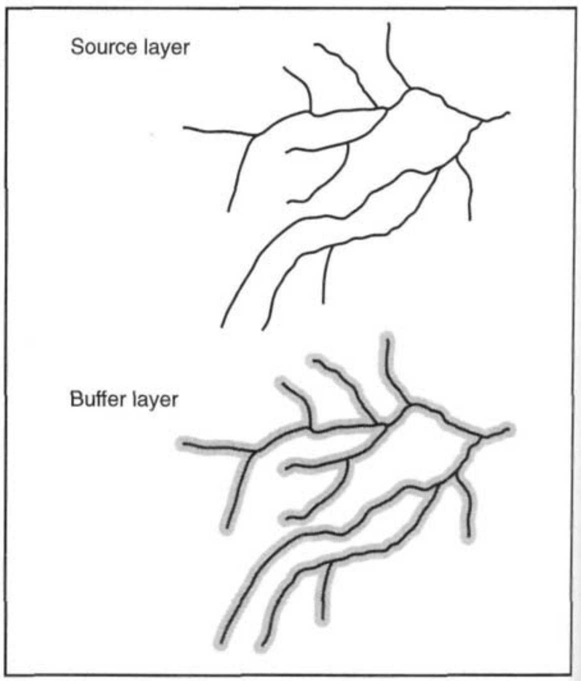

Figure 12.7 A buffer layer derived from a line data layer.

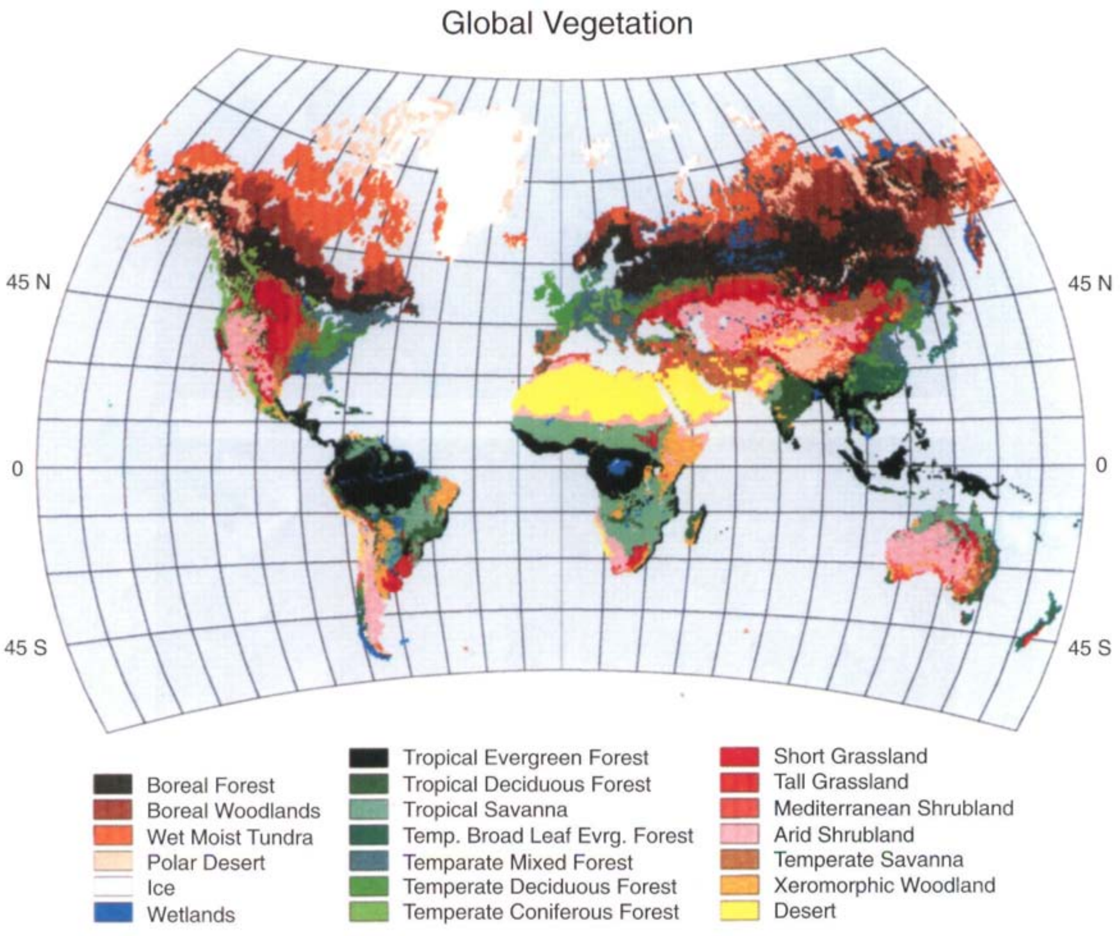

Figure 3.3 Global vegetation map showing the distribution of the forest types discussed in this book. From Landsberg and Gower (4), with acknowledgements to D. Kicklighter and J. Melillo, who provided the original version of the map.

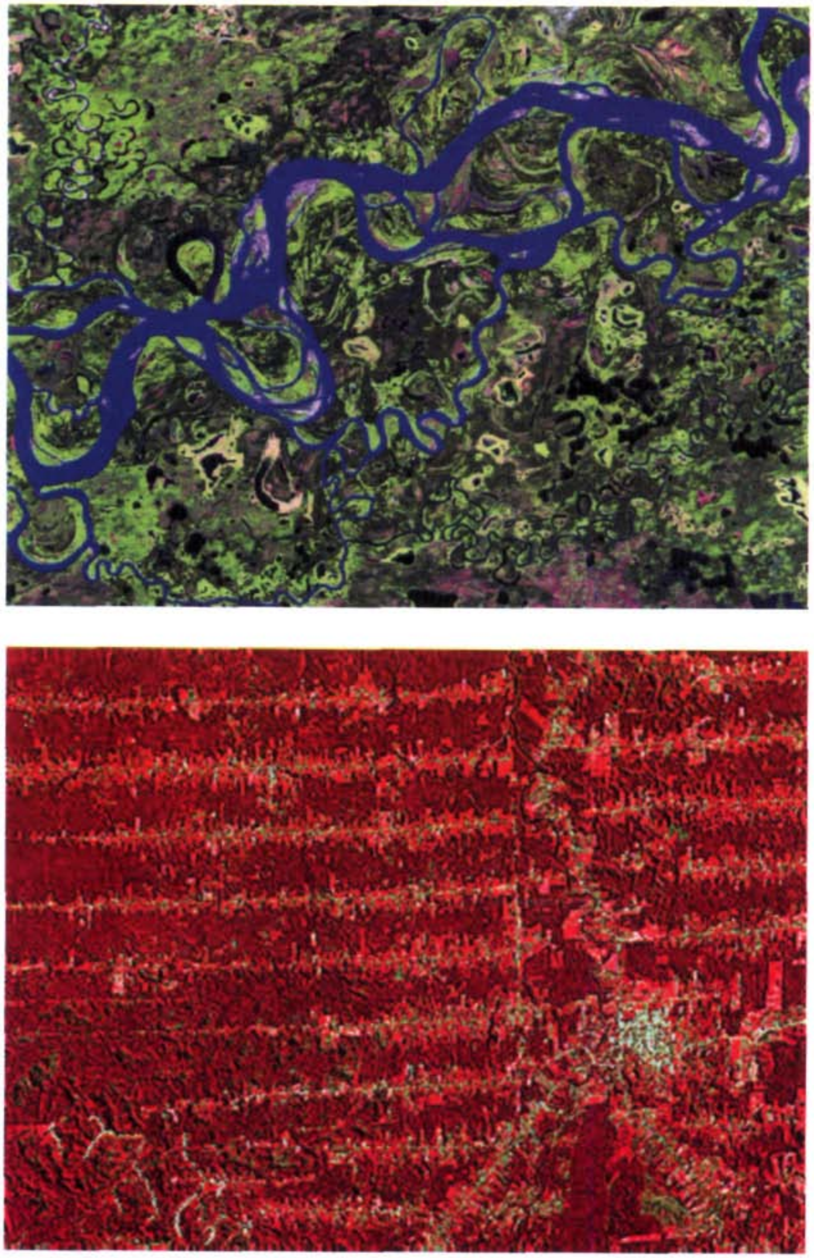

Figure 7.2 At top, a satellite image of a typical landscape pattern of a meandering river system with oxbows of varying age; different shades of green indicate different forest types. At bottom, a deforestation and settlement pattern in the Amazon Basin; dark red areas represent remaining rainforest, light red areas are clearings, and light blue areas are urban areas and roads.

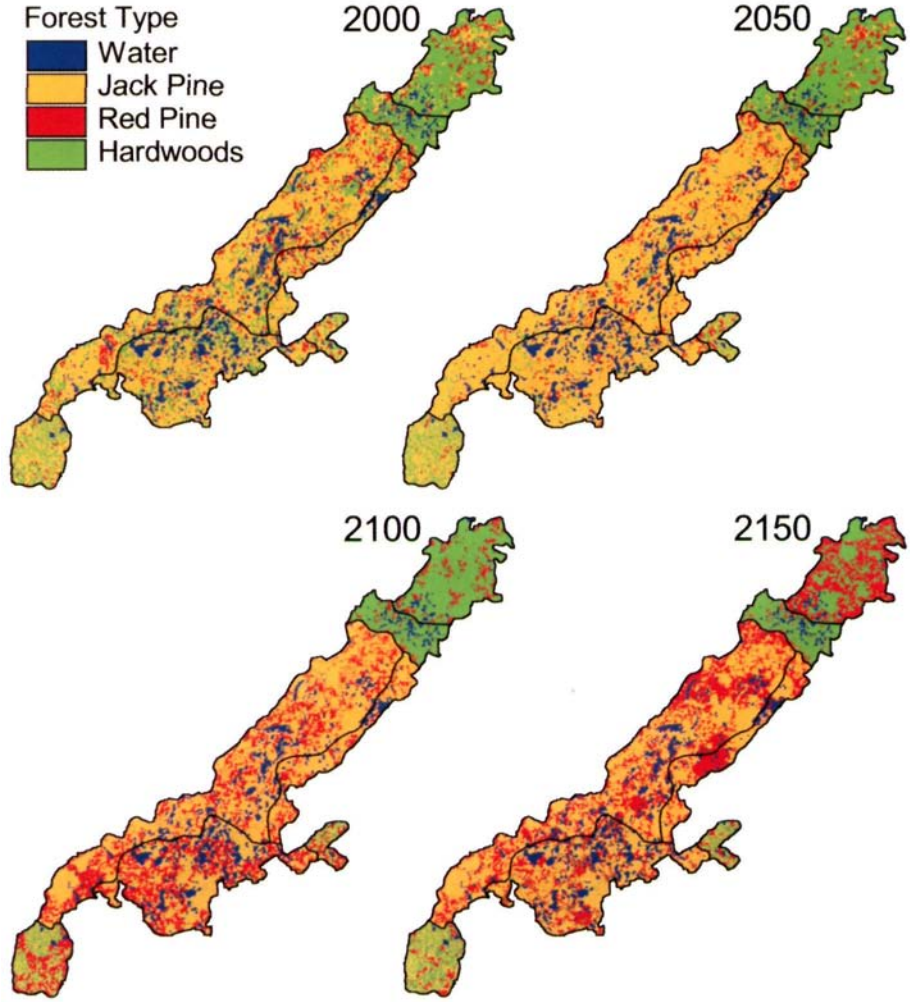

Figure 7.7 Results from a LANDIS simulation model run of the northwest Wisconsin Pine Barrens after 0, 50, 100, and 150 years.

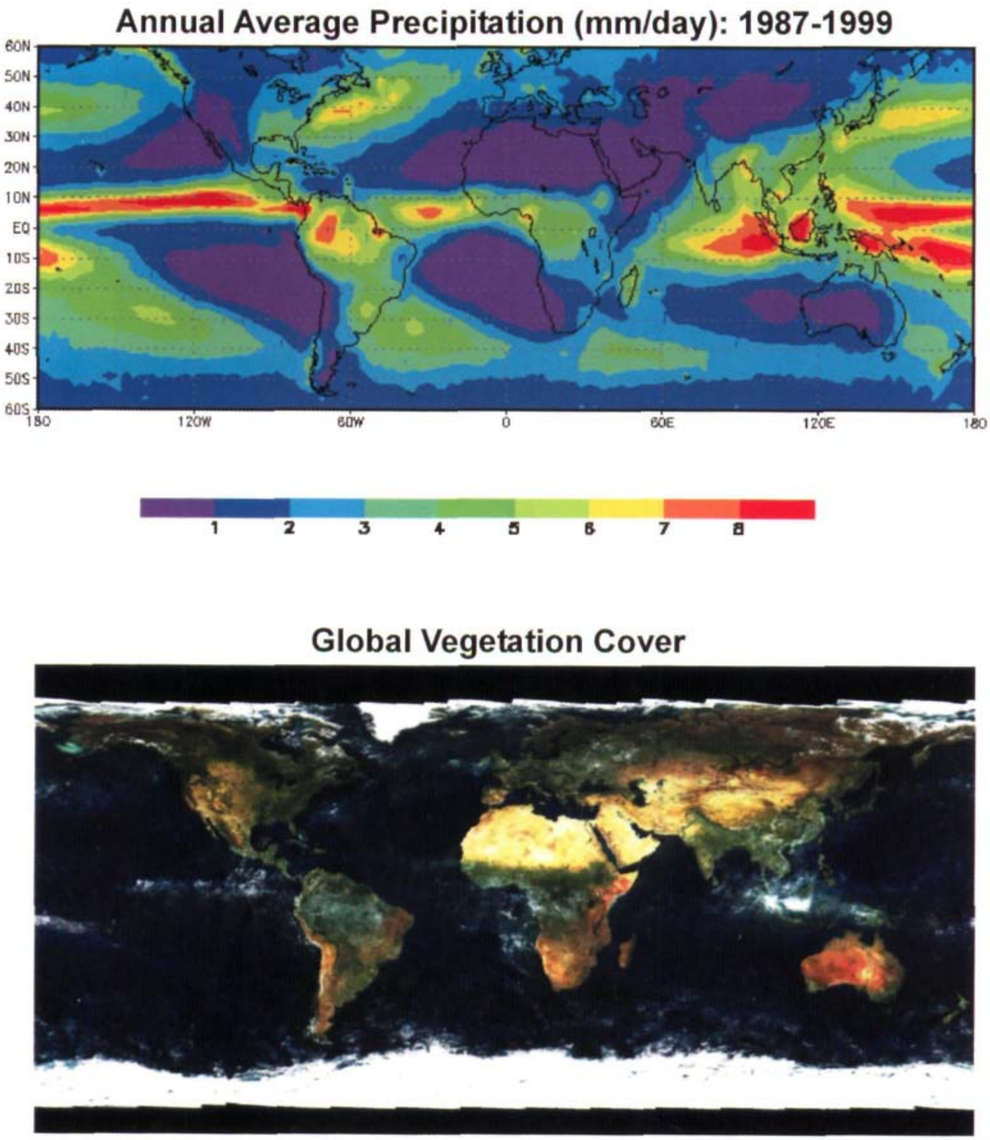

Figure 16.3 The global distribution of precipitation (top figure) and vegetation (bottom figure). Green areas in the lower figure have the highest vegetation density. Deserts and semi-arid areas are orange and yellow. Note the striking resemblance between the patterns of precipitation and pattern of vegetation cover.

Figure 16.6 Before (left) and during (right) the 1993 summer flooding of the Mississippi river. The area flooded represents a high flood stage of the floodplain.

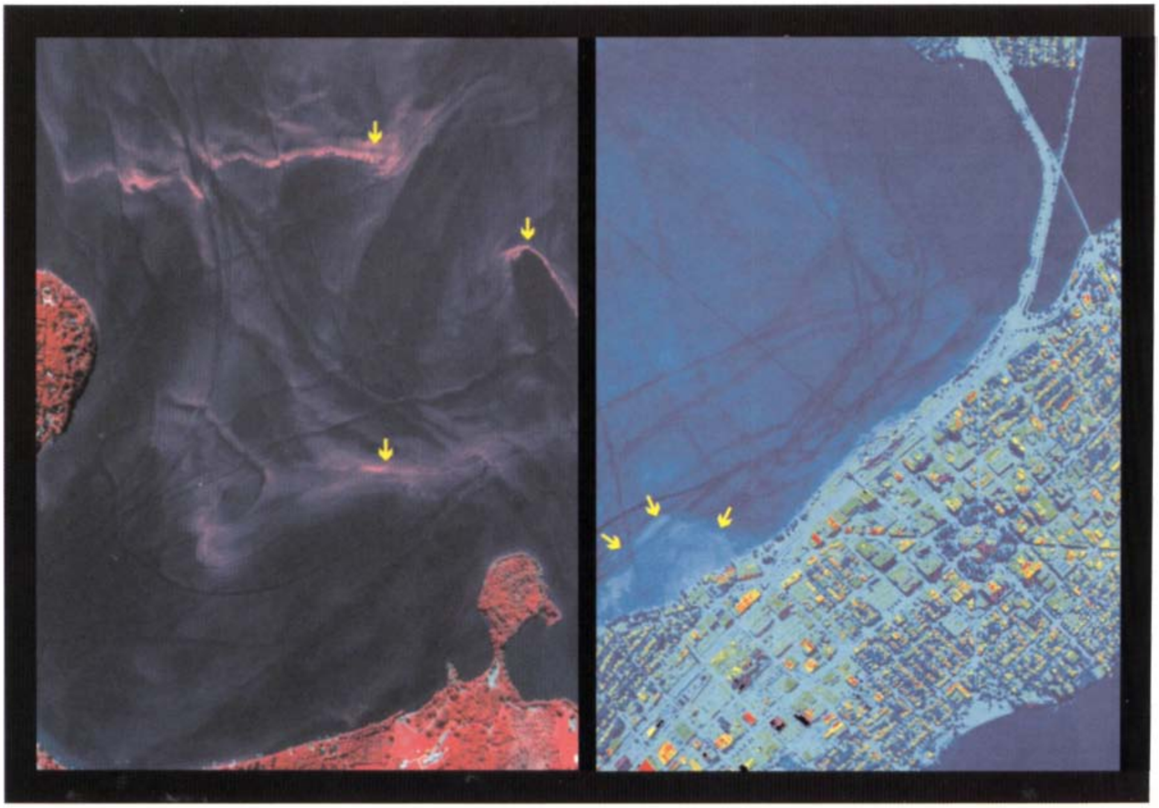

Figure 16.12 The left image shows a near-infrared airborne scanner image over Lake Mendota, Madison, Wis. The magenta colored areas indicated by arrows are algal blooms that show up because of the high reflective properties of living plant cells in the near-infrared. The right image is thermal (energy emitted by the surface). It shows a plume (warmer water) generated by a power plant. Boat wakes with overturned and cooled surface water show as dark blue lines in the water. The brightly colored buildings indicate warm rooftops.

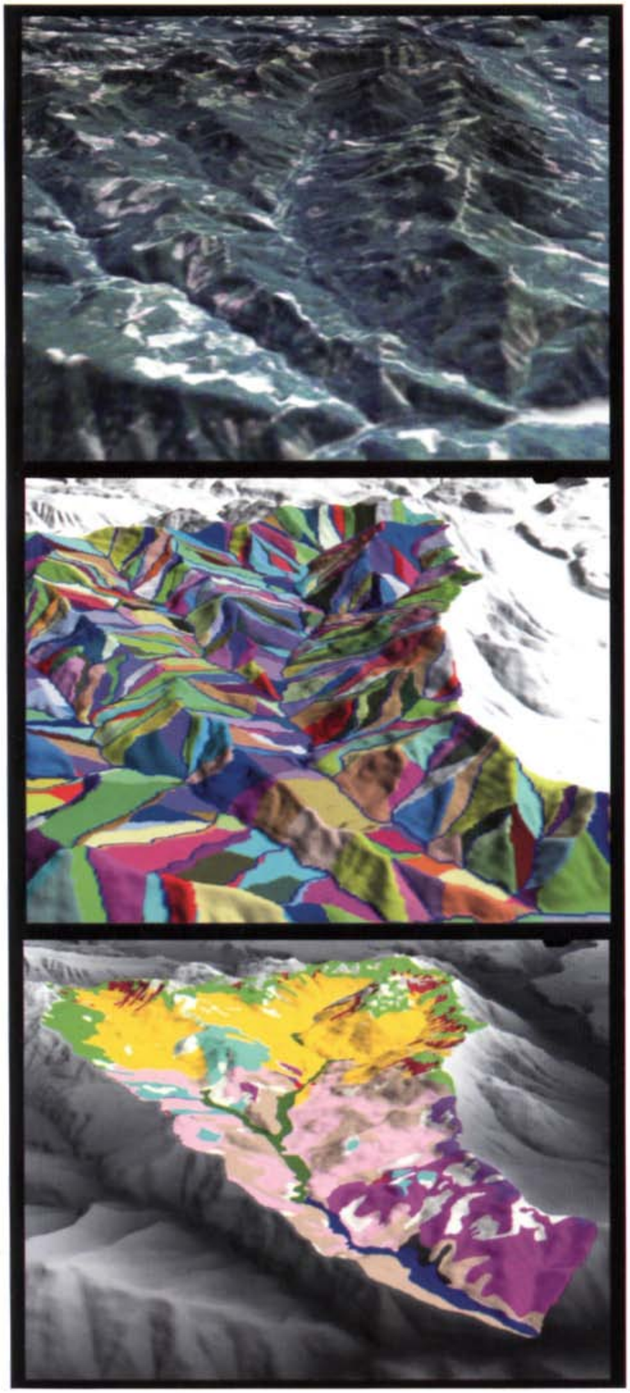

Figure 16.13 Geographical information systems allow for the integration and visualization of spatial data including remote sensing land cover (top), watershed partitioning for input to models (middle), and soils (bottom).

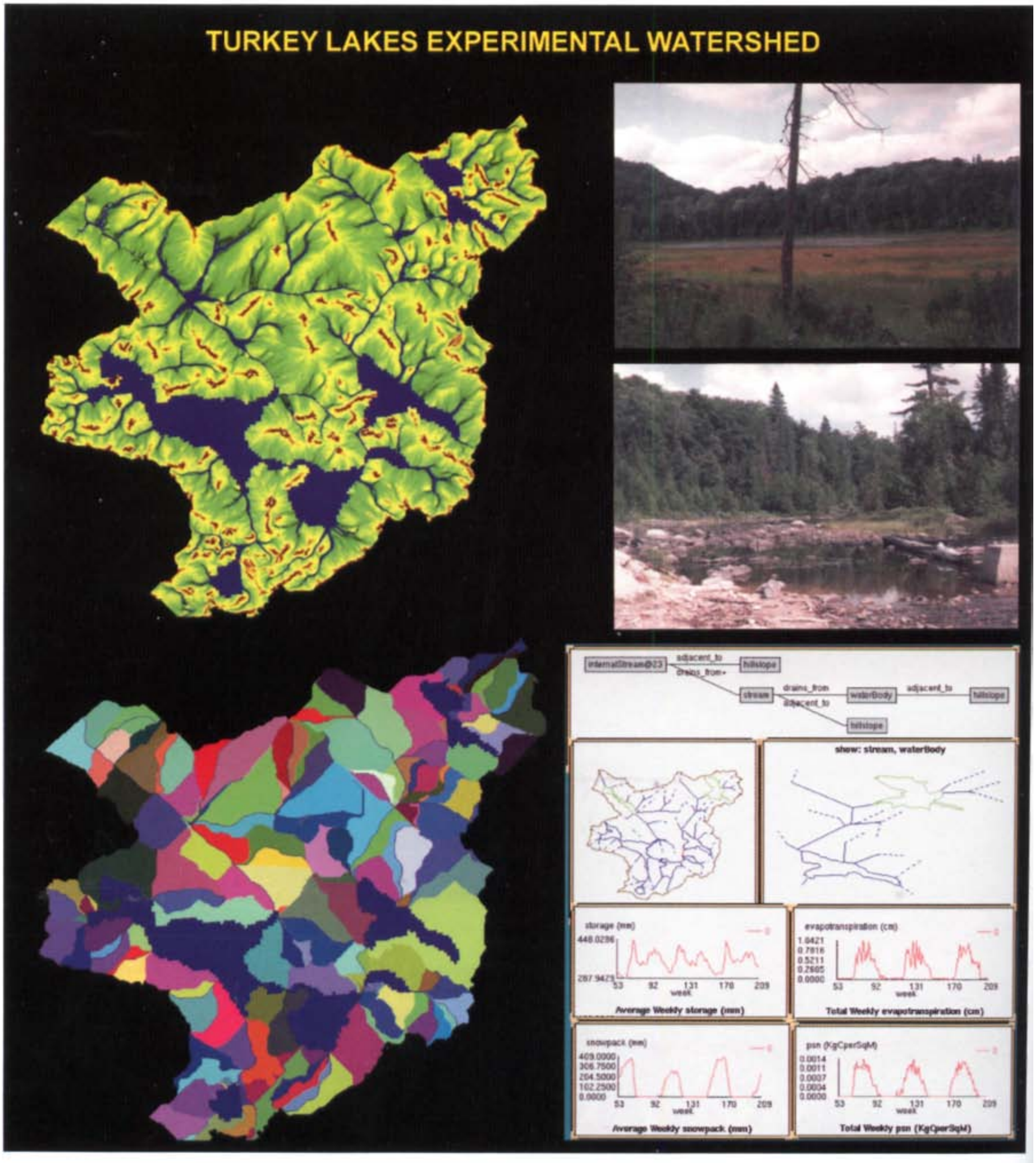

Figure 16.14 Automated tools are becoming standard methods for preparing inputs to hydrologic models. This plate illustrates some of the products (flow path analysis, segmentation of watersheds into hill-slope partitions), as well as modeling tools for making predictions.

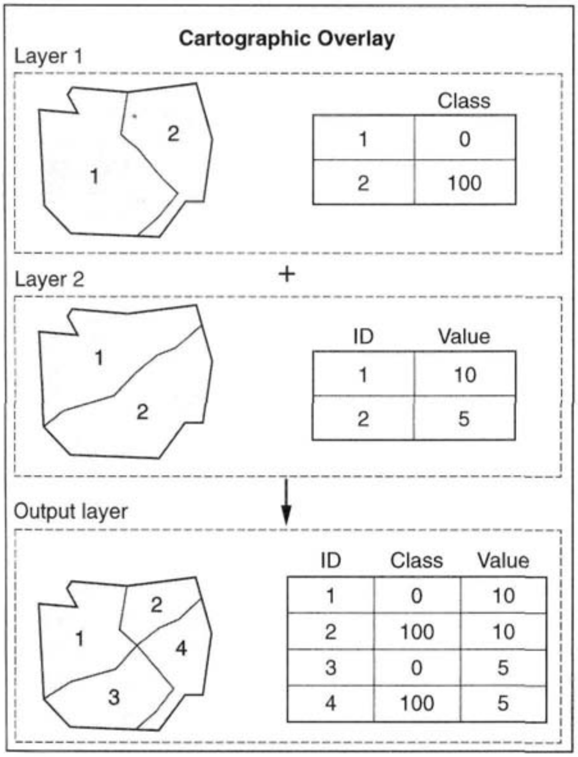

Figure 12.8 Vector data overlay.

lines and the creation of new polygons. Overlays allow the combination of features from different themes and often provide information key to the solution of many natural resource measurement or management problems. For example, land suitability is often defined by criteria based on soils (will support buildings), topography (flat), and current zoning (residential, commercial, etc.). Layers representing these three themes may be overlain in a GIS, and areas that satisfy all three criteria identified.

Geographic operations are often combined in a sequence to construct a cartographic model (Figure 12.9). A cartographic model is designed to answer a specific question, and often results in a data layer providing the answer. Operations are performed in sequence, incorporating single and multiple data layers. Intermediate data layers are generated, and combined or used with additional operations, eventually determining the needed information.

There are many additional, specialized GIS operators designed to address specific geographic problems. *Network analyses, three-dimensional GIS,* and *geostatistics* may used to optimize analyses for specific problems, and are not discussed here because of lack of space. These and many other spatial

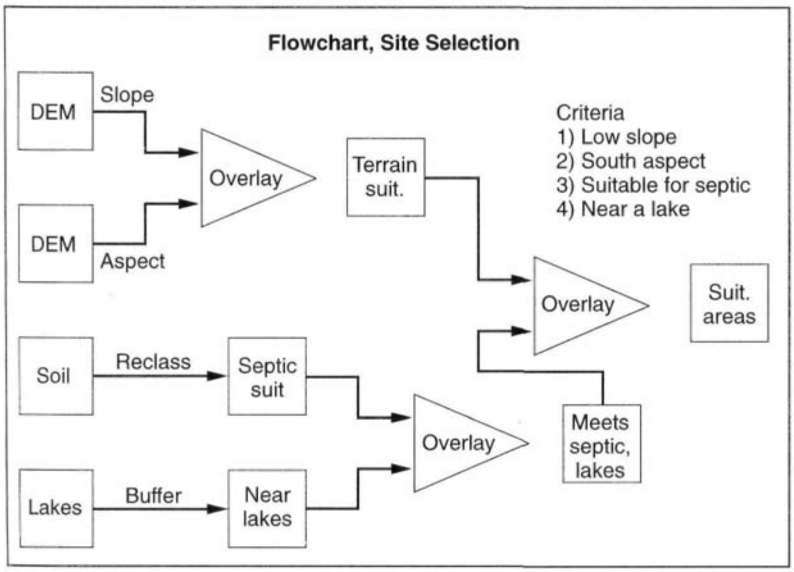

Figure 12.9 Flowchart representation of a cartographic model. Triangles and lines are operations, and squares indicate data layers (DEM = digital elevation model).

analyses are more thoroughly discussed in the references listed at the end of this chapter.

Table 12.1 Wavelength Regions of the Electromagnetic Spectrum that Are Used in or Affect Remote Sensing

Region	Wavelength (μm)
Ultraviolet	< 0.4
Visible—Blue	0.4 0.5
Visible—Green	0.5 0.6
Visible—Red	0.6 0.7
Near Infrared	0.7 1.4
Mid Infrared	1.4 2.9
Thermal Infrared	2.9 100
Radar Microwave	1,000 1,000,000

Remote Sensing

Remote sensing is the measurement of characteristics from a distance (5, 6). Practically defined for forest science applications, remote sensing is the use of airborne cameras, scanners, and satellite imaging devices to gather information about forest resources. Aerial photographs have been used in forest resource management since the 1930s, are well developed, and widely applied. The use of satellite and airborne scanner imagery in forestry is more recent, having begun in 1972. Imaging systems overcome some of the limitations in aerial photographs; however, they also introduce some limitations of their own, and so are unlikely to replace film, at least for the next few decades. Whatever the medium, remotely sensed imagery are unique and valuable data sources that are employed worldwide.

Radiant Energy and Spectral Reflectance Patterns

All remote sensing is based on the detection of electromagnetic energy. Electromagnetic energy is defined by wavelengths, and may be conveniently categorized into spectral regions (Table 12.1). A single wavelength is the distance between successive peaks in the electromagnetic energy wave. Different wavelengths have different energy intensities and are sensed as different colors. Humans sense light in the visible region (from 400 to 700 nanometers), with blue colors resulting from energy at the shorter wavelengths (400 to 500 nanometers), green in the middle (500 to 600 nanometers), and red at the longest wavelengths (700 to 900 nanometers). Intermediate colors are observed by combinations of these three wavelengths at varying intensity. Remote sensing systems may coincide with this range (true color and standard black and white photographs), or they may sense energy beyond the range of human vision. Infrared photographs sense energy in wavelengths just above red (700 to 900 nanometers), thermal imaging systems sense longer wavelengths (3,000 to 14,000 nanometers), and radar the longest wavelengths (1 millimeter to 1 meter). Different information may be obtained from each different wavelength, so several spectral bands of remotely sensed imagery are often used.

Differences in reflected electromagnetic energy forms the basis for remote sensing. Sunlight falling on the forest is either reflected or absorbed. Leaves absorb much of the red and blue radiation, and reflect relatively more green light, and so appear green to the human eye and on true color film. Clean, deep water absorbs most of the light in the visible wavelength regions, and so appears dark, or perhaps slightly blue. Concrete reflects strongly throughout the visible region, and so appears light gray or white. Each of these materials have different spectral reflectance patterns across the electromagnetic spectrum (Figure 12.10), and these different patterns lead to different colors, allowing a photointerpreter to distinguish between different surface features.

Aerial Photography

Cameras and Films A number of different camera types are currently available. Small format cameras, with nominal film dimensions of 35 mm or 70 mm, are routinely used by private and public

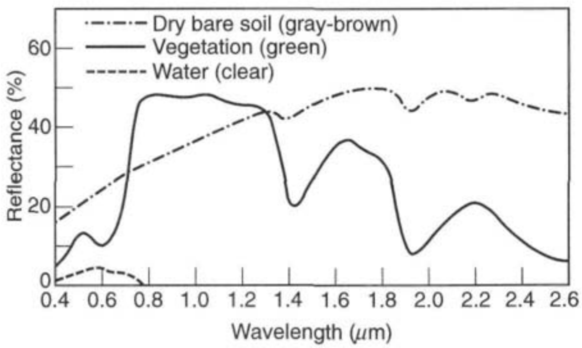

Figure 12.10 Typical spectral-reflectance curves for vegetation, soil, and water. From Lillesand and Kiefer (6), adapted from Swain and Davis (9).

organizations over much of North America. Film and cameras systems are relatively inexpensive, easy to operate, and familiar to many users. However, these film types generally cover relatively small areas with each frame, and the camera systems typically are not designed specifically for precise mapping, so geometric distortions are often unacceptably high for mapping applications. Nine-inch mapping cameras, with film sizes approximately 230 mm on a side, cover 10 to 40 times the area of the smaller formats. Furthermore, these cameras are designed specifically for mapping projects, with camera and lens components optimized to reduce geometric distortion. These cameras also come with sophisticated control and mounting systems that enable them to take photographs in rapid succession, and films are available which capture extremely fine detail. However, these cameras are quite expensive relative to smaller formats, and are most often chosen when accurate mapping over large areas is required.

Four types of photographic films are commonly used. Black-and-white panchromatic film is sensitive to the visible portion of the electromagnetic spectrum, approximately the same as human vision, from 400 to 700 nanometers. Black-and-white infrared film is sensitive to green through infrared radiation, approximately 500 to 1100 nanometers. There are large differences in the infrared reflectance characteristics among many vegetation types, thus infrared films are desirable when the photographs are to be used primarily for vegetation mapping. True color photographs are sensitive to the same wavelengths as the human eye, with blue, green, and red dye layers used in the film to reproduce the full range of visible colors. Color infrared films are sensitive to approximately 500 to 1100 nanometers. These films also have three dye layers; however, the blue layer is sensitive to green light, the green dye layer is sensitive to red light, and the red dye layer is sensitive to infrared light. Because vegetation reflects infrared light much more strongly than visible light, color infrared photographs are typically red in areas of dense vegetation.

Photo Coverage, Scale, and Geometry

The scale of an aerial photograph is the relationship between a distance on the photograph and a corresponding distance on the ground. For example, the distance between two road intersections might be one inch on the photograph and 2000 feet on the ground. The scale is then one inch to 2000 feet. Scale is also commonly expressed as a unitless number. In our example above, the roads are 24,000 inches apart on the ground (2000 ft X 12 in/ft), so the scale might also be expressed as 1:24,000. Scale depends on the lens focal length and flying height. Mapping cameras with a 230 mm film size typically use a lens with a focal length near 150 mm, so scale is most commonly adjusted via aircraft flying height. Scale is inversely proportional to flying height, because scale is determined by the ratio of the focal length to flying height above terrain:

Photo scale = focal length/height above terrain

Photographs taken with a six-inch (150 mm) lens from a flying height of 7,920 feet will have a scale of:

Photo scale = 6 in X 1 ft/12 in/7920 = 1/15,840

This photo scale is commonly used in resource mapping, with four inches equal to one mile.

Scale is rarely constant within a photograph, because although planes may fly at a nearly constant height, the elevation of the earth surface varies below the aircraft. Variation in terrain height within an image leads to variation in scale, and differences can be substantial. Scale often varies by 5 percent or more for photos taken in mountainous areas of North America, because height above terrain may vary by that much within the image.

Photograph scale may also be affected by camera tilt. If the film plane is not parallel with the earth surface when the photograph is taken, there will be some perspective distortion in the photograph (Figure 12.11). This distortion also causes differences in photo scale, and the distortion varies by tilt direction and amount. Mapping contracts typically specify vertical photographs, meaning tilt must be less than three degrees from vertical. Because of variation in scale caused by terrain and tilt, the reported scale for a photograph should be considered an average.

Photographic coverage is related to scale and film format. The edge dimensions of the ground area covered by a photograph are approximately equal to the scale times the edge dimensions of the film. Thus, a 9-inch photograph at a scale of 1:20,000 has an edge dimension of approximately:

$$\text{Dimension} = 9 \text{ in} \times 1 \text{ ft}/12 \text{ in} \times 20{,}000 \text{ in/in}$$
$$= 15{,}000 \text{ ft}$$

Increasing the flying height, and hence decreasing scale, increases the area covered in each photo. However, objects also appear smaller, and at some point it becomes difficult to identify features on the photographs. Choosing the proper photographic scale involves tradeoffs between resolution and area coverage.

The degree of overlap among adjacent photographs is another factor which may affect the number of photographs required to cover a given study area. Photographs are typically taken in parallel flight lines (Figure 12.12). Sidelap is the overlap between adjacent flight lines, and is typically 5 to 15 percent. The endlap specifies how much successive photographs overlap. Endlap is typically 15 to 65 percent of the photo dimension. Higher endlap is specified when stereoviews are required. In a stereoview, the right eye views a photograph, and the left eye views the next photograph on the flightline. If the photographs are properly oriented, a three-dimensional reconstruction of the imaged surface can be perceived. This view is based on *image parallax*, the relative horizontal shift in points based on their differences in elevation. These parallax

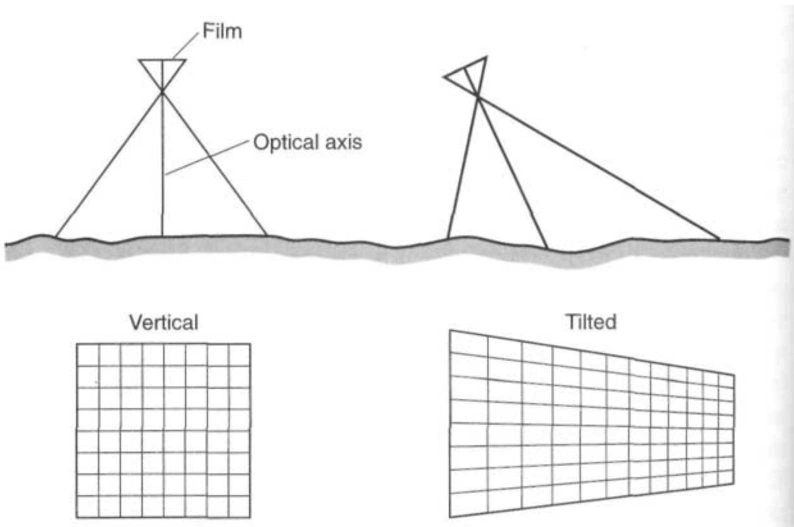

Figure 12.11 Geometric distortion caused by photo tilt.

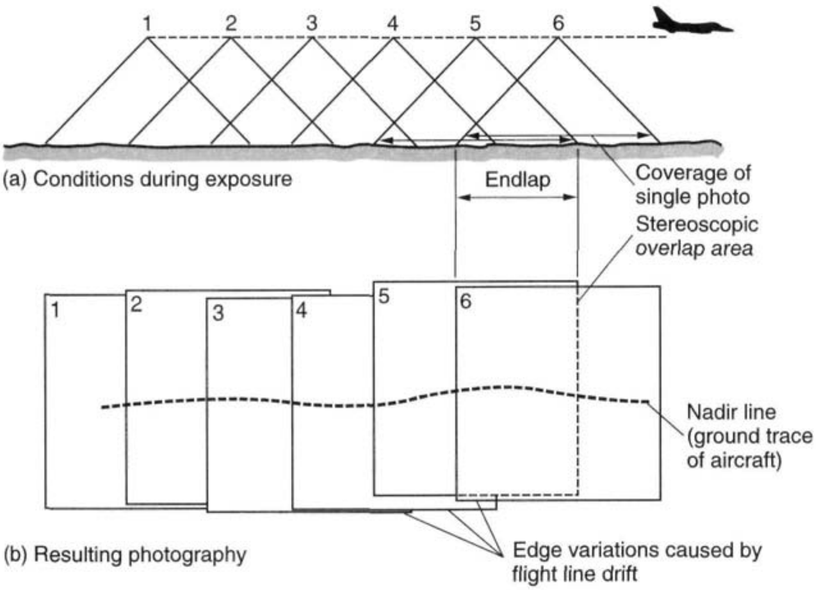

Figure 12.12 Photographic coverage along a flight strip. From Lillesand and Kiefer (6).

shifts result in mountains appearing higher and valleys lower in a stereoview. Slope, terrain shape, and relative heights may be perceived in a stereoview.

The preceding discussion underscores that photographs are not maps. Most photographs, even those from the most precise mapping cameras, contain geometric distortion in the relative positions of features, often caused primarily by tilt and terrain distortion. These geometric distortions must be removed prior to the use of photographs in precise mapping, before making distance or area measurements from photographs, or before entering them in a GIS. The level of geometric error depends on many factors, including the camera system, film format, photo scale, tilt, and terrain variation. In some instances, experience indicates uncorrected photographs will provide measurements within acceptable accuracy limits. The Natural Resource Conservation Service (formerly the U.S. Soil Conservation Service) historically measured field areas on uncorrected 35 mm aerial photographs because they were flown at large scales, and experience indicated acceptable accuracies could be achieved. Many forestry organizations have mapped timber stands on uncorrected vertical 9-inch photographs. These methods were chosen because practical experience indicated the data derived were of acceptable quality, given cost/accuracy trade-offs. However, geometric accuracy assessments and cost/accuracy comparisons should be conducted on a routine basis, particularly when data derived from the photographs will be entered into a GIS.

Photogrammetry and Photo Measurements

The science of *photogrammetry* is dedicated to precise mapping and measurements from photographs (1, 2, 8). Photogrammetric engineers have developed robust, well-known, reliable methods of removing photographic distortion. Until the early 1980s, most photogrammetric work was conducted on analog instruments such as a *stereoplotter* (a device based on lenses, projection, and moveable stages) to extract information from photographs and transfer the information to maps. Stereopairs of photographs are viewed together, and by recreating the relative orientation of the photographs at the time of exposure, and viewing the photographs through stereographic optical systems, a three-dimensional view of the mapping area may be created. Information may then be projected to a planar base for mapping.

Since the 1980s, there has been a rapid growth in digital photogrammetry, in which the photographs are passed through a scanner and converted to a digital image. Various methods have been devised to view digital stereopairs, and photogrammetric techniques adapted to remove tilt, terrain, and other distortions from the digital images. The resulting digital photograph, called a *digital orthophotograph* (DOQ), has positive attributes of both maps and photographs. A DOQ is similar to a map because it has a uniform scale and can serve as a base for area or distance measurements, yet the DOQ also contains the detailed information visible in photographs. DOQs are easily integrated with other spatial data in a GIS, and photo interpretation may be done on-screen. DOQs are so useful that a national program has been established with the goal of making them available for the entire United States.

There are other photographic measurements in addition to area and distance. *Photomensuration* is a set of techniques to estimate tree size and wood volume. Tree heights may be measured on the photograph because trees not directly below the camera (at the nadir point) appear to lean outward away from the nadir. Measuring this form of parallax, from the base to the top of the tree, allows an estimate of tree height. Crown diameters may also be measured, and relationships between crown diameters and stem diameters may be used to estimate diameter and, hence, stem volume. Tree density may also be measured, allowing estimates of total stand volume. Relationships between photographic measurements and measured tree and stand volumes have been summarized in photo stand volume tables, where stand area, species, crown closure, tree height, and crown diameter are used to estimate stand wood volume.

Photointerpretation

Photointerpretation involves converting the variation in color and tone evident on aerial photographs into information about the location and characteristics of important resources. Forest photointerpretation is most often performed to produce a *vegetation type map.* The boundaries of homogeneous vegetation units are defined based on cues in the photograph. Color, brightness, texture or pattern, size, shape, topographic position, and proximity to other features are all used to define the boundaries between different vegetation types. Different cues may be most important for different vegetation types, and there is an art to photointerpretation gained through experience. Characteristics may change with the season, as when leaf colors for deciduous tree species change from summer to fall.

Photo characteristics for a vegetation type may vary within a single photograph. For example, colors are often brighter in the direction of the sun and darker in the direction away from the sun. In a similar fashion, colors are often lighter on slopes facing the sun than on slopes facing away. Colors may darken or change tone near the edge of the photo as a function of the camera/film/filter system. All of this variation must be integrated if the photointerpreter is to produce an accurate map.

Vegetation Types

Forest managers and scientists are often interested in mapping forest types by species, and sometimes age classes (Table 12.2) (1, 2). Classifications are sometimes hierarchical, from less detailed to more detailed classes, and in some cases it is difficult or impossible to accurately separate certain species or species groups. For example, sugar maple *{Acer saccharum)* and black maple *{Acer nigrum)* are indistinguishable from aerial photographs, and so are often grouped (on photointerpreted maps).

Figure 12.13 is a black-and-white stereopair that illustrates some of the principles of species identification using aerial photographs. A pure stand of black spruce (outlined areas) is shown, surrounded by aspen. Black spruce is a needle-leaved evergreen tree species with a slender, conical crown. Pure stands normally exhibit a regular pattern, with uniform or gently changing tree heights. Closed-canopy black spruce stands typcially show a smooth, car-

Table 12.2 A portion of a forest classification system for Lakes States forests. Categories become more specific from left to right. Categories are also hierarchical, in that finer categories collapse into common coarser categories.

Deciduous Forest	Upland Deciduous Forest	Aspen < 10 years old
		Aspen > 10 years old
		Red Oak
		Sugar Maple
	Lowland Deciduous Forest	Ash-Elm
		Alder
Coniferous Forest	Upland Coniferous	Red Pine
		White Pine
		Jack Pine
	Lowland Coniferous	Black Spruce

pet-like texture. Aspen is a deciduous broad-leaved species with rounded, widely-spaced crowns, and often a rougher texture. This difference in texture between aspen and black spruce is illustrated clearly in Figure 12.13.

Color infrared photographs usually allow for the finest discrimination among vegetation types, because of strong differences in the infrared reflectance properties among species. Scales between 1:10,000 and 1:20,000 are usually chosen for stand mapping, as these scales strike a balance between covering large areas with each photo, yet still allowing adequate discrimination among vegetation types. Summer photographs are often acquired. However, fall photographs are superior when distinguishing among deciduous forest types in eastern North America, and winter photographs are better for discriminating among certain types (e.g., among needle-leaved and broad-leaved tree species). For the utmost in accuracy and discriminating ability, photos of the same area but from multiple seasons are recommended.

Regeneration, Health, and Damage Assessment

Aerial photographs are also extensively used for regeneration surveys, for forest health monitoring, and to assess disease, insect, and storm or fire damage. Photographs for regeneration surveys are typically very large scale, from 1:1,500 or larger, and often use small-format cameras because geometric accuracy is not of utmost importance. The costs of using these systems is considerably lower

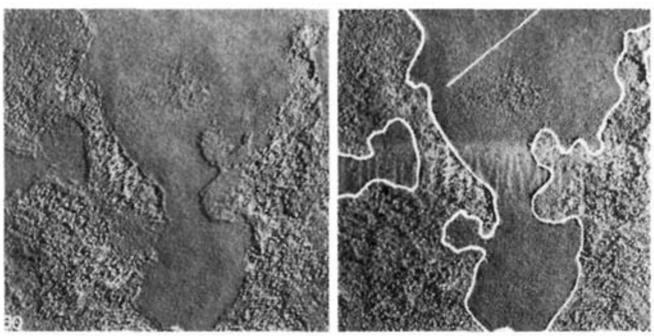

Figure 12.13 Black spruce (outlined area) surrounded by aspen in Ontario, Canada. Scale 1:15,840. Stereogram. From Zsilinszky (10), courtesy of Victor G. Zsilinszky, Ontario Centre for Remote Sensing.

than alternative mapping cameras, and large area coverage in a single photo is typically not required. Living trees on a line or in a fixed area are counted, and a proportion surviving is measured. These data help determine if regeneration was successful, or if additional treatments or plantings are needed.

Aerial photographs are also used extensively for insect pest and disease damage assessment. Most pests visibly alter the forest canopy, either by reducing vigor and changing leaf color, or by direct defoliation. These changes may be observed directly on aerial photographs. Many defoliaters are routinely monitored using aerial photographs. For example, the Gypsy moth (*Lymantria dispar*) is a serious pest in eastern deciduous forests of North America. A number of control strategies have been applied to slow the spread and reduce the severity of defoliation by this introduced pest, and aerial photographs are used in detection, the tactical planning of treatments, and assessment of effectiveness. Aerial photographs are also used for managing other species, including mountain pine beetle (*Dendroctonus ponderosae*), spruce budworm (*Choristaneura fumiferand*), the Douglas fir tussock moth (*Orgyia psueudotsugata*), and the balsam wooly adelgid (*Adelgespiceae*). Management and control of insects are discussed in detail in Chapter 8.

Aerial photographs are also quite useful in assessing wind, ice, or fire damage. Wind damage can severely affect large areas, and access is often difficult because of treefall across roads. Aerial photographs, particularly three-dimensional views on stereopairs, allow accurate identification of windfall gaps and canopy openings. Aerial photographs have also proven useful in assessing the extent and severity of fire damage (also see Chapter 18, Behavior and Management of Forest Fires).

There are many other uses of aerial photographs in forest resource management, including harvest planning, property line surveys, timber and land appraisal, road design and layout, erosion evaluation, estimating wildlife populations, and recreation planning. Aerial photography is a mature technology, and will remain a valuable tool for resource managers and scientists into the foreseeable future.

Filmless Imaging

The last two decades have seen the rapid development of imaging systems that do not depend on film. One of the most amazing achievements of modern remote sensing is the engineering of imaging scanners that collect millions of observations in a few seconds, reconstructed to form geometrically accurate images. These sensors can detect wavelengths well beyond the capabilities of the human eye or film, and in wavelength ranges, or bands, specifically chosen to provide the most information. Data are digitally quantized on collection, so the images are easily transferred to computers for subsequent digital image processing. Ever-finer spatial resolutions and narrow spectral resolutions have led some to predict that these systems will eventually replace aerial photography.

Principles of Imaging Scanners

Imaging devices typically use electronic detectors to measure reflected or emitted electromagnetic radiation. Detectors are typically made from semiconductor materials when designed for the visible through thermal portions of the spectrum, while microwave and longer radiation are detected with metal antenna. Visible and thermal detectors typically change resistance or generate a voltage with the amount of electromagnetic energy striking them. The relative intensity of this energy may then be used to calculate incident energy and identify the features observed. Detectors may be designed to sense energy in a number of arbitrarily narrow wavelength bands by changing the mix of semiconducting materials, so that sensors may be designed to observed specific reflectance properties; for example, differences among vegetation types in the mid-infrared region.

Most nonradar imaging systems are passive, in that they sense reflected or emitted energy that originates from an external source. Much like film-based systems, many passive systems detect reflected sunlight or emitted long-wave radiation. Active systems, such as imaging radar, differ in that they emit energy, and then detect the reflection of that energy.

Three different designs are most commonly found in passive imaging scanners. Many older designs are based on a small number of detectors for each wave band, and a moving mirror that focuses energy on the detectors. The mirror typically scans lines perpendicular to the flight path, and forward motion of the satellite or aircraft advances the scanner over the next line. Linear arrays operate in much the same manner as moving mirror systems, except the detectors are forged in long rows, and each cell in the image (picture elements, or "pixels") is sampled at once. These systems sometimes employ prisms or mirrors to split the signal among various banks of detectors for different wavelengths. The final design type extends this progression from zero dimensions (single pixel) through one dimension (row) into two dimensions. Square arrays of detectors may be fabricated, usually on a single chip, called a *charge-coupled device* (CCD). The CCD samples an entire image at once, although several CCDs may be in one scanner, either precisely aligned to increase the sampling area, or each sampling the same area but sensitive to different wavebands to yield a multispectral image.

Radar systems (RAdio Detection And Ranging) transmit and receive radio waves from an antenna. A beam is directed at a surface, and the microwave reflectance properties and orientation of the surface govern the strength of the return. As with passive scanners, the returns can be organized in their relative positions to produce an image. Radar system characteristics are quite different from contemporary passive systems. Unlike passive systems for shorter wavelengths, radar data can be collected at night because these systems provide the energy they sense. Radar wavelengths penetrate clouds, a major advantage in many parts of the world. Because surface response to radar wavebands is often unrelated to reflectance properties at shorter wavelengths, radar systems often provide complementary information.

Remote Sensing Systems

Landsat

The launch of the satellite Landsat-1 in July of 1972 inaugurated the civilian era of satellite-based, earth—surface remote sensing. The primary sensor of Landsat satellites 1 through 3 was the *multispectral scanner* (MSS), with an 80-meter pixel resolution and a 185-kilometer square image area. The satellites had a repeat cycle of 18 days. The scanner recorded four bands, one each in the blue, green, red, and infrared portions of the electromagnetic spectrum, so both visible and color infrared images could be produced. Landsat satellites 4 and 5 retained the MSS and added a second imaging scanner, the thematic mapper (TM). The TM incorporated many improvements based on experiences gained in analyses of MSS imagery. Among these, band widths were modified somewhat, two mid-infrared bands were included, the pixel size was reduced to 30 m, a thermal infrared band was added and a 16-day return interval was implemented.

While the MSS program was successful and pointed the way to future improvements, TM firmly established the utility of land satellite remote sensing for a diverse array of users. Public and private sector applications have been developed in agricultural and forest management, disaster assessment, oil and mineral exploration, population estimation, wildlife management, urban and regional planning, and many other fields. MSS data had two advantages relative to color infrared photos. The first was a uniformly calibrated digital image, providing data inherently amenable to digital image processing. Some analysis and interpretation could be aided or performed by computers, in part automating image interpretation. Second, the data were inexpensive relative to photographs when large areas were analyzed. Disadvantages were a coarse spatial resolution (80 m versus sub-meter for most photo scales used), and infrequent repeat times. TM provided the same digital format, and included visible, near-infrared, thermal, and new mid-infrared bands that significantly improved the utility of the data for discrimination among vegetation types. The pixel size in TM was improved to 30 m, an improvement over MSS but still much coarser than the effective resolution of most aerial photographs. TM data have been successfully applied in many disciplines, including forest type mapping, inventories, and damage assessment.

SPOT

France has led a consortium of European countries in the development and launch of four earth resource satellites known by the acronym SPOT (Systeme Pour l'Observation de la Terre). The SPOT-1 through SPOT-3 satellites carried similar instrument packages. The main imaging system, known as the HRV, employed a linear array, CCD design, a first for civilian satellite remote sensing systems. The HRV operates in two modes, a single band panchromatic mode, with 10 m resolution and 510 to 730 nanometer spectral range, and a three-band, 20 m resolution, multispectral mode, with green, red, and near infrared bands (Figure 12.14). The HRV is pointable off track, in effect reducing return times to every few days, rather than more than every two weeks as with TM and MSS. Pointable optics also allow the collection of satellite stereopairs, and thus raster elevation data may be collected. The imaged area for a single HRV scene is approximately 60 km on a side, so although the image is significantly higher resolution than typical aerial photographs, it is approximately one-tenth the area of TM and MSS imagery.

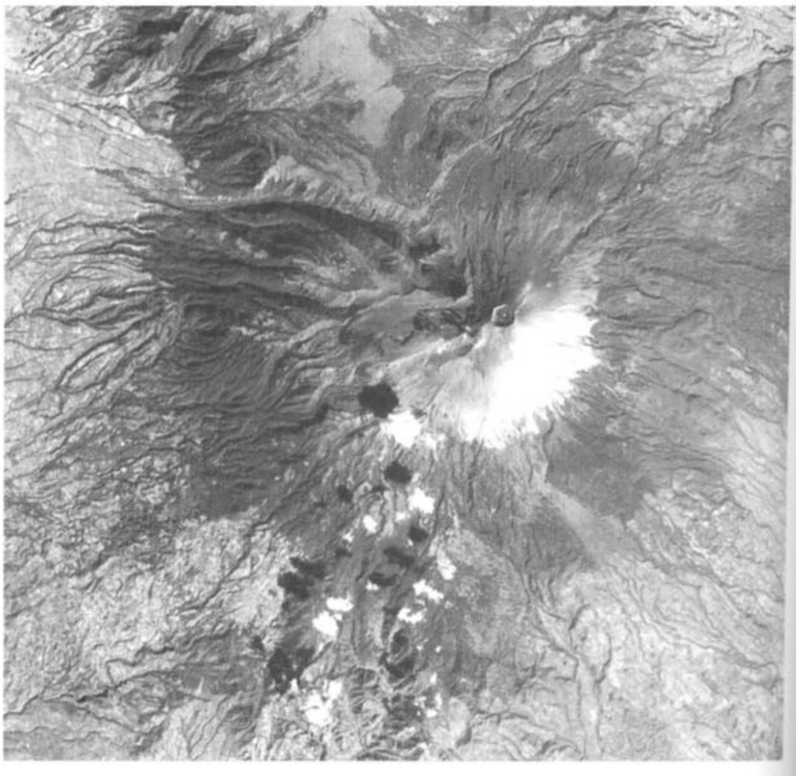

Figure 12.14 Example SPOT HRV image, Popocatepetl Volcano, Mexico. (Copyright SPOT Image, 2000, used with permission.)

Comparison of the TM and HRV illustrates a common tradeoff in scanner system design: smaller pixel sizes typically come with a smaller imaged area. Satellite images to date have pushed the limits of data collection, storage, and transmission from space to ground stations. Smaller pixel sizes are desirable in many instances because they improve the spatial detail and type resolution available on digital images. However, each time pixel sizes decrease by a factor of two, data volumes increase by a factor of four. Thus, systems increase resolution at the expense of smaller images. Advances in data compression and transmission are allowing increasing resolution while maintaining large images; however, the tradeoff still exists.

SPOT-4 carries an improved HRV, as well as a new sensor named VEGETATION. The new HRV carries the three bands carried on previous SPOT satellites, and adds a mid-infrared band. The utility of the mid-infrared band for vegetation mapping was amply demonstrated with the Landsat TM, and is included in the HRV at a 20 m resolution. The VEGETATION sensing system operates independently of the HRV, and is designed for global vegetation productivity, health, and monitoring. The sensor has a pixel size of 1 km and a swath width of 2,250 km, and images the entire globe once a day. Four bands are recorded, a blue (430 to 470 nm), red (610 to 680 nm), near-infrared (780 to 890 nm), and mid-infrared (1580 to 1750 nm).

Radarsat

Radarsat is a side-looking satellite imaging radar system developed and operated by the Canadian Space Agency. The imaging system collects data using a 5.6 cm radar wavelength, with an effective resolution of from 10 to 100 m, depending on look angle. The orbit is repeated once every 24 days, but areas up to 500 km to the side of the orbital track may be imaged. The repeat interval is approximately 6 days at the equator, and less towards the poles. Radarsat data have been used to monitor clearcut extent, particularly in tropical regions where radar penetration of cloud cover is essential to timely measurements. Radarsat data have also been applied to problems in agriculture, hydrology, cartography, and land use.

Other Remote Sensing Systems

Several remote sensing systems are in orbit or will soon be launched that provide useful data for natural resource management. The *Advanced Very High Resolution Radiometer* (AVHRR) is a 1.1 km resolution scanner providing global coverage on a daily basis. Versions of this scanner have been carried aboard National Oceanic and Atmospheric Administration polar orbiting satellites since 1979, and the scanners sense red, near-infrared, and thermal wavelengths. Red and near-IR bands have been used to measure global phenologies and vegetation density and health, chiefly through spectral vegetation indexes such as the *normalized difference vegetation index* (NDVI). The NDVI is the ratio of the near-IR minus red divided by the near-IR plus red bands. Because water and soils absorb infrared, and vegetation reflects infrared, high NDVIs indicate high vegetation density.

A number of radar systems have been or will be launched. The ERS-1 and JERS-1 were radar systems launched by the European and Japanese space agencies, respectively, and the *Almaz-1* was launched by the former Soviet Union. These systems, taken together, sense across a range of radar wavelengths, resolutions, and sensing modes. Experience to date indicates these systems have many useful applications, among them in forest monitoring, *topographic surveys*, *landcover classification*, and *change detection.*

Scanners associated with the NASA *Earth Observing System* (EOS) will provide a wealth of research and data, much of which will prove useful in forest resource measurement and management. Landsat-7 will carry the *Enhanced Thematic Mapper* (ETM), sensing in similar wavelengths as TM, but adding a 15 m resolution panchromatic band, and increasing the resolution of the thermal band to 60 m. The *MODIS* sensor will sample 36 spectral bands at resolutions that vary from 250 m to 1 km and provide global coverage every two days. *ASTER* will sample 14 bands from visible through thermal infrared at resolutions from 15 to 90 m. As ASTER is a pointable sensor, revisit times will be approximately 6 days.

Concluding Statement

Our abilities to collect, organize, and analyze spatial data have improved tremendously over the past two decades, and will continue to develop in the foreseeable future. Remote sensing has provided new tools for rapid data collection over wide areas. GIS technologies allow us to organize and analyze these data with substantially improved speed and flexibility. Spatial data technologies serve our expanding spatial information needs. Our planet contains finite resources and an expanding human population, and spatial data and analyses will be part of intelligent identification, management, and preservation of these resources.

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CHAPTER 13

Silviculture and Ecosystem Management

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Silviculture can be defined as the use of sustainable management practices to establish or guide the development of forest stands in order to fulfill natural resource objectives. These objectives can vary widely to include timber production, management for wildlife and biological diversity, management of aesthetics, modification of forest streamflow volume, and ecological restoration of degraded stands and landscapes. The history of silvicultural practice, like that of forestry in general, has involved a gradual broadening of objectives. A number of major "paradigm shifts" have occurred in the past six centuries in the western world, which have repeatedly redefined the scope and purpose of silvicultural treatments.

Evolution of Silvicultural Practice

European Origins

Most of the basic silvicultural practices originated in western Europe in the 14th to 19th centuries in response to fears of periodic timber famines. By the early Middle Ages, much of the European landscape had already been cleared for agriculture. England, for example, was probably not more than 10 percent forested in 1000 A.D. Population increases brought heavy pressure on the remaining fragments of woodland. These forests were heavily grazed by livestock, plundered by exploitive cutting of the best remaining timber trees, and repeatedly coppiced for small-diameter fuelwood. By the 13th century, there was sufficient alarm over the degraded condition of the woodlands and the limited supply of wood that laws were passed regulating the practice of grazing and the types of trees that could be cut (1, 2).

These early legal measures were largely protective, designed to slow the rate of exploitation and prevent continuing impoverishment of the forest. The first major paradigm shift in human use of the forest occurred as early as 1359, when managers of the city forest of Erfurt, Germany realized that if the haphazard felling of trees were replaced by a more orderly sequence of planned harvests, a perpetual supply of timber could be assured. Wise management, moreover, would actually improve the condition and productivity of the existing forest rather than simply prevent further degradation. Statutes began to specify that harvesting should be concentrated in certain sections of the forest, and subsequent regrowth protected from grazing until the saplings or sprouts were tall enough to be out of the reach of cattle (2). If an owner or government official desired to cut sprout hardwoods at an average age of 50 years, the tract could be divided into 50 sections and a different section harvested each year. These ideas were the first representation of what modern foresters would call *even-aged management for sustained yield.*

Experimentation on methods of active forest management also began to develop, particularly in Germany. In 1368, the city of Nuremberg dabbled with artificial seeding of pine, spruce, and fir. Forest officials also learned that conifer species could be regenerated naturally over large areas by leaving scattered seed trees. The "seed-tree method" of harvesting was introduced in 1454, including prescriptions for the minimum number of seed trees required for adequate stocking of seedlings. An important lesson learned from these early trials was that biological traits of tree species (silvics) imposed certain constraints on how forests could be managed. German foresters discovered, for example, that some species of trees could not be regenerated by selective or partial cutting because the seedlings could not tolerate shade. Books were written to summarize the accumulating knowledge on practical forest management and culture, such as one by John Evelyn called *Sylva, or a Discourse on Forest Trees*, published in England in 1664.

Forestry began to be guided by scientific observations and economic principles in the early 19th century. German texts covered such topics as planting and natural regeneration of new forests, thinning and improvement of existing stands, control of wildfires and disease, and estimates of forest growth and yield. The doctrine of sustained yield was modified to recognize a "financial maturity" of timber that would determine the optimal age at which trees should be harvested. As expressed in an early English document of 1810, "if profit is considered, every tree of every kind ought to be cut down and sold when the annual increase in value of the tree by its growth is less than the annual interest of the money it would sell for" (1).

Silvicultural Practice in North America: From Tree Farming to Ecosystem Management

The German model of forestry as it was practiced in the mid to late 19th century, with its typically European view of the cultivated (as opposed to wild) forest, and the view of forestry as a kind of "tree farming," is the model that was imported from

Germany by the first forestry leaders in America, such as Bernhard Fernow and Gifford Pinchot (see Chapter 1). This fact was to have great significance for the development of forestry in America and how it was practiced during most of the 20th century. Ironically, a more ecological view of forest management subsequently appeared in Germany, with "a recognition of the fact that the forest is not merely an aggregation of individual trees, but is an integrated, organic entity . . . from the smallest soil microbe to the age-old tree veteran" (2). However, this view appeared too late to have much influence on the founding fathers of American forestry. "Full utilization of the productive power of the Forests," wrote Pinchot, "does not take place until the land has been cut over in accordance with the rules of scientific forestry. The transformation from a wild to a cultivated forest must be brought about by the ax" (3).

Forest management in America never did develop fully in line with the Germanic model of the cultivated forest. There was a strong tradition in America of the wild and untamed "forest primeval," as well as the recreational and spiritual values of "getting back to nature." These values, along with increasing accessibility of remote wildland areas made possible by the automobile, fostered a great increase in the demands on use of forestlands for recreation, hunting, and fishing, leading to the doctrine of multiple use as the dominant policy in the management of public forests in the 20th century. Furthermore, foresters in the early 20th century were generally quite conservative in their management, with a tendency to prefer selective cutting methods over clearcutting, and favoring natural regeneration over planting whenever feasible.

Ironically, the clearcutting controversies in the 1960s and 70s boiled over in two sections of the country—the Pacific Northwest and the southern Appalachian Mountains—where selective logging had originally been tried but given up as silvicultural failures. Foresters then found that clearcutting was a more reliable way to regenerate the major species. However, several problems and controversies arose. Clearcutting often gave good regeneration and was economically efficient, but managers underestimated the potential extent of public disapproval. Rather than being blended into the terrain, clearcuts were often laid out as square or rectangular patches, and were sometimes excessive in size. Keeping with the Germanic tradition, natural mixed forests were often replaced by plantations of a single valuable species, such as Douglas fir in the Pacific Northwest. Finally, although the Forest Service was conducting research on management of nongame and endangered species, and this knowledge was gradually being incorporated into management plans, these changes did not satisfy those who sought more comprehensive protection for overall biological diversity.

These concerns have prompted the latest major paradigm shift in silvicultural practice on public lands. This new philosophy is generally known as *ecosystem management.* The purpose of forest ecosystem management is to manage forests in such a way that safeguards the ecological sustainability, biological diversity, and productivity of the landscape (4). The U.S. Forest Service made a commitment to using an ecosystem management approach in 1992.

Compared to the older management philosophy of sustained timber yield, ecosystem management recognizes that true long-term sustainability can be assured only if the integrity of natural ecological processes—ranging from nutrient cycling to predator-prey relations—are maintained. It is a holistic approach that evaluates sustainability of all ecosystem components over larger spatial scales and over longer time frames than traditional timber management. Unlike the traditional multiple-use philosophy, where wildlife management focused primarily on game species or on individual endangered species, ecosystem management seeks to maintain viable populations of all native and desirable non-native species, including such groups as herbaceous plants, lichens, fungi, amphibians, and arthropods. Silvicultural practices, when modified by ecosystem management principles, typically result in forests and landscapes that are more structurally complex than those maintained under traditional systems. More attention is given to retention of older trees, standing and fallen woody debris, soil organic matter, and other features. These are recognized as being important for maintaining ecosystem health and species diversity, but represent a departure from more economically driven approaches to forest management (5, 6).

Ecosystem management is considered to be a "work in progress," and therefore is under continual revision as new evidence and past experience suggest desirable changes. Managers and scientists will never have full knowledge of the forest ecosystem and management effects, but must proceed cautiously with the best evidence available. Shutting down forest management entirely on federal lands, as favored by some groups, would simply shift the burden of timber production to many less developed countries where few environmental regulations exist and where ecosystems are much less resilient.

Natural Disturbance Patterns: A Blueprint for Ecosystem Management

Even as early as 1905, Gifford Pinchot wrote that silvicultural treatments "are based on the nature of the forest itself, and are chiefly imitations of what men have seen happen in the forest without their help" (7). Ecosystem management has strengthened this principle. Harvest practices are most likely to maintain ecosystem health and species diversity if these practices mimic the patterns of natural disturbance to which organisms are locally adapted.

Natural disturbance regimes can be defined as the size, frequency, intensity, and pattern of natural disturbances in a region. Natural disturbance regimes are highly variable among geographic regions because of differences in precipitation patterns, vegetation, soils, landforms, and storm frequency. Large variations may exist even within a region that has high environmental heterogeneity. However, three common patterns can serve to illustrate the impact of disturbance regimes on forest development.

Frequent High-intensity Disturbance

To many people, forests have an aura of timelessness and permanence. However, this appearance of stability, caused by the relatively long lifespans of trees compared to humans, is deceptive. "Forests appear stable because people who admire them die," quipped one ecologist. Disturbances such as fires, hurricanes, tornadoes, insect epidemics, and even ice storms and thunderstorms routinely demolish forest canopies over thousands of hectares (Figure 13.1). U.S. land surveyors traversing vast expanses of virgin forest in the 19th century encountered thousands of extensive windfalls in which the trees were "broken and blown in every direction" (8). Catastrophic disturbances are common in nearly all temperate forest regions, but in some regions they are clearly the dominant force shaping the character of the forest landscape. Prior to the onset of fire suppression in the 20th century, large crown fires (see Chapter 18) were so common in the vast boreal forest of Canada and Alaska that the time interval between stand-killing fires was only about 50 years on average, known as the *natural fire rotation* (9). In Douglas fir forests of the Pacific Northwest, natural fire rotations ranged from about 150-400 years depending on local environmental conditions (10). Forests developing after catastrophic disturbance are said to be even-aged, because all of the trees germinated over a relatively short span of time and are approximately the same age.

Forests in regions that experience frequent crown fires tend to have three characteristics important to silvicultural practice. First, they are usually dominated by early successional species such as pines, birch, aspen, or Douglas fir. These species are adapted to disturbance and in most situations are dependent on it. Seedlings of these species normally develop well only on open sites where the previous stand has been killed by fire, partly because the small seeds require contact with exposed mineral soil, and partly because the seedlings cannot tolerate dense shade. Second, the presettlement landscape in such regions was often a coarse

Figure 13.1 An example of widespread forest destruction by natural disturbance. This photo shows pine forest in South Carolina blown down by Hurricane Hugo in 1989. This hurricane cut a wide swath across the center of the state, causing heavy damage on 500,000 hectares (1.2 million acres) of forestland. (Photo by R. M. Sheffield, U.S.D.A. Forest Service).

mosaic of large even-aged patches of different ages, with each patch dating to some past fire event (Figure 13.2). This pattern is the natural prototype for even-aged forests managed for sustained yield. Because the interval between fires was usually shorter than the maximum lifespan of the trees, succession often did not have a chance to proceed to the theoretical climax stage of shade-tolerant species. A third feature of these regions is that many animal species are also adapted to periodic severe disturbances and depend on them for suitable habitat.

Diffuse Small-scale Disturbance

In areas with fine-textured soils and a moist climate year-round, fires may be relatively uncommon. Catastrophic disturbance typically does occur in these regions as well, but intervals between such events are often long enough that trees can live out their natural lifespans. Tree mortality in these forests therefore does not usually occur synchronously in response to some cataclysmic event, but rather sporadically as scattered old trees or small patches of trees succumb to old age, wind, drought, or disease. New regeneration develops at different times and places wherever old trees die and create canopy gaps. This pattern of disturbance leads to the development of uneven-aged stands, in which several or many age classes of trees are intermixed within a small area of forest. This disturbance pattern is the natural prototype for uneven-aged management or the selection silvicultural system.

Because of the long intervals between catastrophic disturbance and the small sizes of canopy gaps, this type of disturbance regime favors the development of late-successional, shade-tolerant species. Examples include the beech-maple forests of eastern North America, Japan, and central Europe, and the spruce-fir forests of many high mountain ranges. These species germinate readily on the shaded forest floor, and grow slowly for long periods beneath the forest canopy until a canopy gap occurs.

Frequent Low-intensity Fire

The presettlement forest in some regions was dominated by early- or midsuccessional species, such as pines or oaks, that experienced frequent light surface fires (Chapter 18). With their thick bark,

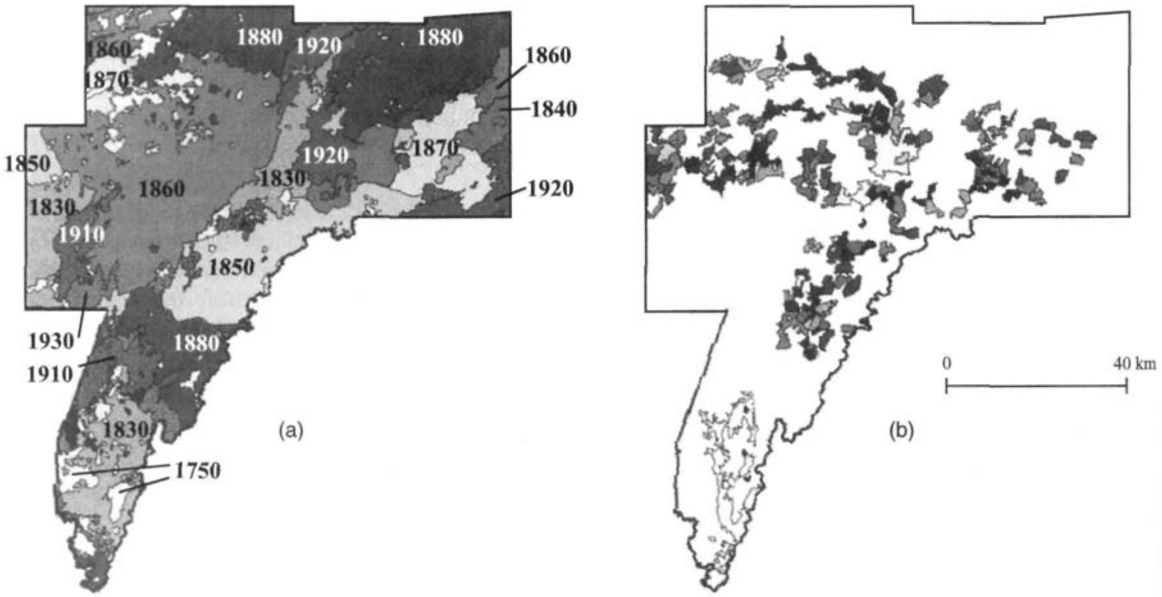


Figure 13.2 The occurrence of periodic severe fires in fire-prone ecosystems leads to a coarse mosaic of large even-aged stands on the landscape. Map (a) shows the mosaic of stands created by wildfire since 1750 in boreal forest of Ontario. Map (b) shows a much finer-grained mosaic produced by clearcuts since the 1930s. (Courtesy of Dan Welsh, Natural Resources Canada.)

these species were usually able to survive these fires, but much of the undergrowth was top-killed or eliminated, leading to relatively open stands of mature trees that were sometimes even-aged and sometimes uneven-aged.

This fire regime created a partial canopy of mature trees that provided a dependable source of seed, a favorable seedbed for early- and midsuccessional species, and partial shade to protect the young seedlings from dessication. Invasion of stands by the more shade-tolerant, fire-sensitive species was hindered, however, by the periodic fires. Good examples of forests with this type of disturbance regime were the longleaf pine savannas of the southeastern U.S., the ponderosa pine savannas of the southwest, and oak woodlands of eastern North America. This pattern of disturbance is the natural prototype for the shelterwood silvicultural system as well as the group selection system.

Growth and Development of Forest Stands

Differences in the mode of origin of even-aged and uneven-aged stands also lead to differences in their structure, manner of development, and value as wildlife habitat. An understanding of natural stand development is helpful in understanding and designing silvicultural treatments.

Even-aged Stands

Even-aged stands, in which all trees are approximately the same age, are generated in response to natural or human-caused disturbance that suddenly removed the previous stand. Even-aged stands are commonly classified by their stage of development, as reflected by the age or average size of the trees. These depend on species and location, but for many temperate forests we can recognize the following stages: seedling stands (1-5 years old), sapling stands (5-15 years), pole stands (15-60 years), mature stands (60-150 years), and old growth (> 150 years).

Young even-aged stands are often very dense, with thousands of trees on a hectare (2.47 acres) of land, but at stand maturity there will be space only for a few hundred trees on the same area. As individual trees become larger and older, competition becomes more severe. Crowns of the slower-growing trees become increasingly crowded and may finally be overtopped completely by adjacent, faster-growing trees shooting up around them. The stands therefore tend to show a certain amount of vertical stratification, and individual trees in even-aged stands are often classified by their relative position in the canopy. These *crown classes* (Figure 13.3) are defined as follows:

Dominant: Trees that project somewhat above the general level of the canopy, having crowns that receive direct sunlight from above and partly from the side.

Codominant: Canopy trees of average size that receive direct sunlight from above but relatively little from the sides.

Intermediate: Trees with crowns extending into the canopy layer, but crowded on all sides so that only the top of the crown receives direct sunlight.

Suppressed: Trees with crowns completely overtopped by surrounding trees so that they receive no direct sunlight except from occasional "sunflecks" that penetrate small gaps in the foliage above.

Once a tree in an even-aged stand has become suppressed, its chance of regaining a dominant position in the stand is slight, and the probability of imminent death is greatly increased. High mortality rates of trees in the lower crown classes result in a steep decline in the number of trees per hectare until the stand matures. In 40 years, the number of trees might be reduced by 50 to 60 percent or more. This natural decrease in numbers of trees in even-aged stands because of competition is known as the *self-thinning process* (Figure 13.4). Older stands tend to be more open and spacious as a result of the natural self-thinning process.

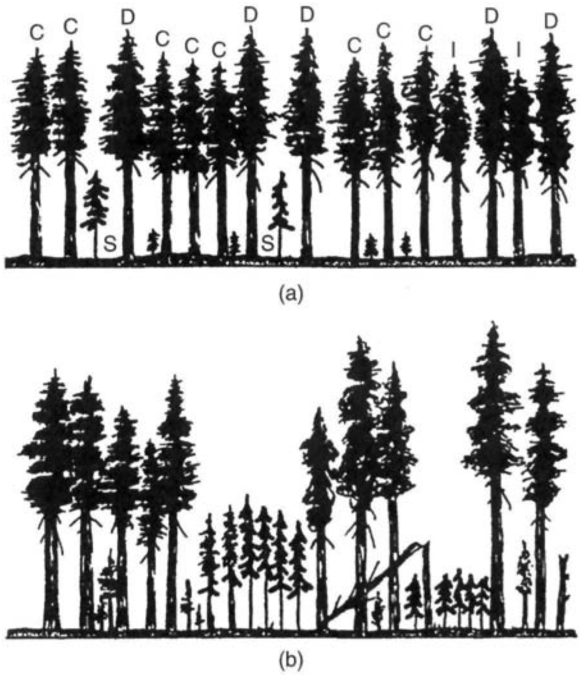


Figure 13.3 Diagrammatic profiles of an even-aged and uneven-aged forest stand, (a) Mature even-aged stand showing the various crown classes. (D = dominant, C = codominant, I = intermediate, S = suppressed.) (b) Mature uneven-aged stand. Note the irregular profile and the small openings in various stages of regrowth.

Trees vary in growth rates throughout their lifespan, often reaching a peak growth rate in early maturity and then showing a gradual decline. Because trees in even-aged stands all go through these different growth phases simultaneously, the rate of wood production for the stand as a whole is also constantly changing. The stand age at which mean annual growth rate reaches a maximum is often adopted as the optimal rotation age for most efficient volume production. The most economically efficient rotation age, however, often occurs

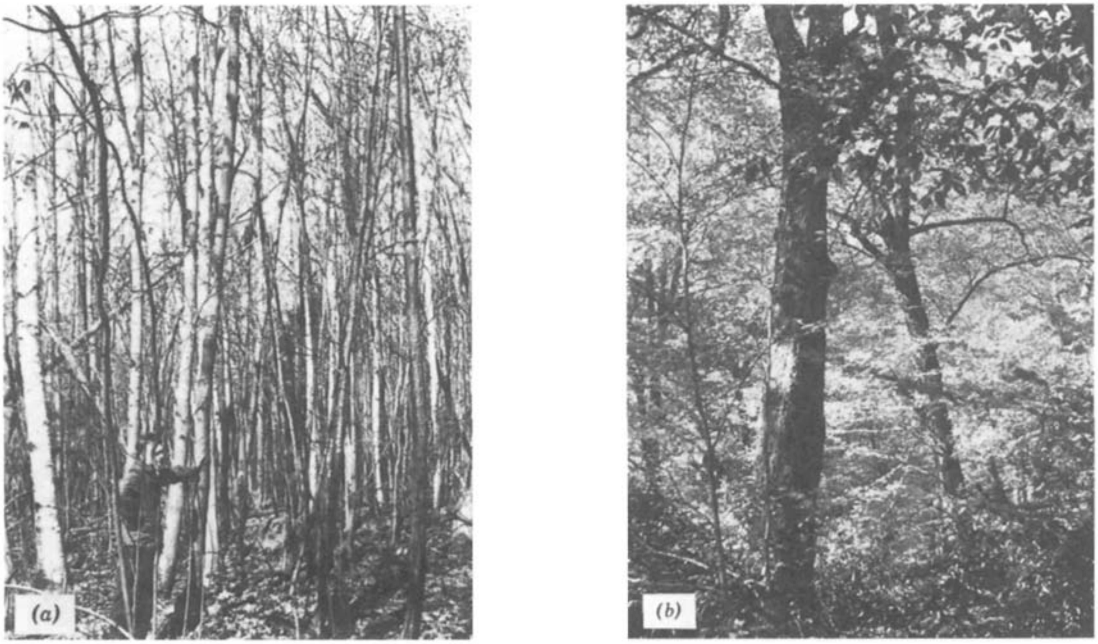


Figure 13.4 Two even-aged hardwood stands showing the reduction in stand density and increase in average tree size over time as a result of the natural competitive process, (a) A dense, young pole stand of oak, birch, and maple. (Courtesy of Harvard Forest.) (b) A spacious 250-year-old hardwood stand.

before this point. Some stands may be managed on extended rotations, far beyond the point of biological maturity, in order to maintain old-growth habitat.

Uneven-aged Stands

Uneven-aged stands are usually defined as stands in which at least three age classes are intermixed (Figure 13.3). Uneven-aged stands are often difficult to distinguish visually from mature even-aged stands without actual age determinations. However, the most reliable visible characteristic of uneven-aged stands is a patchy and irregular canopy of uneven height, with many canopy gaps in various stages of regrowth. That is, some of the canopy gaps will be dominated by seedlings, others by tall saplings, and others by clusters of pole trees (Figure 13.3b). This variation in canopy height and tree size is beneficial to some species of animals, especially songbirds.

If an uneven-aged stand contains many age classes, and each age class occupies an equal proportion of the stand, it is said to be a *balanced all-aged stand.* An interesting feature of balanced stands is that the volume of wood production is approximately constant from decade to decade, unlike even-aged stands where the volume production is constantly changing. In principle, this means that if scattered individual trees are harvested in a way to maintain the balance of age classes, uneven-aged management can provide a constant and perpetual supply of timber from a single stand. While this feature is not of great importance on large landholdings, where only the yield of the entire property is normally of interest, it can be an attractive feature of uneven-aged stands for small landowners.

Pure Versus Mixed Stands

The relative merits of pure versus mixed stands have long been a subject of controversy. Increasing worldwide demand for paper has spurred the establishment of many conifer stands in which a single species has been planted in rows (Figure 13.5). These are frequently unpopular with the general public because the stands look artificial, and perhaps because they suggest that a forest ecosystem is considered by the owners or managers to be nothing more than a crop of trees to be planted in rows and harvested like corn. More importantly, plantation monocultures often have rather low biological diversity. These can be legitimate concerns if plantation monocultures occupy a large proportion of a regional landscape.

Figure 13.5 Tree plantations are often established in rows to reduce costs and simplify management. Although plantations usually have lower biological diversity than natural stands, their greater productivity can help reduce management pressures on natural forests elsewhere.

The establishment of plantation monocultures on public land has greatly decreased in some countries such as the United States, Canada, and Britain in recent years in response to these concerns. However, there are also some countervailing arguments that would suggest that the environmentally optimal solution is not necessarily to discontinue intensive plantation management altogether. Intensively managed plantations can usually produce much more wood fiber in shorter periods of time than natural forests. Some conservationists have recognized that the higher wood yield on these plantations can have the effect of reducing management pressure on natural forests elsewhere. In effect, a certain proportion of the land is dedicated to highly efficient fiber production in the same way that we designate certain lands for agricultural use.

The species diversity issue is also more complicated than it may appear. Natural forest stands strongly dominated by a single tree species are very common in temperate regions of the world. Examples are the nearly pure stands of Douglas fir, lodgepole pine, jack pine, aspen, or black spruce that often spring up after natural fires. And despite their generally lower plant and animal diversity, forest plantations still have greater biodiversity and lower environmental impacts than the other intensive human land uses such as urban/suburban development and agriculture. A study of bird use of conifer plantations in Wisconsin, for example, revealed that they were utilized by 50 species of breeding birds, not markedly lower than the 60 species found in the surrounding natural hardwood forests (11).

Treatments to Improve Existing Stands

Silvicultural treatments applied between the time of establishment and time of harvest are called *intermediate treatments.* The purpose of intermediate treatments is to improve species composition, growth rates, and tree quality.

Intermediate treatments might or might not generate immediate revenue. Thinning a pole stand can often be done at a profit, since the trees cut may be marketable as pulpwood. However, in some intermediate treatments, no products are removed from the stand (as in pruning or fertilization), or else the trees being cut are too small or too poor in quality to have monetary value. Such treatments are considered noncommercial, and are done with the expectation that this investment in the stand will pay off later in the form of increased value of the final harvest.

Controlling the species composition of trees can have some implications for biodiversity, but this varies with forest type and intensity of practice. Sometimes, discrimination against "weedy" species such as red maple, blackgum, or scrub oaks can actually result in a forest type that more closely resembles fire-maintained forests in presettlement times. However, aggressive attempts to favor a single valuable species are less common now than in previous decades. Recent policy on public lands has recognized the need to maintain natural species mixtures, even if some low-value species are represented.

Release Treatments

Treatments to improve species composition in mixed stands are best done when the trees to be favored are still fairly young (not beyond the pole stage) and still capable of responding to release from competition. *Release treatments* are performed to free desirable seedlings or saplings from trees of competing species that have already suppressed the crop trees or are likely to do so in the near future. Release treatments are often needed to ensure successful establishment of conifer stands, since hardwood species often grow much faster than conifers at young ages. Without intervention, many conifer plantations would be crowded out by aggressive hardwoods, or development would be delayed for decades by shrub dominance.

Release treatments often require the use of herbicides, because most hardwood and shrub species resprout vigorously when the stem is cut, often regaining their former height in just a few years because of their well-developed root systems. If the competitor stems are not too numerous, herbicides can be injected in individual stems or applied to cut stumps. Otherwise, herbicides can be applied as a spray treatment from the ground, or sometimes from the air.

Improvement Cuts

Improvement cuts are treatments in pole or mature stands that remove defective, diseased, poorly formed trees, and other trees of low value. Improvement cuts differ from release treatments in that they are done in older stands, and the crop trees are often in the main canopy and not in danger of becoming suppressed. Removal of poor quality trees frees up growing space for the more desirable trees and sometimes stimulates the development of new saplings in gaps. Improvement cuts are especially important in stands that have had a long history of exploitative logging in which only the best trees were removed. Improvement cuts are therefore a valuable silvicultural tool in restoring the ecological integrity of degraded stands.

On public lands, foresters must take care not to eliminate all poor quality trees because these trees may contain cavities used by birds and mammals, and may be more suitable substrate for lichens and fungi than straight, vigorous crop trees. Both ecologically and economically, it makes sense to remove only the undesirable trees that are clearly interfering with promising crop trees that will be carried to the end of a rotation.

Thinnings

Thinnings are treatments that reduce stand density in order to accelerate the growth of the remaining trees. Trees to be cut are typically of the same species and age class as those that remain.

Thinning does not usually increase the total amount of wood produced by a forest, and may even cause a modest decrease. However, since the available light, water, and nutrients are being used by fewer trees, the remaining trees become larger than they otherwise would have been. This is the principal benefit of thinning, for large trees are more valuable than an equal volume of small trees. At the same time, less vigorous trees that would probably die anyway from competition can be salvaged for usable material. The eventual result of thinning is a more open, spacious stand of larger trees. Thus, thinning basically hastens the natural outcome of competition in even-aged stands and is a good example of how silvicultural techniques often have natural counterparts.

