HARVESTED FORAGES

R. Dwain Horrocks
John F. Vallentine

HARVESTED
FORAGES

HARVESTED FORAGES

R. Dwain Horrocks

and

John F. Vallentine

Brigham Young University
Provo, Utah

Academic Press
San Diego London Boston New York Sydney Tokyo Toronto

Cover images: © 1999 PhotoDisc, Inc.

This book is printed on acid-free paper. ♾

Academic Press
a division of Harcourt Brace & Company
525 B Street, Suite 1900, San Diego, California 92101-4495, USA
http://www.apnet.com

Academic Press
24-28 Oval Road, London NW1 7DX, UK
http://www.hbuk.co.uk/ap/

Library of Congress Catalog Card Number: 98-89088

International Standard Book Number: 0-12-356255-4

PRINTED IN THE UNITED STATES OF AMERICA
99 00 01 02 03 04 MM 9 8 7 6 5 4 3 2 1

CONTENTS

PART I

INTRODUCTION TO HARVESTED FORAGES

1

THE ROLE OF HARVESTED FORAGES

PART II

UTILIZING HARVESTED FORAGES

2

FORAGE QUALITY: THE BASICS

3

MARKETING HARVESTED FORAGES

4

FORAGES AND ANIMAL NUTRITION: THE BASICS

5

FEEDING HARVESTED FORAGES

6

ANTI-HEALTH FACTORS IN HARVESTED FORAGES

PART III

GROWING AND PRODUCING FORAGE CROPS

7

PLANT GROWTH, DEVELOPMENT, LONGEVITY

8

CULTIVAR SELECTION

9

ESTABLISHMENT OF FORAGE SPECIES

10

PEST CONTROL: WEEDS, INSECTS, PATHOGENS, AND RODENTS

11

SOIL FERTILITY AND FORAGE PRODUCTION

12

WATER RELATIONS AND IRRIGATION

PART IV

HARVESTING AND STORING FORAGE CROPS

13

FIELD-HARVESTING HAY

14

FIELD-HARVESTING SILAGE

15

FORAGE-HARVESTING EQUIPMENT

16

PROCESSING AND STORING HAY

17

PROCESSING AND STORING SILAGE

PREFACE

Although there is much information on harvested forages, it has often been difficult to locate and synthesize fully. This book is an outgrowth of this problem, and its prime objective is to bring the key knowledge on harvested forages together in a single publication.

As a synthesis of the vast literature on harvested forages, we intend this work to serve as a college text for an upper division college course and as a reference book for professionals involved with harvested forages, for university instructors, for researchers, for producers, and for professional consultants in the forage production industry. Users of the book should have a basic agricultural science background.

We cover the major principles associated with successful forage crops production, harvesting, and storage. Although the geographic coverage of the book targets the middle-latitude areas of North America, the principles apply to similar areas anywhere in the world that use similar technology.

Producing harvested forages on fully arable agricultural lands is the primary topic of this work. Such land resources generally provide moderate to high potential for crop production, including adequate soil moisture through either natural precipitation or irrigation. Harvested forages compete for the use of the land resources that produce other alternative agricultural corps. However, harvested forage crops are sometimes produced on sites where alternative crops are unadapted. We acknowledge that we largely ignore the potential for forage production on these marginal or restrictive sites and instead emphasize the higher potential sites.

The 17 chapters in this book are grouped into four areas: Part I, Introduction to Harvested Forages; Part II, Utilizing Harvested Forages; Part III, Growing and Producing Harvested Forages; and Part IV, Harvesting and Storing Harvested Forages. An attempt has been made to document all salient points covered, and a single cumulative literature cited section follows Chapter 17. Although we each took lead responsibilities in initiating particular chapters, all chapters of the book are considered jointly authored.

R. Dwain Horrocks
John F. Vallentine

PART
I

INTRODUCTION TO HARVESTED FORAGES

1

THE ROLE OF HARVESTED FORAGES

I. INTRODUCTION

Forage is herbaceous plants or herbaceous plant parts made available for animal consumption. Forage can be harvested directly by the grazing animal from the standing crop (**pasturage**) or mechanically harvested and then fed to herbivores (**harvested** or **conserved forages**). **Forage crops** are plant crops grown for feeding as forage to ungulate herbivores, but the term is sometimes used to exclude pasturage. Forage consists broadly of the total aboveground part of herbaceous plants, but only selected portions of the aerial parts of the plant may be included in harvested forages. The term "forage" may be extended to include **browse** (the edible leaf and stem portions of woody plants), but this enlarged usage is mostly associated with grazing mixed rangeland vegetation.

Herbage is similar to forage in pertaining to aboveground herbaceous vegetation, but differs in that it may include plant material not acceptable or physically available to herbivores, these differences being greatest in pasturage. Because **roughage** is described as edible but bulky, coarse plant materials high in fiber and low in digestible nutrients, it is synonymous with forage only in part. Forages do contain significant amounts of plant cell-wall materials, the nutritive value of which is generally significantly lower than that for the cell-contents materials. However, many forages may still be relatively high in digestible energy (70%) and in total protein (25%).