Several different methods of thinning are possible, but it is useful to recognize three basic approaches. In *low thinning* or "thinning from below," the trees to be cut are mostly from the lower and middle crown classes. A light low thinning would remove only suppressed and intermediate trees, while a heavier low thinning would remove some codominants as well (Figure 13.6). A heavier low thinning is usually more desirable because dominant crop trees often do not show any measurable growth response to the removal of suppressed trees. Generally, a growth increase can occur only if gaps are made in the canopy so that adjacent trees can expand their crowns and increase their total exposed leaf surface area. Low thinning is the method that most closely mimics the natural self-thinning process, but some suppressed and defective trees should be purposely retained for use by birds and other organisms.

In *high thinning* or "thinning from above," the primary objective is to create sufficient numbers of small gaps in the canopy to stimulate the growth of the better crop trees. In most cases, this will involve removing intermediate and codominant trees of smaller size or poorer quality to favor the growth of the better dominant and codominant trees. Note that a high thinning may resemble a heavy low thinning in certain respects, but the difference is that suppressed trees are not ordinarily removed in a high thinning. For this reason, a high-thinned stand may not have as much of a spacious, park-like appearance as a stand that has had a heavy low thinning.

Figure 13.6 (a) Before and (b) two years after moderately heavy low thinning and pruning in a twenty-five year old pine plantation, About 35% of the stand basal area was removed. Nearly all the dominant trees remain, but most of the suppressed and intermediate trees were cut, along with 40% of the codominants. In addition to accelerating the growth of the remaining trees, thinning has an immediate effect of creating a more open and spacious forest.

In the third basic approach, *mechanical thinning*, all trees are removed in rows or strips without regard to crown class. The greatest response therefore comes from trees whose crowns are adjacent to the cleared strip. This method is relatively quick and inexpensive and can be easily done in plantations by mechanical tree fellers, but individual tree growth is not likely to be as good as in other methods. In plantations, mechanical thinning is often accomplished simply by removing every second or third row of trees (Figure 13.5).

Although a single thinning will usually increase growth rates and upgrade the overall stand quality, such improvements are likely to be short-lived, since continued growth and competition will again render the stand crowded, usually within a decade or two. For this reason, managed stands are usually thinned at periodic intervals, such as once every 10-15 years.

In addition to increasing timber value, thinning also usually improves biological diversity by creating canopy gaps and down woody debris, and encouraging the development of understory vegetation. Thinning improves aesthetics as well, by reducing the extremely high stem density, improving visibility, and creating a more park-like appearance with larger and more widely-spaced trees. Private landowners who value their forests primarily for recreation or wildlife are often understandably reluctant to have any cutting done on their property, but careful thinning can actually hasten the development of a forest of large stately trees, such as shown in Figure 13.4b. In fact, thinning has great potential value as a tool of restoration ecology for hastening the development of old-growth structural features in younger stands, especially in regions of the world where old growth is rare. One study indicated that thinning in 80-year-old maple stands could reduce the additional time needed for trees to reach the size of old-growth canopy trees from 90 to 45 years (12).

Fertilization

Another method that can be used to stimulate growth rates of trees is fertilization of the soil. Fertilization is apt to be most successful in areas where the soils are known to contain specific nutrient deficiencies. In North America, for example, nitrogen deficiencies are common in the Douglas fir region and in boreal spruce-fir forests, whereas phosphorus is in short supply in many southeastern soils. Standard fertilizer applications may result in 15 to 100 percent increases in growth rate, which often make it an economically attractive operation. However, a decision to fertilize should be weighed carefully. Fertilizers are energy-expensive to produce and usually result in only a temporary increase in site productivity. Some forest types, moreover, show little or no response to fertilization.

Pruning

In a dense forest, lower branches of trees growing in deep shade eventually die and fall off. In some species, however, dead branch stubs may persist for decades. New wood grows around the base of the stub, producing blackened "dead knots" that reduce the strength of the lumber and may fall out when the lumber is dried. To avoid dead knots and produce clear lumber, artificial pruning of dead branches is sometimes done with pruning saws or other equipment. Clear lumber is produced once the new growth covers the cut stub.

Pruning is an expensive operation and is usually economically justified only for select crop trees of high value species. When pruning is done, it is usually limited to the best trees in a stand and limited to a height of about 17 feet.

Salvage Cuts

Salvage operations remove trees that have been killed or weakened by insects, disease, fire, drought, ice storms, wind, and other natural disturbance agents. When losses are minor, salvage cuts may be conducted as part of a thinning or improvement cut. When mortality is heavy, however, the salvage cut may have to be a final harvest operation in which most of the original stand is removed and a new stand regenerated by even-aged methods (see Figure 13.9 in section on clearcutting).

Regeneration of Forest Stands

A principal goal in silviculture is to ensure that when a stand is harvested, most mature trees removed are replaced by vigorous seedlings or saplings of desirable species. If a person is lucky, this might occur without any special effort. However, successful regeneration usually requires careful "up-front" planning. Foresters commonly have several criteria that need to be met for successful stand regeneration:

1. The condition of the ground or seedbed must be suitable for seedling germination and growth. Seedlings of many species—especially those that

are fire-adapted—have difficulty in penetrating the thick mat of leaves and partly decomposed organic matter present in most forests. Reduction of this layer by fire or mechanical means is often needed for adequate seedling establishment.

2. Openings created by tree harvest must be large enough to provide sufficient light and moisture for long-term seedling survival. Minimum acceptable opening size varies among tree species and is smallest for shade-tolerant species and largest for the very intolerant species.
3. Seedlings must initially be established in sufficient numbers to provide for a well-stocked forest, but not too dense to inhibit individual tree growth. A moderate density is usually ideal as it promotes self-pruning and good tree form. Tree seedlings should also be well-distributed to avoid large unstocked areas, although sometimes delayed occupancy by trees is desirable for biodiversity reasons.
4. Competition with other trees and shrubs already on the site is frequently severe, and often needs to be controlled to ensure the success of desired species.
5. Quality of the seed source must be considered to ensure desirable genotypes. With natural regeneration, this usually involves retention of high-quality mature seed trees. With artificial regeneration, foresters need to know the location of the original seed source and its compatibility with the environment of the site to be reforested.

If these principles are not understood or are ignored, the harvest operation may have much the same effect as exploitive logging.

The Role of Site Preparation

Site preparation is treatment of the residual vegetation and ground surface to improve the chances of successful seedling establishment. Site preparation is often done prior to natural seeding treatments as well as before planting. The three main objectives of site preparation are 1) to reduce competition from residual vegetation, 2) to reduce the fire hazard and physical obstacles to planting by chopping or burning some of the treetops and woody debris, and 3) to prepare the seedbed by reducing the depth of the litter and duff, or creating special microsites for planted seedlings.

Site preparation can be accomplished by prescribed burning, mechanical treatments, herbicide application, or a combination of these. Equipment such as the rolling brush cutter (Figure 13.7) breaks up residual wood debris, making the site easier to plant, and tears up roots of shrubs and hardwood saplings which might otherwise overtop the planted seedlings. Other equipment such as the Bracke scarifier scalps small patches of ground to provide a suitable microsite for planting. Prescribed burning is commonly used to accomplish all three objectives of site preparation, especially on steeper slopes where use of mechanical equipment would be impractical and too likely to cause soil erosion. A very simple form of site preparation can be accomplished by having the logger drag logs across the harvested site with the skidder equipment. This causes some partial scarification and competition control.

Natural Regeneration

Natural regeneration can be a desirable way to reestablish a forest stand for several reasons. The subsequent stand will usually have a more natural appearance and spacing than a plantation, it usually maintains a greater mixture of tree species, and natural stands usually have greater biological diversity. Natural regeneration is also usually much cheaper than artificial regeneration.

The main disadvantages of natural regeneration are that it can be unreliable if all the influential factors such as seed production, weather, and seedbed conditions are not favorable, and there is less control over species composition, stand density, and genetic makeup.

There are several pathways or modes of natural regeneration in a harvested area, and so foresters relying on natural regeneration need to be aware which pathway is likely to provide the main source of young trees in each case. One pathway is germination from seed carried by wind or animals into

Sidebar 13.1

"Partial Cutting" and Forest Degradation

Small private landowners usually prefer to do "partial cutting" in their woodlots in order to retain scenic values and wildlife habitat. As commonly practiced, however, partial cutting is a major cause of forest degradation in privately owned forests around the world, leading to the formation of vast areas of "junk woodlots."

Why does this seemingly conservative practice cause so much harm? The reasons are twofold. First, unregulated partial cutting usually involves the repeated and systematic mining of only the best quality trees and most valuable species, leaving behind only low-quality trees. Many once-impressive forests of oak have been converted into junk woodlots of noncommercial species by this process. Second, the owners and loggers usually do not realize that proper seed source, light environment, and seedbed conditions must be provided to ensure regeneration of valuable species. Even if some seed trees of valuable species remain, recruitment of new trees into the canopy is practically impossible because of the dense thickets of low-value species that have been left to dominate the site.

Woodlot degradation can be avoided or reversed by having a forester develop a management plan, a service that is provided free of charge in many states and provinces. The forester will prescribe an improvement cut and competition control treatment, and can reintroduce good-quality genetic stock of the original dominant species through planting. He or she will mark with paint trees that should be removed, specifying in a contract with the timber buyer or logger that only the marked trees can be cut.

A former stand of oak on private land that has been degraded by repeated "partial cutting" of only the best quality trees and species. Although the stand retains some visual appeal, it now has little value because of dominance by defective trees and noncommercial species.

Figure 13.7 Mechanical site preparation reduces competition from advance regeneration and shrubs, and provides a more favorable seedbed for establishment of preferred species. The rolling brush cutter shown here can achieve these results without scraping away or displacing topsoil and nutrients.

the harvested area. This is generally the most unpredictable source because success is heavily dependent on the vagaries of seed production, seed dispersal, damaging insects and fungi, weather patterns, and other factors. Nonetheless, in many situations, foresters have to rely entirely on seed dissemination after the harvest because other options are not present. Success is increased by timing the harvest to coincide with a good seed year and paying careful attention to seedbed conditions and competition control.

Another source of natural regeneration is seedlings or saplings already in the forest understory that survive the harvest operation and continue to grow. These seedlings and saplings are collectively called *advance regeneration.* This is often the principal source of regeneration in the selection silvicultural system. Advance regeneration is not always abundant in forest stands, especially on drier sites, and is often composed primarily of shade-tolerant species. However, when present and of desirable species, it is one of the more reliable sources of natural regeneration.

Some tree species will resprout from dormant buds on the stumps or roots after cutting. Sprouting is rare among conifer species, but is a common and dependable source of natural regeneration among certain hardwoods. Sprouting often causes multiple stems to develop from a single parent tree, which is not always desirable, but sprouts of certain species such as aspen and oak are commercially acceptable (Figure 13.8).

Finally, a few species of trees may regenerate from seed stored in the forest floor. This is not a common trait among commercially valuable species, but a few such as ash and yellow poplar may regenerate partly by this pathway.

Artificial Regeneration

Artificial regeneration can be accomplished either by directly applying seeds to a harvested site or by planting nursery-grown seedlings. Planting gives the forester greater control over stand establishment and growth than artificial dispersal of seeds, but both methods have the following advantages over natural regeneration:

1. Stand establishment may be more reliable because it does not depend on the occurrence of a good seed year or the distance to which seeds are dispersed by wind. If large clearcuts are made, artificial regeneration is often necessary to ensure adequate regeneration on the central portion.

Figure 13.8 Dense vegetative regeneration of aspen from root sprouts one year after clearcutting.

2. Artificial regeneration increases the chances of prompt reforestation. This issue is most important to forest industries, because long delays in reforestation can reduce financial viability of their operations.
3. There is greater control over species composition. Among forest industries that must maximize fiber production on a limited area of land, planting of the single most productive and valuable species adapted to the site is often considered the most economically efficient alternative.
4. There is greater control over tree spacing and subsequent growth. Plantations are often established in rows at a predetermined spacing to optimize stand growth, reduce variability in growth rates, and allow easier access for mechanized equipment (Figure 13.5).
5. Seeds or seedlings can be derived from genetically superior trees.

Direct Seeding Artificial dispersal of tree seed is known as *direct seeding.* It may be accomplished on the ground by hand or machine, or from the air by helicopter or fixed-wing aircraft. Direct seeding is usually cheaper than planting, but it offers less control over spacing and usually has a lower success rate. As a minimal precaution, seeds may be treated with chemical repellents to reduce pilferage by rodents and birds. Germination and survival of seedlings tend to be considerably better on sites with some exposed mineral soil than on sites with a thick covering of litter or logging debris.

Despite its limitations, direct seeding from the air can be very useful when extensive areas must be reforested quickly, as would be the case following a large forest fire. Direct seeding is also useful on steep, irregular terrain where planting by machine would be impossible and hand planting would be difficult.

Planting High survival rates of planted seedlings and the convenience of managing row plantations has led to a great increase in plantation establishment in recent years, particularly among paper companies. Most seedlings intended for outplanting in harvested areas are grown in either large outdoor nurseries or greenhouses. Seedlings may be lifted from the beds and packaged in a bare-root condition or they may be grown in individual containers with a specially prepared potting medium. These containerized seedlings are more expensive to grow than bare-root stock, but the root systems are less likely to be damaged during the lifting and transporting process, and better survival of planted seedlings results in some cases.

Planting is often done in the spring season when soil moisture is high and root growth is most active, but it is possible at other times depending on geographic location. If the site to be planted is extensive, fairly level, and not excessively rocky, planting can be done most quickly and cheaply with mechanized equipment. Otherwise the traditional method of hand-planting crews may be used.

Despite the higher success rate of plantations compared to direct seeding, failures and losses sometimes do occur. Mice and other rodents may cause the loss of many seedlings, especially in grassy areas, and browsing by deer and other large herbivores can be a problem. Planted seedlings may face stiff competition from shrubs and stump sprouts of other trees, which may necessitate application of herbicides. Furthermore, harsh microclimates on some sites may lead to planting failures, particularly on steep slopes facing south.

Planting often represents a sizable proportion of the total cash investment in a forest stand. The cost of the seedlings reflects the expense of nursery establishment and maintenance. The planting operation itself is a fairly labor-intensive operation, and to this must be added the costs of site preparation and other measures taken to enhance planting success. For these reasons, planting is likely to be done primarily where the increased cost can be justified economically by increased returns, where natural regeneration has a low probability of success, and in cases where the funds for plantation investment are available.

Silvicultural Systems

Silvicultural systems are long-range harvest and management schemes designed to optimize the growth, regeneration, and administrative management of forest stands, usually with the goal of obtaining a perpetual and steady supply of timber. The use of silvicultural systems involves making a comprehensive prescription of stand treatments throughout the life of the stand, including the method of harvest, an evaluation of whether or not site preparation is necessary, the use of seeding, planting, or natural regeneration, and a schedule of intermediate stand treatments (Table 13.1). Silvicultural systems are generally classified by the method used to harvest and regenerate the stand. These methods vary in cutting intensity but they may readily be grouped under the categories of even-aged, two-aged, and uneven-aged methods.

Even-aged Methods

In even-aged management the trees are harvested over a relatively short period of time, creating open, sunny conditions, and leading to the development of even-aged stands. Many species can be managed by even-aged methods, and for certain species intolerant of shade the even-aged methods may be almost mandatory, since adequate regeneration would not occur under lightly cut stands. The even-aged methods are *clearcutting, seed tree,* and *shelterwood.* They differ primarily in the span of time over which the original canopy is removed.

Clearcutting Method **In** *clearcutting,* all trees on the harvest unit are felled over a short period of time. Clearcutting is appropriate in forest types in which the dominant species are intolerant of shade and dependent upon severe disturbances such as crown fire for their perpetuation. Regeneration by the clearcutting method is accomplished by natural seeding, direct seeding, or planting. If reliance is placed on natural seeding, the feasible clearcut width is limited by the effective dispersal distance of the seeds. For most conifer species, the effective dispersal distance is only about five or six times the height of the mature border trees, or a distance of about 150-230 meters (500-750 feet). For this reason, clearcuts that rely on natural seeding are usually restricted to fairly small patches or long strips. Sometimes a forester can rely on advance regeneration or stump sprouts to provide most of the regeneration after clearcutting, in which case larger harvest units are feasible. However, advance regeneration is uncommon among the early successional species normally managed by clearcutting, and many commercial species either do not sprout at all or have a low frequency of sprouting among mature trees. Because of these limitations with natural regeneration, clearcutting is often followed by planting (Figure 13.9).

While clearcutting mimics severe natural disturbance in some ways, some scientists have noted

Table 13.1 Silvicultural Information for Some Major Forest Types of North America

Forest Type	Tolerance[a] (Major Species)	Successional Status	Growth Rate	Current Commercial Value	Methods of Regeneration[b]	Ease of Regeneration[c]
Western						
Douglas-fir	Inter	Variable (site-dependent)[d]	Rapid	High	C, SH (SP, P)	M
Hemlock-Sitka spruce	Tol	Climax	Mod-rapid	High	SH, C, GS, S	E
Coast redwood	Tol	Climax	Rapid	High	GS, C, SH, S (SP)	E
Ponderosa pine	Intol	Variable'[1]	Mod	Mod-high	SH, GS, S, ST, C (SP, P)	M-D
Western larch	Intol	Successional	Rapid	Mod	ST, C, SH (SP)	E-M
Engelmann spruce-fir	Tol	Climax	Slow-mod	Mod	GS, S, SH, C (SP)	M
Lodgepole pine	Intol	Successional	Mod	Low	C, SH	E
Eastern						
Spruce-fir	Tol	Climax	Slow-mod	Mod	GS, S, SH, C	E-M
White pine	Inter	Successional	Rapid	Mod	SH, GS (SP)	M-D
Jack pine	Intol	Successional	Rapid	Mod	C, ST, SH (SP)	M
Red pine	Intol	Successional	Rapid	Mod	C, SH (SP, P)	D (Nat), M (Art)
Northern hardwoods	Tol	Climax	Slow-	Mod	S, GS, SH	E
Aspen-birch	Intol	Successional	Rapid	Low-mod	C (SP)	E
Oak-hickory	Inter-Intol	Variable[d]	Rapid	Mod-high	SH, GS, C (SP, P)	M-D
Southern pines	Intol	Successional	Rapid	High	C, ST, GS (SP, P)	M

[a] Abbreviations: Tol = tolerant; Inter = intermediate, Intol = intolerant

[b] Abbreviations: C = clearcutting; SH - shelterwood; ST = seed tree; GS = group selection; S = individual-tree selection; (SP, P) site preparation and planting may be necessary

[c] Abbreviations: E = easy; M = moderate; D = difficult; Nat = natural; Art = artificial

[d] Forest types with a "variable" successional status are generally successional on moist or average sites and climax on dry sites.

that forest fires, windstorms, insect epidemics, and similar disturbances are often quite patchy in their occurrence, with scattered surviving trees and clumps of trees. Also, the logs and standing dead trees remain on the site. All these features help mitigate the impact of disturbance on animal and plant species that prefer late successional forests by providing refugia for these species and a source for recolonization of the disturbed site when conditions permit. Persistence of dead wood on the site is also beneficial for maintaining site fertility. For these reasons, ecosystem management guidelines for clearcuts on public lands frequently involve retaining scattered "green trees," patches of uncut trees, snags, and fallen logs to help maintain biodiversity and productivity (Figure 13.10).

Seed-tree Method Other even-aged methods are designed to overcome some of the problems inherent in clearcutting with natural regeneration. In the *seed-tree* method, scattered mature trees are left on the site to serve as a seed source for the new stand and to provide a more uniform dispersal of seed. Although this may seem like a good solution to the

Figure 13.9 Clearcutting is sometimes done to salvage trees killed in an insect or disease epidemic. Much of the mature pine in this stand had been killed by an outbreak of the jack pine budworm. This photo was taken several years after the replanting of red and jack pine.

problem of seed dispersal, and some state laws used to mandate retention of a certain number of seed trees after harvesting, experience has shown that the seed-tree method may be unsuccessful in many situations. Sometimes the site becomes rapidly invaded by shrubs, and so few of the seeds dispersed by the seed trees actually germinate and survive. In some cases, as with oaks, newly germinating seedlings grow too slowly to compete with advance regeneration and sprouts of other species. The seed-tree method also does not work well with shallow-rooted species, since many of the seed trees will be blown down by wind. The seed-tree method is best suited to situations in which intensive site preparation is feasible and the species are reasonably wind-firm. Western larch and the southern pines are examples of species well suited to the seed-tree method.

Shelterwood Method Seed trees are also retained in the *shelterwood method,* but in this case sufficient numbers are left standing to provide some shade and protection for the new seedlings (Figure 13.11). In the most common variant of the shelterwood method, the first major cut leaves a temporary partial overstory in which percentage of ground surface shaded by tree crowns may vary from 30 to 80 percent, depending on species and local conditions (Figure 13-11b). Once the seedlings are firmly established, after several years, the residual trees are usually removed so that they do not retard the growth of the new saplings (Figure 13.11c).

The shelterwood method is ideal for any species or site where seedlings are not expected to germinate well under open conditions. Even some of the more intolerant species may benefit from the protection of a shelterwood overstory during the first few years when seedlings are vulnerable to desiccation; this is especially true on harsh sites. For example, the shelterwood method has been applied successfully on sites in California and Oregon where clearcutting had failed (13, 14). The shelterwood method also has the least visual impact of any even-aged method, since by the time the last of the residual overstory trees are removed, the new stand is already sapling-sized. It therefore bypasses the typically devastated look of recent clearcuts. In many situations, it probably reduces erosion hazard and nutrient loss as well.

Although the shelterwood method bears a superficial resemblance to heavy partial cutting in

Figure 13.10 On many public forests, scattered mature trees, snags, and logs are retained on clearcut sites to help maintain biological diversity and provide a more complex forest structure, as in this stand in the Pacific Northwest. (Courtesy of U.S.D.A. Forest Service.)

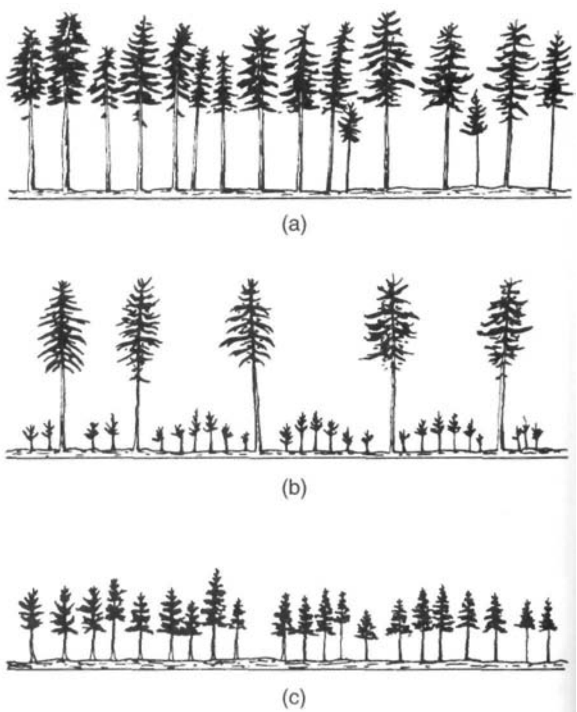


Figure 13.11 An illustration of the shelterwood method to regenerate an even-aged forest. (a) The mature stand prior to treatment. (b) The first major harvest leaves a temporary shelterwood overstory to provide seed trees, partial shade, and a scarified seedbed. (c) After saplings of the desired species are well established, the shelterwood overstory is removed to release a new even-aged sapling stand.

unmanaged forest (see figure in Sidebar 13.1), there are important differences. In the establishment phase of a shelterwood cut (Figure 13.11b), the trees to be retained are among the larger and better' quality trees in the stand in order to serve as a good seed source. The overtopped, intermediate, and smaller codominants are usually removed completely. A heavy partial cutting, on the other hand, will generally accomplish just the opposite by removing many of the larger and better trees and releasing the smaller trees (which may not be of desirable species or quality). A second major difference is that after the removal cut in a shelterwood, the resulting stand is young and even-aged and composed entirely of saplings (Figure 13.11c). Such a stand will in fact differ little from a sapling stand that might have developed after a successful clearcut.

Coppice Method This method differs from all other reproduction methods in that dependence is placed on vegetative regeneration by stump sprouts or root sprouts instead of development of stands from seed. However, since coppice stands are usually harvested by clearcutting, it may be conveniently discussed with other even-aged methods. The coppice method is restricted to species that typically sprout vigorously and have sprouts capable of attaining commercial size. Good examples of such species are aspen (Figure 13.8) and oak. Coppice stands are usually managed on short rotations, and the products may be fuelwood or pulpwood. Use of the coppice method declined in developed countries in the second half of the 20th century as oil and gas became cheap and abundant fuels, but increasing demands for energy have revived some interest in coppice systems. Genetically improved species such as hybrid poplars have considerable potential as fast-growing plantations managed on short rotations.

Two-aged Management

Two-aged management is a practice developed recently as a more aesthetically acceptable alternative to clearcutting in stands of shade-intolerant species. The initial harvest in a two-aged system leaves scattered mature trees, perhaps about 15 percent of the original stand, similar to the density of trees on a seed-tree cut (Figure 13.12). Unlike a seed-tree cut, however, the mature trees are not removed once the regeneration is established, but are carried to the end of the next rotation. During this time, a two-aged stand is produced. When the younger age class is mature, the older cohort and much of the younger cohort are harvested, setting in motion another two-aged forest.

Two-aged management is designed to provide sufficient light for successful regeneration of intolerant species, while retaining some tree cover to preserve scenic values. Retention of the mature trees also probably has some value for biodiversity by creating a more complex forest structure.

Uneven-aged Methods

Uneven-aged management is accomplished by the *selection method,* in which scattered trees or small groups of trees are harvested at 10—20 year intervals. This diffuse pattern of timber removal ensures that many age classes of trees will be intermixed within a matrix of mature forest (Figure 13.13). This system can be used to perpetuate uneven-aged forests that occurred in regions with diffuse natural disturbance (such as northern hardwoods) or in areas that had frequent light surface fires that maintained uneven-aged stands of intolerant species (such as ponderosa pine).

The selection method has some unique advantages. It is the only silvicultural system in which sustained yield can be obtained from a single stand of trees. Provided that cutting is not too intense, trees can be harvested in perpetuity, while the forest canopy remains largely intact with little evidence of manipulation. There is often no need for expensive site preparation or planting. As in natural uneven-aged stands, mature trees removed in the harvest are replaced by saplings already in the understory. Erosion and disturbance to the site are minimal. Fire hazard is relatively low because of the lack of extensive piles of logging debris.

There is, however, a serious limitation with the selection system. With the exception of certain fire-resistant species that can be maintained with frequent prescribed burns, the selection system typically leads to nearly complete dominance of the forest by shade-tolerant species. The opening created by the removal of a single mature tree usually does not allow enough light for adequate survival and growth of intolerant or intermediate species. The list of such species is considerable and includes some of the most economically important species such as Douglas fir, most of the pines, larches, oaks, ashes, birches, and aspens (Table 13.1). Light cutting in stands of these species will not only fail to regenerate the species in most cases, but will actually tend to hasten the conversion to whatever shade-tolerant species happen to be in the understory. For example, use of the selection system in Douglas fir causes a conversion to hemlock and cedar, and its use in oak forests often causes conversion to maples. The shade-tolerant species often have less valuable wood than the species they displace, and are also slower-growing.

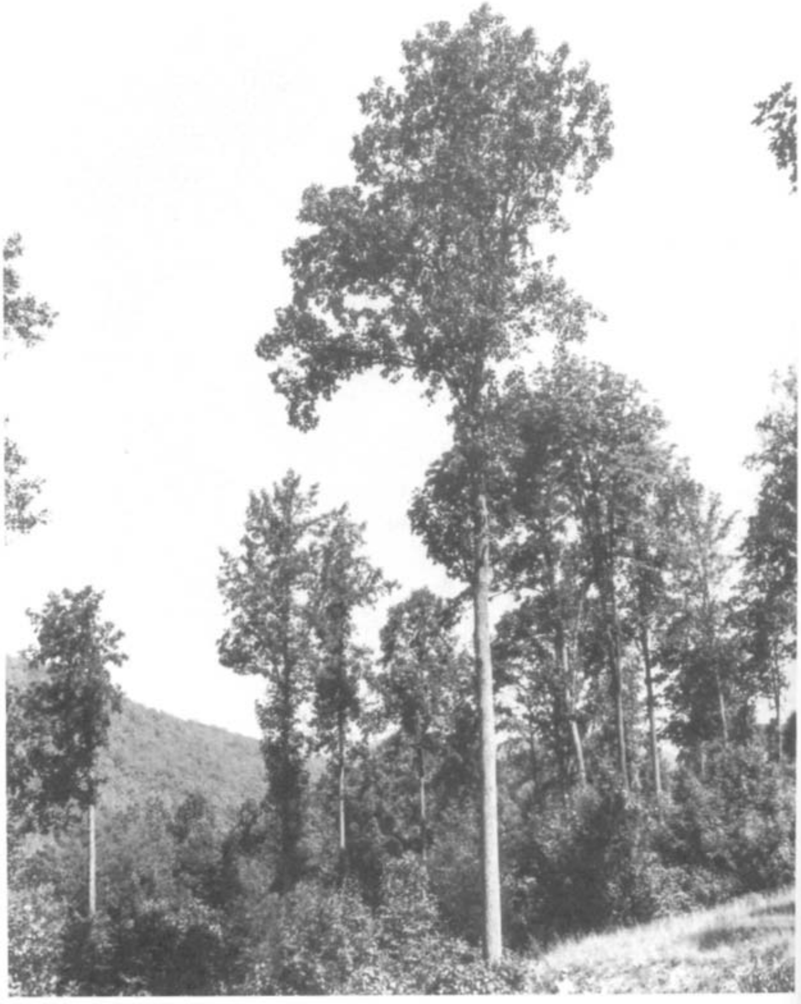


Figure 13.12 With two-aged management, scattered mature trees are retained until the end of the next rotation, helping to maintain scenic values in stands of species that otherwise require full sunlight. This photo shows two-aged management of southern Appalachian hardwoods. (U.S.D.A. Forest Service photo by R. L. Rosier.)

Other disadvantages to the selection system have been cited, but these have usually been minor or inconsistent problems. Logging costs are sometimes 20 to 30 percent higher in the selection system compared to even-aged management because logs must be skidded longer distances (15). However, for both western conifer and eastern hardwoods in North America, logging costs are often not significantly higher with the selection system when costs are expressed per unit volume harvested. This is because a greater proportion of the harvest in the selection system is contributed by large trees, which can be handled more efficiently than numerous small trees. Some authors have suggested that the selection system requires a more extensive road network than even-aged management, but it is not likely that the actual density of roads on each watershed would differ (16). Also, while selective logging can result in injury to the residual standing trees, most scientists have concluded that the problem is minor.

Some of the disadvantages of the selection system can be lessened by modification of the method of harvest. By cutting small groups of trees instead of scattered individuals, the amount of direct sunlight can be increased to the point where some

Figure 13.13 The individual-tree selection method of harvest removes scattered trees at 10-20 year intervals. Disturbance is often hardly noticeable, and old-growth features can be maintained. This example shows a hemlock-hardwood forest on the Menominee Indian Reservation in Wisconsin.

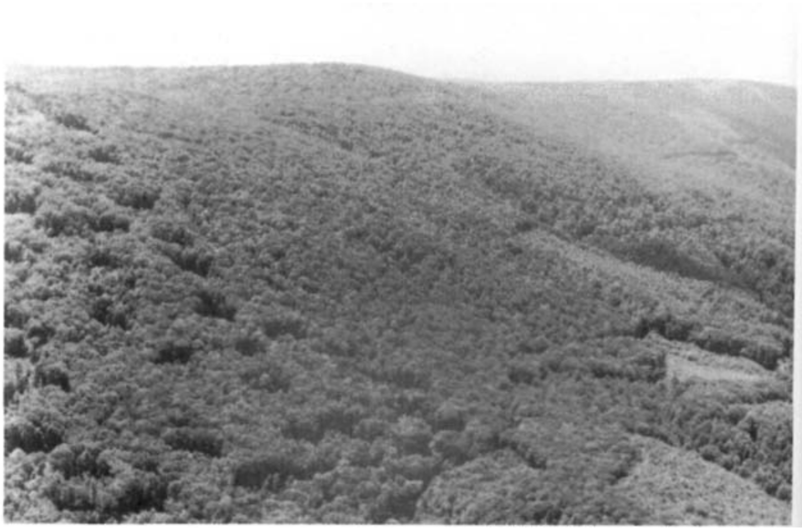
regeneration of shade-intolerant species can occur. When combined with periodic prescribed burning to control shade-tolerant competitors, this *group selection method* can be used to maintain intolerant species such as the southern pines and ponderosa pine in uneven-aged stands with comparatively small openings. Group selection is also being used in Appalachian oak forests as a more publicly acceptable alternative to clearcutting (Figure 13.14). However, the minimum opening size needed for adequate regeneration of oaks and some other species is currently uncertain. In some locations, foresters are creating group selection openings that are large enough to cause possible concerns about forest fragmentation. Especially after several consecutive entries, a patchwork of numerous large openings may become undesirable both visually as well as for certain animal species such as salamanders. Since use of group selection is likely to increase as foresters search for alternatives to clearcutting, a number of research projects have been initiated to resolve some of these issues and provide better management guidelines.

Uneven-aged management is an important and viable silvicultural system for a number of forest types—in particular, forests dominated by shade-tolerant species such as maples, hemlocks, cedars, spruces, and true firs, and a few intolerant species that can withstand periodic prescribed burning. However, in many situations it is not biologically feasible or ecologically desirable. The popular sentiment against clearcutting is so strong, however, that some legislative bills have been introduced that would virtually mandate the selection system nearly everywhere on federal lands. One environmental group drafted a platform that would seek to "end clearcutting and all its variants (i.e., all forms of even-aged management) . . . in any national forest ever." If implemented, such a provision would create extensive new landscapes of shade-tolerant species in uneven-aged stands that were virtually unknown in those regions in presettlement times and which have no natural precedent.

Silvicultural Practices and Ecosystem Integrity

Two guiding principles of ecosystem management are that current management practices should not impair or degrade the long-term productivity of the site, and they should not jeopardize the diversity

Figure 13.14 Aerial view of group selection harvests (left side of photo) in Appalachian hardwood forests. (U.S.D.A. Forest Service photo by J. N. Kochenderfer.)



and viability of native plant and animal populations. It is impossible to judge sustainability from casual visual impressions of forest management practices. However, informed assessments can be made from careful scientific measurements for each ecosystem type-

Frequently, the question of whether a management practice is sustainable depends not only on local forest type, soil conditions, and topography, but also on the intensity of the management practice. Even clearcutting, for example, can span a wide range of management intensity depending on intensity of biomass removal from the site, intensity of site preparation, and rotation length. The following sections focus mostly on clearcutting practices because they are the most intensive and controversial form of silviculture, and have been the focus of a large body of research.

Maintaining Long-term Site Productivity

Soil erosion occurs when soil is disturbed and exposed to the direct impact of rain. Although there are some exceptions, timber harvesting by itself often causes relatively little soil disturbance because the remaining litter layer and ground vegetation are effective in protecting the soil. Thus, scientists are usually more concerned about road-building and site preparation, since both activities can result in significant soil exposure. Many soil scientists agree that with proper road design and use of "low-tillage" site preparation equipment (or light prescribed burning), increases in soil loss over natural erosion rates will often be small, short-term, and within the recovery rate of the ecosystem (17, 18).

Conventional harvest also removes some nutrients in the tree boles, but on reasonably fertile sites, the amount removed is normally only a small fraction (usually <10%) of the total nutrient capital on the site. These amounts are often replaced within the span of one normal sawtimber rotation by nutrients added from precipitation, weathering of soil minerals, and nitrogen fixation.

For these reasons, conventional bole-only clearcut harvests with low intensity site preparation appear to be sustainable in many temperate forests. In the famous long-term clearcutting experiments at Hubbard Brook in New Hampshire, for example, the team of six scientists concluded: "our study indicates that if care is taken during logging, and if sawtimber rotation lengths are followed, there should not be major adverse effects on site nutrient capital, stand regeneration, or productivity. By the 10th year after harvest, hydrologic and nutrient budgets had returned nearly to preharvest levels" (17). Even in the highly erodible and relatively infertile Piedmont soils of the southeastern United States, a soil scientist concluded after careful monitoring that "none of the effects of clearcutting, double roller-chopping, and machine planting appear serious enough to call for special regulation . . . Fears that clearcut silviculture is depauperating soils and eutrophying streams appear unfounded in the Piedmont" (19). It is likely that the newer alternatives to clearcutting, such as green-tree retention and two-aged management (Figure 13.12), will further reduce impacts, although more research is needed.

There is, however, much greater concern about environmental effects of certain intensive practices, such as whole-tree harvesting on short rotations (Figure 13.15) and intensive mechanical site preparation such as disking and root-raking. A number of studies do suggest that these practices might lead to unacceptably high rates of soil and nutrient loss on some sites (20). It is possible that industrial firms using these practices will have to do routine fertilization and use less intensive site preparation methods in order to avoid future declines in yield. Likewise, all foresters need to be cautious about conventional even-aged harvests on soils of inherently low fertility or on high-elevation sites where much of the nutrient capital may be sequestered in the tree biomass. In such cases, some form of partial harvest and careful retention of organic matter may be required, and rotations may have to be lengthened depending on the expected rate of nutrient replacement. Foresters must also be cautious

Figure 13.15 Mechanized whole-tree harvesting reduces costs and logging injuries, while at least temporarily increasing yields. However, it also accelerates the rate of nutrient withdrawal and may not be a sustainable practice on short rotations. (Courtesy of U.S.D.A. Forest Service.)

in planning harvests in certain portions of geologically young landscapes where road-building can trigger landslides on steep, unstable slopes (20).

Maintaining Biological Diversity

Timber harvesting does not have a uniformly positive or negative effect on either the abundance of individual species or on overall biodiversity. Many species of animals and plants have preferences for certain stand ages or successional stages, reflecting their unique adaptations to the regional natural disturbance regime. A recent clearcut dominated by low shrubby vegetation, for example, is ideal habitat for the chestnut-sided warbler and the indigo bunting. After a few years, their populations will decline precipitously as their favored open habitat disappears beneath a canopy of tall saplings. At this point, the young sapling stand becomes suitable habitat for the magnolia warbler and the American redstart. In time, these species will in turn be replaced by those that prefer mature forest, such as the black-throated green warbler and the Blackburnian warbler. Thus, the harvest of mature forest typically replaces one biotic community with another. Maintenance of biological diversity requires that all stages of forest development, including old-growth forest, be represented on the landscape.

It is well known that even-aged management favors populations of game animals as well as "habitat generalists." However, contrary to popular belief, many nongame species of concern to conservationists are also favored by even-aged management. For example, 74 of the 126 species of "neotropical migrant songbirds" in the northeastern United States require early successional stages and young forest habitat, and are rare or absent in mature and old-growth forest (21). Early evidence from scientific studies suggests that green-tree and snag retention in clearcuts, as well as two-aged management practices, will further enhance species abundance and diversity over what would occur under simpler clearcutting regimes (22, 23).

Some measures taken to reduce the effects of clearcutting have had unintended negative effects on biodiversity at the landscape scale. In recent decades, foresters have kept clearcuts small and scattered them on the landscape to minimize aesthetic and environmental impacts. After several decades of this approach, however, the landscape becomes highly fragmented, and the remaining patches of mature forest lose much of their "interior forest" environment because of exposure to clearcut edges (Figure 13.16, top row). This may place some species requiring interior forest environment at risk. One lichen species in the Pacific Northwest, for example, may disappear from mature forest patches if more than 50 percent of the landscape has been clearcut in dispersed patches (*5*). Natural disturbance processes were less disruptive because extensive fires created a mosaic of larger stands with more interior and relatively less edge.

Clearly this creates a public policy dilemma. The public, if it is willing to tolerate clearcuts at all, will usually insist that they be small and scattered, and existing federal regulations mandate small clearcuts on U.S. national forests. Yet in much of the Pacific Northwest and boreal regions of Canada, small dispersed clearcuts clearly do not mimic the natural disturbance processes to which most species are adapted (Figure 13.2). An approach that has been suggested to overcome this dilemma is to keep clearcuts small, but aggregate them in slowly expanding clusters, rather than dispersing them (Figure 13.16, bottom row). This will help preserve the forest interior characteristic of large blocks of forest, and more closely imitate the natural disturbance regime.

Special consideration must be given to plant and animal species having very specific habitat requirements that might not be satisfied under normal forest management practices in a region. Much publicity has surrounded the controversy over the northern spotted owl and the marbled murrulet, two bird species in the Pacific Northwest that appear to require old-growth forests for nesting. There are also other less conspicuous species, such as certain lichens, fungi, and mollusks, that also may be common only in old growth ecosystems, and which may be important for healthy ecosystem functioning. For such reasons, in 1993 President Clinton's scientific advisory panel recommended setting aside

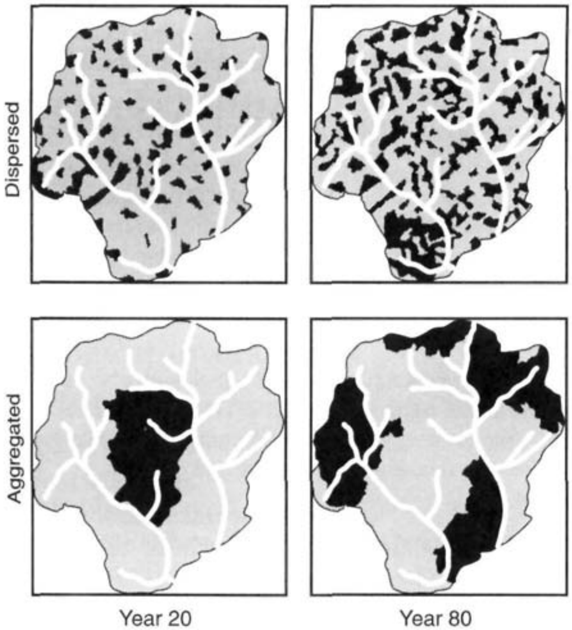


Figure 13.16 Two alternative ways of dispersing small clearcuts are shown above on maps of a watershed. If clearcuts (shown as black patches) are small and dispersed, they eventually cause forest fragmentation and loss of interior forest habitat as in the top row of maps. Aggregation of small clearcuts into larger clusters over time (bottom row of maps) helps preserve large blocks of closed-canopy forest, shown as the gray patches. White areas show streamside protection zones. From David Wallin; courtesy of Ecological Society of America (24).

a number of large "late successional reserves" on national forest land to ensure the viability of these species. It is not yet known whether silvicultural practices designed to hasten or maintain old-growth features in younger stands will be successful in maintaining the viability of such species outside of formal reserves.

Concluding Statement: Public Forests of the Future

How then, should silviculture be applied on large public landholdings such as national forests, and what would the ideal landscape look like? There won't be one answer for all public forests, especially under ecosystem management, since practices will be attuned to the local biota and natural disturbance regime. Thus, a national forest in western Oregon will be managed much differently from a national forest in Vermont, with the selection system being used much more widely in the northern hardwoods of Vermont than in the Douglas fir forests of Oregon.

Nonetheless, it is possible to make some generalizations about how silvicultural practices under the ecosystem management paradigm will change the fabric of the landscape in the 21st century compared with what was produced under the multiple-use paradigm in the 20th century. There will be greater mixtures of tree species, representative of natural species diversity in the region. Traditional "block" clearcuts will probably be replaced largely by two-aged stands, multicohort stands, shelterwood harvests, and modified clearcuts with retention of scattered green trees and small patches of forest. Stand edges will be irregular and blended with the topography. Aggregated patches may be preferred over dispersed harvests to more closely mimic the natural disturbance regime and maintain forest interior species. Rotation ages will be longer, with many areas managed on 150-250-year rotations. Prescribed burning will be used more frequently to maintain historical patterns of species dominance and to maintain ecosystem health. There will be more use of the selection system than at present, and it will be used wherever it meets societal goals and is ecologically appropriate. Nearly all stands will have greater structural complexity, with large living trees, dead snags, and fallen logs for biodiversity. Old-growth stands will be more common in most regions than at present, both as large tracts and as small patches in a matrix of younger forest.

Although this scenario will result in landscapes with a high degree of naturalness, it will not please everyone. It does not maximize wood production in the short run, as some industries might prefer. It does not maintain maximum populations of game animals, as some hunters might prefer, and it does not restore the natural disturbance regime exactly or maintain as much old-growth forest, as some environmental groups might prefer. However, it does fulfill the goals of ecosystem management to manage vital natural resources on a sustainable basis for future generations, and to maintain the diversity and viability of native plant and animal populations.

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CHAPTER 14

Forest-Wildlife Management

MARK S. BOYCE

More than 60 percent of the world's biodiversity is associated with forests (1). From subarctic boreal forests to tropical rain forests, trees provide food and cover for many species of wildlife. Wildlife includes aquatic species such as fish, and forests may be important because they have a stabilizing effect on streamflow that provides habitats for aquatic species. Wildlife is an integral component of forest ecosystems. For example, wildlife may serve as crucial agents for seed dispersal or by selectively foraging on certain plants, can alter patterns of forest succession. Humans alter wildlife populations to assist in forest management, or, alternatively, humans manage forests because of their importance to desired wildlife species.

Wildlife Values

Wildlife most often is viewed as an amenity in forest management. This means that wildlife is viewed to be a bonus value to a forest that is not the primary reason for its management. With increasing interest in biodiversity, this view toward wildlife is changing and in some systems (e.g., the Pacific Northwest), wildlife are primary drivers in shaping priorities for forest management.

Wildlife is a source of recreational hunting and fishing in forests throughout most of the world. With careful stewardship, wildlife resources can be managed sustainably, meaning that harvesting of wildlife populations can be continued indefinitely. Each

Figure 14.1 Hunting constitutes a renewable use of the wildlife resource.

year many more individuals are born than can possibly survive. Human harvest or predation can remove these animals with no long-term consequences to population size (Figure 14.1).

In addition to harvest values, people around the world also value wildlife for aesthetic values. Birdwatching and wildlife safaris are becoming important sources of tourism revenue in many areas. Furthermore, most people who are actively engaged in resource extraction—for example, timber harvest, hunting, or fishing—enjoy opportunities to see bears, deer, bald eagles, songbirds and other wildlife. Also, the appreciation for wildlife is what attracts people to pursue recreational activities in forested ecosystems.

A national survey of participants in wildlife-associated recreation showed that about 14.1 million Americans hunted big and small game in 1991 (2). Expenditures for equipment, lodging, food, and transportation in pursuit of forest-associated game exceeded $12.3 billion in 1991. In the same year, approximately $3.8 billion was spent on wildlife in Canada (3). An estimated 35.6 million Americans spent $24 billion during 511 million days of freshwater fishing. An updated 2001 survey of wildlife recreation has been undertaken and the results are reported on the following website: http://fa.r9.fws.gov/surveys/surveys.html#surv_2001.

Nonconsumptive use of wildlife has become increasingly important. The 1991 national survey showed that more than 76.1 million Americans participated in wildlife-associated recreation (2). An estimated $18.1 billion was spent in 1991 by persons engaged in "nonconsumptive wildlife-associated recreational activities." Perhaps most important, however, is the recognition that maintaining the diversity of wildlife is fundamental to ensuring the sustainability of forest ecosystems. Wildlife contributes to the very fabric of forest ecosystems and helps to ensure the availability of ecosystem services on which humans depend.

Ecological Interactions

Just as trees compete with one another for space, food, water, and sunlight, wildlife living in the forest interact with one another. These interactions occur at two levels, *intraspecifically* and *interspecifically,* and may be described as competitive, consumptive, or commensal interactions.

Many species of wildlife require certain amounts of space or territory to meet their needs. Some species defend their territories aggressively; for example, territory defense is an important function of most birdsong in the spring. Many mammals, as well as some reptiles and amphibians, maintain scent posts or other signs to mark territorial boundaries.

Consumptive interaction includes predation and herbivory and can be either interspecific or intraspecific. Some predators may occasionally kill and eat their own kind. Cannibalism among siblings appears to be frequent in the nests of hawks and owls when the parents are unable to find enough prey to feed the nestlings.

The effect of predation on wildlife populations has been controversial. For many years it was felt that predators were "bad." Then various studies began to suggest that predation was less important than some other factors in limiting wildlife abundance (4). These studies reinforced the concept of carrying capacity put forward in 1933 by Aldo Leopold, the founder of modern wildlife management (5).

This particular notion of *carrying capacity* is the number of individuals of a species that can survive in a given unit of habitat secure from predation. Carrying capacity is a measure of the adequacy of food and other resources in relation to secure cover. Once a prey species has been reduced to carrying capacity, it is no longer profitable for predators to continue hunting these animals (4). However, rather than being a fixed entity, carrying capacity varies from site-to-site; on the same site it might vary from year-to-year depending on the food available, the quality of the cover, and even snow conditions and depth.

Predators enforce carrying capacity, and in the absence of predators, some wildlife may become abundant in habitats that otherwise would be marginal. In the Cloquet Research Forest in northern Minnesota, ruffed grouse *(Bonasa umbellus)* reached a greater abundance in an aspen-pine forest when goshawks *(Accipiter gentilis)* were not nesting in that forest, but then declined sharply when these raptors returned. At the same time, grouse living in sapling aspen stands distant from coniferous cover remained relatively secure from raptor predation (6).

When large herbivorous mammals, like white-tailed deer (*Qdocoileus virginianus*) or elk (*Cervus elaphus*), are living in the absence of their normal predators, available forage needed to maintain the population of animals determines the carrying capacity. When abundant, such herbivores may change the vegetation through their grazing and browsing. For some species in the absence of effective predation, territorial behavior may supplant forage availability as a factor limiting population size. Under these conditions the food and cover resources may have the capacity to support a considerably higher population of a species than intraspecific aggression will permit.

Predation is often opportunistic; that is, it most often occurs when the predator has an advantage. For some species, predation is markedly heavier along the edges between forests and openings, and especially along trails and roadways. Young and old-aged animals are usually more vulnerable than adults to predators (and hunters). Minnesota studies have shown that the percentage loss among young ruffed grouse over a seven-month period from the middle of September to the middle of April is as great as the loss among adult grouse over a twelve-month period, and numerically is about 3.4-fold greater on a monthly basis (7).

Wildlife as Components of Forest Ecosystems

Forest Habitats

Early Successional Species Vegetation succession involves a slow transition from one community to another eventually leading to a relatively long-term state termed a *climax.* Associated with each vegetative state of succession is an entire assemblage of plants and animals (Figure 14.2). Early successional species of wildlife thrive in the early stages of succession following a disturbance to the forest. For example, after fire or clearcutting, we often see increased use by moose (*Alces alces*) or white-tailed deer to feed on the herbaceous forage that is stimulated by the removal of trees. Some species, like the Kirtland's warbler (*Dendroica kirtlandii*), are restricted to early successional forests.

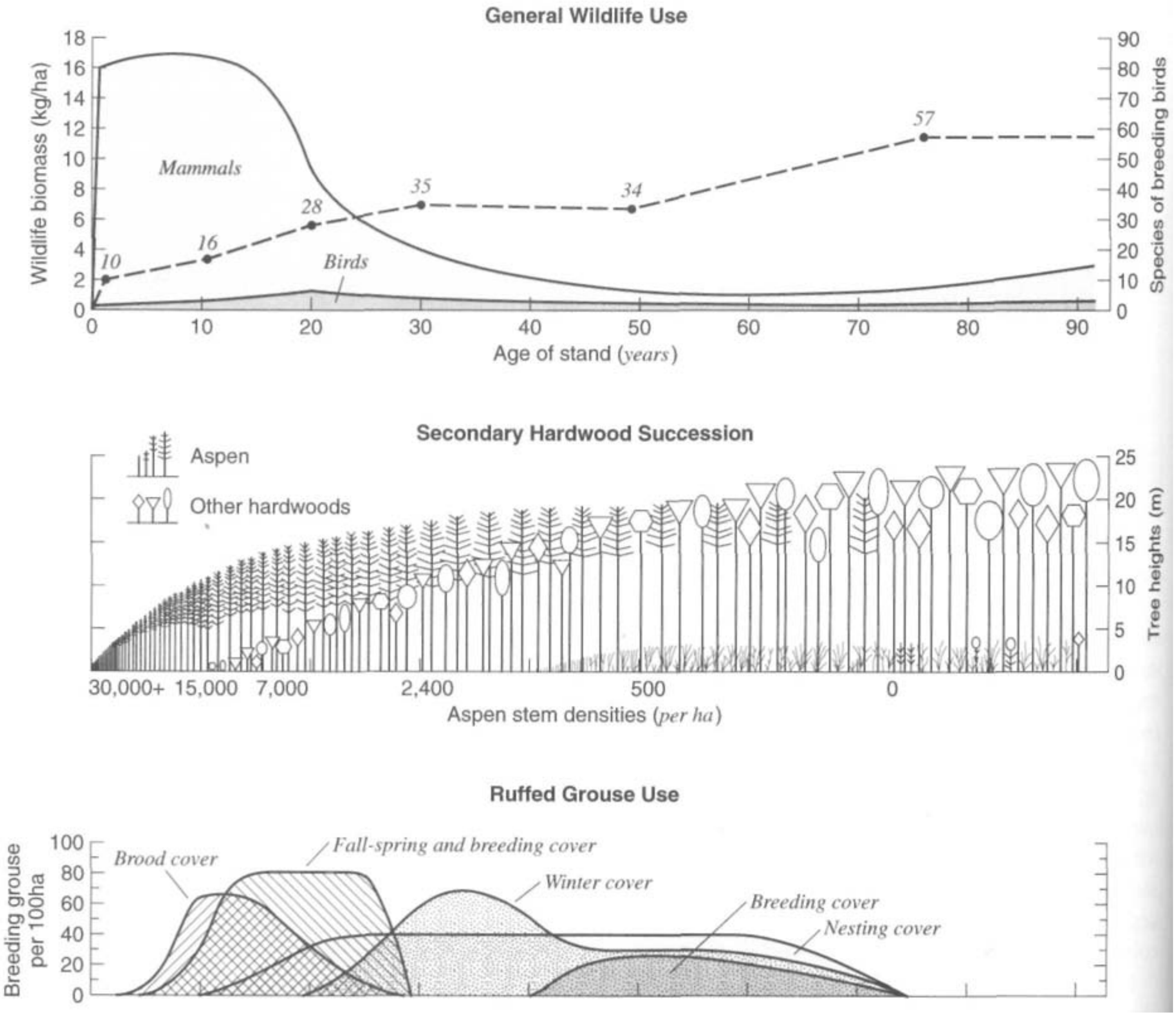


Figure 14.2 Secondary succession in a Great Lakes northern hardwoods forest, showing the sequence of dominant vegetation and the response of ruffed grouse as the forest composition changes. Also graphed is the change in animal biomass and bird species diversity associated with this succession.

Several forest types are known to undergo natural disturbance by fire that resets succession. Elsewhere, windthrow may be an occasional event resulting in gaps in the forest where early successional species would be found. Early successional habitats are often short lived, rapidly reverting to forests. The amount of early successional types on the landscape depends on the frequency and extent of disturbance. Some natural systems with high frequency of disturbance include: (a) the chaparral brushlands of California where mule deer (*Odocoileus hemionus*) are attracted after burning, (b) Rocky Mountain lodgepole pine (*Pinus contorta*) forests used by elk (*Cervus canadensis*) for foraging after fire or clearfelling (8), (c) the oak savanna of midwestern North America where the endangered Karner blue butterfly (*Lycaeides melissa samuelis*) depends on lupine (*Lupinus perennis*) that is maintained by fire, mowing, or grazing, and (d) eroded stream banks created by periodic flooding required for nesting by wood turtles *(Clemmys insculpta).*

Wildlife of Mixed-age Forests Patterns of succession on the landscape are often complex. Fires, windthrow, insect outbreaks, and other disturbances are usually patchy, creating a vegetation mosaic of early, mid-aged, and old growth forests.

Some forms of wildlife require an interspersion of trees of different ages or of different species. Primary consumers or herbivores are the most dependent on interspersion of forest resources because they use forest vegetation in several ways. Conditions favorable for the production of food resources usually differ from those providing secure cover. Additionally, forest-dwelling herbivores tend to be nonmigratory, and therefore require year-round food and cover from the habitats they occupy. Some herbivores in the Great Lakes region forests such as snowshoe hares (*Lepus americanus*), ruffed grouse, and white-tailed deer require this diversity within comparatively small areas. But mule deer (*O. hemionus*) and elk in western mountainous regions find their requirements by being migratory, often moving many kilometers from summer to winter ranges (8).

Moose require an interspersion of forest types, with the addition of streams, ponds, or lakes to provide aquatic vegetation for their summer diet. In Minnesota the proper mixture for moose on an area of 9,300 ha (21,000 acres) has been estimated to be 40 to 50 percent open land less than 20 years old, 5 to 15 percent in spruce fir, and 35 to 55 percent aspen-birch stands over 20 years old, and pond, lakes, and streams (9).

Wildlife of Old-Growth Forests At the opposite extreme from early successional wildlife are species tied to late-successional or old-growth habitats. The most celebrated example is the northern spotted owl (*Strix occidentalis caurina*) that has been responsible for restructuring the management of forest resources in the Pacific Northwest. There are many species tied to mature forests and the unique habitats found in such forests. An ungulate example is the woodland caribou (*Rangifer tarandus*) of boreal forest regions of Canada and northern Idaho. During winter woodland caribou forage on arboreal lichens—pale-green beard-like lichens that hang from tree branches. Clearcutting of the forests has devastating consequences for the caribou because of their reliance on lichens in old trees. Selective logging might provide a creative solution, however, because some old trees are left standing, providing at least part of the lichen forage available before logging.

Edge Habitats Edges are attractive to some species because the forest provides cover and mast (e.g., acorns), whereas clearings may have more forage. Thus, by occupying the edge, individuals may gain benefits from both habitats. Aldo Leopold (5) claimed that the amount of game was proportional to the amount of edge, but this pattern appears to apply primarily to selected species such as white-tailed deer (Figure 14.3) and ruffed grouse. Although many species of wildlife prefer edge habitats, these can be dangerous places because predators often concentrate there. Several species of songbirds, for example, preferentially nest in edge habitats that become mortality "sinks" because crows (*Corvus brachyrhynchos*), jays, raccoons *(Procyon lotor;* Figure 14.4), skunks (*Mephitis mephitis*), and foxes (*Vulpes fulva*) hunt the edges of forest openings (10).

Riparian Zones Vegetation immediately surrounding bodies of water, streams, rivers, lakes and ponds, is known as the riparian zone. Waterfowl nest in riparian vegetation. Some species including semi-aquatic mammals such as beavers (*Castor canadensis*), muskrats (*Ondatra zibethicus*), otters (*Lontra canadensis*), and mink (*Mustela vison*) are found only in the riparian zone. These areas tend to be highly productive because water and nutrients are seldom limiting, and they host a high

Sidebar 14.1

Case Study: Northern Spotted Owl

Species adapted to old-growth forests are threatened by accelerated forest management. Old-growth forests typically contain trees of large size, vertical differentiation of vegetation structure, and large standing dead trees and decaying logs. Old-growth Douglas fir and redwood forests of the Pacific Northwest have these characteristics and provide habitats for the northern spotted owl. Spotted owls forage on rodents under the forest canopy, and require an open stand structure in which to hunt their prey. Young forests have trees that are too dense to permit the owls to fly.

One of the most common prey species for spotted owls, especially in California and Oregon, is the dusky-footed woodrat (*Neotoma fuscipes*). This rodent attained highest density in young regenerating stands that are too dense for hunting owls. Some of the best habitats for spotted owls are old-growth stands adjacent to younger forests that yield woodrats that disperse into the old-growth (1). Because of heavy timber harvests in recent years, young-aged forests are not in short supply. Thus, most fundamental for spotted owl habitats is the maintenance of old-growth forests.

Old-growth forests have declined by approximately 90 percent across the Pacific Northwest in the past century, and if this rate of decline were to continue the spotted owl would have been at risk of extinction within a few years. In 1990, the spotted owl was listed in the United States as a threatened species under the Endangered Species Act. Subsequently large tracts of old-growth forests on public lands have been protected, ensuring the future for the owl and associated old-growth species.

Source:

1. M. S. BOYCE, *Wildl. Soc. Bull., 26*, 391 (1998).

diversity of wildlife often containing complements of both the terrestrial and aquatic fauna. Although riparian habitats occupy only 1 percent of landscapes in North America, they contain over 80 percent of our threatened and endangered species (11).

Disturbance is a fundamental component of riparian ecosystems. Periodic flooding of rivers and streams can be important in retarding succession and altering the distribution of sediments. Periodic flushing flows, to clean out gravel beds, are required to maintain spawning habitats for trout and salmon. Beavers take advantage of stream-course changes following floods where new pools are formed near aspen (*Populus tremuloides*), willow (*Salix* spp.), or cottonwood (*Populus* spp.) stands.

Dams and channelization have altered riparian forests and the disturbance processes associated with the systems. Because water levels are controlled on the Platte River in Nebraska, sand and gravel bars are becoming extensively wooded, thereby eliminating nesting habitats for least terns (*Sterna antillarum*) and piping plovers (*Charddrius melodus*). In other areas along the Platte River, cottonwood (*P. deltoides*) stands are growing decadent with no recruitment of young trees because of the absence of flooding that creates sites for germination. Solutions to the disruption of flooding cycles

Figure 14.3 White-tailed deer. Because of wildlife management efforts, this species has become the most abundant large mammal in North America.

are being found by manipulating flood-control gates to create seasonal high-water-level conditions.

Wildlife Effects on Forests

Figure 14.4 Raccoons frequent forest edges where they will opportunistically prey on bird nests.

Seed Dispersal Wildlife plays a role in the distribution of seeds of many trees. Few of the birds that feed on the fruits of cherries (*Prunus* spp.), mountain ash, junipers (*Juniperus* spp.), and others, actually crush or damage the seeds. The seeds pass through the bird's digestive systems intact and ready to germinate if they are dropped in a suitable place. Indeed, passing through the gut can serve to scarify certain types of seeds enhancing their germination. The common growths of fruit-producing shrubs and trees along fences and under telephone wires or power lines attests to this function. If fruits were eaten by birds during migration seeds might be deposited many kilometers from where they were consumed.

Birds commonly carry seeds for some time in a storage pouch, or crop, before the food passes into their gizzard to be ground and digested. Predators feeding on a bird usually consume the fleshy part of the crop and leave the contents scattered where they eat the bird. Seeds from the crop may germinate thereby achieving dispersal.

Turtles, tortoises, lizards, and fish also transport seeds from one site to another, and if one of these animals happens to be preyed on by a bird, seeds may be moved a considerable distance. Even seeds taken by granivorous mammals may become scattered some distance from the point of origin when they are the victims of predation.

The complexity of forest-wildlife ecology is illustrated by studies of mycophagous or fungus-eating small mammals. Rodents act as vectors in the transmission of fungal spores from one site to another and may promote the establishment of conifers by distributing ectomycorrhizae important to nutrient absorption by tree roots (12) (also see Chapters 4 and 8).

Insect Predation Birds and small mammals can consume large quantities of insects, and sometimes are known to reduce pest species. For example, netting experimentally placed to prevent birds access to trees has been shown to increase the abundance of jack-pine budworm (*Choristoneura pinus*) and western spruce budworm (*C. occidentalis*) (13). Yet, during periods of population outbreaks, these insects become so abundant that birds are unable to check populations of these pests. Insecticides may have relatively minor consequences to birds during insect outbreaks because the insects are so abundant that the birds still have plenty to eat. However, at other times broadcast spraying of insecticides can have serious consequences for birds that depend on insects for food.

Herbivory **Wildlife** can be agents of disturbance maintaining systems in an early successional stage. Browsing by moose, elk (Figure 14.5), and deer can prevent woody plant establishment in grasslands (Figure 14.6) and can reduce recruitment of selected species, such as aspen, that are preferred by ungulates. Beavers can have major influences on riparian vegetation by selectively clearfelling preferred trees such as aspen and cottonwood.

Such herbivory can be the source of frustration for foresters trying to establish young trees.

Figure 14.5 The range of elk or wapiti has expanded extensively during the past 30 years and the populations of the species are now established in Wisconsin, Michigan, Pennsylvania, Kentucky, and Virginia in the United States, and Manitoba, Saskatchewan, and Ontario in Canada, as well as all Rocky Mountain states and provinces.

Figure 14.6 An exclosure on the northern range of Yellowstone National Park where native ungulate herbivory has been prevented for approximately 40 years. Few dense stands of willow can be found in portions of the park due to feeding of elk, bison, deer, and moose.

Rodents and rabbits also do a great deal of damage to forest regeneration by feeding on the tender bark of young trees. During periods when mice populations are large, stands of seedlings or sprouts may be almost completely destroyed by rodent girdling. Likewise, porcupines (*Erithizon dorsatum*) can be responsible for widespread destruction of merchantable aspen, red spruce (*Picea rubens*), balsam fir (*Abies balsamea*), and red and white pine (*Pinus resinosa* and *P. strobus*) by eating the bark of these trees.

Effects of Forest Management on Wildlife

Fire Suppression

The role of fire in forest management is controversial. Fire can cause substantial damage to the commercial value of a forest, but in many areas, fire is a natural disturbance process. For example, wildfire was responsible for maintaining the jack pine on which the Kirtland's warbler depends. Likewise, oak savannas of the midwestern United States and pine barrens of New Jersey and northwestern Wisconsin were fire-maintained systems that gradually disappeared by succession to forests as a result of protection from burning. Again, species such as the endangered Karner blue butterfly (*Lycaeides melissa samuelis*) and its food plant the lupine are dependent on disturbances such as fire. Ruffed grouse, woodcock (*Scolopax minor*), deer, moose, and elk thrive on the food and cover available in areas undergoing post-fire succession.

In contrast, for species dependent on old-growth features of the forest such as spotted owls (Sidebar 14.1), marbled murrelets (*Brachyramphus marmoratus*), ovenbirds (*Seiurus aurocapillus*), or the extinct ivory-billed woodpecker (*Campephilus principalis*), fire can be destructive.

Prescribed Burning

A number of ecosystems are maintained by disturbances such as fire, and these along with associated wildlife are becoming rare because fire is so

Sidebar 14.2

Case Study: Elk in Yellowstone National Park

Large herbivores can have substantial influence on vegetation. Elk (*Cervus elaphus*) in Yellowstone National Park were culled by park rangers during the middle part of the 20th century to reduce their effect on vegetation. Since 1968, however, the elk have been strictly protected inside the park resulting in substantial increases in the elk population, especially on the park's Northern Range. Clearly aspen (*Populus tremuloides*), willow (*Salix* spp.), and various shrubs are heavily browsed. Controlling herbivory by constructing fenced exclosures results in substantial changes in vegetation structure and composition (see Figure 14.6). Some people find this to be objectionable, noting that sound range management practices would not allow such heavy levels of livestock use. Others argue that we need protected places like national parks as ecological baselines where we can document the consequences of human activities outside the parks (1).

In 1995, wolves were reintroduced into Yellowstone National Park, and appear to have caused a decline in the number of elk. Current research is attempting to document response by vegetation to reduced herbivory.

Source:

1. M. S. BOYCE, *Wildl. Soc. Bull.*, *26*, 391 (1998).

aggressively suppressed. The oak savannas and tall-grass prairies of the midwest, heathlands of the eastern coast of North America, aspen parkland of western Canada, and pine barrens of northwestern Wisconsin and New Jersey are a few examples. To ensure perpetuation of these fire-maintained ecosystems, prescribed fire is a useful management tool. The behavior and management of forest fires are further discussed in Chapter 18.

Timber Harvest

Timber harvest can be a surrogate for fire that can benefit early successional species. Florida sand pine scrub responds similarly to fire and mechnical disturbance, and timber harvest may be an acceptable substitute for natural disturbance (14). Likewise, savanna birds in the pine barrens of northwestern Wisconsin readily use openings created by timber harvest (15). Yet vegetation structure and species composition differ in several ways between openings created by fire versus those created by timber harvest (16). Therefore, although timber harvest may simulate natural disturbances, there may be differences depending on the form of disturbance that may require alternative forms of treatment, such as prescribed fire.

Forest Fragmentation

Associated with increased intensity of management of forests, generally we have seen increased fragmentation of the landscape (see Chapter 7, Landscape Ecology). Harvest patterns, road construction, and residential housing have increasingly partitioned forests into smaller and smaller units. In many areas, this has the consequence of lowering species diversity, by eliminating those species that have the largest area requirements and species that require conditions characteristic of forest interior (17). Examples of species that decline with increasing forest fragmentation include the northern spotted owl (see Sidebar 14.1) in the Pacific Northwest and ovenbirds common to woodlands of eastern North America. Much of the decline for these species can actually be attributed to habitat loss (18), which is usually associated with fragmentation.

Effects of landscape change can be complex and fragmentation actually can benefit some species. Throughout eastern North America, forest cover has increased during the past century. Associated with this afforestation has been a decline in many bird species associated with shrublands and grasslands (19). Also, a number of game species including white-tailed deer, elk, ruffed grouse, and bobwhite (*Colinus virginianus*) are more abundant in areas with frequent forest disturbance and edge (5). For these species, forests provide cover for hiding and thermal refuge whereas open areas with greater herbaceous vegetation provide more forage. Areas with a high degree of edge afford easy access to both cover types that provide both cover and forage.

Pesticides and Herbicides

Both pesticides and herbicides may be toxic to wildlife, and many species have suffered with agricultural intensification and the expanded use of these chemicals. Raptors including peregrine falcons (*Falcoperegrinus*) and bald eagles (*Haliaeetus leucocephalus*) suffered serious population declines in the middle of the 20th century from eggshell thinning caused by DDT, a pesticide developed during World War II. In the United States and Canada, many raptors have made remarkable comebacks subsequent to the ban of DDT. Unfortunately, the pesticide is still being used in many developing countries where environmental regulations are not as strict.

In addition to the direct toxicity of pesticides and herbicides, these chemicals can have serious indirect consequences for wildlife. Pesticides are designed to kill insect pests, and herbicides are designed to kill certain plants. Insects are often key] foods for young birds, and most birds cannot live without them. Likewise, amphibians and reptiles are I often insectivorous and elimination of their primary source of food may have devastating consequences. Plants provide cover and food for many animals, so herbicides eliminate habitats.

Wildlife Considerations in Ecosystem Management

Managing for Biodiversity

Threatened and Endangered Species The ultimate cause for at least 80 percent of known avian extinctions has been habitat loss (20). Generally the most crucial management action to prevent future extinctions is ensuring that sufficient habitats are maintained. Some species have huge area requirements; for example, grizzly bears (*Ursus arctos*) and wolves (*Canis lupus*). Species with large area requirements are often called "umbrella" species, because if we maintain large enough areas to protect these species we will also ensure the persistence of smaller species that occur in the same area but have much smaller area requirements.

Protection of habitat may not be sufficient, especially for species that require habitats maintained by disturbance. The Kirtland's warbler, for example, requires early successional jack pine stands for nesting. The Karner blue butterfly requires lupine that is maintained by fire, grazing, or mowing in oak savanna habitats of the Midwest. The red-cockaded woodpecker (*Picoides borealis*) thrives in long-leaf pine (*Pinus palustris*) stands of the southeastern United States where frequent fire prevents invasion of oaks.

Value of Downed Woody Debris One of the most important features of a forest that increases species diversity is the presence of coarse woody debris. This takes the form of downed logs on the forest floor, dead branches, snags, and standing dead trees. Deadwood then is decayed by invertebrates, fungi, and microorganisms that in turn provide food for small mammals and birds. Such woody debris is a characteristic feature of old-growth forests and is why such forests often possess high diversity. Management of forests in ways that retain woody debris is an effective way to enhance biodiversity.

Ecosystem Structure and Function

Streamside Protection Maintaining buffer zones of protected forest adjacent to streams is a common management practice to protect streams from sediment and nutrient runoff. This can be crucially important for maintaining fish habitats and failure to protect streams in the Pacific Northwest has been identified as one of the factors leading to the decline in salmon fisheries. Road crossings associated with logging are especially troublesome because of the potential for large amounts of sediment to be washed into the stream during heavy rains. Generally, the wider the streamside buffer, the more effective the protection of wildlife habitats, for example, Swainson's warblers (*Helmitheros swainsonii*) were never detected in buffers less than 300 m (984 ft) width and had higher densities in buffers >1,000 m (3,280 ft) (21). Large trees falling into the stream can be valuable components of fish habitat, so one guideline is to maintain buffers at least as wide as the height of the tallest trees (22).

Habitat Manipulation Habitats are often manipulated to enhance the value of an area for selected wildlife. Clearcutting aspen is used to stimulate shoot growth to enhance habitat for ruffed grouse, woodcock, and deer. Burning is used to enhance habitats for Karner blue butterflies, moose, elk, deer, and red-cockaded woodpeckers. Planting of food and cover crops is used to attract wildlife, sometimes to distract animals from agricultural crops or forest plantations (8).

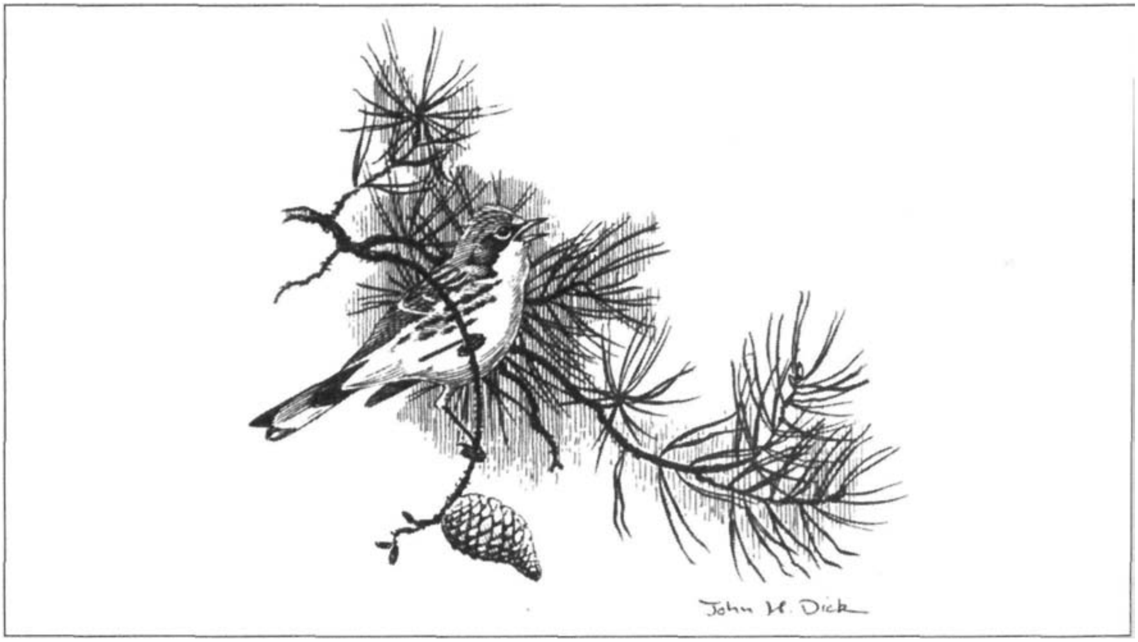
Selective cutting of trees can hasten the development of old-growth characteristics required by northern spotted owls. Similarly, selective logging has been used in the Rocky Mountains to improve lichen

Sidebar 14.3

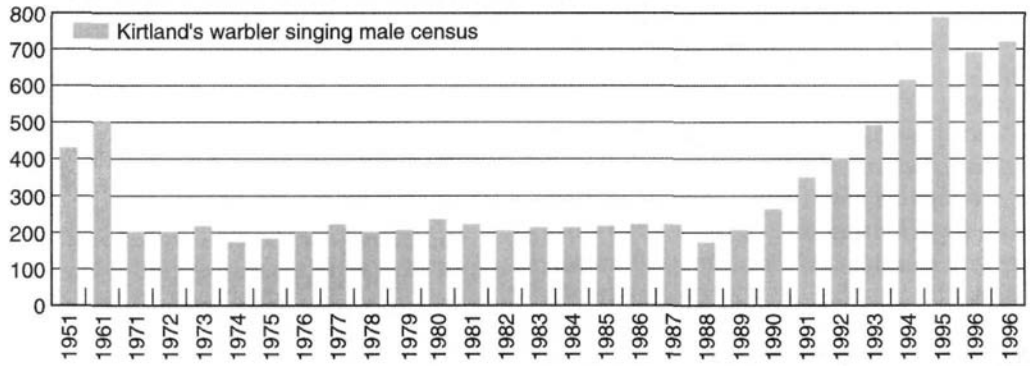
Case Study: Kirtland's Warbler

The Kirtland's warbler (*Dendroica kirtlandii*) is an endangered species that breeds primarily in the jack pine (*Pinus banksiana*) plains of north central Lower Peninsula Michigan and winters mostly in the Bahama Island archipelago. The natural pine barren ecosystem was historically maintained by frequent wildfires, but because of modern fire suppression techniques and alternative land uses, the amount of this habitat has decreased causing the decline of the Kirtland's warbler population. In addition, the warbler population was decreasing because of cowbird (*Molothrus ater*) parasitism. In 1972, land managers began to trap cowbirds, and in 1976, they began to plant jack pine in clearcuts to replicate wildfire habitat. Habitat management and cowbird removals have been successful at increasing the population. By 1999, the population had increased to 903 pairs with 94 percent of the birds occurring in jack pine plantations.

Large areas of low diversity are required to sustain this endangered species. The current goal for forest management is to maintain 10,340 ha of habitat for the Kirtland's warbler. Stand sizes must be greater than about 50 ha, with most



Male Kirtland's warbler.



Counts of male Kirtland's warbler on their breeding range in Michigan.

birds nesting in stands greater than 100 ha. The nesting habitat for the Kirtland's warbler is almost strictly dense young jack pine stands 8-20 yrs old where the trees are 2-6 m tall. Natural habitats were typically post-fire succession, but because of modern concerns about risks associated with wildfires, current stands are typically plantations following clearcutting. Rotations of jack pine in Kirtland's warbler habitat are about 50 years with harvested trees used primarily for paper pulp.

Habitat needs for this endangered species illustrate how biodiversity conservation must be viewed on a large geographic scale. Large areas with low diversity at a local scale are required within the forest matrix to ensure the maintenance of regional diversity.

on remaining trees with the intent of enhancing habitats for mountain caribou. Foresters practicing woodlot management may selectively remove maples with little wildlife value while favoring oaks and conifers that offer greater benefits for wildlife. Another approach is manipulation of water levels, for example, in green-tree reservoirs in the southern United States, to enhance winter habitats for waterfowl (11).

Population Control

Left undisturbed, natural populations of forest wildlife will eventually reach the carrying capacity of their habitats, and over time, populations will fluctuate around this carrying capacity. However, we often find that, when abundant, wildlife may come in conflict with human interests in forest management. Hunting and trapping are probably the most common methods of population control for game species and furbearers, but sometimes these traditional methods are not practical, efficient, or socially acceptable. Under these circumstances, alternative methods of population control must be explored.

Beavers have become abundant in some areas of North America where they cut trees, dam streams flooding roads, or flood lowland forests killing valuable timber trees. Beavers can be trapped and dams destroyed with dynamite. Creative alternatives exist; for example, driving corrugated PVC pipe through a beaver dam to lower water levels.

White-tailed deer have become remarkably abundant in many regions of North America. In one sense, this points to the success of wildlife management during the latter half of the 20th century. However, deer can damage crops, browse nursery trees, and alter forest succession by selective browsing. In populated areas, automobile collisions with deer are a major concern. Although deer hunting can be used for population management, in many areas, hunter harvest has not been sufficient to achieve the desired population levels. This is especially a problem in urban areas where hunting may not be permitted. For example, the city of Milwaukee, Wisconsin has implemented deer control using professional snipers, with silenced rifles, shooting deer at bait stations. Other urban areas have trapped deer and transported them to areas outside the city. Experimental programs are being implemented in some areas using immunocontraceptives. There are no easy solutions to these control issues, because each method requires persistent treatments year after year.

Concluding Statement

Wildlife adds enormous value to the forests of the world; generally, people enjoy wildlife. Managing forests to enhance wildlife habitats often can be accomplished with little additional cost. In some instances, wildlife resources may be worth more than the traditional timber values of the forest. In other instances, wildlife can be viewed as pests by forest managers because they damage trees or interfere with regeneration. In all forests, however, wildlife contributes to ecosystem structure and function and is a key component of biodiversity, and the world is a better place to live because of it.

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CHAPTER 15

Rangeland Management

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JOHN D. STEDNICK

Rangelands are areas of the world that—by reasons of physical limitations: low and erratic precipitation, rough topography, poor drainage, and cold temperatures—are unsuitable for cultivation (1). They are an important source of forage for free-ranging native and domestic animals, as well as a source of wood products, water, and wildlife (2, 3). Approximately 47 percent of the earth's land surface is classified as rangeland, and of the estimated 385 million hectares of rangeland in the United States, a little over one-third is forested range (4, 5). The distribution of rangelands in the United States is given in Table 15.1.

Rangeland Grazing Management

Typically, a ranch operation in the western United States is made up of deeded land (base property) where hay is produced and cattle are "wintered," and in addition, leased land, where the livestock graze in the summer. Summer grazing on federal land is regulated by a permit system. The grazing permit entitles the user to a grazing area, a decreed number of stock, and entrance and exit dates during the summer, demarking the period when the animals can be present on the range.

Many livestock operations in the western United States depend heavily on forage produced in the forest for part of the grazing year (Figure 15.1). In Colorado, for example, approximately 45 and 50 percent of the summer forage utilized by cattle and sheep, respectively, comes from national forests (6). The number of livestock grazing in the National Forests increased steadily until about 1915. By 1918, the rising number of livestock, the long season of use, and the huge increase during the war caused most of the forest range to decline in productivity. This deterioration in the range prompted both a reduction in the number of livestock grazing in the forest and a change in the manner in which livestock were grazed. Specialized grazing systems that provided recurring systematic periods of grazing and deferment from grazing were adopted.

Deferred-rotation and *rest-rotation* grazing are two common grazing systems used in forested rangelands. Under deferred rotation, grazing on a portion of the range is delayed until after the most important range plants have set seed. Then, by rotation of the deferment over a period of years, other pastures are successively given the benefit of deferment until all pastures have been deferred (2). When this has been accomplished, the grazing cycle is repeated. In rest-rotation grazing, a portion of

Table 15.1 Distribution of Rangeland in the United States

Region	Percentage
Rocky Mountains and Great Plains	50
Pacific Region (including Alaska and Hawaii)	37
South Central	12
Other	1

Source: U.S.D.A. Forest Service data.

the range is rested for a full year. Deferring other pastures from grazing is also a part of rest-rotation grazing systems. The deferment and rest periods are designed to allow plants to increase in vigor, produce seeds, and establish new seedlings. The design and advantages of grazing systems have been extensively reviewed (1, 3, 7).

A third grazing system, *short-duration grazing,* is gaining popularity in many regions of the United States. This system employs a large number of pastures (frequently twelve or more) and short periods of grazing in each pasture (generally two days to two weeks). Intensive livestock management is required with this system, because of its high stocking density; that is, the large number of animals per area of land (7).

Major types of forests in which livestock graze in the United States include ponderosa pine, pinon-juniper, aspen, transitory, mountain meadows, and riparian zones.

Forested Rangelands

The ponderosa pine range is the most extensive forested range in the western United States. It occupies the low elevations of the mountains and foothills in many areas, but mixes with other tree species at moderate elevations (8). This type is associated with an understory of bunchgrasses and shrubs. Its value as rangeland is the highest of any of the forested range types. About 560 to 675 kilograms per hectare (dry-weight basis) of understory herbage is produced in open stands of mature pine with 500 saplings per hectare (9). As the density of pines increases, there is generally a curvilinear decrease in understory production (Figure 15.2). This range commonly serves as summer range for cattle, and spring and fall range for sheep that move to higher elevation rangeland during summer. Both rest-rotation and deferred-rotation grazing systems, under proper stocking, have been reported to benefit these forested ranges (10).

The pinon-juniper range is a woodland composed of small trees, generally less than 4.5 meters in height, growing in either open or dense stands. This range is located between the ponderosa pine forest and desert shrub or grassland. The pinon-juniper range generally occurs on rocky, poorly developed soils, and in many locations it alternates with big sagebrush, which occupies deeper soils. Understory productivity ranges from near zero on poorly developed soils to 900 kilograms per hectare on favorable sites (9, 11). Cattle and sheep

Figure 15.1 Sheep grazing in Midway Valley, Dixie National Forest, Utah. (Courtesy of U.S.D.A. Forest Service.)

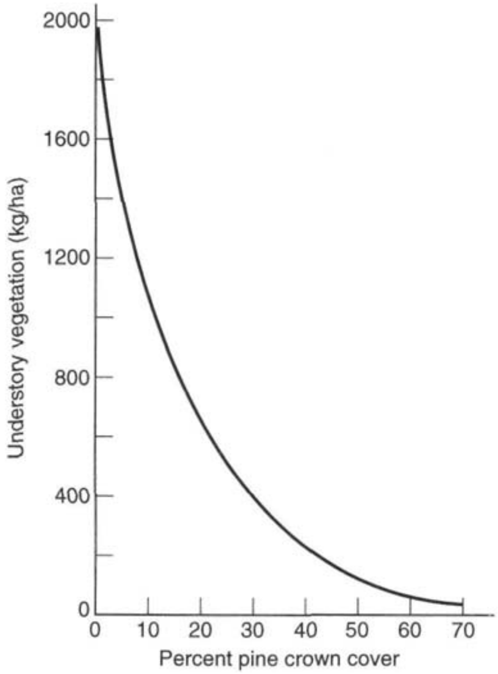

Figure 15.2 Production of understory herbage as related to the density of a ponderosa pine canopy. (After Pase [11].)

frequently graze this range in spring before moving to higher-elevation summer ranges, and again in fall as they return to their wintering areas. The pinon-juniper type is also very important as the seasonal habitat for migratory deer.

Fire suppression and overgrazing by livestock have allowed woodland to expand both upslope and downslope over the past 100+ years (12). Prescribed burns and mechanical removal of pinon and juniper trees by chaining—large tractors pulling anchor chains or cables over the land—are frequently used to reduce the invasion of this type. Desirable grasses are also commonly seeded into recently treated areas to increase forage for livestock and wildlife.

The aspen range has long been recognized for its importance to livestock and wildlife, because it creates diversity in otherwise homogeneous conifer stands. The aspen range is valued for the diversity and productivity of its understory vegetation. This type is the most productive of the forested ranges and often produces more than 2000 kilograms per hectare of understory vegetation. This amount is similar to that of many grasslands. Frequently the aspen range produces more than ten times the amount of understory that associated conifer stands do (13).

Aspen is one of the most common trees in the interior West and grows along moist stream bottoms, as well as on dry ridges and southerly exposures (Figure 15.3), on sloping embankments, and on shallow to deep soils of varied origin. The aspen range extends from Alaska to northern Mexico.

Grazing by cattle and sheep has been the primary consumptive use of the aspen range in the West (14). Livestock grazing usually occurs during summer and early autumn. Overgrazing by livestock during the first half of the twentieth century caused deleterious, long-term changes in much of this ecosystem. Excessive grazing generally changes the composition of understory species and frequently reduces productivity.

Proper management of both the aspen trees and the understory forage resource requires careful planning. Timber management should produce a variety of several aspen seral stages to maximize quantity and quality of the forage and to produce the diversity that is apparently necessary for uses of this type. Grazing guidelines have been summarized for this range (14).

Figure 15.3 Summer grazing on an open mountain meadow range with aspen stands in the background. (Photograph by J. D\Stednick.)

Transitory ranges are forested areas that are suitable for grazing for only a temporary number of years following complete or partial forest removal. After that, the overstory closes in and intercepts the light needed to produce understory forage. Major areas of transitory range in the United States are found in the South and Northwest. These regions have ample precipitation and long growing seasons. Forage yields in these regions commonly exceed 2000 kilograms per hectare in cutover forests or under sparse tree canopies (15).

Tree overstory is the most influential factor determining forage yields in transitory ranges. For example, in the southern pine-hardwood range, forage yield in most clearcuts exceeds preharvesting yields by six to twenty times (16). This substantial increase in forage can in turn be allocated to livestock and wildlife populations.

In the past, foresters had little desire to integrate livestock with timber production. Their concern was that livestock would damage seedling regeneration through trampling and browsing and therefore reduce timber production. It has been well documented that when livestock numbers, distribution, or season of grazing have not been controlled, damage to timber reproduction has frequently been unacceptable (17).

In contrast, when livestock numbers and period of grazing have been appropriate, damage to conifer regeneration has been negligible (18). Although cattle may browse or debark trees, the majority of damage to regeneration done by cattle is from trampling and rubbing. Sheep, on the other hand, primarily damage seedlings by browsing their foliage. Browsing of regeneration by livestock is normally confined to current annual growth and generally the early succulent growth (18). Recommendations for the management of livestock grazing in young timber plantations generally call for the exclusion of livestock either until seedlings are well established (two to three years) or until the terminal leader of the seedlings are out of reach of grazing livestock.

Controlled livestock grazing can potentially benefit timber regeneration in several ways. These include reducing competition, decreasing the fire hazard, preventing the suppression of seedling, and decreasing the habitat of rodents, which damage seedlings. Another important advantage of integrated timber and livestock management, called *agroforestry,* is that profits can be higher than with single-resource management. Changing markets encourage flexibility in the overall operation, because diversification provides a means of surviving poor markets.

Nonforested Rangelands

The mountain meadows range ecosystem consists of wet to intermittently wet sites in the forest zone of the western United States. Typically, this range occurs on nearly flat to gently sloping topography where surface or subsurface water accumulates in the rooting zone for at least a portion of the year (9). Grasses and grasslike plants are generally the dominant vegetation in this type of range (Figure 15.4).

Mountain meadows are extremely productive and often yield ten to twenty times more forage than surrounding uplands (19). These meadows produce very high-quality forage which remains green and nutritious late into the summer. Mountain meadows support more livestock per hectare than any other

Figure 15.4 Cattle grazing on a meadow in Saint Joe National Forest, Idaho. (Photograph by W. W. Dresskell, U.S.D.A. Forest Service.)

type of range in the United States. Because of these advantages, mountain meadows are a very important link in year-round livestock production.

In addition to their great value for the production of livestock, mountain meadows are important for the maintenance of wildlife populations, and many act as a filter to catch sediments from water flowing from surrounding slopes. Mountain meadows also provide scenic vistas and are often preferred by recreationists.

Favorable grazing conditions, coupled with proximity to water and the steepness of slopes in adjacent range types, often encourage high concentrations of livestock and wildlife in the meadows. This uneven distribution of grazing animals can result in overgrazing and deterioration of mountain meadows.

Because mountain meadows already have a great potential for productivity, improving them is frequently cost-effective. Effective range management practices designed to improve livestock distribution include the development of water, placing salt licks in upland ranges, and herding (drifting) stock away from meadows. Where meadows are sufficiently large to be fenced separately from upland ranges, it may be economical to separate the two to protect the meadows from constant use and to ensure utilization of the upland forage (19). Grazing systems that have been developed for upland ranges have generally been ineffective in improving the condition of overgrazed mountain meadows, largely because they have failed to reduce livestock concentrations in the meadow (20).

Riparian zones—areas near streams, lakes, and wet areas whose plant communities are predominantly influenced by their association with water (21)—have been estimated to occupy between 0.5 and 2 percent of western rangelands. Although these zones constitute a relatively minor proportion of any watershed area, their importance in providing places for livestock to.graze, fish and wildlife habitats, and recreational opportunities is disproportionately high.

Healthy riparian ecosystems have become a vanishing resource in the West, particularly in arid and semiarid regions. Estimates are that America has lost between 70 and 90 percent of its indigenous riparian resources and badly damaged much of the rest (22). In 1977, the U.S.D.I. Bureau of Land Management concluded that 83 percent of the riparian systems under its control were in unsatisfactory condition and in need of improved management, largely because of destruction caused by excessive livestock and grazing, road construction, and other damaging human activities. Many riparian zones have been ignored in the planning process because their limited extent made them "sacrifice areas."

Cattle often concentrate in riparian zones and utilize the vegetation much more intensively than that in adjacent areas. This heavy livestock grazing has frequently decreased plant vigor and production, changed the composition of plant species, and altered the streambank channel (20). Numerous studies have reported the deleterious effects of heavy livestock grazing on the regeneration of woody vegetation and the subsequent damage to the fisheries resource (23). Riparian ecosystems are the most critical zones for multiple-use planning and offer the greatest challenge to proper management (20). Techniques of riparian zone management include:

1. Improving livestock distribution, which increases animal use of upland range and decreases stock concentration in riparian zones.
2. Maintaining a minimum amount of residual vegetation (stubble height) to help preserve plant vigor, reduce browsing of willows and other woody plants, trap sediments, and limit streambank impact (24).
3. Implementing a specialized grazing system to provide a deferment and rest from grazing.
4. Changing the kind or class of animals grazing riparian zones. Sheep are generally less damaging than cattle to riparian zones because they are more easily controlled and can be herded away from riparian zones.
5. Managing riparian zones as "special-use" pastures. This increases the flexibility of the operation in regulating the level of grazing in riparian zones and allows grazing during the least damaging period (Figure 15.5).

6. **Excluding the zones from livestock grazing.** Riparian zones are generally very resilient and often improve in condition within five to seven years after livestock have been removed.
7. Constructing in-stream structures. These are expensive but have generally been successful in improving the condition of riparian zones when coupled with a change in grazing management (20).

Rangeland Water Quality

The most important deleterious effect of improper range management on water quality is soil erosion and the subsequent suspended sediment. Vegetative cover and soil properties determine the infiltration rates of precipitation water and the amount of streamflow that occurs on grazed lands. Vegetative cover is the dominant factor in controlling runoff and water erosion from agricultural lands and rangelands (25). Livestock grazing may alter the natural infiltration-runoff relationships by reducing the vegetative cover, by reducing and scattering the litter, and by compacting the soil through trampling. The magnitude of these changes is determined by the physiography, climate, vegetation, stocking rate, and animal species.

Raindrops striking bare soil may dislodge soil particles and increase soil erosion. Dislodged soil particles may block soil pores, further reducing infiltration rates, while other dislodged particles may remain suspended and leave the site in overland flow. However, water yield from overland flow may be increased by the decreased infiltration rates and capacities and the soil compaction (also see Chapter 16 on Watershed Management).

Soil compaction is the packing together of soil particles, thus increasing the soil bulk density (measured in grams per cubic centimeter). As use of an area increases, the probability of soil compaction also increases. Animal bedding grounds, stock trails, watering locations, and salt licks are areas of greatest compaction. Soil texture, moisture, and the amount of organic matter influence the degree of compaction (see Chapter 5). Soil compaction may also reduce plant growth or range productivity through changes in soil aeration and soil moisture. This reduction in vegetative cover may in turn increase the occurrence of overland flow and contribute to the desertification of marginal rangelands.

Land uses that increase water yield by reducing infiltration may also increase soil erosion and the subsequent amount of suspended sediment. Vegetative cover is important in minimizing overland flow. Land uses that increase infiltration rates help

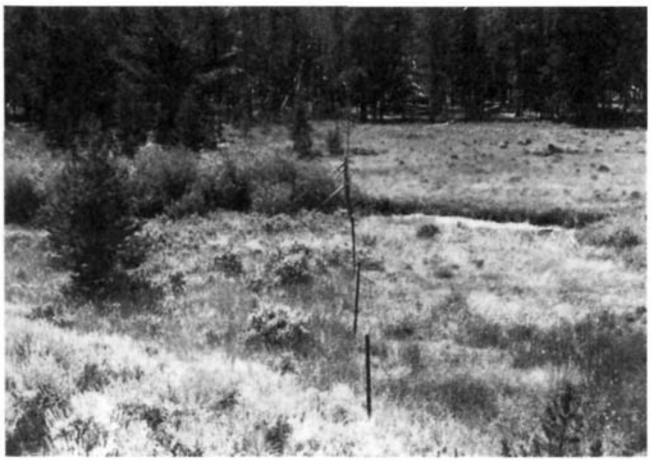

Figure 15.5 Fenceline contrast between a riparian pasture that has been lightly grazed for twenty-five years (left of fence) and an adjacent heavily grazed area. Notice the willow regeneration in the lightly grazed pasture. (Photograph by W. C. Leininger.)

to establish desired plant species and to increase the plant biomass.

Range management practices designed to increase the growth of desired plants and increase water infiltration include vegetation conversion by chaining, contour furrowing, or root plowing. Land treatment by plowing and seeding generally lowers water infiltration rates at first and increases erosion. However, after two years, less soil is usually lost, because vegetative cover is greater than before treatment. Treatment by spraying and seeding has given similar results of lower magnitude. Treatment by burning and seeding may create hydrophobic soils, reduce water infiltration, and increase soil loss (26). The impact of erosion on site productivity has not been quantified for any rangeland plant-soil complex in the western United States.

Moderate continuous grazing or specialized grazing systems that improve the production of vegetation or herbage should reduce sediment yield. If a watershed has been overgrazed, though, institution of a grazing system will not necessarily reduce sediment.

Riparian grazing systems may alter the morphology of stream channels and cause associated changes in channel hydraulics, water quality, and the accumulation of sediment. Livestock grazed along Meadow Creek in northern Oregon did not accelerate the degradation of the streambank. In this study, most streambank erosion occurred during winter periods and was independent of livestock activity during the grazing season (27). In another study in northwestern Oregon, streambank erosion and disturbance were significantly greater in areas grazed by cattle in late summer than in adjacent ungrazed enclosures (28).

Animal activity along stream channels or other open waters may change the chemical and bacterial quality of water. Specifically, animal feces may contaminate waters with bacteria or act as sources of nitrate and phosphate. Studies of two adjacent pastures along Trout Creek in central Colorado indicated only minor chemical effects of cattle grazing on water quality. The bacterial contamination of the water by fecal matter, however, increased significantly. After the cattle were removed, bacterial counts quickly dropped to levels similar to those in the ungrazed pasture (29).

Changes in the chemical quality of water through grazing activities are generally not significant or long-lasting, unless animals and their waste products are concentrated in one area. Specifically, nitrate-nitrogen concentrations may increase and change water quality, since the nitrate-nitrogen is a mobile anion (see Chapters 5 and 16). High nitrate-nitrogen concentrations in groundwaters below feedlots are well known.

Hydrologic Evaluation of Grazing Systems

Most watershed studies have evaluated the impact of livestock grazing on hydrologic variables after grazing treatments have been in effect for several years. Treatment plots, areas, or watersheds are then compared to a nongrazed counterpart and differences are attributed to grazing. The grazing is varied in both duration and intensity. Few studies have assessed seasonal or long-term hydraulic impacts of grazing systems, and additional studies, both intensive and extensive, are needed (30).

In general, the removal of plant cover by grazing may increase the impact of raindrops, decrease the amount of organic matter in the soil, increase surface crusting (puddling), decrease infiltration rates, and increase erosion. Increased overland flow, reduced soil moisture, and increased erosion translate into greater concentrations of suspended sediment. A further discussion of the hydrologic cycle is given in Chapter 16. Other water quality impacts such as increased bacterial and nutrient concentrations do not appear to be a problem with grazing systems, except perhaps in riparian zones.

The impact of livestock grazing on watersheds has recently become a resource management issue of national proportions. Research project data have often been evaluated emotionally or according to the political advantages offered rather than by scientific and objective thinking.

The advantages between light and moderate grazing intensities for watershed protection are often not significantly different (2). Recent interest in federal grazing practices, particularly grazing allotments, may bring a reevaluation of the environmental and economic implications of grazing systems on watershed resources (Figure 15.6).

Concluding Statement

Rangelands occupy nearly half of the world's land surface, and are an important source of forage for wildlife and domestic animals, as well as water, wood products, and recreational opportunities. During the late 1800s and early 1900s, many rangelands were overgrazed by domestic livestock. A reduction in livestock numbers and the implementation of grazing systems allowed many of these areas to recover. Understory forage that is produced in forested communities is critical to many ranching operations in the western United States. These areas are managed with a permit system of grazing and provide summer pasture for cattle and sheep.

Livestock grazing rangelands has the potential to alter the natural infiltration-runoff relationships by reducing the vegetative cover, including litter cover on the soil surface, and compacting the soil through trampling. Animal bedding grounds, stock trails, watering locations, and salt licks are the areas of greatest compaction and have the highest risk to soil erosion. Other water quality impacts such as increased bacterial and nutrient concentrations, do not appear to be a problem with grazing on rangelands, except perhaps in riparian zones. The differences between light and moderate grazing intensities for watershed protection are often not significantly different.

Figure 15.6 Counting cattle on Bull Mountain Allotment, Deerlodge National Forest, Montana. (Photograph by G. R. Walstad, U.S.D.A. Forest Service.)

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CHAPTER 16

Watershed Management: A Regional to Global Perspective

D. SCOTT MACKAY

The Watershed

John Wesley Powell, scientist, geographer, and leader of the first expedition through the Grand Canyon, stated in 1869 (http://www.epa.gov/adopt):

> **. . . that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of the community**

Water plays a central role in most of earth's systems and is essential for all life. Water is the medium for biochemical reactions that sustain living organisms. Water helps redistribute energy via the oceans and atmosphere. Water also contributes to the erosion and transport of minerals, organic material, and other substances. Water in the earth system has remained, on the whole, a constant for billions of years. It is moved within and between the atmosphere, lithosphere, and biosphere in a recirculatory system known as the hydrologic cycle. It may be thought of as a limited resource, which, as a result of human influence on global change, must be properly managed. Management of water resources has the primary task of preserving a supply of water of sufficient quality to meet the demands of society. Water must also be managed, in the sense that too much water may mean flooding, excessive erosion of land, and potentially loss of life. The proper management of water resources requires an understanding of how water is circulated. It also requires an understanding of how water resources interact with natural and anthropogenic processes. A framework for managing water resources could consider any size system, from the entire earth down to an individual organism seeking water to survive. However, there is a need for an integrating framework that can consider systems of all sizes and organize them. The *watershed* is such a framework and it represents the basic unit for watershed management.

A *watershed* is generally defined as an area of land that drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel (1). Watersheds are nature's way of dividing up the landscape. Rivers, lakes, estuaries, wetlands, streams, and even the oceans can serve as catch basins for the land adjacent to them. Ground water aquifers serve the same purpose for the land above them. The actions of people who live within a watershed affect the health of the waters that drain through it. The watershed can be defined in terms of some arbitrary spatial extent, such as 50 to 5,000 hectares (Table 16.1). More generally, the watershed is a unit area of land with well-defined boundaries that promotes the understanding of how water enters an area of interest, is stored, moved and modified within that area, and then may be exported from the area of interest.

The natural evolution of a watershed begins either with the uplifting of land as a result of collisions between moving plates of the earth's crust, or with volcanic activity. Precipitation falling on uplifted land tends to move, either on the surface or below, to the oceans with the force of gravity. Water traveling on the surface will tend to flow along preferential pathways depending upon irregularities in the surface. These preferential pathways channelize the flow of water in rills. Eventually, further erosion expands the rills to produce stream channels as the water erodes the surface. As these channels are incised, their steep slopes become sites for further erosion. Eventually, streams channels are formed. Sites nearest the channels tend to erode the most and sites furthest away from the channels erode the least. Thus, regions intermediate between channels remain at relatively high elevation and form divides. Figure 16.1 shows the basic form of the erosional watershed. A region bounded by divides and a stream channel can be viewed as a hillslope on which there are measurable flow pathways. Surface water can infiltrate the soil or run along the surface. Some of the infiltrated water may be evaporated, and the rest enters a

Table 16.1 Spatial scales of watersheds can be defined with respect to other management unit sizes.

Physical Area	Spatial Scale (order of magnitude, in hectares)	Management
Microsite	10^{-1} to 10^{0}	
Stand	10^{0} to 10^{1}	Cutting unit[a]
Watershed	10^{1} to 10^{3}	Watershed
Landscape	10^{2} to 10^{4}	District[b]
Multi-landscape	10^{4} to 10^{5}	Timbershed[c]
Subregion	10^{5} to 10^{6}	Forest[d]
Region	10^{6} to 10^{7}	Pacific Northwest[e]

Source: Brooks and Grant (2).

[a] Timber harvest for stand replacement is generally smaller on public lands and larger on private lands.

[b] A National Forest Ranger District, for example, representing a minimum area for which community issues, such as effects of towns and groups of towns, can be usefully examined.

[c] This classification is based on timber production and processing; a timbershed contains at least one major timber-processing center, and the majority of the timber processed originates in that timbershed.

[d] National Forests in Oregon and Washington range from 100,000 to 500,000 hectares.

[e] All timberland in western Oregon is about 5 million hectares.

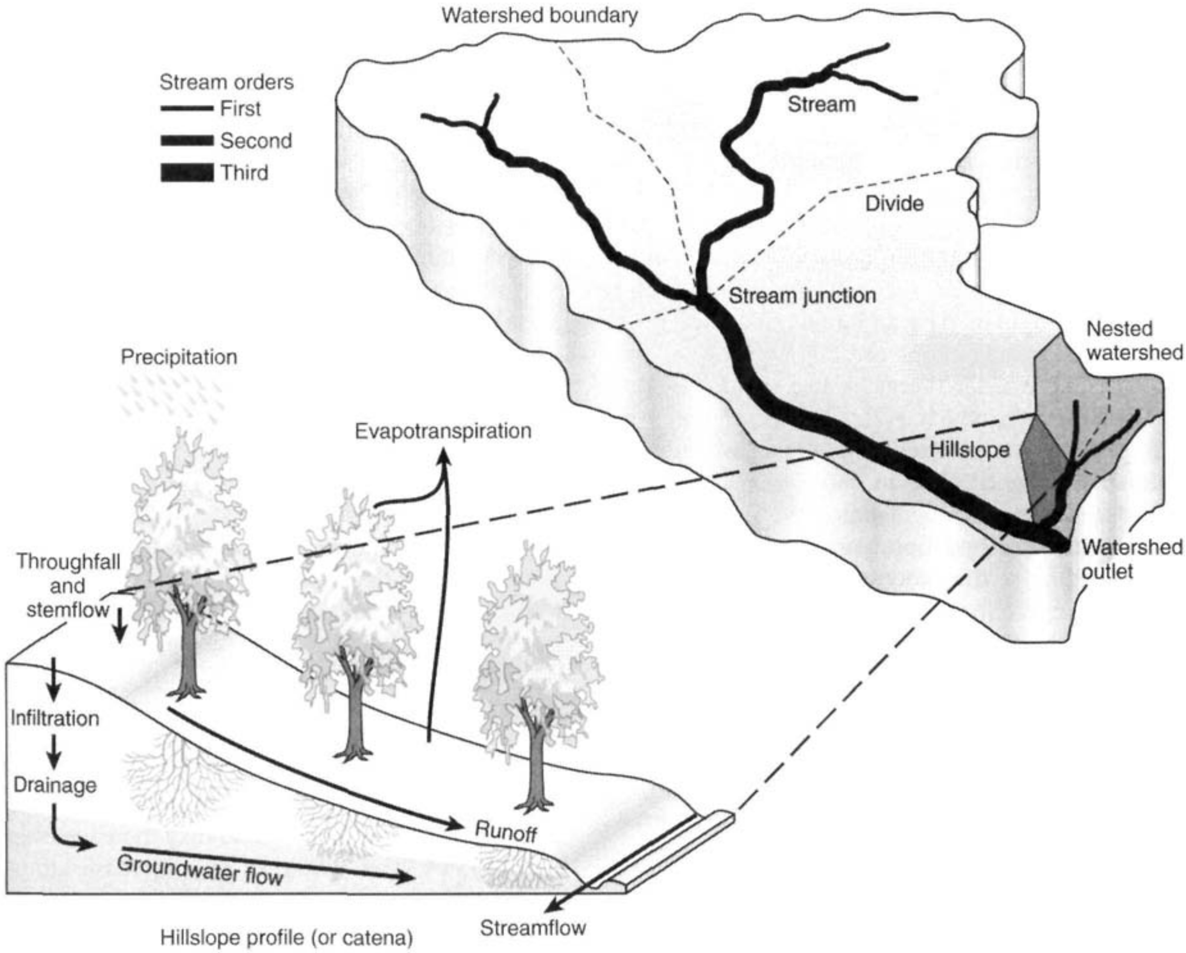

Figure 16.1 Shown are the basic components of the watershed. Stream orders are important in understanding the size of area that influences a given stream reach. Watersheds are naturally nested features, which means that smaller watersheds reside within larger watersheds. At some nesting level, it is possible to distinguish hillslopes for which hydrologic flow paths can often be directly observed. The hillslope profile indicates the major flow paths of water when precipitation falls on a vegetated slope.

groundwater flow. The surface and subsurface characteristics of a hillslope determine the partitioning of flow as surface runoff, as groundwater flow, and as evaporation. Watershed outputs of water, sediment, nutrients, and other pollutants represent the sum of these constituents generated on all hillslopes within the watershed.

It is desirable to limit the amount of surface runoff, since runoff promotes soil erosion. The process of water movement on the surface results in sediment, organic material, and nutrients being carried with the water off the landscape and through the channels. The watershed thus provides a framework within which other resources, such as forests, agricultural crops, and urban landscapes can be managed. The view of the watershed as a unit for management with no implied spatial extent is useful, since the land surfaces of the whole earth can be divided up into watersheds with very large areas. Each of these large watersheds can in turn be divided into smaller watersheds, and so on. Furthermore, at a detailed level it is possible to measure water, sediment, or nutrient budgets on individual hillslopes and then combine them to predict watershed budgets. For instance, one might view the entire Mississippi River basin or the entire Amazon River basin as defining multistate and multination areas for management, respectively. Alternatively, the watershed drained by a tributary of a large river could be a management area. For example, we might be interested in the watershed drained by the Wisconsin River, which is a tributary of the Mississippi River. At a smaller scale, the Lake Mendota Watershed around Madison, Wisconsin, might be considered a management unit.

Once a watershed boundary is delineated, an understanding of the processes that determine the fate of water entering the watershed is needed. Since the full extent of human activity and of natural systems is global, we will begin at this spatial extent and work our way down to smaller watersheds. In this chapter we shall consider the following:

- processes responsible for the hydrologic cycle;
- interrelationships between water and terrestrial vegetation;
- issues and approaches in the management of water resources within a watershed framework;
- recent approaches to watershed management, including the transfer of responsibility from government to nongovernment organizations; and
- use of technology such as geographical information systems and remote sensing for water resource studies and management.

The Global Hydrologic Cycle

Hydrology (*Hydros*, meaning "water," and *ology*, meaning "study of") is the science that seeks to understand the processes of storage, transformation, and movement of water. These processes are collectively referred to as the hydrologic cycle, a global scale recirculatory system that links water in the atmosphere, biosphere, and lithosphere. Most of the components of the hydrologic cycle, except for permanent ice, are depicted in Figure 16.2. The various storage compartments for water include the oceans, permanent ice, ground water, soil water, fresh water bodies and rivers, the atmosphere, and the biosphere (plants and animals). The transformations between the storage compartments for water in the earth system include precipitation, evaporation, transpiration, infiltration, runoff, and groundwater flow. *Precipitation* is formed from the condensation of water in the atmosphere as it cools. *Evaporation* is the transformation of liquid or solid water to a gaseous form. It requires the input of energy, primarily from the sun. Once evaporated and released into the atmosphere, the water vapor moves with the atmospheric air circulation. Water evaporated from one location can then be transported in the atmosphere to another location where it may fall as precipitation. By altering surface properties that affect evaporation, we are in effect altering precipitation patterns. For instance, large-scale removal of vegetation, such as is occurring in the Amazon, may reduce evaporation rates and eventually reduce precipitation amounts in other areas. Climate warming associated with increased levels of atmospheric carbon dioxide may increase evaporation rates. This would in turn increase atmospheric moisture content, which would increase the intensity or frequency of storm events.

Transpiration is a specialized form of evaporation involving the release of water from photosynthesizing vegetation. Vegetation draws water from the soil through its roots, stores it within the plant and releases it to the atmosphere as part of its need to remove carbon dioxide from the atmosphere for photosynthesis. On a global scale, the biosphere stores at any given time less than 1 percent of the amount of water that falls as precipitation, and yet over 60 percent of global annual average precipitation is cycled through the biosphere. Thus, transpiration and evaporation from vegetation form important links between surface water and the atmosphere. Together they form an important contribution to atmospheric moisture levels and ultimately precipitation. It is not difficult to see that by

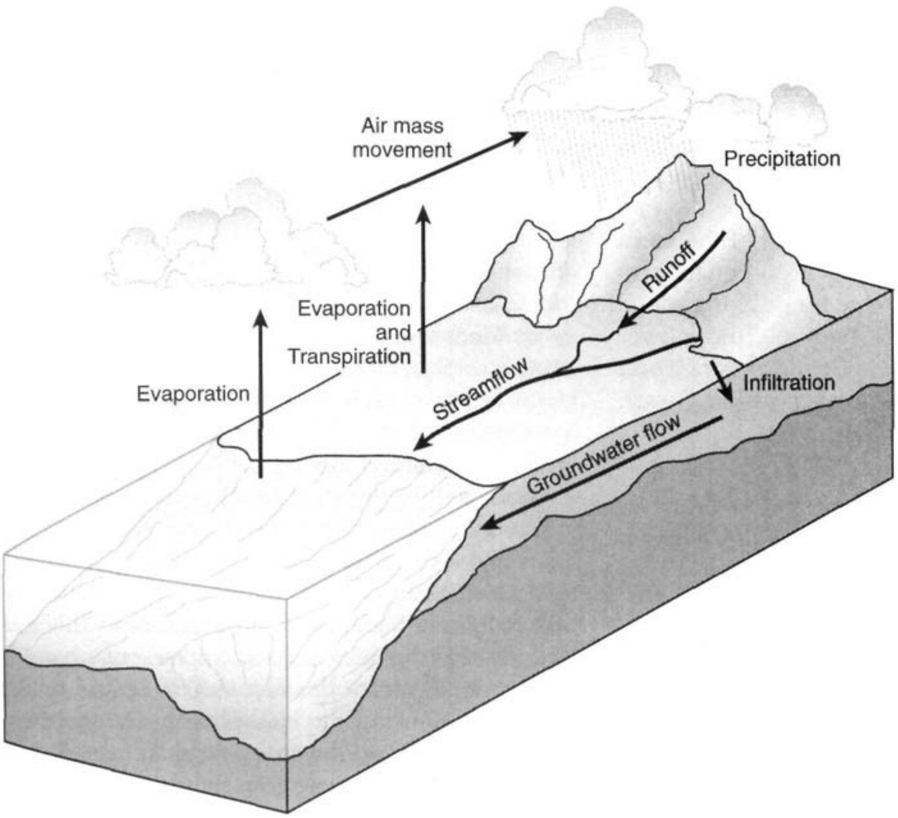

Figure 16.2 The major components of the global hydrologic cycle

altering the distribution of forests one can potentially greatly change the global distribution of evaporation and transpiration, which can in turn result in regional differences in precipitation patterns.

Infiltration and storage of water in soils helps us to link surface water with ground water, to understand spatial patterns of vegetation, to understand and predict flooding, and to trace the movement of pollutants that are carried in surface water. Water infiltrates into a soil at a rate that depends on surface characteristics, soil texture, and the amount and rate of water input (see Chapter 5, Forest Soils). Surface water that does not infiltrate must either pond at the surface or run along the surface.

At a global scale water can be considered conserved, which means that it is neither created nor destroyed.[1] This means that any part of the hydrologic cycle has a water budget that can be described in terms of water inputs, outputs, and change in storage as follows:

inputs - outputs = change in storage

For instance, the water balance equation for a volume of soil is given by:

$$\Delta S = I - (P + E + T)$$

where ΔS is the change in water stored in the soil over a defined time period, I is the amount of water

[1] Water can be released from volcanic activity. However, it is believed that the primary source of water on the earth's surface was derived from comets and meteorites that bombarded the earth during the first billion years after its formation.

that infiltrates into soil, *P* is the amount of water that percolates through the soil, *E* is evaporation of water from the soil surface, and *T* is transpiration by plants drawing water out of the soil during this time period. An equation of this form is known as a *water conservation equation.* Conservation equations can be used to describe the rate of change of water stored in any part of the earth system. We might use a conservation equation to determine groundwater storage for drinking water, reservoir storage used for hydroelectric power generation, water levels in the Great Lakes of North America, or water available for vegetation growth in different areas of our planet.

Global Distribution of Terrestrial Water and Life

Precipitation

The hydrologic cycle can be approached from any one of the storage compartments and flows represented in Figure 16.2. We will start with precipitation, because it is the primary source of water for terrestrial ecosystems. Precipitation occurs because atmospheric pressure affects air temperature, which in turn determines how much water vapor the air can hold. Like all gases, air can be compressed. The weight of a column of atmosphere above a given parcel of air exerts pressure on the parcel, which tends to compress it. When air is compressed, the molecules within it are confined to a smaller volume, which means they are more likely to collide. These collisions produce heat that warms the air parcel. The cooling (or warming) of air from a change in pressure is known as *adiabatic* cooling (or warming). When air rises in the atmosphere, it experiences a reduction in atmospheric pressure and is cooled adiabatically. Similarly, when air sinks, the atmospheric pressure on it increases and it warms adiabatically. Suppose a parcel of air is warmed by solar energy absorbed at the land surface. By warming the air, the increased energy will cause its molecules to move more quickly. Their interactions in turn exert greater pressure, which expands the air. When a parcel of air expands, it becomes less dense. If it is less dense than the surrounding atmosphere, it is buoyant and rises. The warmed air generally continues to rise until it is cooled adiabatically to the same temperature as the surrounding atmosphere. As the parcel of air is cooled, its ability to hold water is reduced. If the parcel of air is cooled sufficiently, it may reach a point where the amount of water it holds exceeds the amount it can hold. The result is condensation, which is a source of water for clouds and precipitation.

In order to understand regional differences in precipitation, we need to know something about global climate and the ways in which precipitation is produced. Figure 16.3 shows average annual distribution of precipitation and vegetation (see Figure 16.3 in color insert). We will discuss the relationships between these later. Precipitation is generally very high in the equatorial zone. This area is known as the inter-tropical convergence zone. It gets its name from the fact that it occurs where southward-moving air masses from the northern hemisphere and northward-moving air masses from the southern hemisphere converge. The winds associated with these air masses are commonly known as the Trade Winds. As the Trade Winds move over the tropical oceans, they collect water vapor that was evaporated from the oceans. Where these winds converge, they are forced to rise upward into the atmosphere where they cool and release precipitation. Other areas of large rainfall amounts include western sides of large mountains where warm, moist air is forced to rise over the mountains. As it rises up the mountain, the air is cooled, which promotes precipitation. For example, the Pacific Northwest receives a large amount of precipitation annually (2500 mm or more). In general, midlatitude areas receive much of their precipitation from extratropical cyclones. These are eastward-moving low-pressure cells that form where arctic and subtropical air masses meet. Extratropical cyclones act as heat engines by drawing warm, generally moisture-laden air northward. At fronts separating warm and cold air masses, this moist air is forced to cool and precipitation results. More localized precipitation occurs in thunderstorms, which are the result of intense warming of moist air at the ground surface. The warm, buoyant surface air rises high in the atmosphere where it cools adiabatically and forms thunder clouds. In all cases, precipitation occurs where moisture-laden air is forced to rise and lose its ability to hold the moisture.

Deserts and semi-arid areas occur in areas where relatively dry air descends and warms adiabatically. This occurs in subtropical regions, including north-central Africa and central Australia. Arid and semi-arid areas also occur on eastern sides of large mountain ranges where air is descending after losing its water to precipitation on the western side of the mountain. Semi-arid areas are found in inter-mountain areas of western North America, which receive Pacific air masses that have released much of their moisture on the western (or windward) sides of the mountains. Midcontinental areas tend to be drier than coastal because of their great distance from oceanic sources of moisture. The eastern part of the United States and southeastern Canada experience greater quantities of precipitation from moisture evaporated from the Gulf of Mexico.

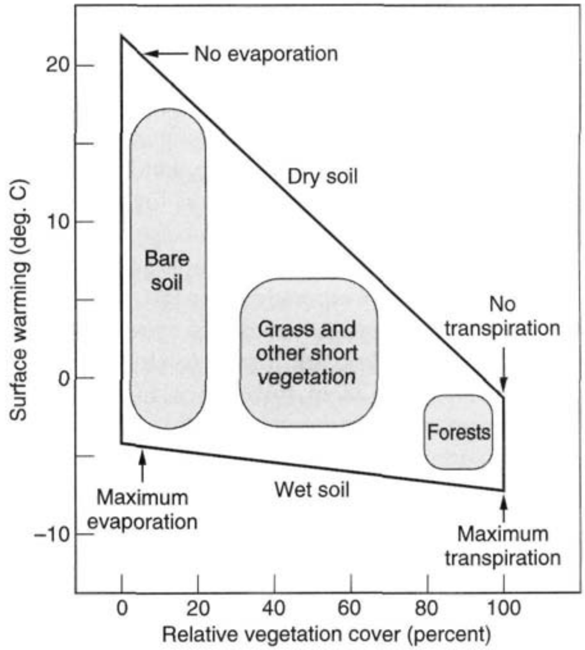

Figure 16.4 This figure shows how surfaces of different vegetation types and moisture availability partition solar radiation. In general, wet surfaces use the energy to evaporate water and dry surfaces heat up. Dense vegetation has an abundance of leaf surface area for both shedding evaporated water and heat. Bare soil has a minimal surface area exposed to the atmosphere, so its heating depends much more on energy partitioning.

Evaporation and Transpiration

Air masses moving over water bodies and other sources of water pick up some of this water through evaporation. Evaporation is the process by which solid or liquid water on the surface is converted into vapor form and released into the atmosphere. The conversion to water vapor uses energy, most of which is received from solar radiation. Energy from the sun that enters the earth system and is intercepted at the surface is used either to heat the surface or to evaporate water. For most surfaces, some of the energy goes into surface heating and some goes into evaporating water. Wet surfaces tend to use most of the energy for evaporation, while very dry surfaces heat up (Figure 16.4). For example, when a water body absorbs solar energy, it is mostly used to evaporate water rather than warming the water. At the other extreme, deserts usually have little moisture available for evaporation and so absorbed energy here is used to heat the land surface. Energy used for warming is referred to as *sensible heat energy* and energy used in evaporating water is *latent heat energy.* The ratio of latent to sensible heat energies is known as a *Bowen ratio.* Bowen ratios for the tropical oceans are about 10:1, and they are about 1:10 for deserts. Well-watered forests and other terrestrial vegetation have Bowen ratios that average about 1:1, which means they use about half their absorbed energy to convert water from liquid to vapor.

The rate at which water converted into vapor form is transferred from an evaporating surface to the atmosphere depends on two factors. The first is how dry the air interacting with the surface is. The second is turbulent winds that promote the uplift of water vapor into the atmosphere. As stated above, warm air can hold more moisture than cool air. Warm, dry air promotes a faster rate of evaporation than cool, moist air. We will refer to this as the evaporative demand of the atmosphere. Air masses that have moved across dry land areas tend to have low moisture contents and high evaporative demands. Alternatively, air masses that have moved through wet regions, such as over oceans, have relatively low evaporative demand. Winds traveling over rough surfaces, such as forests, tall buildings, and even grass, are forced to slow near the surface. This results in turbulence in the lower atmosphere, which promotes greater mixing of air near the surface. This mixing helps to remove evaporating water and promote further evaporation. The rougher the surface, the more efficient it is at generating turbulence. For example, tall vegetation (e.g., a tree) creates a more efficient evaporative surface than shorter vegetation (e.g., grass), because they have more leaf surface in direct contact with the atmosphere. This increased exposed surface area also allows forests to more quickly shed sensible heat, so they remain cooler than grass or bare soil.

Interception (I) is the amount of precipitation that is trapped on leaves, branches, and surface organic matter and residues. Once intercepted, this water may evaporate and thus never infiltrate into the soil. Forests have relatively large intercepting surface areas (the leaves), and as described above, these surface areas promote high rates of evaporation. The effect of interception is most evident when walking in a forest at the beginning of a rain event. There is usually a short time in which you can remain dry under the forest canopy. Once the canopy's capacity to store water has been exceeded, further rainfall will either drip down to the ground from the leaves, a process known as throughfall, or it will travel along branches and stems until it reaches the ground, a process known as stemflow.

The importance of interception in the water balance of forests depends on the ability of the canopy to intercept water, the atmosphere to dry the canopy, and the frequency and magnitude of rainfall. Small, infrequent rainfall may never reach the soil surface in dense forests. However, most of the precipitation from large or frequent events will go to throughfall or stemflow. Given enough time between precipitation events and high enough evaporation rates, interception can be a very important part of the hydrologic cycle. Numerous studies have shown that the reduction in interception when forests are harvested results in higher rates of soil recharge, greater runoff, and high potential for soil erosion. Interception can be as important or more important than water plant transpiration. Table 16.2 illustrates some typical amounts of interception for different vegetation types. Clearly, the conversion of land cover from one form of vegetation to another can have an impact on interception. For example, Law (3) found that a Sitka spruce plantation produced 280 mm less soil recharge than adjacent grasslands. Swank and Miner (4) found a 33-94 mm reduction in groundwater recharge in watersheds where deciduous cover was replaced with white pine. Hibbert (5) showed a five-to-six-fold increase in annual runoff resulting from the removal of brush and replacement with grass. Some of these differences are attributable to transpiration rates, which we will discuss next.

A special form of evaporation known as *transpiration* is the release of moisture from stomatal openings on the leaf surfaces of terrestrial vegetation. Stomatal openings permit atmospheric carbon dioxide to mix with the water and be drawn into the leaf for photosynthesis (see also Chapter 4, Forest Ecophysiology). The water is drawn from the soil through the roots, and through the xylem up to the leaves. When stomatal cells are open to the atmosphere, photosynthesis can occur. However, the stomatal openings may be thought of as small evaporating surfaces subject to the atmospheric demand for water. Water released from the stomatal cells to the atmosphere is called transpiration. When the atmospheric demand is very high or the availability of moisture in the soil is too low, the stomatal openings are closed in an effort to regulate xylem water potential. Stomatal closure reduces or shuts off transpiration and photosynthesis. The physiologic controls on transpiration dis-

Table 16.2 Estimates of the Percent of Precipitation that Is Intercepted by Different Vegetation Types

Vegetation Type	Percent Precipitation Intercepted
Forests	
Deciduous	13
Coniferous	28
Crops	
Alfalfa	36
Corn	16
Oats	7
Grasses	10-20

Source: Dunne and Leopold (1).

tinguish it from other forms of evaporation, and yet evaporation and transpiration are often combined in a single term known as *evapotranspiration* (ET). However, it is important to remember that the two forms of evaporation are different. Stomatal closure reduces both transpiration and photosynthesis. It is through stomatal control that primary production is linked to atmospheric demand and soil moisture availability, both of which depend upon precipitation. By understanding this relationship, we can interpret the global distribution of terrestrial vegetation in terms of patterns of precipitation (see Figure 16.3 in color insert). The observant reader will note that boundaries and transitions between vegetation densities and precipitation quantities correspond. The global distribution of vegetation can thus be partially related to the various controls on the distribution of precipitation.

More directly, the density of vegetation supported should depend on a balance between precipitation and ET. This can be accounted for as soil water storage. The amount of water available in the soil depends on precipitation as a source of water, ET, and hydraulic characteristics of the soils. It is often useful to consider soil moisture content as more or less constant over a long period of time. It allows us to approximate water availability for plant use using the relationship between precipitation and potential ET. Potential ET is considered to be the rate of evaporation from vegetated surfaces when soil moisture is high enough to keep the leaf stomata open. In general, areas with high amounts of precipitation in relation to potential ET rates can support denser vegetation canopies. High water use in areas of low precipitation will not allow this vegetation to grow and thrive (Figure 16.5). Deserts have low precipitation inputs and high evaporative demand from high solar radiation inputs, high temperatures, and dry air masses. Only vegetation that is adapted to semi-arid and arid conditions will survive in these areas. There is a tradeoff between moisture availability (precipitation) and moisture demand (energy input or temperature). Areas with lower energy inputs have lower potential ET rates. These areas can support relatively denser vegetation with lower precipitation than higher energy locations. In general, low latitude areas are warmer and so they require greater amounts of precipitation to support a given vegetation density than high latitude sites. Similarly, low altitude sites are warmer than high altitude sites, so they require higher precipitation rates to sustain the same amount of vegetation. These vegetation-water relations are adequate for explaining

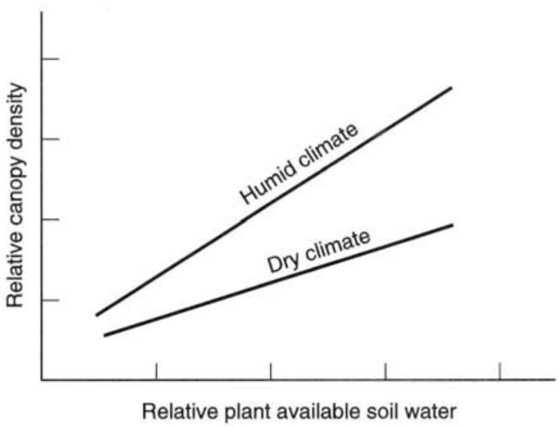

Figure 16.5 A hydrologic equilibrium can exist in which a humid climate with a large storage of soil water can support a dense vegetation cover. A dry climate will tend to require a greater amount of soil water storage in order to support the same vegetation cover supported in a humid climate.

regional to global scale patterns of vegetation, but are incomplete for watershed scales. Within watersheds, the vegetation-water relations are complicated by the need to understand patterns of soil water holding capacities and ground water flow that can produce patterns of drying and wetting based on topographic control. These are considered next.

Soil Water

Soils are made up of minerals, organic matter, water, and air. Natural field soils are porous. The pore spaces are filled with air, water, or a combination of air and water. Most soils have porosity between 45 and 55 percent of the soil volume. Soil pore spaces are pathways for the movement of water. When these pathways are completely filled with water, the soil is saturated; otherwise, it is unsaturated. The rate of flow of water through a saturated soil is called *saturated hydraulic conductivity,* and depends on the texture of the soil. Soil texture refers to the size of the individual particles that make up the soil. For mineral soils, these particles include some combination of sand, silt, and clay, which are respectively considered of coarse, intermediate, and fine texture as described in Chapter 5, Forest Soils. In general, soils with a high sand content have high hydraulic conductivities at saturation, while clayey soils tend to have low saturated hydraulic conductivities.

When a saturated soil begins to drain, it becomes unsaturated. As it does so, its rate of hydraulic conductivity decreases because of a reduction in the number of connected draining pathways. Hydraulic conductivity rates fall rapidly as the soil becomes less saturated, and at low moisture contents they are negligibly small. Soils never drain completely free of water, as there are forces that hold the water against gravity. These forces, known as *capillary forces,* exert a tension on the water within the soil pores. In order to understand the role of tension on water movement in soils, it is important to understand a few conventions in the way in which soil water tension is reported. The point where atmosphere and a saturated soil layer or free-standing body of water meet is said to be at atmospheric pressure. Here the gravitational force exerted on a water molecule is the weight of the atmosphere that lies directly above the water molecule. Below the water surface, the pressure exerted on a water molecule is higher, since it also has the weight of the overlying water column. Capillary forces act on water molecules in all directions, not just downward. Capillary forces are caused by electrical bonds that form between the sidewall of the soil pore space and water molecules. The tension exerted by these electrical forces tends to get larger as the pore spaces become smaller, and so clay soils have greater capillarity than sandy soils. The greatest tension occurs where the moisture content on the soil pore spaces is lowest. Upward tension exerted on water that would otherwise drain freely because of gravity allows the soil to retain water against the force of gravity. Because the net downward forces exerted on water molecules held under capillary tension are less than that of free-draining water molecules, unsaturated soils have less than atmospheric pressure. By convention we usually state that atmospheric pressure is our datum, which means that the pressure is given as zero. This means that water in unsaturated soils is held under negative pressure and water in saturated soils has a positive pressure. This process of holding water at negative pressure is known as soil water retention and the relationship between moisture content and this negative pressure is known as a moisture retention characteristic. When the upward tension on the water equals the downward force of gravity on the water, drainage from the soil ceases and the soil is said to have reached *field capacity.* The field capacity of a soil is very important because it defines an upper limit normally associated with plant available water.

Plant available water is the difference between field capacity and wilting point. In order to understand what the wilting point is, it is important to recognize that plant roots are able to draw water from soils at higher negative pressures than field capacity and that water moves from a location of high pressure to a location of low pressure. Field capacity for most soils occurs at a pressure of about

-340 millibars (mb). Capillary forces within most plant roots can produce pressures much lower than soil field capacity, and can go to -15,000 mb or lower depending on the species. At pressures much lower than this, plants are unable to maintain cell turgor. Thus, at wilting point, many plant species close their stomata and may eventually be damaged.

An important property of soils is their ability to absorb incoming water from above, such as precipitation or snow melt water. Water infiltrates soils at a rate that depends on a number of properties of the soils. These include saturated hydraulic conductivity, the moisture content of the soil prior to the input of water, and the intensity of the water input. Soils with higher hydraulic conductivities have higher infiltration rates. Soils that are dry prior to a rainfall event have to be recharged, so they tend to have longer periods of high infiltration rates. As stated earlier, hydraulic conductivity depends on soil texture, such as whether the soil is predominantly sand or clay. It also depends on how compacted the soil is. A loose soil has a higher porosity than a compacted soil, and in general, near-surface soils under vegetation have high porosity that is produced by roots and organisms such as worms. Soils at greater depth tend to be more compacted by the weight of the overlying layers. At greater depth, there is also lower root and animal content. When soils are dry, incoming water generally infiltrates at a rate above the saturated hydraulic conductivity. This is caused by the combined drainage rate resulting from gravity and capillary forces that draw the water into the soil. Eventually, the rate of infiltration slows down to the rate of the saturated hydraulic conductivity as the surface soil layers become saturated. Knowing something about the infiltration capacity of a soil is key to understanding how the soil will respond to precipitation events. If rate of precipitation onto a soil surface exceeds the rate at which water can infiltrate then water will pond on the surface and eventually run off. However, if the soil has a very high infiltration capacity, as occurs in most forests, then very few precipitation events will be intense enough to produce runoff. If the rate of water infiltration into a soil is high, but an impermeable layer, such as bedrock or highly compacted soil, or a water table, underlies the soil, then the soil may saturate from below. Once a soil is saturated, it can hold no more water and further water input runs off.

Ground Water

Ground water is water that completely fills the pore spaces of permeable materials, or ground water aquifers, below the ground surface. It includes water stored below the water table in soils and in deeper aquifers in porous bedrock. Ground water is an important part of the hydrologic cycle. It represents about 30 percent of the world's fresh water resources, and 99 percent, if permanent ice is excluded. It is an important source of water for domestic consumption, for irrigation, and for industrial uses. It is also a critical link in the terrestrial portion of the hydrologic cycle, because it links water that infiltrates into soils to streams and other surface water bodies. Ground water tends to move from upland source areas to lowland discharge areas. Through this lateral flow of water, groundwater can help to sustain riparian forests and gallery forests in valleys even in semi-arid regions.

Ground water is important both in terms of quality and quantity. Streams, lakes, and other surface water bodies can be thought of as areas in the landscape where the ground water reaches the surface. As such, water bodies can be important diagnostics of watershed health. For instance, lake acidity is a good indicator of the acid-neutralizing ability of the watershed in response to acid rain. Also, human consumption of ground water from well pumping frequently lowers regional water tables. Excessive ground water pumping may result in the land subsiding, as is occurring in some coastal areas of Texas.

Runoff

In the last thirty years, hydrologists have come to understand the mechanisms of runoff generation. Prior to the 1960s, it was believed that runoff was produced over all areas of watersheds. This runoff was believed to occur when precipitation rates exceeded the infiltration capacity of the soils. Studies have shown that most natural soils have infiltration capacities that exceed all but the highest rates of precipitation. Usually runoff is limited to only parts of the watershed, and for most precipitation events these areas remain unchanged for a given watershed. For instance, urban watersheds have fixed, impermeable surfaces. Forested watersheds with harvested areas may have low infiltration capacities and high runoff rates if the soils have become compacted during a logging operation. The low infiltration capacity sites are the most likely to produce runoff.

Most runoff in undisturbed, well-drained watersheds occurs where soils have become saturated from ground water that returns to the surface, such as near streams and in concave areas on slopes. Areas where ground water returns to the surface are usually called *seepage faces.* They occur where soils are recharging at much higher rates than in surrounding areas. This is called ground water mounding. Seepage faces also occur where thin soils are underlain with an impermeable layer, such as bedrock. Water infiltrating into the soil hits this impermeable barrier and travels down slope. In valley bottoms the water may slow down or converge, which means a water table grows upwards to the soil surface. The resultant breakout flow then runs along the surface until it reaches a stream or until it re-infiltrates in an area where the soil is not saturated. Also, precipitation that falls on a saturated soil directly runs off. Breakout flow and direct precipitation runoff are collectively known as saturation excess runoff.

Streamflow

Streams and streamflow are often the focus of watershed management. Rivers have always played a central role in human settlements. One of the earliest known human settlements, Mesopotamia (from the Greek *mesos* "middle" and *potamos* "river;" literally "land between the rivers"), developed on fertile alluvial plains watered by the Euphrates, the Tigris, and their tributaries. In addition to their importance for agriculture, rivers were historically a key for trade and commerce, transportation, as a source of food and water, and in the last century as a source of hydroelectric power. The North American fur trade relied heavily on rivers. Rivers became the focal point for the exploration and settling of both the United States and Canada. One only has to consider the commerce, culture, and growth of cities along the Mississippi and St. Lawrence rivers as illustration of the role of large streams.

Streams store very little water when viewed in terms of the world's total water budget, but they are the link between terrestrial and aquatic ecosystems. Water is moved in streams a great distance from ground water aquifers, lakes, and glaciers to the oceans. Streamflow is the cheapest and easiest to monitor of all hydrologic fluxes. Stream gauges regularly monitor most major rivers in the continental United States, Canada, and most other countries. The United States Geological Survey (or USGS) maintains a network of stream gauges, which are monitored regularly by people or by automated recording instruments. Data from these monitoring stations are routinely used by federal, state, and local regulatory agencies with a vested interest in water resources. For example, the state of California has invested considerable resources in a network of monitoring stations and experimental watersheds to improve the understanding and management of its scarce water resources.

Of concern with streamflow are low flows, which occur between precipitation events, and peak flows, which occur during or shortly after precipitation events. Low flow, called base flow, is an important source of water for human consumption and for sustaining stream ecosystems. Peak flows are regularly studied because they have the greatest potential of causing damage to ecosystems and human structures. For instance, peak flows occur during rainfall events that promote a rapid melting of snow packs in the Cascade Range in the Pacific Northwest of the United States. These events are associated with debris flows that severely damage near stream and in-stream ecosystems and wash out roads. Large streamflows may also result in stream

Sidebar 16.1

Case Study: The 1993 Mississippi Floods

The Mississippi River experienced one of its worst flooding events during late spring and summer of 1993, resulting from a combination of eight months of high rainfall followed by high amounts of snowmelt in the Rocky Mountains. From late June to late July the flood wave overtopped the river banks in Minneapolis, Minnesota, exceeded a 9.5 m levee built to contain the 500-year flood level, and reached 5.2 m above flood stage in St. Louis, Missouri. For the first time since flow records were first collected on Mississippi flooding, flood crests of the Mississippi, Missouri, and Illinois Rivers met simultaneously. Many midwestern rivers remained at flood stage until September (see Figure 16.6 in color insert). The floods resulted in 50 deaths, property damage in excess of $7 billion, evacuation of 37,000 people from their homes, flooding of 30 million ha of farmland and $3 billion in crop damage.

Weather radar and a network of rainfall and river stage gauges linked by satellite to the Army Corps of Engineers offices provided data for real-time flood-routing models. Early warning of the flood was used by the Army Corps of Engineers to open the gates of the 29 regulation dams on the Mississippi in order to release as much water as possible during the spring. However, longer warning times and improved predictive models were needed, according to the National Oceanic and Air Administration (NOAA). In addition, there has been increased questioning of policies of building levees, draining wetlands, clearing the channels and building towns on floodplains. Over the last 200 years, half of the United States wetlands have been drained, and yet these areas, along with backwaters and the floodplain, provide important storage areas for delaying runoff. The national Wetlands Reserve Program was formed to pay farmers to restore 2.5 million ha of wetlands by 1995, but as of 1994 they had rehabilitated only 125,000 ha. The U.S. National Wildlife Foundation has been campaigning to stop subsidized insurance for land owners in flood-prone areas (1).

Source:

1. J. A.JONES, *Global Hydrology: Processes, Resources and Environmental Management,* Addison Wesley Longman Limited, Edinburgh Gate, U.K., 1997.

water levels exceeding the heights of stream banks and overflowing into the surrounding flood plain. Hydrologists use probabilistic terms to describe how big a streamflow event is. The most common term used is the recurrence interval. A recurrence interval of 10 years, which may also be called a "ten-year flood," refers to a streamflow event with a magnitude that on average occurs once in ten years. Longer recurrence intervals mean larger flood events. A 100-year flood is very damaging, but will on average occur only one time in 100 years. However, hydrologists are keenly aware that a 100-year flood could happen in two consecutive years. Recent examples of large floods are the 1993 flooding of the Mississippi River valley (see Sidebar 16.1, and see Figure 16.6 in color insert), and the 1998 flooding of the Red River in North Dakota and southern Manitoba, Canada. 100-year floods result in great losses of life and property because human development occurs most frequently in floodplains, which are generally more fertile land with fewer irrigation costs.

The measured flow, Q, at a stream gauge represents water that has been concentrated from an entire watershed area over a period of time. The time taken by water as it travels from a recharge area in the watershed to the stream gauge results in a delay between the time of peak precipitation and time of peak streamflow. Measurements of streamflow over a period of time can be portrayed in a graphical form known as a *hydrograph.* The hydrograph can portray a single storm event or a sequence of events over a long period of time. The shape of the hydrograph for an event reveals much about the physical characteristics of the watershed that collects and moves water. For example, a large watershed tends to have a larger hydrograph than a small watershed. An elongated watershed tends to have longer flow path lengths, giving it a less pronounced hydrograph peak and a longer duration than a watershed with a more compact shape. A steeper sloped watershed has a higher peak and shorter storm flow duration than a shallow sloped watershed because steep slopes promote a faster acceleration of the watershed because of gravity. In addition, land cover plays an important role in delaying and reducing peak runoff amounts. Figure 16.7 illustrates the effects of urbanizing watersheds on storm runoff responses. In this case, natural vegetated surfaces are replaced with impervious surfaces, such as rooftops, roads, sidewalks, parking lots, and driveways. One consequence is that a greater proportion of annual flow in a stream comes from storm water runoff rather than base flow. In addition, as impervious cover replaces natural surfaces, there is a reduction in soil infiltration capacities, which results in reduced recharge of ground water. This can produce reduced base flow levels during long dry periods between rainfall events. Low flow amounts are considered important for aquatic ecosystems, fisheries, and municipal water supply. Storm runoff moves more rapidly over relatively smooth urban surfaces than over natural vegetation. As a result, rising limbs of storm hydrographs are steeper, have higher peaks, and recession limbs decline more steeply in urbanizing areas. The result is an overall increase in the amount of streamflow, a higher peak streamflow, and a more rapid streamflow response to a rainfall or snow melt event.

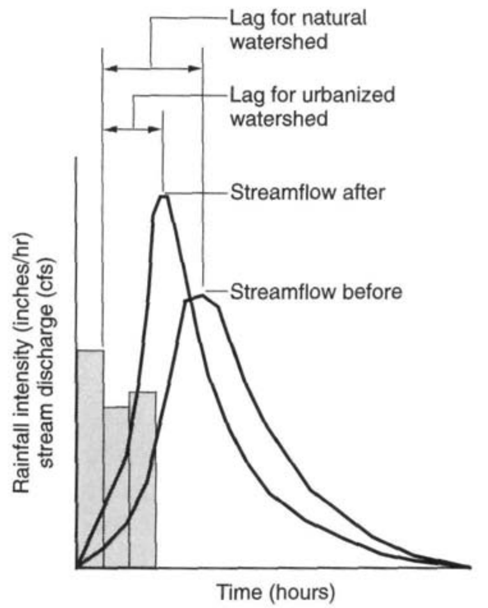

Figure 16.7 This figure shows streamflow hydrographs (curves) and input precipitation (bars), comparing a natural surface cover to an urbanized cover. The effect of urbanizing watersheds is to reduce the lag to peak flow and increase the peak flow, as a result of increased amounts of impervious surface within the watershed.

Integrated View of the Watershed and Its Management

Land Use

It should be evident that human activity has altered land cover, and this should have an impact on water resources. On a global scale, the expansion of deserts is an extreme illustration of how human land use may be causing the spread of non-arable land (see Sidebar 16.2—Land Use and the Global Expansion of Deserts). On a local to regional scale, the primary concern of watershed management is the sound use and protection of water resource quantity and quality. However, the management of water resources cannot be entirely separated from the management of other resources. All forms of land use activities influence and are influenced by water resources. For instance, forest harvesting has an immediate effect on water resources because removing the vegetation reduces interception and transpiration. However, if the forests are encouraged to grow back, then the increased water yield is short lived (3—7 years) and may result in a medium-term reduction in water yield as young forests grow to a closed canopy (Figure 16.8) (6).

Conversion of forests to agriculture or to other types of vegetation cover can have profound impacts on water balance. More precipitation falls directly on the soil surface. This in turn may increase soil water content and potential for runoff. The mechanisms of runoff generation are an important consideration in terms of watershed management. Runoff that occurs from infiltration excess tends to travel long distances, with high velocity, as sheet flow down slopes. This type of runoff promotes the erosion of soil. In contrast, runoff that occurs as saturation excess tends to either begin flowing in regions close to streams where they travel at low velocities and with little capacity for eroding soil, or they are produced in isolated depressions, travel a short distance and re-infiltrate into drier surrounding soils. Soil compaction resulting from certain forest harvest practices may result in reduced infiltration capacity with greater likelihood that the infiltration excess will result in overland flow.

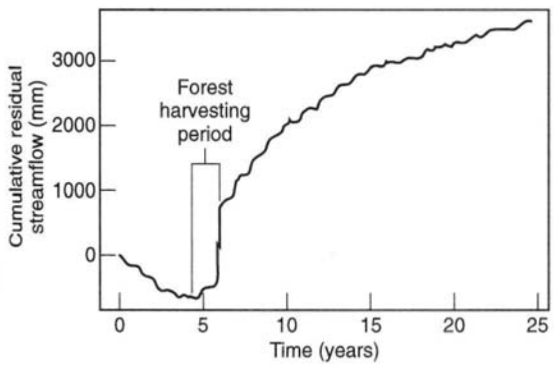

Figure 16.8 This graph shows a cumulative total of the differences between streamflow in a clearcut watershed and a fully vegetated watershed. Prior to the forest harvesting (indicated), the watershed to be dearcut has a lower streamflow. Shortly after the harvest, there is a rapid increase in streamflow in the clearcut watershed. This increase gradually declines with time. After 20 years or so, the vegetation has sufficiently recovered to show little difference between the two watersheds. (Data courtesy of the Forest Science Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Forest Service Northwest Research Station, Corvallis, Oregon. Significant funding for these data was provided by the National Science Foundation.)

Water can also serve as a means of transferring the effects to another resource. For instance, removal of vegetation in riparian areas can result in warming of streams, which can be detrimental to aquatic resources such as fish. Agricultural practices result in increased surface runoff, which erodes soil. Land cover and land use are important concerns for determining the potential for soil erosion. Energy from the impact of precipitation on bare soil surface will loosen or excavate soil from the surface, making it available for transport by runoff. By having organic materials and residues on the surface, there is less opportunity for rainfall impact to promote soil erosion. In addition, plants reduce the velocity of precipitation by intercepting and releasing it through stemflow or throughfall. After vegetation is removed, burning, plowing, or surface grading removes surface organic material. The soils are then exposed to potential erosion from precipitation impact and subsequent runoff. Erosion may occur in agricultural fields, in formerly forested areas that have been logged and where soils have been compacted under logging equipment, and in overgrazed pastureland.

Overgrazing is a classic example of how land use can dramatically alter the balance between soil protection and soil erosion. Many so-called "badlands" occur in areas where overgrazing triggers rapid soil loss. The photos in Figure 16.9 are taken from an area of badlands on the back slopes of the Niagara Escarpment in southern Ontario, Canada, where a slope composed of weathered shale has

Sidebar 16.2

Land Use and the Global Expansion of Deserts

Deserts presently cover about 37 percent of the global land cover, 7 percent of which is because of land use. The current total area amounts to about 45 million square kilometers, and this is increasing at a rate of about 60 thousand square kilometers per year (1). A key trigger appears to be the reduction of soil fertility through destruction of topsoil. One theory to explain how this happens is that devegetation along the margins of subtropical deserts results in a reduction of convective heating needed for the formation of clouds. Several feedback mechanisms can help to explain why this might happen. The destruction of vegetation, for instance through harvesting, results in rain striking soil surfaces with greater force. This seals the soil surface and may produce splashpans, which lowers the rate of infiltration, and leads to greater runoff and soil erosion. Increased runoff and erosion mean reduced storage of water in the soil and reduced soil fertility. The chances for vegetation to regenerate are thus reduced. The soils are also more likely to crack as they dry. Soil surface cracks act as channels for water and promote accelerated soil erosion rates. In addition, the dry, cracked soil is much more prone to have its topsoil blown away. The bare soil surface reflects much more solar energy than the former vegetated surface, which means the surface absorbs less energy and heating is reduced. In addition, some of the topsoil blown off the surface is carried into the atmosphere where it increases the amount of radiation reflected back to space. This reduces the amount of energy that the atmosphere can absorb, resulting in cooler air aloft. This cooling forces the air to sink, which means it warms adiabatically and forms an inversion. The inversion suppresses strong convective uplift and cloud formation is reduced (2). This theory has been used to explain the expansion of the Sahel Desert in Africa, although the actual influence of land use is unsubstantiated.

Sources:

1. J. A. JONES, *Global Hydrology: Processes, Resources and Environmental Management*, Addison Wesley Longman Limited, Edinburgh Gate, U.K., 1997.
2. R. A. BRYSON AND T. J. MURRAY, *Climate of Hunger*, University of Wisconsin Press, Madison, 1977.

been gullied by the removal of natural vegetation by overgrazing. Once the erosion was initiated, the soils were too nutrient-poor and compacted for vegetation to re-establish. Features such as this underscore the importance of feedback between hydrological processes and land use.

Cumulative Watershed Analysis

Important considerations in watershed management are the cumulative effects of land use activities. Cumulative watershed effects stem from the connectivity of different areas of the watershed because of pathways of movement of water, sediment, organic material, energy, and pollutants. Degradation of the land can potentially follow a vicious circle (Figure 16.10) (7), in which overuse of land and removal of forests leads to reduced soil infiltration rates, which promotes greater soil erosion, degradation of site quality and increased susceptibility of streams to flooding.

Specifically within the context of forest harvesting, numerous examples of cumulative effects can be identified. We will assume an order of oper-

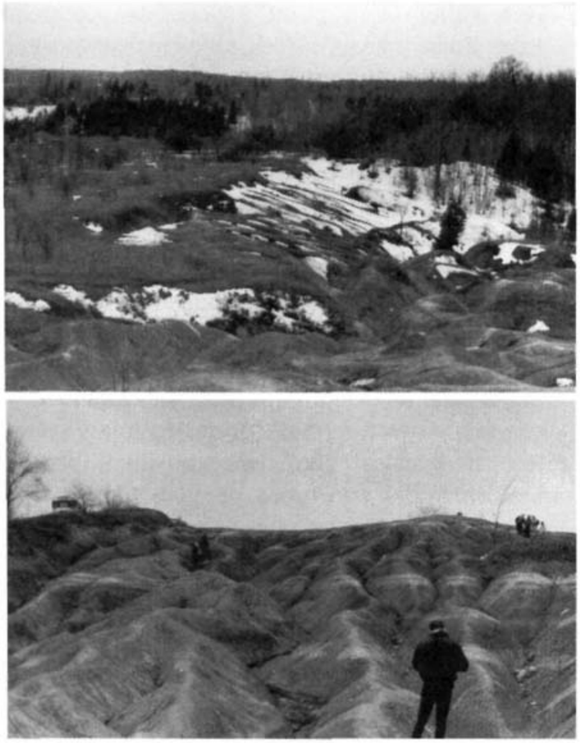

Figure 16.9 Formation of badlands as a result of the removal of vegetation, most likely from overgrazing. The upper photo shows the transition between the vegetation pasture and the badland formation. The lower photo provides a view of the channel formation that prevents establishment of ground-protecting vegetation.

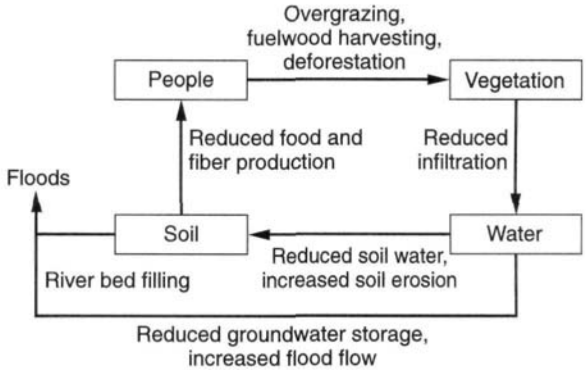

Figure 16.10 A vicious cycle exists because land use activities result in a degradation of soils, increased erosion, and flooding. To compensate for lost arable land, new land is sought and exploited, completing the cycle. (Source: Doherty and MacDonald, 1992.)

ations that includes 1) construction of logging roads, 2) actual harvesting, 3) skid trail development following harvesting, and 4) site preparation for subsequent planting. Road construction bares and compacts soil, which reduces infiltration capacities and increases runoff. Road networks in mountainous forest watersheds may increase peak streamflow by replacing subsurface flow paths with surface flow. This occurs because forest road incisions capture subsurface flow and also promote greater infiltration excess runoff. Subsurface flow is captured by the road and channeled through culverts. A study conducted in two western Washington catchments indicated that the effect of roads and culverts was to increase the effective channel network density by *64* percent and 52 percent, respectively. Model estimates indicated that this translated into about an 11 percent increase in mean annual floods (8).

Harvesting reduces transpiration, which increases runoff. Skid trails channelize water, which promotes greater runoff. Site preparation reduces ground cover, which increases the transport of sediment. These localized effects in turn accumulate downstream. During large storms, the increased peak streamflows and sediment loads in managed areas can accelerate channel erosion and sedimentation. In mountainous watersheds, an important manifestation of localized increases in soil moisture are earth flows or landslides, which send debris flows through stream reaches. A debris flow can take out much of the existing riparian vegetation and alter the shape of the stream channel. Subsequently, new riparian vegetation establishes itself on the debris. The photo in Figure 16.11 shows a stream channel covered in debris from a flow that resulted from a large buildup of snow followed by rain on the snow during the winter of 1996/1997 (see Sidebar 16.3). The resulting alteration to the channel sides

Figure 16.11 Stream channels like this are common in the Pacific Northwest. The stream bed is dominated by the remnants of a debris flow that swept through the stream channel in early 1996. It was the result of rapid melting of snow during a rainfall event, combined with storage of weathered material on an unstable slope. The effects of forest cover removal are to make slopes much more susceptible to debris flows such as this.

and bottom can severely harm stream ecosystems and domestic water supply. For example, spawning fish require cold water, high levels of dissolved oxygen, and well-aerated gravels that are free of silt and clay. Fish also require deep pools, undercut banks to protect juveniles, and overhanging riparian vegetation to provide shade for the stream ecosystem and for a source of decaying vegetation to sustain lower levels of the aquatic food chain. Lack of consideration of these factors can cause damage to economically important fish stocks, such as salmon. This has traditionally only been the concern of fisheries personnel; other land uses including forestry were considered to be competing with fisheries.

The eroded soil causes sedimentation of streams and other water bodies. In addition, pollutants attached to the sediments are also moved from the runoff-generating surface to water bodies. Pollutants include dissolved nutrients and chemicals. Pollution is normally classified as increased concentrations of these constituents over natural levels. It occurs either from point sources or nonpoint sources. Point sources include municipal sewers and industrial waste output. Nonpoint source pollution represents by far the most significant source of pollution. By definition, nonpoint source (NPS) pollution occurs over a widespread area and is concentrated in rivers, lakes, and estuaries. In the United States, the primary source of NPS pollution is agriculture. Nutrients applied on agricultural fields are carried through streams and concentrated in lakes and other water bodies. These nutrients promote accelerated aquatic vegetation growth, such as algae blooms (see Figure 16.12 in color insert). When this vegetation dies, it remains in the water, where it decays. The decomposition of this organic material consumes oxygen, that is then depleted from the water. This loss of oxygen in surface water is called *eutrophication.* It is observable most immediately as a reduction in water clarity and decline in fish and other aquatic organisms.

A legal basis for a shift towards a more ecologically sound management of water resources began with the United States Congress passing the National Environmental Policy Act, the National Forest Management Act, and the Clean Water Act (9). These laws respectively required federal agencies to prepare environmental impact statements for projects having the potential to significantly affect the environment, directed the Forest Service to guarantee protection for all water bodies, and established Best Management Practices (BMPs) for controlling nonpoint source pollution. Section 319 of the Clean Water Act of 1987 required states to identify and submit BMPs for EPA approval to help control nonpoint source pollution. As of 1993, 41 of 50 states had EPA-approved voluntary or regulatory silviculture-based BMP programs. The state BMPs are all similar; the majority deal with roads. Montana, for example, has a total of 55 specifically addressed forest practices. Of those 55 practices, 35 deal with road planning and location, road design, road maintenance, road drainage, road construction, and stream crossings. (See Sidebar 16.4.)

Unified watershed assessments are directed at integrating state, interstate, tribal, and federal assessment programs. Priority watersheds from different agencies can be overlaid on maps for comparison. An advantage of this approach is that watersheds can be evaluated at different scales, ranging from small watersheds around single water bodies up to a regional extent. Having nested watersheds, in which smaller monitored watersheds lie within larger monitored watersheds, helps to target activities identified in watershed restoration action strategies. To make these new approaches feasible, there has been a shift of responsibility of monitoring water resources from government agencies to nongovernment agencies. Monitoring consortiums that involve partnerships between government agencies, public and private organizations are becoming common (10).

International Watershed Management: The Case of the Great Lakes Basin

Watersheds that are shared by two or more countries present unique challenges for managing water resources. High-profile examples include the Amazon River basin and the Great Lakes river basin. The Great Lakes are the largest system of fresh surface water on earth, containing roughly 18 percent of the world supply. Only the polar ice caps contain more fresh surface water. The resources of the Great Lakes basin have been central to the history and development of the United States and Canada. For the early European explorers and settlers, the

Sidebar 16.3

Case Study: Pacific Northwest Floods of 1996

Warm winds, intense rainfall, and rapid snowmelt during the winter of 1995-96 and again in the winter of 1996-97 caused major flooding, landslides, and other damage throughout the Pacific Northwest. Watershed damage included large and damaging debris flows, which are fast-moving and carry large rocks eroded from high elevation sites, fallen trees, and other debris through valley channels (see Figure 16.11). The hardest-hit areas had the worst flooding in over 30 years. Damage to roads, trails, watersheds, and water resources was widespread on National Forest Service lands. The events offered an opportunity to study the effects of severe weather, examine the influence and effectiveness of forest management techniques, and implement repairs that follow ecosystem management principles. Based on long-term access and travel requirements, road repairs were made by relocating roads to areas outside of floodplains. Table 16.3 summarizes the major buffer strip requirements for managing stream corridors in Pacific Northwest states. These guidelines are in place for the protection of streambanks and for maintaining the health of the aquatic ecosystems. Examination of road crossings at streams concluded with the design recommendation to keep the water moving, align culverts horizontally and longitudinally with the stream channel, and minimize changes in the stream channel cross-section at inlet basins to prevent future debris plugs. Areas with stable, well-vegetated slopes and streambanks, as well as fully functioning floodplains, buffer the effects of floods. Common restoration practices include streambank stabilization and riparian plantings to aid the natural processes in these systems.

(continues)

Sidebar 16.3 *(continued)*

Table 16.3 Major buffer strip requirements for stream corridor maintenance in the Pacific Northwest. The guidelines distinguish between fisheries and water supply as primary protection areas and other impacts for secondary protection.

	Protection Areas	Required Width of Buffer Strip	Shade or Canopy Requirement	Leave Trees Requirement
Idaho	Water supply, fisheries	Fixed minimum (75 feet)	75% current shade[a]	Yes; number per 1000 feet, dependent on stream width[b]
	Other influences	Fixed minimum (5 feet)	No requirement	No requirement
Washington	Water supply, fisheries	Variable by stream width (5-100 feet)	50% (75% required if temperature>60°F)	Yes; number per 1000 feet, dependent on stream width and bed material
	Other influences	No requirement	No requirement	25 per 1000 feet, 6 inches diameter
California	Water supply, fisheries	Variable by slope and stream class (50-200 feet)[c]	50% overstory and/or understory; dependent on slope and stream class	Yes; number to be determined by canopy density[d]
	Sediment transport[e]	No requirement	50% understory[f]	No requirement[f]
Oregon	Water supply, fisheries	Variable, three times stream width (25-100 feet)	50% existing canopy, 75% existing shade	Yes; number and basal area per 1000 feet by stream width
	Significant impact downstream	No requirements[g]	75% existing shade	No requirement

[a] In Idaho, the shade requirement is designed to maintain stream temperatures.

[b] In Idaho, the leave tree requirement is designed to provide for recruitment of large woody debris.

[c] May range up to 300 feet for some types of timber harvest.

[d] To be determined by field inspection.

[e] In streams capable of sediment transport.

[f] Residual vegetation must be sufficient to prevent degradation of downstream beneficial users.

[g] In eastern Oregon, operators are required to "leave stabilization of undergrowth ... sufficient to prevent washing of sediment into Class I streams below."

lakes and their tributaries were the avenues for penetrating the continent, extracting valued resources and carrying local products abroad. By the end of the twentieth century, the Great Lakes basin was home to more than one-tenth of the population of the United States and one-quarter of the population of Canada. The United States considers the Great Lakes a fourth seacoast, and the Great Lakes region is a dominant factor in the Canadian industrial economy.

The original logging operations in the Great Lakes basin cleared the land for agriculture. Some of the wood was used in construction. Most of it was burned. By the 1830s, commercial logging

Sidebar 16.4

Case Study: Best Management Practices in Wisconsin

Nearly half of Wisconsin is forested. Its forests are critical to much of its nearly 20,000 kilometers of rivers and streams and nearly 15,000 lakes. The Wisconsin Department of Natural Resources (DNR) Forestry Divison, began a Best Management Practices (BMP) program in 1995 to determine the effects of timber harvesting on water resources. The objectives were to identify where BMPs are being used, their effectiveness, and to determine the effects of not applying BMPs. Although forestry practices contribute only 3 percent to the state-wide nonpoint source pollution, there are nevertheless important local impacts on water quality. Three primary focus areas were riparian management zones, forest roads, and wetlands. Riparian management zones are areas within about 30 meters of lakes and perennial streams. Within these zones, the highest priority BMPs designated no construction of roads or landings, that soil exposure and compaction be minimized, that no slash be placed within the zone, and that harvesting be selective. Harvesting was specified to promote long-lived species, including sugar and red maple, white and black ash, oaks, eastern hemlock, white and red pine, and cedar. Recommendations for road BMPs included planning to minimize overall road area and to not exceed road grades of 10 percent to minimize runoff. Recommendations for wetland BMPs include avoiding equipment maintenance and fueling, avoiding construction, and keeping slash away from open water.

From 1995 to 1997, individual timber sales were evaluated by teams consisting of individuals from government agencies, professional forestry organizations, environmental organizations, and the forest products industry. Only timber sales on wetlands or within 60 meters of a lake or stream were monitored. The results of the study indicated that BMPs were applied correctly 85 percent of the time when needed, and that only 6 percent of the time did the absence of BMPs have a major impact on water resources. The results of the study called for greater emphasis on BMPs for riparian management areas and forest roads. Riparian management is recommended for areas within about 30 meters of lakes and perennial streams. A key element of successful implementation will be education, because about two-thirds of the state forests are owned by about 260,000 private land owners. This includes encouraging land owners to participate in BMP training. Another recommendation of the study was to conduct further research to determine whether steep terrain or soil type correlates with the effectiveness of BMPs in some areas. This is a study that could be conducted with the application of geographic information systems and models.

began in Upper Canada (now southern Ontario), followed by Michigan, Minnesota, and Wisconsin. Cutting was generally done in the winter months, by traveling up rivers and felling trees that were floated down to the lakes during the spring thaw. Timber was eventually carried in ships specially designed for log transport. The earliest loggers harvested mainly white pine. In virgin stands, these trees reached 60 meters (200 feet) in height, and a single tree could contain 10 cubic meters (6,000 board feet) of lumber. As the forests were cleared, loggers migrated farther west and north in search of white pine. When this resource was exhausted other species were utilized. The hardwoods such as maple, walnut, and oak were cut to make furniture and specialty products. Lower-grade pulpwood would eventually support papermaking and the region became a major source of paper. With the pulp and paper industry came a mercury pollution problem on the Great Lakes until the early 1970s, when mercury was banned.

The logging industry was exploitive during its early stages. Huge stands were lost in fires, often because of poor management of litter from logging operations. In Canada, lumbering was largely done on crown lands with a small tax charged per tree. In the United States, cutting was done on private land, but when it was cleared, the owners often stopped paying taxes and let the land revert to public ownership. In both cases, clearcutting was the usual practice. Without proper rehabilitation of the forest, soils were readily eroded and lost to local streams, rivers and lakes. In some areas of the Great Lakes basin, reforestation has not been adequate and forests may be considered a diminishing resource. Pollution that had immediate local effects eventually spread throughout the basin.

An evolution in understanding how environmental damage has resulted from human use of natural resources in the basin has arisen out of the research, monitoring and commitment to Great Lakes protection by both countries. Ecosystem management requires the involvement of all levels of government, as well as industry and nongovernment organizations. Each has its own responsibilities and often work in partnership to protect the basin ecosystem. Originally, water pollution was treated as a separate problem. Eventually the connections between land, air, and water resources were better appreciated. In 1905, the International Waterways Commission was created to advise the governments of both countries about levels and flows in the Great Lakes, especially in relation to the generation of electricity by hydropower. The Boundary Waters Treaty was signed in 1909 and provided for the creation of the International Joint Commission (IJC). The IJC has the authority to resolve disputes over the use of water resources that cross the international boundary. Water pollution was one of the first problems referred to the IJC for study. Public and scientific concern about pollution of the lakes grew as accelerated eutrophication became more obvious through the 1950s. The IJC reported in 1970 that eutrophication was the result of excessive phosphorus. The study proposed basin-wide efforts to reduce phosphorus loadings from all sources. It was recognized that reduction of phosphorus depended on control of local sources. Uniform effluent limits were urged for all industries and municipal sewage treatment systems in the basin. Research suggested that land runoff could also be an important source of nutrients and other pollutants entering the lakes. This research resulted in the Great Lakes Water Quality Agreement in 1972. It was revised in 1978 to establish target phosphorous discharge levels, 1 part per million (ppm) (mg per liter), and for the virtual elimination of toxic chemicals. In 1987, the Agreement was revised to emphasize ecosystem objectives, including nonpoint source pollution, airborne pollution, pollution from contaminated groundwater, and ecological indicators such as human and aquatic community health.

In addition to government legislation, communities, local groups and individuals play a key role in the management of the Great Lakes. The management process starts with individuals and families taking action as consumers, recyclers, neighborhood stewards and health promoters. Nongovernment organizations are taking responsibility for public education, citizen-directed projects, and for providing direction to government. Businesses are key in managing their own operations in a sustainable, ecological fashion, being partners with community and governments, and in complying with regulations set by themselves and others. Most successful management requires partnership arrangements among the various sectors in the public. People are getting involved in local decision-making processes, via groups such as Public

Advisory Committees in Areas of Concern and local community groups throughout the Great Lakes basin that exert pressure toward change.

New Technologies for Integrated Watershed Management

Recent developments in computer-based technologies are changing the way in which integrated views of watersheds are being maintained. Geographic information systems (GIS) are computer-based methods for the capture, storage, display, analysis, and output of geographically referenced information. GIS are integrative tools for spatial analysis and modeling (see also Chapter 12). A GIS can combine information of different themes that is traditionally portrayed on paper maps. A theme could represent soils, topography, vegetation, hydrography, land use, or other data collected spatially. The GIS allows for these themes to be placed in a common geographic coordinate system so that information from multiple themes can be addressed by location. Once in this form, it can be used for visualization (see Figure 16.13 in color insert), watershed modeling, and analysis. Watershed modeling tools increasingly rely on geographic data preparation as inputs and to support decision making (see Figure 16.14 in color insert).

Remote sensing is the art and science of collecting information about the earth's surface without being in physical contact with the surface. Most of the time it refers to photographs or images acquired by cameras or imaging scanners flown on aircraft or spacecraft. Information obtained using this technology is normally characterized by its spatial resolution and spectral characteristics. Spatial resolution refers to the smallest discernable element of the picture. For photographs, this depends on photographic emulsions and processing. For digital imagery, it refers to the smallest picture element. The smallest identifiable object on the ground that can be seen in a photo or image also depends on the height of the aircraft or spacecraft and the instantaneous field-of-view (IFOV) of the camera or scanner. A low flying height and small IFOV yield the highest spatial resolution. However, a small IFOV means the sensor receives reflected or emitted energy summed from a small area on the surface, potentially giving very little information. The tradeoff between spatial resolution and spectral information content is sometimes balanced by simultaneously capturing energy over a range of wavelengths. Spectral resolution refers to the range of wavelengths from the electromagnetic spectrum that is captured by one photo or image. Photographs can capture visible wavelengths or both visible and near-infrared. These are wavelengths of energy from the sun that are reflected off the earth's surface. Image scanners can also detect thermal infrared energy emitted by the surface. In addition, there are microwave radar sensors that have shown some promise for mapping topography, detecting near surface soil moisture, and distinguishing between vegetation canopy and ground.

The most common remote sensing technologies that have been used in water resources management are aerial photography: both visible and near-infrared, and imaging scanners: visible, near-infrared, and thermal. Near-infrared energy is useful for mapping vegetation, as healthy cells in leaves are highly reflective in this part of the spectrum. In addition, chlorophyll is a good absorber of energy from the red part of the electromagnetic spectrum. By combining these two properties, researchers have developed numerous indexes of leaf quantity that correlate well with ground-based measurements of leaf area. These indexes provide a spatially large inventory of vegetation canopy density, which can be incorporated into watershed models to make estimates of transpiration. Remote sensing is increasingly being used for monitoring water quality, particularly in lakes and estuaries. Figure 16.12 shows two images over Lake Mendota in Madison, Wisconsin (see Figure 16.12 in color insert). One shows near-infrared reflectance, which highlights the presence of algal blooms. The second shows thermal infrared emitted energy, which highlights the presence of a heat plume coming from a power generation plant. The dark lines in the water are boat wakes. These appear darker because they are cooler at the surface because of mixing of the surface and deeper waters as a boat moves across the surface.

Concluding Statement

The watershed is the basic organizing framework for water and related resources management. By virtue of the nested structure of large watersheds containing smaller watersheds, a means is provided to telescope from lesser detail to greater detail. From a global level, one can telescope down to regional level, and then to a management level, and ultimately down to the hillslope level where water flow pathways can be directly measured. This allows for quantifying the storage and movement of water using conservation equations. Knowing where the water goes then assists in understanding the fate of sediment, nutrients, and other pollutants.

The distribution of global vegetation can be explained by an examination of the balance between precipitation and potential evapotranspiration (ET). When potential ET exceeds precipitation, there is generally not enough water to support dense vegetation, including forests. Forests generally occur in regions where precipitation greatly exceeds potential ET. However, for a smaller spatial extent, the presence of ground water recharge from upland to lowland sites can help offset an average water deficit by locally providing a source of soil water.

An understanding of hydrologic flow pathways is important for understanding how land use will affect the sustainability of the soils, soil erosion, and cumulative impacts on aquatic life and human water supply. Removal of vegetation can result in a decline in soil fertility, in part because of removal of nutrients and also because of a reduction in ET and soil water storage. More precipitation goes into surface runoff, which promotes the loss of soil. Pollutants attached to the lost soil are then moved into stream channels and carried out of the area of land management. In addition, there can be a vicious cycle as land use is expanded into new areas to compensate for lost soil fertility. This leads to increased loss of fertile land, and increased runoff during storms leading to greater flooding and loss of life.

An integrated view of the watershed recognizes the role of all activities within a nested watershed on water quality downstream. It requires government agencies, nongovernment organizations, and individual landowners to take on joint responsibility for the management of water and related resources. In North America and other areas in the world, there is a shift from regulation by governments towards improved education of all resource users. Best Management Practices (BMPs) are becoming widely adopted within the United States. They address the management of stream corridors to limit development in these areas that act as buffers to runoff, and as shelter for aquatic life.

BMPs and other forms of watershed management are beginning to benefit from new technologies, such as GIS and remote sensing. These tools allow for the management of large amounts of geographically referenced data to gain a broader spatial perspective on land management. By integrating these tools with models of flood prediction and nonpoint source pollution, it is possible to make better decisions for identifying priority watersheds and determining how to implement monitoring programs within limited budgets.

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CHAPTER 17

Managing Recreation Behavior

ROBERT O. RAY

It would be relatively easy to manage natural resources if it weren't for all the people. People are both the problem and the solution to environmental management issues. Recreational demand manifests itself as a need for participation opportunities in natural settings that hold interesting, challenging, and complex experiences for consumers. This experience-seeking behavior creates equally interesting, challenging, and complex issues that managers of natural resources must address.

While forested public lands were initially set aside for timber production and strategic reserve in a younger and more agrarian society, major changes in the structure, values, and policies of the country have had a serious impact on the management philosophy for those lands. Over time, recreation has emerged as one of the principal reasons people visit these sylvan areas. This often presents a major conflict between those who advocate wise use of resources encouraged by individuals like Gifford Pinchot and the aesthetic value of preservation fostered by Muir, Thoreau, Jensen, and others who introduced nature as an entity with value that transcends that of resource extraction (1). In more recent history, the concept of nature as a place and agent to refresh the soul and restore and cleanse the spirit, mind, and body has captured the fancy of the American public (2, 3).

This century-long trend began at a time where we moved to a more urbanized industrial base that began to separate us from the land. It was further influenced by a growth in economic affluence that permitted us the luxury of improving infrastructure (roads, airports, hotels, resorts, restaurants, etc.) that, in turn, enhanced access to formerly remote natural areas. Current technological advances in recreational equipment allow a greater number and variety of people access and opportunities for recreation that were not previously available. This affluence also permits the public to set aside large areas of land, water, forests, and historical and cultural sites for the greater benefit of society.

With these changes, it is not surprising that many controversies have risen over how to best use and manage the forest resource base. For example, are the forests more useful for recreation than for timber harvest, or should the forest be managed as an integral part of global environmental enhancement (clean air, water conservation, etc.)? The evolution of legislation and litigation over resource use issues has been enormous over the last century. What is more amazing is that it appears to have a good prospect for a vigorous and healthy (if not all enjoyable) political and judicial future.

Those who manage forest-based resources have the blessings and best wishes of many as the good and faithful stewards of natural resources in some quarters. Others vilify them as demons to be feared and exorcised either because they allow exploitation and destruction of nature or because they are overly restrictive of land use. People's perspectives on management and managers are important and critical pieces of this chapter. How do we best determine the use of the lands we have? What should they yield and to whom? Should they yield consumable products only or should they add more aesthetic and spiritual value to living? How should we manage the land, water, air, and history of the people in ways that help them respect what managers do? If we are unable to accomplish this, will the people cease to believe in us such that we will no longer be useful?

Perceptions of Forest Use

Nature has always offered an extraordinary appeal to people for countless reasons: the romance of adventure, the promise of the unexpected, the chance to find beauty, the chance to secure one's religious faith, or perhaps to find something for dinner. The forests in particular have offered a wide range of opportunities and challenges for people that have proven strongly seductive over the course of human history. It is fair to note, however, that our love affair with the deep woods and its denizens is relatively recent in origin. Many of our ancestors carried a serious respect, distrust, and even deep fear of the forests they encountered. Evil was known to live in the form of fierce creatures and embodied in the trees, along with the promises of useful resources, cool temperatures in the summer, and fresh clean water. There were many who would not set foot in the woods without serious reason, good company, and something to defend against the creatures and spirits of nature.

The fear of nature began to shift in the settlement of the New World as our founders began the chants of "manifest destiny" with the seemingly limitless natural resources for exploitation in the New World. This perspective, too, changed over time, and people gradually awakened to the limits of the resources and increasingly realized that human activities could easily and quickly threaten the most abundant and desirable attributes of natural places. Along with recognition came questions that continue to arise.

This chapter begins with a short description of recreation concepts, identifies typical recreation behaviors, and discusses them in the context of recreation resources management. Sketches of social change are used to present key current issues, concerns, and management strategies and their effects. Finally, the future of recreation management is addressed in light of changes in technology, social structure, user demands, population shifts, and global changes.

Throughout the chapter, readers are faced with the most difficult question faced by managers that almost never has a single, enduring answer, "What is the right thing to do?" This is followed by an almost equally difficult question, "Who says so?" This is addressed at the end of the chapter in a discussion on the evolution of new strategies for recreation management.

Some Background on Management of Recreation

Why do people pursue recreation in the out-of-doors? This is often a question that people look at, and conclude: why bother asking? However, it has evolved into probably the most important question that an area manager will face. Why? Knowing why people show up and participate allows the manager to do everything from designing an area to addressing consumer preferences and aims to managing their behavior and deciding on the most appropriate placement of amenities like rest rooms, concessions, and trash disposal sites.