Harvested forages are produced almost exclusively for feeding to livestock, principally ruminants and horses. Harvested forages are commonly fed on the farm where they are produced. However, an alternative is to sell harvested forages, primarily hay, off the farm where produced for feeding elsewhere. Regardless of which utilization alternative—or combination of alternatives—is followed, the production of harvested forages should be considered an earning enterprise on the farm and planned and operated accordingly.

Although not covered in detail in this text, hay production is often locally important at restrictive sites such as mountain meadows, wetlands and flood plains, certain native prairie sites, and selected range seedings (the last on the better sites or in abundant rainfall years). Whereas most of the principles of harvested forage production covered in this book apply to these unique sites as well, additional information, adaptations, and suggestions may be desired.

Further adaptation of management techniques to hay production at these cites can be found in the following references: on **native prairies,** Hyde and Owensby (1975), Conrad (1954), Coon and Leistritz (1974), Klebesadel (1965), Burzlaff and Clanton (1971), Streeter *et al.* (1966), Keim *et al.* (1932), and Towne and Ohlenbusch (1992); on **mountain meadows,** Siemer and Delany (1984), Delaney and Borelli (1979), Hart *et al.* (1980), Rumberg (1975), Lewis (1960), Hunter (1963), Willhite *et al.* (1962), Eckert (1975), Seamands (1966), and Barmington (1964); on **flood meadows,** Gomm (1979), Cooper (1956), Rumburg (1963), Britton *et al.* (1980), and Raleigh *et al.* (1964); and on **introduced wheatgrass grazing lands,** Peake and Chester (1943).

II. FORMS OF HARVESTED FORAGE

The standing crop of forage in the field commonly ranges from 60 to 90% moisture. Unless harvested forage is fed immediately in the fresh form, some method of preservation and storage is required. **Green chop** (syn. **zero grazing** and **green soiling**) is forage mechanically cut and chopped in the field and hauled directly to livestock for consumption in the fresh form.

No storage is involved other than the short period in the feedbunk prior to consumption. Because of rapid consumption, no preservative treatment is required. The forage is mechanically harvested daily or more frequently, and the moisture content is essentially the same as that of the standing crop in the field. However, because of the manner in which it is fed, green chop offers less opportunity for selective consumption than grazing.

Harvested forage to be stored for later feeding must be protected against mold formation and heating. The two primary methods of preserving and storing forage for later feeding are (1) drying by the sun in the field or mechanical drying after removal from the field to reduce moisture content to 10 to 20% and (2) ensiling under acidic conditions to prevent deterioration and spoilage (this generally following field wilting down to 60 to 70% moisture). Each of these methods, along with the many variations in final product form and handling practices they offer, has various benefits and limitations in meeting the needs of specific livestock programs. In fact, multiple methods of preserving and storing harvested forages are commonly utilized in the same farming or ranching operation.

Freezing is also an effective means of preserving forage but is too costly and time consuming for use except in conjunction with certain analytical and research procedures. **Fractionization** is yet another procedure by which high-quality forages such as alfalfa can be fractioned into graded nutritional components either during harvesting or afterward, each component being targeted to meet the nutritive requirements of specific classes and kinds of animals. The more nutritive portions can be directed to special animal needs in prepared feeds or may even be appropriate for human consumption; the more fibrous portions can be ensiled or dried and ground into meal for animal consumption where lower planes of nutrition are appropriate.

A. PRESERVATION BY DRYING

Hay consists of the aerial parts of finer-stemmed forage crops, primarily grasses and legumes, preserved and stored in the dry form. Drying alone is generally sufficient to preserve hay when the moisture content is under 20%, but high-moisture hay (20 to 30% moisture) will require addition of special preservatives. Coarse grasses such as corn and sorghums harvested with the seed and leaves intact and dry cured for animal feeding are referred to as **fodder.** When the seedheads, and often part of the leafage also, have been removed from the corn or sorghum plants, the resulting dry forage is designated **stover.** Although generally of low nutritive content, stover can be effectively utilized in the maintenance rations of mature ruminants and even horses. It has its counterpart in **straw,** the remaining parts of mature cereal crops after threshing or combining for grain removal and preserving in dry form.

Hay is most commonly baled before being stored but is sometimes stored in loose or compressed-stack form. Some hay is chopped and stored in overhead storage. When dried down to 8 to 10% moisture, hay can be compressed in the field into cubes or pellets for bulk reduction and ease of handling; this form is more common in low-humidity, low-rainfall areas where drying conditions are more favorable. Rapid dehydration of high-quality, fresh forage in rotating drums that have an artificial heat source for removing the moisture is another approach to dry preservation. The resulting forage form known as **dehy** (from the word dehydration) can subsequently be pelleted or ground into meal. In a 1982 study made in the United States of forages in which alfalfa was a component, 89% was baled, 14% was ensiled as haylage, 3% was kept as loose hay, 2% was made into meal and pellets, and less than 1% was fed as green chop (Pauli *et al.*, 1988).

B. PRESERVATION BY ENSILING

Ensiling is a process by which fresh or wilted forage material is preserved by fermentation through bacterial production of acetic and lactic acid. The process continues under aerobic conditions until the oxygen is removed and then subsequently under anaerobic phases until a pH of 3.5 to 4.5 is reached. At this stage the bacterial action is essentially complete, and the forage is preserved and can be stored indefinitely in air-tight (oxygen-free) facilities. The end product is a succulent form of forage known as **silage** with a moisture content ranging from 65 to 55%. Silage made from fine-stemmed grasses and legumes generally must be wilted in the field to reduce moisture content, properly ensile, and limit seepage and freezing after being placed in the silo. The term **haylage** is commonly applied to low-moisture silage (40 to 55% moisture) made from fine-stemmed grasses and legumes, but requires storage in a structure that effectively excludes all oxygen to avoid heating (including even spontaneous combustion) and spoilage.

Almost any forage can be preserved as silage; this includes not only green growing crops but also crop aftermath and wastage from fruit and vegetable processing. **Stalklage** refers to crop residues, primarily stalks, remaining in corn or sorghum fields after grain harvest that are mechanically harvested and then preserved by ensiling after the addition of water. Good-quality, whole-corn plants ensile well and provide the major silage crop in the United States. Silage made from sorghums, grasses and legumes, cereals, and miscellaneous crops is locally important. Dry forages and semidry forages still too high in moisture to dry cure can be effectively ensiled by adding water up to optimum levels. This permits damp bales or windrows or drought-damaged grain crops to be preserved and stored by ensiling. Silage made from large round bales or small stacks may even be a partial alternative to haying (Anonymous, 1984).

Under most conditions it is economically more sound to make hay than silage. The high moisture level of silage limits the distance it can be hauled;

thus, it must usually be used on the farm that produces it. An advantage of silage is that the field harvesting losses are reduced considerably; thus, there are cases in which silage may be the choice over hay. For example, dry matter yields may be increased under arid, irrigated conditions from 18 (McGill, 1991) to 25% (Wallentine, 1986) in a silage-making operation because the interval between cutting and irrigation is reduced to a minimum, thus allowing earlier initiation of regrowth. Over the course of a season, 1 week can be gained on each harvest. Thus, in a three-harvest system, 3 weeks can be gained for growth, accounting for the 18 to 25% increase in dry matter production. Park and Wallentine (1986) showed that at least 150 acres of alfalfa were needed to justify the bagger used in the AgBag system. In the California study cited in McGill (1991), one dairyman transports alfalfa silage 100 miles and still shows an economic advantage over feeding hay. Nevertheless, this is the exception rather than the rule when it comes to transporting silage.

III. HARVESTED FORAGE AS AN ENTERPRISE

Harvested forages may be fed to livestock on the farm where produced, marketed off farm for feeding elsewhere, or utilized in some combination of these two alternatives. Most harvested forage was originally fed on the farm producing it. However, the urbanization of America and the development of specialized, intensive livestock enterprises such as dairy, beef feeding, and horse production on high-priced lands near these population centers have provided a ready market for large quantities of harvested forages. This demand has been met by agricultural specialization, the development of efficient forage harvesting equipment and techniques, and the resulting capacity for producing large quantities of harvested forages for direct marketing.

Consideration must be given to whether a farm-produced forage truly has alternative utilization outlets or will be limited largely to home farm feeding. Only top-quality forage of high dry matter content should generally be produced or considered for marketing off farm. Even when hay supplies are high, there is often a shortage of high-quality hay. Thus, high-quality hay will nearly always bring a premium price to those producers who have developed a market and built a reputation for excellence and dependability.

Hay is a major North American crop; about 154 million tons is produced annually (Gray, 1989) on the estimated 50 million acres harvested annually (Rohweder *et al.,* 1983). During the 1977–1980 period, an average of 125 millions tons of hay was produced annually, 60% of which was alfalfa and alfalfa–grass mixtures. Of the total amount of hay produced annually during this period, 25% was sold off the farm and had a cash value of $6.5 to $7.0

billion. The value of all hay produced annually is conservatively estimated at $15 to $16 billion.

Alfalfa provides the bulk of harvested forages that are marketed, primarily in the form of baled hay but also in the form of compressed bales and concentrated meal. Lesser markets exist for grass-legume hays, prairie and meadow hays, cereal plant hays, and even straw. The high moisture level of silage limits the distance it can be hauled; thus, it must usually be fed on the farm where produced or on other farms in the immediate vicinity.

Flexibility in forage utilization plans will permit some variation from year to year depending on needs and farm production levels. More harvested forage can be marketed off farm in high production years and less in low production years to balance forage supply with farm needs; opportunities may also exist to expand or reduce livestock-growing enterprises to meet annual fluctuations in annual forage production.

The forage producer may also be a purchaser of harvested forages, i.e., during low production years, when livestock enterprises are temporarily expanded beyond farm forage production capabilities, or where certain kinds of harvested forages cannot realistically or as economically be produced on the farm. Where farm plans provide for regularly marketing substantial quantities of harvested forages off farm and favorable marketing outlets have been developed, special care should be taken to fully service these outlets as regularly as possible.