Historically, inventories of recreation behavior were of only marginal interest to land and resource management agencies. This changed around late 1950s and early 1960s. It was in this time frame that the first systematic study of outdoor recreation in America was conducted by the Outdoor Recreation Resources Review Commission (ORRRC), which made its final report to Congress in 1962. The report was instrumental in reshaping the policies and approaches made to managing public lands for outdoor recreation use (also see Chapter 1). Simultaneously, legislators recognized that increased demand with a lack of systematic planning to satisfy future use and demand for outdoor recreation could be a political and natural disaster. In 1960, they passed the Multiple-Use and Sustained Yield Act, which first changed the management priorities of U.S. Forest Service Lands from timber and natural resource management to include recreation as an equally important activity. The present National Forest Service is the largest provider of outdoor recreation opportunities among all federal agencies. Information in Table 17.1 illustrates the breadth and expanse of their responsibilities.

The momentum built by these landmark pieces of legislation prompted a cascade of actions that crested in the late 1960s but have never ceased being important legislative considerations over the last four decades. While space to describe in detail the elements of all legislation is not possible here, it is important to call attention to a few significant actions.

In 1963, the Outdoor Recreation Act explicitly recognized the need and desirability to assure continued access and opportunities for recreation by asking all levels of government to participate in an assessment of available recreation resources and to estimate what it would take to meet future needs. Knowing the available resources and understanding their potential to meet public demand for access and quality by current and future populations is absolutely essential. It is critical for developing and implementing appropriate management policies and practices that respond to population dynamics and resource needs. To foster participation by varied levels of government, the Land and Water Conservation Fund Act was passed in 1965. This act was one of the most significant pieces of legislation of the time, because it provided incentive in the form of funds for states and local governments to plan, develop, and maintain outdoor recreation areas that fit into a nationwide perspective.

The '60s were quite an active period for outdoor recreation legislation. Growing from the momentum created by the ORRRC report and riding public sentiment, other significant acts were passed. The National Wilderness Preservation System, the National Wild and Scenic Rivers System, the National Trails System and the National Recreation Areas creation were all products of this period.

Table 17.1 Recreation Facts, U.S.D.A. Forest Service

Information	
Land Area	
Number of National Forests and Grasslands:	177 (155 forests, 22 grasslands), 192 million acres
States, Territories, Commonwealths having National Forests and National Grasslands:	42
Wilderness Areas:	399 (34.7 million acres)
Percent of National Wilderness Preservation System Managed by Forest Service in lower 48 states:	63%
Percent of National Wilderness Preservation System Managed by Forest Service in total U.S.:	34%
Number of National Recreation Areas (NRA) (includes Land Between the Lakes NRA):	20
Number of National Scenic Areas (NSA):	9
Number of National Monuments and Volcanic Monuments (NM):	4
Total acreage of NRA, NSA, and NM (includes Land Between the Lakes NRA):	6.7 million
Recreation Roads, Trails, and Rivers	
National Forest Scenic Byways:	136 (9,126 miles)
Wild and Scenic Rivers:	95 (4,418 miles)
Trails:	133,087 miles
Scenic and Historic Trails:	6,709 miles
Sites, Facilities, and Services	
Heritage Sites:	277,000
Campgrounds:	4,300
Developed Recreation Sites:	23,000
Alpine Ski Areas:	135
Picnic Sites:	1,496
Boating Sites:	1,222
Swimming Areas:	140
Recreation Facilities:	18,000
Recreation Residences:	14,900
Resorts:	480
Outfitter/Guide Permits:	5,700
Miscellaneous Information	
Employees in Forest Service:	32,000
Total people-at-one-time capacity:	157 million
Developed sites people-at-one-time capacity:	1.8 million
Amount of recreation-deferred maintenance:	$812 million
Recreation facilities backlog:	$664 million
Trails backlog (trails and trail bridges):	$148 million

Source: http://www.fs.fed.us/recreation/recinfo/facts_sheet.shtml

The legislation slowed in the 1970s and new interests began to emerge. Among them was an effort to more closely examine the role of private landholders as participants in the recreation system. Ways to entice the landholder into participation vary but one of the more critical aspects was liability for user well-being. This is an important idea for managers to understand, since private land holdings that could be used for recreation are often held in close proximity to public recreation lands. If proper agreements for landowner protection are reached, the lands available for recreational use could be significantly expanded. This problem has been addressed in many ways, but the primary and least expensive enticement has been legislation that allows landowners who open their lands for pubic access at no charge to be relatively free of responsibilities for user liability. For the last 30 years, this has been a major concern for public land managers. The changes in liability laws effectively increased the lands accessible to participants.

Other ways to increase the access to lands for recreation continue to emerge and should be closely examined by managers. For example, gaining use of rights of way from varied utilities and services has been used for many years with considerable success. More recently, new tools have emerged. Among them include the purchase of development rights from landowners (e.g., farm and range lands). In brief, this process allows government to enter an agreement with the landowner that the land will not be developed for an activity like housing or industry in exchange for money based on the value of the profit from development. Another emergent tool has to do with collaborations between and among Non-Government Organizations (NGOs) and public agencies. For example, an NGO like the Nature Conservancy might enter into an agreement with the Forest Service for cooperative recreational use of an adjoining land for restricted purposes (e.g., birding or hiking).

As might be expected, there are always problems in new approaches to management. One recently raised by Fairfax (4) is that partnerships are often based on the assumption that partners will always have common goals that do not change over time. This may or may not happen since each partner may need to change or respond to different goals or situations that retain or conflict with initial understandings. Does this mean they should not be pursued? Absolutely not. Managers simply need to know that these changes are possible and try to find ways to either anticipate their appearance and impact or adapt to the situation by continuous dialogue with partners.

Forest-Based Recreation Management

Forests and other natural resource-based recreation management is applicable from small public resource-based recreation areas near urban centers to large, commercial forest lands. It is also appropriate for massive public land management agencies of the U.S. Forest Service, the Bureau of Land Management, the U.S. Fish and Wildlife Service and the National Park Service. The management emphasis is on the resource base and guided by decisions on the best recreation opportunities possible given the limitation of the resource, budget, and context.

A significant difference between the management of public and private lands lies in their authority and locus of control in making decisions about the use of the land. In private holding, those who own the land are able to make their own decision on what actions will be permitted (e.g., who can hunt, camp, hike, fish, or swim) on their property, whether there is a fee for use, and what the rules of use and behavior might be. As one might guess, there is quite a range of management objectives and styles among and between land owners in accommodating public use. The critical point is that a private owner does not need public input on how to manage the recreation needs of the consumer.

Those charged with management of public lands have quite a different set of needs and expectations. A brief examination of the U.S. Forest Service's document "The Recreation Agenda" (Sidebar 17.1) provides some important clues on how public agencies are trying to accommodate the continued

Sidebar 17.1

The Recreation Agenda—U.S.D.A. Forest Service

Americans cherish the national forests and grasslands for the values they provide—clean water, clean air, natural scenic beauty, important natural resources, protection of rare species, majestic forests, wilderness, a connection with their history, and opportunities for unparalleled outdoor adventure. Recreation visitors want a great deal from the Forest Service in terms of settings, experiences, facilities and services, and they will expect even more in the future. Recreation is the fastest-growing use of the national forests and grasslands.

The national forests and grasslands offer a diversity of opportunities across the Recreation Opportunity Spectrum. The Forest Service manages 63% of the wilderness system in the lower forty-eight states, and a much larger percentage of backcountry experiences. It also cares for 4,268 miles of the wild and scenic rivers system; 399 wilderness areas in the National Wilderness Preservation System; 133,087 miles of trails; 383,000 miles of authorized roads, more than 277,000 heritage sites; over 4,300 campgrounds; and 31 national recreation, scenic areas, and monuments. As outstanding as these assets are, the Forest Service is more than a custodian of a recreation infrastructure.

As Americans increasingly rely on non-federal forestlands for a variety of goods and services, the federal and non-federal sectors must work together to plan for the future. About 60% of the nation's forests are in non-federal ownership. As on federal lands, the future use of these forests is moving from product use to an anesthetic and ecological management. State and private forestry programs, state foresters, private foresters, and communities are developing an ever-increasing set of knowledge, skills, and tools to meet society's desire for open space, management of urban sprawl, and new applications of agroforestry.

As one of the multiple benefits from these resources, the national forests and grasslands contribute $134 billion to the gross domestic product, with the lion's share associated with outdoor recreation. Resource-based travel and tourism provide a window through which an increasingly urban society can enjoy and appreciate the natural world. The Forest Service has a unique "niche" or brand of nature-based recreation to offer. This brand of recreation includes an undeveloped setting, a built environment that reinforces this natural character, and an array of services that complement enjoyment of these special wild places.

The Forest Service has the opportunity to open that window to special places and experiences even wider to reflect changes in demographic trends and recreation visitor preferences. The Forest Service serves as a catalyst among tourism professionals in working together in travel and tourism opportunities. It seeks out tourism professionals that can represent the diversity of existing and potential customers.

Both the deteriorating infrastructure, estimated at $812 million dollars, and the recreation customers are demanding more. This agenda is aimed at meeting as much of that demand as possible with the highest quality experiences and within ecological and social limits. These limits include impacts on the resource, impacts on experiences of other visitors, and capacity limits of the recreation infrastructure.

Management of these cherished resources requires a long-term viewpoint and investment strategies. Years of declining budgets and a dwindling recreation workforce have made the

(continues)

Sidebar 17.1 ***(continued)***

challenges even more formidable. The Agency has responded with innovative efforts such as the fee demonstration program, permit streamlining, nongovernmental partnerships, and help from volunteers. The Forest Service must find even more innovative ways to accomplish the work to be done.

This agenda is a guide to four goals: protect the ecosystem to guarantee that special natural settings are available for future generations, increase service satisfaction and education of Americans about their public lands, build community connections to expand available resources, and improve relationships to get the job done.

Source:

1. Adapted from U.S.D.A. Forest Service, "The Recreation Agenda," 1999, http://www.fs.fed.us/recreation/Recstrategy/recStratV70.shtml.

public demand for recreation on U.S. forest lands (5).

In response to increased public awareness and demand, there are enormous numbers of recreational services that are programmed into certain agencies and businesses. It is rather easy to assume if recreation is simply a set of leader-led activities, all an agency needs to do to satisfy recreational need is to hire a program designer and leader to organize and conduct recreation activities for users. In many community-based recreation agencies this is the dominant way that recreation activities and services evolve. However, once examined, recreation activities take on a more complicated view heavily influenced by individual choice and self-direction. It is interesting to note that in an e-mail discussion among professors of recreation (through SPRENET), researchers pointed out the paradox that what people say they like to do for recreation is usually *not* organized by an agency. They prefer to pursue recreation activities outside the programmed service arena (e.g., driving for pleasure, walking, and hiking). This is reflected repeatedly in recreation activity surveys. It is also important to note which are recurrent when discussing the reasons for managing an area to maximize recreation opportunity. What is it that people are looking for in recreation?

What Is This Recreation Stuff Anyway?

The question is not new and neither are the answers. There are many ways to think about recreation and there have been a number of books written on the topic. However, even though the answers are not crystal clear or uniform in their conclusions, the question has importance for management.

Recreation Is Personal

One of the most agreed-upon elements that characterize recreation is rejuvenation, or, literally, the re-creation of oneself. It implies a significant and refreshing change or departure from the activities done in the normal course of life. An assumption is that such a change is necessary for one to live a pleasant existence, and a further assumption is that what we do in the course of life has a stagnating effect on our quality of life. In short, we need a change to refresh us for a return to the ordinary activities of the world. Pieper (6) wrote of this need in his classical essay on *Leisure: The Basis of Culture.* People head to the great outdoors expecting (and usually getting) a change from the ordinary day-to-day experiences of life. Neulinger (7) added to this concept in the 1970s by identifying recreation as a psychological phenomenon characterized by the individual's perception of freedom and intrinsic motivation in pursuing an activity. Recreation is also commonly conceived as a set of usually pleasurable activities that one does as a way to counter the drudgery of day-to-day routines. There are at least three common elements that run throughout all these ideas of recreation: 1) it is individually focused; 2) it is a departure from the normal routines of life; and 3) it is a personally worthwhile experience. How can the recreation manager work to promote personal satisfaction for participants?

Recreation Can Be Seen as an Activity Free of Obligations

This concept of recreation tries to make a distinct difference between the ordinary day-to-day activities, like work, that may be seen as drudgery for many people. Going fishing is a good change of pace for many and the restorative powers are extolled by its participants. However, what happens if you need to take with you the boss or a colleague you really would like to leave behind? Or, more commonly, if one's spouse comes along and is expected to continue household responsibilities for cooking, childcare, and so forth, would the experience fit the description of recreation as a restorative activity? How much can recreation management make the experience more pleasant by assuring a change from the activities of daily living?

Recreation Is Multifaceted

There is more to hiking than a walk in the woods. Consider hiking and look at it carefully. It is easy to see there are a number of ways to understand its appeal to different people on the same day (Figure 17.1). There are people who take hiking very seriously and spend enormous amounts of time planning, obtaining the best equipment, studying the route, and anticipating the probability of extraordinary things happening. There are others who simply pass by an interesting trail or opening and decide to take a walk on a spur of the moment with no planning or strong expectations for a predictable outcome. One person may be

Figure 17.1 Hiking in the Cascade Mountains near Mount Shuksan in northwest Washington. (Photo by R. A. Young.)

interested in the physical challenge of a difficult climb, while another might be more interested in a gentle walk to a beautiful vista. Others may seek both in the same outing. Using more of this sort of probing, you can easily see that hiking is more that just a singular activity. The same reasoning can apply to most outdoor recreation activities (e.g., fishing, boating, and camping). The real trick for recreation management is to determine the range of services to offer for a single activity that might satisfy a range of reasons for participating (e.g., how many different types of fishing experiences can a particular site offer?).

Recreation Is a Multiphasic Activity

Another common understanding of the recreation experience is that it is a multiphasic activity as noted by Clawson and Knetsch (8) and Clawson (9). This means that there are different stages and phases to any recreational activity: anticipation and planning, travel to the site, on-site activity, return travel from the site, and recollection of the trip.

Knudson (10) has reduced the original five phases of the experience to four. Phase I is the *anticipatory stage* where flights of fancy begin to take shape in the mind of the participant. The actual event may or may not take place and the romance may change as realism begins to assert its presence (e.g., the constraints to the activity become more real). However, there is often a great personal or group satisfaction that may come from imagining possibilities even when the activity never takes place. Similarly, there is the potential for disappointment if the ideal does not occur.

Phase II is the *planning stage.* It is in this phase that the plans are taken from imagination to reality through preparation for the event. Gathering information, determining feasibility, assembling supplies and equipment, questioning those who have been there before, and developing the skills necessary for the event are all included as a part of this phase.

Phase III is the *participation stage.* It is in this phase where the activity actually takes place. It includes all elements from start to finish and in-between occurrences that are both planned and unplanned.

Phase IV is the *recollection and reflection phase* of the experience. After the activity, memories begin to take hold. Reflection and reinterpretation of the events are likely to persevere long periods of time into the future. One of the ways people enhance the experience is by obtaining souvenirs, like photographs, which carry much symbolic meaning. They tend to invoke sensations apparent only to the participant. That is why it may be hard to understand why your friends are enthralled with pictures of their trip while you may be a captive audience wondering what all the excitement is about.

This multiphasic understanding is a useful way to understand recreation experience for a single person. However, it is more complex when more than one person is involved. Each person will have a unique interpretation of the experience. This makes the recollection phase far more interesting than a singular report.

An even more interesting phenomenon is the cry "Let's do it again!" It is interesting because the chance of replicating a peak experience for a recreation participant is very small. Recapturing the exact pleasure and excitement of a previous time is almost impossible to replicate. Participants often experience the same event and obtain pleasure but it is somehow different from the previous time. The place and people may be the same but they are not in the same time element. As an ancient philosopher is often quoted, "you can never step in the same stream twice." Using these elements as a starting point for understanding recreation, it seems reasonable to examine the recreation activities people pursue in the out-of-doors.

Pursuing Recreation

The outdoors has always offered an attractive array of opportunities and experiences for people. Only relatively recently has it become important to understand what people do and why as noted in the section on legislative interests. Much of this interest evolved in response to a recognition that what people do affects the natural environment incrementally over time (and vice versa). Knowing the resources and appropriately managing them for use by people will accomplish a number of goals. Among the most important is offering people high quality opportunities for a variety of experiences while keeping the natural environment healthy for current and future generations.

Outdoor recreation is highly valued for many people. In 1994, the Roper Starch Survey reported that at least two-thirds of all American adults (18 years of age or older) participate in outdoor recreation every year and at least half participate monthly. Table 17.2 shows the "important" or "very important" reasons that the respondents gave for participating in outdoor recreation.

Clearly people participate in outdoor recreation for many personally important reasons. The survey also revealed that those who were more active in outdoor recreation rated their quality of life higher than those who participated less frequently. Such benefits make outdoor recreation an important part of American culture. In 1995, the National Survey on Recreation and the Environment reported which outdoor recreation activities were the most popular (of 13 listed in the survey) (Table 17.3). Respondents were at least 16 years of age at the time of the survey.

Outdoor recreation is important to and pursued by a large number of individuals. It is apparent that the trend for participation in outdoor recreation is increasing. Cordell et al. (11) compared outdoor recreation data from 1982/83 and 1994/95 and reported increases in participation for 29 outdoor recreation activities among individuals 16 years of age or older. Some examples of the percentage increases in a few selected activities are given in Table 17.4. The increases points to a more active population as noted in the visitation records from the U.S. Forest Service over a four-year period starting in 1993. The number of visits on national Forest Service lands grew from 729,474,200 093), to 839,238,900 094), 829,757,100 095) and 859,282,800 096). However, a few outdoor recreation activities declined in participation over this time period. They included horseback riding, hunting, fishing, sailing,

Table 17.2 Why People Participate in Outdoor Recreation

Reason	% Responding Either "Important or Very Important"
To have fun	76
For relaxation	71
For health and exercise	70
For family to be together	69
To reduce stress	66
To teach good values to children	64
To experience nature	64
To be with friends	60
For excitement	53
To learn new skills	48
To be alone	39
For competition	24

Source: Roper Starch Survey (39)

Table 17.3 Most Popular Outdoor Recreation Activities

Activity	%of People Reporting
Walking	66.7
Viewing a beach	62.1
Family gatherings	61.8
Sightseeing	56.6

or waterside outdoors

Source: National Survey on Recreation and the Environment (40)

Table 17.4 Change in Participation for Selected Outdoor Recreation Activities

Activity	% Change from 1982/83 to 1994/95
Bird Watching	155.2
Hiking	93.5
Backpacking	72.7
Boating (power)	39.9
Swimming	38.2
Downhill Skiing	58.5

Source: Cordell (11; p. 239)

ice skating, and tennis. This decline poses management issues, because even though they have declined, there are still participants. The question is how to manage the recreation resource base for a smaller number of participants.

These participation trends are likely to continue and are influenced by many of the changes in population dynamics and related trends in economy and technology. It is useful to take some time to look at how these factors relate to outdoor recreation experiences and think about the implications they hold for managers.

The patterns of recreation use are always reflective of a greater set of population factors. It is useful to look at a few population characteristics to address and understand their effects on recreation behaviors. They include education, age, gender, minorities, immigration, wealth, and technology. Although these are presented separately, they are very interrelated.

Education

The average level of education in the United States has been steadily increasing since the turn of the century. According to data from the National Center for Educational Statistics (NCES), Americans had more years of education in 1998 than 1990. In 1998 among adults over 25, 83 percent had completed high school and 24 percent had completed 4 or more years of college (12). Education affects participation in outdoor recreation in many ways. Among them is the exposure to new activities and introduction to ideas and possibilities that might enhance the quality of life. Through education, people often get new ideas for outdoor recreation which they pursue well beyond the formal school years. It is clear that more education also leads to greater sophistication in demand and greater expectations for the quality of the recreation experience. There is also a consistently strong link between education and economic success (i.e., the more formal education one has, the greater the level of income throughout the life span). With affluence, people have greater means to pursue activities in outdoor recreation experiences that would not be possible otherwise.

Age Structure

There is always an age influence in outdoor recreation, but it is sometimes difficult to draw definitive relationships with specific activities. However, there is a clear age-related trend in participation patterns represented in selected results from the 1994-95 National Survey on Recreation and the Environment shown in Table 17.5.

At the youthful end of the age spectrum there is a clear impact on outdoor recreation for higher risk, adventure, and "extreme" sports influenced by media coverage and advanced technology. These activities make management of outdoor recreation more interesting. For instance, how does one create policies for rock or cliff climbing that are compatible with public management plans and agency responsibility?

At the other end of the age continuum, vigorous and demanding physical activities tend to decline in intensity and number with advancing age. The reasons for this trend are numerous, but among

Table 17.5 Participation in Recreation Activities by Age (% of Respondents)

Activity/Age	16-24	25-29	30-39	40-49	50-59	60+
Fitness	77.2	74.7	76.1	72.0	64.0	49.7
Running	50.4	33.2	28.3	23.3	17.4	8.1
Biking	37.9	36.2	37.4	30.7	21.9	10.6
Walking	68.1	72.4	74.6	71.9	64.0	49.7

Source: National Survey on Recreation and the Environment (40) them are the lack of time to maintain a level of fitness appropriate to the activity demand. This is often related to increased demands of adult responsibility. This lack of time also encourages people to make more deliberate choices in their activities, which means greater selectivity and the sacrifice of those deemed of lesser value or feasibility.

Activities may be pursued with adaptation across the years as well. For example, one who enjoys wilderness camping may redefine wilderness over time and pursue the adventure in areas with greater ease of access and better amenities in later years of life. Other adaptations that may be made include the use of technological advances in equipment that make continued participation possible. For example, the advances in technology for canoe construction have reduced the weight significantly and therefore the need for heroic body strength has been reduced. This one change has opened the canoe experience to many individuals who were once prohibited by the physical demands of the activity. It is important to understand, however, that this improved technology comes at a higher price that may result in restricted access just as much as age and strength.

Before leaving the issue of age, there should be a bit of warning. While there are a number of age-related effects on the physical abilities of recreationists, it is absolutely imperative to remember that Americans are in better condition now than in previous generations. Jogging, wilderness backpacking, Whitewater canoeing, and many other physically demanding activities are pursued successfully into very old age by many. The good manager will not assume that age is a deterrent to participation.

Gender

The movement toward gender equity has initiated many changes in how management functions. Gaining momentum from the 1960s, these changes have increased access and opportunities for women in many areas of life and outdoor recreation participation shows significant increases for women. Outdoor recreation managers need to be thoughtful of policies and practices that are inclusive across gender lines. The most recent outdoor recreation survey data show that women participate in almost equal numbers and types of recreation as men for many categories of activities (NSRE 1994/95). For those who want to know more about gender issues related to outdoor recreation and leisure, see Henderson et al. (13, 14), Freysinger (15, 16), and Bialeschki and Walbert (17), among others.

Minority Populations

Minority populations in the United States are most commonly represented by those of African, Hispanic/Latin, Native American, or Asian ancestry. The most recent census data indicate that approximately 25 percent of the population is represented by one of these groups (U.S Census Bureau, 1994). New data from the 2000 census reflect an even larger proportion of the population, since minority populations are growing at a faster rate than the majority population. Each of these categories represents an ever greater diversity when closely examined. For instance, Hispanic/ Latin ancestry is used to designate those who may be Cuban, Puerto Rican, European, Mexican, or any number of other cultural or ethnic groups within the broader category. The growth in minority populations also means that they are likely to pursue recreation in forested areas in greater numbers (Table 17.6).

Managers need to understand that they will need to think about the implications of ethnically and racially diverse users. For example, in some areas of the southwestern U.S., it is becoming a common practice (and a necessity) to hire bilingual staff and produce signs, brochures, and other communication tools in both Spanish and English. In the West, Asian languages (e.g., Japanese, Korean, Chinese) are important to help other cultural groups learn about the area's opportunities, rules, and regulations.

Some understanding of ethnic traditions and preferred use patterns are also helpful to managers wanting to be more accommodating to these users. Equally important might be a better understanding

Table 17.6 Outdoor Recreation Participation Patterns Among Minority Groups (% of Respondents)

Activity/Group	Hispanic	Native American	Asian
Camping	21.1	27.7	18.6
Hunting	6.4	21.1	4.6
Fishing	24.9	43.1	29.2
Hiking	27.0	30.0	24.3
Picnicking	50.8	61.2	60.0

Source: National Survey on Recreation and the Environment (40)

of cultural history to avoid potential conflicts among a diverse set of users.

Most minority populations reflect settlement patterns of the dominant culture, in that they are highly urbanized. Many do not (or cannot) take advantage of the more remote or non-urban outdoor recreation environments, although their numbers are showing a slight increase. Urbanized areas present an interesting area of outreach work for managers of recreation areas. These populations can be a powerful political force in future generations. If they understand and appreciate the value of resources for recreation, they can help preserve these lands by political action. If they do not value the resource, it could prove troublesome.

Immigration

The United States has been shaped and directed in many ways by the immigration patterns of the most recent Americans. The first major waves of immigration were mostly from Europe who came seeking land and freedom and those who were brought here under less-than-voluntary circumstances (the Africans); however, both are now integral parts of our longer-tenured demography. Subsequent waves of immigration at the turn of the century again were heavily European and looked much like those who were already here. The newest surges of immigrants are of Latin and Asian ancestry. All groups bring unique contributions to the culture and all participate in outdoor recreation activities. One of the most intriguing problems recreation managers face is how policies reflect the dominant culture's perspective. Sometimes these policies are in direct conflict with the values, traditions, and understandings of a minority or newly arrived culture, and the educational responsibilities of an agency require much more serious attention. It quickly becomes important to develop an understanding of new visitor groups and design responsive education and information programs for staff as well as visitors.

One of the first natural resource management texts to address these issues was written by Ewert, Chavez, and Magill (18) and it is still an excellent resource for understanding many of the cross-cultural issues facing recreation area managers. Chavez (19), Floyd and Shinew (20), Floyd (21), and others continue to increase our understanding of improved management strategies that accommodate multicultural understandings of recreation participation and the natural environment. Cordell et al. (11) also present useful data on outdoor recreation participation patterns by cultural, ethnic, racial, and disability categories.

These trends lead to yet another caution for recreation resource managers. Even though we need to group information on people by some common factor, remember that this is an administrative convenience and not an accurate portrayal of culture or behavior. There is enormous variation between groups and their specific cultural beliefs that can and sometimes does lead to serious user conflicts if not well understood by the manager. Further, as multiple cultures share the same space, it is simultaneously an opportunity to promote understanding and appreciation of diversity, but which could quickly become a situation promoting conflict.

Affluence

It is important to be cautious with the proclamation that individual wealth has increased dramatically. While it is true for a large sector of the population, there are still others who remain low income and live at the margins of society. However, it is true that on a national scale, personal wealth has increased dramatically and created a unique out-migration of people from urban areas to be near nature. This growing divide between affluence and poverty has had a significant impact on recreation policy. As agencies increase fees to offset declining budgets, how will access by the poor be maintained? Data from the NSRE 1994-95 survey show the direct effect of income on participation in outdoor recreation activities like boating, sailing, canoeing, water skiing, and motor boating. Where price of participation equipment is high, affluence plays a predictably prominent role.

Urbanization

From agrarian roots, we moved into the cities at the turn of the century, and over the years, became a very urbanized society. The attachment to the land became quite distant (22). Most people experience the out-of-doors in urbanized areas where some vestiges of nature continue in the forms of parks, arboretums, and urban forests. The conceptualization of nature is then colored by these settings. Media, museums, and other exhibitions have shaped an idealized and romantic concept of nature. Paired with new affluence, this has made for interesting changes to the once rural and relatively inaccessible wilderness.

Rural and small-town communities have been dramatically changed as a result of the in-migrations from urban areas (23). For example, small towns in northern Wisconsin have changed their character to serve urban tastes (e.g., fine wine and dining have replaced the bait and burger shop; four-star hotels instead of rustic cabins; and upscale furniture is in demand). These situations also change recreation demands and sometimes bring conflict over use. Hunting is often disliked by those from urban areas who see all animals as desirable for nonconsumptive recreation activity (e.g., bird watching), but is seen as a way of life among those who have long tenure in rural areas. The manager of a natural recreation area is likely to be found right in the middle of the debates over the proper use of a recreation site (like a national or state forest) which is often the reason people move to an area.

It is important for managers to recognize that the boundaries of a recreation area are paper agreements. The borders are quite permeable, presenting a series of concerns by residents. The protected area is actually part of an ecological region where plants, animals, and people interact with unpredictable and often uncomfortable results. Managers are required to involve the general public in design and implementation of management policies. Cases where readers might look for these issues include the Buffalo/Cattle conflict in Yellowstone (24), or user rights and control in the Boundary Waters Canoe Wilderness Area of the Superior National Forest (25).

Access to these areas is an additional result of societal affluence. Airports and superhighways now exist that allow easier access to once rural and remote areas that were at one time considered inaccessible. Increased accessibility promotes a change in the context for management. No longer is the job of the manager one of simply managing a designated area. It is now the task of the manager to see the recreation site as a part of the larger region and to promote policies, procedures, and plans that reflect that view.

Technology

This is one of the more interesting factors that has changed outdoor recreation participation in many ways, resulting in improved communications among and between employees, better record keeping, easier data base management and access to information. Conversely, each of these assumes that all the innovations are good for management. The cost of capitalization is often high, continuous training is usually needed to use the equipment properly, and maintenance is a requisite for proper function. Office management technology can also become outdated quickly and there is a continual need to upgrade. In short, it can be very expensive, but at the same time, it is much more effective and efficient, making the investment worthwhile.

On the user side, interesting consequences appear as a result of technological advances. I have had the opportunity to be in the Boundary Waters Wilderness Canoe Area on a portage where another party was passing and one member was talking away on a cell phone. Is this a proper technology for the wilderness experience? On the other hand, a cell phone or beeper could be a life-saver in cases where wilderness overwhelms the recreation participant. Should these communication technologies be encouraged, banished, or controlled in some way? How does the manager decide? Is it the manager's decision to make?

Similarly, equipment technologies have made management strategies even more interesting. Equipment like aluminum canoes that were once heavy and difficult to manage have given way to lightweight durable products like those made from Kevlar. Superhuman strength is no longer a requirement for wilderness canoe experiences. The same can be said for a wide array of recreation equipment. Off-road bicycle advances in technology permit a new access to wilderness that was impossible a few years ago. There are new versions of in-line roller skates that are designed to go across rugged terrain in addition to smooth, hard surfaces. The list of advances goes on for some length and the management implications get more intriguing. Questions for management include how to address these changes as a part of recreation policy. Is it fair to assume that all the changes are bad or that changes should be considered a fact of life? More realistically, what criteria would one invoke to make such a distinction?

Section Summary

In this section, some of the large issues for recreation managers related to innovations and change in society have been outlined. It is impossible to separate these issues in reality, because they are all interactive. Managers need to understand the effects of complex systemic interactions like these have on achieving good management practice. What happens when managers impose selected regimes on areas? What responses of users may be forthcoming? We turn now to a brief discussion of these issues.

User Conflict

Inevitably one of the stickiest problems facing recreation managers is the conflict that occurs between and among users of a recreation area. It often seems that one of the daily tasks of management is to resolve some complaint where one group or person has infringed on the experience of another group or individual. Sometimes these are minor nuisance complaints (e.g., playing music loudly into the night) but others are quite serious (e.g., assault or other criminal behavior).

Let me address the most serious of conflicts in a brief manner. Outdoor recreation areas are not immune to illegal activities. Some sites have reported the most serious of predatory of criminal behaviors (e.g., kidnapping, drug trafficking, theft, sexual assault, and murder). These are clearly not minor conflicts and must involve authorities with police powers. In some recreation areas, staff will have some police powers and in others there may be none. Regardless, managers have policies and plans in place to confront these possibilities through joint agreements with local authorities (or with federal agencies such as the FBI and DEA) where warranted.

More frequently, managers will need to face participants who come to a site for one reason only to be confronted by other participants who have a different use of the resource in mind. For example, snowmobile operators and cross-country ski participants may share a common space (a trail) for very different and noncompatible purposes. There are numerous reports of encounters between the two groups with each complaining about the other. Similarly, runners, mountain bikers, hikers, and horseback riders may all have a common trail with multiple purposes and expectations for the experience. Lakes are also primary areas where multiples users with multiple expectations might encounter each other at close range (e.g., fishers, swimmers, sail boarders, power boaters, canoeists, and sail boaters).

Often, users resolve their diverse expectations without intervention. As noted elsewhere in this chapter, one way to resolve the conflict is to change the experience by arriving at different times to avoid or minimize undesirable interactions. Another is to relocate to another site for the experience. Finally, sometimes users can decide mutually that some modification to experience and behavior is in the best interest of all.

However, in many cases managers will need to come forward with policies, rules, and regulations that attempt to minimize conflicts among and between users. One of the first places the managers must look is into the laws and legislation creating the recreation area. Here is the place to discover what powers the agency has for making policies and rules as well as what abilities they have to enforce them.

Second, the manager needs to examine his or her personal abilities to confront and address the parties and move toward resolution. Sometimes the skills of a negotiator or arbitrator are useful when dealing with human interaction problems. Often issues of conflict arise as an exception to daily routines. For instance, a group of people playing catch with a Frisbee in an area designated for picnicking may result in a conflict where simply speaking with the parties involved might be sufficient. In situations where conflict is recurrent, it is important to reexamine existing policies and rules for applicability and enforceability. It might be possible for the manager to create and enforce a new guideline, but this also runs the risk of alienating at least one of the user groups and may lead to some legal or personal challenge.

One of the more recent evolutions in management is to create a users' advisory committee or a "Friends" group to help guide policy development and implementation. In these groups, the conflicting users must sit and discuss their concerns and develop rules that might be useful in preventing unpleasant interactions. These groups do take time and energy on part of the manager but ultimately result in better management and experience outcomes.

An example of how this process might work effectively can be found with some Lake Homeowners Associations members, who meet to determine use patterns for the lake they surround. The net effect of their deliberations results in the zoning of the lake by area, activity, and time of day. For example, power boats are not allowed on the lake before 8 A.M. and must be off by 7 P.M. Swimming is confined to a certain area where boats are forbidden. Jet skis are banned altogether. These rules are communicated to users and respected with the force of law, but mostly by assent of the users. Where people feel they are a part of the resolution of conflict, greater adherence and respect for the experiences of others increases.

This method of conflict resolution by participation is in widespread use with federal and state land management agencies. It is a very powerful tool, but requires some special talent and ability to make it work well.

Social Succession

When a management plan is implemented on an area that has been either unmanaged or managed for different experiences in prior plans, any number of outcomes are likely. The shift in management strategies may create a social succession of users and behaviors.

The net effect of succession is often displacement of one group of users by another. If the primary objective is to maintain a particular experience, the manager may change the use pattern by widening the road, improving the trail, or putting in a footbridge. Often these minor modifications of existing developments are sufficient (particularly their cumulative effect) to shift the experience enough that it appeals to a new type of user and not the traditional user. The former users are displaced by users whose expectations more closely fit the new context. Displacement is a move away from an unacceptable situation, not a move toward a desired one. This distinction is useful in differentiating displacement, a form of reactive movement, from other forms of movement which include the following:

1. *Active Migration.* People seek a suitable destination according to their values—for example, white-water canoeists seek a variety of risk and skill testing.
2. *Passive Migration.* People select a location because it is convenient, such as visiting areas to meet friends for picnics, or because other members of the participation group desire that location.
3. *Movements for Diurnal Requirements of an Activity.* People move to different locations on a lake to fish at various times of day.

Movement is then a general term, whereas displacement is a negative reactive movement (26). However, as a manager, it is possible to envision situations when one wishes to encourage displacement of one set of users who may be destructive of the environment (physical or social) by intentionally contriving the context to be less appealing for them. To effectively manage an area that facilitates user satisfaction is a serious challenge to recreation managers. It is important to examine some of the tools and practices available to managers.

The Recreational Opportunity Spectrum (ROS)

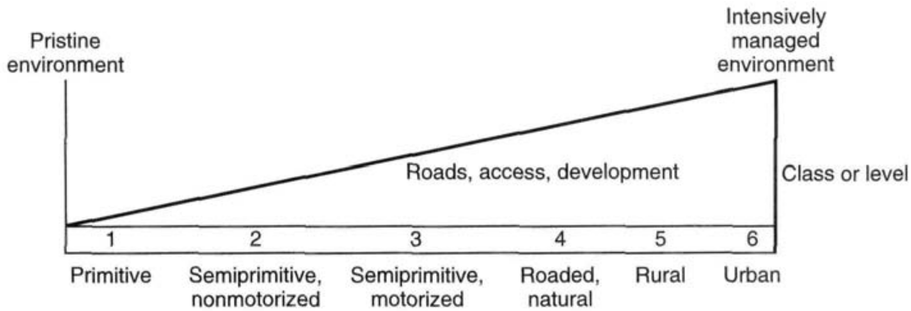
Since the types of recreational experiences desired by participants varies widely, it is difficult to provide opportunities that meet the needs of everyone. In fulfilling the mandate for multipurpose use of the forests, the managers had to think more systematically about the interaction of users with the resource base. If participants of varied interests, abilities, needs, and purposes were to derive some individual benefit from use of a common base, a tool was needed to help organize how the resource could do this (27). The solution was the Recreation Opportunity Spectrum (ROS), which was developed to examine and categorize landscapes on a continuum from highly developed (e.g., lots of structural development) to totally undeveloped (i.e., primitive) areas. At the extremes, and between these polar ends, landscapes were categorized by descriptors that allowed a visitor and manager to better understand the types of experiences and activities available. Conceptually, the experience offered by the totally pristine environment without development would be the antithesis of the experience offered by the urban environment. While this may be a reasonable assumption of the expected outcome, it is not without argument. Indeed, for some individuals, an urbanized recreation area might prove quite an exotic and satisfying "wilderness" experience where for others even the vast open spaces of large reserves may seem too "urbanized." The point is that the ROS is a useful tool for managers to assess, describe, design, and develop the resource base; however, predicting the experiential outcome remains a speculative venture (27, 28). A simplified description of the ROS can be found in Figure 17.2 and a description of its application to the Pacific Crest National Scenic Trail is found in Figure 17.3.

Management by Design

Realizing there is great variation in the recreational experiences of individuals, it is impossible to guarantee an expected outcome for any one person. Therefore, managers must use the best tools they have available to design and develop areas that enhance the probability of a positive experience outcome for a class of users.

Obviously, it is impossible to design a site to fulfill every user's expectations. As indicated earlier, it is very important to establish a plan for area design that is compatible with the purposes of the area. The master plan needs to accommodate appropriate uses of the land based on the best available knowledge of the ecosystem (e.g., topography, soils structure, hydrology, etc.). It then needs to address the expectations of certain classes of consumers (e.g., campers, canoeists, hikers).

Figure 17.2
The Recreation Opportunity Spectrum (ROS), using the Forest Service terminology to describe specific opportunities.



For example, the design and placement of a campground can greatly affect the recreational experience of a camper or campers. The design might accommodate the landform and consumer by its placement in an area sufficiently isolated from hazards and nuisances like busy roads, parking lots, or garbage drop areas, screened by select native trees and shrubs so a feeling of privacy exists; thus, the context is set for a pleasant experience by the visitor while the ecological integrity of the site is maintained.

Observing human behavior preferences can be helpful in other design applications. For example, most people like ease of access to recreation areas. The more challenging the access, the numbers of users declines and the characteristics of the users change. People who use the Boundary Waters Canoe Area Wilderness (BWCAW) are likely to be younger, more fit, stronger, and looking for privacy and an experience of relative isolation. Those with younger children, those who are less physically capable, or those who like or need to have service amenities close by (e.g., concessions, rest rooms) are not likely to choose the BWCAW (or any other wilderness) as their destination. In planning, it is possible to create levels of challenge as well as development to address the variations in need among participants (Figure 17.4).

One of the major purposes of a master planning process for recreation areas is determining the appropriate uses of the land and how the users can be dispersed across the land on a continuum of use as noted in the section on the ROS. The degree of development to address certain experiences is important to consider in advance of use when possible. Anticipating the use intensity of an area clarifies the degree of site hardening required. *Hardening* refers to the degree of development for a particular site. Generally, hardening an area facilitates a greater intensity of use with less environmental damage and a greater ease of maintenance. For example, if a site is developed for high use (e.g., a public beach area with multiple activities like swimming, boating, fishing, hiking, camping, picnicking, open space for physical activities), it will likely have asphalt surfaces, grasses that tolerate heavy traffic, concessions, and so forth, with a concentration of human services for continuous maintenance and upkeep. Damaged portions can more quickly and easily be repaired and litter and waste are more easily and efficiently removed than in more remote and wild areas. More remote areas, where little or no hardening has occurred, are much more susceptible to damage and abuse that cannot be easily corrected. When wilderness areas are maintained, the cost is relatively high and the repair by nature could take many years (Figure 17.5).

Just how much development should take place? Who decides? These questions have emerged as critical points for management in a new era of forest use planning. If it is assumed that we can and

ROS Descriptions

Many believe chat the Pacific Crest National Scenic Trail (PCNST) passes for the most part through wild and beautiful country. In fact, it passes through a wide variety of environments offering a range of recreational experiences. The kinds of surroundings and experiences can be viewed as a spectrum of recreational opportunities, from urban, highly developed and used by many people; to primitive, undeveloped and used by very few people. Recreation managers use this Recreation Opportunity Spectrum (ROS) to judge the appropriateness of public facilities, roads, trails, sanitation, and so forth, within particular settings, and to gauge the appropriate design for roads and timber harvest operations in areas where they are allowed. Hikers can also use the ROS to find areas that offer the hiking environment they seek.

Urban The urban setting may be where you live! There are many buildings, paved roads, and a great many people. You will not experience the urban setting along the PCNST in Oregon. Hiking and biking trails through city parks and residential areas would provide an urban recreation experience.

Rural The land between the cities and the forest provides a rural setting. It includes pastoral farmland, small communities, and commercial facilities, or large campgrounds and trailheads along paved highways in the forest. Expect to find many other people along these parts of the trail. These areas offer convenient day hikes and sites for off-road vehicle travel throughout the year.

Roaded Natural Along or near main forest roads and highways, you will find subtle modifications of the natural environment. Improvements are limited to roads, trails, and a few scattered structures. The natural environment still dominates, but timber harvest and preparations for the next generation of trees are visible. Posted regulations as well as contacts with others are likely. In fact, there are limited opportunities to get away from others. You are farther from towns and their conveniences, so you must be self-reliant in supplying your personal needs. Substantial day hikes and opportunities for more relaxed biking and camping prevail. The PCNST trail traverses such areas as it passes near many trailheads and road crossings.

Roaded Modified Along less-used forest roads you will likely find large clearcuts, skid roads, and landings dominant to the view. You will encounter more chances to get away from other recreationists, but logging operations may be dominant. No facilities are provided. You are on your own.

Semiprimitive Leaving roads behind you, you become more isolated from the sights and sounds of human activity. The degree of risk and isolation increases, and recreational activities become dependent on the natural scene. No picnic tables and other improvements are provided; human comfort and satisfactions will be gained through your personal initiatives.

Primitive Primitive settings are the most remote parts of the forest and are little influenced by the works of people. The natural environment dominates the setting and dictates the kinds of recreational challenges: beauty, isolation, uncertainty, risk, and discovery. Woodsmanship skills are important in providing safety and comfort.

Figure 17.3 Recreation Opportunity Spectrum: an example. Source: From the southern Oregon portion of the Pacific Crest Scenic Trail map.

Figure 17.4 The Boundary Waters Canoe Wilderness Area in the Superior National Forest provides unmatched beauty, challenge, and renewal for recreationists. (Photo by Robert O. Ray.)

should provide a spectrum of opportunities for recreational use and experience based upon the intersection of good ecosystem science, finite management resources, and human behavior, which seems to have an unlimited demand for experience, how far can and should we go in modifying the landform? This moves the discussion into a very interesting and challenging area of management.

Figure 17.5 Nature also poses interesting questions for managers. The damage from the 1999 storm in the Boundary Waters Canoe Wilderness Area introduced challenging questions related to recreational use, fire potential, and natural renewal. (Photo by Robert O. Ray.)

Limits of Acceptable Change (LAC)

The Recreation Opportunity Spectrum previously addressed is not a rigid tool for managers to impose behavior limits. It is instead a guide or index of the relationships between site constraints and visitor options. Limits of Acceptable Change (LAC) is a planning procedure that enumerates changes to the physical environment that will cause little harm to the recreational visitor's experience opportunities. An integrative procedure, LAC brings together the work of researchers on visitor expectations and the efforts of managers to understand site resource constraints. It assists managers in arriving at site management judgments by specifying the products and recreational opportunities that specific resources provide and by clarifying what would threaten their quality. However, to be successful, the process depends on a clear enunciation of management objectives.

Management by Objectives

Management by Objectives (MBO) is still an important tool in administering outdoor recreation if we are to maintain a specific identifiable recreation opportunity on the basis of resource capabilities. Simply put, management by objectives means establishing goals or outputs that are agreed on by the members of an organization. It is an effort to focus attention and resources toward a common end. An MBO exercise helps participants first to sort out a desired option from among the wide range of alternatives and then to direct their energies at providing the desired objective or product. A modification of the MBO model has the following inputs for recreation program objectives (29).

$$\left.\begin{array}{l}\text{Resource Capability}\\ \text{Institutional Constraints}\\ \text{Existing Situation}\\ \text{User Preferences}\\ \text{Coordination}\end{array}\right\}\ \begin{array}{l}\text{Recreation Program}\\ \text{Objectives}\end{array}$$

In this model, *resource capability* describes the overall limitations on programs, but typically agencies are more institutionally constrained by laws, regulations, or policies that effectively constrict the scope of operations for a specific agency. If the recreation pattern on a specific path has never been managed using program objectives, a certain clientele has usually developed over time. The existing situation (the norms of the existing clientele) will probably dictate the direction of the initial management planning. If other user preferences can be accommodated in the resource base, they should be included. The need and opportunity for coordination of efforts typically occurs when two or more land management authorities overlap or adjoin an area and the desire to provide continuity for the recreation experience is mutual. Interagency agreements must then be negotiated to assure that continuity is maintained.

Some Notes on Management Planning

The preceding discussion of the Recreational Opportunity Spectrum (ROS), Limits of Acceptable Change (LAC), and Management by Objectives (MBO) make the management planning process seem very straightforward and linear. It also implies that those who are the leaders in the management organization are the ones who get to set the management plans in place based upon their authority, knowledge of the ecosystem, and a belief that they know what the recreation participant prefers. There is also the implicit concept that the recreation area under consideration is a world separate from the local residents. This conceptualization of recreation area management is too narrow and needs to be revisited in light of several emerging understandings.

The multiple-use philosophy of forest management that has emerged over the last decade or more has placed a new emphasis on planning and has significantly increased the role of the public in the planning process. Forested lands in the United States have experienced a marked change in use over this time. Whereas timber production was the main reason for existence earlier in the 1900s (and continuing), there is now a much greater emphasis on managing the forests for the environmental services they render (e.g., water conservation, flood control, conservation of natural resources, and recreational use) (5, 30). Furthermore, as affluence has grown in the United States and access to these natural resources has improved, there is a growing recognition that protected areas like U.S.F.S. lands are a part of the larger communities where they are found.

As Field (3D notes,

> ***The traditional philosophy of resource managers and land management agencies is that people are clients, guests, or visitors to the system. As a result, the tendency has been to consider people and their resultant behavior as a problem to solve. . . . These [parks or forests] are the places where cultural and institutional practices of the agency meet the cultural and institutional practices of the population occupying the resource on either a temporary or permanent basis.***

In recognition of these changes in philosophy and culture, there is now a larger mandate to land management agencies. As each of the sites develops a required management plan, there is a further required element for public participation in the decision making. While this is an interesting and necessary way to function successfully in a new century, it is often a confusing and challenging process that requires a set of management skills that transcends scientific knowledge of both the ecosystem and the science of recreational behavior. There is a need to understand sociopolitical processes, group dynamics, and collaborative processes with new partners. These considerations have until very recently been beyond the need of managers and planners and have resulted in the new classification of Social Forestry further discussed in Chapter 23.

It is interesting and challenging to determine first how to involve the public (e.g., whom to invite, how far to reach, what is the best format for input) and then determine what to do with their advice (e.g., does it make sense, how exclusive will the land become). Finally, how does one create a meaningful management plan with input from varied perspectives (e.g., ATV users who want no restriction on their movement, birders who want *all* vehicles banned from the area).

There are a number of models that presently exist to involve the public in planning for natural resource management. The space and focus of this chapter limits discussion of those processes but readers who are interested are encouraged to look at some recent works on collaborative planning (32-35).

All the management elements discussed (ROS, LAC, MBO) are no longer the singular product of the scientific manager. They are elements largely defined and determined by consumers. They are far more politically charged than one might first be led to believe. Creating management plans in cooperation with these new inputs is an essential, and not always easy, part of successful land management for recreation uses.

Partnerships deserve a bit more attention here. This is a relatively new phenomenon in recreation management, but there are vestiges that go back into history. Newer partnerships have evolved between governments (federal, state, and local) and organizations that were at one time distinctly separate, critical, and even hostile toward each other. Over the last decade, there has been a deliberate approach to work more collaboratively for common goals, since much of the land and water resources controlled by government, nongovernment, and private groups is in close proximity or adjacent to public lands.

Obviously, joining resources increases the ecological integrity of a region and can provide wider ranges of recreation opportunities for participants. The trick for managers is to understand how to approach these groups (or understand that how to interpret an approach from them), to arrive at common goals, monitor the processes, and help the public understand how these agreements function. It is also important to understand that these can be complex agreements with organizations that may have very different management objectives and practices. These practices may not be replicas of those endorsed by any one agency and difficult to understand by the average user. Furthermore, leadership changes in all agencies and new leaders may bring an agenda for use that challenges the assumptions of an existing agreement. Being understanding, adaptable, and strong are important characteristics that recreation managers must maintain. Some of these "new" partners in recreation could include Lake Home Owners Associations, private timber companies, NGOs (e.g., The Nature Conservancy, Ducks Unlimited, Sierra Club), Native American Tribal Councils, or private land holders. It is an interesting task to keep these organizations working cooperatively and simultaneously holding the public concerns at the forefront in recreation management.

For many years, various agencies have addressed services by concessionaires in recreation areas. As recreation area managers begin implementing business practices to improve service, there are some lessons to be learned. For example, the state of Wisconsin moved to a centralized reservation system for campgrounds in 1999. While eventually working well, Sidebar 17.2 has warnings for new ventures that go beyond the simple rationale of decision making.

Often agencies like the Forest Service or National Park Service seek bids for specific vendors to provide a service in an area (e.g., garbage removal, food services, equipment rental). These are long-tested relationships at many levels of government where both parties contractually agree to a service or product and share in the revenue. As resources for local operating budgets decrease, this fee revenue idea has broadened. The next section addresses the evolution of fees and charges as a management tool, which are increasingly important sources of operating revenue for recreation area managers.

Fees as a Recreation Management Tool

While fees are not new to recreation on public lands, they have changed in the way they have been presented to the public and used by various

Sidebar 17.2

Public Relations and Parks Management—Change is a Challenge!

The State of Wisconsin Parks System implemented a telephone reservation system for those wishing to reserve a campsite in any of the state parks. A request for vendor applications was issued and a company outside the state was awarded the contract. In the days following implementation, complaints began to mount.

Some of the complaints were about the changes in the process. The phone reservation system replaced a mail-in reservation system that had been used for many years. A further public relations issue was created by a major change in the cost of reserving a campsite. The fee was increased from $4.00 to $9.50 per reservation and a cancellation fee of $8.50 was added. These were serious changes to the relatively inexpensive and traditional process; however, people came to understand the need for the cost increase to improve and maintain facilities for their service.

The more interesting and least anticipated reactions were to the manner in which reservations were being taken. Many of the reservation center representatives were based in California. They could not read the maps and were not familiar with the state or the parks within the system. Some also found it difficult to tell tented sites from those with motor home facilities. They mispronounced the park names and had accents that were clearly not familiar to those in the Midwest. Interestingly, one of the biggest problems that distressed local residents most was the mispronunciation of the state name. "Wes-consin" rang across the lines to the great irritation of already testy consumers.

The problem was given partial remedy when the reservation system calls were redirected to a local site that had been opened with new employees hired from a local phone-based retailer that had gone-out of business. Having people well trained in phone service and knowledgeable about the locale was critical to making an effective change in a large and outdated system.

The major lesson here is that managers must think beyond the simple logic of improved efficiency when implementing change. Public reactions are key to success in making change.

Source:

1. M. BALOUSEK, "Reserving a Campsite in "Wes-consin," Wisconsin State Journal, Sunday, July 25, 1999, p. 1C

agencies like the U.S.F.S. In general, the practice of charging fees for the recreational use of public lands is almost a century old. Auto permit fees were issued as early as 1908 to help pay for a roadway at Mt. Rainier National Park (36). However, the debate over the use of fees for use of public spaces has been controversial over the same period of time (probably longer).

The general concerns that people have about fees can be expressed in several ways. One is that fees are a double tax on the user. Users pay into the federal general revenue fund for a wide array of goods and services. To pay a fee on top of those taxes is to pay twice. A second argument is that fees change the concept of public land to one that says the land is a commodity available to those who can most afford it. In this argument, it is possible to raise the issue that users will be treated differently based on the ability to pay. Those with more might get the campsites on the water and those who have less might find their tent pad next to the garbage drop where bears tend to gather in the night. A final argument is that a fee discourages the participation of those who are economically disadvantaged, promoting a gap between the "haves" and "have nots" of society.

Until recently, these arguments have been very effective in preventing the significant use of fees in parks and forest recreation management. Very low and no fees were the way of life for most agencies until the concept was revisited in 1996 with the implementation of the Recreation Fee Demonstration Program (PL 104-134) for the U.S. Forest Service, National Park Service, Bureau of Land Management, and the U.S. Fish and Wildlife Service. The Forest Service describes the evolution of this program in the following way (37):

> ***More and more people recreate on national forests each year. As more and more people recreate, keeping up with the needs of those visitors and of the natural resource becomes more and more difficult. Seeing that national forests, parks, and other federal lands were suffering from the lack of funding to care for these lands. Congress passed a law to test bringing more funds to these lands in a new way.***

This quotation indicates a very important change in the way that fees have been conceived, used, and desired by the agency. First there is the recognition that general revenue funds are increasingly hard to obtain from Congress for many reasons. Prior to the fee demonstration program, the site managers were given very little incentive to raise funds. Fundraising was discouraged and the assumption was that a site manager would receive an allocation from a central source. Funds might be more equally distributed, but for high-demand, high-use areas, the needs for management funds are likely higher than those in smaller, less-used areas. This placed an intense and often unpleasant internal competition for funds among the various site managers. Revenue created by a particular site was not permitted to stay at the generating site. Rather, the money was returned to the general fund of the Treasury and never returned. Under the Fee Demonstration program, a site is allowed to retain a majority of the revenue to supplement funds allocated from the general fund (38).

This change obviously gives considerable incentive to local sites for generating extra income to do things they may never have been able to do otherwise. It is at this point where cautions again become appropriate. Some sites are so popular that affluent users are willing to pay relatively large fees to gain exclusive use of the area. The balancing act is to instill equitable access into a framework of pricing that is more market-oriented. This is a program in evolution among Forest Recreation managers. Most are not well trained in economic pricing and its effects on user patterns, so it is logical to assume that there is a steep learning curve to find the right way to establish, assess, collect, and use fees. Currently the fees retained on site are used in ways that make good sense for the site. Table 17.7 shows breakdown of uses of fee revenues for 1999 according to the Forest Service (37).

> **As *of September 30,1999, the Forest Service spent $42 million of the* $56.6 *million collected since the Forest Service began collecting these fees in 1996. Planning and time requirements for accounting and issuing contracts explains the unspent balance.***

As managers become more comfortable with the mechanisms and as the public becomes more accustomed to paying for use, it is logical to assume that new applications with specific purposes might come into use. Presently, fees are rather uniform over an

Table 17.7 Revenue Spending by the U.S. Forest Service in Fiscal Year 1999

30.8% of fees on general operations, like garbage pickup and cleaning toilets
18.8% on cost of collection
18.3% on repairs and maintenance
10.3% on interpretation and signs
6.2% on upgrading facilities
6.0% on health and safety
3.5% on law enforcement
3.1% on resource preservation
2.6% on other costs
0.4% on habitat improvement

area. For instance, there might be one common fee for entry regardless of the length of stay, or size of vehicle, or need for services (e.g., a sanitary dump station). Similarly, there might be a single fee for campsite regardless of its location (e.g., waterfront costs the same as a fringe site near a traveled roadway). It is likely that different prices will be attached to sites as ways to reflect value and need. Those who need more services and those who want to use prime sites will pay more. Furthermore, managers might use differential pricing to get users into other locations. For example, a nice site that is difficult to approach might be priced lower than an equally nice site that has easier access. Thus, fees become a way to redistribute users. Similarly peak demand use may incur a higher fee than use in less popular times.

It is clear that one lesson has already been learned and shows the public is generally favorable to the use of fees in recreation sites. That lesson is that fees without explanation provoke the anger and political wrath of people. However, when people learn what the fees are for and see their use in a place they personally know (and know needs attention), their approval increases dramatically. The data in Table 17.8 illustrate the public sentiment over fees in selected recreation areas.

While it is clear that fees as a management tool will always have sharp edges and pointed debate, their use is likely to increase. It is incumbent on current and future managers to keep focused on fair and appropriate uses to benefit the entire population through creative and imaginative application.

Concluding Statement

Recreation in the out-of-doors is a passion showing no sign of decline into the future. More people than ever are seeking the possibilities of pleasure and personal renewal through activities in natural settings. Forest and range lands, wilderness, and parks are all areas where user demand is increasing at such a rate that serious and thoughtful management is needed to make sure that subsequent generations of citizens have an opportunity to enjoy the wildness of land that current generations might find. Resource managers then need to have some understanding of reasons why people come to nature and the experiences they seek. Managing human behavior requires careful and imaginative thinking along with innovative and adaptable management strategies.

The most critical thought to take from this chapter is that managing recreation is less about managing the natural resource base and more about managing human behavior. Increasing intensity and volume of use is a serious threat to natural settings, yet people need to have access for many reasons. Preserving the resource with intelligence and wis-

Table 17.8 General Opinions About Fees for Use of Recreational Resources in Percent (by Survey Locations)

Location	% Positive	% Negative
Boundary Waters Canoe Area	87	13
Vail Pass Winter Recreation Area	46	22
Desolation Wilderness	64-78	22-36
White Mountain National Forest	68-72	15-16
Cataract Lake Fee Area	*64*	14
Tonto National Forest	55-64	22-26
National Comment Cards	77	19
News Article Analysis	65	35

Source: U.S.D.A. Forest Service. Recreation, Heritage and Wilderness Resources web site, http://www.fs.fed.us/recreation/fee_demo/fee_intro.shtml.

dom is critical if people are to respect and enjoy nature. If we are unsuccessful in meeting this challenge, then people will have the opportunity to love nature to its death. This is an unacceptable outcome. This complex subject of forest-human interactions is treated further in Chapter 23 on Social Forestry.

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CHAPTER 18

Behavior and Management of Forest Fires

CRAIG G. LORIMER

In many areas of the world, humans have historically been the principal cause of forest fires, both in the actual number of fires and in the total area burned. Yet lightning fires have probably occurred for as long as there have been regions of dense vegetation and occasional periods of dry weather (Figure 18.1). In some regions, bits of charcoal embedded in lake sediments testify to the periodic occurrence of fires over thousands of years, and it is likely that some of these were caused by lightning. Evidence of fires in the distant past can also sometimes be found on the forest site itself. Long-lived and relatively fire-resistant trees such as coast redwood and ponderosa pine often bear visible external wounds caused by fire (Figure 18.2). When the trunks of such trees are examined in cross-section, scars of fires that occurred centuries ago

Figure 18.1 Several minutes of lightning during a thunderstorm in the mountains of western North America. In this region, lightning causes 30-60% of all fires. (Courtesy of U.S.D.A. Forest Service.)

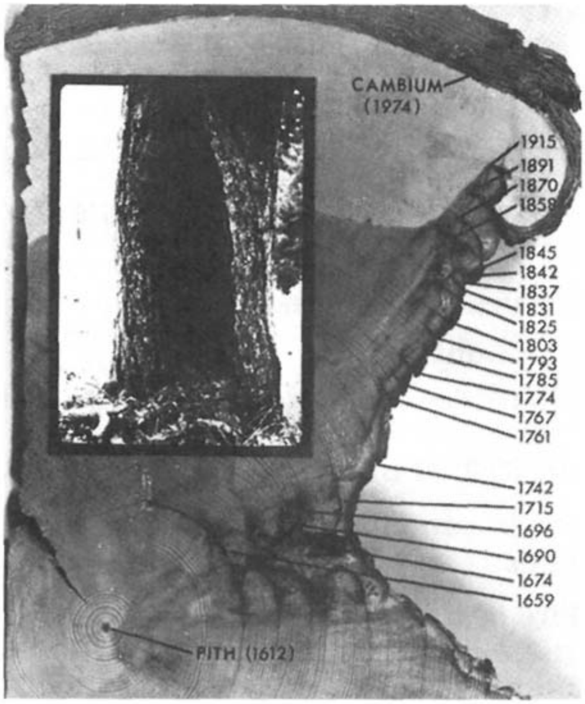


Figure 18.2 Multiple fire scars visible on a cross-section of an old ponderosa pine tree (inset) in the Bitterroot National Forest, in western Montana, reveal that twenty-one fires occurred on this site between 1659 and 1915. (Courtesy of U.S.D.A. Forest Service.)

may be evident. Even in forests that show no obvious indication of recent fire, careful examination of the lower layers of the forest floor will often reveal fragments of charcoal from fires that occurred hundreds of years ago.

Natural Fire Regimes

On a worldwide basis, it is estimated that approximately 500,000 cloud-to-ground lightning discharges occur in forested regions each day (1). Most of these discharges probably strike trees, although only about 10 percent of them actually result in fires. The frequency of lightning fires is highly variable in different parts of the world, even over relatively short distances. Lightning fires are infrequent in tropical rain forests, and they are relatively uncommon in moist temperate areas such as western Europe and much of eastern North America. However, in some regions, such as the mountains of western North America, lightning is the single leading fire cause, accounting for 30-60% of all fires. A single storm can generate a "blitzkrieg" of lightning strikes as it passes across a mountain range (Figure 18.1), igniting more than 50 fires in a few hours. It is estimated that lightning causes about 10,000 wildland fires in the United States each year (2).

Much of the variability in lightning fire frequency can be attributed to climate and topography. Lightning fires are more common in regions with a pronounced dry season and in mountainous country that is subject to more thunderstorms. However, the nature of the vegetation seems to exert considerable influence as well. Fires are usually more common in conifer forests than in stands of broad-leaved deciduous trees, probably in part because of differences in the chemical composition, moisture content, and porosity of the fuels.

Many lightning strikes are accompanied by rain or humid weather, which can initially cause sluggish fire behavior. However, it would be incorrect to assume that lightning fires never or seldom become conflagrations. "Dry" lightning strikes in the absence of rain are common events, and even under damp conditions, a fire can smolder in leaf litter or a dead tree for days or even weeks until dry conditions return. For example, the lightning-caused Sundance Fire of 1967 in Idaho smoldered undetected for 12 days until dry, windy weather turned it into a roaring crown fire that traveled 26 km (16 miles) in only 9 hours (3). Assessment of the possibilities of lightning fires reaching a large size has become increasingly important in recent years as greater attention has been given to restoration of natural fire regimes in parks and wilderness.

The Natural Role of Fire

Given that lightning fires are common events in some regions, it is not surprising that a number of species show evidence of adaptations to periodic fire. Although the nature of this adaptation varies among species, most fire-adapted species possess characteristics that enable them to colonize rapidly and dominate severely burned areas. Some of the birches and aspens have abundant light seeds that can be transported considerable distances by wind, thus increasing the chances that seeds will reach a recently burned site. Other species, such as jack pine, lodgepole pine, and black spruce, have seeds that are held in tightly closed *serotinous cones.* Unlike the cones of most gymnosperms, serotinous cones are sealed by resin, and seeds are not released until high temperatures melt the resin and allow the cones to open. The seeds can then be dispersed even if the parent trees are killed by the fire.

Seeds of fire-adapted species germinate rapidly on charred surfaces or exposed soil, and the seedlings tend to be tolerant of the dry surface conditions and extremes of temperature common to exposed sites. As is typical of shade-intolerant species, they grow rapidly and usually outcompete other species that may arrive on the site. Many of these species are also able to produce seed at a relatively young age, which increases their chance of persisting on a landscape subject to frequent fires. In regions prone to repeated surface fires, some fire-adapted tree species also develop thick bark at maturity that makes them fairly resistant to injury from light fires.

Fire may also have subtle beneficial effects on ecosystems. In cold, dry climates, forest litter and woody debris have a tendency to build up faster than they can be decomposed. Occasional light fires can reduce this accumulation of fuel, converting nutrients that were previously locked up in organic matter into a form that is available for uptake by plants.

Influence on the Landscape

A regime of frequent low-severity fires is common in regions of the world with savanna or tree-grassland ecosystems and dry climates. In the ponderosa pine savannas of western North America, fire scars on old trees show that the average length of time between successive fires was only 6-20 years in most stands (Figure 18.2). These frequent low-intensity fires kept the forests open and "park-like," helped maintain the grasses and pines, and discouraged invasion by shade-tolerant species. By keeping fuel accumulations low, these low-intensity fires also reduced the chances of large conflagrations.

Forests with high-severity fire regimes are usually made up of trees with flammable foliage (such as conifers or Australian eucalyptus) that occur on somewhat moister sites. Weather conditions may not be conducive to fire spread in most years, but the great buildup of fuels may make these forests susceptible to widespread conflagrations during occasional episodes of severe drought and high winds. Natural fire rotations can vary from 50 to 400 years or more (4). Landscapes in such areas are often dominated by even-aged stands of fire-adapted species (see Chapter 13), but because some fires may be variable in their intensity, two- or three-aged stands are sometimes present.

Although regions of the world with moist year-round climates often have a low fire frequency, fire can still have a significant impact on the landscape. For example, in the northern hardwood forests of North America, severe fire may occur at intervals much longer than the life span of the trees, leading to dominance of the landscape by shade-tolerant species not highly adapted to fire. However, fire may still be common on locally dry sites (such as ridgetops and sandy soils), and conflagrations can still occur on moist sites where the trees have been blown down by wind or killed by insect epidemics (5). Such episodes were historically important in maintaining a component of early successional species on the landscape.

Human Influence and Fire Policy

Human modification of the natural fire regime is not a recent development. Primitive societies commonly used fire to improve hunting and overland travel, to aid in land clearance, and to reduce insect and snake populations. The shifting pattern of slash-and-burn agriculture has been widely practiced by native peoples of the tropics. Intentional burning was also a common practice among native American tribes. For example, in 1632, a Massachusetts colonist named Thomas Morton wrote (6):

> **The [natives] are accustomed, to set fire of the Country in all places where they come; and to burne it, twize a yeare.... And this custome of firing the Country is the meanes to make it passable, and by that meanes the trees grow here, and there as in our parks, and makes the Country very beautifull, and commodius.**

Early European settlers continued to use fire, especially as an aid to clearing land for agriculture. So many settlers used this method that occasionally the amount of smoke and particulates in the atmosphere was sufficient to cast semidarkness over the land. One such "dark day" in 1780, caused by fires raging in Vermont and New York, was described as follows.

> **The legislature of Connecticut was in session at Hartford on that day. The deepening gloom enwrapped the city, and the rooms of the state house grew dark. The journal of the house of representatives reads "None could see to read or write in the house, or even at a window, or distinguish persons at a small distance" (7).**

Settlers often let these fires smolder for weeks or even months, creating a potentially explosive situation. With hundreds of these fires smoldering across the landscape, it only required a worsening drought and a strong wind to turn them into a raging inferno. This indeed happened repeatedly throughout the 19th and early 20th centuries from New England to the Pacific Northwest, with massive conflagrations ranging in size from 100,000 to a million hectares. In at least five of these conflagrations, there was also a great loss of human life, ranging from 200 to 1,500 people killed.

These repeated disasters set the stage for a policy of vigorous fire suppression. It is therefore not surprising that one of the top priorities of the American Forestry Association when it convened in 1875 was the "protection of the existing forests of the country from unnecessary waste," of which fire was the leading cause. These efforts led to passage of the Weeks Law of 1911 and the Clarke-McNary Act of 1924, which for the first time provided federal funding to assist the states in developing a cooperative forest fire control program (see Chapters 1, 9, and 10). Although the actual amount of money provided was small at first, it did allow the construction of fire towers, hiring of fire wardens, and purchase of equipment. Fire control on publicly owned lands underwent several major changes in the 20th century. In the 1920s and 1930s, a policy *of fire exclusion* was attempted, in which all wildfires were suppressed as quickly as possible. In 1935, the "10 A.M. fire-control policy" was formulated, setting the objective of rapid and thorough suppression of all fires during potentially dangerous fire weather by ten o'clock the next morning.

Some modification of the 10 A.M. policy was required in certain areas. In parts of the western United States, labor and equipment were not always sufficient to suppress all fires, and it was recognized that such attempts had probably passed a point of diminishing returns in terms of costs and benefits. Fire suppression was therefore handled on a priority basis from about 1940 to 1960. On federal lands, fires burning in areas of highest resource values were attacked first. Remote areas of noncommercial forest with low-hazard fuels were attended to last.

Furthermore, as early as the 1920s and '30s, a few pioneering resource managers began to rediscover the beneficial effects of certain fires and realized the potential disadvantages of trying to exclude fire from ecosystems that were historically fire-dependent. The planned use of fire under specified conditions, known *as prescribed burning,* was gradually acknowledged to be useful in achieving certain objectives such as reducing hazardous fuel accumulations after logging, and preparing the forest floor as a seedbed. Initially, prescribed fires were always set by resource managers under predetermined conditions.

Beginning in the 1970s, forest fire policy on federal lands in the United States was broadened further to an overall policy *of fire management,* not simply fire control. This policy takes advantage of the beneficial effects of some unplanned forest fires while still continuing suppression of fires expected to have undesirable effects. Several features of this policy represent a bold departure from previous policies. First, it is recognized that the decision on how to handle a particular fire on federal lands should be based not only on the anticipated behavior and effects of the fire, but also on the long-range management objectives for each unit of land, and the potential costs and benefits of control. In some national forests, foresters write a management plan for each homogeneous unit of vegetation and fuels, and the degree to which fire is necessary to accomplish the objectives of the plan is clearly stated.

Second, there is a provision for allowing certain unscheduled ignitions to burn under supervision if the predictions of fire behavior indicate that the fire will help achieve the management objectives. For example, a lightning fire or other unplanned ignition may be allowed to burn under surveillance if fuel reduction is needed on that unit of land, and the current and forecasted weather conditions indicate that fire behavior and intensity would be manageable. Fires that threaten human life or property, or which have the potential to become uncontrollable, are still vigorously suppressed. However, choice of the method and equipment to be used in suppressing the fire may be determined in part by weighing the cost of these various options against the value of the resource and the potential for damage.

Finally, fire in the new policy is acknowledged to be more than simply a management tool. It is considered to be an environmental factor that may serve a necessary function not easily accomplished by other methods. Thus, although understory hardwoods in southern pine forests can be controlled by cutting down the hardwood stems and applying herbicides to the stumps, it is recognized that other beneficial effects of fire cannot feasibly be duplicated by mechanical means.

Fire Behavior

Anticipating the behavior of a fire is one of the most critical aspects of fire management. The choice of strategy in suppressing wildfires and carrying out prescribed burning depends largely on how the fire is expected to behave—its rate of spread, direction of travel, and intensity. The prerequisites for the start and spread of a forest fire are 1) flammable fuels, 2) sufficient heat energy to bring the fuels to the ignition temperature, and 3) adequate oxygen. These three factors are often referred to as the *fire triangle*, because all three factors are necessary for combustion, and further combustion can be stopped by removing any one of the three elements. Virtually all the phenomena influencing the behavior of a fire, including those related to weather and topography, can ultimately be attributed to one or more of these three factors. Thus the size, total weight, and moisture content of fuel elements partly determine the amount of heat required for ignition and the heat released by combustion. Their spatial arrangement influences the availability of oxygen. Variations in these factors are ultimately reflected in the rate at which the fire spreads and its intensity. Grass fires, for example, spread rapidly but are of relatively low intensity, whereas fires in heavy logging debris spread slowly but burn intensely.

Fuel Conditions and Fire Types

Fuels are often classified in a general manner by their spatial location in the forest. *Surface fuels* constitute a large, heterogeneous group of fuels found on or close to the surface of the ground. Included are undecomposed leaf litter, fallen twigs and branches, logs, grass, herbs, tree seedlings, and low shrubs. *Ground fuels* are found beneath the loose layer of surface litter. They include partly decomposed organic matter or duff, roots, and muck or peat in wet areas. *Aerial fuels* include all flammable material in the subcanopy layers of the forest and in the tree crowns. Fuels are classified in this manner partly because of the three distinctive types of fires associated with them: surface fires, ground fires, and crown fires.

Surface Fires The most readily available fuels for a forest fire are the dry surface layers of litter on the forest floor, interspersed small dead branchwood, and the cured grass in some forests. This is the material consumed in most *surface fires* (Figure 18.3). Green herbs and understory vegetation are usually a deterrent to the spread of fire in the spring because of the high moisture content of the foliage, but they may contribute significantly to fire intensity and rate of spread when in a cured condition.

Although the larger fuels, such as fallen logs, may be partly or wholly consumed by the time a surface fire has died out, such material is too large and often too damp to influence the forward momentum of the fire. Thus, research indicates that the effect of fuels on the forward rate of spread of a surface fire is largely determined by the amount, arrangement, and moisture content of the fine fuels. The effect of larger surface fuels, such as fallen logs, is to cause a more intense fire. For this reason, the most intense fires are usually those that start in logging slash or other areas of heavy fuel accumulations. In general, the higher the total weight of fuels, the more difficult the fire will be to control.

Figure 18.3 Surface fire. (Courtesy of U.S.D.A. Forest Service.)

Ground Fires In finely divided ground fuels such as peat or duff, oxygen is often limited to the point that only glowing combustion is possible. As a result, *ground fires* are often of low intensity and spread slowly. They are, however, remarkably persistent, often smoldering for days or weeks. For this reason, they present an especially serious problem, and it is often difficult to judge whether suppression activities have been successful in completely extinguishing the fire. Ironically, extinguishing ground fires that burn in bogs may require great quantities of water, much more than might be required on upland sites. One peat fire in Michigan took 36 days for containment at a size of 80 hectares, but attempts to extinguish it were not successful until a small river was diverted by bulldozers 20 days later to drown the fire completely (8).

Crown Fires Fires that sweep through the canopy of a forest are known as *crown fires* (Figure 18.4). The susceptibility of tree crowns to ignition varies among species. Crown fires are much more common in coniferous forests than in hardwoods, because of lower foliar moisture content, flammable organic compounds, greater amounts of dead twigs, and a conical shape that allows easier access of flames to the crown. Yet even in conifer forests, the probability of a crown fire is low if the understory is sparse and the trees are mature. When they occur, crown fires often cause heavy or complete mortality of the tree canopy (Figure 18.5). Although crown fires are relatively uncommon and account for only a small percentage of all fires, they account for most of the area burned annually because of their large size.

Most crown fires start as surface fires, and the reasons why a fire may make the transition in particular cases are still not well known. The surface fire must reach a rather high intensity in order to dessicate and consume live foliage in the crown,

Figure 18.4 Crown fire. (Courtesy of U.S.D.A. Forest Service.)

especially in mature forests where the lowest limbs are high above the ground. However, if conifer saplings are present in the understory, these can act as "ladder fuels," enabling a surface fire to climb into the crowns of the mature trees.

Weather Conditions

Within a given fuel type, fire behavior is regulated largely by the state of the weather. Particularly important are the effects of atmospheric moisture and wind. Fuel moisture is determined not only by the amount and duration of precipitation, but also by relative humidity during rainless periods, As humidity increases, fuels take up moisture from the air, and more of the fire's energy is used to drive off this moisture prior to combustion. As humidity decreases, fuels lose moisture to the air. Both the probability of ignition and fire intensity are closely related to relative humidity and fuel moisture (Table 18.1).

The rapidity of fuel response to atmospheric humidity depends on the size of the fuel elements. The "flashy" fine fuels, which normally determine the rate of fire spread, respond quickly to changes in relative humidity. As a result, fires may alternately flare up during midday when humidity is low and die down again at night when humidity is high.

Fire behavior is also affected by *atmospheric stability,* which is defined as the resistance of the atmosphere to vertical motion. An unstable atmosphere is characterized by gusty, turbulent winds, vertical air motion, and towering cumulus clouds. Crowning and erratic fires are more likely when the atmosphere is unstable, for the vertical air movement encourages the development of a strong convection column of smoke and burning debris fragments. However, if fuel moisture is at a moderate level, indicating little potential for severe fires, days with an unstable atmosphere may be preferable for prescribed burning, because smoke disperses better.

Wind has a dramatic effect on the rate of fire spread and intensity. It has long been a rule of

Figure 18.5 Aftermath of a blowup fire, showing the numerous dead trees that can act as a fuel source for subsequent fires.

Table 18.1 Effect of Relative Humidity and Fuel Moisture on Fire Behavior

	Moisture Content (percent)		
Relative Humidity (percent)	Forest Litter	Small Branchwood	Fire Behavior
>95	>25		Little or no ignition.
>60	>20	>15	Very little ignition; fire smolders and spreads slowly.
45-60	15-19	12-15	Low ignition hazard, but campfires become dangerous; glowing brands cause ignition when relative humidity <50%. Fire spreads slowly but readily; prescribed burning may be feasible.
35-45	11-14	10-12	Medium ignitibility; matches become dangerous, "easy" burning conditions. Many prescribed burns are conducted in this range.
25-35	8-10	7-10	High ignition hazard; matches always dangerous. Occasional crowning, spotting caused by gusty winds. "Moderate" burning conditions.
15-25	5-7	5-7	Quick ignition, rapid buildup, extensive crowning; any increase in wind causes increased spotting, crowning, loss of control. Fire moves up bark of trees igniting aerial fuels; long-distance spotting in pine stands. Dangerous burning conditions.
<15	<5	<5	All sources of ignition dangerous. Aggressive burning; spot fires occur often and spread rapidly, and extreme fire behavior is probable. Critical burning conditions.

Source: Adapted from Albini, 1979 (9).

thumb among fire control officials that the rate of spread is approximately proportional to the square of the wind speed; hence, a doubling of wind speed will quadruple the rate of spread.

The effect of wind on the pattern or shape of fires is illustrated in Figure 18.6. Under conditions of steady moderate or strong winds, fires tend to burn in elliptical patterns with the long axis in the direction of the wind. The strategy of fire suppression is partly based on estimates of the increase in perimeter of this elliptical zone of flames per unit time. The pattern of spread, however, can be greatly changed by abrupt wind shifts, which can turn the flank of a fire into a much expanded burning head. This greatly increases the area burned by the fire and is often a major contributing factor to the large final size of conflagration fires. Abrupt wind shifts are especially common during the passage of a cold front, which is one reason why cold fronts are often dreaded by fire control personnel (see Sidebar 18.1).

Topography

Fires burn more quickly up steep slopes, largely because heat generated by the fire front is directed more closely to the surface of the ground, thereby decreasing the moisture and increasing the temperature of the fuels ahead of the fire. Topography also has many effects on the microclimate of a particular site. Slopes facing toward the south and southwest, for example, tend to be the warmest and driest slopes because they are exposed to the direct rays of the sun during the hottest part of the day. As a result, fires are more frequent and spread more quickly on southern slopes. Topography also modifies and channels airflow patterns. Rugged, moun-

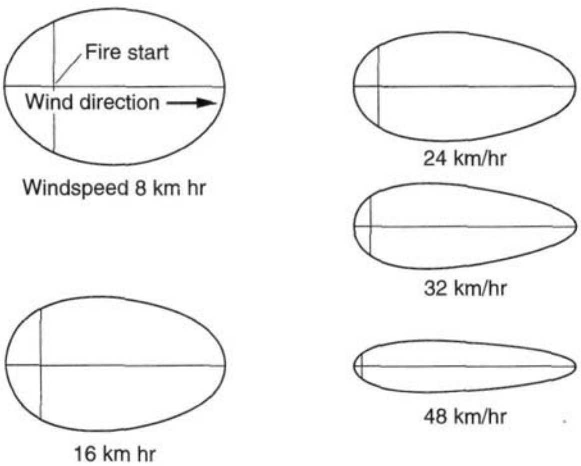


Figure 18.6 Approximate fire shapes created by winds blowing in a constant direction at different velocities. The various fire shapes are drawn to different scales. [From Albini (9).]

tainous topography often induces turbulent winds that increase fire intensity and the possibility of erratic behavior.

Erratic Behavior

Fires sometimes undergo a rather abrupt transition from a low-intensity to a high-intensity fire, which may be visibly apparent from the development of a violent convection column of rapidly rising smoke and hot gases. Such fires are often called *blowup fires* and represent an unfavorable turn of events for firefighters because they are often uncontrollable by conventional fire-fighting techniques (Figure 18.5). Blowup fires may be caused by a sudden increase in windspeed (see Sidebar 18.1) or by the start of crowning. The convection column tends to create its own "draft," which helps maintain fire intensity at a high level.

The behavior of blowup fires is frequently erratic. They may spawn tornado-like winds in excess of 300 kilometers per hour (185 mi/hr), further increasing fire intensity, as well as whirlwinds of hot air and flames that may hurl burning debris far ahead of the main fire front. Such behavior, known as *spotting,* can start many new fires. Most blowup fires can be extinguished only by rain or snow, and human control efforts are usually restricted to attempts at blocking further lateral spread along the flanks.

Prediction of Fire Behavior

A fire researcher named H. T. Gisborne remarked at a conference in the 1940s, "I doubt that anyone will ever be able to sit down to a machine, punch a key for every factor of the situation, and have the machine tell him what to do." Be that as it may, the advent of computer simulation techniques in recent years has proved to be very useful to fire managers. Clearly it is desirable at least to have an estimate of the rate of spread and intensity of a fire, given certain weather and fuel conditions.

The quantitative study of fire behavior and prediction has been intensively pursued for several decades in research labs such as the U.S. Forest Service's Northern Forest Fire Lab in Missoula, Montana. A basic aim of this research has been to use physical laws, such as the law of conservation of energy, to describe the process of combustion and fire spread in mathematical terms (11, 12). The use of basic principles of physics to predict fire behavior has advantages over statistical approaches to studying factors influencing past fire behavior, because theoretical models are more universal in their applicability. That is, they can be used to predict fire behavior in a wide variety of forest and fuel types. Developing these equations required elaborate experimentation with fire behavior in a laboratory environment because some of the mechanisms of heat transfer and combustion were not known, and carefully controlled experiments were the only way to determine empirically the required factors.

This type of research has had handsome payoffs in practical application, one of the most useful of which has been the development of a revised *National Fire-Danger Rating System.* Various systems for rating fire danger had long been used to indicate the relative severity of fire-weather conditions, probable suppression forces needed, and other information. With the new system, more specific and accurate predictions are possible.

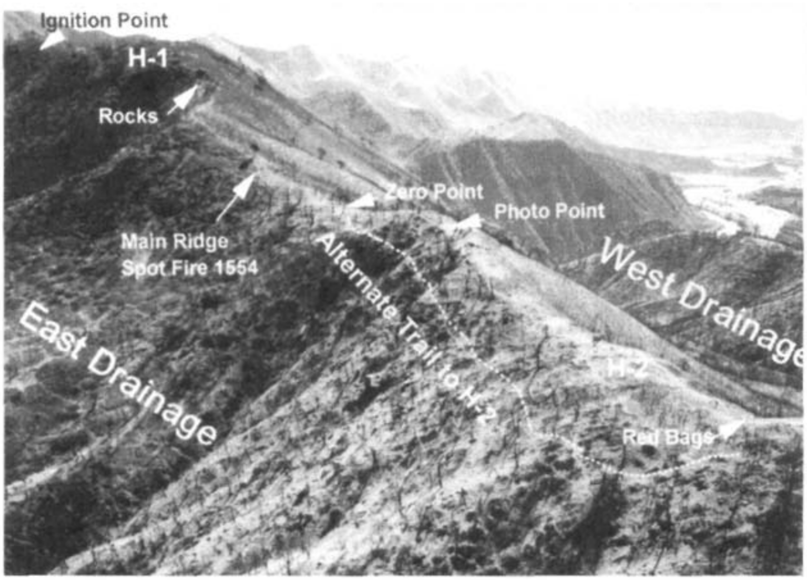
Sidebar 18.1

Firefighting Fatalities at Storm King Mountain

On July 2, 1994, dry lightning ignited a blaze on a ridgetop of Storm King Mountain in western Colorado. The "South Canyon Fire," as it came to be known, would not ordinarily be included even as a footnote in the annals of historic forest fires, attaining a final size of only 856 hectares (2100 acres). However, the South Canyon Fire will long be remembered for the loss of 14 elite young firefighters who were killed during the suppression attempt.

Typical of ridgetop fires, the South Canyon fire behaved sluggishly for the first several days, creeping slowly downhill through shrubby oak and pine toward the base of the canyon. There was little sense of danger. However, on the afternoon of July 6th, a dry cold front roared through the Colorado mountains, causing sustained winds of 48-72 kilometers per hour. Propelled by the strong canyon winds, fire engulfed the entire west slope of the mountain in only 10 minutes, shooting flames 30-100 meters into the air. With the fire traveling 2-3 times as fast as the firefighters could scramble uphill, 14 of the 49 firefighters were overtaken by smoke and searing heat before they could even deploy their portable fire shelters.

Although not all tragedies of this type can be foreseen or avoided, investigators raised several concerns about safety procedures during the suppression attempt. The out-of-state firefighting crew had not been briefed on the local fuels, the approaching cold front, or fire weather forecasts before being sent to the fire. The extreme fire behavior on July 6th could have



Aftermath of the South Canyon Fire of July 1994 on Storm King Mountain, Colorado. (Courtesy of U.S.D.A. Forest Service.)

been anticipated given existing fire models. Twelve of the 18 standard federal safety precautions had not been followed. The investigators concluded that the combination of fuel, weather, and topographic conditions behind the disaster were not unusual in the region, which is precisely why cases such as this should be studied carefully by firefighting crews and natural resource managers.

Included are predictions of the number of fires expected per unit area, ease of ignition, rate of spread, and fire intensity. A current limitation of the system is that it applies only to surface fires. However, it is possible to infer the likelihood of crown fire and spotting from the surface fire ratings.

As with all theoretical models of natural phenomena, these predications must be compared with the observed behavior of many fires before proper interpretation can be made.

Ratings of fire danger are computed daily by utilizing measurements of such variables as wind speed, fuel moisture, amount and duration of precipitation, lightning activity, and the condition of the herbaceous vegetation. Although some of the needed measurements can be obtained from stations maintained by the Weather Service, such stations do not ordinarily make measurements of important fire variables as fuel moisture or vegetative conditions, and the locations of ordinary weather stations (usually in valleys) are often not representative of vast tracts of forestland. A network of fire-weather stations in forested areas has been established in recent years to meet these needs. There has also been a trend toward replacing manually operated fire-weather stations with a ground network of small, remote automated weather stations (RAWS) that transmit data on weather and lightning conditions to central computing facilities via satellite signal (Figure 18.7).

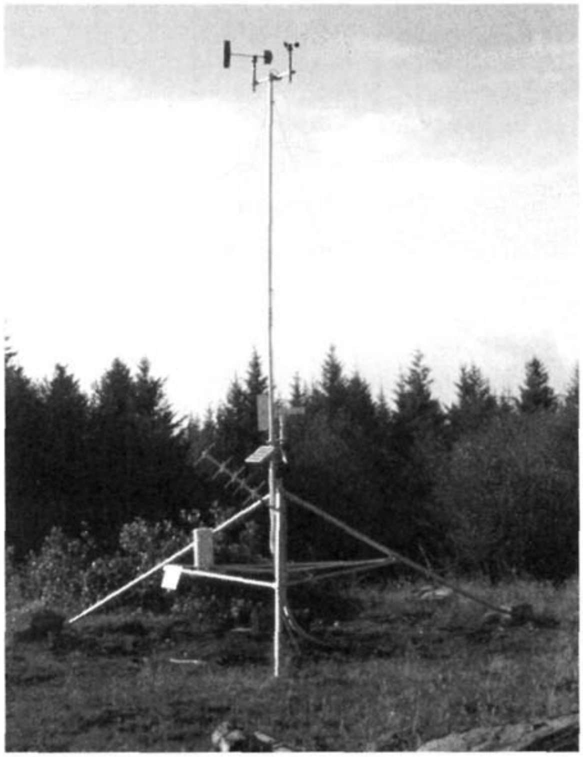


Figure 18.7 Fire danger in the United States is calculated daily from weather and fuel observations at weather stations. Automated weather stations, such as the one shown here, transmit data to computers via satellite signal and are gradually replacing manually operated stations. (Courtesy of U.S.D.A. Forest Service.)

Information generated by the National Fire-Danger Rating System is now readily available to the general public as well as resource managers through the Wildland Fire Assessment System website (http://www.fs.fed.us/land/wfas). National maps showing zones of fire danger are updated daily based on data provided by a network of 1,500 weather stations (Figure 18.8). This large-scale regional view of fire danger helps managers coordinate fire prevention and suppression activities on a state or regional level, including how best to allocate fire suppression personnel and equipment.