Whereas high-quality harvested forage can alternatively be fed on the farm where produced, low-quality forage or forage of high water content will mostly be restricted to use on the farm where produced. Although some hay producers typically sell the best hay and feed the rest in their own feedlots, other producers must work out arrangements with neighbors for using the lowest quality hay, damaged hay, and broken bales.

Harvested forages should be considered as one or more earning enterprises and evaluated using complete budgets. If harvested forage is home fed, its value must be fully but fairly credited to the harvested forage enterprise rather than to the livestock enterprise(s) consuming the forage. This requires separating harvested forages from the livestock enterprises consuming the home-fed forages. This permits profits and losses to be determined for both phases independently and permits more management analysis in making economic decisions on whether the harvested forages should be home fed or sold. The harvested forage enterprise is terminated when the harvested forage is either marketed off farm or transferred to one or more livestock enterprises and its value fully credited to the forage enterprise. To be efficient and fully competitive with alternative uses of prime farm land such as grain crops, harvested forage crops require equivalent levels of planning, cultural inputs, and harvesting control.

IV. CURRENT IMPORTANCE AND FUTURE PROJECTIONS

Because of concern about world human food supplies and possible future shortages, there is widespread interest in reducing concentrate levels and increasing the levels of forages in animal rations. The ability of ruminants (cattle, sheep, and goats) to convert fibrous organic substances not consumable by humans into human food of high quality is truly a natural phenomenon of great benefit to humankind. These high-fiber feedstuffs include not only forage crops but also by-products of agriculture, forestry, and industry. Horse populations kept for either pleasure or work can also be largely maintained on such high-fiber feedstuffs.

It has been estimated that the total feed consumed by livestock in the United States is composed of 40% pasturage, 40% concentrates, and 20% harvested forages (Allen and Devers, 1975). Fitzhugh *et al.* (1978) estimated that ruminants consume diets of about 90% forage and other roughages on a world average and about 70% in the United States. More recent estimates (Reber, 1987), however, raise these figures to 95 and 80%, respectively. It seems reasonable to anticipate that in the future, the ruminant will be used relatively even more than in the past to convert low-quality biomass into useful production, i.e., annual products. However, ruminant rations may continue to include some low quality grain, grains bred specifically as "feed grains," and even food grains when in surplus of market demands. Also, Americans continue to show preferences for leaner cuts of red meats, but from animals finished on high grain diets.

The beef industry constitutes the largest market for forages in the United States (Oldfield, 1986). Efforts are now under way to bolster the beef market by lowering the fat content, and substituting more forages for the grain now used in finishing rations is known to be an effective technique. However, forages for beef cattle probably represent a static to only slightly increasing demand. Dairying probably represents a static to slightly declining demand for forages. Even though dairy cows are becoming larger and more productive, with an accompanying increase in the consumption of high-quality forage, numbers are down and dairy product substitutes have become commonplace. Even if sheep and goat populations in the United States show some increase in the future, as expected, their numbers are relatively so small that only a major increase would significantly increase total forage needs. The numbers of workhorses in the United States are very low and are expected to remain so; the much larger population of pleasure horses is expected to remain static.

The U.S. Department of Agriculture (USDA) has projected the future demand for forages by domestic livestock (USDA, For. Serv., 1981). The projected demands for the different categories of forages for the years 2000 and 2030, with the 1976–1978 data as the base, are shown in Table 1.1. For purposes of conversion, each animal unit month (AUM) of harvested forage is equivalent to about 340 kg (750 lb.) of air-dried forage. Although the projected increase in demand is relatively greater for forage supplied by grazing than for that by mechanical harvesting, there are obviously substantial flexibility and complementarity between the two in meeting total future forage needs.

The AUM is a quantitative measure of carrying capacity and provides no opportunity for expressing nutritive quality except when each source is fully described nutritionally. The AUM is particularly useful with livestock production and growing enterprises using range and other grazing lands as the principal source of forage. The AUM can be expanded to include harvested forages when fed in controlled amounts in conjunction with pasturage. However, when harvested forages and concentrated energy feeds are fed with minimal intake restriction or free choice for more rapid weight gains, increased consumption commonly increases energy intake by 50 to 100%. This suggests that under drylot conditions or when pasturage makes only minimal contribution to the daily ration, use of the AUM should be foregone and rations calculated on a nutrient weight basis (Vallentine, 1990).

Mountain hay meadows, both irrigated and naturally subirrigated, play an essential role in ranching and livestock production in the western United States. It is estimated there are approximately 1.5 million acres of irrigated native grass hay in the mountain and intermountain regions of California, Oregon, Idaho, Utah, Nevada, Montana, Wyoming, and Colorado (Jacobs, 1983). Traditionally, these mountain hay meadows round out the year-round forage supply by providing hay for livestock during winter.

Mechanical forage harvesting need not be the slow, laborious process it once was. Advances in forage harvesting equipment and handling methods have been greatly improved. Hay conditioners, bale throwers, and windrowers that handle wide swaths at high speeds are developments that remove much of the major bottlenecks in forage handling. A single machine with

TABLE 1.1 Projected Demand for the Different Categories of Forages

	Millions of AUMs[a]		
Year	Total forage	Total grazing	Harvested forage
1976–1978	1358	914	444
2000	1830	1398	432

[a] AUM (animal unit month) is defined as the potential forage intake of one mature, nonlactating cow or its equivalent for 1 month; an AUM is equivalent to 30 AUDs (animal unit days).

interchangeable heads to harvest both row crops and close-sown forages is another significant development. Mechanization of forage handling in the feedlot to approach a push-button operation, combined with the development of high-yielding forage plant cultivars, has enabled greater dependence on confinement feeding of livestock where benefit : cost relationships have been favorable.

V. ROLE IN CROP ROTATION SYSTEMS

Harvested forage crops play a prominent role in the conservation ethics that are part of **grassland agriculture,** a land management system emphasizing cultivated forage crops, pasture, and rangelands for forage and livestock production and soil stability (Barnes, 1982). Emphasis in grassland agriculture is given to the use of grasses, legumes, and other plants in forage production while providing groundcover for the protection of soil resources. Forage plant species planted in close-sown rows or broadcasted give the greatest conservation advantages. When forage plants such as corn and sorghums are grown as row crops, there may be times when insufficient or no cover exists to protect soil against erosion and leaching. However, these problems can be greatly reduced by using contour farming, conservation tillage leaving mulch on the soil surface, strip cropping, and interplanting or double cropping with cover crops.

Land suitability classification provides a means of planning for proper use of agricultural lands (Klingebiel and Montgomery, 1964). Land capability classes I through IV are suited to cultivation, with I having the fewest limitations and IV the most limitations; class VIII is unsuited to agricultural use except minimally as wildlife habitat. The use of classes V through VII, and often IV as well, should be limited to permanent vegetation for use as grazing lands, forestry and wildlife, or continuous grass or legume haylands. An exception in the latter is during periodic reestablishment under intensive management practices in the more humid or irrigated areas. However, the highest forage yields are grown on land capability classes I through III. When properly planned and intensively managed, harvested forages such as alfalfa, grass-legume, or silage corn or sorghums on such sites are financially competitive with grain crops and provide opportunity for effective crop rotation.

Crop rotations between forages and other crops are complementary on Class I to IV lands. Some of the advantages of rotating forage crops with other crops include: (1) the favorable effect of grass and legume roots on soil aggregation, reduced erosion, and water infiltration; (2) more continuous soil protection—even year-round with perennials; (3) more effective control of weeds, insects, and plant diseases; and (4) nitrogen fixation by legumes. The resulting benefits are reflected not only in the forage yield but also in enhanced yields of other crops produced in rotation with forages. These benefits in excess of the market value of the forage itself might well be counted as additional income generated by the forage crop and credited to the market value of the forage itself.

A. SOIL BUILDING

Soil is the basic resource in crop production, and maintaining good soil tilth is greatly enhanced by including a sod-forming forage crop in the rotation, thereby increasing organic matter levels and soil aggregation. The benefits do not stop at the soil surface; the network of both dead and living roots that is formed by sod crops not only stabilizes the soil but tends to improve soil aeration and promotes water penetration, percolation, and storage in the soil profile. The resulting stable soil structure resists the negative effects of tillage implements (including compaction), enhances the ease of seedbed preparation, and reduces the beating action of raindrops during the period when the land is in intertilled crops.

The kind of forage crop in the rotation materially affects the type, chemical composition, and amount of plant residue that remains, and this influences the amount and stability of the soil aggregates. Materials left by legumes bring about aggregation in a relatively short period of time (2 or 3 weeks), but lose their effectiveness within 2 or 3 months. However, the more fibrous materials of grasses require a longer period to affect aggregations, but they have a more lasting effect on soil structure. Although the fibrous grass roots permeate the plow layer, the roots of alfalfa often penetrate 10 to 15 feet into the subsoil and improve soil drainage. The soil-binding characteristics of rhizomatous grasses such as reed canarygrass may permit support of machinery and equipment not otherwise possible on wet sites.

Forage legumes not only provide high-quality feed for livestock but also convert atmospheric nitrogen into forms available for their own growth and that of other plant species as well. This nitrogen-fixing capability results from the symbiotic relationship with bacteria of the genus *Rhizobium;* an adequate number of bacteria to achieve high levels of nitrogen fixing is ensured by inoculating the legume seed prior to planting. On productive sites, alfalfa and clovers in pure stands commonly produce 100 lb of usable nitrogen per acre and up to twice that much under ideal conditions. The economic contribution of nitrogen fixed by legumes is becoming more widely recognized as at least a partial alternative to the high cost of inorganic nitrogen fertilizers. The benefits of nitrogen fixing accrue not only to companion crops growing in the forage mixture but also as carryover to the next crop in the rotation.

B. EROSION CONTROL

Solid-seeded, close-growing forage plants are a highly effective means of protecting the soil surface from wind and water erosion. Plants with dense canopies of leaves and stems such as close-sown forages protect the soil surface by intercepting and reducing the beating effects of raindrops, and channels left by decayed roots greatly aid in water infiltration into the soil. The combined effects of the living biomass and mulch slow down and regulate water flow from an area and reduce siltation downstream. However, even after being plowed for row crop production, grass roots continue to furnish protection to the soil surface by holding and binding soil particles together and enhancing percolation. Maintaining acceptable environmental quality in some regions may require a substantial shift from more or less continuous row-crop production to part-time forage production as provided for in optimal crop rotations.