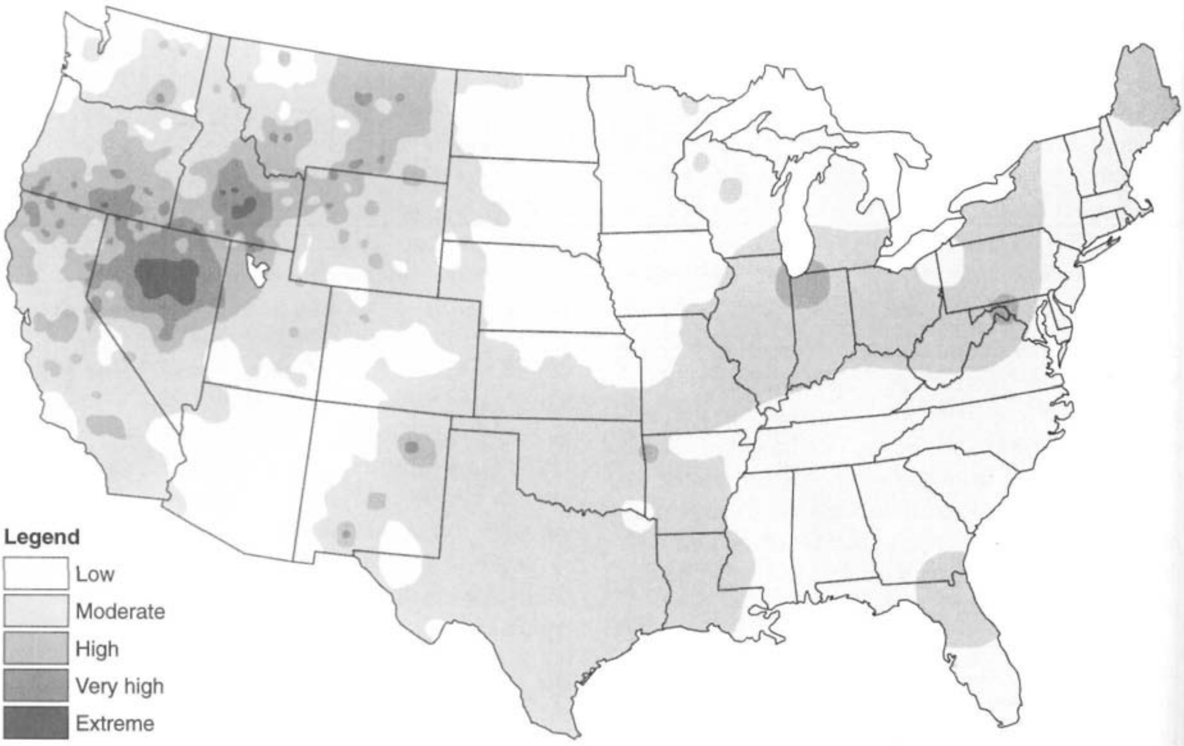


Figure 18.8 A national map showing zones of low to extreme fire danger for a specific day as predicted by the National Fire-Danger Rating System. This map is updated daily and is available on the Wildland Fire Assessment System webpage (http://www.fs.fed.us/land/wfas) The ratings are based on data from a network of 1,500 weather stations and show fire danger for the dominant fuel type at each station.

Other advances in fire modeling have enabled fire managers to obtain predictions about the shape and spread pattern of individual fires. A computer program known as BEHAVE, for example, forecasts the perimeter location of individual fires at various intervals of time (13) and forthcoming versions of the BEHAVE model will have the capability for predicting crown fire spread.

Fire Prevention

Because humans are the leading cause of forest fires in most areas, fire prevention campaigns have been vigorously promoted to reduce the number of these fires. The most visible efforts are public-education campaigns via conventional media—radio messages, signs, magazine articles, news releases, and so on. Such efforts as Smokey the Bear and Keep America Green programs have relied heavily on public education.

A recent statistical compilation of fire reports (14) indicates that in the United States, the leading cause has been arson, which has accounted for 29 percent of all fires. Other major causes have been debris burning, 25 percent; lightning, 11 percent; machine use, 7 percent; smoking, 6%; children, 5%; and campfires, 3 percent. There are some important regional variations. While arson and debris burning are important causes in all regions, lightning is usually the leading cause of fires in western states by a large margin.

This information about specific causes helps indicate where the thrust of prevention campaigns should be directed. Escaped fires from debris burning can be reduced by notifying the public of periods of high fire danger and by regulation through use of burning permits. Arson is a more difficult problem to tackle, although it is probable that education and legal action have some deterrent effect. Fires caused by sparks from mechanized equipment can be reduced by strict enforcement of regulations pertaining to the installation of spark arresters. A high frequency of fires attributable to escaped campfires in some locations may indicate the need to install outdoor fireplaces in popular but undeveloped recreation areas. Fires caused by smoking can be reduced by regular public reminders to crush cigarettes and use ashtrays, especially along highways where most cigarette fires occur.

Fire prevention can also be accomplished by hazard reduction, commonly by reducing accumulations of particularly hazardous fuels or by constructing barriers to the spread of fire. Controlled burning in areas of heavy logging slash, along railroad tracks, and even in some forests can reduce particularly serious accumulations of fuel.

Unhealthy Forests and Wildfire Risk

A particularly dramatic example of the need for hazard reduction is a fuel accumulation problem caused by decades of fire suppression in forests of ponderosa pine and larch in western North America. These once park-like forests have become invaded by dense thickets of firs and other species. Stressed by drought, blitzed by insect epidemics, and plagued by diseases such as dwarf mistletoes, millions of trees from eastern Washington state to New Mexico have been killed, creating what has been called a "forest health crisis of unprecedented proportions" (15).

The tremendous quantity of understory ladder fuels and standing dead trees have greatly increased the risk of high intensity wildfires over historic norms. Figure 18.9 shows that despite greater expenditures for fire control, the annual area burned has in fact markedly increased since the 1970s.

The suggested remedy for the forest health crisis is a combination of mechanical thinning, salvage cutting, and extensive prescribed burning. Current

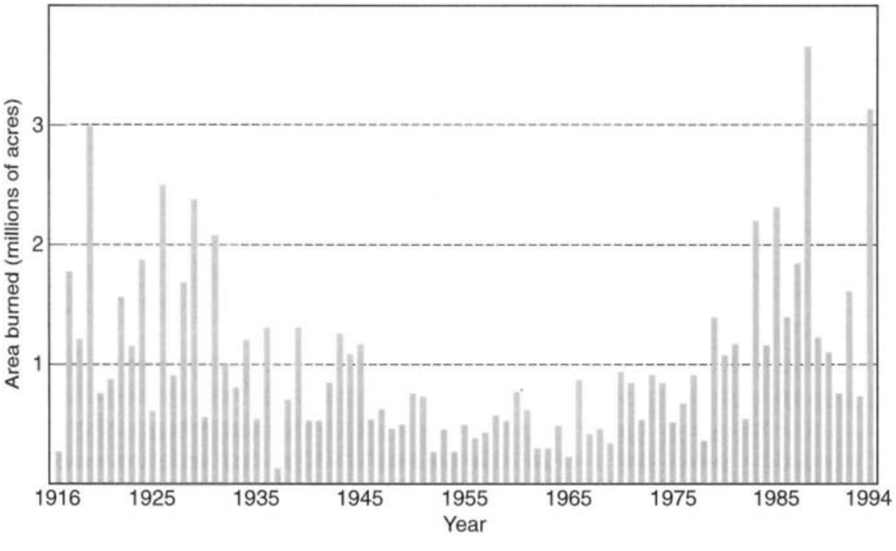


Figure 18.9 Historical trend in annual area burned by wildfires in eleven states of the western United States from 1916-1994. Despite costly expenditures for fire control, annual area burned has generally increased since the 1970s, in part because of increased fuel accumulations from fire suppression. (Courtesy of the National Interagency Fire Center.)

plans call for prescribed burning on 3 million acres annually, or five times current levels.

Politically, this is not an easy program to implement. Congress is usually more willing to appropriate money for emergency fire suppression than for preventive measures like prescribed burning. There are also environmental objections to prescribed burning ranging from endangered species protection to air pollution. However, the annual costs of widespread prescribed burning are modest compared to the billion dollars typically spent on wildfire suppression in a bad year, when suppression is often unsuccessful anyway (16), and environmental effects of prescribed burning are trivial compared to those of conflagrations. It is becoming increasingly clear that it is futile to attempt to exclude fire from fire-dependent ecosystems. Such areas will eventually burn anyway, despite vigilant fire control—but will occur with much higher economic and ecological costs.

The Urban-Wildland Interface

A social problem of even wider scope is the increasing trend toward rural housing to be built in a scattered or haphazard fashion within an extensive matrix of highly flammable wildland vegetation. This pattern of development, called the *urban-wildland interface,* couldn't be more poorly designed from a fire protection viewpoint. As one analyst remarked:

> **You could go into just about any state and find houses with wood shingle roofs, open eaves to suck fire into the attic, and firewood piled against the back wall, sitting in the midst of dense flammable vegetation, backed up against a wildland ecosystem so overloaded with fuel that it would burn with uncontrollable fury (17).**

The urban-wildland interface also creates strategic problems for firefighting agencies, and places severe strains on their budgets. When protecting a compact village in a rural area, a coherent strategy for protecting the community can be developed that relies on building a defense perimeter. Firefighting responsibility in these cases is usually in the hands of the local fire department, which is better trained than wildland firefighters to control structural fires. Dispersed development, however, is much more difficult to protect:

> **Instead of one defense perimeter to develop ... there may now be hundreds. Instead of relying on a community group or local fire company, now there may be virtually no organized protection other than the wildland agency itself. Access is scattered ... and the costs of fire protection skyrocket while its effectiveness goes down.**
>
> **In the most frustrating paradox, the people who live in the [dispersed development pattern] still want fire protection, but they also want to spend less on public services, while their living patterns impose far higher costs on the community. They want to live with nature, but they don't want to pay for the real costs of that lifestyle. Not surprisingly, nobody else wants to pay it on their behalf either (17).**

Efforts toward reducing the urban-wildland interface problem initially focused on teaching landowners how to use more suitable building materials and how to reduce fire hazards in a wide zone around their homes. More recently, the federal wildland agencies have taken a more "hard-line" stance on their responsibility in protecting homes. While human life is still accepted as the highest protection priority of agencies such as the Forest Service, second priority is to "protect resources and property, based on the relative values to be protected." Decisions on the relative value of homes versus forest resources may be left up to the local incident commander.

Fire Control

Wildland fire control in the United States is administered as a cooperative venture by the Forest Service, the Bureau of Land Management, the National Park Service, and the various state governments. In some areas, private owners and industrial firms also participate in the suppression of fires. Fire control activities on large fires are usually very tightly organized, and the suppression activity itself may resemble a military campaign.

Detection

In the early 20th century, lookout towers formed the backbone of the fire detection system. Sufficient numbers of lookouts were placed on higher points of land in the area to provide reasonably thorough coverage of the landscape. Aerial detection of forest fires by systematic airplane flights, however, has gradually overshadowed fixed-point lookouts, partly because it is cheaper and allows for more complete and detailed coverage. Most agencies continue to use a skeletal system of lookouts, however. An important advantage of fire towers is that they provide continuous surveillance, so fires during dry spells are more likely to be spotted at an early stage, before they can become large and potentially uncontrollable.

Conventional aerial detection has also been supplemented with the use of *airborne infrared scanners.* These electronic devices can detect infrared radiation produced by small, smoldering fires that do not produce enough smoke to be seen by the unaided eye. Although infrared detection is not very effective through clouds, it works well at night and can detect the presence of spot fires even when obscured by a blanket of smoke. Following a major lightning storm, airplanes equipped with infrared scanners can be used even at night to plot the locations of incipient fires while they are still small. On large fires, a thermal map of the fire can be created showing the current locations of fire fronts and hot spots. Such information is useful for the fire boss in determining and updating the overall fire suppression strategy.

Suppression of Wildfires

When a fire has been spotted by a lookout or aerial observer, its location is reported by two-way radio to the dispatcher at the fire control headquarters. The dispatcher plots the location of the fire on a map, estimates the probable size of the attack force needed to contain the fire, and sends the needed people and equipment to the fire site.

Fire suppression can be accomplished by removing any one of the three essential "ingredients" of fire: fuel, oxygen, and heat. Fuels are removed by digging, scraping, or plowing a strip of earth known as a *fire line* in advance of the fire to halt its progress (Figure 18.10). The application of dirt, water, or fire-retardant chemicals serves to

Figure 18.10 Construction of a fire line (a) by hand tools in a western conifer forest, and (b) by a tractor and plow unit in a southern pine forest. (Courtesy of U.S.D.A. Forest Service.)

reduce both the fuel temperature and the supply of oxygen.

If the fire is not too intense, the preferred method of control is *direct attack.* The fire line is constructed near the fire edge and the flames are knocked down by water, dirt, or other means (Figure 18.10). If the fire cannot be safety approached at close range, the fire line must be constructed at a distance. In such cases, controlled burns will usually be set just inside the line and allowed to spread toward the flanks of the wildfire in order to rob the fire of fuel. This is known as *indirect attack.* As a last resort, controlled burns known as *backfires* may be set ahead of the main fire and induced to burn backwards toward the head in order to remove fuels in the path of the advancing fire front.

Although the suppression of large forest fires generally requires the use of hand tools, bulldozers, and water pumps over a period of many hours or days, significant contributions to the overall suppression effort can be made by aerial techniques. Airplanes and helicopters are used to apply water or fire-retardant chemicals to active forest fires. The usual effects of water on a fire can be augmented by adding flame-inhibiting chemicals or other additives that enhance the "wettability" of water or increase its smothering effect on the combustion of fuels. Fine clays are often mixed with water to increase the cohesiveness of the mixture and prevent excessive dissipation during its descent from fixed-wing aircraft. These mixtures of clay and liquids are known as *slurries.* The application of slurries from the air is particularly helpful as a delaying tactic that allows time for people and equipment to arrive on the scene, especially when the fire occurs in a remote location. However, aerial retardants and slurries are not usually sufficient to extinguish a forest fire, and follow-up work by ground crews is almost always necessary.

The more intense the fire, the more problematic spotting is likely to be for the ground crews. Because spotting may cause the fire to jump the line in many places (Figure 18.11), constant surveillance for spot fires by the suppression crew is necessary. Experienced fire fighters realize that under blowup conditions, the spread of a fire is seldom restricted by the location of firebreaks. Conflagration fires can easily leap over rivers, bogs, and even lakes. Under extreme conditions, spot fires can flare up several miles ahead of the main fire front, and humans usually can do little to stop the fire's progress.

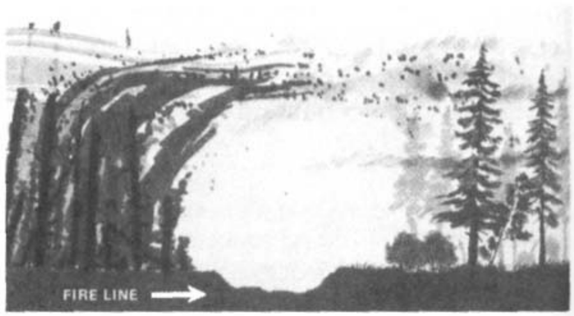


Figure 18.11 Careful surveillance is necessary to control spot fires caused by burning embers hurled across the fire line. (Reproduced from *Wildfires* with permission of the Robert J. Brady Company.)

When the fire line around the perimeter of the fire has been completed and the fire is no longer spreading, it is said to be *contained.* There remains, however, the often long and tedious process of "mop-up"; all smoldering fires and firebrands near the inside edge of the fire line must be extinguished. Mop-up is necessary to ensure that the fire will not flare up again and cross the line—a quite common occurrence. Fires can even creep beneath a fire line by burning underground along root channels and then suddenly resurface on the other side of the line. Burning stumps and roots near the line may therefore have to be excavated and soaked with water. Successful mop-up will make the line safe, but the interior section of a large burned area might not be officially declared extinguished until much later, sometimes not until the arrival of winter rains or snows.

Prescribed Burning

The controlled use of fire to accomplish specific objectives is known as *prescribed burning* (Figure

18.12). There can be many reasons for controlled burning in different situations, including: 1) reduction of logging debris or "slash fuels" following clearcutting, thereby reducing the risk of intense wildfires; 2) preparation of a seedbed for tree species that require exposed mineral soil; 3) reduction of fuel accumulations in standing forests to lessen the probability of a crown fire; 4) control of understory vegetation in certain forest types, such as hardwood saplings in southern pine stands; 5) control of certain diseases such as brown spot needle blight in the southern United States and dwarf mistletoes in the western United States; 5) improvement of wildlife habitat, especially for fire-dependent species; 6) range improvement for livestock grazing in some areas; and 7) restoration of prairie habitat.

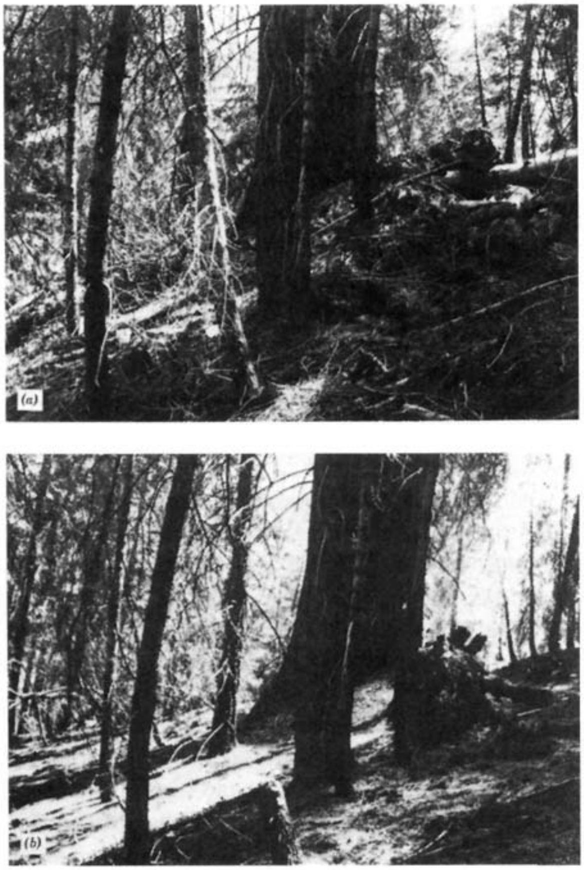


Figure 18.12 Before (a) and after (b) prescribed burning in a sequoia-mixed conifer forest in California. In addition to reducing the amount of litter, dead branches, and logs, the fire killed most of the pole-sized white fir trees shown in these photographs. (National Park Service photographs [a] by Bruce M. Kilgore and [b] by Don Taylor.)

Prescribed burning requires careful planning to minimize risk and to enhance the likelihood that objectives will be accomplished. Topography and fuel conditions on the treatment area should be assessed in terms of probable effects on fire behavior and desirable location of fire breaks. Fire lines should be established in advance of any burning. Fuel weights and fuel moisture are normally assessed using standard sampling or monitoring techniques. The chances for adequate smoke dispersal must also be evaluated. This information can then be used to write the *fire prescription,* which outlines the specific objectives of the burn, the range of weather conditions under which burning would be effective and safe, the method and sequence of ignitions, and the personnel and equipment needed. A good fire prescription is very specific and includes such information as the actual amount of fuels to be reduced, the flame length and intensity needed to accomplish the objectives, and the range of acceptable windspeed, relative humidity, and fuel moisture. The National Fire-Danger Rating System can provide valuable help in deciding whether a particular day is acceptable since it gives estimates of fire spread rate and intensity under various combinations of weather and fuel conditions. Before proceeding, it is also a good idea to conduct a *test burn* on a small area within prepared lines where there is no chance of escape, in order to see whether the behavior of the fire is similar to what was expected.

Prescribed fires may be set by ground crews using a device such as a drip torch (Figure 18.13), or they may be ignited from the air by delayed-ignition devices ejected from aircraft or by a drip torch attached to a helicopter. Risk may be further reduced by burning the area in consecutive strips, sometimes with each delimited by a fire line. Regulation of fire intensity is achieved not only by

Figure 18.13 Prescribed burning with a drip torch to reduce the fuel accumulated on the ground and to prepare the forest floor as a seedbed. (National Park Service photograph by Bruce M. Kilgore.)

selecting days with desired weather conditions but also by planning the sequence of ignitions and the direction of spread. Fires allowed to burn in the direction of the wind are known as *headfires* and have relatively fast rates of spread and high temperatures. Fires can be induced to burn against the wind by igniting the fuels on the inside edge of a fire line. Spread in the direction of the wind is therefore prevented by the fire line, and the flames move slowly against the wind. Such *backburns* are somewhat easier to control and may be preferable to head fires on days of relatively high fire hazard.

Although some of the common objectives of prescribed burning can be accomplished by other means—for example, seedbed preparation by mechanical scarification—prescribed burning is often the most economical option available and the one least demanding of petrochemical energy. The principal disadvantages of prescribed burning are the risks involved, the problem of air pollution from the smoke, and the fact that the number of days per year suitable for burning may be few in some regions.

The chances of a prescribed burn escaping control can be minimized by careful planning, but the operation is never entirely free of risk. In May 2000, a prescribed burn on national park land in New Mexico escaped and destroyed 235 homes in the nearby town of Los Alamos, even at one point threatening the nuclear lab facilities there. Although a 30-page burning plan with detailed maps had been prepared prior to the burn, a subsequent investigative team considered the plan to be inadequate and faulted the practitioners for violating some of the standard procedures. The crew believed unpredictable weather patterns were to blame. Regardless of who or what is at fault in such situations, it is clear that even a single disastrous "escape" can be very damaging to any long-term prescribed burn program. An escaped burn in Michigan, known as the Mack Lake Fire (1980), largely shut down a program of prescribed burning for the endangered Kirtland's warbler for the following 20 years. The young jack pine habitat required by the warbler is now largely recreated through use of clearcutting and planting instead of fire.

Environmental Impacts of Forest Fires

In the 19th and early 20th centuries, observers of burned over lands frequently commented on the seemingly destructive effects of fire on the forest and site. Careful scientific measurements in recent decades, however, have resulted in a more nuanced assessment of fire impacts. The effects of fire on site productivity, for example, are so variable that generalizations are difficult to make. Some authors have noted that almost any effects of fire-positive, negative, or neutral—can be documented by the results of reputable researchers (18). Clearly the intensity of the fire, characteristics of the site, and weather conditions after the fire have much bearing on the outcome.

Most erosion following fires can be traced to either or both of the following causes: 1) exposure of bare soil through burning of the protective litter layer; 2) reduction of soil porosity (and hence increased runoff of water) through intense heating or clogging of soil pores by fine particles carried in runoff. Light or moderate fires such as most prescribed burns usually do not expose enough soil to cause serious erosion. Similarly, soil temperatures during prescribed burning are rarely hot enough to cause structural changes in the soil.

Crown fires or fires burning in logging slash, on the other hand, may be intense enough to alter soil structure, as well as leave bare patches of unprotected soil. Erosion will usually be more severe on steep slopes than on gently sloping or level sites. Following a severe wildfire in Idaho, about 30 percent of the sample plots on gently sloping sites showed significant erosion, compared to over 80 percent on steep slopes (19). A burned area is usually revegetated by shrubs and tree seedlings within a few years, so the critical period of susceptibility to erosion does not last long.

The influence of fire on soil fertility also depends on fire intensity and location. Significant quantities of some nutrients, particularly nitrogen, can be lost to the atmosphere during the combustion of organic matter, with losses proportional to fire intensity. These losses, on the other hand, may be partly or fully compensated by an increase in available nutrients and processes such as nitrogen fixation. For example, thirty years of annual or periodic prescribed burns in South Carolina had little effect on the total amount of nutrients in the forest floor and soil layers (20).

Fires influence animal populations primarily by modifying habitat. Most fires cause little direct mortality to mobile animals, which usually can move away from the fire or escape beneath the ground in soil burrows. Prescribed burns may improve habitat for some animals by increasing the protein and nutrient content of forage, but they may decrease habitat suitability for others that prefer the presence of dense undergrowth and woody debris. Crown fires that kill most of the canopy trees often cause a major shift in animal species composition from those that prefer mature forest to those that prefer open, shrubby habitat and early successional forests.

Smoke from forest fires has come under scrutiny in recent years as a significant contribution to the overall air pollution problem. One ton of burning forest fuel releases approximately 1 ton of CO_2, 25 kilograms of carbon monoxide, 5 kilograms of hydrocarbons, 5 kilograms of particulates, and small amounts of nitrogen oxides. Forest fires are responsible for about 8 percent by weight of all atmospheric pollutants in the United States (21). Although open burning is restricted in many states and counties, exceptions are often granted for prescribed burning, partly because it does not constitute a major source of pollutants. It is probable that prescribed burning will be more closely regulated in the future; even now, air quality is often considered in selecting days suitable for burning.

Fire in the Wilderness

In 1968, without much fanfare and on an experimental basis, the National Park Service began to allow certain lightning fires to burn unhindered in parts of Sequoia and Kings Canyon National Parks in California. This marked the beginning of an official policy to restore natural fire to certain wilderness areas. This alteration of the long-established policy of suppressing all forest fires came about partly in response to the obvious changes that were occurring in the national parks as a result of overprotecting them from fire. Like many western forests, 19th century forests in the Sierra Nevada were often park-like with little undergrowth because of frequent surface fires. By 1963, the Leopold Committee, assigned by the Department of the Interior to make recommendations on elk habitat and management in the parks, noted that much of the western slope of the Sierra Nevada was a "dog-hair thicket" of young trees and brush. The committee wondered:

> **Is it possible that the primitive open forest could be restored, at least on a local scale? And if so, how? We cannot offer an answer. But we are posing a question to which there should be an answer of immense concern to the National Park Service.**

Other pressing problems dictated a prompt response. The giant sequoias, whose preservation was entrusted to the Park Service, were not regenerating, because they lacked a suitable seedbed and because of competition with the dense understory of white fir. Moreover, understory fuels were accumulating to the point that conflagrations were likely. In 1965, prescribed burning was initiated in some sequoia groves to correct this situation.

If the goal of park and wilderness management were merely to maintain certain desirable forest environments, it is likely that the policy of fire suppression would have merely been modified to allow for an active program of prescribed burning. However, such action would seem to violate the spirit and intent of wilderness preservation. The congressional act of 1916 that created the National Park Service, to be sure, emphasized mainly protection of parklands in order to leave them "unimpaired" for future generations. However, the Wilderness Act of 1964 was much more explicit in defining wilderness to be an area that retains its "primeval character and influence," where "man himself is a visitor who does not remain," and that is managed to preserve natural conditions.

Neither prescribed burning by itself nor total fire suppression seems appropriate under this concept of wilderness—the former because it is manipulative and somewhat arbitrary and the latter because it constitutes major indirect human modification of the vegetation in naturally fire-prone environments.

The Approach

Full restoration of the natural fire regime in wilderness areas is usually not feasible, because some fires would inevitably threaten to burn beyond the park boundaries onto private land, or endanger human life inside or outside the park. The current intent of the natural-fire management policy is to allow fire to "more nearly play its natural role" whenever possible. In most wilderness areas, several management zones corresponding to different vegetation types and fuel conditions have been established. Each lightning fire is monitored, and a particular fire may be allowed to burn, or its spread may be blocked in one direction, or it may be totally suppressed. The decision is based on the vegetation types, fuels, projected fire weather, and location of the fire in relation to human development or private property (Figure 18.14). Most fires caused by human beings continue to be suppressed. Prescribed burning is sometimes used in zones where management of natural fires is not feasible or where heavy, unnatural accumulations of fuels must be reduced artificially in preparation for natural-fire management.

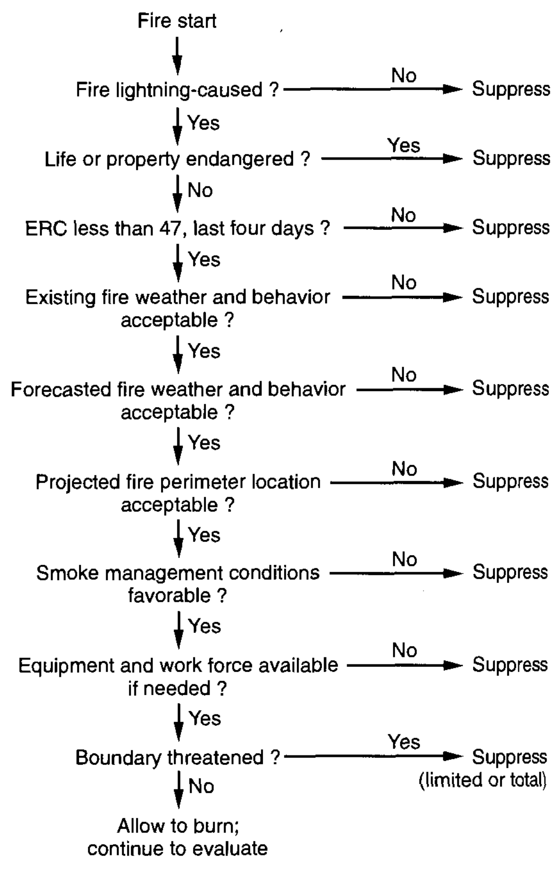


Figure 18.14 Decision flowchart for evaluating fires occurring in high-elevation areas of a wilderness tract in the Kootenai National Forest of Montana. "ERC" refers to the Energy Release Component, an index from the National Fire-Danger Rating System that indicates potential fire intensity. (Courtesy of the U.S.D.A. Forest Service.)

Thirty Years of Natural Fire Management

Wilderness fire restoration programs have been established primarily in the high-elevation zones of some major western wilderness areas, such as Yellowstone, Yosemite, Sequoia, Kings Canyon, and Grand Teton National Parks, and the Selway-Bitterroot Wilderness Area in Idaho. Everglades National Park in Florida is an example of an eastern park firmly committed to natural-fire management.

Experience with the policy in a number of different wilderness areas has shown that most lightning fires in high mountainous terrain never burn more than a small area before they die out naturally. In Sequoia and Kings Canyon National Parks, for example, 80 percent of lightning fires allowed to burn never reached more than 0.1 hectare (one-quarter acre) in size, and only 5 percent exceed 120 hectares (300 acres) (22). Yet some large and dramatic fires have also occurred since 1968. Perhaps the most difficult and controversial aspect of managing natural fires is that in certain forest types, fire cannot be harnessed to burn a small percentage of the forest at regular intervals, analogous to a forest placed under sustained even-aged management. If 1 or 2 percent of a park were to be burned in isolated patches every few years, the policy might not attract more than mild curiosity from the media and most of the general public. However, occasional large and dramatic blazes can understandably provoke opposition to the policy from some citizens and government officials, even though most conservationists have accepted natural fire management as the best way to maintain biotic diversity and wildlife habitat in wilderness areas.

The first major test of the policy occurred in 1974, when a lightning fire in a dry year burned 1,400 hectares (3,500 acres) in Grand Teton National Park (Figure 18.15). This event attracted widespread media attention, and for most people it was the first time that they had heard of the policy. The fire, although sizable, was not troublesome to manage and left a desirable mosaic of mature forest and younger vegetation. It also affected only a small percentage of the park.

Figure 18.15 A lightning fire allowed to burn in Grand Teton National Park, Wyoming, as part of a program to restore the natural occurrence and effects of fires in wilderness areas. (*Denver Post* photograph by Bill Wuensch.)

The most difficult test of the natural-fire policy occurred in the summer of 1988 in Yellowstone National Park. A natural-fire policy had already been in effect at Yellowstone for seventeen years, but fires of significant size (greater than 20 hectares) had occurred in only four of these years. Before 1988, none of the fires had ever burned more than a tiny fraction of the park's 890,000 hectares (2.2 million acres). Weather conditions in the late spring of 1988 were fairly close to normal, and a few lightning fires at that time were burning under surveillance. However, by midsummer it became apparent that drought conditions, carrying over from the previous year, were approaching a very hazardous level. In mid-July park officials shifted to a policy of vigorous suppression of all fires, regardless of origin. Because of the severe drought and high winds, however, suppression of existing and subsequent fires was virtually impossible.

By the end of the season, eight separate fires had engulfed about 45 percent of the park, although nearly half of this total area was affected by surface fires that did not kill the trees. Three of the fires, totaling 276,000 hectares (690,000 acres) were started by humans and had been fought vigorously from the time of their discovery. Park biologists pointed out that even if the natural-fire policy had not been in place, at least 25 to 30 percent of the park would have burned anyway.

There is little doubt that in naturally fire-prone environments—which include most of the western national parks—occasional large fires are inevitable, even with a policy of total suppression. However, a panel appointed to review federal policy was very critical of Yellowstone Park for not having experienced fire managers on its staff, for not having a detailed written fire management plan (such as the one summarized in Figure 18.14), and for minimal efforts at public education and public input into the plans. Other agencies in the Rocky Mountain region recognized the extraordinary drought conditions in 1988 and aggressively fought fires that season (23). Since 1988, regulations for allowing natural fires have been tightened, resulting in fewer and smaller fires.

The Yellowstone experience has also raised the question of whether even our largest parks are necessarily viable microcosms of wilderness ecosystems. Most ecologists have assumed that in order to sustain viable populations of plants and animals, a park needs to be large enough that individual disturbances cannot alter the balance of the overall park ecosystem. The 1988 fires demonstrated that Yellowstone is probably not an "equilibrium landscape," despite its vast size. Thus, while management of lightning fires and prescribed burning are likely to remain a prominent aspect of wilderness management, the details of how managers might deal with the wildly erratic fluctuations in natural fire occurrence have yet to be determined.

Concluding Statement—The Challenge of Fire Management

There is a strong consensus among ecologists and resource managers that fire should not, and ultimately cannot, be excluded from those ecosystems that were historically adapted to fire. In such ecosystems, exclusion of fire will lead to a buildup of fuels and unhealthy trees that will increase the risk of widespread conflagrations. However, several decades of experiments with natural fire management have put into sharp relief some challenges that fire managers will face in the coming years. First, it is becoming increasingly apparent that true restoration of natural fire frequency on a large scale may be impractical for many public lands because staff size, time, and funds are too limited for such a vast undertaking (24), and there are many constraints imposed by weather and private property. Second, despite careful planning, it is likely that some prescribed fires and natural lightning fires will continue to escape beyond intended bounds. This is especially likely for lightning fires in wilderness areas, since such fires often burn for months and can potentially reach an unmanageable size. Blowups and uncontrollable behavior become increasingly likely along some point of a sprawling fire perimeter if weather conditions suddenly change. Third, in less remote areas, continued development of vacation homes and tourist-related businesses dispersed within the patchwork mosaic pattern of public and private land ownership may compromise the ability of agencies to implement a large-scale program of prescribed burning.

Solving these problems may require a fundamental rethinking of land-use zoning policies in wildland areas, as well as a willingness of resource managers to set more modest goals in restoring the natural role of fire. In areas outside of parks and near human development, fire use may have to be more limited and supplemented by other methods of fuel reduction such as mechanical thinning. While such measures may not be ideal in the ecological sense, they may be the only practical solution to maintaining diversity and resilience in a landscape that is no longer governed largely by natural forces.

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CHAPTER 19

Timber Harvesting

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The United States is the world's largest producer and consumer of forest products. Each American uses an average of 749 pounds of paper products and 18 cubic feet of solid wood products annually (1). As the world's economies grow, so does the global demand for paper and forest products. The U.S.D.A. Forest Service estimates that worldwide annual consumption of forest products, currently at 18 billion cubic feet, will continue to increase, reaching a total of 25 billion cubic feet by 2050 (2).

America's logging industry performs the critical process of supplying the raw wood necessary to meet the growing demand for manufactured forest products. There are approximately 35,000 independent logging firms operating in the United States today (3). These small businesses typically employ 5-15 workers and have anywhere from $500,000 to $1.5 million invested in logging equipment. Many independent logging companies contract with forest industry firms to provide timber harvesting services. Other logging firms purchase stumpage, or standing timber, directly from forest landowners, then harvest and sell the processed logs or pulpwood to consuming forest products mills. Many loggers are third and fourth generation—they often employ other family members in their operation. Logging contractors are generally paid on a production basis, and are heavily impacted financially by factors that affect their production, like inclement weather, absentee workers, equipment breakdowns, and temporary wood inventory surplus at the mill they supply. Today's typical logging firm is characterized by high fixed costs, including substantial equipment payments, high labor turnover, high insurance costs, and a relatively low profit margin.

Today's loggers operate under intense public scrutiny. They must plan and conduct their operation so as to meet federally mandated forest water quality protection standards and minimize site impacts to ensure long-term sustainability of the forest resource. At the same time, logging contractors must operate efficiently and productively and satisfy their customers, both forest landowner and forest industry, to remain in business. Finally, they must have a high awareness and comittment for safety, since logging is one of the nation's most hazardous occupations, with an injury rate 2.5 times the average for all other industries (4). To successfully meet these challenges, many loggers regularly participate in professional education and training opportunities sponsored through state forestry associations, the Cooperative Extension Service, or forest industry firms. National and state logger associations also provide educational opportunities, as well as a voice for loggers on issues affecting their business. Additional general and technical information on the logging industry can be obtained through the websites of the Forest Resources Association [http://www.forestresources.org] and the American Loggers Council [http://www.americanloggers.org].

Figure 19.2 This track-mounted feller-buncher generates low ground pressure and minimizes soil compaction and rutting.

Timber Harvesting Operations

The common functions of a timber harvesting operation are: 1) felling the tree; 2) delimbing and topping the tree; 3) moving (skidding, forwarding, yarding, flying) the tree from the stump to the landing or log deck (a centralized location where the trees are gathered, processed, and loaded onto a truck); 4) bucking the tree into specified merchantable lengths; 5) loading the logs onto a truck; and 6) hauling the logs to a forest products mill.

Felling can be acomplished manually with a chainsaw or mechanically with a rubber-tired (Figure 191) or track-mounted (Figure 19.2) feller-buncher or a multifunction machine called a harvester (Figure 19.3). Mechanical felling machines eliminate much of the safety risk involved with manual chainsaw felling, the most dangerous part of a logging operation.

Delimbing and *topping* (removing the limbs and unmerchantable top of the tree) can be accomplished manually with a chainsaw or mechanically with a

Figure 19.1 Rubber-tired feller-bunchers are productive—this highly maneuverable three-wheeled model is well-suited for thinning.

Figure 19.3 A harvester is a multifunction machine that fells, delimbs, tops, measures, and bucks the tree at the stump.

stroke (Figure 19.4) or pull-through delimber or with a multifunction harvester. Loggers can reduce the likelihood of injury by incorporating mechanical delimbing and further reducing their use of a chainsaw. Delimbing and topping may be performed at the stump or at the log landing, depending on the logging system employed.

Skidding (dragging the tree with one end suspended) the trees from the stump to the landing or log deck can be accomplished with a rubber-tired (Figure 19.5) or track-mounted skidder. Skidders are equipped with a hydraulic grapple or a winch and set of wire rope cables to support the ends of the trees above the ground. Skidders generally transport tree-length stems. A small number of loggers continue to use draft horses or mules to drag cut-to-length logs from the stump to the landing.

Forwarding (carrying the logs on the back of a machine) the trees from the stump to the landing is accomplished with a rubber-tired (Figure 19.6) or track-mounted forwarder. Forwarders generally transport log-length stems, which must be delimbed, topped, and bucked at the stump.

Cable yarding (lifting and moving suspended trees attached to an overhead cable) the trees from the stump to the landing is accomplished with a stationary cable yarder (Figure 19.7) equipped with a drum winch set and tower. Yarders come in many sizes and the cable system can be set up in many different configurations. Yarders can move fully or partially suspended trees or logs either uphill or downhill along a preselected corridor.

Flying (lifting and moving fully suspended trees attached to a helicopter cable) the trees from the

Figure 19.5 A rubber-tired grapple skidder, combined with a feller-buncher, forms a productive and cost-efficient logging system.

Figure 19.4 A stroke delimber is a safe and effective mechanical delimbing machine for most softwood species.

Figure 19.6 A forwarder loads and transports cut-to-length logs from the stump to a roadside landing.

Figure 19.7 A skyline cable yarder system can harvest timber on steep mountain slopes with minimum soil disturbance.

stump to the landing requires a specially designed and equipped helicopter (Figure 198).

Bucking (cutting the tree into merchantable lengths) can be accomplished manually with a chainsaw or mechanically with a slasher saw or multipurpose harvester.

Loading the tree-length stems or cut-to-length logs onto a truck can be accomplished by a trailer-mounted (Figure 19-9) or track-mounted hydraulic knuckleboom loader or by a rubber-tired front-end loader.

Hauling the tree-length stems or cut-to-length logs to the forest products mill can be accomplished with a tractor-trailer log truck equipped with either a pole trailer or double-bunk log trailer (Figure 19.10), or a tandem-axle, straight-frame log truck.

Planning is a critical part of every timber harvesting operation (5). Good planning is necessary to meet production goals, comply with environmental and water quality protection standards, operate safely, minimize site disturbance, and meet silvicultural objectives. In several states, loggers are required to submit a timber harvesting plan to the state for review and approval before logging can begin. A typical timber harvest plan contains information on haul road location and construction techniques, location and layout of log landings, provisions for water quality and riparian zone protection measures (commonly called Best Management Practices or BMPs) (6), safe operating considerations, stream crossing locations and structures, wildlife considerations (if applicable), protection of residual timber, mitigation of site impacts, and post-harvest soil stabilization procedures.

Figure 19.8 A helicopter logging system can greatly reduce the need for logging road construction in environmentally sensitive areas.

Figure 19.9 A hydraulic knuckleboom loader is a common sight on most logging operations in the United States today.

Common Timber Harvesting Systems

A number of timber harvesting systems operate throughout the various forested regions of the United States. A particular logging system is chosen on the basis of topography, timber stand characteristics, silvicultural considerations, accessibility, local mill requirements, environmental considerations, and safety concerns. The system that is best for logging a group-selection timber sale in an oak-hickory forest on 40% slopes in the Appalachian mountains may not be the best system for harvesting a pine plantation thinning in the coastal plain region of Georgia. Professional logging engineers, logging contractors, and industrial foresters have the training and expertise to develop and match the proper logging system to each timber harvesting site to accomplish the production, safety, economic and environmental goals that will make the operation a success. The more common timber harvesting systems operating in various regions of the United States today are described in the following sections.

Figure 19.10 A truck with a double-bunk log trailer can haul either tree-length stems or cut-to-length logs.

Manual Chainsaw/Cable Skidder System

Trees are felled, delimbed, and topped manually, skidded with a rubber-tired cable skidder to the landing where they are manually or mechanically bucked, and loaded onto a log truck with a hydraulic knuckleboom loader. This system typically produces 200-300 tons of cut-to-length logs and pulpwood per week. It requires 3-5 employees, a moderate capital investment, and can be used in a wide variety of operating conditions and harvesting applications. This versatile logging system is most common in the Northeast, Appalachian region, Lake States and Midwest, but can be found in every forested region of the country. In some areas of the mountainous West, a tracked skidder is more commonly used in this system.

Feller-Buncher/Grapple Skidder System

Trees are mechanically felled and bunched in multiple-stem piles, the bunches are skidded with grapple skidders, mechanically topped and delimbed at the landing with a stroke or pull-through delimber, and loaded tree-length onto log trailers with a knuckleboom loader. This highly productive and cost-efficient system can produce 700-1000 tons per week with 8-10 workers. It is restricted to moderate slopes and requires a capital investment exceeding $500,000. Nearly 70 percent of the wood harvested in the South is produced by this logging system. The feller-buncher/grapple skidder system can be combined with a large wood chipping machine (Figure 19.11) to produce in-woods chips from pulpwood, which can be efficiently hauled in chip vans (modified box trailers) from the logging site to a paper mill.

Harvester/Forwarder (Cut-to-Length) System

Trees are mechanically felled, topped, delimbed and bucked at the stump with a rubber-tired or track-mounted harvester equipped with a multifunction processing head. The cut-to-length logs or pulpwood are then self-loaded onto a forwarder and transported to roadside where they are off-loaded onto double-bunk log trailers. This two-worker, two-machine logging system (not counting log truck drivers) is "soft" on the environment and can produce 400-600 tons per week on gentle topography. Capital investment for this system exceeds $600,000. The harvester/forwarder logging system originated in Scandinavia, and is beginning to find a niche in all regions of the United States.

Figure 19.11 An in-woods chipper can fully utilize the woody biomass on the site and reduce subsequent reforestation costs.

Cable Yarder (Skyline) System

Trees are manually felled, delimbed, topped, and bucked at the stump, attached by wire-rope chokers (cable fasteners) to a moveable carriage suspended from a large overhead skyline cable strung 1,000-2,000 feet or more along a corridor between the stationary yarder tower and a tail-hold stump or tree in the woods. Large mechanical drum winches in the yarder are powered to lift and reel in the carriage and attached logs along the highly tensioned skyline cable to the landing, where they are loaded onto trailers with a track-mounted hydraulic loader. Cable yarding systems are highly technical and can be configured to move logs uphill or downhill. This system is ideal for steep mountain terrain and is the predominate logging system in the Pacific Northwest. A typical operation employs 8-10 workers, has more than $1 million invested in equipment, and produces 1000+ tons of logs per week.

Helicopter Logging System

Trees are manually felled, delimbed, topped, and bucked at the stump. Logs are attached with short wire-rope chokers to a coupling device at the end of a long, high-strength cable hanging from a helicopter hovering above. The specially designed helicopter lifts a pre-measured, precisely weighted bundle of logs and flies them quickly to the landing. At the landing, the helicopter pilot carefully lowers the logs to the ground and releases them electronically from the coupling device. The logs are moved a short distance from the landing's drop zone to the truck loading area with a grapple skidder, then loaded onto trailers with a hydraulic knuckleboom loader. Helicopter logging crews can produce as much as 2,500 tons of logs per week with a crew of 10-15 workers. A helicopter equipped for logging can cost well over $1.5 million. Helicopter logging is expensive and may not be economically feasible for accessible timber harvesting sites with average timber values. However, for high timber-value sites where accessibility is difficult and road building costs are excessive, or where environmental constraints prohibit conventional ground-based or cable logging systems, it offers a viable alternative. Helicopter logging systems can be found operating in challenging harvesting sites from the mountains of Alaska to the coastal plains of Florida.

Logging machines and systems are constantly evolving to meet the needs of society. Where high productivity was once the paramount criteria, minimizing environmental impact is now an equally important consideration in the development or application of new or modified timber harvesting machines or systems. For example, skidders can be equipped with super-wide, high-flotation tires to reduce ground pressure and eliminate soil rutting. Temporary bridge mats can be used in lieu of earth-filled culverts for temporary stream crossings on sites where water quality protection is critical. Cable yarding systems can be configured to provide full suspension to move logs cleanly over the tops of trees retained in a forested riparian buffer zone. Special underlayment fabric can be used with crushed rock surfacing to protect sensitive soils during haul road construction and usage.

Safety is also a major consideration in logging machine and system development. Because of its historically high injury rate, logging industry firms must pay Workers' Compensation Insurance (WCI) premium rates that are among the highest for any industry (7). Studies have shown that replacing a worker on the ground using a chainsaw with a worker in the enclosed, protected cab of a machine will dramatically reduce the incidence of accidents, injuries, and fatalities. For example, a logging contractor who replaces a worker performing manual chainsaw delimbing with a stroke delimbing machine can expect to see the firm's annual injury rate fall by nearly 50 percent (8). Accordingly, the firm's WCI premium rates will eventually decline as well, thus reducing overhead costs.

Logging Aesthetics

Modern timber harvesting has a public image problem. Overwhelming scientific evidence confirms the fact that logging, when well planned and performed properly, has little or no detrimental effect on water quality (9), site productivity, soil erosion, wildlife populations, biological diversity, endangered species, or forest resource sustainability. Forestry experts agree that timber harvesting is a critical tool to achieve silvicultural objectives such as forest regeneration, species or stocking control, or timber stand improvement. A timely and well-managed timber harvest can protect or improve forest health by surgically removing a source of insect or disease infestation, recover value through the salvage of dead and dying timber, and manage the threat of wildfire through strategic woody fuels reduction.

However, the general public often views a timber harvest as something akin to environmental devastation, simply because an unattractive landscape now exists where a mature forest of beautiful trees recently grew. To many people, it only seems logical that any operation that would create such an unattractive scene *must* be harmful to the environment, even if the area is quickly reforested. It is this line of uninformed reasoning that sometimes drives individuals to petition their local and state officials to prohibit or unduly restrict timber harvesting in their area.

In response to this issue of timber harvesting aesthetics, many logging contractors, forest industry firms, and forest landowners have voluntarily adopted techniques that can soften the initial negative visual response to a recently harvested site (10). A few of these techniques include:

- Retain a visual buffer of trees along public road corridors adjacent to the harvested area.
- Shield log landings from public view by using topography or vegetative buffers; clear landings of all woody debris, level and smooth the ground, and "green-up" the area with grass seed and mulch.
- Avoid leaving rutted haul roads or skid trails. Lop and scatter large, unmerchantable tree tops and limbs in highly visible areas.
- When clearcutting, create a natural-appearing, uneven edge, and leave small clumps of trees irregularly placed across the harvested area.
- Minimize the amount of logging debris by maximizing the utilization of each tree.

While judicious use of these and other techniques may somewhat reduce the negative aesthetics of a recent timber harvest, many people will continue to express concern any time they see an area where trees have been cut. Educating them that forests are truly a renewable and sustainable resource may be the most effective way to influence public opinion.

Logging in the 21st Century

A number of emerging technologies will likely have an impact on timber harvesting machine and system development into the 21st century (11). Among them are:

1. *Machine control systems.* Timber harvesting machines may be equipped with intelligent control systems that will enable the machine to adapt to the surrounding environment. For example, sensors will signal the machine when it is on wet or steep ground or when the wheels are beginning to lose traction. The machine will then automatically adapt to its working conditions in a way that will optimize performance and minimize environmental impact.
2. *Robotics.* Machines may accomplish systematic and repetitive functions robotically. These functions could include placing logs in a pile, acquiring a tree for delimbing, or moving ahead to the next tree. In such a system, the operator may simply point a control lever in the desired direction, and onboard computers will control the hydraulic valves and cylinders to achieve the desired function.
3. *Positioning systems.* Timber harvesting machines may be equipped with satellite-linked navigation controls based on global positioning system (GPS) technology. (See Chapter 12 for a description of GPS). The operator would deploy the machine using a map displayed on a computer screen in the cab.
4. *Machine vision.* Timber harvesting equipment in the 21st century may incorporate a form of

machine vision that will recognize and evaluate trees or logs to be handled or processed and will automatically respond accordingly. For example, an intelligent camera system will measure and select trees by diameter and form for an automated felling machine to cut.

5. *Lightweight machine components.* Lighter, stronger logging machine components constructed with aerospace materials like kevlar, aluminum, and carbon fiber will help to increase logging machine capacity and reduce environmental impacts. For example, telescoping booms made of lightweight composites could be extended on felling machines to allow operators to reach further into a timberstand to fell a tree without moving the machine, thus minimizing ground disturbance.
6. *Enhanced communications.* In the years ahead, a logging manager will be able to use a portable computer to check on the exact location of a log truck, monitor the fuel level in a skidder, or determine the up-to-the-minute production from several harvesting sites. A customer in France will be able to instantaneously send a lumber order to a sawmill in North Carolina, who will communicate the log species and size specifications needed to produce the lumber to a logging contractor at a harvest site in the forest, who will program the harvester's on-board computer to fill the order, all in the same day.

Concluding Statement

As long as there is a demand for paper and wood products, the professional logging contractors who own and operate the high-tech logging machines and systems will continue to face the challenges of efficiently and safely producing wood for a global market at a competitive cost. In addition, they must protect the environment and do their part to ensure the long-term sustainability of the forest resource.

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CHAPTER 20

Wood Products

EUGENE M. WENGERT AND
RAYMOND A. YOUNG

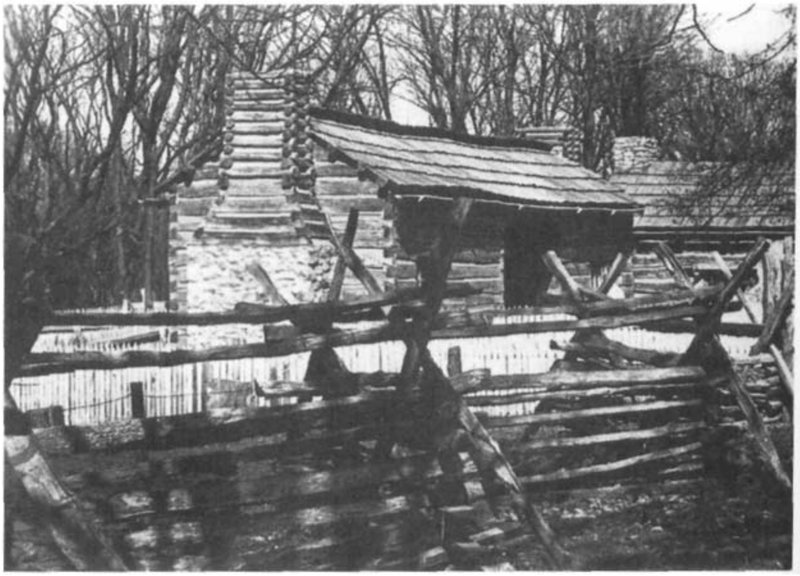


Figure 20.1 Early European settlers to North America used the plentiful wood supply for housing, fencing, and a myriad of other essential purposes.

Importance of Wood Products

Trees produce many benefits, including watershed protection, wildlife habitat, and recreation opportunities. However, of all the benefits of trees, the greatest is probably from the wood they produce. Wood is nature's nearly perfect composite material, and it is also renewable (1).

Wood provides the fuel for cooking and heating; the material for shelters (Figure 20.1); the material for furniture, cabinets, and other "essentials" for living; and wood is the raw material for fiber-based panels, paper, and paper products (2). For millenniums, the primary use for wood has been for fuel—cooking and heating—worldwide. It is only in the so-called "developed countries" that oil and coal have replaced wood-based fuels. As a result, uses of wood in developed countries are at about the same level for both solid wood products and pulp-derived products (Table 20.1). Pulp is used to make paper and paper-related products, such as fiberboard, and chemical commodities, while sawlogs are used for lumber, which in turn is used for housing construction, cabinets, furniture, and the like (Figure 20.2).

The amount of wood used annually in the United States is tremendous—over 500 billion pounds (227 billion kilograms) annually. It is estimated that the weight of wood used in the United States is equal to the weight of applications of all metals, plastics, and Portland cement. In fact, this large amount certainly indicates that the potential for significantly reduced reliance on wood would be difficult to achieve by substitution of metal, plastics, or Portland cement.

The general term for the various uses of wood is either *wood products*, or the more general term, *forest products*, which includes nonwood items such as pine cones, nuts, Christmas trees, mushrooms,

Table 20.1 How We Use Timber in the United States

Major Uses	Volume (%)
Sawlogs for lumber	30
Pulpwood for papermaking	29
Energy and other products	27
Composite boards (MDF, OSB, etc.)	9
Veneer and plywood	5

MDF—Medium-Density Fiberboard;
OSB—Oriented Strandboard
Source: Forest Products Laboratory, U.S.D.A., Forest Service, based on 1997 data.

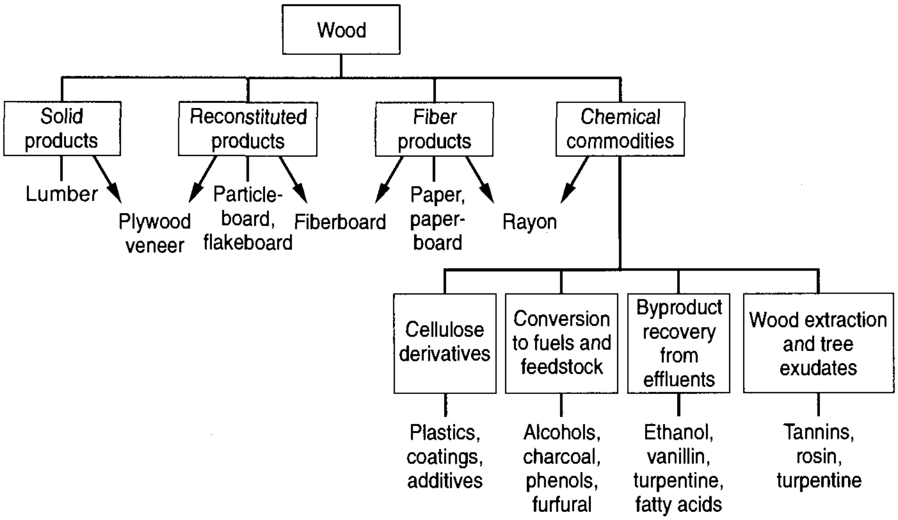


Figure 20.2 Summary of uses for wood.

and so on. Certainly in North America, as well as other developed countries, it is the monetary value received from harvesting, manufacturing and selling wood products (often called value-added processing) that allows for many timber stand improvement activities. Forest products activities result in the generation of substantial value-added income, especially in rural economies, thereby creating and generating an important source of individual and community economic viability. For example, in Wisconsin in 1998, forest products industries employed nearly 100,000 people and ranked as the #1 manufacturing industry in nearly 1/3 of the counties in the state. Forest products generated 17 percent of the value-added manufacturing income in the state.

Wood Properties

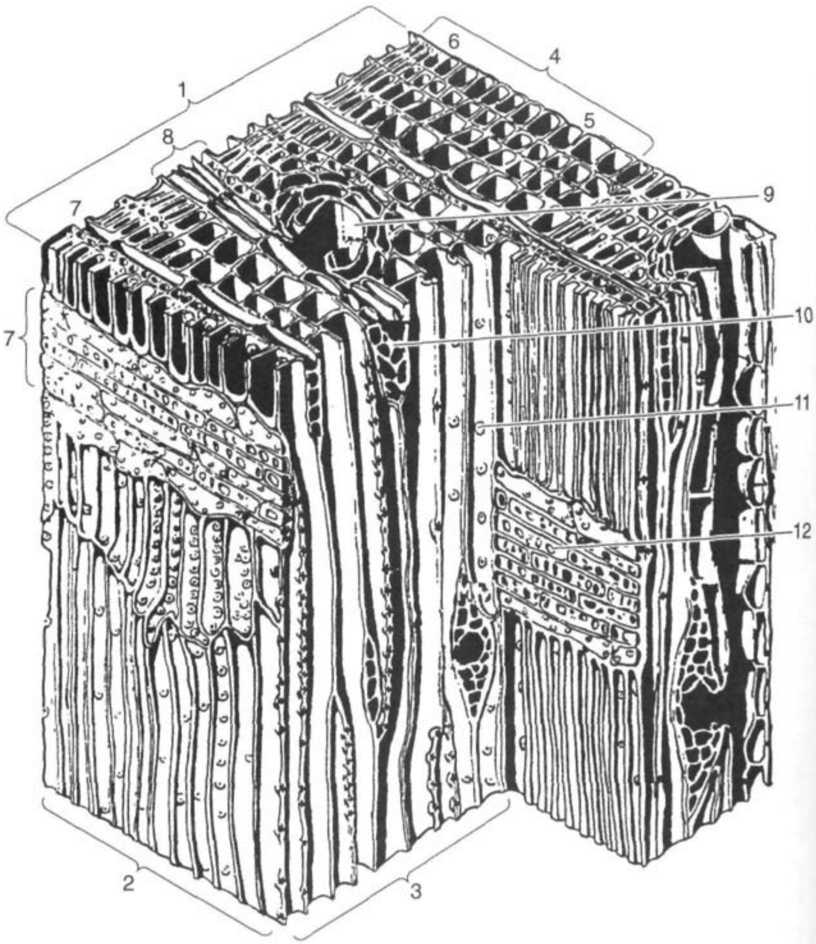
Wood is a composite product that has distinct properties, both advantages and disadvantages such as:

- renewable, complex, cellular biological material
- biodegradable—most species are easily decomposed by fungi (and bacteria) back into carbon, hydrogen, and oxygen when the moisture content is over 20 percent (oven-dry basis)
- anisotropic (different properties in different directions)
- hygroscopic (continually absorbs or desorbs moisture from the surrounding air in order to achieve moisture equilibrium)
- shrinks with loss of moisture and swells with gain in moisture
- combustible (over 400°F [200°C])
- relatively inert to most chemicals
- durable, if protected from moisture
- good insulator of sound, heat, and electricity, especially when dry
- easily cut to size required with simple tools and with little energy
- easily fastened with nails, screws and adhesives
- high strength-to-weight ratio

What Is Wood?

Wood is made of cells, which are typically long, slender (100 times longer than their diameter), hollow tubes (Figure 20.3). The role of the cells in the living tree is to conduct fluids from the roots to the leaves. In softwoods, the major cells runs vertically in the tree (called the longitudinal direction) and

Figure 20.3 Wood is made of long, hollow tubes called cells. In a softwood, more than 85% of the cells run vertically in the tree, with the remainder of the cells running horizontally from the bark toward the center of the tree. This is a resinous softwood, shown schematically.



Softwood Key

1. Cross-sectional face
2. Radial face
3. Tangential face
4. Annual ring
5. Earlywood
6. Latewood
7. Wood ray
8. Fusiform ray
9. Vertical resin duct
10. Horizontal resin duct
11. Bordered pit
12. Simple pit

are called *tracheitis*. Their length is 0.1 to 0.2 inches (3 to 5 mm). In hardwoods, the major cells are vessels, running longitudinally. Their length are typically 0.04 to 0.08 inches (1 to 2 mm). In addition to the longitudinal cells, 5 to 15 percent of the cells run radially (from the bark toward the center of the tree) in both softwoods and hardwoods and are called *ray parenchyma* cells. These are short, stubby cells that are involved in the storage of starches and sugars. Parenchyma cells that ran longitudinally can also be found frequently in hardwoods. Occasionally, there may be an opening between the cells. Softwoods also contain resin ducts or resin canals and hardwoods may have gum ducts. Various resins and other compounds are secreted into these ducts (3).

There are no cells that run tangent to the annual growth rings, called the tangential direction. However, each cell has numerous small openings, called pits, which connect the cells both longitudinally and radially, and provide a multitude of flow paths for water and nutrients to flow from the roots to the leaves.

The hollow spaces in the cells, called lumens in softwoods and pores in hardwoods, are filled with water, various chemicals including starches and sugars, and air bubbles. In fact, because the predominant component of wood, cellulose (discussed later in the chapter), is 1.5 times heavier than water, if the air bubbles were not present in wood, it would not float. Hemlock is one species that at times has very few air bubbles and will not float; these logs are called sinkers and may be found on the bottom of lakes and streams where logging was a past activity.

Sometimes, various chemicals will be deposited in the lumens or pores. These chemicals, called extractives, will give wood color, odor, and certain other properties including natural decay and insect resistance. These depositions are in cells that are usually several years old or older. Such cells are no longer participating in the life processes of the tree and so are called *heartwood* (Figure 20.4). The younger cells, which start at the cambium (bark) and proceed inward, and which eventually will become heartwood cells as they age, are called *sapwood.* Sapwood is usually white-colored, may have a higher moisture content than the heartwood, has a higher porosity, and has no natural decay resistance. Some species have only a few years of sapwood cells, such as northern-grown red oak

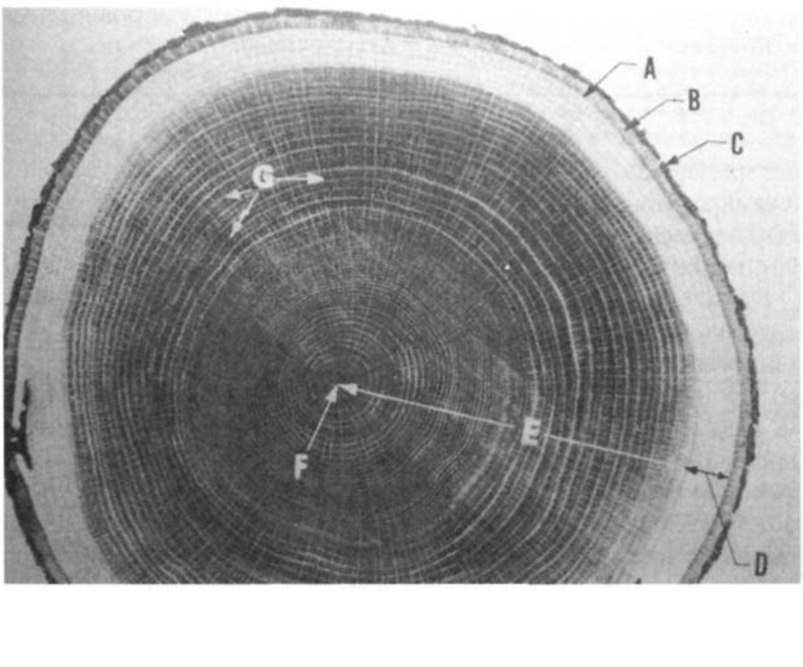


Figure 20.4 Cross-section of a white oak tree trunk: A, the cambium layer (microscopic), forms new wood and bark cells; B, the inner bark, contains living tissue and carries nutrients from the leaves to the growing parts of the tree; C, the outer bark, provides protection for the tree against physical damage, pathological damage, and drying; D, the sapwood, containing both living and dead tissue, carries sap from the roots to the leaves; E, the heartwood, containing dead tissue, is age-altered sapwood and usually contains chemicals that provide distinctive color, odor, low permeability, and decay and insect resistance; F, the pith, is the central nonwood core of the stem; G, the wood rays, running horizontally in the stem between the bark and the pith, transport liquids and chemicals, as well as store various nutrients.

Sidebar 20.1

Dendrochronology

Dendrochronology is the study of annual tree rings and is of value to scientists in a wide variety of disciplines. For example, climatic conditions can be evaluated according to the size of the rings. Narrow rings would be indicative of low rainfall or drought, while wide rings may indicate extensive rainfall (see Figure 20.4). Through the study of annual rings of very old trees, it is possible to reconstruct major climatic changes in the past. This area of emphasis is termed *dendroclimatology* and can provide information on such things as drought cycles. Of course there are other factors that influence the size of the annual rings, such as crowding by growth of other vegetation, which would reduce ring size, or harvesting and thinning operations, which would result in increased ring size. Defoliating insects could also reduce the size of the annual rings.

In 1937, Andrew Douglas founded the Laboratory of Tree Ring Research at the University of Arizona to promote the use of this approach. He utilized dendrochronology to date ancient pueblos in the Southwest by matching ring patterns from living trees, remains of fallen trees and wood samples from the ruins of the Pueblos. The dry conditions in the Southwest make this approach more viable, whereas in other, moister climates, the size of the rings are more consistent and there is greater decay of fallen and stored timber. However, dendrochronology continues to find new applications by scientists studying such things as the effects of pollution, forest fires, volcanoes, pests and earthquakes.

(perhaps 0.5 inch [1.3 cm] wide). Other species may have considerable amounts of sapwood, such as southern-grown red oak (perhaps 4 [10 cm] inches wide); yet other species, such as hard maple, are almost all sapwood, unless injured.

Moisture and Wood

In the living tree, there is about 60 percent wood and 40 percent water by weight, although there can be considerable variation from species to species, heartwood to sapwood, and tree to tree. For most uses of wood, much of this water must be removed (4).

Moisture content (MC) of wood is calculated and expressed in two different ways—the oven-dry basis and the wet-weight basis. The units are always in percent. For wood chips, particles, and pulpwood, the moisture content is:

$$\text{MC (\%)} = \frac{\text{Weight of water in wood}}{\text{Wet weight of wood (water + wood)}} \times 100$$

For lumber and other solid wood products, the moisture content is:

$$\text{MC (\%)} = \frac{\text{Weight of water in wood}}{\text{Oven-dry weight of wood}} \times 100$$

The oven-dry (O-D) weight is obtained by drying the wood in an oven at 216°F (102°C) until weight loss stops. Both moisture content measuring systems agree at 0 percent MC, but the difference between them increases as the MC increases. Considering a living Southern yellow pine tree with 50 percent oven-dry wood and 50 percent water—the MC is 50 percent MC (wet basis), but 100 percent MC (O-D basis).

Wood is a hygroscopic material, meaning that it will absorb or desorb moisture to obtain an equilibrium with the moisture in the air surrounding the wood. The relationship between the relative humidity of air (RH) and the MC varies little from species to species for most North American woods (Table 20.2). Some tropical species differ—they have lower MCs for the given RH than North American species. Wood that has been heated above 250°F (120°C), chemically treated, or inadiated with gamma rays may also have lower MC. The MC that wood achieves at a given RH is called the *equilibrium moisture* content (EMC) of the air.

Table 20.2 Key Values of RH and MC (Oven-dry Basis) for Wood

RH%	MC%	EMC%
0	0	0
30	6	6
50	9	9
65	12	12
80	16	16
100	28	28

RH—relative humidity; MC—moisture content; EMC—equilibrium moisture content

The RH/EMC values (Table 20.2) are important values in that most houses and offices in North America range from 30 percent RH (winter) to 50 percent RH (summer). Most unheated buildings and most exterior climates in North America average 65 percent RH, while most coastal climates and most island climates average 80 percent RH.

If wood changes MC, then the wood will shrink (moisture loss) or swell (moisture gain) about 1/4 percent for every 1 percent MC change. MC change problems account for the vast majority of problems and poor performance with wood. However, if wood is dried to a MC close to the EMC in use, then little MC change and, therefore, little shrinkage or swelling will occur in use.

North American Wood Consumption

Wood has been an important material in the recent history of the United States. Native Americans used wood for heating, cooking, and shelter, as well as for implements and tools, including arrows. Early European settlers used wood for construction of commercial buildings (such as the windmill that has been reconstructed at Colonial Williamsburg), as well as for homes, implements, tools, fences, roads, piers and wharves, ships and other watercraft, and a myriad of other uses. "Wood was indeed the material that built America during the last three centuries. When wood is kept dry (under 20 percent MC), it does not deteriorate, so it will last for centuries unless attacked by termites or other dry wood insects.

Today, annual wood use per capita continues to grow (Table 20.3). The uses for wood in the United States are over 60 billion board feet of lumber annually—about 75 percent of which is softwood lumber. About 1/3 of the lumber is used for new housing construction, 1/6 used for remodeling homes, 1/12 used for new nonresidential construction, 1/12 for manufacturing, and 1/12 for

Table 20.3 Per Capita Consumption of Several Wood Products in the United States over Past Years

	Consumption, per capita per year			
Product	1962	1970	1976	1986
Lumber (board feet)	210	194	205	237
Structural boards, including plywood & OSB (sq. ft—3/8")	51	69	82	107
Paper & fiberboards (pounds)	434	566	587	677

OSB—oriented strandboard

shipping (mainly pallets—over 600 million wooden pallets every year—Figure 20.5). The remaining is used for miscellaneous purposes including railroad ties, bridge timbers, and the like.

Home building is the bellwether of the U. S. economy. Although in 1991 we built only 1.0 million new homes, which is the lowest since WWII, in 1993 nearly 1.3 million homes were built in the United States. In the late 1990s, new housing construction was about 1.7 million annually, with over 1 million of these as single family units. A new home will use over 13,000 board feet of lumber (Figure 20.6) and 7,000 square feet of structural panels. This recent level of new housing growth is adequate to provide for the number of new households in the United States—in 2000 there were about 110 million households in the United States and by 2010, there will be about 121 million. In addition to strong housing, new houses today are larger and use more wood than in the previous decades—1,150 square feet in the '50s, 1,500 in the 70s, and 2,000 in the '90s. Many construction techniques today provide for more efficient use of wood (Figure 20.7). Accompanying housing growth is growth in allied products such as cabinets and furniture.

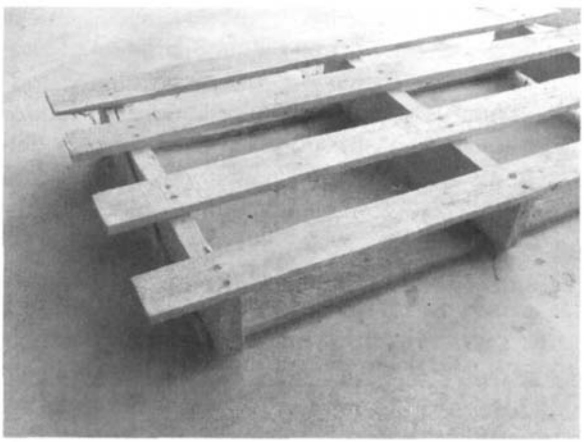


Figure 20.5 Wooden platforms, called pallets, are typically 40" X 48" and permit easy access by forklifts, so that large volumes of goods can be handled easily.

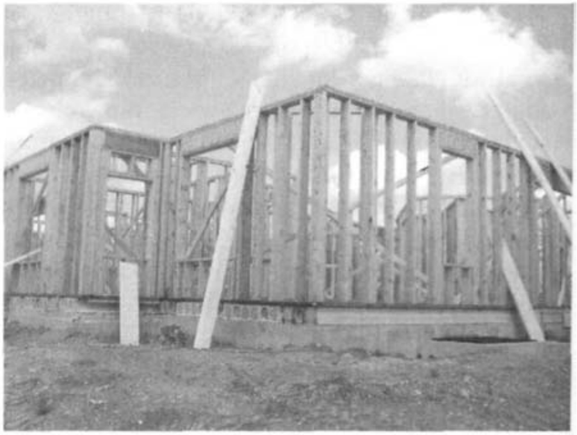


Figure 20.6 Wood frame construction is the typical construction method for homes in the United States.

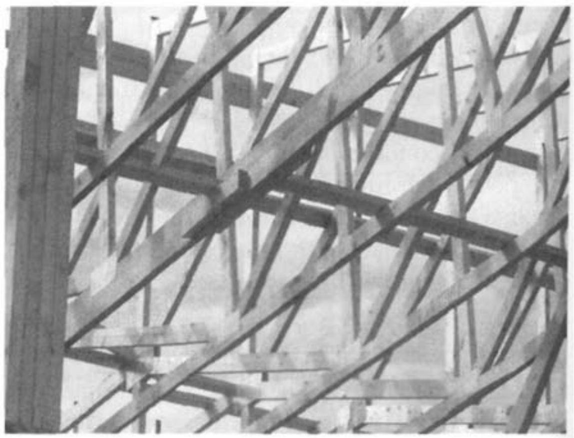


Figure 20.7 Roof trusses are commonly used to speed construction and conserve natural resources. Similar truss systems are used for floors.

Conversion of Wood into Primary Wood Products

Wood products are divided into two main categories—primary products and secondary products. Primary products are those wood products made from a log. Primary products include lumber, poles, and pulp. Secondary products are those wood products made from a primary product. Secondary products include furniture, cabinets, and paper.

The procedures for converting logs into primary wood products vary depending on the product. Although the conversion efficiency also varies, it is not unusual to find that about 50 to 60 percent of the log's volume will end up in the primary wood product. Each product has certain raw material requirements as well. The following sections consider five products—lumber, plywood, particleboard, OSB (oriented strandboard), and MDF (medium-density fiberboard). Use of wood as a fuel is considered later in the chapter.

Raw Material Requirements

Each of the forest products that are produced from trees have certain quality specifications that are enumerated in the following paragraphs—straightness and diameter are usually paramount. Often, these specifications are dictated by economics, rather than by the physical properties of the wood itself. Nevertheless, it is important to consider these specifications when considering the potential uses and management for forests and forest lands. The following are generalizations.

Pulp, used primarily for papermaking, and fiber logs, used for MDF, and hardboard, can use just about any inexpensive source of wood fiber, but the fibers must be intact. Sawdust and some (recycled) papers, because of the damage to the fibers in milling, cannot always be used. Likewise, decayed wood fibers are unsuitable. The longer fibers from softwoods are often preferred for strength, but the shorter hardwood fibers can be used in many cases, especially for fine papers. Economics (specifically, transportation costs) dictate that the pulpwood sources be close to the manufacturing facility—a 50-mile radius would be ideal. Most pulpwood logs, called roundwood, will be under 8 inches (20 cm) in diameter and 4 to 8 feet (1.2 X 2.4 m) long.

Softwood lumber, used for construction, requires that logs typically be between 8 to 24 inches (20-61 cm) in diameter, although a few mills can process 6 to 8 inch (15-20 cm) logs. Logs should be as straight as possible, with no decay. Knots or knot scars, especially for large branches, are not desired. Certain species are not highly desired, for example, eastern hemlock, because of poor lumber markets, while other species are quite desirable, including Southern pine, Douglas fir, and cedars. Shake (separation of the wood within the log running parallel to the rings), bad odors, and fungal activity of any sort is usually undesirable because of the high risk of strength loss in such logs. Due to low profit margins in softwood lumber manufacturing, softwood timber should be within 50 miles of the mill (25 miles is better yet).

Hardwood logs typically are 8 inches (20 cm) and larger, up to the optimum capacity of the mill, which typically is around 24 inches (6l cm) in diameter. Log lengths are 8 to 16 feet (2.4 to 4.9 m), but the typical length in eastern mills is 12 feet (3.7 m); southern mills, 16 feet (4.9 m); and midwestern mills, 8 or 10 feet (2.4 or 3 m). Logs should be as straight as possible, but most logs are fairly crooked, with several inches of sweep being common. As most hardwood lumber is sold based on the amount of clear area in the lumber, any branches, knots or knot scars should be well spaced apart. Some species, including sweetgum, aspen, and cottonwood, have very poor lumber markets, with low lumber prices even for higher grade material; log prices are low and profits are also usually low. On the other hand, some species, such as cherry, walnut, hard maple, and red oak have very high prices and demand, with high log prices and high demand and profits. Shake, bad odors, and fungal activity of any sort are usually undesirable because of the high risk of color loss and strength loss in such logs. Hardwood timber should be within 75 miles of the mill, although 25 to 40 miles is better.

Logs used for particleboards and flake boards, including OSB, can be small diameter (as small as 4 inches [10.2 cm]), no larger than 12 inches (30.5 cm) in diameter typically, crooked or straight, knotty or clear, and short or long (typically length is 8 feet [2.4 m] long). Although almost any species can and will be used, the lighter weight species, such as aspen and yellow poplar, are preferred, as they will press together better than a denser species; nevertheless, Southern pine is also often used for OSB. Logs with decay are not acceptable. Timber should be within 25 to 50 miles of the mill in most cases to avoid excessive transportation costs.

Because of the high capital costs of pulp and fiber plants and particle board manufacturing facilities (including OSB plants), these facilities will obtain the required timber no matter what the cost, size, or distance. In short, these facilities cannot afford to run out of raw material, so they will be, at times, rather ruthless in wood procurement, even using sawlogs, or going further than 50 miles from the plant. Their critical need for raw material must be considered by a land planner that is within or near the plant's procurement area.

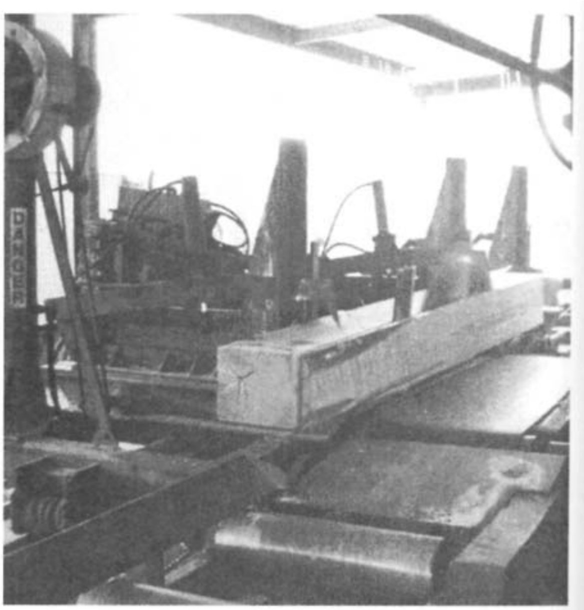


Figure 20.8 A sawmill can be an important source of value-added income in rural economies.

Lumber Manufacturing

Early sawmills used human power to move the saw through the log. However, in North America, the availability of water power led to development of water-power mills throughout the early European settlements. Lumber, especially for ship building, but also for shipping containers including barrels (called cooperage), was a critical commodity for ocean-based shipping economies during the 18th and 19th centuries. Although these historic sawmills would seem primitive without fancy computers and powerful motors, many mills produced as much or more lumber annually than an individual mill does today.

Today, there are two different mills—hardwood and softwood. A hardwood sawmill typically has 1 to 15 million board feet of annual production. Most of the lumber produced is *4/4* thick (4/4, pronounced "four quarter," is the number of quarter inches of thickness; 8/4 would be 2 inches (5.1 cm) thick). Lengths run from 4 feet to 16 feet (1.2-4.9 m); width is random. The primary quality factor is the amount of large clear areas, as hardwood lumber is seldom used "as is" but will be dried and then sawn into smaller pieces for furniture, millwork and cabinets. A softwood sawmill (Figure 20.8) typically produces in excess of 200 million board feet annually. Most of the lumber is 8/4 nominal thickness (which would be sold as 2" [5.1 cm] by a specified width), although the actual thickness is 1.5 inches (0.6 cm). Lengths are usually 8 to 20 feet (2.4-6.1 cm); widths would typically be 4, 6, 8, or 10 inches (10.2, 15.2, 20.3, or 25.4 cm) nominal size, or 3-1/2, 5-1/2, 7-1/2, and 9-1/4 inches (8.9, 14, 19.1, and 23.5 cm) actual size. Most softwood lumber will be dried, planed, and graded, and then used "as is" without additional manufacturing, except cutting to length at times.

A modern softwood sawmill producing lumber for construction is highly automated, with high manufacturing efficiency and high production, thereby assuring good profitability and good stewardship of the natural resource. In a typical mill (Figure 20.9), logs are debarked, scanned for metal, scanned for size to determine the best sawing pattern, and sawn into lumber and cants at the headrig. Then cants are resawn into lumber. Any pieces with wane (wane is the absence of wood) are edged. Lumber is then trimmed and sorted by size. Most of these processing procedures are computer-controlled with manual override possible. Volume

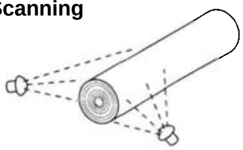
Computerized Bucking

The long log (perhaps 40 feet long) is cut into shorter lengths, called sawlogs, based on log diameter, crookedness, and market demand for particular lengths.

Debarking

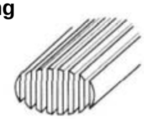
The bark is removed from the sawlogs so that the logs do not have any imbedded grit that would rapidly dull saws and other cutting equipment. It also ensures that any nonlumber byproducts are free of bark (required for pulp chips) and grit.

Scanning



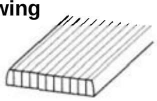
The sawlog is scanned for length, diameter, and straightness in order to determine the best (most profitable) sawing procedures. The results of this analysis include the finished lumber size, probable value and market demand, as well as the best position for the log when it enters the headsaw.

Headsawing



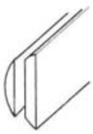
The headsaw is a multiple-saw machine that is usually computer-controlled. It uses the results from scanning to cut the sawlog into several flat pieces of wood of a desired thickness; these pieces are called cants. The cant usually has two flat, wide faces and two rounded edges, due to the log's round shape. The outermost piece of wood is called a slab; a slab has only one flat face, and the oppostie side is rounded.

Gang-sawing



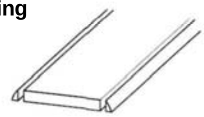
Large, thick cants are cut into several pieces of lumber in a multiple-saw machine called a gang-saw. Often, the cant is approximately 4 inches thick and the gang-saws are 2 inches apart; the end-products are 2" x 4" lumber, often referred to as studs.

Resawing



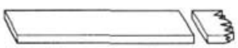
The slabs that are thick enough to be sawn into lumber are put through a resaw, producing a piece of lumber and a thinner slab. The resaw is also used to saw double-thickness cants into two thinner pieces.

Edging



The edger saw makes the edges of the lumber flat by removing the round edges, and also makes the two edges parallel to each other. Cants can be routed to the edger from the headsaw, gang-saw, or resaw.

Trimming



Trimming squares the ends of the lumber and removes any excess length, necessary since almost all softwood lumber is manufactured and sold in 6, 8, 10, 12, 16, 18, or 20 foot lengths. As both ends are typically trimmed, this process is also called double-end trimming.

Green-chain and Sorting

Lumber is sorted by grade, length, width, and thickness. Each size is accumulated separately. The system that conveys the lumber from the trim saw to the sorter is called the green-chain; the sorter, which typically has 30 or more bins for each size into which the lumber is dropped, is called a bin sorter or drop sorter.

Figure 20.9 The typical wood flow pattern for a softwood sawmill includes nine basic processes. It begins with a long log that has been brought in from the woods and ends with lumber that is ready to be stacked and kiln-dried, and eventually planed, graded, and packaged.

conversion efficiencies can exceed 65 percent—the 35 percent of the log not converted into lumber is used for pulp and for fuel. After the green lumber is produced, the lumber is kiln, dried, planed, and graded according to the rules of the American Lumber Standard.

Extending the Service Life of Wood Products

Wood products are subject to deterioration when they are exposed to the elements. Furniture, millwork, cabinets and other products are often coated with paints, lacquers, varnishes, and the like to retard the effects of moisture changes in the environment and the resultant shrinkage. Wood siding is often stained and coated to prevent erosion (although such deterioration is very slow) from airborne particles, water, and ultraviolet light, as well as to enhance the beauty. Poles, posts, railroad ties (also called sleepers), decks, and other wood products exposed outdoors are often treated with chemicals that are poisonous to fungi and insects. Sometimes wood is also treated with chemicals to retard or prevent ignition from fire.

In all these cases, there are tradeoffs between many factors, including the cost of the protection versus the benefit, the environmental risks or damage from applying the protection (and the risk from the ultimate disposal of the wood product), safety risks from poor performance (such as a broken electrical pole or tower, or the loss of lives in a fire), the cost of using nonwood materials, and the potential savings in wood harvested because of the longer life. The evaluation of the use of various wood treatments to prolong or enhance performance are societal issues; there is no one correct, easy answer. In fact, the answer will vary as societies change and as more knowledge is obtained.

One of the most widespread, yet controversial treatments used to prolong the service life of wood products is the use of pesticides (called wood preservatives) that are impregnated into the wood. The application and use of such chemicals is strictly controlled by the Environmental Protection Agency (EPA); quality assurance for the consumer is provided by the American Wood Preservers Association (AWPA).

Wood preservatives used today can be divided into two classes: 1) oilborne preservatives such as creosote (a coal-tar product; used for heavy timbers, ties, poles, and pilings) and petroleum solutions of pentachlorophenol; and 2) waterborne preservatives such as CCA (chromated copper arsenate; widely used for treating Southern pine, imparting a green color to the wood) and new treatments that often include copper compounds. Treatment of wood usually involves drying the wood partially to remove water so that there is room for the preservative chemicals, and impregnating the wood with the chemicals using a combination of heat, vacuum, and pressure in a large cylinder. The wood is sometimes dried again before being put into use. The type and amount of chemical used varies depending on the expected risk of damage; for example, wood in contact with the ground (such as a post or pole) would receive more chemical than wood exposed above the ground (such as a deck). Untreated wood of many species exposed to a wet environment may last only a few years, compared to more than 50 years for treated wood.

Plywood Manufacturing

Plywood panels consist of several large thin wood veneer-type layers joined with adhesive. Some or all of the layers are sheets of veneer. Other layers, particularly in the core, may be particleboard, hardboard, lumber strips, and special materials. The fiber direction of each layer is at right angles to that of the adjoining layer. This cross-banding makes plywood more uniform and less anisotropic than lumber; its properties in the direction of panel length resemble those in the direction of panel width.

Cross-banding affects strength in a logical way in both directions of the plane, the transverse layers contribute practically no strength; plywood is roughly one-half as strong as lumber is lengthwise. But by the same principle, plywood is stronger than lumber in the direction of width and can therefore be thinner. Moreover, it does not split like solid-wood products. Plywood and lumber properties naturally are the same in the thickness direction, provided that the layers are adequately bonded together.

Cross-banding gives plywood dimensional stability. To understand this effect, consider first the fiber direction of the surface veneers. Both surface veneers and the core veneer tend to swell and shrink (move) very little, whereas the two transverse veneers or cross-bands have a very strong tendency to move. The adhesive bonds compel all five veneers to move by the same amount, somewhere between the small longitudinal shrinkage and the large transverse shrinkage of lumber. However, since wood is many times stiffer in the fiber direction than in the transverse direction, longitudinal movement dominates and the panel remains fairly stable. Similarly, in the other direction of the plane, the cross-bands dominate and restrain the movements. According to a rule of thumb, plywood shrinks and swells in directions of length and width about twice as much as lumber moves lengthwise, which is still very little. For most practical purposes, plywood can be considered to be dimensionally stable. Of course, the cross-banding does not affect movements in the direction of the panel thickness, which are large in terms of percentages but small in absolute terms and unimportant.

Many plywood panels are 6 millimeters (1/4 inch) thick; the thinnest measure about 1 millimeter, and the thickest several centimeters. In addition to house sheathing and siding, plywood is used in cabinets, billboards, furniture, bookshelves, concrete forms, skins of flush doors, paneling, boxes, in mobile homes, and for trailers.

Particleboard Manufacturing

Particleboard, also called chipboard and chipcore (Figure 20.10), is a product that was developed about 50 years ago. It uses chips, as small as 1/4 inch (6.3 mm) cubes, that are glued together. Often the chips are sawmill residue, so the raw material cost is quite low. Initially considered to be a cheap substitute for lumber when manufacturing furniture, cabinets and shelves, the product was improved and is now highly respected as an excellent building material (especially for subfloors and for counter tops) and for furniture (especially for knocked-down, ready-to-assemble cabinets and case-goods). In most cases, however, particleboards cannot withstand prolonged exposure to liquid water without developing excessive swelling and loss of integrity. Special fasteners are required to develop good joints.