C. PEST CONTROL

Crop rotations provide a means of cultural control of crop pests such as weeds, insects, and diseases by breaking up their life cycles. Many insects and diseases are destructive to only one kind of crop, and many weeds receive minimal or ineffective competition from certain crops or are enhanced by management practices associated with the production of that crop. If the host plant (of diseases and insects) or low-competing plant (with weeds) is continually grown in the same field for many successive years, the pests have an opportunity to increase in large numbers. Growing other crops in rotation, including forages, provides an opportunity for tackling the pests in different ways and at different times of the year.

The development of new pesticides and refinements in their effective use have provided additional means of pest control. However, cultural practices included in rotations may be required to make the use of pesticides most effective, but environmental considerations are placing more restraints on the use of pesticides as sole control methods. Unfortunately, not all weeds can be controlled by crop rotation alone, even when competition is provided periodically by aggressive forage plant species or species mixes. Not all insects are restrictive in their food habits but are general feeders, and some plant diseases have alternative hosts or may remain viable in the soil for years. Although crop rotations including forage crops may not eliminate pest populations completely, they may effectively reduce their levels to allow acceptable crop yields. **Integrated pest management,** in which various control measures are combined rather than reliance on a single method, utilizes cultural practices and suitable patterns of crop rotation; this multiple approach is now being widely recommended and more widely used than in the past.

This Page Intentionally Left Blank

PART

II

UTILIZING HARVESTED FORAGES

This Page Intentionally Left Blank

2

Forage Quality

The Basics

D. Climatic Factors
E. Weather and Harvesting Practices
F. Diseases and Insect Damage
G. Nutrient Enhancement Agents

I. MANAGEMENT PHILOSOPHY: QUALITY VERSUS QUANTITY

A. YIELD NOT ENOUGH

Higher production of harvested forages can be made in terms of greater yields of dry matter per hectare, higher nutritional quality (percentage composition of selected nutrients), or combined into nutrient yields [kg total digestible nutrients (TDN)/ha or kg digestible protein/ha]. High dry-matter yields are desirable and have been the primary measure of forage yields in the past, but quality is also important in harvested forages. Research on harvested forages, in general, has shown that the maximum quantity—that is, maximum dry-matter yield—that can be produced does not occur simultaneously with maximum quality. There are trade-offs that must be considered in evaluating the characteristics of forage quantity and quality. The most successful forage-plant breeding and management programs generally combine high yields with better quality. Greater emphasis on nutrient yields, especially with alfalfa, have been made possible by new plant cultivars with multiple pest resistance and rapid regrowth characteristics.

Highest quality can be obtained by selecting only the new shoots of the forage plant, but this would result in large sacrifice of yield. On the other hand, there is a point beyond which projected increases in yield would not offset the loss in quality that results from the larger quantity of dry matter characteristic of older plants. The point at which the most favorable quantity : quality ratio is obtained differs among the many forage species.

Hay growers have always been confronted with a dilemma. On the one hand, feeders of hay, especially dairymen, want high quality (i.e., high level of digestible energy and protein). On the other hand, buyers (often the same individuals as the users) pay for hay by the ton. High-quality hay is inversely related to maturity of the crop: the more mature the crop, the higher the dry-matter yield and the lower the quality; conversely, the higher the quality, the lower the production per unit area. For producers, the solution to this quandary has been to harvest hay when maximum yield could be realized. The product was of a lower quality than feeders seeking high-quality feed for dairy animals needed, but it was what they were willing to pay for. Their solution was to add more energy (grain) and protein (meal) to the ration.

The "cubing" industry took some steps in helping educate producers and consumers to the potential of forages, especially alfalfa, as high-quality feed (i.e., high in energy and protein and low in fiber). However, it was not until a new technology, near-infrared spectrophotometry (NIRS), was introduced (Norris *et al.,* 1976) that producers began to see the possibility of realizing their long-time goal of receiving payment for hay based on its quality (Marten, 1984). In most parts of the United States, the goal has not been realized but positive steps have been taken. When harvested forages are sold on the open market, the amount of premium paid for high quality influences the emphasis that should be given to quality relative to quantity.

Mechanical harvesting of forages provides maximum control in determining the quality of the forage being preserved. Both the quality and the quantity of a forage are set when mechanically harvested and preserved from further losses, assuming good processing and storage practices are followed. By contrast, when forages are harvested by grazing, losses in quality result from advancing maturity, weathering, trampling, and fouling. The selection of proper mechanical harvesting schedules not only ensures high-quality forages, but also provides a means of considering physiological needs of the forage plants so that their productive life can be prolonged.

B. HIGH QUALITY AND ANIMAL PRODUCTION GOALS

Feeding value is related to quality of the forage. Voluntary intake of alfalfa by ruminants is higher than that for grasses because much more dry matter from alfalfa and other legumes is in the form of cell solubles, which are readily absorbed into the digestive system (Van Soest, 1964, 1982). Although levels of cell-wall material (fiber) are lower in alfalfa than in grasses, the cell walls themselves are highly lignified and are less available than are the cell walls of grasses (Tomlin *et al.,* 1965).