The typical manufacturing flow for particleboard is sorting of the chips and breaking larger chips into smaller sizes, drying in drum dryers, spreading adhesive and waxes on the particles, spreading the particles on a conveyor in a thick layer (called a mat), compressing the mat, using heat, to activate the adhesive. After cooling, the panels are cut into the required sizes and may be sanded if required. Properties of particleboards are controlled by the amount of adhesive used and the density of the board. However, particleboard is not as strong and stiff as an equal thickness of lumber, plywood, or OSB.

Figure 20.10 Manufactured wood products include flakeboard (at top of stack), OSB (at middle of stack), and particleboard (at bottom of stack).

Oriented Strandboard (OSB) Manufacturing

OSB (Figure 20.10) is a newer product, less than 20 years old. However, because small trees and crooked stems can be effectively utilized, the raw material cost, compared to product cost, is about 38 percent ($53 out of $141 per cubic meter). Plywood requires more than double the raw material cost ($117 out of $206 per cubic meter). Lumber requires even more ($133 out of $191 per cubic meter). As a result, OSB has rapidly gained acceptance in the construction market. OSB plant capacities exceed 20 million cubic meters annually; more new plants are being constructed each year. If lumber were used to do to the same job as OSB, we would need in excess of 8 billion more board feet of lumber annually, and this lumber would have

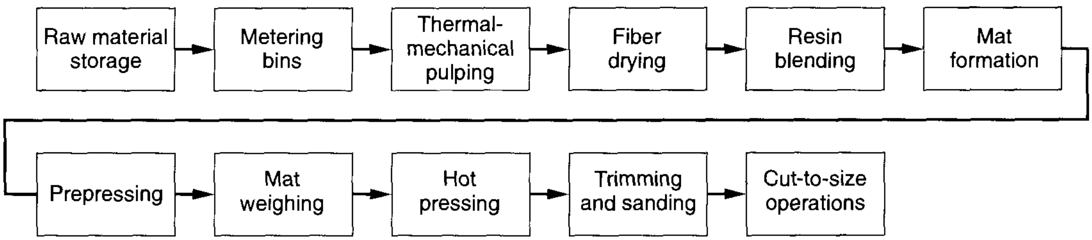


Figure 20.11 Typical material flow in an OSB facility.

to come from larger, higher-quality, more expensive trees. It is easy to understand why OSB is considered the wood product of the future in the construction business.

The typical material flow in an OSB plant (Figure 20.11) provides very high conversion efficiencies. Any "waste" is used for fuel for the manufacturing process. Logs are debarked, heated in hot water, cut into short lengths, and flaked into wafers or strands using knives. The strands are dried in large drum driers, coated with adhesive, and assembled into a thick mat. The strands in the mat are oriented to provide parallel strands in the various layers in the mat. The mat is compressed and heated, and cut to size. By controlling the panel density, the amount of adhesive, and the strand orientation, a panel can be designed and produced with properties that meet the engineering needs of the building designer and engineer.

Medium-Density Fiberboard (MDF) Manufacturing

As the name implies, MDF (Figure 20.12) is a fiber product. To obtain fibers, the log is broken down in the same manner as when wood is disintegrated for paper. However, for MDF, synthetic adhesives are added to the fibers before heating and pressing. This adhesive sets MDF apart from paper, low-density fiberboards (commonly used for ceiling tiles) and high-density boards (commonly used for pegboards and the backs of cabinets). MDF has a very smooth finished surface to which wood veneer, paper, or plastic can be easily laminated. The surface can be directly printed on as well. Special fasteners are required to develop high joint strength.

Chemical Nature of Wood

Although the relative value of wood as a source of energy and chemicals has varied considerably through the decades, wood continues to be an important source of specialty chemicals and renewable energy, and may be even more important in the future. Here we discuss the chemical

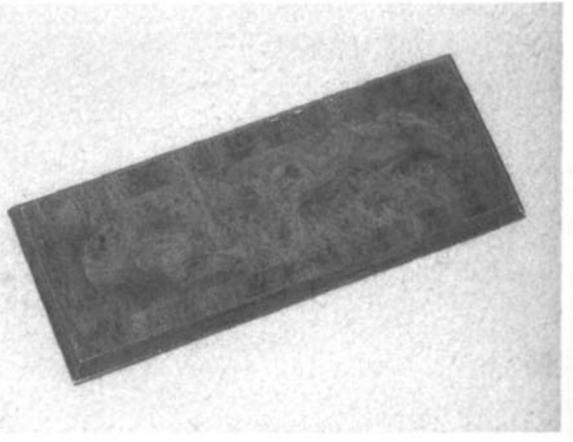


Figure 20.12 Medium-density fiberboard (MDF) panels, which can be printed or covered with thin films and made to look like solid wood, are widely used in furniture manufacturing.

nature of wood and in the following sections provide a description of the technology for conversion of wood to pulp fibers for papermaking, to fuels for energy, and to chemicals for industry and consumers.

As described in Chapter 4, wood is like all other plant material, in that it begins with the basic photosynthetic equation in which carbon dioxide and water are combined by means of the sun's energy to produce glucose and oxygen. To understand the chemical nature of wood, we need to trace the developments in the plant starting with glucose, a basic sugar. Glucose is only one of a series of sugars that occur in nature. The sugars are generally classified according to the number of carbon (C) atoms in their structure; thus, sugars with six carbons are referred to as hexoses, and those with five carbons are referred to as pentoses. The sugars important in wood structure are the hexoses (glucose, mannose, and galactose) and the pentoses (xylose and arabinose). Because sugars are so important in our lives, a separate field of chemistry, termed carbohydrate chemistry, is devoted completely to sugar derivatives.

Sugars generally do not occur as simple compounds in wood but as higher-molecular-weight structures known generally as polymers. The concept of a polymer can be visualized by considering one sugar unit as one link, the monomer, in a long chain, the polymer. Thus, with each link an identical sugar, a chain of sugar units is formed—a polymer of sugars known commonly as polysaccharides. This linking is depicted schematically as follows:

o	o-o-o-o-o-o-o-o-o-o
Monomer	Polymer
(sugar)	(polysaccharide)

Polysaccharides are characterized by the number of sugars in the chain or the degree of polymerization (DP).

Because there are many different sugars, many different polysaccharides can be formed. A polysaccharide formed from glucose is a glucan, from xylose a xylan, from mannose a mannan, and so on. If combinations of sugars occur in one polysaccharide, a mixed polymer is formed, usually named for its predominant sugars. Thus, if glucose and mannose are present, the polysaccharide is a glucomannan; if arabinose and galactose are present, a arabinogalactan; and so on.

Polysaccharides are of paramount importance in wood and to the uses of chemically processed wood. Cellulose is the common term used for the glucan present in wood; it constitutes about 42 percent of wood's dry weight. Cellulose is the primary component of the walls of cells making up wood fibers and is the main structural material of wood and other plants. Paper, paperboard, and other wood fiber products are therefore also composed mostly of cellulose. The chemical structure of the cellulose macromolecule is shown in Figure 20.13. In the plant, the DP of cellulose is approximately 14,000.

Closely associated with cellulose in the wood structure and in paper products are other polysaccharides termed hemicelluloses. The hemicelluloses have often been labeled as the matrix material of wood. In hardwoods, the primary hemicellulose is a xylan (polymer of xylose), whereas in softwoods, the primary hemicellulose is a glucomannan, although both of these polysaccharides occur to some extent in both types of wood. The DP of the hemicelluloses is much less than that of cellulose, in the range of 100 to 200.

Table 20.4 gives a comparison of the chemical composition of extractive-free hardwoods and softwoods. (The nature of wood extractives is treated in a later section.) (5, 6) Since cellulose and the

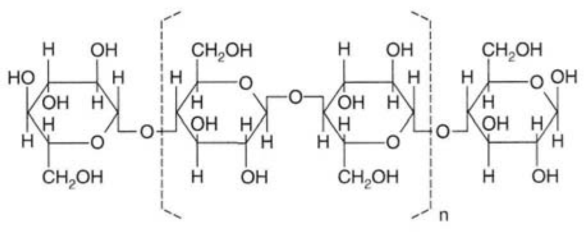


Figure 20.13 The chemical structure of cellulose; the cellulose repeat unit is shown in brackets.

Table 20.4 Chemical Composition and Fiber Length of Extractive-free Wood (by percent)

Component	Hardwood (Red Maple)	Softwood (Balsam Fir)
Cellulose	44	42
Hemicelluloses		
Xylan	25	9
Glucomannan	4	18
Lignin	25	29
Pectin, starch	2	2
Average fiber length (mm)	0.8-1.5	2.5-6.0

hemicelluloses are both polysaccharides, it is obvious that the polysaccharide component of wood is by far the dominant one, making up approximately 70 percent of both hardwoods and softwoods. Additional polysaccharides may occur as extraneous components of wood, components that are not part of the cell wall; for example, the heartwood of species of larch can contain up to 25 percent (dry weight) of arabinogalactan, a water-soluble polysaccharide that occurs only in trace quantities in other wood species.

The third major component of wood shown in Table 20.4 is lignin. Although lignin is also a polymer, it has a different chemical structure compared to that of the polysaccharides. The monomeric units in lignin are phenolic-type compounds. The spaces between fibers in wood are almost pure lignin and are termed the middle lamella (5, 6). Lignin is also considered the gluing or encrusting substance of wood and adds mechanical strength or stiffness to the tree and to wood. Higher plants are commonly referred to as lignocellulosic because of the typical joint occurrence in them of lignin and cellulose. The spaces between fibers are filled with lignin and make up the middle lamella.

A fourth class of wood components is known as extraneous material and is present in wood in amounts of 1 to 10 percent. These materials comprise a vast array of chemical compounds that are not constituents of the cell wall. Most of these compounds, because they can be extracted with water or organic solvents or volatilized with steam, are called extractives. They are considered in detail subsequently. A small portion of the extraneous materials (starch, pectin, and inorganic salts) are not extractable.

Microscopic Structure of Wood and Wood Fibers

In the tree, the cellulose polymers are laid down uniformly, the chains paralleling one another, and the long-chain molecules associate strongly through hydrogen bonds that develop between hydroxyl groups. These bonds create very strong associations between the cellulose macromolecules. These associations between the cellulose chains give a very uniform crystalline (ordered) structure known as *micelles* or microcrystallites, shown in Figure 20.14.

The micelles are also associated in the tree to give long threadlike structures termed *microfibrils* (Figure 20.14). The structure of the microfibrils is not completely uniform throughout. There are regions of non-uniformity between the micelles in the microfibrils called amorphous (disordered) regions; the cellulose microfibril therefore has a crystalline-amorphous character. Water molecules enter the amorphous regions and swell the microfibrils; ultimately, this is the mechanism by which fibers and wood swell in moist or wet environments.

The final fiber cell wall structure is essentially layers of the microfibrils or macrofibrils aligned in several different directions. The entity holding the fibers together, the middle lamella, is almost pure lignin (90 percent), as mentioned earlier. For the cellulose fibers to be separated, the middle lamella lignin must be chemically removed, a process that also removes most of the hemicelluloses, or mechanically degraded to free the fibers for paper-making (Figure 20.15). A paper sheet can then be formed from the separated cellulose fibers by depositing them from a water slurry onto a wire screen. The water drains away and the fibers collapse, leaving a fiber mat that derives its main strength from re-association of the fibers through many hydrogen bonds, the same type of bond that gives mechanical integrity to the fibers (Figure 20.16)

The long fibers from softwoods (Table 20.4) are usually preferred in papermaking for products that must resist tearing, such as grocery bags, whereas the shorter hardwood fibers give improved opacity, or covering power, and printability to the final paper sheet. The type of pulping process also

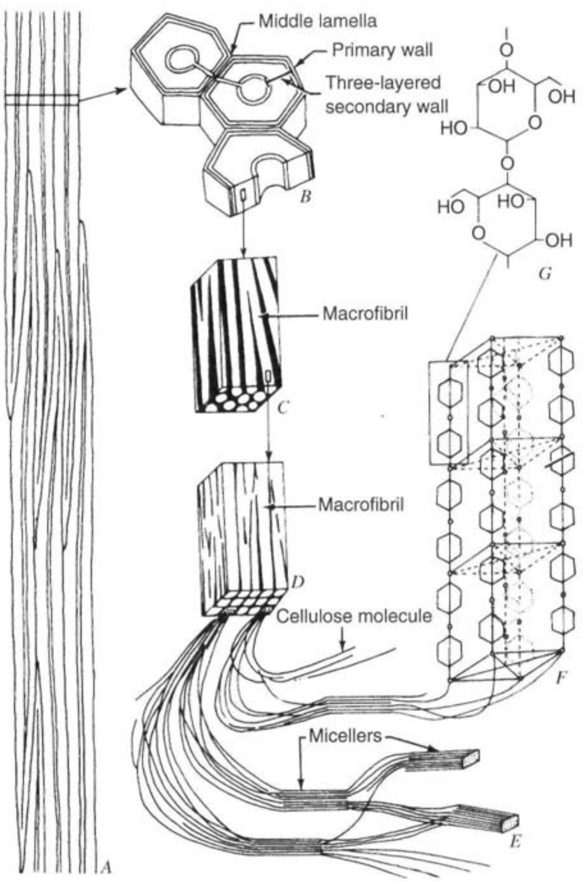


Figure 20.14 Detailed structure of cell walls. *A,* strand of fiber cells. *B,* cross-section of fiber cells showing gross layering: a layer of primary wall and three layers of secondary wall. *C,* fragment from the middle layer of a secondary wall showing macrofibrils (white) of cellulose and interfibrillar spaces (black), which are filled with noncellulosic materials. *D,* fragment of macrofibril showing microfibrils (white), which may be seen in the electron micrographs. The spaces among microfibrils (black) are filled with noncellulosic materials. *E,* structure of microfibrils: chainlike molecules of cellulose, which in some parts of microfibrils are orderly arranged. These parts are the micelles. *F,* fragment of a micelle showing parts of chainlike cellulose molecules arranged in a space lattice. *G,* two glucose residues connected by an oxygen atom—a fragment of a cellulose molecule. (From K. Esau, *Anatomy of Seed Plants,* Second Edition, 1997, courtesy of John Wiley & Sons.)

Figure 20.15 Scanning electron micrograph of a cluster of eastern white pine elements after pulping or maceration of a small wood cube. (Courtesy of Wilfred Cote and Syracuse University Press.)

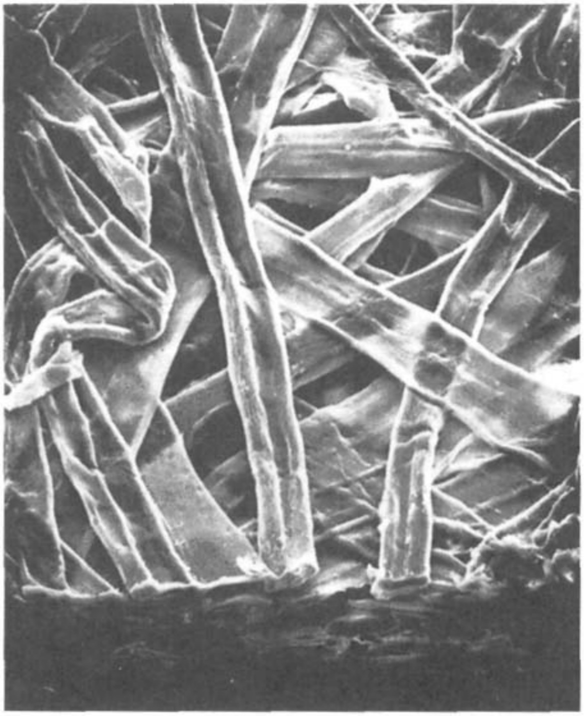


Figure 20.16 Scanning electron micrograph of paper surface showing random arrangement of coniferous tracheid fibers in the sheet. Note the flattened or collapsed nature of the fibers in this cross-section cut with a razor blade. (Courtesy of Wilfred Cote and Syracuse University Press.)

affects the pulp properties, as described in a later section.

History of Pulp and Papermaking

The concept of making paper from the fibers from lignocellulosic materials, an integrated system of fiber separation (pulping) and reforming of the fibers into a mat (papermaking), is attributed to T'sai Lun, a court official in southeast China in 105 A.D. The, first fibers were obtained from old hemp rags and ramie fishnets, but shortly thereafter, the inner bark fibers from paper mulberry trees were also utilized for papermaking. Bamboo was used as a source of fiber several centuries later. The rags were macerated into a pulp in water with a mortar and pestle; then, after dilution in a vat, the pulp was formed into a wet mat on a bamboo frame equipped with a cloth screen to drain the free water. The mat was dried in the sun. The invention was based on the need for a writing material to replace the expensive silk and inconvenient bamboo strips. The invention was a closely guarded secret for many centuries but filtered to the West at Samarkand in western China early in the eighth century. Papermaking was introduced to the United States in 1690 with the first mill near Philadelphia, Pennsylvania.

Paper was made by hand essentially as just described above, spurred by development of the Gutenberg printing press (1455), until the invention of the long, continuous wire screen machine by Louis Robert in France in 1798. The machine was subsequently developed commercially in England by the Fourdrinier brothers, whose name is associated with it to this day (see Figure 20.19 in the section on Papermaking).

Wood became a source of fiber in the mid-1840s, when a groundwood pulp grinder was manufactured in Germany. The wood was defibered by pressing against a grindstone. After 1850, several chemical methods were developed to produce chemical pulps, which will be described later. The major sources of fiber in the United States for papermaking are pulpwood (roundwood), byproduct sawmill chips, and recycled paper.

Although wood is the dominant raw material for pulp and paper in the developed world, a wide range of fibers are utilized for papermaking in other parts of the world. In many countries, pulp production is based entirely on agro-based fibers and over 25 countries depend on agro-based fibers for over 50 percent of their pulp production. The leading countries for production of pulp and paper from agro-based fibers are China and India, with China having over 73 percent of the world's agro-based pulping capacity. China mainly utilizes straw for papermaking, while India and Mexico utilize large quantities of sugar cane bagasse (fiber waste from sugar production). India also incorporates some jute fiber and large quantities of bamboo, although the supply of bamboo is not sufficient to meet demands for paper production (7). There has been considerable interest in the use of kenaf as an alternate fiber source in the United States and a number of successful press runs of kenaf-based paper (82-95%) were carried out in the pressrooms of the *Bakersfield Californian,* the *Houston Chronicle,* the *Dallas Morning News* and the *St. Petersburg Times* (7).

Practically any natural plant can be utilized as a source of papermaking fibers, but there is considerable variation in the quality of paper realized from alternate plant sources. Factors such as fiber length, content of nonfibrous components such as parenchyma tissue, contaminants such as silica, and so forth greatly influence the quality of the final sheet. Procurement of sufficient quantities of the raw material and seasonal fluctuations in supply can also pose problems. It is also necessary to use alternate pulping equipment to handle the plant materials, since the material tends to mat down in the digester, making it difficult to get uniform circulation of the cooking chemicals (7, 8).

Production of paper and paperboard in the United States constitutes about 35 percent of the world's total; papermaking in North America and Europe together made up about 75 percent of the world production. The difference in the economies of the developed and less-developed countries is shown in the accompanying tabulation by the wide range of relative per capita consumption of paper and paperboard (9):

United States	323
Japan	249
Germany	192
China	27
Russia	14
Egypt	10
India	4
Afghanistan	<1

Pulping of Wood

To prepare the wood for pulping, the standing tree in the forest is felled, delimbed, bucked to length, and conveyed to the pulp mill or sawmill (Figure 20.17). At the pulp mills the logs are usually debarked by tumbling against one another in large rotating drums, which removes the bark by impact and abrasion. The debarked logs are next taken to the groundwood mill (5 percent) or to the chipper (95 percent). After chipping, the chips are screened to remove oversize chips and fines.

Three major methods are used to pulp wood; namely, mechanical, semi-chemical, and chemical.

Figure 20.17 Unloading at a pulp mill in Kingsport, Tennessee. (Courtesy of U.S.D.A. Forest Service.)

Each process produces pulps with different properties for different applications. The major pulping processes in use are classified in Table 20.5.

Modern mechanical pulping includes stone groundwood pulping (SGW), in which bolts of wood are pressed against a revolving grindstone, and refiner mechanical pulping (RMP), in which chips are passed between single or double rotating plates of a vertical-disk attrition mill (Figure 20.18). Recent developments in stone grinding are

Table 20.5 Wood Pulping by Process and Yield

		Treatment		
Process	Acronym	Chemical	Mechanical	Pulp Yield(percent)
Mechanical Processes				
Stone groundwood	SGW	None	Grinder	93-95
Pressure groundwood	PGW	None	Grinder	93-95
Refiner mechanical	RMP	None	Disk refiner (pressure)	93-95
Thermomechanical	TMP	Steam	Disk refiner (pressure)	80-90
Chemi-thermomechanical	CTMP	Sodium sulfite or sodium hydroxide[1]	Disk refiner (pressure)	80-90
Chemi-mechanical[2]	CMP	Sodium sulfite or sodium hydroxide	Disk refiner	80-90
Semi-Chemical Processes				
Neutral sulfite	NSSC	Sodium sulfite + sodium carbonate	Disk refiner	70-85
Green liquor	GLSC	Sodium hydroxide + sodium carbonate	Disk refiner	70-35
Nonsulfur	—	Sodium carbonate + sodium hydroxide	Disk refiner	70-85
Chemical Processes				
Kraft	—	Sodium hydroxide + sodium sulfide	None	45-55
Sulfite	—	Calcium bisulfite in sulfurous acid[3]	None	40-50
Magnefite	—	Magnesium bisulfite in sulfurous acid[4]	None	45-55
Soda	—	Sodium hydroxide	None	40-50
Soda-oxygen	—	Sodium hydroxide + oxygen	None	45-55
Soda-anthraquinone	SAq	Sodium hydroxide + anthraquinone	None	45-55
Dissolving Processes				
Prehydrolysis kraft	—	Steaming and kraft (two-step process)	None	35
Acid sulfite	—	Acid sulfite (Ca, Na)	None	35

[1] Sodium sulfite or sodium hydroxide, 2-7% of wood,

[2] Also chemical treatment after fiberizing.

[3] Also sodium, magnesium, and ammonia; pH 2.

[4] pH 5.

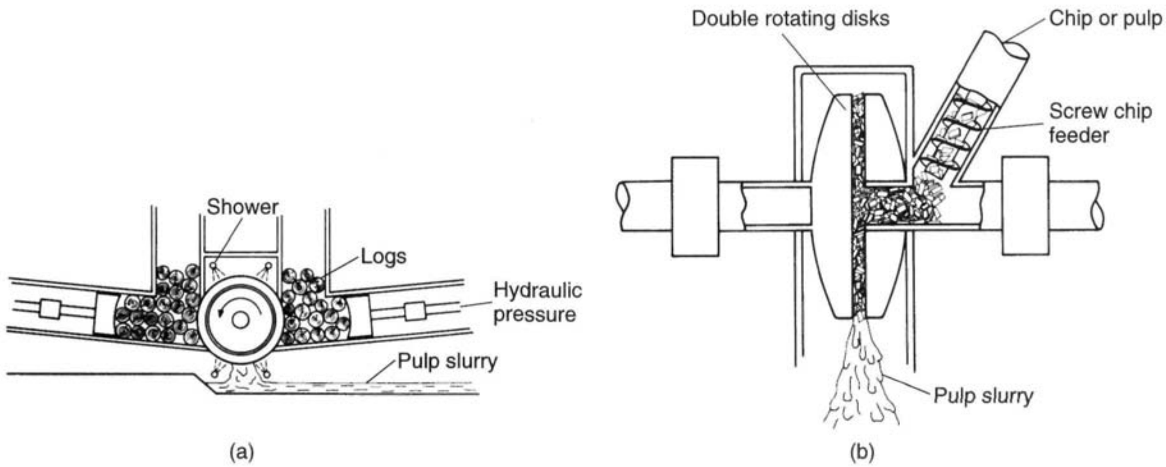


Figure 20.18 Schematic of (a) a stone grinder that pulverizes wood bolts for groundwood pulp and (b) a disk refiner that grinds wood chips for refiner and thermomechanical (TMP) pulps. Showers provide water for both methods.

applying pressure to the grinder (PGW) and controlling temperature (Table 20.5).

Basic changes in mechanical pulping technology are to pretreat chips with chemicals, steam, or both. These developments started forty years ago when chips were pretreated with caustic soda, termed chemi-mechanical pulping (CMP). Presteaming and pressure refining of chips gives a thermomechanical pulp (TMP); and when chemical pretreatment and pressure steaming are combined, the pulp is referred to as chemi-thermomechanical pulp (CTMP). There are many variations of these processes. These treatments are employed to improve pulp quality. The steam and chemicals aid fiberizing by giving a less-damaged fiber, which makes the final paper stronger.

Mechanical pulps are a major component of newsprint. The mechanical pulp imparts valuable properties to the newsprint, all of which are related to printability. These are absorbency, bulk, compressibility, opacity, and uniformity. However, because mechanical pulps are weak, up to 30 percent of a chemical pulp (described later) is blended into the pulp mixture, called a furnish, to provide greater strength. Sufficient strength is required of the newsprint to withstand the tension forces produced by the printing press. Modern mills, however, now use 100 percent TMP or CTMP to produce newsprint with sufficient strength. Mechanical pulps are also an important component of publication paper grades, which are generally coated magazine papers. Obviously, printability is important in this application as well.

Semi-chemical pulping combines a mild chemical treatment with mechanical action for final liberation of the fibers. The major semi-chemical process is neutral sulfite semi-chemical (NSSC). The semi-chemical processes were developed to improve the economic return. These processes give higher yields (75 to 80 percent) than full chemical pulping and better strength than mechanical pulps. The semi-chemical pulps are very suitable for the stiff corrugating medium in cardboard boxes. The recovery of chemicals and heat value from the semi-chemical spent liquors is well developed.

Chemical pulping is conducted on wood chips using lignin-dissolving reagents in vessels, called digesters, under elevated temperature and pressure (10). The major chemical pulping processes were developed about a century ago and are the soda (1855 in England), sulfite (1867 in the United States), and kraft or sulfate (1884 in Germany) processes.

The word "kraft" comes from the German word meaning strong. The ability to utilize all wood species, especially pines, and the excellent strength of the resulting pulp have contributed to the growth of the kraft process. Kraft pulping dominates, accounting for almost 80 percent of the total pulp production in the United States.

The mechanisms for removing lignin and separating fibers in chemical pulping are hydrolysis, which cleaves the lignin bond, and conversion of the lignin to water-soluble fractions through reactions with sulfur compounds. Recovery of spent pulping reagents is economically necessary with the kraft process and involves a series of cyclic steps. Although the kraft process has an efficient chemical recovery system, many older sulfite mills around the world have closed because of poor chemical recovery schemes for this process.

Chemical pulps, such as kraft and sulfite, and in particular, softwood kraft pulps, are generally used when considerable strength is required. Bags, stationery, and ledger and bond papers contain high percentages of chemical pulp. Sanitary tissues such as facial and toilet tissues also contain large amounts of chemical and recycled pulps. For them, a combination of softness and absorbency are sought, along with sufficient strength.

Solvent pulping is another method that has received renewed interest; organic solvents rather than the traditional aqueous sulfur pulping are used for what is called *organosolv pulping.* Since lignin is an organic polymer, it is naturally soluble in organic solvents once some of the lignin bonds have been broken by an acid, usually, or by a base included with the aqueous organic solvent. Thus, a sulfur derivative of lignin is not necessary to solubilize and solvate the lignin, and the severe environmental hazards of sulfur are eliminated from pulping and chemical recovery (11).

A variety of organic solvents have been evaluated for organosolv pulping. Two systems are alcohol pulping (50:50, ethanol/water) and "ester pulping." Ester pulping is based on three chemicals, in roughly equal proportions: acetic acid, ethyl acetate, and water. Energy costs are reduced with the ester pulping process because chemical recovery is based on a liquid-liquid phase separation after pulping. The two liquids do not mix, similar to the way water and gasoline do not mix. Since it is necessary to recover the solvent from all organosolv systems for economic reasons, the pollution hazards are considerably reduced. However solvent pulping systems have not been commercially successful to date (11).

Bleaching and Brightening of Pulp

Although pulpwood is generally light-colored and can retain its brightness in the acid and neutral sulfite processes, pulps from the dominant alkaline kraft process are dark-colored. This color is evident in unbleached kraft packaging paper and boards.

About one-half of chemical pulps are bleached to different degrees of brightness (whiteness). Substantial amounts of mechanical and chemi-mechanical pulps are also brightened to intermediate brightness levels. In bleaching, the residual colored lignin in pulp is dissolved chemically, whereas in brightening, the lignin is altered to a lighter-colored compound without removal (11).

Kraft pulps of high brightness (90 percent) are generally produced in a multistage sequence. In a series of bleaching towers, the pulp is treated with chlorine (C) or oxygen (O), caustic extraction (E), and chlorine dioxide (D), generally in a sequence of C(O)EDED. Multistage bleaching has the serious disadvantage of requiring a considerable capital investment in large, corrosion-resistant equipment with high maintenance costs. In addition, the bleaching process produces chlorinated lignin phenols, which can pose serious toxicity pollution problems. In recent years, oxygen bleaching has been substituted for chlorine in the first stage to reduce such hazards.

Regulatory agencies in Europe, and particularly in Scandinavia, have imposed even greater restrictions on emissions from pulp mill bleach plants and several new approaches have been developed. These are Elemental Chlorine Free (ECF) bleaching and Totally Chorine Free (TCF) bleaching of pulps. Generally for ECF, oxygen (O) treatment is substituted for chlorine (C) in the first stage. For TCF more radical changes are necessary with substitution of both (C) and (D) stages with ozone (O), peroxide (P), and enzyme (X) stages in a sequence such as OXZP. The use of enzymes is the newest development in bleaching technology as further described below (11).

Biotechnology—Biopulping and Biobleaching

The pulping of wood is at present based on either mechanical or chemical methods or combinations thereof, as described in this chapter. The interfiber lignin bond is broken down by the mechanical and chemical treatments to free the cellulose fibers for papermaking. In the forest, white rot fungi perform a similar task on wood left behind. The enzymes of the fungi do the work of lignin degradation. This is the basis of new biopulping approaches which have been under development for more than ten years. Wood chips or agricultural materials are treated with a white rot fungus and nutrients for about two weeks which breaks down and alters the lignin gluing substance in the lignocellulosic material. The biomass then can be much more easily disintegrated by mechanical treatment in a disk refiner (Figure 20.18b). Since some mechanical treatment is required, the method is more properly termed biomechanical pulping. Investigators at the U.S. Department of Agriculture, Forest Products Laboratory in Madison, Wisconsin evaluated hundreds of fungi for this purpose and found that treatment with the white rot fungus, *Ceriporiopsis subvermispora,* resulted in the greatest reduction in energy reqirements for mechanical disintegration and the best strength properties from the resulting paper.

Biobleaching is also possible for brightening or whitening pulp fibers in lieu of the toxic chlorine compounds utilized at present by the industry as described above. At least one enzyme based process developed in Finland has been applied commercially. The process uses xylanase to make lignin more vulnerable to oxidation by attacking the surrounding polysaccharides that protect the lignin. Another exciting application would be to use these and other enzymes for removal of lignin pollutants from waste effluents. Biotechnology should lead to safer and cleaner methods for pulping and bleaching.

Paper and Paperboard

The production of pulp of paper and paperboard for the market proceeds in three successive steps: stock preparation, papermaking, and converting to the enormous number of paper products.

Stock Preparation

The separated fibers from the pulping operation, except those in mechanical pulps, are generally not suitable for papermaking. To obtain the optimum paper properties, the fiber bonding must be improved by supplemental mechanical treatment of the fiber surface, and by imparting special properties through blending of additives and other pulps. Beating or refining, a basic step in the transition from pulp to paper, is accomplished by cutting and shortening, rubbing and abrading, and crushing and bruising the pulp fibers as they pass between the rotating and stationary bars of a beater or the disks of a refiner (Figure 20.18b). These actions promote fiber flexibility and the area of contact between the wet fibers by exposing the fibrils and microfibrils on external and internal surfaces. The close contact enables hydrogen bonds to form between the adjacent fibers on drying, as explained earlier in this chapter.

Paper is rarely made from pure fibers. The color is altered by dyes; the writing and printing capacity is improved by internal and surface sizing agents (rosin and starch, respectively); the wet strength is enhanced with resins; opacity is increased with pigments such as clay and titanium dioxide; and alum (aluminum sulfate) is added for flocculation. These additives can be introduced during the beating operation or in blending chests before the fibers go to the paper machine.

Seldom is paper made from any one kind of fiber. In addition, the pulp can enter the stock preparation system either as a pulp slurry (slush pulp) from an adjoining pulp mill integrated with the paper mill or as bales of dried pulp which need to be repulped in a beater or hydrapulper. Other functions of the stock preparation stage are control of the fiber length for sheet uniformity, removal of unwanted dirt, specks, and particles, and dispersal of the fibers.

Papermaking

The cleaned and dispersed fibers are formed or combined into a fibrous mat in the papermaking stage of the system by deposition from a dilute headbox suspension (0.5 percent solids) onto the traveling continuous wire screen of the Fourdrinier paper machine mentioned earlier (Figure 20.19). The surplus water is removed by drainage from this wire screen aided by vacuum boxes, foils, and a vacuum "couch" roll, by pressing between rolls, and by drying on steam-heated drums or in a hot-air chamber.

Other functions of the papermaking stage are to control the sheet density and surface smoothness through application of pressure and some friction in the calender (Figure 20.19). Another function is the application of a surface coating. The solids content of the paper during papermaking progresses from 15 percent after drainage, to 40 percent after presses, to 95 percent after the drum dryers.

Finishing and Converting of Paper

The objectives in the final stage of the total papermaking system are to improve the paper surface, to reduce rolls and sheets in size, and to modify paper for special properties, by coating or embossing, for example. Paper must also be converted into finished products, such as bags and corrugated boxes, and packaged for shipping. Paper is generally coated to improve printing properties. A surface coating of a pigment, usually kaolin or china clay, calcium carbonate, or titanium dioxide; and an adhesive, starch, or casein are applied to the partially dried web by brush, blade, spray, or other method, and dried during the papermaking (on-machine) operation or in a separate operation. The paper surface is brought to a high finish by passing through calenders or supercalenders. Supercalenders are stacks of alternate steel and densified fiber rolls that create a rubbing action on the sheet, imparting an extra gloss to the sheet surface.

Recycled Paper

Wastepaper fibers can be turned back into paper, depending on the price and supply of new pulp.

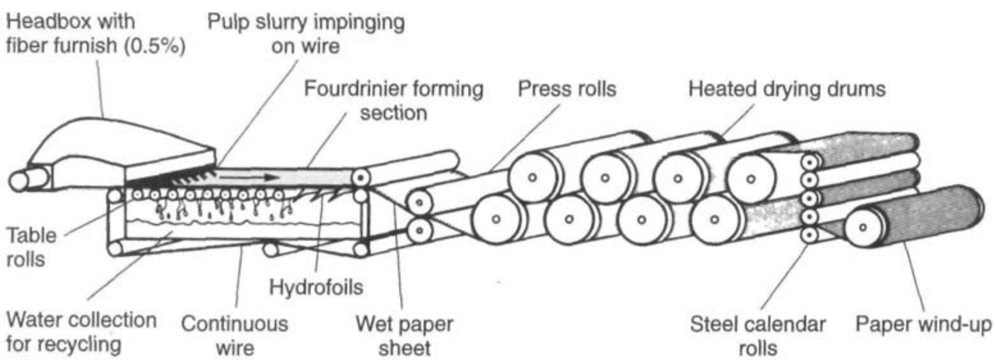


Figure 20.19 Schematic of a modern Fourdrinier paper machine.

The amount of the total recycled fiber for papermaking in the United States was 47.3 million tons in 2000, for a recovery rate of 45 percent. The United States is a major exporter of wastepaper—over 4 million metric tons per year.

The majority of the wastepaper exported from the United States goes to "fiber-poor" countries. These countries have much less virgin fiber and therefore recycle greater quantities of paper. Countries that recycle over 50 percent of their paper include the Netherlands, Japan, Mexico, South Korea, Argentina, Hungary and Switzerland. A variety of problems are associated with paper recycling, such as collection, distribution, and wild cyclic swings in the market. However, with landfill sites at a premium and paper representing about 40 percent of municipal solid waste, it makes good sense in the long run to promote paper recycling, which reduces both landfill needs and the consumption of virgin timber (9).

Pulp is produced from sorted wastepaper (paper stock) by separating the bonded fibers in the recovered paper and paperboard through mechanical action. This is done in water in a hydrapulper, which is a tub equipped with a powerful propeller rotor and auxiliary equipment to separate rags, wire, and other coarse contaminants. During the repulping operation, sodium hydroxide loosens the ink, called de-inking. The coarse contaminants are first removed by screening and cleaning equipment; then the pulp is given an extra fiberizing treatment and finally subjected to fine screening and cleaning. For use in newsprint, tissue, fine and toweling grades, the de-inked pulp requires bleaching in single and multistage processes (9).

Environmental Protection

The manufacture of pulp and paper is a chemical process industry and produces air emissions, effluents, and solid and toxic wastes that are potential hazards. The paper industry uses large volumes of water as a fiber carrier and as a chemical solvent. An increasing volume of water is recycled, but makeup water is still required to cover losses. A bleached pulp and paper mill may use 100 cubic meters (26,400 gallons) of fresh water per metric ton of product and 50,000 cubic meter (13.2 million gallons) daily for a plant producing 500 metric tons of products. In addition to this aqueous effluent that the mill must clean up, it must also contend with polluted air and solid and toxic wastes. Pulp and paper mills are considered to be minor toxic waste offenders. In this connection, the paper industry has generally been in good compliance with governmental environmental regulations, although at considerable capital expense, which amounts to about 10 percent of the cost of the mill.

In the 1970s, procedures for removal of the fibers and clay from the paper mill effluents were incorporated through settling or clarification or primary effluent treatment. About the same time secondary effluent treatment (biochemical treatment) of the pulp mill effluent was necessary to remove pulping residuals. The purpose of this treatment is to reduce the biological oxygen demand (BOD) of the effluent, which, if untreated, reduces the oxygen content of the stream to a level incapable of supporting aquatic life. The most common method uses microorganisms that react with the wood sugars and other oxygen-consuming compounds in the spent liquors; this is called the activated-sludge method. The products of primary and secondary treatments are sludges.

Solid wastes represent the ultimate in mill residues and include the accumulated refuse of the mill and the sludges from primary and secondary effluent treatment. There is difficulty in removing water from the secondary sludge; the primary and secondary sludges are often mixed to aid in water removal, which is important if the sludge is to be incinerated for disposal. The sludges from pulp and paper mills are handled mostly as landfill, and sometimes, if not toxic, they are spread for agricultural purposes.

Most mill solids are slightly toxic, predominantly from chlorination compounds in the wash waters from bleaching. This toxicity can be reduced with lime pretreatment and biological treatment. Toxicity has been the main concern of governmental regulating bodies.

Two objectionable air emissions have characterized pulp mills for years: the sulfur dioxide of the sulfite pulping mill and the malodorous reduced sulfur compounds (TRS) (mercaptans and hydrogen sulfide) of the kraft mill. Still another less noxious air emission is the particulate matter from steam boilers. Coal-burning boilers also emit sulfur dioxide, as is well known.

Cellulose Derivatives

Although most wood pulp fibers are produced for papermaking as described in the previous section, a small percentage (3 percent) are produced as dissolving pulp for the production of other cellulose based commodities. As shown in Table 20.5, the yield from dissolving pulp processes is only 35 percent. The percentage is low because all the hemicelluloses, in addition to the lignin (and some low-molecular-weight cellulose), are removed in the pulping process to give an almost pure cellulose fiber pulp. This pulp is then the raw material for the chemical and textile industries (12, 13).

Fibers and Films

Rayon and cellophane are produced from dissolving pulps and cotton linters by modifying the cellulose with carbon disulfide in caustic solution to give a cellulose derivative, namely, cellulose xanthate. The cellulose xanthate is then soluble in dilute alkaline solution, and when dissolved, the pulp fiber structure is lost. The resulting viscous solution of cellulose xanthate is termed viscose. This viscose can be "spun" into fibers by extrusion of the solution through tiny-holed spinnerets or cast into films by forming a thin sheet of the viscose. The original cellulose is regenerated by contact of the viscose with an aqueous acid bath, which splits off the carbon disulfide to give regenerated rayon fibers or cellophane films. The first textile fibers were produced from cellulose and were termed "artificial silk."

Cellulose acetate is formed from dissolving pulp or cotton linters by reacting the fibers with acetic anhydride using sulfuric acid as a catalyst. The cellulose acetate is then soluble in organic solvents such as acetone and can also be spun into fibers and cast to films. The cellulose is not regenerated but remains as cellulose acetate. The "acetate" fibers are used for textile fabrics and cigarette filters. The films are used in photographic products and as excellent osmotic membranes (13).

Chemical Commodities

Cellulose nitrate is one of the oldest cellulose derivatives and today is most widely used as an explosive (gun cotton) and as an ingredient in "smokeless powder." Alfred Nobel, who bequeathed the Nobel prizes, combined gun cotton with nitroglycerin to form a jellylike substance (blasting jelly) that was more powerful than dynamite. Nitrocellulose is also used as a lacquer coating material.

Carboxymethylcellulose (CMC) is a large commercial-volume cellulose ether. The nontoxic nature of CMC makes it very useful in the food, pharmaceutical, and cosmetic industries. It is used as a sizing agent, an emulsion stabilizer, a paint thickener, an oil-well-drilling mud, and a superabsorbent material (in the fibrous form). Methylcellulose and ethylcellulose are also cellulose ethers, but with quite different properties. Ethylcellulose provides exceptionally durable films and is used where extreme stress is encountered, such as in bowling pin coatings. Other uses include paper coatings, lacquers, and adhesives. Hydroxyethylcellulose became a commercial product in the 1960s and is chiefly used as a component of latex paints (13).

Conversions of Wood to Energy, Fuels, and Chemicals

The net photosynthetic productivity (NPP) of the earth has been estimated at 140 X 10^9 metric tons of dry matter per year. Forests account for about 42 percent or 59 billion metric tons of the NPP, which is equivalent to more than the annual world consumption of fossil fuels. In the United States, the equivalent of 80 quads of energy is produced each year as total plant biomass; however, much of this is inaccessible, uneconomical to collect, or already utilized for agricultural crops or forest products. It has been estimated that there are approximately 200 quads of standing timber in the nation's forests today. Thus, if an attempt were made to have wood as the sole source of energy in the United States, the country would be totally depleted of this reserve in two years. Woody biomass will therefore never be a panacea to an energy crisis, but certainly a greater contribution to the overall energy diet can be supplied by this important resource.

Probably the most significant advantage of biomass is the renewability. The U.S. Department of Energy has estimated that the equivalent of about 8 quads of energy in the form of biomass is produced annually in the nation's forests, but roughly one-half or the equivalent of 4 quads is already harvested annually for lumber and paper products. Much of the forest that is not harvested is inaccessible or under harvesting restrictions. Thus, the major contribution from woody biomass will probably be in the form of more efficient use of residues and waste.

If all types of waste are included in the scenario of biomass utilization, including urban and agricultural wastes in addition to wood wastes, these wastes and residues represent close to 1 billion metric tons or the equivalent fuel value of approximately 15 percent of the total energy needs of the United States. Wood, in the form of logging and manufacturing residues, accounts for about 25 percent of this figure. In addition, roughly 40 percent of most municipal waste is composed of wastepaper, which represents the wood cellulose ultimately derived from the forest. Thus, a significant energy contribution could be made by efficient utilization of waste material. The use of wood as a primary source of industrial chemicals decreased dramatically in the 1940s when oil became the preferred raw material. The term *silvichemicals* is sometimes used to refer to wood-derived chemicals analogous to petrochemicals.

The use of wood for energy, fuels, and chemicals can be conveniently divided into four major categories: direct combustion, saccharification-fermentation (SF), thermal decomposition, and thermochemical liquefaction (9). Each of these methods is discussed in more detail in the following sections.

Direct Combustion

The concept of using wood as a source of energy through direct combustion dates back to the very beginning of human existence. As soon as early people learned to use fire, wood became the major source of energy. It is important to note that even now approximately one-half of all the wood harvested worldwide is used for fuel by direct combustion. Thus, direct combustion is probably the most important method for deriving energy from wood.

Wood has certain advantages over fossil fuels, the most important of which is that it is a renewable resource. In addition, it has a low ash content which is easily and usefully disposed of on land as mineral constituents essential for plant growth. The sulfur content of wood is low, usually less than 0.1 percent, so that air pollution from this source is negligible, although particulates may cause a serious problem. Generally, wood fuel is used close to where it is grown; thus the need for energy in long distance transport is reduced. The use of fossil fuels unlocks the carbon that has been stored in them for ages and increases the carbon dioxide content of the atmosphere. In contrast, wood fuel releases the same amount of carbon dioxide that the forest has recently fixed.

Wood does have disadvantages as a fuel. It is a bulky material, and in contrast to other fuels, it has a low heat of combustion. The gaseous and liquid fuels, from methane to petroleum have a higher potential heat content because they do not contain oxygen.

All wood species consist of essentially the same chemical compounds; therefore, the various woods differ little in heat content per pound. The differences noted in the fuel value of different woods when compared by volume are caused by differences in density. One cord of hickory, a dense commercial wood, for example, gives two times more heat than one cord of low-density species such as aspen or spruce. The heat values and densities of important woods grown in the United States are shown in Table 20.6 (4, 14). An exception to the density rule of thumb are coniferous woods, which contain energy-rich resin. These species can contain up to 12 percent more heat potential.

Green wood at 50 percent moisture content has only about one-half the fuel value of dry wood. The amount of energy released in a fire depends on the wood moisture content more than on any other factor. Moisture affects the energy release in two ways, by consuming heat for moisture evaporation, and by causing incomplete combustion (2).

Incomplete combustion has several other bad effects in addition to wasting fuel. Gases from burning wood contain formic and acetic acids; these acids, when condensed, corrode stovepipes. The corrosion can be so severe that the pipes may need to be replaced after only one year of operation. Other condensed vapors form creosote, a brown or black stenchy liquid that may leak out of stovepipe joints and cause unsightly stains. Prolonged exposure to heat converts the creosote to a flaky layer of carbon known as soot. Carbon particles in the fire effluents tend to aggregate and adhere to the inside surfaces of stoves, stovepipes, and chimney flues, augmenting the accumulation of soot. These deposits insulate and hinder flow of gases; with unusually hot fires, these deposits can ignite as chimney fires, which can crack the chimney and ignite the house. For this reason, chimneys should be cleaned periodically depending on the amount of use and completeness of combustion. Hot, oxygen-rich fires reduce chimney deposits, but hot effluents also carry heat out of the chimney (2).

Wood-burning units have evolved over centuries of use in homes around the world (2). Many old-time stoves in Europe relied on immense heat-storing masses of fireclay, firebrick, and other masonry. Hot, oxygen-rich fires facilitated complete combustion, and the fire effluents passed through a long labyrinth of flues to deliver the heat to the solid mass. The Russian-Ukrainian type of stove, still in use today in rural areas, was constructed with a low cooking section containing the combustion chamber, and a much larger (6 to 8 feet) flue section with an immense, flat top surface, which provided warm sleeping quarters for the whole family.

The German Kachelofen or tile stove was a showpiece in the living room; many small tile stoves still heat rooms of homes, particularly farmhouses throughout Europe. All stoves store some heat, but modern types lack the storage capacity and versatility of the old brick monsters.

Many Americans have become more interested in burning wood in their homes to reduce heating costs. Household wood burning varies considerably with the region of the country; roughly 50 percent of the residents of Maine, Vermont, and Oregon burn more than one-third of a cord of wood annually, but fewer than 10 percent of the residents of most southern states burn this much wood.

Many hundreds of different types of stoves, furnaces, fireplaces, and accessories for heating with wood have appeared on the market as a result of the increased interest in wood burning. A few of these are discussed further in the following paragraphs.

Fireplaces The open built-in fireplace is the least efficient heating device. Warm air bypasses the fire, as shown in Figure 20.20a, and escapes through the chimney. This draft pulls equal amounts of cold outside air through joints at doors and other openings into the house so that, in very cold weather, the use of the fireplace may actually cool rather than heat the house. A fireplace door obstructs the bypass of the air and, with the help of a baffle between the grate and door (Figure 20.20b), can eliminate the bypass of air so that the fireplace will heat more efficiently. Whatever the design, watching and hearing a crackling fire has a gratification not to be matched, and people have enjoyed it since the dawn of humanity.

Stoves and Furnaces In stoves and furnaces, the air takes various paths through the wood fuel. In all these variations, the intent is to have the air pass through the burning wood pile to promote combustion, heat the air, and then pass to the outlet at the top or back of the stove. There is no intrinsic

Table 20.6 Densities and Heat Values at 12% Moisture Content[a] of Important Wood Grown in the United States

Tree Name	Density(g/cm^3)	Heat Value[b] (million kj/m^3)	Heat Value[b] (million Btu/cord[c])
Hardwoods			
Live oak	0.99	17.60	40.32
Shagbark hickory	0.81	14.40	32.99
White oak	0.76	13.60	31.16
Honeylocust	0.72	12.80	29.32
American beech	0.72	12.80	29.32
Sugar maple	0.71	12.60	28.86
Northern red oak	0.71	12.60	28.86
Yellow birch	0.69	12.40	28.40
White ash	0.67	12.00	27.49
Black walnut	0.62	11.00	25.20
Sweetgum	0.58	10.40	23.82
Black cherry	0.56	10.00	22.91
American elm	0.56	10.00	22.91
Southern magnolia	0.56	10.00	22.91
Black tupelo	0.56	10.00	22.91
Sycamore	0.55	9.80	22.50
Sassafras	0.52	9.20	21.08
Yellow poplar	0.47	8.40	19.24
Red alder	0.46	8.20	18.79
Eastern cottonwood	0.45	8.00	18.33
Quaking aspen	0.43	7.60	17.41
American basswood	0.41	7.40	16.95
Softwoods			
Longleaf pine	0.66	12.63	28.92
Western larch	0.58	11.13	25.49
Loblolly pine	0.57	10.92	25.00
Shortleaf pine	0.57	10.92	25.00
Douglas fir	0.54	10.27	23.53
Bald cypress	0.52	9.85	22.55
Western hemlock	0.50	9.00	20.62
Ponderosa pine	0.45	8.56	19.61
White fir	0.44	7.80	17.87
Redwood	0.43	7.60	17.41
Eastern white pine	0.39	7.49	17.16
Engelmann spruce	0.39	7.49	17.16
Western red cedar	0.36	6.40	14.66

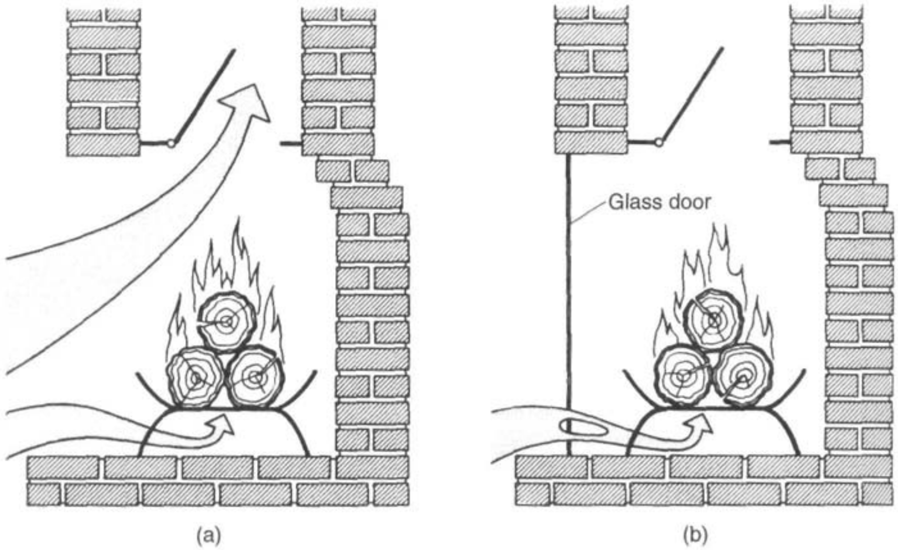
Source: Densities from reference 4, heat values from P. J. Ince, U.S.D.A. For. Serv., Gen. Tech. Rept. FPL 29, Forest Products Laboratory, Madison, Wis., 1979.

[a] Moisture content based on weight of ovendry wood.

[b] Heat values include heat in fire effluents. Calculated on the basis of British thermal units (Btu) per pound of ovendry wood, 9200 Btu for resinous-wood species.

[c] One cord equals 128 cubic feet or 3.6246 cubic meters; it is assumed that the pile is two-thirds wood and one-third air (between the pieces); hence, one cord contains 2.4164 cubic meters of solid wood.

Figure 20.20 Movement of air (a) through an open built-in fireplace and (b) through a fireplace with a door to obstruct bypass of air.



reason why one type is better than another as long as the air passes through the burning wood in an efficient manner. Hot air streams naturally upward, but the air velocity depends mainly on the chimney draft and can be regulated with vents and dampers. Modern "airtight" stoves provide the best air control and thus more efficient heating.

A completely different heating appliance, the stick wood furnace, was developed at the University of Maine (Figure 20.21). In this stove, long sticks or logs stand in a tight jacket. Air enters only at the bottom where burning of the sticks takes place. To confine the burning to just the bottom end of the stove, water cools the jacket and can then be used for hot water in the home. The sticks burn slowly at the bottom and are self-feeding because of their own weight. Theoretically, the stick wood furnace can be used to burn whole-tree stems.

Saccharification-Fermentation

The saccharification-fermentation (SF) method is based on the breakdown or hydrolysis of the polysaccharides in wood to the constituent monomeric sugars. The six-carbon or hexose sugars (glucose, galactose, and mannose) are then fermentable to ethyl alcohol (ethanol or grain alcohol, C_2H_5OH) by yeast fermentation in the same way that ethanol is produced from grains or fruits. Obviously the concept is not a new one; the polysaccharide character of wood has been known for over 100 years.

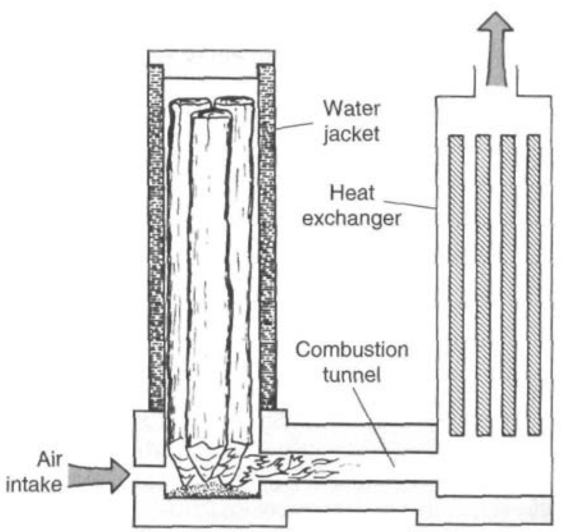


Figure 20.21 A stick wood furnace.

The limitations to the use of wood for ethanol production have been primarily the difficulty in separating and hydrolyzing the crystalline cellulose component in wood. Both acids and enzymes can be used to hydrolyze the cellulose to glucose, but only acids have been utilized commercially for wood hydrolysis to sugars, and only in foreign countries.

Interest in producing alcohols from wood was revitalized by the dramatic increase in the price of petroleum in the 1970s and the push to decrease oil imports by substituting gasohol, which is one part alcohol in nine parts gasoline, for 100 percent gasoline at gas pumps. Both ethanol and methanol can be used in gasohol blends. Because of the high oil prices, the country of Brazil took the dramatic step of shifting to much greater use of fuel alcohol. Most of their sugars are produced from sugarcane. One wood hydrolysis plant was constructed, but it was uneconomical to operate and was shut down. However, their experience demonstrates that fermentation ethanol (95 percent ethanol and 5 percent water) is a perfectly satisfactory motor fuel. At least 500,000 Brazilian automobiles operated on undried alcohol continuously, and most of the rest of their fleet operated on this fuel on weekends when only alcohol was available at the gas stations (9). A number of methods can be used for production of ethanol from wood.

Thermal Decomposition

A number of terms are used interchangeably for thermal decomposition of wood and generally refer to similar processing methods: carbonization, pyrolysis, gasification, wood distillation, destructive distillation, and dry distillation. All result in the thermal breakdown of the wood polymers to smaller molecules in the form of char, tar (a condensible liquid), and gaseous products. A liquid fuel derivable from wood by this method is methyl alcohol (methanol or wood alcohol, CH_3OH). A wide variety of other chemicals are also derivable from wood by thermal decomposition, a method with a long history of applications.

During World War II in Germany, automobiles were fueled by the gases produced from thermal decomposition of wood, and research is active today on more efficient gasification of wood. Destructive distillation has been used throughout most of recorded history to obtain turpentine from pinewood; this is discussed further in the section on wood extractives. The range of chemicals derivable from thermal decomposition of wood is summarized in Figure 20.22.

Charcoal and Other Chemicals Production of charcoal and tars by destructive distillation is the oldest of all chemical wood-processing methods. Charcoal was probably first discovered when the black material left over from a previous fire burned with intense heat and little smoke and flame. For centuries, charcoal has been used in braziers for heating purposes. Destructive distillation of hardwoods has been performed seeking charcoal as the desired product, with volatiles as byproducts; for softwoods (pines), volatiles were the principal products (naval stores, discussed later), with charcoal considered a byproduct.

Basic techniques for producing charcoal have not changed over the years, although the equipment has. Charcoal is produced when wood is burned under conditions in which the supply of oxygen is severely limited (15). Carbonization is a term that aptly describes the thermal decomposition of wood for this application. Decomposition of carbon compounds takes place as the temperature rises, leading to a solid residue that is richer in carbon than the original material. Wood has a carbon content of about 50 percent, whereas charcoal of a quality suitable for general market acceptance can be analyzed as follows: fixed carbon, 74-81 percent; volatiles, 18-23 percent; moisture, 2-4 percent; ash, 1-4 percent. Charcoal with a volatiles content over 24 percent will cause smoking and is undesirable for recreational uses.

Thermochemical Liquefaction

Although a reasonable amount of research effort has been expended on thermochemical liquefaction of wood, extensive commercialization of this process is not anticipated in the near future. The

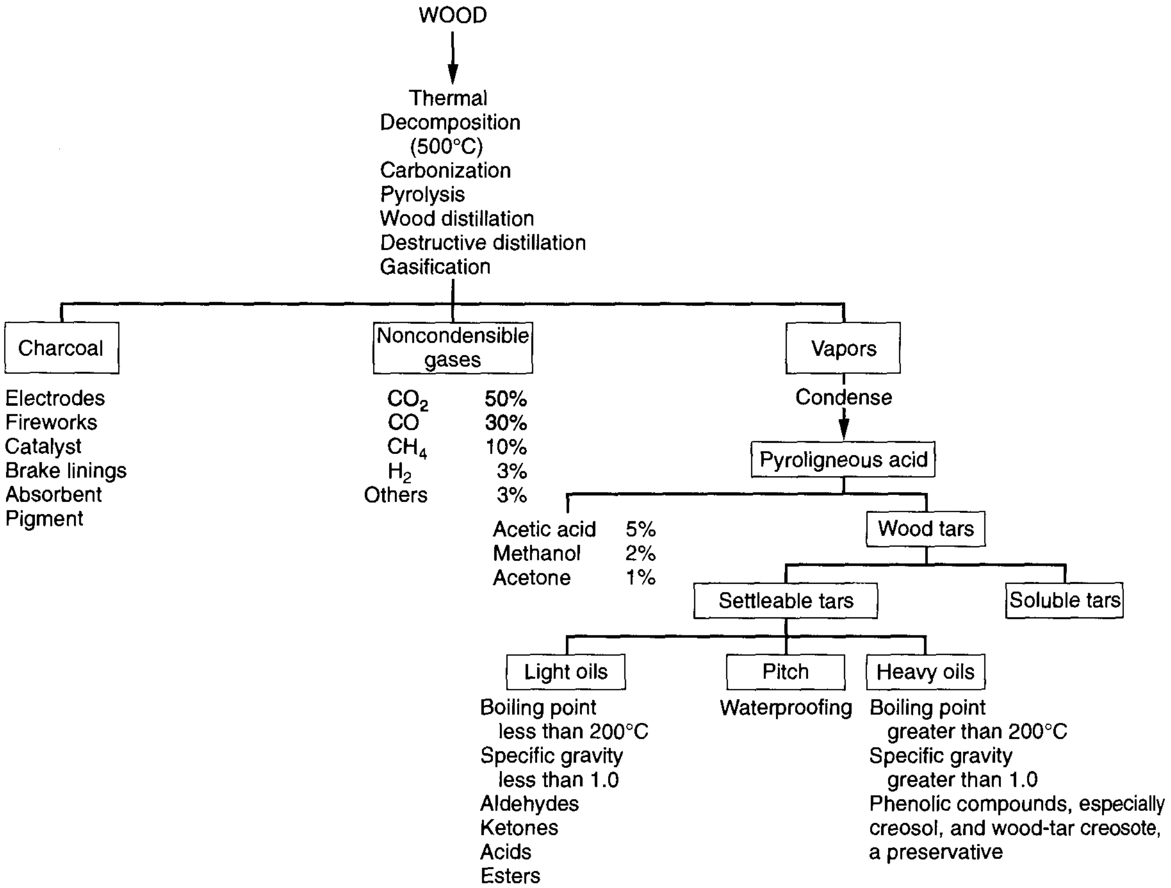


Figure 20.22 Products obtained from the thermal decomposition of wood.

basis of the method is a high-pressure and high-temperature treatment of wood chips in the presence of hydrogen gas or syngas to produce an oil instead of a gas. The low-grade oil produced could potentially be substituted for some present petroleum uses.

Wood Extractives

All species of wood and other plants contain small (mostly) to large quantities of substances that are not constituents of the cell wall, as pointed out previously. The entire class is called extraneous components. Extractives are the largest group by far of this class. The extractives embrace a very large number of individual compounds that often influence the physical properties of wood and play an important role in its utilization. Colored and volatile constituents provide visual and olfactory aesthetic values. Certain phenolic compounds lend resistance to fungal and insect attack with resulting durability, and silica imparts resistance to the wood-destroying marine borers (16).

Extractives can also have a detrimental effect on the use of wood. Alkaloids and some other physiologically active materials may present health hazards. Certain phenols present in pine heartwood inhibit the calcium-based sulfite pulping process and cause pitch problems. The loss of water absorbency properties of wood pulps can also result from extractives. Extractives from cedarwood and the woods of a number of other species can cause severe corrosion problems in the pulping operation (16). A wide variety of extractives are utilized commercially, as will be described.

Two broad classes of extractives occur in wood 1) those soluble in organic solvents, such as wood resins including turpentine, rosin, fat, and fatty acids; and 2) those soluble in water, mostly polyphenolic material including tannins and lignans and the polysaccharide arabinogalactan.

Extractives Soluble in Organic Solvents

The largest aggregate volume and value of industrial extractives are those derived from pinewoods. These materials, which include turpentine, rosin, and fatty acids, are also often referred to as naval stores. This term derives from the use of pitch and tars from pine extractives as caulking and waterproofing agents for wooden ships in early American history. The term naval stores has remained in use and now mainly refers to the turpentine and rosin derived from pine trees.

There are three sources of naval stores: *gum, wood,* and *sulfate. Gum naval stores* are produced by wounding pine trees and collecting the oleoresin. The oleoresin is a sticky substance composed of an essential oil, turpentine, and a resin, rosin. Since turpentine is a low-boiling, volatile material, the two products can be separated by a distillation process (9, 17).

In this country, the gum naval stores industry is based on two Southern pine species, slash and longleaf, and is centered in the state of Georgia. Though very important in the past, this method today accounts for only a few percent of U.S. rosin and turpentine production. Typically the oleoresin is collected in containers by cutting grooves in the tree so that the wound opens the resin ducts (Figure 20.23). Various means have been used to stimulate oleoresin production such as repeated wounding and spraying with sulfuric acid or the herbicide paraquat. The so-called lightwood, high-oleoresin-content wood, then contains up to 40 percent resin (17).

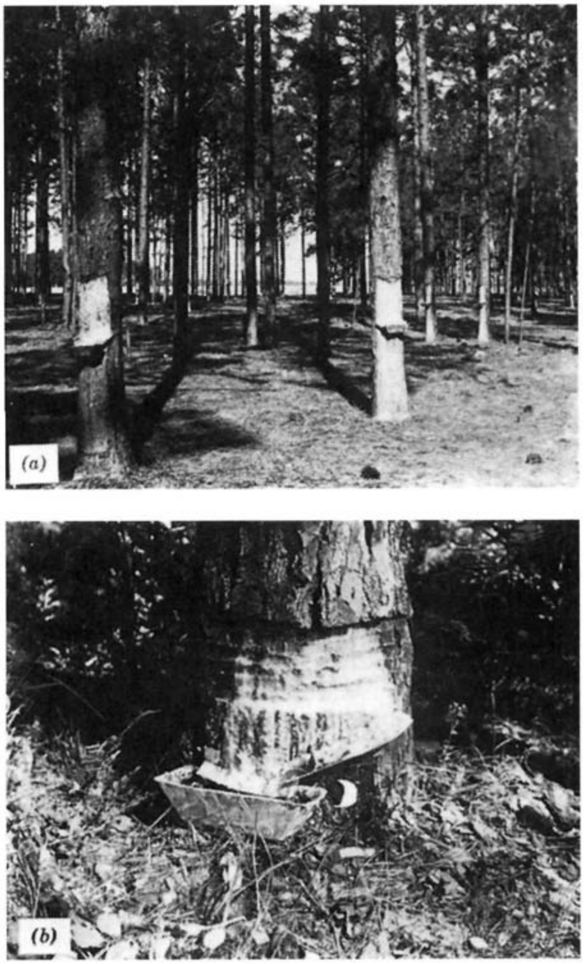


Figure 20.23 Scarification of pine trees for collections of oleoresin. (a) View of stand, (b) Close-up of tree wound. (Courtesy of University of Georgia, College of Agriculture.)

Wood naval stores are obtained by organic-solvent extraction of chipped or shredded old pine stumps. The old pine stumps have lost most of the outer sapwood through decay and are made up primarily of the oleoresin-rich heartwood where the extractives are mainly deposited. Turpentine and crude resin fractions are obtained by this method.

Sidebar 20.2

Cholesterol-Lowering Margarine

Benecol margarines and spreads are based on stanol esters, a class of sterols that are obtained from waste-pulping liquors from kraft pulping of pine species. Recent studies have shown that by regular use of these products, the so-called "bad cholesterol" can be reduced by up to 14 percent. Raisio, a Finnish company, built plants in Finland and Charleston, S.C., to make the ester from sterols extracted from tall oil pitch supplied by such firms as Arizona Chemicals. The Raisio company has also embarked on a $50 million project with a tall oil refiner in Chile to build the world's largest sterol extraction plant.

The product has been a large commercial success in Finland; however, the American market has been much more subdued. The Food and Drug Administration has allowed labeling of Benecol foods with a statement that they have been proven to lower cholesterol and may lower the risk of heart disease, which may increase sales. This is an excellent example of how continued research on plant and waste materials can lead to new important medicinal products in the market.

Sulfate naval stores are derived as byproduct streams from the kraft pulping process. As pine chips are treated in the digester to produce pulp, the volatilized gases are released and condensed to yield a sulfate turpentine.

Turpentine was used as a solvent in its early history, particularly as a paint solvent. Today this use is small, and turpentine is used for the most part as a feedstock for manufacture of many products, including synthetic pine oil, resins, insecticides, and a variety of flavor and fragrance chemicals. Flavors and fragrances derived from turpentine include lemon, lime, spearmint, peppermint, menthol, and lilac. The synthetic pine oil is further converted to terpin hydrate, a cough expectorant. Obviously, turpentine has become a valuable byproduct of the forest and pulp-and-paper industry (17).

Rosins are usually used in a form modified by further chemical reaction. Rosin found considerable use at one time in laundry soap (38 percent in 1938), but this use is negligible today. Rosin soaps are at present important as emulsifying agents in synthetic rubber and chemical manufacture and for paper sizing. The sizing is used to reduce water absorptivity of paper. Rosin is also used in surface coatings, printing oils, and adhesives. Typically pressure-sensitive tapes such as "scotch" tape contain considerable quantities of rosin (17).

Water-Soluble Extractives

The most important group of water-extractable compounds are the polyphenolics. These substances are generally extractable with water at 80-120°C from the heartwood and bark of many trees. Of the polyphenolics, only the tannins have shown commercial value. The traditional source of tannins in the United States was chestnut wood and bark, but this source was removed when the chestnut blight of the 1930s devastated the chestnut tree in North America. The South American tree, quebracho, is now the major source of tannins. Acacia bark extracts, called wattle or mimosa, are also an important source of tannins, and together with quebracho extractives, amount to a production of 250,000 tons per year (5, 18).

The primary use of tannins is for manufacture of leather from hides. The natural tanning agents continue to dominate the market, even though synthetic tanning agents are available. The extractives from each different wood species provide their own unique color and properties to the leather.

Wattle tannins have also been successfully substituted for phenol in phenol-formaldehyde adhesives in South Africa. The phenol-formaldehyde adhesives are used in the production of plywood, particleboard, and laminated beams.

Biotechnology Chemicals

As with pulping and bleaching, biotechnology could also have a considerable impact on the production of chemicals from wood and other forms of plant biomass. The effects of biotechnology will probably first be noticed in areas of enzymatic hydrolysis of polysaccharides and fermentation technology.

It should be possible to improve the efficiency of the cellulose enzyme complex for hydrolyzing cellulose to glucose. The enzyme complex contains decrystallizing and hydrolysis enzymes that work together to convert cellulose to glucose. Isolation of the specific enzymes and genetic engineering could provide a more efficient complex.

As discussed earlier in this chapter, enzymes are also the basis for yeast conversion of hexose (six carbon) sugars, such as glucose and mannose, to ethanol. These enzymes could also be genetically engineered to improve the efficiency of alcohol production, and several biotechnology firms are exploring this possibility.

Many other chemicals can be obtained from both yeast and bacteria fermentation of sugars and pulp mill effluents. Potential fermentation products from wood hydrolysates include acetone, organic acids (acetic, butyric, lactic), glycerol, butanediol, and others (18).

Concluding Statement

The unique properties and the renewable nature of wood make it a very desirable material for a great variety of uses. Even with the advent of new polymers, plastics, and high technology materials, wood products are still pervasive in our life. The ready availability and workable properties of wood make it valuable for building materials and furniture. Mechanical and chemical disintegration allows us to convert wood into a myriad of paper products so important to communication and packaging. Finally, a wide variety of chemical commodities are derivable from wood from cellulose superabsorbents to flavors, fragrances and fuel alcohols. Truly, wood is one of nature's most attractive and, useful products.

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CHAPTER 21

Economics and the Management of Forests for Wood and Amenity Values

JOSEPH BUONGIORNO AND
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Foresters, be they practitioners or students, often accept only reluctantly that economics has any role to play in their profession. They chose this career for their love of the woods. The counting of money seems foreign, indeed contrary, to the powerfully romantic attraction of the wild forest. Yet, the current forest endowment of nations is to a large extent the result of past economic forces. Among them, the industrial revolution of Europe and the settlement of America's New England are economic watersheds that have changed forever the nature and extent of forests. Presently, the economic development of Latin America and Africa are largely deciding how much forest, if any, will remain in the Amazon and the Congo basin.

Furthermore, economics deals with much more than money, and contrary to common opinion, it does have something to say about value. In the words of Ludwig Von Mises: "Everybody thinks of economics whether he is aware of it or not. In joining a political party and in casting his ballot, the citizen implicitly takes a stand upon essential economic theories" (1). More specifically, Nobel prize economist Paul A. Samuelson defines economics as "the study of how people and society end up choosing, with or without the use of money, to employ scarce productive resources that could have alternative uses, to produce various commodities and distribute them for consumption, now or in the future, among various persons and groups in society. It analyzes the costs and benefits of improving patterns of resource allocation" (2).

In this spirit, this chapter considers the wide array of goods and services that are provided directly or indirectly by forests. They include wood products that we use in our daily lives: lumber, plywood, particleboard, and other panels for houses and furniture; paper for newsprint, books, and stationery, fuelwood for heating, and many chemical derivatives. Services from forests include their protective role against erosion and avalanches in mountain areas, the aesthetic and other pleasures that one derives from hiking through them, and their role as biodiversity preserves and carbon sinks. The purpose of this chapter is to review briefly how economic reasoning can help in the wise management of forest resources.

Economics of Timber Production

Because wood has been throughout human history an essential element of civilization, for fuel, construction, transport, and defense (3), the art of forest management has long been organized in a set of general principles founded on the scientific method. Over time, this has led to elaborate rules to optimize forest harvests in sustainable fashion. In the process, some foresters realized early on that economic principles were more important to forestry than to perhaps any other production activity. Few other ventures require as much time between initiation of production and sale of the product. Instead, much of the rest of the economy evolves in a groping process with inefficient firms losing to more efficient firms. In relatively short order, firms know whether they have a positive cash flow given the prices consumers are willing to pay. The firms either learn to operate efficiently enough to stay in business or they quickly disappear. They learn by internally developing insights or by using the example of more successful firms. Although forestry enterprises do also partake of this economic selection process, the results are generally slower, and simply doing the same as others is not always the best. Thus, for forest managers, well-considered economic reasoning is of paramount importance.

This importance has been long recognized, and solutions of some forest economic problems predate the discovery of similar principles in general economics. The most famous example is probably Martin Faustmann's rigorous derivation of the value of forestland (4). General economists largely missed Faustmann's insight, and it was not until the 1930s that, extending beyond the work of Irving Fisher and others, the general theory of investment was formulated as soundly as Faustmann's forestry formula. Interestingly, Fisher, though possibly "the greatest single economic writer on interest and capital," gave a poor solution to Faustmann's problem (5).

The Value of Forestland and Faustmann's Formula

In seeking the value of forestland, Faustmann recognized that it must be equal to the value of the net returns that one could expect from that land, if it were used in forestry. However, much of these returns would occur only very far into the future, so that they would be worth less now; that is, they must be discounted at a suitable interest rate. Thus, the land value had to be equal to the net present value of the full future stream of costs incurred and benefits derived from the forest. This insight seems ordinary now with the common use of benefit-cost analysis to evaluate projects and policies, but it was remarkable at the time. It defines unambiguously the general principle to follow in choosing between forest management alternatives and different land uses: maximize the land expectation value.

By simplifying the forest management problem to only the value of wood harvested from a stand of trees, Faustmann showed that the economic optimal rotation is less than the rotation that produces the maximum average annual biological yield. This conclusion seems to contradict the intuition that higher average annual production must also mean higher income. Faustmann's insight was to recognize that, besides the magnitude of the harvests over the rotation, their timing also matters.

Cutting and selling early gives income to either consume or to reinvest in forestry or alternative investments. The interest rate reflects this opportunity cost of postponing a harvest. One elegant aspect of Faustmann's method is that it recognizes the opportunity to plant a new stand of trees earlier when the rotation age is shortened. By summing the costs and revenues of an infinite series of replanted stands, Faustmann accounts for the opportunity cost of these future stands. Alternatively, he could have maximized the present discounted value of a single rotation, and included the land rental value of the bare land left at the end of the rotation. However, the calculation of the appropriate market land rental rate is fraught with difficulties. It is one of the notable advantages of Faustmann's approach that the land rental value is not needed, but that instead it results directly from his formula.

In its simplest form, the Faustmann model can be symbolized as in Figure 21.1. We begin at time 0, with a piece of bare land, we plant trees and let them grow for R years, the rotation. All the trees are harvested at rotation age. Immediately after the harvest, we establish a new plantation, identical to that of time 0. The trees then grow exactly as in the first rotation, and they are harvested at the same rotation age. This sequence is assumed to continue indefinitely.

In this simple model, let V_R be the volume of timber per unit area at age R, c the reforestation cost per unit area, p the price of timber per unit of volume net of harvesting cost, and i the interest rate per year. The volume V_R depends only on the age of the trees, and the parameters R, c, p, and i are assumed to be constant over time, for example, equal to their current value.

It can be shown that the discounted value of all future returns, net of all costs is:

$$LEV = \frac{pV_R - c}{(1+i)^R - 1} - c \qquad (1)$$

where the first term on the right is the present value of all future harvests net of reforestation cost $(pV_R - c)$ recurring every R years, indefinitely, and the second term is the cost, c, of establishing the initial plantation, at time 0. The result is the *land expectation value, LEV;* that is, value of bare land used in this kind of forestry. This result, is, in a very simplified form, Faustmann's great finding, a fundamental contribution to forestry economics, and also a precursory insight into the general theory of investments (5). Faustmann also gave an extension of formula 1 to calculate the value of a stand with trees younger than the best rotation.

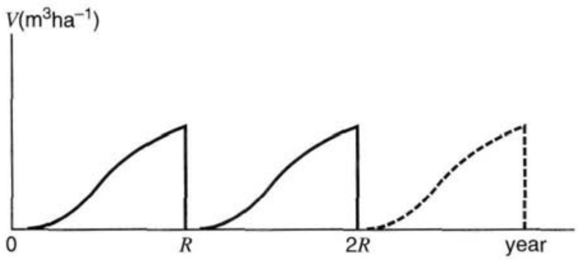

Figure 21.1 Stand growth and harvest in simple Faustmann model; V is the stand volume, per unit area, and R is the rotation age.

Economic Comparison of Alternative Land Uses

Equation 1 has numerous applications, to compare different land uses, or to compare different forest management strategies. For that purpose, it usually includes much more detail such as density in plantations, commercial and pre-commercial thinning, and so forth. As an illustration, equation 1 can be used to find the best economic rotation, R; that is, the rotation that maximizes the land value, *LEV*. This economic rotation can be determined with simple calculations in a spreadsheet, along the lines illustrated in Table 21.1.

In Table 21.1, the first column is tree age, from 20 to 100 years. The second column shows the volume per unit area. It is largest for 100-year-old trees. The third and fourth column show the gross and net return, respectively, from harvesting the trees at different ages. The fifth column shows the present value of \$1 paid every R year, indefinitely. The interest rate is 2.5% yr^{-1}. For example, the present value of a perpetual series of \$1 paid every 20 years is \$1.57. However, if the same \$1 is paid every 40 years, the present value is only \$0.59.

The land expectation value, in column 6 is the product of columns 4 and 5 minus c. It is negative for R = 20 years. Thus, if the trees were cut when they were 20 years old, the present value of the returns would be less than that of the present value of the costs, so that this would be a bad policy indeed. A rotation of 60 years is best from a purely financial viewpoint because for that age, the land expectation value is highest, at \$1387 ha^{-1}. Note that this is not the age at which the trees are largest or

Table 21.1 The best economic rotation leads to the highest land expectation value, *LEV;* it is shorter than the best biological rotation.

(1)	(2)	(3)	(4)	(5)	(6) = (4) × (5) − c	(7)
R (yr)	V_R (m^3ha^{-1})	pV_R ($\$ha^{-1}$)	$pV_R - c$ ($\$ha^{-1}$)	$\frac{1}{(1+i)^R - 1}$	LEV ($\$ha^{-1}$)	V_R/R ($m^3ha^{-1}yr^{-1}$)
20	29	377	−117	1.57	−677	1.5
40	274	3,562	3,068	0.59	1,327	6.9
60*	530	6,890	6,396	0.29	1,387	8.8
80**	728	9,464	8,970	0.16	951	9.1
100	868	11,284	10,790	0.09	504	8.7

p=13 \$/m^3, c=\$494/ha, i=2.5%/yr, *=economic rotation, **=biological rotation

most valuable, nor is it the age of highest physical productivity. As shown in the last column, the highest physical productivity, in m^3 ha^{-1} yr^{-1} occurs at age 80. Indeed, the economic rotation age is always shorter than the biological rotation age set by physical productivity alone. Tis is because financially, \$1 next year is worth only 1/(1+i) now.

The land expectation value obtained by Faustmann's formula, \$1,387 ha^{-1} in this example, is the highest possible return from land used in this kind of silviculture. It is, therefore, the price a buyer would pay for this kind of land, and it is also the price at which an owner would be willing to sell. This land expectation value can then be compared with the land expectation value for alternative land uses (obtained with the equivalent of Faustmann's formula, regardless of the land use). A necessary condition for sustainable forestry in a free market economy is that the land expectation value obtained with a crop of trees be at least as large as the highest land expectation value obtainable by other land uses, such as agriculture, cattle grazing, or urban development. It is because the land expectation value for forestry is much lower than for agriculture or ranching that large areas of the tropical forests are currently being converted to those other uses.

Faustmann extended his approach to compute the value of immature forest stands, that is, stands younger than rotation age. The method has also been generalized to the case of uneven-aged or selection forests, forests where some trees are always left standing. In such a stand, the land expectation value is equal to the net present value of future returns minus the value of the remaining trees. Again, the sequence of harvests that leads to the greatest land value (i.e., the greatest return to the fixed input) is best, from a purely economic viewpoint. Faustmann's formula can also be generalized to include benefits in addition to harvested wood. The difficulty, of course, is in determining this nontimber value of forests, a question to which we shall return, below. Another difficulty not addressed here, lies in choosing a proper interest rate (6, 7).

Dealing with Risk

Risk of natural catastrophe and other uncertainties are ignored in the simplifying assumptions of the Faustmann analysis, but dealing with biological and economic risk and uncertainty are important in practical forest economics (8). The simplest way to handle risk is to increase the interest rate, i, in equation (1) when the risk is high, and to lower it otherwise. This is essentially what banks do when they lend money. They protect themselves against possible losses by charging higher interest for loans in risky ventures. In forestry, other things being equal, a higher interest rate will lead to a shorter economic rotation. This is consistent with the intuition that would suggest to cut trees earlier if there is a definite risk of a natural catastrophe, such as tornadoes or fires.

The problem with handling risk by changing the interest rate is that it is hard to know by how much to change the rate. For that reason, other approaches use the same interest rate, regardless of risk level, but recognize risk explicitly in the production function, that is, in the second column of Table 21.1, and in the price level, p. One approach, called simulation, consists in calculating *LEV many* times, each time with a different production function or price, in a pattern similar to what might happen in reality. The economic rotation is then the one that gives the highest *LEV* on average, or the one that insures the lowest variation in *LEV*, and thus the lowest probability of a major loss. Another approach is the Markov decision process model (MDP). It describes changes in the forest stand and other variables (especially prices) with a table of probabilities: each being the probability of a future stand and market state given the current state. Hool (9) first proposed such a model for even-aged forests, but the first operational application was Lembersky and Johnson's work with Douglas fir plantations (10). Other applications of MDPs to forestry have shown that they are adaptable to uneven-aged forests. With them it is possible to investigate management strategies with economic and ecological criteria as objective functions or constraints, while taking full account of risk (11).

Economics of Forest Product Markets

Key to the evaluation of the economics of timber production with Faustmann's formula and its derivatives is a correct assessment of interest rates, prices, and costs. In particular, future prices depend on the demand and supply conditions in the wood products markets. Here again, economics gives foresters useful tools to better understand what causes prices to change, and help predict their future direction, if not their exact level.

Demand and Supply

The simplest abstraction, or model, of a market consists of two equations: one representing demand, the other supply. For economists, demand is a relation, not a quantity. Figure 21.2 shows such a relation. Assume that it represents the demand for timber in the United States. On the horizontal axis is the quantity of timber consumed, Q_d (m^{3}yr^{-1}); on the vertical axis is the price of timber, P (\$nr^3). A downward-sloping line, such as D, represents the demand for timber. It shows that other things being equal, the higher the price, the lower the consumption. Of the two demand lines in Figure 21.2, the one farther from the origin, D_2, corresponds to the higher demand, since it leads to higher consumption at a given price. For example, in the United States, much lumber goes into houses. Therefore, as the number of houses built increases, the demand for lumber increases, and the demand line in Figure 21.2 shifts to the right. Another way to represent the United States demand for timber is with an equation:

$$Q_d = a - bP + cH \tag{2}$$

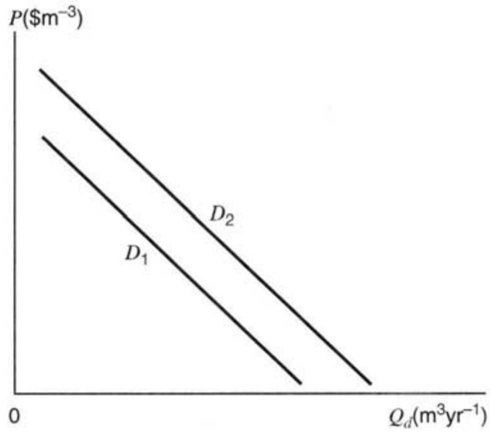

Figure 21.2 Every point on a demand line represents the quantity demanded at a given price. The lines slope downward because demand decreases as price increases. Lines that are farther from the origin correspond to higher demand.

where P stands for the price of timber, and //stands for the number of houses started in a given year, and a, b, c are parameters that can be estimated with statistical methods. The equation shows that demand for lumber is a derived demand. We do not consume lumber directly like food, but instead we use it to build houses. Thus, the demand for lumber and most of the other wood products derives from the demand for housing.

Like demand, the term "supply" for economists also means a relation rather than a quantity. For example, Figure 21.3 symbolizes the supply of timber in the United States. The private supply is an upward sloping line, S_1, indicating that as the price increases, private producers have an incentive to produce more timber. However, a good part of the timber is produced in the United States by government from federal and state forests. Government supply is set by policy and is usually independent of price. In Figure 21.3, the distance Q_g represents government supply.

We can express the total supply with the following equation:

$$Q_s=dP-ei+Q_g \qquad (3)$$

where the positive coefficient d means that private timber production increases as price increases. Instead, the negative coefficient $-e$ implies that private supply decreases as i, the interest rate decreases. Both of those facts derive from the Faustmann's formula 1, which shows that at a higher price, timber production becomes more profitable (*LEV* increases), while at a higher interest rate, timber production becomes less profitable {*LEV* decreases). The cumulative effect of all those changes in each private property leads to the aggregate national supply response symbolized by equation 3. Q_g is the government supply, independent of interest rate or price.

Market Equilibrium and Price

By overlapping Figures 21.2 and 21.3, one gets a picture of a market equilibrium, as in Figure 21.4. At the intersection of the demand and supply lines, the quantity of timber demanded in the United States is just equal to the quantity supplied, that is, $Q_d = Q_s = Q^*$, and the price paid by demanders of

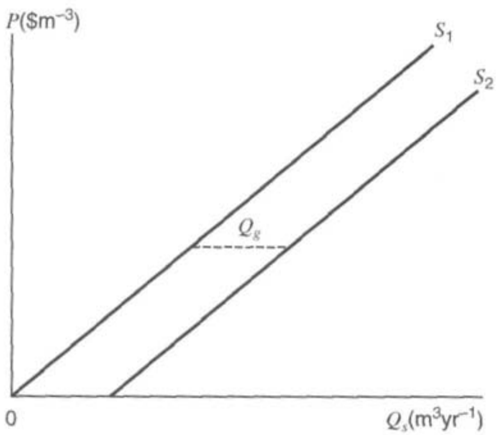

Figure 21.3 Every point on a supply line represents the quantity of timber supplied at a given price. The lines slope upward because production rises as price increases. Lines that are farther right correspond to higher supply.

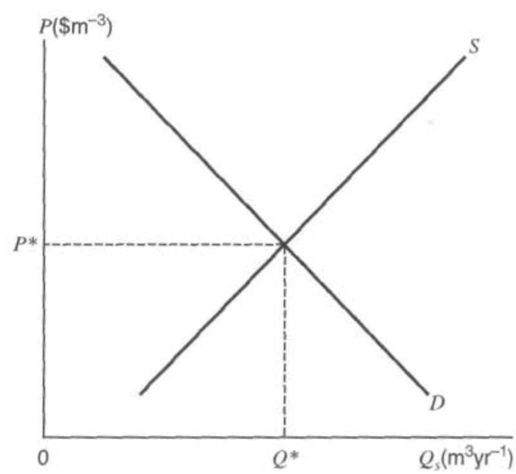

Figure 21.4 The market for timber is in equilibrium when demand is equal to supply. This is the quantity Q^* where the supply and demand lines intersect. A single equilibrium price, P^* corresponds to the equilibrium quantity.

timber is just equal to the price received by suppliers, P^*. We say that the market is in equilibrium.

The equilibrium can also be computed by solving the demand equation 2 simultaneously with the supply equation 3, under the condition that quantity demanded be equal to quantity supplied. Since, at equilibrium, $Q_s = Q_d$, we get:

$$dP - ei + Q_g = a - bP + cH$$

which gives the equilibrium price:

$$P^* = f + hi - kQ_g + mH \quad (4)$$

And, by substituting the equilibrium price in the demand equation 2, we get the equilibrium quantity:

$$Q^* = u - vi + wQ_g + zH \quad (5)$$

The parameters in equations 4 and 5 are defined completely by the parameters of equations 3 and 4. The price equation 4 shows that the price of timber in the United States increases with the interest rate and the number of houses started, while it decreases with the amount of timber produced from public forests. The quantity equation 5 shows that the quantity of timber consumed (and produced) decreases with the interest rate, and increases with public timber production, and it also increases with the number of housing starts.