The cell-wall concentration of a forage is the best single chemical indicator of intake potential (Van Soest and Robertson, 1980; Waldo, 1985). This is because intake is regulated by ingested and retained (undigested) residue in the rumen (Raymond, Redman, and Walthamn, 1986a,b). Ample evidence exists comparing intake and gain on alfalfa and grasses. Despite nearly equal digestibility, the intake on alfalfa, passage rate, and animal gains are higher than those for grasses (Balwani *et al.,* 1969; Troelsen and Campbell, 1969; Barnes and Mott, 1970; Donker *et al.,* 1976, 1982; Waldo *et al.,* 1982).

Because available energy is often the limiting factor in high forage rations, animal performance can often be estimated from digestible energy intake. However, digestible energy obtained from high fibrous material is not utilized as efficiently for high production as is that from higher quality material (Moore *et al.,* 1953, Lofgreen and Garrett, 1968). Thus, the advantages of high-quality alfalfa go beyond that indicated by digestible nutrient concentration and include increased consumption, increased digestibility, and a faster rate of passage through the animal's rumen, as well as possibly more efficient conversion of digested energy. In addition, the high concentration of inorganic nutrients may have a beneficial effect on animal performance (Burroughs *et al.,* 1950; Horn and Beeson, 1969).

High-quality hay cannot be made if the primary regulator of forage quality (i.e., plant stage of development) is ignored. Troelsen and Campbell (1969) reported that as plants mature, animal performance is reduced, partly because of lowered concentration of digestible energy (DE) in the forage and partly because of lowered voluntary intake. They also reported that for each day the harvest is delayed beyond the vegetation (late bud) stage, first-crop alfalfa intake is reduced by 0.21 g kg^{-1} (body $weight)^{0.75}$. Variation in intake can be more important than digestibility (Anderson *et al.,* 1973; Waldo and Jorgensen, 1981).

The balance between forage quality and quantity depends largely on the production desired for a particular class of livestock, and the optimization of forage quality and quantity may be quite different between different livestock enterprises and between different phases of the production cycle within each enterprise. The goals in terms of animal responses desired largely determine the level of forage quality necessary to permit adequate nutrient intake for achieving the desired livestock performance. Although livestock producers must be concerned with production obtained per animal, economic assessment of the combined forage crop and livestock enterprises must consider marketable production obtained per unit of land area; this requires consideration of both response per animal and efficient forage production and utilization.

The relative dependence on forages and supplemental feeds in a livestock enterprise generally reflects profit making, involving production costs and marketing returns. High-quality forages can be at least a partial alternative to buying supplemental concentrates. When energy and protein costs from feed grains are high, emphasis should turn toward increased forage utilization with consideration given to both quantity and quality. In contrast, cheap feed grains and other supplemental feeds may encourage producing lower quality forage in favor of greater productivity per acre.

Consideration of forage quality (dry-matter digestibility, percentage protein, or percentage TDN) should generally take precedence over quantity when economic yield is related to livestock production. Producing and feeding the highest quality forages possible increase animal performance and are apt to reduce feeding costs and ultimately result in the highest net returns from the forage enterprise. If the nutritive value of the stored forage exceeds the requirement of the animal production desired, limitations on daily feed intake could be made by reducing the amount of feed allowed daily. On the other hand, the tendency for forage intake and digestibility to be strongly related puts low quality squarely in the position of limiting the level of forage intake achieved.

Forage quality is a complex characteristic of forages. Forages exist for the purpose of providing the nutritional needs of animals, but high quality also implies being acceptable to the animals and being reasonably free of harmful substances and nonnutrient foreign materials. **Forage quality** is probably best defined as the extent to which a forage has the ability to produce a desired animal response. Thus, the ultimate test of harvested forage quality is animal performance. In addition to measuring the nutritional quality of the available forage and the nutrient intake of livestock, attention must be given to monitoring the performance of animals consuming the forage as a final measure of its forage value.

II. VISUAL CRITERIA FOR HIGH QUALITY

Generally, **visual appraisal** should be the first phase of quality evaluation. Visual inspections including smelling and feeling forage samples can, in fact, identify problems in the harvested forage that may not be determined by forage analyses alone. The visual factors that have been used to judge the quality of harvested forages include stage of development, leafiness, green color, condition and odor, palatability, and foreign material.

A. STAGE OF DEVELOPMENT

Stage of development refers to the maturity of the forage. Highest quality in harvested forages generally results from avoiding advanced maturity, natural dormancy, and weathering. Stage of development is easiest to estimate in the standing crop just prior to harvesting and is much more difficult to assess after chopping. Amounts and maturity of flower and grain, coarseness and size of stems, and shear strength of leaves and stems may help in assessing stage of maturity. Texture and toughness can be evaluated subjectively by handling and feeling the harvested forage.

B. LEAFINESS

Leafiness provides a helpful tool for evaluating the quality of harvested forages and may range from about 30 to 70% in alfalfa hay. Because most of the digestible nutrients are in the leaves and most of the fiber is in the stems, hay quality is greatly dependent on leafiness. A high proportion of leaves to stems generally indicates higher nutritive value and general palatability. Leafiness can be determined by visual estimation or by more precise objective procedures. Leafiness can also be diminished by loss of leaves during harvesting.