Forecasting and Policy Analysis

Forest economists estimate the parameters in demand-and-supply equations like 2 and 3 by statistical methods with regional, national, or international data, depending on the context. Econometric models of this kind have a long history (12). After calibration, the model can be used for forecasting and policy analysis. For example, above, given the equilibrium condition of demand-supply equality, the two-equation demand-supply system 2, 3 has been solved for price as a function of the demand and supply shifters (interest rate, housing starts, government supply). This price equation 4 can then be applied to predict price, conditional on the future values of interest rate, public timber supply, and housing starts. Presumably, interest rate and housing starts are themselves predicted by macroeconomists and demographers, and in that way the forest sector is linked to the rest of the economy. The public supply variable, Q_g, instead, is a policy variable, since the government can choose how much timber to produce from public forests. Equation 4 can be used to predict the effect of this government policy on timber prices. Such a price projection is important for benefit-cost analysis, including calculations with Faustmann's formula to decide whether to begin, continue, or stop forest production activities on private as well as public lands.

Economic forest sector modeling of this kind has progressed greatly during the past thirty years. The models are used extensively to help set national forest policy (13). Even at the international level, multi-country models of production, consumption, trade, and prices of wood products now help to study policy issues (14). These models are based typically on the equilibrium theory sketched above, whereby at every point in time there exists a unique set of prices that equilibrate markets for all products in all countries. Their implementation often involves a combination of statistical and mathematical techniques (12).

Forest sector models represent a significant advance in how forest policy is decided, and forest decisions are made. This is because the methods and assumptions are transparent, facilitating greatly the communication of ideas, their critique, and ultimate progress. Still, current forest sector models lack accuracy. At best, they give an indication of possible direction of changes, given an internally consistent set of assumptions, but the future may turn out quite differently from what the models predict. Thus, in the foreseeable future, the timber prices that foresters should use even in the simplest Faustmann's formula will always be greatly uncertain. In addition, foresters must deal with the rising importance of the complex nontimber values of forests.

Non-Timber Values and Benefit-Cost Analysis

As the ecological value of forestland is increasingly recognized and understood by foresters and by the public, the nontimber value of forests that stems from their variety of life forms and functions is of growing interest. Economic theory can help define these values in monetary terms, and econometric techniques can be used to measure them. Hartman (15) reanalyzed Faustmann's optimal harvest age problem after including nontimber values of a mature forest such as flood control, recreation, and wildlife. He showed that if the services of the mature forest are valued more than the services of a newly planted forest, then it is best to extend the harvest age beyond the Faustmann rotation computed with timber prices only. Strang (16) showed that it might be preferable never to cut an existing old growth forest, even if it is optimal to eventually harvest the same land if initially barren. This is because of the considerable nontimber values embedded in the old-growth forest.

Forest Externalities

Often, values that derive from the presence of forest cover, such as flood and erosion control, may benefit others than the forest owners, so the owners do not include such benefits in the *LEV* calculation. These values are externalities for the firm making the economic decision. Since, by definition, externalities do not profit the owners, the amount of the externality is incidental to their decisions. If the externality is good, like erosion control, then society at large might desire more than the private owners will provide spontaneously. The private owners may guard against excessive erosion during harvest to a degree because they want to preserve the land fertility, but a municipal water processing plant downstream will want more effective erosion control so they have less silt to remove.

One approach to achieving the socially best level of erosion control is direct regulation, that is, decreeing and enforcing standards to control erosion. As another example, cedar rust is a disease that is incubated in red cedar and that attacks the leaves and fruit of apple trees. A 1914 law of the state of Virginia gave apple orchards the right to remove all red cedar trees within two miles of an orchard (17). Though draconian, the law was an attempt to force cedar owners to bear the cost of the damage they inflicted on orchards.

Another approach is taxation. For example, to control erosion, a tax could be waged on the forest owner for each ton of silt in the runoff. If the tax is set at the right level, the forest owner will choose the socially optimal degree of erosion prevention. Discovering the correct tax rate is the main difficulty in this approach.

A third approach is to establish clear property rights. To pursue the water pollution example, if the water plant had the right to silt-free water then the forest owners must pay the water plant for adding silt to the water. In this way, the forest owners incur an added expense for each ton of silt they add to the water, so they consider that cost in their management decision. The cost of enforcing the property right can make this approach impractical. Monitoring erosion on all the watersheds and estimating how much purification costs increase for each incident of erosion might be more costly than ignoring the right.

In some cases, property rights are impossible to establish. The beauty of the forest and the protection of threatened species are public goods that anyone can enjoy freely without preventing others from doing the same. A public nontimber forest good, such as its beauty, may be valuable to the owners, yet it tends to be underprovided compared to the social optimum. The combined value of a public good for all citizens is greater than the value to each, so as forest owners make the best decisions for themselves, they provide less than what all citizens desire.

Benefit-Cost Analysis of Forestry Projects

While externalities are common for private forests, nothing is external for a public forest. Thus, managers of public forests must consider many constituencies in setting policy. Benefit-cost analysis (BCA) helps in this process by including all known costs and benefits with a project or policy change. In the United States, ideas about a quantitative approach to policy formation began to emerge in the 1930s. In particular, the Flood Control Act of 1936 required BCA for all flood-control projects. The introduction of quantitative methods into management was accelerated by the logistical needs of World War II. BCA was at first limited to governmental projects, but was later increasingly applied to evaluate policies and regulations. Currently, BCA has many champions who believe that it is a rigorous approach that will become adopted internationally (18). In particular, the transparency of the BCA process leaves less room for corrupting influences in countries with weak democratic institutions (19).

In the United States, BCA is required on federal lands. Both the Bureau of Land Management through the Federal Land Policy and Management Act of 1976 and the Forest Service through the National Forest Management Act of 1976 must use BCA to set policy. The Forest Service's procedures include U.S.D.A. Forest Service directives, which require that lands be managed to maximize net public benefits (20). This public BCA includes not only financial flows but also any benefit or cost accruing to all U.S. citizens. Therefore, as applied to forestry, BCA is essentially a generalization of Faustmann's reasoning, to include all the goods and services that derive from the land and the trees that it carries.

Nevertheless, an emerging school of thought questions the use of BCA in policy formation. For example, Vatn and Bromley argue that rather than trying to maximize anything, policy formation should deal with how to achieve a desirable future state (21). In this view, BCA is useful only to determine if that future state is achievable. Indeed, a most difficult part of BCA is to quantify how much we value particular outcomes. If instead we implement a process to set as a goal the future state we most value, then one of the main objects of BCA is achieved, by definition. Determining the socially desired future state is not a simple process, but it could at least be more transparent than the convoluted valuation methods of BCA.

In public forest management, the limitations of BCA, revealed by the numerous lawsuits brought by interest groups to stop management plans on National Forests, have led to attempts to replace them with multidimensional decision methods. For example, Niemi and Whitelaw divided forest "clients" into four interest groups. They cataloged all effects of a change on each group, without trying to convert them in money. They formalized a process by which balanced policy decisions could be made and they illustrated its application in southern Appalachia (22). However, such methods are still experimental, and far from being as institutionalized as BCA is. The attractiveness of BCA is that it deals with monetary value, a dimension that every decision maker would like to have, and that lawyers covet.

The crucial step in BCA is assigning a monetary value to all costs and benefits. To bring some order to this complicated issue, benefit-cost analysts classify the value of the many qualities or output of forests as use-value, option-value, bequest-value, or existence-value. *Use-value* derives from a particular use of the forest or its products. For example, timber has a use-value, and so do hunting, grazing, and nonconsumptive uses such as recreation and flood control. *Option-values* pertain to forest resources that might have value in the future. A pharmaceutical use for a biochemical compound produced by an understory species might be discovered in the future. We maintain the option of collecting this value as long as forest conditions allow the species to survive.

Bequest-value is the value of maintaining a resource to pass on to future generations. The satisfaction we gain from the idea of passing a forest intact to future generations is its bequest-value to us. Last, the value that individuals and society derive from the forest merely being there now is its existence-value. *Existence-value* may be, but is not necessarily related to, some use values. An individual who greatly values the beauty of a forest is using the forest while viewing it, yet the greater part of the value of sightseeing might be confirming the existence of the forest. Others might value the existence of rare animal species harbored by the forest even though they might never see or in any other way use them. As suggested by the subtlety of their definitions, quantifying their value is no easy task.

Measuring Social Welfare

Economists have developed many techniques to do benefit-cost analysis. The easiest use-values to estimate in monetary terms are those that are bought and sold at a "market price." Suppose the good is timber, traded in a region where there are many small private forests, and a large public forest. Under the current policy, the public forest produces nothing, so that the upward sloping line, S_1, in Figure 21.5 represents supply (all private), while the downward sloping line, *D*, represents demand.

Demand and supply cross at *B*, the quantity of private timber sold and bought is F(m^3yr^{-1}), and the equilibrium price is *A* ($\$m^{-3}$). Suppose that the managers of the public forest consider producing timber independently of price level. This policy would result in a shift in the total regional supply line from supply S_1 to supply S_2. The new equilibrium would them be at a lower price, *C*, for a larger volume bought and sold, *G*. However, the amount sold by private forests would decrease from *F* to *J*. Consequently, there would be an increase in the welfare of timber buyers, measured by the area of the polygon *ABEC*, but a decrease in the welfare of private sellers, equal to the area *ABHC*. There would then be an increase in total welfare of consumers and producers, equal to the area *BEH*. This is an example of complete welfare accounting, with a full evaluation of benefits and costs, and of winners and losers. It still demands work to estimate the necessary demand and supply relations, and it is not possible without a market.

Assessing the Value of Forest Amenities

It appears, then, that for public goods, even those with use-value, such as forest scenery, the assessment of value in monetary terms is difficult. If we knew the demand schedule for the good, we would calculate the value of, say, a change in supply as we did above, but there are usually no market data to estimate the demand schedule. We can count the number of sightseers and tabulate the time they spend viewing forest scenery, but short of a wall hiding the forest and a tollbooth, we can neither limit sightseers nor charge them a fee. In this example, the ability to limit access to or charge for the public good is difficult or impossible; so most consumers will "free ride," that is, benefit without paying to view the scenery. One can observe the quantity of a public good that free riders use at zero cost, but construction of the full demand equation requires the methods described later.

In another example, the absorption of air pollution by forests provides clean air that anyone can use without paying. Without a way of charging for the use of that clean air, we cannot observe how use of clean air changes with price. As private forests purify the air, owners rarely consider the

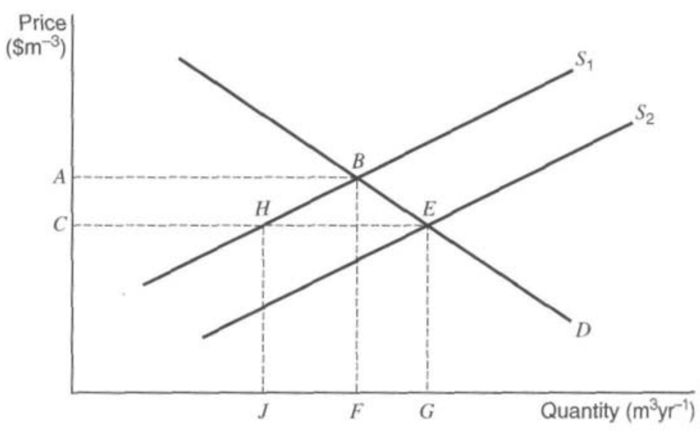

Figure 21.5 As public timber supply increases, the welfare of society increases by the amount measured by the area of the triangle *BEH*.

value of the clean air to others. In choosing to build houses where there was forest, the air cleaning capacity of the forest is typically not considered by the builders, so we cannot directly infer the value of air cleaning by observing the behavior of land developers.

For resources with option-value, such as the unknown medicinal value of forest flora, we might observe a value in an options market. Since the option-value exists because of a potential future market good, rights to that resource could be traded and a market value observed. For example, the pharmaceutical company Merck bought the right to bioprospect in Costa Rica for $1 million plus royalties (23). The biotech company Diversa paid the U.S. National Park Service $175,000 plus a percentage of profits to do the same in the Yellowstone hot springs (24). To the extent that those deals were competitive, they should represent the expected value of patentable biological discoveries over costs for the companies. However, these two companies are searching for short-term value in the genetic material, which we as a society have retained the option to use by maintaining the ecosystems with those life forms. The uncertainties Merck and Diversa face in finding valuable biological material are small compared to the difficulty of evaluating longer-term option values.

Effective markets for long-term option-value are hard to envision with the short profit horizon typically important to businesses. The option-value of future nonconsumptive goods is also not subject to market valuation. In the Midwest of the United States, the existence value and recreational value of traditional tall grass prairie ecosystems has been discovered in the last few decades after the destruction of all but small remnants. The option of recreating prairies was preserved in the plants left in those areas. Since not so long ago few would have predicted that the prairie would some day have a nonconsumptive value, they would have had a hard time guessing its option-value.

The bequest-value and existence-value of forestlands are in part revealed when forestlands are bought and sold. These non-use values are part of the price paid. But separating bequest values and existence values from the total price paid for the complex bundle of goods represented by the forest is not a simple task. Furthermore, if the price data come from private transactions, to obtain the total value of the forestland, we must add its value to the rest of society to the private value.

Economists use three kinds of methods to estimate the value of forest goods that are not traded directly and unambiguously: travel cost, hedonic pricing, and contingent valuation. In the *travel cost approach,* the cost of travel to the forest is used to infer the value of visiting the forest for an individual, and also the value of different forests for different people. Hanley and Ruffell used the travel cost method to determine the value of the physical characteristics of forests in Canada (26). Fix and Loomis found that a mountain bike trip to Moab, Utah was worth $205 (27).

In the *hedonic pricing method,* a market good is viewed as a bundle of attributes. The value of each attribute is inferred from price differences between goods with various amounts of attributes. For example, the price of houses can be used to estimate the amenity value of a neighboring forest. Along with pure housing attributes such as square footage, number of bedrooms, and so forth is access to the forest, measured for example by its distance from the house. Given a sufficient number of houses bought and sold, we calculate by statistical methods the best equation to relate house price to the attributes. We can then infer how much more an otherwise equivalent house is worth just for being near the forest. From this hedonic price analysis, we have inferred the amenity value of the forest as the amount a household is willing to pay for being close to it. With this technique, Li and Brown found that a house is worth $250 more near a conservation area and $2800 more next to a recreation area (28). Examples of application of hedonic pricing in forestry include Turner, et al. (29), and Roos (30) who inferred the value of particular characteristics of forest estates, such as their location. Scarpa and Buongiorno estimated the amenity value of a stand of trees as the difference between what the owners could have gotten had they tried to maximize profits (according to Faustmann's rule), and what they actually cut. By then comparing the amenity value of many different stands, they inferred the amenity value of trees of different species and size. They found that for most owners, the amenity value of trees was much larger than their timber value (31).

The travel cost approach and hedonic pricing use market prices; for example, the cost of gasoline or the price of a house, to infer the nonmarket value of forest amenities. These methods are based on actual choices of people who reveal their preferences by their actions. In the *contingent valuation method* (CVM), instead we ask individuals about how much they are willing to pay for a particular nonmarket good or service supplied by a forest. One advantage of contingent valuation is that it can deal with non-use values such as the existence of a healthy forest, as well as use-values such as viewing that healthy forest (32). As a result CVM is used extensively in benefit-cost analysis. For example, Crocker asked forest visitors their willingness to pay for a visit to a forest if the trees showed slight, moderate, or severe damage from air pollution (33). With these data he estimated the public willingness to pay to prevent damage to trees. Mattson and Li used the CVM to quantify the value of on-site consumptive use (berry and mushroom picking), on-site nonconsumptive use (hiking, and camping), and off-site visual experience (34). Still, there is much controversy concerning the theory and techniques of CVM, such as how to design surveys for public opinion polling, and the magnitude of biases in the assessment of willingness to pay for a nonmarket good (35).

Opportunity Cost of Non-Timber Objectives

While measuring the economic value of forest amenities is difficult, determining the opportunity cost of a decision to preserve or enhance some amenities values is much more straightforward. For example, it is hard to tell how much the spotted owl is worth, but it is much easier, and yet useful, to determine the cost of protecting the spotted owl, in terms of revenue foregone by curtailing timber production in the Pacific Northwest. To take a simpler example, refer again to Table 21.1, and assume that instead of cutting trees at their economic age of 60 years we wanted to keep them growing for one century, possibly because of the aesthetic and ecological superiority of stands of old trees. Then, Table 21.1 shows that the land expectation value for a rotation of 100 years would be $504 ha^{-1} only. This would be $1,387 ha^{-1} - $504 ha^{-1} = $883 ha^{-1} less than the land expectation value of the purely economic policy.

The opportunity cost of the "big tree" policy would then be $883 ha^{-1}. If the forest were public, this is what citizens would have to be willing to give up in order to enjoy the bigger trees. In the case of a private forest, the opportunity cost gives an estimate of what would have to be paid to private owners to induce them to keep trees growing beyond the age of financial maturity. Knowledge of such opportunity costs is precious for objective policy making, and it is well within the capacity of standard economic tools.

Concluding Statement

From Faustmann's classic valuation of forestland to the complex multidimensional choices in modern forest policy, economic principles and methods have contributed much to forest management decisions. Economics help foresters grapple with the fundamental issue of opportunity cost, as it applies to time, alternative land uses, and conservation. It also gives us the framework and tools to handle risk objectively. Applied to the timber sector, economics is essential to predict the demand, supply, and prices of wood products. In the more difficult realm of amenity values, the methods of benefit-cost analysis are put to work constantly to measure the full social value of forests. As economic theory and methods continue to develop, new opportunities open for their application to the management of forests. The amenity value of forests is likely to grow in importance, and to take more time in the day-to-day concerns of forest managers. Economics is helping in the assessment of these values.

Nevertheless, there are definite limits to economics. Some forest policy issues, such as the preservation of species, far transcend the purely economic dimension, and reach into the realm of ethics and religion. One may, then, question whether economic methodology can truly give a definitive measure of value in those circumstances. Conservation goals will most likely be set on more grounds than purely economic considerations. Nevertheless, the means to achieve conservation will certainly have an important economic dimension. They involve budgets, reallocation of resources, and sacrifices in current consumption. In sum, there is a very real opportunity cost to any forestry decision. It is the role of economics, and its power to determine this cost exhaustively and accurately.

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PART 4

Forests and Society

Social forestry seeks to understand the relationships among human behavior, social systems, natural resources, and the environment. Because natural resource issues are embedded in social and cultural contexts, future forest managers must consider the changing relationships between the biophysical and social environments that shape forest communities and the people who depend on them (Figure P4.1).

Specialization in this area includes studies of forest-dependent communities, sociology of natural resources, forest and environmental history, forest and resource policy, park and protected area management, sustainable forestry, human dimensions in ecosystem management, urban forestry, international forestry, and economic development of forests, including nontimber forest products and agroforestry.

Figure P4.1 Community forestry project in Algeria. (United Nations Photo.)

Underlying all areas of social forestry is the understanding of how people shape and are shaped by natural resource systems through their social institutions and cultures. Central to social forestry is the recognition that people and human behavior are natural components of ecosystems. We have already been introduced to some of the management issues in social forestry in Chapter 17, Managing Recreation Behavior.

The two chapters in this section deal with additional various aspects of social forestry. Chapter 22 on urban forestry treats the unique situation of management of trees and forests located in urban environments. Finally, Chapter 23 provides a description of community-based management of natural resources, which has applications both domestically and internationally. The many issues and challenges of this complex subject are described in detail based on global experiences.

CHAPTER 22

Urban Forestry

GENE GREY

Urban forestry concerns the care of trees and related organisms within the environs of cities, towns, and other developed areas, and is a specialized application of forest science (and art) to the dynamic physical, social, and political environments in which people live and work. Totaling an estimated 69 million acres, the nation's urban forests are complex mixtures of planted and naturally occurring trees and related vegetation in close proximity to the structures and activities of human life. In simplest terms, "urban" areas are made up of trees and other vegetable and animal organisms, structures, and people (Figure 22.1). It is the challenge of urban forestry to make trees and other organisms compatible and serviceable within and to this environment (1-7).

Urban forestry merges the knowledge and skills of traditional forestry—of working with natural forest

Figure 22.1 The urban forest is a dynamic environment of manmade structures, such as buildings and streets, and organisms, such as plants and trees.

ecosystems and planted forests—with disciplines involving landscape plant materials and design, arboriculture, urban wildlife, engineering, planning, legal matters, and social and political science. The complexity of the urban forestry environment requires no less.

The language of urban forestry can sometimes be confusing. For example, the very word "urban" can give the impression that only large metropolitan areas are involved, even though the principles and practices are equally applicable to tiny hamlets. To counter this impression, the term "community forestry" is often used. Also, the title of urban forester often goes by other names, such as city forester, city arborist, or even city horticulturist. To avoid confusion, the term "urban forestry" is used throughout this chapter, as is the word city, being generic to all human habitat situations. Furthermore, the term urban forest manager is used except when referring to the specific public office of the person responsible for urban forestry within a city. In such cases, the term "city forester" is used.

Although, in any given city, many individuals are involved in urban forestry as professionals or volunteers, overall responsibility is usually vested in the office of city forester. Operating under ordinances specific to the urban forest, the city forester is responsible for coordination of activities relating to the needs of the entire forest.[1] To be effective, the city forester and other urban forest managers must have a thorough working knowledge of the urban forestry environment—of what the urban forest needs, how to plan and budget for necessary management programs, and how to implement them successfully. The following sections discuss each in more detail.

[1] Please note that the following approach from the perspective of the city forester does not ignore or diminish the role in and contribution to urban forestry of countless other professionals and volunteers in public agencies and private business; nor does it fail to recognize that the function of city forester is often carried out by volunteer boards or committees and that some programs are successfully conducted without formal ordinances.

The Urban Forestry Environment

The total urban forestry environment (the environment in which urban forestry must operate) includes all the physical (including biological), institutional, social, legal, and political factors that either facilitate or inhibit care of the urban forest.

Physical Environment

To understand the physical environment of the urban forest, one first needs an overall vertical perspective, as from an aircraft or aerial photograph. Below is an extremely complex mixture of land-use situations—streets, roads, highways, railways, utility corridors, business and industrial areas, parking lots, athletic fields, parks, residential areas, riparian areas, and other natural forests—most having trees and related vegetation in varying degrees. A further look at the ground reveals how trees and other vegetation serve and relate to each situation, particularly in context with buildings, utilities, and other structures. As noted above, trees make up an integral element in cities and are thus a part of the urban infrastructure, providing aesthetic and other environmental benefits (Figure 22.2). The totality of trees and other vegetation in all areas within a city is properly the urban forest.

Figure 22.2 Design of streetside landscapes is an important component of urban forest management.

The physical environment also involves the nature of the forest itself, its composition (by species, age, and size), condition, and distribution, over all land use situations. In a later section, Determining What the Urban Forest Needs, we will explore composition and distribution in more detail.

It is important to understand also that the urban forest is extremely dynamic, and that expansion into natural woodlands, construction within the city, and the simple fact of vegetation growth and death cause continual changes in composition, condition, and distribution.

Socioeconomic Environment

Perhaps the most important aspect of the urban forestry environment is who is responsible for management. As suggested by the aerial overview, there are myriad owners, both public and private—city and other government, business, institutions, industry, and homeowners—each influencing the state of the urban forest within its area of responsibility. Ownership is not absolute, however, in that rights for the greater society must be given. In the case of the urban forest, such rights are manifested by easements for public utilities, giving electrical, telephone and other utility providers authority for treatment of trees on such areas. Thus, there are four general categories of "managers" of the urban forest: 1) city government, generally with direct authority for parks and streetsides; 2) other government agencies, particularly state highway departments; 3) private owners, especially homeowners; and

4) public utilities. From the perspective of the city forester, responsible for coordination of management of the total urban forest, these categories represent the four principal audiences for his or her efforts.

Critical also within the urban forestry environment are those individuals and organizations that influence or have the potential to influence management of the urban forest: neighborhood associations, advocacy and volunteer groups, civic clubs, the media, and service individuals such as arborists and nursery people. This is, in part, related to the political environment, which will be discussed later.

A final factor in the socioeconomic environment concerns attitudes of people regarding trees and other vegetation. Attitudes, obviously, vary greatly by individuals, having been formulated by past experiences—physical, cultural, and economic. Of these, economics is perhaps the most important, as care of trees may be an unaffordable luxury to some, or may be the ultimate expression of ownership pride by others. Economics may also effect community pride, with resulting influences on budgets for public urban forestry programs.

Legal Environment

The legal environment of urban forestry has three major aspects: management responsibility and authority; tree protection and landscape matters; and safety and liability. Management responsibility and authority is normally established by city ordinances that establish and define the office of city forester, outline responsibilities, and grant authority for operations. In most cities, ordinances give city foresters responsibility for streetside and park trees and for vegetation on other city-owned areas. Commonly called management ordinances, such statutes typically have the following elements, although items 5, 6, and 7 may be included in a separate "Standards" section:

1. Definitions
2. Designation of City Forester
3. Establishment of citizen tree board
4. Responsibility for trees on city property and easements
5. Planting regulations (permits, official species, spacing, location)
6. Maintenance standards
7. Tree removal requirements and standards
8. Catastrophic authority on private property (condemnation and treatment)
9. Requirements for private contractors
10. Violations and penalties

Tree protection ordinances concern special trees and groves (because of size, species, scarcity, historical or cultural significance, or environmental contribution) and allow them to be set aside and maintained. Landscape ordinances generally relate to development and construction, and concern maintenance of tree cover and protection of individual trees. Tree cover requirements for developers are normally expressed as a percent of total land area, stems per acre, or percentage of crown cover. Critical drainage areas, wetlands, special wildlife habitat, and other ecosystems may also be delineated.

In addition to city ordinances, the legal environment of urban forestry is extended by state and federal regulations concerning rare, threatened, or endangered species; wetlands or critical habitats; point and nonpoint source pollution; pesticides; and workplace safety. Also, many subdivisions have specific regulations concerning establishment and care of trees and other vegetation. Generally, such regulations are based on concerns for maintenance of property values, public safety, and protection of the environment.

Safety is of utmost concern within the urban forest. Trees can be threats to life and property. Accidents because of fallen trees or limbs, slippery leaves and fruit, and obstructed views often leave property owners and those responsible for management liable for damages. Liability is based on the tort law principle of prudent and reasonable care; thus property owners and their agents have a responsibility to exercise due care concerning trees and related vegetation. With the trend of increasing litigation and higher damage awards by the courts, the issue of liability is extremely important in urban forestry, calling for increased emphasis on hazard prevention (discussed in a later section).

Political Environment

The political environment of a city has to do with those who influence decisions. Budget decisions are of particular importance, as there is generally intensive competition for funds, and those programs and services having key political support are usually well funded. Every city has its political structure, within city government, but also made up of influential citizens and leaders of civic, service, and business organizations. Identifying and working with such people is essential to successful urban forestry programs, since, ultimately, political support is a manifestation of the public's concern for trees.

Management Structure

The Office of City Forester

As indicated, responsibility for coordination of overall urban forest management is legally vested in the city forester. Varying by cities, the function of city forester may be in a separate department or may be included in other governmental units such as Public Works, Parks and Recreation, or Land Management. In larger cities, forestry departments may be divided into divisions according to responsibility, such as streetside trees and park trees.

Tree Boards

Many cities have tree boards, a generic title for citizen's groups with official support or administrative responsibilities for urban forestry programs. Known variously as commissions, committees, or boards, such groups have official roles which may be advisory, policy making, administrative, or operational. *Advisory boards* are charged with giving counsel on urban forestry matters—to study, investigate, and make recommendations. *Policy-making boards* have broader responsibilities, including program planning and even budgeting. *Administrative boards* are independent commissions with full program responsibilities and independent funding, often from specific tax levies. The city forester is directly responsible to the administrative board, whose duties include long-range planning, policy development, budget approval, and program evaluation. *Operational boards* usually function in tiny communities lacking the resources to support a municipal program. Such boards assume the function of city forester, doing it all, from program planning to actually caring for trees.

In addition their various duties as indicated above, tree boards provide invaluable service as advocates for trees and by giving strong program support. Normally made up of respected, public-spirited citizens, tree boards give added importance to urban forestry, by their presence and through special activities aimed at building support for trees.

Determining What the Urban Forest Needs

Fundamental to planning and implementing a successful urban forestry program is knowledge of the urban forest—its distribution, composition, and condition—and ultimately what is needed to set it in order. Called *structural information,* this knowledge includes health, vigor, safety, diversity, stocking, functionality, and aesthetics. All this must be translated into quantifiable needs for the future—numbers of trees to be established, pruned, removed, or otherwise treated—within the context of ensuring safely, diversity, functionality, and aesthetics.

While general information about what the urban forest needs can be gained by observation, from past work records and other documents, and by simply listening to complaints, comprehensive information can be obtained only by formal surveys or inventories. The beginning point is with aerial photographs to develop cover type maps, identifying general vegetative situations such as riparian areas and other natural woodlands, park lands, homogeneous residential areas, and tree cover in business and industrial areas. Ground checks can confirm or refine type identification. If cost-effective and otherwise practical, this process may be facilitated by use of Geographic Information Systems (GIS) and computer technology to scan visual images from photographs and maps, allowing cover types and other features to be featured as layers (see also Chapter 12).

For many areas, such as natural woodlands and passive parks, such cover type information, coupled with ground observations, will be sufficient to develop prescriptions for management. For other situations, however, such as streetsides, active parks, and other areas where intensive management is needed, more detailed information must be obtained (Figure 22.3).

The amount of information to be gathered by surveys or inventories must be determined by the need and the capability to use the information. For example, if the need is for information sufficient to develop a long-range plan in the hopes of establishing a city forestry program, which has been the case in countless small cities in recent years as urban forestry has expanded, more general, non-site-specific information is needed. If, however, the need is for information to enable an established city forestry department to more intensively manage streetside and park trees, a detailed site-specific inventory—that is, where individual trees are located on the ground—is necessary. Thus, the distinction: surveys are non-site-specific and are generally for long-range planning purposes; and inventories are site-specific and are for intensive management purposes. There are, of course, degrees of need within both, but the distinction is important, because both, especially inventories, are expensive and time-consuming.

Figure 22.3 Urban forests of residential areas often include natural woodlands, riparian zones, church yards, cemeteries, parks, and golf courses.

Surveys

Cover type maps from aerial photographs are essential to urban forest surveys, in that they allow areas of homogeneity to be identified. Once identified, selective sampling systems can then be developed. One such system that works extremely well for streetside trees is to drive sample streets, recording trees by species, size, and condition class. From a slowly moving vehicle, trees on both sides of the street are recorded by species, estimated diameter (DBH), and condition class. Condition classes are as follows.

- *Good.* Healthy, vigorous tree. No apparent signs of disease or mechanical injury. Little or no corrective work needed. Form representative of species.
- *Fair.* Average condition and vigor for area. May be in need of some corrective pruning or repair. May lack desirable form characteristic of species. May show minor insect injury, disease, or physiological problem.
- *Poor.* General state of decline. May show severe mechanical, insect, or disease damage, but death not imminent. May require major repair or renovation.
- *Dead or dying.* Dead, or death imminent from mechanical, disease, or other causes. Removal needed.

Vacant spaces in need of planting are also identified. Compiled data allows species and size diversity, stocking, and condition to be determined. From this information, reasonable conclusions may be made as what is needed to set the streetside urban forest in order: number of trees to be removed, pruned and planted; and species to be favored or avoided in future planting. Such information is absolutely essential to long- range planning, as will be discussed in a following section.

Inventories

Inventories serve the need of intensive management and thus must be more precise, identifiable to individual trees. Consequently, inventories are more costly, requiring on-site decisions as to tree location and condition. Only that information which is directly applicable to future management should be collected, since too much (or too little) information can be excessively costly. The information needed may be summarized as: what the tree is; what it needs; and where it is. Data collected concerning each tree then becomes:

What it is:	Species, diameter, crown spread
What it needs:	Pruning (by type), mechanical work (cabling or bracing), insect or disease treatment, soil treatment, removal of physical impediment, tree removal
Where it is:	Street name, lot number or other location method

Decisions as to what the tree needs can either be made on site, or indicators of need recorded: trunk, branch, crown, and leaf condition; and environmental factors such as proximity to overhead wires, root-zone restrictions, apparent soil problems, and other inhibitors of growth and vigor. Generally it is best to record such factors, since on-site judgments of need are for a single point in time and do not indicate the causes of need. Knowing where trees are is critical to management. Work crews must be able to unfailingly locate individual trees, as the wrong tree treated or removed can have unfortunate consequences. Trees (and tree spaces) may be located by lot number or by sequential numbering within city blocks.

Most inventories are computerized, including automatic data entry from the field. Multiple cross tabulations allow near-instant retrieval of information, including virtual reality displays of streetside situations and individual trees. A common shortcoming of inventories is that they are not continuous and quickly become obsolete, with life spans rarely exceeding 5 to 7 years. Hence, a system for information feedback and an allowance for tree growth is necessary. Effective information feedback ensures that everything that changes a tree—prescribed treatments, construction disturbance, accidents, storm damage, other—is recorded.

In addition to streetside tree management, inventories may be for other special purposes, such as land condemnation, wildlife habitat evaluation, species or ecosystem preservation, and tree hazard evaluation. In such cases, objectives must be clearly defined and systems designed to meet specific needs. Inventories of park trees normally involve a grid system for locating individual trees (Figure 22.4). GPS can also be a valuable aid in park tree inventories.

Planning and Budgeting for Urban Forestry

Planning, no matter how detailed, has five basic elements: 1) an assessment of what you have; 2) a vision of what you want it to be; 3) how to get there; 4) what it will take to get there; and 5) an "occasional" look at how you are doing. Applied to urban forestry planning, this simply means that planning must start with an assessment of the forest situation from surveys, as discussed in the preceding section. A vision of what the urban forest should be—safe, healthy, fully stocked, diverse, functional, and aesthetically pleasing—should next be developed, with each visionary element becoming an objective of a long-range plan. Strategies can then be developed for each objective, priorities determined, estimates made of costs, and a timetable developed to carry out each strategy. Evaluation is ongoing, allowing adjustments to be made as necessary, according to the factors of change within the urban forestry environment. Thus, urban forestry planning must be ongoing.

Urban forestry planning must begin with a long-range plan. As indicated above, the long-range plan states the vision, identifies objectives, determines

Figure 22.4 Parks may be designated for either active or passive uses.

priorities, estimates costs, and provides for evaluation, thus providing the framework within which operational plans and budgets are developed. Operational plans which are normally annual, depending on a city's fiscal cycle, are expressions of what must be done within a given year to achieve the objectives of the long-range plan. In such plans, annual goals are set—number of new trees to be established, amount and kind of pruning to be accomplished, number of trees to be removed, and other activities—and budgets developed to meet the goals. Budgets so developed thus have a solid planning basis, rather than being simply annual adjustments for inflation, as is unfortunately the case with many urban forestry programs. Plans of work are then developed, listing activities and timetables by various personnel. Finally, a system of evaluation is implemented, involving monitoring and end-of-the-year program evaluation. Thus, the long-range plan provides the framework, operational plans follow, budgets are derived from operational plans, plans of work facilitate annual goals, and evaluation is both ongoing and retrospective. The planning "flow" is summarized as follows.

- *Long-range plan.* States the mission and defines objectives. Identifies strategies and sets priorities to achieve objectives. A function of tree board and city forester.
- *Operational plans.* Usually annual. Based on long-range plan. Set incremental goals, establish procedures, and identify resources for meeting goals. A function of city forester.
- *Budgets.* Based in items in operational plans and reflect resources needed to accomplish goals.
- *Plans of work.* Internal documents, giving tasks and timetables.
- *Evaluation.* Ongoing, often with emphasis on end-of-year review.

Long-range planning, as indicated above, is normally conducted by tree boards in conjunction with the city forester, and often with other involved citizens. Such planning must utilize accurate information, from surveys and other sources, and must consider all other urban forestry environmental factors, particularly the rights and needs of people. Such planning is fundamental to urban forestry, as it is the basis for all that follows.

In addition to planning as discussed, there is a need for emergency planning. No city is immune to natural disasters, such as severe storms, fires, floods, or even earthquakes. Such planning, coordinated with other city departments, should consider the role of the city forester, tree board, and other urban forest managers concerning such disasters, giving first priority to public safety, followed, in order, by clean up, repair, and replacement of trees. Obviously, if a disaster happens, the strategies and priorities of long-range plans may have to be revised.

Program Implementation

Fundamental to urban forestry program implementation is a working knowledge of the technical aspects of *arboriculture*—how to correctly establish, prune, and do whatever else is necessary to maintain trees and related vegetation. This knowledge, coupled with the working concept of the urban forest as a complex ecosystem, allows each operation to be in context with overall objectives.

The urban forest has four basic and interrelated management needs: establishment; maintenance; protection; and removal. Each need, with its various elements, must be addressed in meeting long-range objectives as identified in the planning process.

Tree Establishment

Tree establishment is a continuing need in the urban forest: to replace mortality; to enhance existing stands of trees; and to landscape new developments. Although most often referred to as *tree planting,* tree establishment is a more accurate term, as it reflects the broader need—to ensure that trees are properly selected, located, planted, and given adequate care until they are able to thrive on their own. Thus, planting is but one of five steps (evaluation should also be included) in tree establishment.

Location and Selection

"The right tree in the right spot" is a common, and accurate, expression concerning the urban forest, and means simply that all factors of site and species adaptability must be considered. Tree establishment must be in context with long-range objectives for the urban forest, as summarized by the following four "rules."

1. Tree establishment must be in accordance with the needs (numbers and locations) as identified in urban forestry plans.
2. Tree establishment must maintain or enhance diversity of the urban forest.
3. Trees selected must be consistent with the limiting factors of planting sites (soil, space, climate, other).
4. Trees selected must meet the remaining criteria as identified by objectives in long-range plans (safe, healthy, diverse, functional, other).

Three factors are paramount in tree selection: the tree's purpose in the landscape; what the site will allow; and how much care will be needed. Although most trees will also have secondary purposes, such as shade, wind protection, screening, enframement, accent, contrast, or wildlife attraction, the primary purpose is the first factor in narrowing the choices. In most urban forest situations, the precise planting spot will largely determine the primary purpose.

Virtually all planting sites will impose constraints, primarily because of soils and space, both above and below ground. In many urban forest situations, particularly streetsides and building sites, soils are less than ideal for tree establishment because of compaction, lack of depth, pollution, low fertility, alkalinity, or acidity. In some situations, depending on costs, it is necessary to amend the soil, replace it entirely, or build special drains or other structures (Figure 22.5).

Restricted space is perhaps the largest (and costliest) single problem with urban trees. There is often a proliferation of overhead wires, underground utilities, buildings, and pavement. There may also be constraints because of sun, shade, wind exposure, and air pollution. The challenge of urban forest tree establishment is to match trees by purpose to their planting sites. Fortunately, nature, with help by scientists, has designed trees with enough characteristics to provide choices in nearly every situation.

Figure 22.5 In central business areas where paving is common, trees are often located in special planters.

Trees must be adaptable to local climates, with the primary limiting factor being cold hardiness. Plant hardiness zone maps should be consulted, with the understanding that such zones are based on average minimum temperatures and do not take into account extremes, nor do they allow for local microclimates because of terrain or other factors. Additionally, as indicated above, trees must be tolerant to site-specific factors of sun, shade, wind, air pollution, and soil.

To fit space restrictions, trees may be grouped into three general mature size classes: small (30 feet); medium (60 feet); and large (100 feet). Additionally, landscape trees have characteristic forms, or shapes, created by branch structure and growth habit: irregular, vase, oval, pyramid, fastigiate (narrow), round, and weeping (Figure 22.6). Such shapes allow trees to be fitted to specific situations. For example, vase-shaped trees are generally best for streetsides, as their ascending branches allow for lateral clearance. Conversely, pyramid-shaped trees do not serve well as streetside trees, as excessive pruning of lower branches is necessary to allow for pedestrian and vehicle passage.

Negative characteristics must also be considered: excessive fruiting, bad odors, heavy leaf fall, surface rooting and suckering, attraction to nuisance wildlife and insects, dense foliage that shades out grass, and excessive production of pollen.

Finally, but not least, cost of planting stock, relating to size, type, and planting sites must be considered. Planting stock varies by size and type. Sizes are usually expressed by height in feet or trunk caliper in inches. Stock types are bareroot, balled and burlapped, containerized, container-grown, or machine transplanted; hence, costs vary greatly. Generally, bareroot planting stock is least expensive; however, not all species can be successfully transplanted in bareroot condition.

Planting

Planting should be considered as a process following selection and location, and involves quality assurance, contracting for plant materials and for implementation, site designation, and implementation. Quality assurance begins with the ability to recognize good planting stock. Standards for planting stock have been published by the American Association of Nurserymen and should be the criteria for contracting for plant materials. Quality can be further assured by proper handling of stock

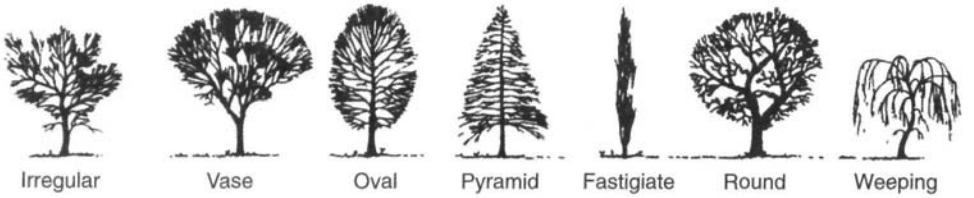

Figure 22.6 Typical shapes of landscape trees.

during delivery and during storage prior to planting.

Precise spots where individual trees will be planted must be designated, with assurance that the correct tree will be planted in each spot. Underground utilities must first be checked. In many cities, excavators, including tree planters, are required by law to give notification of planned excavations. Planting spots can be marked on the ground with stakes, flags, or by spray paint with species code designations identifiable to planting crews.

From a management perspective, implementation of tree planting involves logistics of plant materials, equipment, supplies, and labor. Also involved is quality control, proper handling of planting stock, hole digging, back filling, mulching, and other details. Implementation also involves internal and external public relations. Internal coordination with other agencies of city government (as is necessary in all other urban forestry activities) helps ensure safety and minimizes public inconvenience. External public relations are directed primarily toward making people, particularly nearby residents, aware that trees are being planted and to gain support in protecting "their" trees.

Aftercare

Aftercare involves treatments after planting to ensure health and vigor: corrective pruning, watering, mulching, removing staking materials (needed only in special cases), monitoring insects and diseases, and repairing wounds. An established tree is one that will thrive on its own after a given period of time, generally two to four years.

Evaluation

Tree establishment evaluation is quite important in making future decisions, allowing comparisons to be made between species, by size and type of planting stock, among nursery sources, by planting sites, and by management activities. Timely and accurate monitoring is necessary. Of particular importance is determining the causes of mortality.

Maintenance

Maintenance involves everything necessary between establishment and removal to ensure the optimum quality of the urban forest. While all are interrelated, there are three basic areas of maintenance: hazard management, plant health management, and tree quality improvement (primarily pruning).

Hazard Management

Safety must take top priority as a management activity in the urban forest. Trees, by their very nature, can be dangerous. Branches may fall or entire trees may topple during storms, leaves and fruit are discarded, roots may heave sidewalks, and trunks and branches may pose physical or sight barriers. Consequences can be disastrous in terms of human suffering and because of liability obligations of urban forest managers. Thus, tree hazard management requires a continuing commitment in urban forest management. Two elements are necessary for hazards: trees predisposed to any of the preceding, and the presence of someone or something of value (targets) (Figure 22.7). Thus, hazard management involves prevention and correction of tree "problems" and removal of targets.

Hazard prevention is integrated with all other management activities and involves the following:

- *Species selection:* avoiding species with inherent problems that may make them unsafe; and selection of high-quality planting stock to ensure strong future branching structure and tree vigor.
- *Planting location:* judicious location of planting sites to avoid making trees, by their presence, hazards.
- *Health care:* insect and disease management, correction of soil problems, water management.
- *Pruning:* to develop strong scaffold branches, to discourage decay entry to wounds, and to provide physical and visual clearance for pedestrians and vehicles.
- *Protection during construction:* root-zone protection, and prevention of trunk and branch wounding.

Figure 22.7 For a tree hazard to exist, there must be a potential for tree failure (i.e., the possibility of a limb falling off), as well as a target (i.e., a playground).

Hazard correction is also a major need, particularly in urban areas with substantial populations of older trees. Correction requires recognition and anticipation of potential hazards—recognition of current unsafe situations, and anticipation of predictable events such as fallen leaves, fruit, and other materials potentially hazardous to people and property. Effective recognition requires periodic inspections, identifying indicators and signs of potential tree failure, followed by timely treatment, generally by pruning or other arboricultural measures. In some instances, particularly in cases of large, decadent trees of historic or other value where pruning or other practices cannot ensure safety, "target" removal may be required, by fencing, signing, or otherwise prohibiting public access.

Plant Health Management

Plant health management requires an understanding of the interrelationships of the biological environment of the urban forest, with emphasis on soils, sites, physiological needs of plants, and life cycles of insect and disease pathogens. A major objective is maintenance of health and vigor, so that insect and disease impacts will be minimized, thus reducing the necessity of direct treatments, particularly chemical pesticides (see Chapter 8). Plant health management is integrated with other management and includes such activities as plant selection and location, enhancement of the growing environment, pruning, wound prevention and repair, direct and indirect insect and disease control, public education, and monitoring and recording.

Tree Quality Improvement

Quality improvement applies to individual trees and primarily involves pruning, although site enhancement by fertilization, soil amendments, and other methods is sometimes done. Few landscape trees in the urban forest go without the need for pruning during their life spans—for hazard prevention, for health and vigor, and for physical and visual clearance. Pruning is, in fact, the largest single item in most city forestry budgets, and is also a major cost item for utility providers. Ideally, pruning should be a part of programmed or cycled maintenance, according to varying needs of the total tree population, depending on growth characteristics of individual species and other factors. Emergency pruning, however, will also be needed as hazards are identified, or in the aftermath of storms or accidents.

Programmed pruning requires a pruning cycle, or the number of years required to prune all trees in a particular area—a 5-year pruning cycle meaning, for example, that one fifth of the trees will be pruned every year and each tree will be pruned every 5 years. Optimum pruning cycles are determined by marginal cost and return analysis, accord-

Sidebar 22.1

Florida Citrus Canker Program

Urban foresters can encounter many political as well as technical problems when managing trees in urban settings. An example of a very controversial approach was the plan developed by the Florida Department of Agriculture and Consumer Services for eradication of the citrus canker of citrus trees in south Florida in the late 1990s. The citrus canker is a bacterial disease that is harmless to humans but scars fruit and causes it to drop prematurely, although the fruit remains edible. This highly contagious disease threatened the state's $8.5 billion citrus industry, so the decision was made to eradicate all infected trees, as well as all healthy trees within 1,900 feet of the infected trees. The tree removal was mandated for both citrus plantations and all residential areas. Thus, many homeowners were very disturbed when healthy trees were removed from their yards, often without prior notification. Some south Florida residents brandished guns, padlocked gates and let guard dogs run free around their citrus trees. Citizens of several counties, including Miami-Dade, Broward, and Palm Beach, filed a lawsuit to stop the eradication program. To placate homeowners who lost trees, a $100 voucher was offered, regardless of how many trees were removed, which could be redeemed for replacement trees or garden supplies. However, the canker program prohibits replanting citrus trees for two years. It is estimated that it cost the state $80 million to reimburse homeowners for the estimated 800,000 trees removed in residential areas at the end of the eradication program. However, the small monetary reimbursement did not quell the anger of many homeowners some of whom lost orange and grapefruit trees that were with families for generations.

ing to separate situations of age, species, and other factors within the total tree population.

Pruning of city-owned trees may be accomplished by city forestry department crews or by contract with private arboricultural firms, with decisions whether to prune with city crews or by contract based largely on economics. Most cities find contracting the preferable alternative. Pruning standards have been developed by the National Arborists Association and are used in most contract situations. In some cities, usually those with smaller populations, streetside tree pruning and other maintenance is the responsibility of adjacent property owners. In such cases, the role of the city forester or tree board is largely educational, directed toward helping property owners better care for their trees.

Removal and Utilization

Trees, by nature, discard various things—leaves, fruit, dead branches, and such—and ultimately die. In natural forests, such materials decay on the forest floor and are a part of nature's continuing process. In urban forests, however, much of what is discarded, and dead trees themselves, must be removed. Some of what is removed can be used—fuelwood, for example—but such utilization is minor when all that must be removed is considered: dead trees, hazardous trees, oversize or competing trees, trees in the way of construction, stumps, and occasionally roots, hazardous branches, other branches removed during pruning, leaves, obnoxious or hazardous fruit, seeds and seed carriers, and sometimes even flower petals.

Except in cases of storms or other disasters, most removal can be anticipated and removal work can be scheduled according to season and proximity to people. As suggested, some material can be utilized: trunks and branches for fuelwood; leaves for compost; and occasionally, seeds and seed carriers for ornaments and novelties. Timber products may also be produced, but utilization is limited because of volume, inconsistency of supply, and metal and other foreign objects in logs.

Removal and utilization can also be difficult because of public sensitivity to trees being cut down and because of noise and disruption. Thus, there is the need for effective public relations explaining the necessity of such work in context with long-range objectives for the urban forest.

Other Management Considerations

The preceding discussion has concerned the primary things necessary to meet the basic establishment, maintenance, protection, and removal needs of the urban forest. There are, however, other interrelated considerations, each quite important to the well-being of the forest.

Trees and Construction

Construction is a near-continuous activity in most urban forests: erection of buildings and other structures, street widening, and trenching for utilities. Such activities may cause wounds to trunks and branches, but the main concern is for root-zones of trees, by severing of roots, soil compaction, changes in grade, and alterations of water tables. Coordination with construction planners and developers by urban forest managers is necessary. Alternative locations for construction may be found in cases of historic or other extremely valuable trees, but the largest need is for on-site protection measures, particularly for tree root-zones (Figure 22.8).

In addition to protecting individual trees, the impact of long-term development on the urban forest must be considered: watershed values, wetlands, critical wildlife habitat, and threatened or endangered species. Concerning such, there are three basic considerations: 1) How may the values of natural forests be protected and enhanced during development? 2) Are such values recognized and

Figure 22.8 Construction activity can have severe negative impacts on root-zones of trees.

provided for by planners, administrators, developers, and other decision makers? and 3) If such values are not recognized, what measures are necessary to ensure them? By addressing these questions, urban forest managers can play an important role in comprehensive city planning and development.

Fire Protection

Except in areas where subdivisions have been developed in natural forests, particularly in the arid West, fire protection is of relatively lesser concern to urban forest managers. The primary focus of fire protection in urban areas is on structures, and "forests," if considered, are looked upon as "carriers" of fire. Fire protection in urban forests is usually the responsibility of city or other local fire departments. The urban forest manager's role is often cooperative with such agencies, providing input in protection planning and disaster recovery.

Urban Wildlife

While some urban forestry management practices (particularly removal of dead branches and trees) are detrimental to urban wildlife, many wildlife species abound in cities, some existing in even greater numbers than in natural habitats. For example, most large cities in the nation now have resident populations of Canada geese and abundant raccoons. People generally value urban wildlife highly, delighting in feeding and watching birds and observing other creatures (Figure 22.1). Wildlife can cause problems, however, by being dangerous to traffic, having annoying habits (noisy, destructive, messy), and occasionally carrying diseases. Urban wildlife management has three general aspects: 1) providing and enhancing habitat; for example, by establishing wildlife-friendly plants, protecting natural vegetation in new developments, providing travel lanes, and leaving dead trees and branches in nonhazard areas; 2) providing for viewing or consumptive opportunities, through such methods as construction of trails, viewing platforms, and boat ramps; and 3) controlling damage or nuisances by exclusion, lessening attractions, or reducing populations.

Urban Forest Valuation

Because of casualty losses or condemnation of properties to be developed, valuation of individual trees and urban woodlands is often necessary. Generally, woody plants in the landscape have no real value unto themselves; their only value being in their influence on real estate values. The appropriate method for assigning monetary values to woody plants depends on plant size, species, condition, function, location in the landscape, and other situational factors. Valuation can be subjective, and the urban forest manager must offer his or her best professional judgement in determining the method to use and in the appraisal process. Methods of appraisal are: direct replacement cost; compounded replacement cost; present value of future returns; cost of repair; cost of cure; forest product value; crop value; and trunk formula.

Of the above methods of appraisal, *trunk formula* is most commonly used with larger, specimen trees. This method, developed by the Council of Tree and Landscape Appraisers, begins with a base value derived from the cost per square inch of trunk diameter of the largest locally available transplantable tree of the same species of the tree being appraised. This value is applied to the total square inch trunk area of the appraisal tree and then reduced by species class, condition, and location in the landscape.

Information Management

The importance of information management cannot be overemphasized. Keeping accurate records and being able to retrieve information is absolutely essential to effective urban forest management. *Records:* reveal what has been done to trees and serve as the basis for future care; allow program evaluation; are essential to planning and budgeting; and furnish proof of care in disputes involving liability. Modern computer technology allows massive amounts of information to be efficiently handled. The key, however, is information entry, reasonably recording everything that happens to the urban forest—planting, pruning, insect and disease infestations and control, construction disruptions, fire, accidents, storm damage, tree removal, and such. Without such information, the basis for making reasonable judgements is greatly reduced.

Information management is not limited to internal records. Computers allow Internet access to virtually all topics concerning urban forestry. Many urban forest managers have their own websites, and communication with contemporaries worldwide is commonplace. Computer software is available for tree inventories, planning, budgeting, cost accounting, program analysis, tree selection, and other management applications.

Figure 22.9 The urban forest often includes areas of mature natural forests.

Program Needs Analysis

Information management is the basis for program analysis. Program analysis begins with the simple question: Is the program as effective as it should be in meeting the needs of the urban forest? Program analysis must be done at both the macro and micro levels. Macro-analysis is an administrative function, and addresses the six elements necessary for comprehensive management of the urban forest: a central organization with responsibility and authority; knowledge of the total urban forestry environment; knowledge of what the urban forest needs; plans for meeting the needs; adequate budgets; and effective implementation (Figure 22.9). If any element is missing completely, comprehensive management cannot occur. If any element is partially missing, management cannot be as effective as possible. As missing parts are identified, the questions then become: Why is it missing? What are the barriers to putting it in place? and how may the barriers be overcome? The answers identify what should be the highest priorities for urban forestry program administrators. Micro-analysis looks within the program to identify strengths and weaknesses, and must be ongoing. The basic questions involve what is wrong and how it might be fixed, and what works well and whether more of it should be done.

Indirect Management

The preceding text was concerned primarily with urban forestry activities on streetsides, parks, and other areas where trees and other vegetation are managed directly by the city forester. A major portion of the urban forest, however, from private yards to business and industrial sites, is not the direct responsibility of the city forester. While the arboricultural and landscaping practices discussed are applicable to these areas, the city forester can influence their enactment only indirectly. The objective of indirect management is for other owners to better care for their parts of the urban forest. Thus, there are two approaches: information dissemination; and working with those who service the urban forest.

Information Dissemination

The objective of information dissemination is education, in the hope that new knowledge will be applied to the urban forest. Information may be addressed to the generic needs of the urban forest, as identified in the long-range plan (safety, diversity, health, function), or may be specific, as related to storm damage, insect or disease infestations, poor arboricultural practices, or other situations. Each need can be addressed according to the following principles and practices of information dissemination:

- *Principles:* identify specific audiences; use methods appropriate to audiences; take advantage of the teachable moment; be specific as to what should be done; keep the message simple; use others to tell your story; and repeat, repeat, repeat.
- *Practices:* public meetings; tours and demonstrations; flyers, door-hangers, and posters; newsletters; inserts in newspapers and utility statements; newspaper special editions; newspaper articles; telephone hotlines; television and radio through programs or public service announcements; and direct mail.

Of the above principles, getting others to tell your story is especially important, as many credible "others" have the ready capability to extend information. Cooperative Extension Service agents, state forestry agency personnel, garden editors of newspapers, arboricultural and nursery firms, and even the clergy are examples.

Working with Those Who Service the Urban Forest

Those who service the urban forest have a direct positive or negative influence on its well-being. No one is in a better position to do good or harm to the urban forest than the person with a saw in his or her hand, or the person who supplies and plants trees. Hence, upgrading the knowledge and skills of such individuals must be of high priority for urban forest managers. An additional goal should be to have each service individual and firm (commercial and utility arborist, and nursery people) dedicated to the long-term objectives for the urban forest. Approaches involve: sharing of long-range plan information; sponsoring pruning schools and other training sessions; publishing newsletters; encouraging arborists to become members of professional associations; and aiding nurseries in furnishing diverse planting stock.

Program Support

Urban forestry programs at the city level are supported by various volunteer, technical, and financial resources. Volunteers are generally from local sources, while technical support may come from state or national organizations. Financing is largely from local sources, but other opportunities are sometimes available.

Volunteers

Volunteers provide valuable services to the urban forest and are utilized in virtually every successful city forestry program in the nation. Volunteers may be unaffiliated individuals or may be members of a group. Volunteer groups may be advocacy-, project-, or program-oriented.

- *Advocacy-oriented groups:* generally focused on specific causes or single issues; strong emphasis on fundraising and lobbying.
- *Project-oriented groups:* often part of a larger organization (civic or service club, business, youth organization); focused on individual projects, such as tree planting or environmental improvement.
- *Program-oriented groups:* focused on broader, long-range concerns (tree boards are an example).

Volunteers are a valuable resource for urban forest managers. Not only do volunteers provide labor, but they can also, particularly in the case of advocacy and program-oriented groups, be a source of involved program support. It is especially important for urban forest managers to consider the role of volunteers during annual program planning, with a "plan" for recruitment and utilization. Recruitment can be facilitated by working through various community organizations such as project-oriented groups, as above.

Technical Support

Technical support for local urban forestry programs, in the form of information and direct assistance, is available from a number of governmental and private sources. A primary source is the State Forestry Agency. Supported by the U.S.D.A. Forest Service, each state has an urban forestry coordinator with responsibility for facilitating development and better implementation of local programs. Specific activities include consultation, guidance in developing new programs, coordination of conferences and training events, administration of special projects, and direct assistance with application of new technologies. The Cooperative Extension Service is also a valuable resource. Backed by university specialists in areas pertaining to urban forestry, extension agents sponsor educational events such as workshops, field days, demonstrations, provide publications, and access research findings on special topics. Other sources of assistance are materials suppliers, arboricultural firms, nurseries, state arborists' associations, and national organizations such as the International Society of Arboriculture, the National Arborists Association, the American Association of Nurserymen, The National Arbor Day Foundation, and American Forests.

Financing

The majority of local urban forestry program funds are from public monies allocated through the planning and budgeting process. Such monies are usually from the city's general fund, but may come from specific tax levies. Occasionally there are also special (usually one-time) assessments for special projects, most generally tree establishment in a specified area. Opportunities for additional funds for general operations are rare. Funds provided through recurring budget cycles provide for continuity consistent with planned long-range objectives. Although often useful, funds from other sources, particularly those earmarked for tree planting, can result in more trees than can be established and maintained by regular program funds. There are, however, special needs that will not result in additional unfundable costs over time, such as tree inventories, systems for processing information, new technologies, and staff or tree board training. There may also be need of special funding for insect, disease, or storm emergencies. Sources of special funding are state and federal agencies, and grants by various philanthropic organizations.

Concluding Statement

It is the challenge of urban forestry to make trees and other organisms compatible and serviceable within an environment largely dominated by people and structures. In so doing, urban forestry merges the knowledge and skills of traditional forestry with disciplines such as landscape plant materials and design, arboriculture, engineering, planning, legal matters, and social and political science. The urban forest manager must have a working knowledge of the physical, social, legal, and political environment of the urban forest, of how to plan and budget for necessary management programs, and how to successfully implement them.

The urban forest has four basic and interrelated needs: vegetation establishment; maintenance; protection; and removal—each to be met in an extremely dynamic natural and human-influenced environment. From the perspective of the city forester, management is both direct and indirect; the former requiring physical attention to the four basic needs of the urban forest, and the latter directed toward various public audiences in an attempt to influence better management.

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CHAPTER 23

Social Forestry: The Community-Based Management of Natural Resources

J. LIN COMPTON AND JOHN W. BRUCE

Social forestry is rapidly gaining the attention of those concerned about the continuing degradation of the environment around the world. The need to find solutions to the global environmental crisis becomes more critical daily. Scientists, legislators and policy makers, development program administrators, and enforcers of laws do not have all the answers to the complex problems and issues confronting that segment of the world's population that lives in close proximity to or that is in some manner or degree dependent upon forest resources. Neither do impoverished rural people who, caught up in the struggle to survive, sometimes pursue practices of forest and forest product use that work to diminish the very resource upon which their continued survival may depend. During the past two decades, many efforts have been launched in a variety of locations around the globe to deal with deforestation and resulting land degradation. Much has been tried and much has been learned about the requirements of an effective response to this environmental crisis. The purpose of this chapter is to present a selection of those experiences and the lessons learned from them and to highlight some of the issues and challenges ahead.

Social forestry revolves around a complex set of concepts and propositions concerning the *community-based management* of natural resources. Social forestry as an action strategy is seen as one means to promote rural development and maintain forest biodiversity and forest health (Figure 23.1). The major proposition is that this can be done by simultaneously producing income and empowering people while promoting sound forestry practices. In some settings, forest user groups, having rights to trees but not to the land, have taken an active role in protecting, harvesting, and regenerating

Figure 23.1 The tropical forest in the heavily populated city-state of Singapore is under many competing utilization pressures. (Photo by R. A. Young.)

forests. Specific collective activities range from establishing home gardens, carrying out alley cropping, setting up tree nurseries, and operating woodlots to meet wood needs, to practicing contour farming by integrating trees into hedgerows to prevent soil erosion and campaigning for local natural heritage development. Such activities may be integrated with efforts to improve animal production and the propagation of improved varieties of crops and species of trees. Strategies to support local social forestry efforts range from legislative activities, to overseeing quality control, to fostering effective relationships among participating institutions. In the following sections, examples drawn from world-wide experience in social forestry will be given and concepts and principles imbedded within these experiences highlighted. Finally, some of the continuing and major issues and challenges will be discussed.

Global Experience in Social Forestry

In April 1995, Prabinder Das, the Chief Forest Conservator for West Bengal State in India, visited Hayfork, a town in northern California, under Ford Foundation funding. A month later, a community organizer from Orissa State followed him. They were consulting with the Watershed Research and Training Center in this forest-dependent community in Trinity National Forest, sharing experiences of community forestry.

There is less old growth forest in Trinity now, and environmental legislation has also constricted production. Hayfork residents set up the Center to help them explore ways to diversify and to think through ways to get more of the existing revenue from forestry for local people. India has pioneered a program of joint forestry management (JFM) in which local communities manage areas of state forest for the Forestry Department, and the people in Hayfork were interested (1).

Hayfork is not alone. American forestry was wasteful of forest resources for generations, but in recent decades there has been a broad recognition of the need for sustainable production and the sustainable livelihoods that this can bring with it (2). The boom and bust progression historically associated with forestry-dependent communities has been too costly in human terms. Because of mill closures, these communities have found themselves thrust from rugged self-sufficiency into a life on remittances. The results are devastating, with the ideology and images of forestry long outliving its economic viability (3).

Even where bust is averted, scholars have noted that forestry-dependent communities that have moved out of the boom stage exhibit persistent poverty. Sociological studies of poverty in forest-dependent communities have identified root causes and suggested solutions. Current thinking suggests that stability is a vain hope, and that sustainability means something different: an acceptance of the inevitability of change by these communities and a lively and creative response by them to the challenges and the opportunities posed by change. There is a renewed interest in social capital issues in these communities. Scholars are asking exactly what that capital consists of, and how best to build it (4, 5).

Where communities can respond effectively, what are some of the strategies for social forestry that have been identified as promising? One strategy is to assure greater diversity of species and products within the timber industry, thus decreasing vulnerability to change. More processing locally and more exploitation of nontimber forest products reduce risks. The development of complementary enterprises when timber is still booming can make things easier later. Scaling up of operations may be important. Large enterprises may be better able to make the investments that will enable them to survive in a harsh competitive environment. Strong local markets and diversified production may provide insulation from major ups and downs of national markets for timber. Investment is more likely where there is local ownership of forests and forest product industries and when less money from forestry flows out of the community.

This last point brings to thinking about American forestry a radical critique developed in recent years in the Third World. Forest-dependent communities exist in the midst of a rich endowment of natural resources, and yet often they are subject to persistent poverty. There is little capital accumulation and investment in those communities, because the resource belongs to government or to large private forest landholders. This phenomenon is not limited to forest-dependent communities, but applies to natural resource-dependent communities more generally, such as communities that rely on tourism for their major income (6).

This is why Hayfork is interested in joint forestry management in India and other models of forestry in which local communities assume control over forest resources, and there is a large body of experience from the Third World to be consulted. Beginning in the early 1980s, a series of experiments in village forestry in India led to a national program that gives village forestry committees access to state forests, mostly small areas of degraded state forest in need of reforestation. An agreement between the Forestry Department and the village forestry committee sets out a co-management scheme, in which the Forestry Department assists the community in replanting the area and the community undertakes to exploit it in accordance with an appended Forest Management Plan. Communities own the trees they grow, but market them through the Forestry Department, which recovers its own costs of production from the sales before passing along the community's share. The purpose of the program is to turn around communities whose members had sometimes been engaged in degrading these resources, and create incentives in those communities for the conservation and good husbandry of the resource (7, 8).

Many programs in developing countries aim to increase community participation in forestry and provide new incentives for sustainable forestry. All have as an essential component a reduction of emphasis on enforcement and a new stress on creating incentives for local communities to support sustainable resource use by giving those communities more direct control of forest resources and improved income opportunities generated by access to those resources. In the Philippines, a community stewardship program gives long-term leaseholds of large areas of land with forests to local foundations, often ethnic territories of minority groups represented by those foundations (9). In Thailand, the government has been experimenting with "forest villages." Villagers reafforest areas of state plantations around villages within the plantation, but also have fields for family agricultural production around the village. In China, villages now hold the ownership of substantial areas of mountain land and have initiated tree planting under a variety of institutional patterns including village (local government) forestry, village shareholder associations, and long-term leases to family partnerships (10).

In Africa, an innovative management program for Niger's Guesselbodi National Forest organized local users bordering the forest into cutters cooperatives and licensed them to cut in the forest (11) (Figure 23.2). In the Mgori Forest of central Tanzania, five communities have become the active guardians of a large miombo woodland; which was in danger of disappearing because of uncontrolled wood extraction, shifting cultivation, and settlement. Through a collaborative arrangement with government, the villagers are recognized not only as the prime users, but as the controlling managers and potentially, owners of the forest, for as long as they protect the forest from damaging use or diminishment. Their main tools of management include village forest management plans, detailed rules concerning forest use, vigiliant patrolling of the forest by forest "watchers," and the establishment of a monthly forum in which representatives from the five villages meet to discuss and resolve problems of mutual concern (12).

Figure 23.2 Felling of okoume in Gabon, W. Africa. Okoume is a major raw material for plywood in Europe. (Photo by Neuhoff, Center for Tropical Forestry, France.)

In mountainous Yunnan, China, an innovative project is underway for the testing of two models for sustainable management of upland forest-based ecosystems: 1) a model for the adaptive co-management of the buffer and development zones surrounding nature reserves by villagers and government reserve staff, and 2) a model for multi-village watershed ecosystem management councils and interwatershed forest ecosystem management councils. Mountain dwellers depend upon the timber, nontimber forest products, and the headwaters of streams located within the forests of such upland areas to sustain their livelihoods. Additionally, as the lives of lowland dwellers have been increasingly affected by the soil erosion, river siltation, and flooding caused by deteriorating upland ecosystems, the government has become more inclined to mobilize and support the ecosystem management efforts of local mountain communities (13) (Figure 23.3).

In South America, there are a variety of new institutional models being used to provide forest-dwelling peoples with more control over the forest resource or at least to protect their access to it (14). Mexico's *ejidos* have in the past decade taken over direct management of the forests they have long owned from concessionaires. In Canada, the Kedgewick Loggers Co-op, New Brunswick, is now exploiting a former private forest whose exploitation had come to be regarded as uneconomic by the owner (15). In Quebec, the provincial forest department began leasing out large holdings of provincial forest to individuals under a forestry sharecropping program (16).

Many of these programs have yet to prove themselves economically. The JFM program in India is still awaiting an adequate economic evaluation of benefits to villagers. Mexico's *ejidos* need to restructure for greater efficiency in the face of stiff competition from cheap lumber coming into Mexico under the liberalized trade regime of NAFTA. However, the response in the local communities to these opportunities has engendered an intense interest in such programs and motivated the Ford Foundation

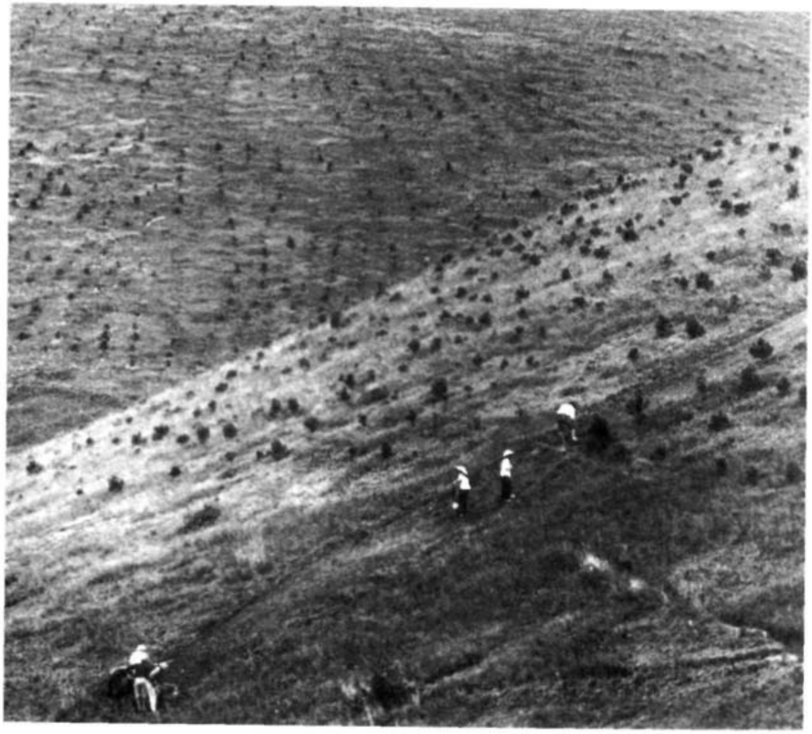

Figure 23.3 Hillside reforestation in Vietnam. (F. Mattioli, World Food Program, UN-FAO.)

to sponsor a research program to explore the potentials of community forestry in the United States.

The new interest has led to new assessments of the potential of community forestry (17) and has focused attention on previously unsung cases of community forestry at home. Wisconsin, Michigan, and Minnesota boast county forestry programs. In Wisconsin, the counties are the largest forest landowners in the state, with 2.3 million hectares in 28 counties (also see Chapter 10, Nonindustrial Private Forests). The county forest ownership originated in Depression-era tax defaults that caused the land to revert to the counties, providing the legal basis for local government forestry (18).

Also, in Wisconsin, 25 miles west of Green Bay, there is an important example of Native American community forestry. Menominee Tribal Enterprises (MTE) has a forest of 220,000 acres on its reservation of 235,000 acres. The Menominee have been engaged in commercial timbering since before the turn of the last century, and managed to avoid the "allotments" of land to individuals that broke up so many reservations in the region in the early and mid-1900s. MTE operates its own sawmill and grows a diversity of species that both reflect traditional values and allow it to access specialized market niches (19).

Managers of federal forests in the west are seeking to respond to demands for new modes of collaboration with local communities (20), and urban forestry is receiving new attention, not only for ornamental and recreational purposes, but also for reservoir and watershed management around cities (21). These programs seem to have a potential for engendering new enthusiasm for forestry in these communities (see Chapter 22, Urban Forestry).

Social forestry programs draw upon strengths in the community itself. One of those strengths that has been recognized in many Third World community forestry programs is the indigenous knowledge of the sustainable use and management of both timber and nontimber forest products within local ecosystems that local people possess. In northern Thailand, the traditional watershed ecosystem management practices of the Karen ethnic minority have been carefully studied and highly acclaimed for the soundness of underlying scientific principles, principles that have been worked out through centuries of discovery learning within the micro-environments inhabited by the Karen (22). Tree, crop, soil, water, animal, and wildlife relationships are managed to promote sustainability of the ecosystem (Figure 23.4).

The indigenous or local experiential knowledge of such groups as the Karen, as well as all such indigenous knowledge everywhere, can be conceptualized as falling into six categories or levels: 1) indigenous technical knowledge (ITK), the cognitive structure of indigenous knowledge and its language forms; 2) indigenous knowledge about local social organization, how people organize themselves to use ITK in relation to, for example, the conservation and use of resources; 3) indigenous knowledge about decision-making processes and patterns, how knowledge regarding resource conservation and use is employed by individuals or groups to decide courses of action; 4) indigenous knowledge about innovations and experimentation, how knowledge is developed and refined; 5) indigenous knowledge as manifested in values and beliefs systems, how people feel about their knowledge; and 6) indigenous knowledge about teaching-learning transactions and communication, how people share or exchange their knowledge. Such local, experience-based indigenous knowledge about biological or natural phenomena may often contain scientific principles or, through careful scrutiny, yield new insights into important relationships specific to a particular location or ecosystem or perhaps generalizable to other similar settings or contexts.

Sometimes indigenous knowledge may be the only knowledge which exists about such phenomena, as particular insect-plant interactive relationships. Just as important, if not more so, is the improved communication that can occur between the lay population and scientists when the language for expressing the local knowledge is known. Scientific information can then be translated into the local language forms. Such communication is

Figure 23.4 A newly planted hillside in Thailand. (UN-FAO photo.)

needed to close the current gap between scientist-derived knowledge and indigenous, experience-based knowledge, to facilitate the functioning of an additional laboratory for scientific investigation, to identify and correct weaknesses or errors in either knowledge system, and to facilitate further discovery. The sustainable management of community forests in the future may depend upon the progress made in closing this gap (22).

Indigenous knowledge of how to sustainably manage natural resources exists wherever people have been actively engaged for decades in meeting the challenge. The Menominee of Wisconsin, mentioned above, practice logging by starting at one end of the reservation and, over a period of several years, progressively moving toward the opposite boundary of the reservation, selectively cutting only mature trees before returning to the initial starting point to restart the process. The Menominee have found that this procedure enables them to take mature trees for timber, maintain the integrity and quality of the forest ecosystem, and provide a continuous source of livelihood for the community.

In the Philippines, farmers in mountain communities have joined together to develop multistory systems of agroforestry, which allow the growth of a variety of tree crops within the same plots, taking advantage of the photosynthesis, shade requirements and tolerance, and soil nutrient needs of such trees and plants as coconut, banana, papaya, and pineapple. Many combinations of such intercropping have been tested and found effective by the local farmers through their own experiments and the intergenerational transmission of the resulting and gradually accumulating knowledge. Other farmers have developed ways to reinforce hillside terraces, where agricultural crops are produced, by planting deep-rooting trees along the edge of terraces to hold soil in place, thereby preventing or reducing soil erosion (Figure 23.5). The trees selected (e.g., calliandra) also provide a steady supply of fuelwood and leaves for fodder for animals (23).

In many areas of the world, cooperation among government organizations in the delivery of services to community-based social forestry programs is still rare or weak. In some areas, progress is being made in strengthening such interagency cooperation. In Thailand, the Royal Forestry Department and Department of Community Development, recognizing each other's respective strengths, have joined forces in a pilot experiment for supporting

Figure 23.5 Palm trees incorporated in terraced hillside planting in Indonesia. (Photo by K. L. Young.)

local participation in community forestry and natural resource conservation. The two government units, with advisory inputs from faculty at two universities, aim to establish a model to guide the provision of the technical expertise of the 400 forestry staff members and the social organization expertise of 6,000 community development workers to the country's 60,000 village communities in the promotion of the sustainable management of community forests. Using a participatory land-use planning strategy and raised topographical maps as a tactile device for fostering visual clarity, villagers are encouraged to identify, agree upon, and implement needed changes in the conservation and use of the natural resources in the surrounding area. The work thus far has resulted in significant changes and improvements in both agricultural practices and forest resource management in the pilot villages.

Improved patterns of cooperation also are needed among communities having access to the same resource base. For example, forest conservation efforts are often located within watersheds containing a number of village communities, requiring cooperation in the management of common-pool forest and water resources. Laos, with assistance from the UNDP, has begun the piloting of watershed ecosystem-based development emphasizing technical analysis of watershed resources, constraints, and potential; the decentralization of governmental authority; local participation in intervillage watershed ecosystem management councils; and mobile district management teams that include training and monitoring and evaluation specialists. The rules governing the sustainable use and management of forest resources are determined locally and enforced by the communities themselves. The major issue encountered in the project to date has been failures in the devolution of power from government bureaucracies to local communities, even though the project objectives previously agreed upon were to do exactly that. It seems that entrenched bureaucracies are difficult to change and are frequently an obstacle to the achievement of community-based management of natural resources in many settings (24).

Efforts to alleviate rural poverty through the promotion of community-based agroforestry programs have had mixed degrees of success. The Forestry Bureau of Yunnan, China, discovered that the increased apple production stemming from Bureau provision of tree saplings to mountain communities resulted in a flood of apples into the market and the lowering of prices so drastically that farmers became disinclined to further expand production. The basic problem seems to have been an insufficient range of agroforestry crops that would allow farmers to adjust to changing market demands (Figure 23.6). A subsidiary issue is the singular control of tree nurseries by the Forestry Bureau, a policy that inhibits possibilities for diversification and provision of tree stocks that are in line with farmer preferences. Field studies of villager interests in the cultivation of various types of trees and their preferences for planting trees in different locations within their farm area, showed clear choices of specific trees for different locations (near family dwelling, at edge of fields, near streams, on a hilltop) and purposes (shade, windbreaks, soil conservation, wildlife habitat). Yet the Bureau was not able to respond to these choices and preferences (25).

Community-owned and -operated tree nurseries can sometimes provide an answer to the diversity of needs and preferences for tree stocks. Commu-

Figure 23.6 Agroforestry development in Amazonia. (UN-FAO photo.)

nity forestry programs in Costa Rica have emphasized the establishment and control of tree nurseries by the communities themselves. The saplings nurtured are those desired by the community. In some communities, a deliberate effort has been made to turn the responsibility for the management of the nurseries over to the most impoverished segment of the community's inhabitants. Oftentimes the managers are women who find nursery management work and sales correspond conveniently with other family or household responsibilities. The income earned from the sale of the saplings also goes directly to meeting family needs.

In Andhra Pradesh State of India, one joint forest management 0FM) project has enabled villagers to become self-sufficient with money earned from timber and bamboo (Figure 23.7). "Poverty was caused by environmental degradation. So we made poverty alleviation our primary target through environmental regeneration," says one spokesman for the project. The project was implemented in an area under the control of the Naxalite movement, which started as a revolt against the inequitable distribution of land and water. Vana Suraksha Samiti (VSS) or Forest Protection Committees were established and govern the redistribution back to the villagers of all income earned from timber and bamboo (26).

Issues and Challenges

In addition to the lessons, principles, strategies, problems, needs, questions, issues, and challenges described thus far, there are several others that warrant mentioning, because they will be the focus of scientific endeavors and development work during the decades ahead.

Participation and Local Initiative

Local citizen participation in social forestry programs and schemes seems to be critical to success. Yet considerable disagreement exists over the nature and amount of participation that is desirable, obtainable, and sustainable. Creating a participative environment, one that contains an appropriate incentives structure and works to positively affect and sustain interest and active participation, appears to remain an elusive goal in most programs

Figure 23.7 Fuelwood supply and collection is a critical problem in many developing countries, shown here in India. (Photo by R. A. Young.)

and projects. How to stimulate local initiative and a sense of ownership for a social forestry program among local groups from the very inception of an activity, how to assure participation in an equitable distribution of benefits, and how to assure co-learning by both local citizens and project facilitators remain challenges for the developers of the science and practice art. Failure to set the right tone in participation can lead local people to misunderstand and react negatively to the whole enterprise, and at worst, can lead local people to feel that government is asking them "to plant government trees on their land." The design and testing of mechanisms for facilitating empowerment, autonomy, self-realization, and community-based management seem to be in an early stage of design and testing and will need to be developed or refined in the years ahead.

Community Control

Another key to effective social forestry is community control of forest resources, related money flow, and local capacity for money management. Reports on social forestry programs around the world suggest these are some of the most critical factors in determining success. Often little information exists regarding either the land and forest resources available or the nature of the conditions of the surrounding human population. Community forest resource assessments have sometimes been carried out to help secure tenure and rights to forest resources, seek compensation for lost or threatened resources, provide an information base for use in managing forests sustainably, and monitor biodiversity for conservation. Securing tenure, creating appropriate economic incentives, and strengthening institutional capacity for social forestry programs require considerable managerial ability and mutual understanding and cooperation, that is, a *modus cooperandi* writ large, between people and their governments. Yet many local groups seem to lack, for one reason or another, the requisite skills needed to effectively manage, especially within collective arrangements, valuable and scarce natural resources and related organized human behavior. The training of citizens for administrative tasks, the local provision of technical assistance and economic advice, and for forestry-related business roles to promote independence, self-reliance, and sustainability remain important challenges that warrant much attention.

Program Planning and Development

The achievement of success in social forestry programs and in the advancement of the science and art of the field of practice calls for much reflection, theory building, skills development, planning, implementation, and evaluation. Community-based management of forests entails participatory land-use planning and management, the development of land stewardship, a continual reinvestment of benefits derived, and an ensuing strengthening of the social dimension of local communities. Many issues, questions, and propositions concern the nature of such local natural resource planning: 1) the necessity of decentralization of decision-making and responsibility in support of community-based management of forests, 2) the nature and degree of top-down and bottom-up interactions in program planning and implementation, 3) ways and means of arriving at appropriate site-specific recommendations, 4) the nature of formats and processes for comprehensive planning of social forestry programs, and 5) the problems of and prospects for co-management of social forestry and for mediating system incompatibilities. One choice seems to be that of finding common ground between state and local management in the benefit distribution of collective forest resources, on the one hand, as against having a local state-sponsored entity managing forestry activities. A question seems to be whether this is the best course for local social and ecosystems. The design and testing of more site-specific management plans based on considerations of indigenous knowledge systems and defined in terms of local needs and benefits must go forward. In this regard, China's contract responsibility system may be a model with potential for worldwide applicability.

Legal and Policy Environment

A people's approach to social forestry also requires the formation of supportive policies. Social forestry can only occur within a supportive legal and policy environment. Such policy must be blended with both culture and legislation. There needs to be clarity in terms of access to resources, contractual accountability, and regulatory responsibility. When local communities and their members are asked to make forestry a more important part of their livelihood strategies, they need to be provided with clear terms on which to do so and assurance that government is committed to those terms. In parts of Africa, social forestry has been discouraged when national governments grant tree-cutting concessions to urban elites, who so empowered show up to cut forest resources which communities have been husbanding. More studies of the range of factors and forces that hinder or enhance policy implementation are needed.

Ecological Settings and Processes

Social forestry is practiced in a wide variety of geophysical landscapes such as hillsides, mountain tops, river valleys, watersheds, arid plains, wetlands, buffer zones around protected areas, and degraded lands. Each of these provides unique features and parameters that influence if not dictate the nature of social forestry activities which take place. Sometimes the major concerns are forest disturbance, transformation, or recovery, while at other times the major concern is with the nature of practices and rates of utilization of forest resources that are sustainable within each context. Because of insufficiency in laws and regulations for governing forest use and in forestry personnel to enforce them, locally organized community-based groups for supervising forest use are essential in many locations if forest-based ecosystems are to be restored and sustained.

Watershed Management

There are many locations around the world where an ecosystem approach to natural resource management will frequently involve the conservation and protection of forests by multicommunity groups that reside within the same watershed. A better understanding of how such groups can work together to protect and sustain the watershed ecology is needed in many areas. How to approach and work effectively with such groups remains a major challenge for most government and nongovernment organizations.

Land and Tree Tenure

People's social forestry-related behavior is affected by their real or perceived security of ownership or user rights to land and land-based natural resources. A sense of security influences human motivation and ability to protect forests from exploitation by outside forces. *Tenure* itself is a broad concept. In reality, it may include a variety of tenure "niches": state-controlled lands, trees in communal areas, sacred sites, resettlement areas, or individual lands, for example. Other tenurial contexts such as private timber lands, collective tree tenure, and private tree tenure will also influence the nature of social forestry activities. Tenurial processes within changing forest use patterns need to be clearly understood. Often land or tree tenure is based on gender, and the stability of such rights, especially those of women, varies from one area or culture to another. The length of time for which tenure is awarded also affects the motivational base of land husbandry and forest stewardship and the type of practices of agriculture and forest protection and use. In some locations, it has become necessary to award long-term stewardship certificates to local communities as a basis for encouraging desired behaviors.

Land Use Patterns

Changes in landscapes frequently result from large-scale infrastructural developments such as hydroelectric dams of major streams, vast irrigation and electricity networks, new roads or other transportation systems, oil or gas pipelines and storage facilities, and the setting aside of lands as biosphere reserves or natural parks and recreation sites. How such developments affect land use patterns and the practice of social forestry by local populations or the adaptations they make to these large macrospective infrastructural changes that are beyond their control is a subject that warrants much study.

Agroforestry

As stated by the previous Director-General of the International Center for Research in Agroforestry (ICRAF) in Kenya, the world's farmers are far ahead of the scientists in regard to knowledge of and experience with crop/soil/tree/animal/water relationships because they have been doing it for thousands of years. One strategy for efficiently advancing our scientific understanding of such relationships is to study what farmers are already doing and then testing and measuring observed concepts and relationships for validity and utility under varying conditions. In much of the world, the "agroforestry" of fuelwood, food, fiber, livestock, soil fertility, water, and income generation is central to social forestry concerns (Figure 23-8). Working with groups of farmers or even whole communities, it may become possible to find acceptable ways to resolve such issues as the conversion of forests to pasture, of preventing soil erosion in hilly regions with tree reinforced contours, or preventing wind erosion through strip planting, and which type of tree crops to use in which locations as a means of nitrogen fixation.

Forest and Woodland Management

More frequently today, local communities or social groups are formed to manage forests and woodlands, quite often because there are not sufficient government personnel to do such work, sometimes because of the realization that local people may be highly motivated to do the work well. Thinking and action regarding forest management ranges from scientific certification systems for sustainable forest management to indigenously derived systems for managing the sustainable extraction of renewable wood and nonwood resources. Issues exist concerning whether to practice selective, or partial, or clearcutting of trees, and under what conditions and why; the feasibility of compartmental management of forests; the solving of differences in ideal choice of tree species and type of forest cover versus local preference; whether local peo-

Figure 23.8 Roadside fuelwood plantation in Tanzania. (Photo by B. K. Kaale, World Food Program, UN-FAO.)

pie (especially the rural poor) can be sufficiently trained and entrusted with the tasks of managing tree nurseries and tree planting; and the validity of indigenous methods and locally created "appropriate" technologies. Social forestry provides a context for the search for answers to such questions and resolution of such issues.

Wood Industry

In many parts of the world, the ups and downs of the wood industry are tied inextricably to local community acceptance of or resistance to the extraction rates and patterns practiced by timber companies. Controversy over the nature and length of timber leases has pitted local communities concerned with the ecological basis of their own economic survival against the voracious appetites of timber companies and sometimes corrupt forestry officials. The mobilization of community protests against destructive wood industry practices is a major theme in many parts of the world. These problems are so pervasive that during the last four years of the 1990s, the World Bank has refused to fund any projects involving commercial logging. A recent evaluation of the Bank's policy pointed out, however, that this had simply left a lucrative area of lending open to private lenders who lack the Bank's compunctions.

Reforestation and Ecological Restoration

Invigorating the biophysical and socioeconomic landscape of severely denuded and impoverished regions becomes a more realistic and necessary proposition as the human population continues to expand and the number of suitable alternative placements decrease. The challenge of restoring degraded areas to ecologically desired states requires the cooperation of governments and local communities. Certainly, in many locations, current policies of removing inhabitants from areas under restoration represents a debatable issue. The root causes of ecosystem degradation, whether social, political, economic, or natural/environmental, must be addressed and ways and means must be sought to help local forest-dependent communities find economic opportunities that will enable them to survive while protecting their forest resources. Much community forestry work is based on the failure by weak governments to enforce negative sanctions effectively, and the hope that providing an interest in the preservation of the forest to local people will give them the necessary incentive to help police the resource. An integrated set of actions may be needed: from improving logging practices, to diversifying local economies, to identifying incentives so that local people will feel that they have a "stake" in the restoration efforts, to strengthening local governance, to formulating and enforcing policy reforms. Social forestry will be of central importance to success in these actions.

Biodiversity Conservation

Much current social forestry focus is on the rationale for and means of creating effective buffer zones around biosphere reserves. Buffer zones are envisioned as means to resist land speculation, reduce negative forest edge effects, increase biodiversity, deflect forest pressures, and improve community conditions. The conceptual and programmatic links to community development are potentially strong but require the formulation of means to promote a wise use of nontimber forest products (NTFP), to alleviate fuelwood pressures, reduce environmentally destructive and, therefore, unsustainable agricultural practices, and optimize community participation in the protection of the nature reserves. Prospects for the establishment of effective buffer zone programs will also depend on the extent to which appropriate and locally accepted forms of economic and legal freedom are achieved because capacity for direct enforcement by government authorities is too limited. Cultural factors must also be considered. In Africa and Asia, "sacred forests" are proving an important source of biological diversity, preserved by indigenous systems of sanctioning including religious prohibitions. Obviously, social forestry must encompass such considerations.

Sociocultural Context

Various sociocultural factors affect the prospects for sustained health of forest resources. Some progress is now being made in understanding the differences between Western property laws and indigenous tenure systems, of how local life is often intertwined with various aspects of a forest, and the perceptions of different ethnic groups regarding forest-people reciprocity. Studies that have explored the cultural basis of human interaction with natural resources should be assessed for insight into the cultural basis of social forestry.

Indigenous Knowledge Systems (IKS)

The prospects for designing site-specific social forestry plans that will be implemented on a sustained basis by the people inhabiting a target area will largely hinge upon the extent to which local, indigenous knowledge is studied, understood, and taken into account. Such knowledge may often become the foundation from which sustainable programs can be built. They can be the curriculum from which a "conscientization" or awareness-building process can be launched. In some locations, this may be the only way, outside of external economic or legal inducements, that sustained local participation can be achieved. The process whereby local communities or groups adapt to changes taking place around them in order to survive calls for a dynamic interaction between indigenous, experience-based knowledge systems and scientist-derived knowledge systems. This proposition poses as much of a challenge to scientists today as it does to local people because the process and methods for learning from indigenous experience require a considerable investment of valuable time and energy. Hope for blending the traditional governance of local societies and cultures with the functioning of an international economy in a mutually beneficial manner may rest, at least in part, upon the extent to which IKS is brought into the equation.

Gender and Poverty

Women comprise the majority of the world's population and suffer the effects of gender-based biases and inequalities. The importance of integrating women into decision-making processes concerning the management and use of natural resources is undeniable. In social forestry, a major need today is understanding the differentiation of gender-specific tasks based on tree species, products, and local culture. In Africa, there are some cultural practices that interfere with women participating in social forestry, such as prohibitions of tree planting by women, tree planting being treated as a men's activity, or taboos that will not allow women to deal with certain tree species. On the other hand, the example of rural poor women in Costa Rica taking on the task of operating tree nurseries as a means of earning income while simultaneously providing a service essential to the restoration or reforestation of degraded areas suggests a potentially fruitful direction. It is also an example of the type of social forestry activities that need to be designed and tested. The alleviation of rural poverty in degraded resource areas constitutes a major challenge for many governments, many having already experienced significant difficulty in finding effective means of improving the quality of life of the weaker sections of their population.

Migration and Settlement

Of increasing concern to environmentalists is the shifting and resettlement of human populations, as a part of nomadic traditions, as a result of natural disasters, as a result of the overcrowding of urban areas, or just because of formal government plans to occupy or create more favorable human environments (Figure 23.9). It is likely that the pressure for this will become larger in years ahead as the world's base population expands. Much work needs to be done in designing and testing the nature and extent of services required by new settlements in forested areas and in finding ways and means of working effectively in partnership arrangements

Figure 23.9 Creation of logging roads, such as this one shown in Papua, New Guinea, opens access for migration and settlement in forest regions leading to further decline of tropical forests.

with such new communities to promote a viable form and level of human existence while sustaining the surrounding forests.

Economic Change

Several key economic questions and issues surround social forestry: 1) the design and conduct of cost-benefit analyses of programs and activities; 2) the determination of rates of return for social investments; 3) the distribution of benefits from collective endeavors; 4) the efficiency of community-based forest enterprises; 5) the economic viability of state monopolies versus farmers responding to free markets; 6) the required nature and degree of reinvestment of derived benefits at the local level to maintain sustainability; 7) the balancing of community economic development with forest sustainability; 8) the formation and functioning of forestry cooperatives as a means to protect the environment and improve the local economy; 9) the division of profits for reinvestment and for individual and group benefits; 10) estimating the costs of forest assessments (labor, capital, maintenance, professional expertise); 11) managing for the market versus managing for biodiversity and maintaining a choice among species; 12) the clash of interests between community forest enterprises (CFE) and world trade efficiencies; and 13) the nature and amount of compensation required for "ecological" services delivered by the poorer segments of the population, for example, community tree nurseries run by women in impoverished rural villages in Costa Rica. What types of socioeconomic alternatives exist to thwart the excessive use of forest and forest products or what alternatives might be developed? What incentives are necessary for individuals to become willing to consider such alternatives?

Interorganizational Collaboration

Integrated service delivery remains an elusive goal for many government and nongovernment organization-sponsored social forestry projects. Appropriate and timely response to local needs and perceptions of the same is not easily achieved. Social forestry programs are not immune from this aspect of programming failure. Some success has been experienced when agencies or organizations move from acting as patrons of local efforts to becoming encouragers and facilitators of local initiative and responsibility. The big challenge in the community-based management of natural resources continues to be the acceptance and use of adaptive and facilitative styles for dealing with diverse forests and the human users of the same. Ways and means of achieving and maintaining interorganizational collaboration in such responsive programming need to be sought, tested, and adapted to fit varying local circumstances.

Conflict Resolution

Disputes over access to and the control and management of natural resources occur; 1) within communities; 2) between communities; 3) in contests between public versus private property rights; and 4) between individual rights and the community good. In many cases, organizational structures and dispute settlement mechanisms for "mediating" democratic processes of conflict resolution often exist for categories 1 and 4, but not for 2 or 3.

Extension

Key concepts and issues regarding the role of extension in social forestry programs are: 1) forester credibility; 2) prospects for fostering farmer-to-farmer exchanges regarding agroforestry practices; 3) establishing and working effectively with farmer associations to arrive at group decisions on policies and practices; 4) achieving accuracy in target grouping; 5) the willingness to revamp strategies in a continuing quest to increase relevance, effectiveness, and efficiency in program actions; 6) improving communications with clientele; 7) improving rural people's understanding of the limits on forest use; and 8) extension staff willingness to serve as catalysts and facilitators working among the ranks of (and not trying to serve as representatives for) the people they serve.

Measurement and Evaluation

There are serious social, ecological, and economic implications attached to the types of evaluation and measurement methods and techniques used in social forestry programs. The results of using or emphasizing one method or approach over another may influence the balance of ecological parameters with the marketplace or the balance between promoting income generation and maintaining resource base integrity. Assessment methodology has advanced rapidly in recent years as a result of the development of: 1) remote sensing capacities; 2) pairing geographic information systems (GIS) with thematic mapping using participatory rapid appraisal (PRA) or participatory land-use planning (PLP) techniques; 3) conducting continuous forest or timber inventories; 4) mapping resource boundaries; and 5) inventorying nontimber forest products (NTFP). A related issue is the use of different monitoring and evaluation methods by different organizations and agencies working in the same service area, resulting in varying kinds and levels of data being collected and, therefore, different interpretations being given to local conditions and needs. This situation often seriously reduces the chances for effective interorganizational response to local community forestry efforts. Additionally, most measurement science assumes the involvement of local citizens, yet ways need to be designed and tested for properly introducing it to them and effectively developing their abilities and willingness to employ it themselves.

Concluding Statement

Social forestry as a science and practice art is evolving rapidly in response to increasing pressures on forest resources and forest-based ecosystems around the globe. A recognition of the necessity to mobilize human communities to assume a greater responsibility and role in conserving the earth's natural resources has gradually emerged. Yet the consolidation of the principles and lessons from decades of experience in diverse settings and situations remains an unfinished task.

An ecosystem approach to local management of natural resources will require collaboration at all levels, but community responsibility will remain the key to success. It has been and will continue to be a challenge to combine an ecosystem approach and community management because communities may not be organized for natural resource management at the ecosystem scale. It will continue to be necessary to: 1) raise levels of public awareness, understanding, and appreciation of the need for and nature of community-based natural resource management; 2) create capacities for intercommunity collaboration in ecosystems occupied by several communities; 3) develop the forestry science that must undergird such work, 4) identify the policy frameworks necessary to support community control and initiative; and 5) empower local groups with a wide variety of skills critical for getting the job done well. Much of what will be needed has been discussed in the preceeding sections. Much more will need to be discovered or developed.

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APPENDIX I

Common and Scientific Names of Tree Species Mentioned in the Text

Common Names	Scientific Names
Acacia	*Acacia* spp.
Achin	*Pistacia mexicana*
Ailanthus or tree of heaven	*Ailanthus altissima*
Alder, common or European	*Alnus glutinosa*
red	*Alnus rubra*
Aliso	*Alnus jorullensis*
American hornbeam (see Beech)	
Ash, American mountain	*Sorbus americana*
common	*Fraxinus excelsior*
flowering	*Fraxinus ornus*
green or red	*Fraxinus pennsylvanica*
mountain	*Eucalyptus regnans*
Oregon	*Fraxinus latifolia*
white	*Fraxinus americana*
Aspen (European)	*Populus tremula*
largetooth or bigtooth	*Populus grandidentata*
quaking or trembling	*Populus tremuloides*
Bald cypress (see Cypress)	
Balsa	*Ochroma pyramidale*
Bamboo	*Cephalostachyum pergracile*
Basswood, American or American linden	*Tilia americana*
small-leaved linden	*Tilia cordata*
white	*Tilia heterophylla*
Beech, American	*Fagus grandifolia*
blue, or American hornbeam	*Carpinus caroliniana* (*Carpinus betulus virginiana*)
common or European	*Fagus sylvatica*
eastern hornbeam	*Carpinus orientalis*
European hornbeam	*Carpinus betulus*
southern	*Nothofagus* spp.
Bigcone Douglas fir (see Fir)	

Common Names	Scientific Names
Birch, gray or field	*Betula populifolia*
river	*Betula nigra*
silver	*Betula verrucosa*
sweet or black	*Betula lenta*
white or paper	*Betula papyrifera*
yellow	*Betula alleghaniensis* (*Betula lutea*)
Blackgum (see Gum)	
Blue beech (see Beech)	
Box elder (see Elder)	
Buckeye, Georgia	*Aesculus georgiana*
yellow	*Aesculus octandra*
Butternut	*Juglans cinerea*
Camaron	*Alvaradoa amorphoides*
Caoba	*Swietenia humilis*
Carob tree	*Ceratonia siliqua*
Castano bellota	*Sterculia mexicana*
Catalpa, northern or hard	*Catalpa speciosa*
southern	*Catalpa bignonioides*
Cedar, Alaska yellow	*Chamaecyparis nootkatensis*
Alantic white	*Chamaecyparis thyoides*
eastern redcedar	*Juniperus virginiana*
incense	*Libocedrus decurrens*
Japanese	*Cryptomeria japonica*
northern white, or eastern arborvitae	*Thuja occidentalis*
Port Orford	*Chamaecyparis lawsoniana*
prickly juniper	*Juniperus oxycedrus*
western juniper	*Juniperus occidentalis*
western red cedar	*Thuja plicata*
Cherry, black	*Prunus serotina*
cornelian	*Cornus mas*
pin	*Prunus pensylvanica*
Chestnut, American	*Castanea dentata*
Spanish	*Castanea sativa*
Chinatree or chinaberry	*Melia azedarach*

Common Names	Scientific Names
Chinkapin, golden	*Castanopsis chrysophylla*
Chokeberry	*Aronia* spp.
Coffeetree, Kentucky	*Gymnocladus dioicus*
Cottonwood (see Poplar)	
Crape myrtle	*Lagerstroemia indica*
Cucumbertree or cucumber magnolia	*Magnolia acuminata*
Cypress, bald cypress	*Taxodium distichum*
Monterey	*Cupressus macrocarpa*
Montezuma	*Taxodium mucronatum*
Dogwood, flowering	*Cornus florida*
Douglas fir (see Fir)	
Doveplum	*Coccoloba diversifolia*
Elder, box	*Acer negundo*
Elm, American or white	*Ulmus americana*
English	*Ulmus procera*
Japanese	*Ulmus japonica*
rock or cork	*Ulmus thomasii*
Siberian	*Ulmus pumila*
winged	*Ulmus alata*
Eucalyptus	*Eucalyptus* spp.
False mastic	*Sideroxylon foetidissimum*
Filbert (see Hazel)	
Fir, alpine, or subalpine	*Abies lasiocarpa*
balsam	*Abies balsamea*
bigcone Douglas fir	*Pseudotsuga macrocarpa*
California red	*Abies magnifica*
Douglas fir	*Pseudotsuga menziesii*
Fraser	*Abies fraseri*
grand or lowland white	*Abies grandis*
noble	*Abies procera (Abies nobilis)*
Pacific silver	*Abies amabilis*
silver	*Abies alba*
white	*Abies concolor*
Fish poison tree, Florida	*Piscidia piscipula*
Ginkgo tree	*Ginkgo biloba*
Gmelina	*Gmelina arborea*
Goldenrain tree	*Koelreuteria paniculata*
Gum, black or black tupelo	*Nyssa sylvatica*
red or sweetgum	*Liquidambar stryaciflua*
swamp tupelo	*Nyssa sylvatica biflora*
tupelo or water tupelo	*Nyssa aquatica*
Gumbo-limbo	*Bursera simaruba*
Hackberry	*Celtis occidentalis*
Hazel, European or filbert	*Corylus avellana*

Common Names	Scientific Names
Hemlock, eastern	*Tsuga canadensis*
mountain	*Tsuga mertensiana*
western	*Tsuga heterophylla*
Hickory, bitternut	*Carya cordiformis*
mockernut	*Carya tomentosa*
pignut	*Carya glabra*
shagbark	*Carya ovata*
Holly, American	*Ilex opaca*
Honeylocust	*Gleditsia triacanthos*
Hoja fresca	*Gilbertia arborea*
Hophornbeam, eastern	*Ostrya virginiana*
European	*Ostrya carpinifolia*
Hornbeam (see Beech)	
Horsechestnut (Buckeye)	*Aesculus hippocastanum*
Huisache	*Acacia farnesiana*
Ironwood	*Dialium guianense*
Judas tree	*Cercis siliquastrum*
Juniper (see Cedar)	
Karri	*Eucalyptus diversicolor*
Kentucky coffeetree (see Coffeetree)	
Larch, American, eastern, or Tamarack	*Larix laricina*
European	*Larix decidua (Larix europaca)*
subalpine	*Larix lyallii*
western	*Larix occidentalis*
Laurel, bay	*Laurus notilis*
California, Oregon-myrtle	*Umbellularia californica*
Leadwood	*Krugiodendron ferreum*
Lemonwood	*Psychotria capensis*
Lignum vitae	*Guaiacum sanctum*
Linden (see Basswood)	
Locust, black or yellow	*Robinia pseudoacacia*
Madrone, Pacific	*Arbutus menziesii*
Magnolia, cucumber (see Cucumbertree)	
southern	*Magnolia grandiflora*
Mahogany, West Indies	*Swietenia mahagoni*
Mangrove, black	*Avicennia nitida*
red	*Rhizophora mangle*
Maple, bigleaf	*Acer macrophyllum*
Norway	*Acer platanoides*
red (including trident)	*Acer rubrum*
silver	*Acer saccharinum*
sugar	*Acer saccharum*

Common Names	*Scientific Names*
sycamore	*Acer pseudoplatanus*
vine	*Acer circinatum*
Melina	*Gmelina arborea*
Metasequoia	*Metasequoia glyptostroboides*
Monkey pod, monkey puzzle	*Araucaria araucana*
Mulberry, red	*Morus rubra*
white	*Morus alba*
Nettle tree, European	*Celtis australis*
Oak, black	*Quercus velutina*
blackjack	*Quercus marilandica*
bur	*Quercus macrocarpa*
California black	*Quercus kelloggii*
California live	*Quercus agrifolia*
California white	*Quercus lobata*
canyon live	*Quercus chrysolepis*
cherrybark	*Quercus falcata pagodaefolia*
chestnut	*Quercus prinus*
cork	*Quercus suber*
durmast	*Quercus petraea*
English	*Quercus robur*
holm	*Quercus ilex*
Hungarian	*Quercus frainetto*
live	*Quercus virginiana*
northern red or eastern red	*Quercus rubra (Quercus borealis)*
Oregon white	*Quercus garryana*
overcup	*Quercus lyrata*
pin	*Quercus palustris*
post	*Quercus stellata*
pubescent	*Quercus pubescens*
scarlet	*Quercus coccinea*
silky	*Grevillea robusta*
southern red	*Quercus falcata*
swamp chestnut	*Quercus michauxii*
turkey (United States)	*Quercus laevis (Quercus catesbaei*
turkey (Europe)	*Quercus cerris*
water	*Quercus nigra*
white	*Quercus alba*
willow	*Quercus phellos*
Olive	*Olea europaea*
Oriental plane	*Platanus orientalis*
Osage-orange	*Maclura pomifera*
Oyamel	*Abies religiosa*

Common Names	*Scientific Names*
Paulownia	*Paulownia tomentosa*
Pecan	*Carya illinoensis*
Persimmon, common	*Diospyros virginiana*
Pine, aleppo	*Pinus halepensis*
apache	*Pinus engelmannii*
bishop	*Pinus muricata*
black or Austrian	*Pinus nigra*
bristlecone	*Pinus aristata*
Caribbean	*Pinus caribaea*
Chihuahua or piño chino	*Pinus leiophylla* var. *chihuahuana*
Coulter	*Pinus coulteri*
Digger	*Pinus sabiniana*
eastern white	*Pinus strobus*
foxtail	*Pinus balfouriana*
jack	*Pinus banksiana*
Jeffrey	*Pinus jeffreyi*
Khasia	*Pinus kesiya*
knobcone	*Pinus attenuata*
limber	*Pinus flexilis*
loblolly	*Pinus taeda*
lodgepole	*Pinus contorta*
longleaf	*Pinus palustris*
maritime	*Pinus pinaster*
Merkus	*Pinus merkusii*
Mexican weeping	*Pinus patula*
Monterey	*Pinus radiata*
Norfolk Island	*Araucaria heterophylla*
pinabete	*Pinus ayacahuite*
piño Colorado	*Pinus teocote*
piño de Montezuma	*Pinus montezumae*
piño prieto	*Pinus oocarpa*
pinyon	*Pinus edulis*
pitch	*Pinus rigida*
pond	*Pinus serotina*
ponderosa or western yellow	*Pinus ponderosa*
(Rocky Mountain form)	*Pinus ponderosa* var. *scopulorum*
red or Norway	*Pinus resinosa*
sand	*Pinus clausa*
Scotch or Scots	*Pinus sylvestris*
shortleaf	*Pinus echinata*
slash	*Pinus elliotti*
southwestern white	*Pinus strobiformis*
spruce	*Pinus glabra*
stone	*Pinus pinea*

Common Names	Scientific Names
sugar	*Pinus lambertiana*
Virginia or scrub	*Pinus virginiana*
western white	*Pinus monticola*
whitebark	*Pinus albicaulis*
Poplar, California or black cottonwood	*Populus trichocarpa*
eastern or eastern cottonwood	*Populus deltoides*
swamp cottonwood	*Populus heterophylla*
yellow, or tuliptree	*Liriodendron tulipifera*
Prickly ash, lime	*Zanthoxylon fagara*
Quebracho	*Schinopsis* spp.
Redberry eugenia	*Eugenia confusa*
Red cedar (see Cedar)	
Redwood	*Sequoia sempervirens*
Rompezapato or saffron-plum	*Bumelia celastrina*
Rosewood	*Dalbergia* spp.
Royal palm, Florida	*Roystonea elata*
Sassafras	*Sassafras albidum*
Sequoia, giant	*Sequoiadendron giganteum*
Silk-cotton tree	*Ceiba pentandra*
Silktree	*Albizzia julibrissin*
Soapberry, wingleaf	*Sapindus saponaria*
Sourwood	*Oxydendron arboreum*
Spruce, black	*Picea mariana*
blue	*Picea pungens*
Engelmann	*Picea engelmannii*
Norway	*Picea abies*
red	*Picea rubens*
Sitka	*Picea sitchensis*
white	*Picea glauca*
St. Johns bread (see Carob tree)	
Strangler fig, Florida	*Ficus aurea*
Strawberry tree	*Arbutus unedo*
Sugarberry	*Celtis laevigata*
Sugi (see Cedar, Japanese)	
Sumac, winged	*Rhus copallina* var. *copallina*
Sweetbay, southern	*Magnolia virginiana*
Sycamore, American	*Platanus occidentalis*
Tamarack (see Larch)	
Tamarind, wild	*Lysiloma bahamensis*
Tanoak	*Lithocarpus densiflorus*
Teak	*Tectona grandis*
Torreya, California	*Torreya californica*
Tree of heaven, see Ailanthus	
Trumpet wood	*Cecropia mexicana*
Tupelo (see Gum)	
Walnut, black	*Juglans nigra*
Willow, black	*Salix nigra*
Yellow-poplar or tuliptree	*Liriodendron tulipifera*
Yew, common	*Taxus baccata*
Pacific	*Taxus brevifolia*

APPENDIX II

Common and Scientific Names of Animal Species Mentioned in the Text

Common Names	Scientific Names
Insectivores	
Mole, eastern	*Scalopus aquaticus*
Shrew	*Sorex* spp.
Hares and Rabbits	
Hare, snowshoe	*Lepus americanus*
Cottontail, eastern	*Sylvilagus floridanus*
Rodents	
Beaver	*Castor canadensis*
Gopher, pocket	*Thomomys* spp.
Mouse, white-footed deer	*Peromyscus maniculatus*
Porcupine	*Erethizon dorsatum*
Squirrel, flying (southern)	*Galucomys volans*
Squirrel, ground	*Spermophilus* spp.
chipmunk least (western)	*Eutamias minimus*
Squirrel, tree	
gray, eastern	*Sciurus carolinensis*
pine or chickaree	*Tamiasciurus douglasi*
red	*Tamiasciurus hudsonicus*
Voles	*Microtus* spp.
Carnivores	
Bear, black	*Ursus americanus*
grizzly	*Ursus horribilis*
Coyote	*Canis latrans*
Fisher	*Maries pennanti*
Fox, gray	*Vulpes fulva*
red	*Urocyon cinereoargenteus*
Lynx	*Lynx canadensis*
Mink	*Mustela vison*
Mountain lion	*Felis concolor*
Otter	*Lutra canadensis*
Raccoon	*Procyon lotor*
Wolf, gray or timber	*Canis lupus*
Wolverine	*Gulo luscus*

Common Names	Scientific Names
Even-Toed Ungulates	
Caribou, woodland	*Rangifer* spp.
Deer, mule	*Odocoileus hemionus*
white-tailed	*Odocoileus virginianus*
Elk (wapiti)	*Cervus canadensis*
Moose	*Alces alces*
Birds	
Bluebird, eastern	*Sialia sialis*
Catbird	*Dumetella carolinensis*
Chickadee, black-capped	*Parus atricapillus*
Cranes	*Grus* spp.
Creeper, brown tree	*Certhia familiaris*
Crossbill	*Loxia* spp.
Dove, mourning	*Zenaida macroura*
Duck, American golden-eye	*Glaucionetta clangula*
Barrow's golden-eye	*Bucephala islandica*
black	*Anas rubripes*
buffle-head	*Bucephala albeola*
hooded merganser	*Lophodytes cucullatus*
mallard, common	*Anas platyrhynchos*
wood	*Aix sponsa*
Eagle, bald	*Haliaeetus leucocephalus*
Falcon, peregrine	*Falco peregrinus*
Finch	*Carpodacus* spp.
Flycatcher, least	*Empidonax minimus*
Grosbeak, evening	*Coccothraustes vespertinus*
Goose, Canada	*Branta canadensis*
Grouse, blue	*Dendragapus obscurus*
prairie chicken or pinnated	*Tympamuchus cupido*
ruffed	*Bonasa umbellus*
sharp-tailed	*Pedioecetes phasianellus*
spruce	*Dendragapus canadensis*
Hawk, broad-winged	*Buteo platypterus*
goshawk	*Accipiter gentilis*

Common Names	Scientific Names
red-shouldered	*Buteo lineatus*
Heron	*Ardea* spp.
Jay, pinyon	*Gymnorhinus cyanocephalus*
Kestrel	*Falco sparverius*
Kingbird	*Tyrannus* spp.
Magpie	*Pica pica*
Martin, purple	*Progne subis*
Merganser, hooded	*Lophodytes cucullatus*
Nuthatch, white-breasted	*Sitta carolinensis*
Oriole, Baltimore	*Icterus galbula*
Osprey	*Pandion haliaetus*
Ovenbird	*Seiurus aurocopillus*
Owl, barred	*Strix varia*
horned	*Bubo virginianus*
saw-whet	*Aegolius acadicus*
Quail, bobwhite	*Colinus virginianus*
Raven	*Corvus corax*
Redpoll	*Carduelis* spp.
Siskin	*Carduelis pinus*
Swallow, tree	*Iridoprocne bicolor*
Swift, chimney	*Chaetura pelagica*
Thrush	*Hylocichla* spp.
Turkey, eastern	*Meleagris gallopavo silvestrii*
Vireo, red-eyed	*Vireo olivaceus*
Warbler, black-and-white	*Mniotilta varia*
blackburnian	*Dendroica fusca*
Kirtland's	*Dendroica kirtlandii*
Waxwing	*Bombycilla* spp.
Woodcock	*Philohela minor*
Woodpecker, downy	*Dendrocopus pubescens*
flicker	*Colaptes auratus*
hairy	*Dendrocopus villosus*
ivory-billed	*Campephilus principalis*
pileated	*Dryocopus pileatus*
red-cockaded	*Dendrocopus borealis*
yellow-bellied sapsucker	*Sphyrapicus varius*
Wren	*Thyrothorus* spp.
Insects	
Aphid, balsam woolly	*Adelges piceae*
Beetle, Douglas-fir	*Dendroctonus pseudotsugae*
Japanese	*Popillia japon ica*
mountain pine	*Dendroctonus ponderosae*
native elm bark	*Hylurgopinus rufipes*
smaller European elm bark	*Scolytus multistriatus*
southern pine	*Dendroctonus frontalis*
western pine	*Dendroctonus brevicomis*
Borer, bronze birch	*Agrilus anxius*
hemlock	*Melanophila fulvoguttata*
poplar	*Saperda calcarta*
two-lined chestnut	*Agrilus bilineatus*
Budworm, jack pine	*Choristoneura pinus*
spruce	*Choristoneura fumiferana*
Casebearer, larch	*Coleophora laricella*
Engraver, fir	*Scolytus ventralis*
pine	*Ips pini*
Looper, hemlock	*Lambdina fiscellaria*
linden	*Erannis tiliaria*
Moth, gypsy	*Lymantria dispar*
shoot, European pine	*Rhyacionia buoliana*
Douglas-fir tussock	*Orgyia pseudotsugata*
pine tussock	*Dasychira plagiata*
white-marked tussock	*Hemerocampa leucostigma*
Pitch nodule maker	*Petrova albicapitana*
Sawfly, European pine	*Neodiprion sertifer*
European spruce	*Diprion hercyniae*
jack pine	*Neodiprion pratti banksianae*
larch	*Pristiphora erichsonii*
red-headed pine	*Neodiprion lecontei*
red pine	*Neodiprion nanulus nanulus*
Swaine jack pine	*Neodiprion swainei*
Sawyer, southern pine	*Monochamas titillator*
white spotted	*Monochamus scutellatus*
Scale, pine tortoise	*Toumeyella numismatica*
Spanworm, elm	*Ennomos subsignarius*
Spittlebug, pine	*Aphrophora parallela*
Saratoga	*Aphrophora saratogensis*
Tent caterpillar, eastern	*Malacosoma americanum*
forest	*Malacosoma disstria*
Walkingstick	*Diapheromera femorata*
Wasp, wood	*Sirex* spp.
Weevil, pales	*Hylobius pales*
pine root collar	*Hylobius radicis*
white pine	*Pissodes strobi*

APPENDIX III

Unit Conversion Table

Linear Measure

	cm	*m*	*km*	*ft*	*mile*	*chain*	*link*
1 centimeter	1	0.01	10^{-5}	0.0328	6.214×10^{-6}	4.971×10^{-4}	0.04971
1 meter	100	1	0.001	3.2808	6.214×10^{-4}	0.04971	4.971
1 kilometer	10^5	1,000	1	3,280.84	0.6214	49.7097	4970.97
1 foot	30.4801	0.3048	$3{,}048 \times 10^{-4}$	1	1.8939×10^{-4}	0.01515	1.5152
1 mile	160,934.4	1,609.344	1.6093	5,280	1	80	8,000
1 chain	2,011.68	20.1168	0.02012	66	0.0125	1	100
1 link	20.1168	0.2012	2.0117×10^{-4}	0.66	1.25×10^{-4}	0.01	1

Mass Measure

	kg	*m ton*	*pound*	*short ton*
1 kilogram	1	0.001	2.2046	1.1023×10^{-3}
1 metric ton	1,000	1	2204.6226	1.1023
1 pound	0.4536	4.5359×10^{-4}	1	0.0005
1 short ton	907.185	0.9072	2,000	1

Area Measure

	m²	*ha*	*ft²*	*chain²*	*acre*	*mile²* (*section*)
1 hectare	10,000	1	107,639.1	24.7105	2.4711	0.0039
1 square meter	1	1×10^{-4}	10.7639	2.4711×10^{-3}	2.4711×10^{-4}	3.8610×10^{-7}
1 acre	4,046.86	0.4047	43,560	10	1	1.5625×10^{-3}
1 square mile	2.5910×10^6	258.999	27,878,400	6,400	640	1
1 township	—	9,323.9892	—	—	23,040	36
1 section	2,589,988	258.9997	27,878,400	6,400	640	1
1/4 section	647,497	64.7499	6,969,600	1,600	160	0.25
1/4-1/4 section	161,874	16.1875	1,742,400	400	40	0.0625

Volume Measure

	cm³ (ml)	*m³*	*in³*	*ft³*	*L*	*qt*
1 cubic centimeter	1	1×10^{-6}	6.1024×10^{-2}	3.5315×10^{-5}	0.001	1.0567×10^{-3}
1 cubic meter	10^6	1	6.1024×10^4	35.3147	1,000	1,056.688
1 cubic inch	16.3871	1.6387×10^{-5}	1	5.7870×10^{-4}	1.6387×10^{-2}	1.7316×10^{-2}
1 cubic foot	28,316.85	2.8317×10^{-2}	1,728	1	28.3169	29.9221
1 milliliter	1	1×10^{-6}	6.0124×10^{-2}	3.5315×10^{-5}	0.001	1.0567×10^{-3}
1 liter	1,000	0.001	61.0237	3.5315×10^{-2}	1	1.0567
1 quart	946.3529	9.4635×10^{-4}	57.75	3.3420×10^{-2}	0.9464	1

APPENDIX IV

Taxonomy of Selected Forest Trees

MAGNOLIOPHYTA (angiosperms)
Magnoliopsida (dicots)

Willow family (Salicaceae)
- Poplars, aspens *(Populus)*
- Willows *(Salix)*

Birch family (Betulaceae)
- Alders *(Alnus)*
- Birches *(Betula)* .

Beech family (Fagaceae)
- Chestnut, chinkapins *(Castanea)*
- Beeches *(Fagus)*
- Oaks *(Quercus)*

Elm family (Ulmaceae)
- Hackberries *(Celtis)*
- Elms *(Ulmus)*

Magnolia family (Magnoliaceae)
- Tuliptree *(Liriodendron)*
- Magnolia *(Magnolia)*

Laurel family (Lauraceae)
- Sassafras *(Sassafras)*

Witch-hazel family (Hamamelidaceae)
- Sweetgum *(Liquidambar)*

Sycamore family (Platanaceae)
- Sycamore *(Platanus)*

Mulberry family (Moraceae)
- Mulberry *(Morus)*

Maple family (Aceraceae)
- Maple *(Acer)*

Basswood (linden) family (Tiliaceae)
- Basswood *(Tilia)*

Legume family (Fabaceae)
- Honeylocust *(Gleditsia)*
- Locusts *(Robinia)*

Olive family (Oleaceae)
- Ashes *(Fraxinus)*

Walnut family (Juglandaceae)
- Hickories, pecan *(Carya)*
- Walnuts *(Juglans)*

Buckeye family (Hippocastanaceae)
- Buckeye, horsechestnut *(Aesculus)*

Rose family (Rosaceae)
- Hawthorns *(Crataegus)*
- Mountain ashes *(Sorbus)*

Liliopsida (monocots)

Palms and palmettos family *(Arecaceae)*

Lily family (Liliaceae)
- Yucca *(Yucca)*

CONIFEROPHYTA (gymnosperms)
Pine family (Pinaceae)
- Pines *(Pinus)*
- Firs *(Abies)*
- Spruces *(Picea)*
- Hemlocks *(Tsuga)*
- Douglas-fir *(Pseudotsuga)*
- Larches *(Larix)*
- True cedars *(Cedrus)*

Bald cypress family (Taxodiaceae)
- Bald cypress *(Taxodium)*
- Redwood *(Sequoia)*

Cypress family (Cupressaceae)
- Junipers *(Juniperus)*
- Cypresses *(Cupressus)*
- Cedars *(Chamaecyparis, Thuja)*

Yew family (Taxaceae)
- Yew *(Taxus)*

APPENDIX V

Glossary

A

Abiotic factors. Nonliving elements (factors) of the environment—that is, soil, climate, physiography.

Abscission. Dropping leaves, flowers, fruits, or other plant parts following the formation of a separation zone at the base of the plant part.

Absorbance. A measure of the ability of a surface to absorb incident energy, often at specific wavelengths.

Absorbed light. Light rays that are neither reflected nor transmitted when directed toward opaque or transparent materials.

Absorption. A process of attenuation through which radiant energy is intercepted and converted into other forms of energy as it passes through the atmosphere or other media.

Absorption band. A range of wavelengths over which radiant energy is intercepted by a specific material that may be present on the earth's surface or in the atmosphere.

Adaptation. Genetically determined character or feature of an organism that serves to increase reproductive potential or chance of survival.

Adsorption. Adhesion of the molecules of a gas, liquid, or dissolved substance to a surface, particularly of water molecules to the internal surface within the porous walls of wood and bark cells.

Advance regeneration. Young trees that have become established naturally before a clearcut is made.

Adventitious. Plant part that develops outside of the usual position or time or both.

Aerial film. A specially designed roll film supplied in many lengths and widths to fit aerial cameras. See *Color, Color infrared film, Infrared,* and *Panchromatic.*

Aerial photograph, oblique. An aerial photograph taken with the camera axis directed between the horizontal and the vertical.

Aerial photograph, vertical. An aerial photograph made with the optical axis of the camera approximately perpendicular to the earth's surface and with the film as nearly horizontal as is practical.

Aerial photographs, composite. Aerial photographs made with a camera having one principal lens and two or more sunounding and oblique lenses symmetrically placed; the several resulting photographs may be rectified in printing to permit assembly as verticals with the same scale.

Agrisilviculture. System of cultivation combining agriculture and forestry whereby tree plantations are interplanted with agricultural crops (the crops can yield a fast return while trees slowly mature).

Agroforestry. A system of planting agricultural crops in a compatible fashion with tree species, often in the forms of plantations.

Air-dry. Of timber or wood dried to equilibrium with the surrounding atmosphere.

Albedo. The percentage of the total illumination of a planet or satellite that is reflected from its surface.

Albuminous cells. Certain ray and axial parenchyma cells in gymnosperm phloem; associated with sieve cells.

Alkaloid. Nitrogen-containing toxins produced by plants that serve as defense compounds.

Allelopathy. Suppression of germination, growth, or the limiting of the occurrence of plants when chemical inhibitors are released by some plants.

Allogenic succession. Ecological succession resulting from factors (such as prolonged drought) that arise external to a natural community and alter its habitat (i.e., changes the vegetation).

Amorphous. Formless.

Anadromous. Ascending upriver from the sea to spawn; relating to such fishes as salmon.

Analog. A form of data display in which values are shown in graphic form, such as curves. Also, a form of computing in which values are represented by directly measurable quantities, such as voltages or resistances. Analog computing methods contrast with digital methods in which values are treated numerically.

Angiosperm. Vascular flowering plants that produce seeds enclosed in an ovary. Include monocotyledons (grasses and palms) and dicotyledons (herbaceous and woody plants).

Angle of incidence. The angle formed by a straight line, ray of light, or the like, meeting a surface and a normal to the surface at the point of meeting.

Anisotropic. Of a material whose properties vary according to the direction of measurement. The anisotropy of wood corresponds to the main features of wood structure and the marked anisotropy of the cellulose long-chain molecules.

Annual ring. One growth layer as seen in cross-section of a woody plant stem. Formed by contrast of springwood and summerwood.

Apical dominance. Influence exerted by a terminal bud in suppressing the growth of the lateral buds.

Apical meristem. Growing point at the tip of the root or stem. Gives rise to primary tissues.

Autecology. Study of the relationship between an individual organism and its environment.

Autogenic. Involving or resulting from a reaction between or in living organisms.

Autotrophic. Referring to green plants that make their own food by photosynthesis, and of bacteria that can grow without organic carbon and nitrogen. Self-nourishing.

Auxin. A plant growth-regulating substance. Among other effects, it controls cell elongation.

Avifauna. Bird life of a given region.

Axil. Angle between the upper side of a leaf or twig and the supporting stem.

Axis. Longitudinal support on which organs or parts are arranged; the stem and root; the central line of the body. Axial, adjective.

Azimuth. The geographic orientation of a line given as an angle measured clockwise from north.

B

Backfire. Fire set along the inner edge of a fire line to consume the fuel in the path of a forest fire, to change the direction of the fire, or both.

Bark. All tissue outside the cambium.

Basal area. Area of the cross-section of a tree stem, generally at breast height (1.3 meters or 4.5 feet) and inclusive of bark.

Bast fiber. Any of several strong, ligneous fibers obtained from phloem tissue and used in the manufacture of woven goods and cordage.

Bedrock. Bottom layer, lowest stratum; unbroken solid rock, overlaid in most places by soil or rock fragments.

Bilateral aid. Aid based on a formal agreement between a single donor country and the recipient; in contrast to multilateral aid, which originates from several countries, usually through an international agency.

Biltmore stick. A graduated stick used to estimate tree diameters.

Binder. Extraneous bonding agent, organic or inorganic, used to bind particles together—for example, to produce particleboard.

Biological control. Regulation of pest species through the use of other organisms.

Biomass. Quantity of biological matter of one or more species present on a unit area.

Biome. Usually terrestrial ecological communities of very wide extent often defined by botanical habitat and characterized by soil and climate; the largest ecological unit.

Biosphere. Part of the earth's crust, water, and atmosphere where living organisms can subsist.

Biotic factors. Relation of living organisms to one another from an ecological view (as opposed to abiotic or nonliving elements).

Black liquor. Liquor resulting from the manufacture of pulp by alkaline processes and containing, in a modified form, the greater part of the extracted lignin and sugar degradation products.

Blowup fire. Sudden increase in intensity and rate of flame spread, often accompanied by a violent convection column of smoke and hot gases.

Board foot. Unit of measurement represented by a board 1 foot long, 1 foot wide, and 1 inch thick (144 cubic inches), measured before surfacing or other finishing. Abbreviations: b.f., bd ft, ft.b.m.

Bole. Tree stem of merchantable thickness.

Bolt. Any short log, as a pulpwood or veneer bolt.

Boreal. Of or pertaining to the north.

Brightness. Blue reflectance of a sheet of paper, a measure of the maximum whiteness that can be achieved with proper tinting.

Browse. Leaves, small twigs, and shoots of shrubs, seedling, and sapling trees, and vines available for forage for livestock and wildlife.

Bryophyte. Any plant of the division Bryophyta, a division containing the liverworts and mosses. These plants do not possess a vascular system.

Buck. To cut a tree into proper lengths after it has been felled.

Bud primordium. Embryonic shoot formed in the axil of a leaf.

C

Calender. Machine in which cloth, paper, or the like is smoothed, glazed, or otherwise manipulated by pressing between revolving cylinders.

Caliper. An instrument for directly measuring tree diameters.

Canopy. More-or-less continuous cover of branches and leaves formed collectively by the crowns of adjacent trees or shrubs. See *Understory.*

Capillary water. Water that fills the smaller pores less than 0.05 millimeter in diameter and that by adhesion to the soil particles can resist the force of gravity and remain suspended in the soil. This water constitutes the major source of water for tree growth, except in soils having a high water table.

Carbonization. Decomposition by heat of organic substances in a limited supply of air accompanied by the formation of carbon. See *Destructive distillation.*

Carnivore. Organism that consumes mostly flesh.

Carrying capacity. Number of organisms of a given species and quality that can survive in a given ecosystem without causing its deterioration.

Cation. Positively charged atom or group of atoms. Cation exchange capacity is the total capacity of soil colloids for holding cations.

Chain. A unit of linear measurement equal to 66 feet.

Chaining. Using a surveyor's chain or tape for linear measurements along the ground.

Charge-coupled device (CCD). A solid-state sensor that detects light; a microelectronic silicon chip.

Chipper. Machine for cutting logs or pieces of logs into chips.

Chlorophyll. The green pigment of plant cells, necessary for photosynthesis.

Chloroplasts. A plastid in algal and green plant cells in which chlorophylls are contained; site of photosynthesis.

Chlorosis. Abnormal yellowing of foliage, often a symptom of mineral deficiency, infection, root or stem girdling, or extremely reduced light.

Chlorotic. Leaf tissue that has yellowed because of chlorosis.

Chromosome. Body in the cell nucleus containing genes in a linear order.

Clearcutting. Silvicultural system in which the entire timber stand is cut. See *Seed-tree method, Shelterwood method.*

Climatic release. Relaxation of environmental resistance factors and the recurrence of favorable weather for several successive years. Together, these conditions allow a pest species to approach its reproductive potential.

Climax community. Community that has achieved the maximum possible development. The end point of a sere.

Clinal variation. Variation occurring in a continuous fashion along a geographic or environmental gradient.

Clone. All the plants produced by asexual means (e.g., grafting, layering, budding) from a common ancestor and having identical genetic constitutions.

Collenchyma. Supporting tissue containing elongated living cells with irregularly thickened primary cell walls; often found in regions of primary growth in stems and leaves.

Color. The property of an object that is dependent on the wavelength of the light it reflects or, in the case of a luminescent body, the wavelength of light that it emits.

Color-composite image. A color image prepared by projecting individual black-and-white multispectral images in color.

Color infrared film. A color film consisting of three layers in which the red-imaging layer responds to photographic infrared radiation ranging in wavelength from 0.7 to 0.9 micrometer. The green-imaging layer responds to red light and the blue-imaging layer responds to green light.

Combustion. Consumption by oxidation, evolving heat, and generally also flame and incandescence.

Community. Unit of vegetation that is homogeneous with respect to species composition and structure and occupies a unit area of ground.

Companion cell. Specialized parenchyma cell in angiosperm phloem; associated with sieve tube members.

Conifer. Division of gymnosperm; plant producing naked seeds in cones, mostly evergreen, with timber known commercially as softwood.

Coppice system. Silvicultural system in which crops regenerate vegetatively by stump sprouts and the rotation is comparatively short.

Cord. Volume measure of stacked wood. A standard cord is 4 X 4 X 8 feet and contains 128 cubic feet of space. Actual wood volume varies between 70 and 90 cubic feet per cord. A face cord is a short cord in which the length of the pieces is shorter than 8 feet (Figure 11.2).

Cordillera. Entire chain of mountain ranges parallel to the Pacific Coast, extending from Cape Horn to Alaska.

Cork cambium. Lateral meristem that produces cork toward the outside of the plant and phelloderm to the inside.

Cortex. Ground tissue of the shoot or root that is located between the epidermis and the vascular system; a primary-tissue region.

Cotyledon. Embryonic leaf, characteristic of seed plants; generally stores food in dicotyledons and absorbs food in monocotyledons.

Crown fire. Fire that burns the tops of trees and brush.

Cruise (timber). Survey of forestlands to locate and estimate volumes and grades of standing timber.

Cutting cycle. Period of time between major cuts in an uneven-aged stand. See *Rotation age.*

Cytoplasm. Term commonly used to refer to the protoplasm of the cell exclusive of the nucleus.

D

dbh (diameter at breast height). Tree diameter at breast height, 1.3 meters (4.5 feet) above the ground as measured from the uphill side of the tree.

Deciduous. Perennial plants that are normally leafless for some time during the year.

Decurrent. Having a leaf base elongated down the stem. See *Excurrent.*

Deferred-rotation grazing. A system of range management whereby grazing is delayed on a portion of the land until after the most important range plants have gone to seed. Then grazing is deferred on adjacent portions in rotation over a period of years so that all pastures receive the benefit of deferment.

Defoliation. Loss of a plant's leaves or needles.

Deleterious. Harmful, injurious, or destructive.

Dendrology. Branch of botany dealing with classification, nomenclature, and identification of trees and shrubs.

Dendrometer. Instrument for measuring the dimensions of trees or logs.

Denitrification. Process by which nitrogen is released from the soil (as a gas) to the atmosphere by denitrifying bacteria.

Density. Proportion of cell wall volume to total volume of wood. The number of individuals (trees, animals) per unit area at a given time.

Derived demand. Demand for a good coming from its use in the production of some other good; for example, timber is demanded not by consumers but by firms that manufacture wood products.

Desertification. Exhaustion of the soil, often because of removal of vegetative cover in semiarid regions, leading irreversibly to an unproductive desert.

Dessicated. Dehydrated.

Destructive distillation. Decomposition of wood by heating out of contact with air, producing primarily charcoal, tarry distillates, and pyroligneous acid.

Detritus. Any organic debris.

Diameter tape. A tape measure specially calibrated to convert circumference of the tree to its corresponding diameter, assuming the cross-section of the tree to be a perfect circle.

Diapause. State of arrested physiological development of an insect.

Dicotyledons. One of two classes of angiosperms; a plant whose embryo has two seed leaves.

Differentiation. A process by which a relatively unspecialized cell undergoes a progressive change to a more specialized cell; the specialization of cells and tissues for particular functions during development.

Diffuse-porous wood. Wood (xylem) of hardwoods in which the vessels are small in diameter; vessels in springwood do not have much greater diameters than those in summerwood. See *Ring-porous wood.*

Digital computer. A computer that operates on the principle of counting as opposed to measuring. See *Analog.*

Digital elevation model. Model resulting from the matrix of elevation data obtained by systematically scanning a stereomodel.

Digital image. An image having numeric values representing gray tones; each numeric value represents a different gray tone.

Digital image processing. Computer manipulation of the digital values for picture elements of an image.

Digitize. Using numeric values to represent data.

Dioecious. A condition in which staminate and pistillate flowers (or pollen and seed cones of conifers) are borne on different individuals of the same species. See *Monoecious.*

Dominant. Pertaining to trees that project somewhat above the general level of the canopy, having crowns that receive direct sunlight from above and partly from the side. See *Suppressed.*

Dormancy. A special condition of arrested growth in which the plant and such plant parts as buds and seeds do not begin to grow without special environmental cues.

Duff. Organic matter in various stages of decomposition on the forest floor.

E

Ecology. Science that deals with the relation of plants and animals to their environment and to the site factors that operate in controlling their distribution and growth.

Econometric. Pertaining to a system of analysis of economic affairs using a specialized statistical technique for large masses of assembled data.

Ecosystem. Any complex of living organisms with their environment considered as a unit for purposes of study.

Ecotone. Transition zone between two adjoining communities.

Edaphic. Pertaining to soil conditions that influence plant growth.

Edge. Boundary between two or more elements of the environment, for example, field-woodland.

Elasticity. Relationship, expressed mathematically, between a percentage change in one variable and the resulting percentage change in an other variable, when all other things are held constant. The price elasticity of demand (supply) is the percentage change in quantity demanded (supplied) when price changes by 1 percent, with all other variables such as income and population held constant.

Electromagnetic energy. Energy propagated through space or through material media in the form of an advancing interaction between electric and magnetic fields; also more simply termed *radiation.*

Electromagnetic spectrum. The ordered array of known electromagnetic radiations, extending from the shortest cosmic rays, through gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, and including microwave and all other wavelengths of radio energy.

Emulsion. A suspension of photosensitive silver halide grains in gelatin that constitutes the image forming layer on photographic materials.

Endemic population. Natural low population level of most species native to an area.

Energy exchange. Flow of energy through the ecosystem beginning with the capture of radiant solar energy by photosynthesis and ending when the energy is lost back to the environment as heat through metabolism.

Entomology. Study of insects.

Entomophagous. Feeding on insects.

Environmental resistance. Physical and biological factors that inhibit the reproductive potential of a species.

Ephemeral. Short-lived; completing the life cycle within a brief period.

Epicormic growth. Growth of lateral buds after the apical bud is damaged.

Epidermis. Outermost layer(s) of cells on the primary plant body.

Ericaceous. Belonging to the heath family of plants, including the heath, arbutus, azalea, rhododendron, and American laurel.

Ethanol. Ethyl alcohol, C_2H_5OH; a colorless, volatile liquid manufactured from starchy or sugary materials by fermentation; also synthetically produced.

Eutrophication. Aquatic succession characterized by gradual nutrient enrichment and subsequent depletion of dissolved oxygen.

Evapotranspiration. Combined loss of water through evaporation and transpiration from the soil and vegetal cover on an area of land surface.

Even-aged stand. Stand in which relatively small age differences exist between individual trees, usually a maximum of 10 to 20 years.

Excurrent. Tree with the axis prolonged to form an undivided stem or trunk (as in spruces and other conifers).

Exotic. Not native; foreign; introduced from other climates or countries.

Extractive. In wood, any part that is not an integral part of the cellular structure and can be dissolved out with solvents.

F

False color. See *Color infrared.*

Fecal coliform. Colon bacilli, or forms that resemble or are related to them.

Fermentation. Change brought about by an agent such as yeast enzymes, which convert sugars to ethyl alcohol.

Fiber. Narrow cell of wood (xylem) or bast (phloem), other than vessel elements and parenchyma; includes tracheids. Or a cell material with a length-to-diameter (1/d) ratio greater than 20:1.

Fiberizing. Separation of wood and other plant material into fibers or fiber bundles by mechanical (sometimes assisted by chemical) means.

Field moisture capacity. The greatest amount of water it is possible for a soil to hold in its pore spaces after excess water has drained away.

Filter, optical. A material that, by absorption or reflection, selectively modifies the radiation transmitted through an optical system.

Fines. Pulp fractions having very short or fragmented fibers.

Fire line. Strip of plowed or cleared land made to check the spread of a fire.

Fluvial. Pertaining to or formed by a river.

Food chain, food web. Chain of organisms existing in any natural community such that each link in the chain feeds in the one below and is eaten by the one above; at the base are autotrophic (green) plants, eaten by heterotrophic organisms including plants (fungi), plant-eating animals (herbivores), plant and animal eaters (omnivores), and animal eaters (carnivores).

Forb. Any herbaceous plant that is not a grass or grass-like—such plants as geranium, buttercup, or sunflower.

Forest yield. The volume of timber in a forest at a specific point in time.

Forties. Term applied to 40-acre parcels of land, equal to one-sixteenth of a township in the standard rectangular survey system.

Fourdrinier. Name associated with the wire-forming section or the entire papermaking machine. Originally developed by the Fourdrinier brothers in England (1804).

Fruit. In angiosperms, a matured, ripened ovary containing the seeds.

Furfural. Oily liquid aldehyde, $C_5H_4O_2$, with an aromatic odor, obtained by distilling wood, corncobs, bran, sugar, and other ingredients with dilute sulfuric acid.

Fusiform initials. The vertically elongated cells in the vascular cambium that give rise to the cells of the axial system in the secondary xylem and secondary phloem.

G

Gall. Pronounced, localized, tumor-like swelling of greatly modified structure; occurs on plants from irritation by a foreign organism.

Gamete. Male pollen cell or a female egg cell, typically the result of meiosis, capable of uniting in the process of fertilization with a reproductive cell of the opposite sex.

Gasification. Conversion of a solid or liquid substance to a gas.

Gene. Unit of heredity; portion of the DNA of a chromosome.

Gene flow. Migration of genes from one population to another via the dispersal of individuals, or of propagules such as seed or pollen.

Gene pool. Sum total of genetic information distributed among the members of an interbreeding population.

Genetic drift. Change in gene frequency in small breeding populations because of chance, in contrast to a similar change under selection.

Genotype. Total amount of genetic information that an individual possesses. See *Phenotype.*

Geographic information system. An information system that can input, manipulate, and analyze geographically referenced data to support the decision-making processes of an organization.

Girdle. To destroy tissue, especially the bark and cambium, in a rough ring around a stem, branch, or root. Girdling often kills the tree.

Globose. Pertaining to a tree having the shape of a globe or globule; approximately spherical.

Grade. Established quality or use classification of trees, timber, and wood products; to classify according to grade.

Gross national product (GNP). Total value at current market prices of all final goods and services produced by a nation's economy, before deduction of depreciation and other allowances for consumption of durable capital goods.

Ground fire. Fire that not only consumes all the organic materials of the forest floor, but also burns into the underlying soil itself—for example, a peat fire. See *Surface fire.*

Ground tissue. Tissues other than the epidermis or periderm and vascular tissue; conjunctive parenchyma, fundamental tissue.

Growth impact. Pervasive, ongoing destruction of forests because of growth loss and mortality. See *Growth loss, Mortality.*

Growth loss. Difference between potential and actual tree growth, caused by destructive agents such as insects, diseases, or weather. See *Growth impact, Mortality.*

Gymnosperm. Vascular plants that produce seeds not enclosed in an ovary.

H

Habitat. Immediate environment occupied by an organism. In forestry, habitat usually refers to animal habitat.

Habitat type. Unit of land capable of supporting a single climax community type.

Hardpan. Indurated (hardened) or cemented soil horizon. The soil may have any texture and is compacted or cemented by iron oxide, organic matter, silica, calcium carbonate, or other substances.

Headbox. Final holding container of pulp slurries for regulation of flow onto the moving papermaking-machine wire.

Head fire. Fire spreading, or set to spread, with the wind.

Heartrot. Decay in the central core of a tree, usually caused by fungus.

Heartwood. Inner core of a woody stem, wholly composed of nonliving cells and usually differentiated from the outer enveloping layer (sapwood) by its darker color. See *Sapwood.*

Height poles. Sectioned, telescoping poles used to measure the height of trees.

Hemicellulose. Any of the noncellulosic polysaccharides of the intercellular layer and of the cell wall that can be extracted with aqueous alkaline solutions and are readily hydrolyzable by acids to give sugars.

Hemocoel. General insects' body cavity in which blood flows.

Herb. Any seed-producing plant that does not develop persistent woody tissue above ground. Includes both forbs and grasses. May be perennial. *Herbaceous,* adjective.

Herbivore. Organism that consumes living plants or their parts.

Heritability. Proportion of any observed variability that is caused by genetic effects, the remainder being attributed to environment.

Heterotrophic. Referring to organisms dependent on the environment for obtaining organic food because they are unable to synthesize organic material. All animals, fungi, and many bacteria are heterotrophs. The obtain almost all their organic material either directly or indirectly from the activity of autotrophs.

High grading. Type of exploitation cutting that removes only trees of a certain species, or of high value.

Hogged wood. Wood reduced to coarse chips—for example, for fuel or manufacture of wood pulp or chipboard.

Horizon, soil. Layer of soil roughly parallel to the land surface, distinguished from adjacent layers by different physical, chemical, or biological characteristics.

Hue. The attribute of a color that differentiates it from gray of the same brilliance and that allows it to be classed as blue, green, red, or intermediate shades of these colors.

Humus. Decomposed lower part of the soil organic layer, generally amorphous, colloidal, and dark-colored.

Hydrarch succession. Primary succession beginning on a substrate of water, usually a pond or lake.

Hydration. Chemical combination of water with cellulose or hemicelluloses (usually in fibers) to give a swollen structure; endowing fibers with an increased capacity for water retention through mechanical beating.

Hydrolysis. Conversion, by reaction with water, of a complex substance into two or more smaller molecules.

Hypertrophy. The excessive growth or development of an organ or tissue.

Hypha. A single tubular filament of fungus; the hyphae together constitute the mycelium.

Hypsometer. Device for measuring tree height.

I

Improvement cutting. Silvicultural treatment in which diseased or poorly formed trees or trees of undesirable species are removed.

Inbreeding depression. Loss of vigor that frequently results from mating closely related individuals.

Incident energy. Electromagnetic radiation impinging on a surface.

Increment. Increase in girth, diameter, basal area, height, volume, quality, or value of individual trees or crops.

Increment borer. Auger-like instrument with a hollow bit, used to extract cores from trees for the determination of growth and age.

Infection court. Site of infection by a pathogen.

Infiltration. The amount of water that penetrates the soil, governed by the texture of the soil, vegetation cover, and the slope of the ground.

Infrared. Energy in the 0.7- to 15-micrometer wavelength region of the electromagnetic spectrum; for remote sensing the infrared wavelengths are often subdivided into near-infrared (0.7 to 1.3 micrometers), middle-infrared (1.3 to 3.0 micrometers), and far-infrared (7.0 to 15.0 micrometers); far-infrared is sometimes referred to as *thermal* or *emissive infrared.*

Ingrowth. The increase in timber volume of a given stand owing to new trees that were not measured in previous surveys. See *Survivor growth.*

Inhibition. Prohibition, or checking, of an action or process.

Initial. Undifferentiated cell that remains within the meristem indefinitely and adds cells to the plant body by division.

Initial point. The origin point of the standard rectangular survey system, the intersection of a baseline and a principal meridian.

Inland Empire. Area lying between the crests of the Cascade Mountains and Bitterroot Mountains, and extending from the Okanogan Highlands to the Blue Mountains of northeastern Oregon. Timber production is very important in this region.

Integration (economics). Expansion of a firm into production of other, often closely related, types of products (horizontal integration) or into prior or later stages of the production of a given product (vertical integration).

Intercellular space. Space between the cells of a tissue.

Interception. (1) The process by which rainwater is caught and held on the leaves of trees and vegetation and is returned to the air by evaporation without reaching the ground. (2) The part of precipitation caught by vegetation.

Internode. Portion of a stem or branch that is between two successive nodes.

Intolerance, shade. See *Shade tolerance.*

Ion. Electrically charged atom or group of atoms.

J

Juvenile wood. Wood formed close to the central core of the tree that contains a high percentage of thin-walled cells.

K

Kerf. The narrow slot cut by a saw advancing through the wood.

Kiln-dry. Dried in a kiln to a specified range of moisture content.

Knot. Portion of a branch enclosed in the xylem by the natural growth of the tree.

Kraft pulp. Chemical wood pulp obtained by cooking—that is, digesting wood chips in a solution of sodium hydroxide (caustic soda) and sodium sulfide.

L

Lammas shoot. Abnormal shoot formed late in the summer from expansion of a bud that was not expected to open until the following year.

Landsat. An unmanned, earth-orbiting satellite of the National Aeronautics and Space Administration that transmits images to earth receiving stations; designed primarily for collection of earth resources data.

Larva. Immature, wingless, feeding stage of an insect that undergoes complete metamorphosis.

Lateral meristems. Meristems that give rise to secondary tissue; the vascular cambium and cork cambium.

Lattice. Crossed strips with open spaces between to give the appearance of a screen-like structure.

Leaching. Removal of soluble substances (e.g., from soil or timber) by percolating water.

Leaf primordium. Lateral outgrowth from the apical meristem that will become a leaf.

Lenticel. Small breathing pore in the bark of trees and shrubs; a corky aerating organ that permits gases to diffuse between the plant and the atmosphere.

Lesion. Circumscribed diseased area.

Lignification. Impregnation with lignin, as in secondary walls of xylem cells. See *Lignin.*

Lignin. Noncarbohydrate (phenolic), structural constituent of wood and some other plant tissues; encrusts the cell walls and cements the cells together.

Lignocellulosic. Of materials containing both lignin and cellulose; a characteristic of higher forms of terrestrial plants.

Lignosulfonic acid. Soluble derivative of lignin produced in the sulfite pulping process and present—in the form of salts (lignosulfonates)—in the waste liquor.

Limiting factor. Environmental factor needed by an organism but in shortest supply.

Linear programming. A mathematical programming technique that either maximizes or minimizes a single, linear objective function. The objective function may be subjected to sets of linear equalities or inequalities, called constraints.

Lithosphere. Crust of the earth.

Littoral. Of vegetation growing along a seashore or very large lake. See *Riparian.*

Loam. Rich friable soil containing a relatively equal mixture of sand and silt and somewhat smaller proportion of clay.

Loess. Particles, mostly silt-sized, transported and deposited by wind.

Log rule. Table showing the estimated or calculated amount of lumber that can be sawed from logs of given length and diameter.

Lumen. Cell cavity (often hollow).

M

Macerate. To soften, or separate the parts of a substance by steeping in a liquid, with or without heat.

Mast. Nuts and seeds of trees, serving as food for livestock and wildlife.

Mature. Stage of tree growth when height growth slows and crown expansion and diameter increase and become marked. See *Seedling, Sapling, Pole, Senescent.*

Megasporangium. The ovule-bearing structure in gymnosperms.

Mensuration, forest. Science dealing with the measurement of volume, growth, and development of individual trees and stands and the determination of various products obtainable from them.

Merchantable height. The height above the ground, or in some cases above stump height, to which the tree stem is salable.

Meristem. Undifferentiated plant tissue from which new cells arise. See *Apical meristem, Lateral meristems.*

Mesarch succession. Primary succession beginning on an intermediate substrate that is neither open water nor solid rock, such as a recent mudflow or glacial moraine. See *Hydrarch, Xerarch succession.*

Mesophyll. Parenchyma tissue in a leaf between the upper and lower epidermis.

Methanol. Methyl alcohol, CH_3OH; a colorless, volatile liquid, a product of the destructive distillation of wood, derived mainly from the lignin; also manufactured synthetically.

Microclimate. Climate of small areas, especially insofar as this differs significantly from the general climate of the region.

Microsporangium. The pollen sac of a staminate cone in gymnosperms.

Microwave. A very short electromagnetic radiation wave between 1 meter and 1 millimeter in wavelength or 300 to 0.3 gigahertz in frequency.

Middle lamella. Layer of intercellular material, rich in lignin and pectic compounds, cementing together the primary walls of adjacent cells.

Mineralization. Breakdown of organic compounds in soil releasing inorganic constituents that can be taken up by plant roots.

Monocotyledones. One of the two classes of angiosperms; a plant whose embryo has one seed leaf.

Monoculture. Crop of a single species, generally even-aged. See *Even-aged stand.*

Monoecious. A condition in which both staminate and pistillate flowers (or pollen and seed cones of conifers) are borne on the same plant. See *Dioecious.*

Monophagous. Feeding on a single host species.

Morphology. Study of form and its development.

Mortality. Volume of trees killed by natural causes in a given time or a given forest, exclusive of catastrophes.

Multispectral scanner. A scanner system that simultaneously acquires images in various wavelength regions of the same scene.

Mutagen. Substance known to induce mutations.

Mutation. Sudden, heritable change in the structure of a gene or chromosome or some set thereof.

Mycelium. The mass of interwoven filaments or hypae making up the vegetative part of a fungus, as distinct from the fruiting body.

Mycoplasmas. Smallest of free-living organisms, lacking a cell wall, but possessing a distinct flexible membrane.

Mycorrhizae. Symbiotic association between nonpathogenic or weakly pathogenic fungi and living cortical cells of a plant root.

N

Naval stores. Historical term for resin products, particularly turpentine and rosin from pine trees, previously also pine tars and pitch.

Necrosis. The localized death of plant or animal tissue; for example, the response of a leaf to invasion of a pathogen. An affected area is described as being *necrotic.*

Necrotic. An area of dead plant tissue from necrosis.

Nematodes. Parasitic or free-living, elongated smooth worms of cylindrical shape; roundworms.

Niche. Status of a plant or animal in its community—that is, its biotic, trophic, and abiotic relationships. All the components of the environment with which an organism or population interacts, especially those necessary to its existence: its habitat.

Nitrification. Process whereby protein, amino acids, and other nitrogen compounds in the soil are oxidized by microorganisms, with the production of nitrates.

Nitrogen cycle. Worldwide circulation of nitrogen atoms in which certain microorganisms take up atmospheric nitrogen and convert it into other forms that may be assimilated into the bodies of other organisms. Excretion, burning, and bacterial and fungal action in dead organisms return nitrogen atoms to the atmosphere.

Nitrogen fixation. Conversion of elemental nitrogen (N_2) from the atmosphere to organic combinations or to forms readily utilizable in biological processes.

Node. Part of a stem or branch where one or more leaves or branches are attached.

Nodules. Enlargements or swellings on the roots of legumes and certain other plants inhabited by symbiotic nitrogen-fixing bacteria.

O

Oblique photograph. A photograph acquired with the camera axis intentionally directed between the horizontal and vertical orientations.

Oleoresin. Group of "soft" natural resins, consisting of a viscous mixture of essential oil (e.g., turpentine) and nonvolatile solids (e.g., rosin) secreted by the resin-forming cells of the pines and certain other trees.

Optical dendrometer. An instrument for measuring the upper stem diameters of trees to aid in accurate product scaling.

Organ. Structure composed of different tissues, such as root, stem, leaf, or flower.

Organic compounds. The compounds containing carbon that pertain to living organisms in general, and those compounds formed by living organisms.

Orthographic projection. Projection in which the lines are perpendicular to the plane of projection.

Orthophotograph. A photographic copy prepared from a perspective photograph in which the displacements of images caused by a tilt and relief have been removed.

Osmoregulation. Regulation of the osmotic pressure in the body by controlling the amount of water and salts in the body.

Osmosis. The diffusion of water, or any solvent, across a differentially permeable membrane. In the absence of other forces, movement of water during osmosis will always be from a region of greater water potential to one of lesser water potential.

Oven-dry. Of wood dried to constant weight in a ventilated oven at a temperature above the boiling point of water.

Overgrazing. Grazing above and beyond the level that a given range can sustain without change.

Oviposit. To lay eggs or deposit eggs by means of an ovipositor.

Ovipositor. The tubular organ at the extremity of the abdomen in many insects by which the egg are deposited.

P

Pacing. A simple method for measuring linear distance for surveys, when great accuracy is not required, whereby a person's individual premeasured pace is used as the measuring tool.

Panchromatic. Pertaining to films that are sensitive to a broad band of electromagnetic radiation, such as the entire visible part of the spectrum, and are used for broadband photographs.

Parallax. The apparent displacement of the position of an observed body with respect to a reference point or system, caused by a shift in point of observation.

Parallax wedge. A simplified stereometer for measuring object heights on stereoscopic pairs of photographs.

Parasite. Organism that lives in or on another living organism of a different kind and derives subsistence from it without returning any benefit. See *Predator, Saprophyte.*

Parenchyma. Tissue composed of living, thin walled, brick-shaped cells; primarily concerned with the storage and distribution of food materials. Axial parenchyma cells are vertically oriented; ray parenchyma are laterally oriented.

Pathogen. Organism directly capable of causing disease in living material. See *Saprogen.*

Pectin. Complex organic compound (polysaccharide) present in the intercellular layer and primary wall of plant cells; the basis of fruit jellies.

Ped. Visible structural soil aggregate—for example, crumb, block, or prism.

Perforation. Gap in the cell wall lacking a pit membrane; occurs in vessel members of angiosperms.

Pericycle. Root tissue located between the epidermis and phloem.

Periderm. Outer protective tissue that replaces the epidermis; includes cork, cork cambium, and phelloderm.

Perspective projection. Projection in which the lines converge at an arbitrarily chosen station point, to represent on a plane the space relationships of natural objects as they appear to the eye. The perspective projection of the camera lens causes scale variations and displaces image positions.

pH. A measure of acidity; the logarithm of the reciprocal of the hydrogen ion concentration. The value 7 pH is neutral; the values above are alkaline; and the values below are acid.

Phelloderm. Tissue formed toward the inside of the plant by the cork cambium.

Phenol. Hydroxyl derivative of benzene, C_6H_5OH.

Phenology. Study of biological events as related to climate.

Phenotype. Outward appearance or physical attributes of an individual. See *Genotype.*

Pheromone. Hormonal substance secreted by an individual and stimulating a physiological or behavioral response from an individual of the same species.

Phloem. Tissue of the inner bark; contains sieve elements through which carbohydrates are transported.

Photogrammetry. The art or science of obtaining reliable measurements by means of photography.

Photograph. A representation of targets formed by the action of light on silver halide grains of an emulsion.

Photographic scale. An expression or ratio stating that one unit of distance on a photograph represents a specific number of units of actual ground distance.

Photoperiod. Duration of daily exposure to light; length of day favoring optimum functioning of an organism.

Photosynthesis. Synthesis of carbohydrates from carbon dioxide and water by green plant cells in the presence of light, with oxygen as a byproduct.

Phototropism. Growth movement in which the direction of the light is the determining factor, as the growth of a plant toward a light source; turning or bending response to light.

Physiography. A general description of nature or natural phenomena; the science of physical geography.

Physiology. Study of the vital functions of living organisms. *Note:* Differences in physiological character may not always be accompanied by morphological differences.

Phytochrome. Chemical compound used by plants to detect daylength.

Piedmont. Plateau between the coastal plain and the Appalachian Mountains.

Pioneer community. First stage in the ecological development of a community.

Pit. Gap or recess in the secondary cell wall that facilitates the interchange of materials between cells.

Pith. Ground tissue occupying the center of the plant stem or root, within the vascular cylinder; usually consists of parenchyma.

Pixel. A picture element or cell within a spatially ordered matrix of numbers.

Planer. Machine for surfacing sawed timber.

Plasmolysis. Contraction of the cytoplasm because of removal of water from the protoplast by osmosis.

Pole. Still-young tree larger than 4 inches (10 centimeters) dbh, up to about 8 inches (20 to 23 centimeters) dbh; during this stage, height growth predominates and economic bole length is attained. See *Seedling, Sapling, Mature, Senescent.*

Polymerization. Transformation of various low molecular-weight compounds (monomers) into large molecules—that is, polymers.

Polyphagous. Feeding on many different host species.

Predator. Any animal which preys externally on others; that is, hunts, kills, and feeds on a succession of hosts. See *Parasite.*

Prescribed burning. Controlled use of fire to further certain planned objectives of silviculture, wildlife management, fire hazard reduction, and so forth.

Present net worth. Single amount measuring the net current value of a stream of future revenues and costs.

Price index. Price of a good or group of goods in any year divided by the price of the same good or group of goods in a base year. See *Relative price index.*

Price leadership. Determination of prices by one or a few firms, with other producers in the industry tacitly accepting the prices thus determined.

Primary growth. Growth originating in the apical meristem of shoots and roots. See *Secondary growth.*

Primary succession. Succession beginning on a substrate that did not previously support vegetation, such as open water, fresh glacial moraine, or bare rock. See *Secondary succession.*

Primordial. A cell or organ in its earliest stage of differentiation.

Profile, soil. Vertical section of the soil through all its horizons and extending into the parent material.

Progeny. Offspring produced from any mating.

Progeny test. Evaluation procedure in which parents are rated based on the performance of their offspring.

Protoplasm. Living substance of all cells.

Protoplast. Entire contents of the cell, not including the cell wall.

Provenance. Natural origin of seeds or trees, usually synonymous with "geographic origin," or a plant material having a specific place or origin.

Pulp. Fibers separated by mechanical or chemical means; the primary raw material from which paper is made.

Pupa. Insect in the nonfeeding, usually immobile, transformation stage between larva and the adult. *Pupae* (plural).

Pyric climax. An ecosytem that never reaches its potential climax vegetation because of frequent fires.

Pyroligneous acid. Aqueous portion, after separation of the tar, of the liquor obtained during the destructive distillation of wood; a complex mixture of water (80 to 90 percent) and organic compounds. See *Destructive distillation.*

Pyrolysis. Subjection of wood or organic compounds to very high temperatures and the resulting decomposition. See *Destructive distillation.*

Q

Quad. Unit of energy measure; 1 X 10^{15} British thermal units (Btu).

R

Radar. Acronym for radio detection and ranging, an active form of remote sensing that operates at wavelengths from 1 millimeter to 1 meter.

Radial increment. The diameter growth over a given period obtained by measuring the length of the last several annual rings in a core sample.

Radiation. The propagation of energy in the form of electromagnetic waves.

Rangeland. Areas unsuitable for cultivation, which are a source of forage for free-ranging native and domestic animals.

Ray. Laterally oriented, ribbon-shaped tissue extending radially in the xylem and phloem; functions in the lateral transport of water and nutrients.

Ray initial. An initial in the vascular cambium that gives rise to the ray cells of secondary xylem and secondary phloem.

Recombination. Formation of new combinations of genes as a result of segregation in crosses between genetically different parents.

Recurrence interval. Frequency of fires in a given stand.

Reflectance. The ratio of the radiant energy reflected by a body to that incident upon it.

Reflectance, spectral. Reflectance measured at a specific wavelength interval.

Refugia. Areas that have escaped alteration during glaciation.

Regeneration. Renewal of a tree crop, by natural or artificial means.

Regulated forest. Forest that produces a continuous flow of products of about the same size, quality, and quantity over time.

Relative price index. Price index for one good divided by the price index for another good or group of goods. The divisor is usually the wholesale or consumer price index.

Release cutting. Silvicultural treatment in which larger trees of competing species are removed from competition with desired crop trees.

Relief. The vertical irregularities of a surface.

Relief displacement. The geometric distortion on vertical aerial photographs. The tops of objects are located on the photograph radially outward from the base.

Remote sensing. Collection of data by a device that is not in physical contact with the object, area, or phenomenon under investigation—for example, aerial photography or satellite imagery.

Reproductive potential. Ability of a species to multiply in the absence of countervailing forces.

Resin. Pitch; the secretions of certain trees, oxidation or polymerization products of the terpenes, consisting of mixtures of aromatic acids and esters insoluble in water but soluble in organic solvents; often exuding from wounds.

Rest-rotation grazing. A system of range management whereby one portion of the land is left ungrazed (rested) for a full year; the next year another portion is rested.

Rhizome. Horizontal underground stem, usually containing stored food.

Rhizomorph. A densely packed strand of fungal tissue with the appearance of a root that is produced by some higher fungi such as *Armillaria.* Rhizomorphs enable fungi to spread.

Rickettsia. Bacteria-like microorganisms of the genus *Rickettsia,* parasitic on arthropods and pathogenic for human beings and animals.

Ring-porous wood. Wood (xylem) of hardwoods in which the earlywood vessels are much larger in diameter than vessels in the latewood; the vessels generally appear as a ring in a stem cross section. See *Diffuse-porous wood.*

Riparian. Of vegetation growing in close proximity to a watercourse, small lake, swamp, or spring. See *Littoral.*

Root cap. Thimble-shaped mass of cells covering and protecting the growing root tip.

Root hairs. Tubular outgrowths of epidermal cells of the young plant.

Rosin. Solid residue after evaporation and distillation of the turpentine from the oleoresin of various pines, consisting mostly of rosin acids.

Rotation age. Period of years required to establish and grow timber crops to a specific condition of maturity. Applies only to even-aged management. See *Cutting cycle.*

Roundwood. Timber or firewood prepared in the round state—from felled trees to material trimmed, barked, and crosscut.

Ruderal. Plant that occupies a niche with high resource availability (water, nutrients, and light) and frequent disturbances. Also a plant living on wasteland in built-up areas.

S

Saccharification. Conversion of the polysaccharides in wood or other plant material into sugars by hydrolysis with acids or enzymes.

Sahel. Semi-arid region of Africa between the Savannas and the Sahara extending through Senegal, Mauritania, Mali, Niger, Sudan, northern Nigeria, and Ethiopia. Since the late 1960s, this region has been afflicted by devastating drought leading to the starvation of hundreds of thousands of people.

Sapling. Young tree at least 1 meter (3 feet) high, but not larger than 10 centimeters (4 inches) dbh; crowns are well elevated and usually many lower branches have started to die. See *Seedling, Pole, Mature, Senescent.*

Saprogen. Organism capable of producing decay in nonliving organic material. See *Pathogen.*

Saprophyte. Plant organism which is incapable of synthesizing its nutrient requirements from purely inorganic sources and feeds on dead organic material. See *Parasite.*

Sapwood. Predominantly living, physiologically active wood; includes the more recent annual layers of xylem that are active in translocation of water and minerals. See *Heartwood.*

Savanna. Any large area of tropical or subtropical grassland, covered in part with trees and spiny shrubs.

Sawlog. A log considered suitable in size and quality for sawn timber.

Scale. Estimated solid (sound) contents of a log or group of logs.

Scanner. An optical-mechanical imaging system in which a rotating or oscillating mirror sweeps the instantaneous field of view of the detector. The two basic types of scanners are airborne and stationary.

Scarification. Wearing down, by abrasion or chemical treatment, of the bark or outer coat.

Scion. Detached living portion of a plant grafted onto another plant.

Sclerenchyma. Supporting tissue composed of cells with thick, often lignified secondary walls; may include fiber cells or sclereid cells.

Sclereid. Sclerenchyma cell with a thick, lignified secondary wall.

Sclerophyll. A term that describes the thick, tough foliage of many tree species of the Mediterranean area and parts of the United States and Australia (i.e., eucalyptus).

Secondary growth. Growth derived from lateral meristem; results in increase in girth. See *Primary growth.*

Secondary succession. Succession starting after the disturbance of a previously existing plant community. See *Primary succession.*

Sedimentation. Deposition or accumulation of mineral or organic matter.

Seedling. Youngest trees from the time of germination until they reach a height of 1 meter (3 feet). See *Sapling, Pole, Mature, Senescent.*

Seed orchard. Plantation of trees established to provide for the production of seeds of improved quality.

Seed-tree method. Silvicultural system in which the mature timber is removed in one cut, except for a small number of seed trees left to provide a source of seed for the next crop. See *Clearcutting, Shelterwood method.*

Selection. Any discrimination by natural or artificial means that results in some individuals leaving more offspring than others.

Selection cutting. Silvicultural system in which scattered trees or small groups of trees are cut, providing sustained yield from an uneven-aged stand.

Selection differential. Difference between the value of a selected individual (or mean value of a selected population) and the mean value of the original unselected population.

Senescent. Growing old; aging stands at this stage are over-mature; losses from mortality and decay may exceed additions in volume. See *Seedling, Sapling, Pole, Mature.*

Sensor. A device that receives electromagnetic radiation and converts it into a signal that can be displayed as data or an image.

Serotinous cones. Cones of some species of gymnosperms that are sealed by resin, requiring high temperatures to open the cones and release seeds.

Serpentine. Common mineral, hydrous magnesium silicate, $H_2Mg_3Si_2O_2$.

Shade tolerance. Capacity of trees to reproduce and grow in the shade of and in competition with other trees.

Shelterwood method. Silvicultural system in which the mature timber is removed, leaving sufficient numbers of trees standing to provide shade and protection for new seedlings. See *Clearcutting, Seed-tree method.*

Shifting cultivation. Itinerant forms of agriculture, common in tropical regions, whereby the farmers clear a parcel of the forest and cultivate the soil until it becomes unproductive, then move onto another area where the process is started anew.

Shoot. Aboveground portion of a vascular plant.

Short-duration grazing. A system of range management employing a large number of separate pastures grazed individually for short periods of time, generally two days to two weeks.

Shrub. Woody perennial plant, seldom exceeding 10 feet in height, usually having several persistent woody stems branching from the ground.

Side-looking radar. An all-weather, day/night remote sensor that is particularly effective in imaging large areas of terrain; it generates energy that is transmitted and received to produce a photo-like picture of the ground. Also called *side-looking airborne radar.*

Sieve element. Cell of the phloem concerned with the long-distance transport of food substances. Classified into sieve cells (gymnosperms) and sieve tube members (angiosperms).

Silvichemicals. Chemicals derived from wood and trees.

Silviculture. Manipulation of forest vegetation to accomplish a specified set of objectives; controlling forest establishment, composition, and growth.

Site index. A particular measure of site quality based on the height of the dominant trees in a stand at an arbitrarily chosen age.

Site quality. A loose term denoting the relative productivity of a site for a particular tree species.

Size, sizing. Additive introduced to modify the surface properties of manufactured board or paper.

Skidding. Loose term for hauling logs by sliding, not on wheels.

Slash. Open area strewn with debris of trees from felling or from wind or fire; the debris itself.

Slurry. Watery suspension of insoluble matter—that is, pulp slurry.

Snag. Standing dead tree from which the leaves and most of the branches have fallen.

Soil-plant-atmosphere continuum. The continuous column of water that begins in the soil, travels across the roots, up the xylem within the roots and stem, through the xylem in leaf vascular bundles, to the wet surfaces of the mesophyll cells, and continues by evaporating into the atmosphere, all of which results in a close coupling of evaporation and uptake of water by a siphonlike action.

Specific gravity. As applied to wood, the ratio of the oven dry weight of a sample to the weight of a volume of water equal to the volume of the sample at some specific moisture content.

Spectral reflectance. The reflectance of electromagnetic energy at specified wavelength intervals.

Spectral-reflectance curve. A plot of the reflectance of electromagnetic energy for a series of wavelengths.

Spectral response. The response of a material as a function of wavelength to incident electromagnetic energy, particularly in terms of the measurable energy reflected from and emitted by the material.

Spectral-response envelope. The range of frequencies in which the spectral response is greatest.

Spectrum. A continuous sequence of energy arranged according to wavelength or frequency.

Sporangium. A hollow unicellular or multicellular structure in which spores are produced.

Spot fire, spotting. Fire set outside the perimeter of the main fire by flying sparks or embers.

Stand density. The average total basal area per acre of a given stand.

Stand table. A table showing the number of trees by species and diameter (or girth) classes, generally per unit area of a stand.

Stenotopic. Organisms limited to a very specific habitat.

Stereogram. A stereopair of photographs or drawings correctly oriented and permanently mounted for stereoscopic examination.

Stereomodel. A three-dimensional mental impression produced by viewing the left and right images of an overlapping pair with the left and right eye, respectively.

Stereopair. A pair of photographs which overlap in area and are suitable for stereoscopic examination.

Stereoplotter. A device that will plot as a contour map data obtained from aerial photographs; operates by means of a stereoscopic instrument.

Stereoscope. A binocular optical device for viewing overlapping images or diagrams to obtain the mental impression of a three-dimensional model.

Stereoscopic image. The mental impression of a three-dimensional object that results from stereoscopic vision.

Stereoscopy. The science or art which deals with three-dimensional effects and the methods by which these effects are produced.

Stomata. Openings in the surface of a leaf through which water vapor, carbon dioxide, and oxygen pass.

Stratification. Placing dormant seeds between layers of moist material, usually a sand and peat mixture, and exposing them to low temperatures to satisfy the pre-germination chilling requirements.

Structure, soil. Combination or arrangement of primary soil particles (e.g., sand, silt, clay) into secondary particles called peds. See *Ped.*

Stumpage. Value of timber as it stands uncut; uncut marketable timber.

Suberin. Fatty material in cell walls of corky bark tissue.

Subsoil. Bed or stratum of earth or earthy material immediately under the surface soil.

Substrate. Underlying material; the soil beneath plants or animals; the material on which an en2yme or fermenting agent acts, on which adhesive is spread, or on which a fungus grows or is attached.

Succession. Change in community composition and structure through time.

Sulfite pulp. Chemical wood pulp obtained by cooking—that is, digesting wood chips in a solution of bisulfites and sulfurous acid.

Suppressed. Pertaining to trees with crowns completely overtopped by surrounding trees so that they receive almost no direct sunlight. See *Dominant.*

Surface fire. Fire that burns only surface litter, loose debris of the forest floor, and small vegetation. See *Groundfire.*

Survivor growth. The increase in timber volume of a given stand owing to the continuing growth of previously measured trees. See *Ingrowth.*

Sustained yield. Yield a forest can produce continuously, such as timber.

Sweep. Curve in stem or log as distinct from an abrupt bend, generally as a reaction to environmental conditions.

Symbiosis. Mutually beneficial relationship between two dissimilar living organisms, called *symbionts.* In some cases, the symbionts form a single body or organ, as in mycorrhizae or lichens.

Synecology. Study of the community and its environment.

Syngas. Synthesis gas; a synthetically produced gas containing two parts hydrogen (H_2) and one part carbon monoxide (CO).

Systemic. Of a pathogen, capable of spreading throughout its host. Of a pesticide, absorbed by a plant so as to be lethal to agents that feed on it.

Systems analysis. Method of analysis which deals with the movement of energy or materials to different parts or components of a complex system.

T

Tall oil. Byproduct of the kraft pulping of resinous woods (e.g., pine), consisting mainly of resin acids and fatty acids.

Tannins. Complex extracellular water-soluble substances, generally formed from a variety of simpler polyphenols; part of wood extractives.

Terpenes. Class of hydrocarbons, with their derivatives, commonly occurring in many species of wood and generally having a fragrant odor; characteristically noted with pine trees.

Texture, photo image. The frequency of change and arrangement of tones; descriptive adjectives for textures are fine, medium, or coarse, and stippled or mottled.

Texture, soil. Relative proportion of the various mineral particles such as sand, silt, and clay, expressed as a textural class—for example, sandy loam, clay loam.

Thermal band. A general term for middle-infrared wavelengths that are transmitted through the atmosphere window at 8 to 13 micrometers; also used for the windows around 3 to 6 micrometers.

Thermal radiation. The electromagnetic radiation emitted by a hot blackbody, such as the filament of a lamp.

Thermal scanner. A detector which sweeps the instantaneous field of radiant energy across the terrain in either the 3- to 5-micrometer or 8- to 14-micrometer region of the spectrum.

Thermochemical liquefaction. Decomposition of organic compounds to smaller molecules often in the form of an oil. The reaction is usually carried out in the presence of a catalyst and hydrogen or synthesis gas at high pressure and temperature.

Thinning. Silvicultural treatment in which stand density is reduced to accelerate diameter growth in remaining trees.

Threshold dosage. The minimum dose necessary to produce a measurable effect in a given organism.

Throughfall. All the precipitation eventually reaching the forest floor—that is, direct precipitation plus canopy drip.

Tissue. Group of similar cells organized into a structural and functional unit.

Tissue system. Tissue or group of tissues organized into a structural and functional unit in a plant or plant organ.

Tone. Each distinguishable shade of gray from white to black on an image.

Tracheary element. Tracheid or vessel member.

Tracheid. Elongated, thick-walled conducting and supporting cell of xylem. Has tapering ends and pitted walls without perforations. Found in nearly all vascular plants; the main fibrous component of wood. See *Vessel member.*

Tree. Woody perennial plant, typically large and with a single well-defined stem and a more or less definite crown.

Triploid. Individual having one set of chromosomes more than the typical number for the species.

Trophic, -troph, tropho-. Pertaining to nutrition, feeding.

Trophic levels. Steps in the movement of energy through an ecosystem.

Turgor. Normal distention or rigidity of plant cells, resulting from the pressure exerted from within against the cell walls by the cell contents.

Turpentine. Essential oil that can be obtained by distilling the oleoresin of conifers, particularly pines, consisting of a mixture of terpenes. Most turpentine is now obtained as a byproduct of the kraft pulping of pines.

U

Understory. Any plants growing under the canopy formed by others. See *Canopy.*

Uneven-aged stand. Stand in which more than two distinct age classes and a range of size classes (seedling, sapling, pole, etc.) are present.

Ultraviolet radiation. Electromagnetic radiation of shorter wavelength than visible radiation but longer than X-rays; roughly, radiation in the wavelength interval between 10 and 4000 angstroms.

Uptake. Amount of water and nutrients absorbed by vegetation.

V

Vascular cambium. Cylindrical sheath of meristematic cells, the division of which produces secondary xylem and secondary phloem.

Vascular tissue. Specialized conducting tissue in plants forming a vascular system—in woody plants making up the whole of the xylem and phloem.

Vector. Any agent capable of transporting a pathogen or saprogen to a host.

Veneer. Thin sheet of wood of uniform thickness, produced by rotary cutting or by slicing.

Vessel member. Elongated cell of the xylem characterized by perforations. Its function is to conduct water and minerals through the plant body. Found in nearly all angiosperms and a few other vascular plants. See *Tracheid.*

Visible radiation. Energy at wavelengths from 0.4 to 0.7 micrometer that is detectable by the eye.

Volatiles. Essential oil distilled from plant tissues, generally characterized by a low boiling point.

Volume table. Table showing the average cubic contents of trees or logs by diameter and merchantable length in a specified unit of volume.

W

Watershed. Total area above a given point on a river, stream, or other waterway, that contributes water to the flow at that point.

Watershed management. The analysis, protection, repair, utilization, and maintenance of drainage basins for optimum control and conservation of water with regard to other resources.

Water stress. Stress or negative pressure exerted on a water column in a plant owing to transpiration.

Water table. Upper surface of the groundwater. A perched water table is one separated by relatively impermeable material from an underlying body of groundwater; may be seasonally impermanent.

Wavelength. The distance between successive wave crests, or other equivalent points, in a harmonic wave. The symbol is X.

Weathering. The physical and geothermal processes by which rock minerals are broken up and decomposed.

Wholesale price index (WPI). Weighed average of wholesale prices of a representative bundle of goods and services produced by the economy. The rate of increase (decrease) in the WPI is one measure of the rate of inflation (deflation) in the economy.

Wood. Secondary xylem.

Woody plants. Trees or shrubs exhibiting secondary growth.

X

Xerarch succession. Primary succession beginning on a substrate that is solid rock and therefore has minimal water-storing capacity.

Xeric. Of, pertaining to, or adapted to a dry environment.

Xylem. Tissue containing tracheary elements through which water and minerals are transported; wood is secondary xylem.

Y

Yard. To haul logs to a central spot to prepare them for transport.

Index

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