C. GREEN COLOR

Color often relates positively to early stage of maturity and proper handling and processing, and is best determined by visual observation. A bright green color in alfalfa hay is generally taken as an indicator of optimal feeding value. With alfalfa, the green color also indicates that the hay was rapidly and properly cured, with no damage from rain or overheating during storage.

D. CONDITION AND ODOR

Objectionable odors, mold, dust, and rodent and insect damage and moisture levels departing greatly from the norm for that harvested forage imply loss of forage quality. Moldiness and odors that decrease palatability as well as nutritive value often result from processing or storing too wet, whether preserved in dry form or ensiled. When harvested too wet and subsequently allowed to heat to 130 to 140°F, hay may become brown and caramelized, whereas hay that has heated to more that 150°F will likely turn black and be rendered worthless as forage. However, baling hay when it is too dry results in greater leaf loss and a resulting lower quality. High yeast or mold populations in silages are promoted by slow filling of silo, air leaks in silo, slow feedout, improper moisture levels, long chop length, and insufficient compaction during filling of the silo.

E. PALATABILITY

Palatability of the forage is an indirect measure of quality; it is the summation of the plant characteristics that determine the relish with which a forage is consumed by an animal. Livestock find some harvested forages much more acceptable than others, and low palatability may greatly reduce consumption levels or may result in animals refusing to consume even smaller amounts. Potential intake level by the ruminant animal is considered one of the two universal factors in forage quality, the other being nutritive value (Marten and Martin, 1986). Palatability is determined by observing how well animals like the forage or by estimating or measuring forage intake. However, degree of hunger and familiarity with the particular forage may initially modify observed acceptability, and palatability is always relative to the availability of other alternative feedstuffs to select from.

Animal preferences of forages result primarily from the senses of smell and taste (Marten, 1978; Walton, 1983). Many feedstuffs of low palatability but otherwise wholesome for animal consumption are relished when sprayed with molasses or artificial sweeteners such as saccharin, indicating a high dependence on taste in dietary selection. The presence of antipalatability (bad taste) factors such as alkaloids, volatile chemical components, rancidity, moldiness, and contamination with agricultural chemicals can sharply reduce palatabilty. The sense of touch or feel may also be important; palatability is related to physical characteristics such as fiber content, toughness, steminess, leafiness, level of maturity, and succulence. The sense of sight apparently plays an insignificant role in determining forage preference by domestic livestock.

F. FOREIGN MATERIAL

Foreign material in harvested forages includes weeds, old hay stubble, rocks, soil and dirt clods, dung, baling twine or wire, sticks, or any other materials that have little or no nutritive value. Weeds are a common problem and are often, but not always, of low quality and palatability; some are poisonous or are injurious to the mouths of the animals. Small, metal objects may be picked up in the harvesting process and be ingested along with the harvested forage. Visual examination is the best test for amount of foreign material present.

III. MEASURES OF NUTRITIVE VALUE

General knowledge and visual appraisal of such factors as maturity, leafiness, color, plant species, and even palatability are suggestive in predicting the adequacy of many specific nutrients in harvested forages. Tables of average composition, such as Table 2.1, provide generalized information about different forage species at different stages of growth. However, such tables deal only with averages and not with the nutritive value of specific forage lots.

A. DIGESTIBILITY

Digestion comprises the body processes within animals involved in conversion of feed nutrients into forms that can be absorbed from the digestive tract. These "digestible" end products move through the linings of the small and large intestines and, in ruminants, the rumen into the blood and/or lymph systems and are transported throughout the body to points of utilization. **Digestibility** refers to that portion (usually expressed as a percentage) of the ration, individual feedstuff, or specific nutrient that exits the digestive system into the circulatory system; **indigestibility** refers to the remaining portions that exit through the anus. This concept of digestibility provides the basis of the terms **digestible dry matter, digestible organic matter, digestible energy, digestible protein,** and so on. Although the term *digestible* can also be applied to individual minerals, the term *available* is in

TABLE 2.1 Nutrient Composition of Common Forages (100% Dry-Matter Basis)[a]

Species	Dry matter (%)	Crude protein (%)	Bypass protein (%)	Ether extract (%)	Total ash (%)	Crude fiber (%)	Neutral detergent (%)
List 1							
Alfalfa							
Meal dehy., 15% protein	90	17.3	—	2.5	10.4	29.4	51
Meal dehy., 17% protein	92	18.9	59	3.0	10.6	26.2	45
Meal dehy., 20% protein	92	22.0	—	3.7	11.3	22.5	42
Meal dehy., 22% protein	93	23.9	—	4.4	11.0	19.8	39
Hay, early vegetative	90	23.0	—	4.0	10.2	20.5	38
Hay, late vegetative	90	20.0	—	3.8	9.2	22.0	40
Hay, early bloom	90	18.0	18	3.0	9.6	23.0	42
Hay, midbloom	90	17.0	22	2.6	9.1	26.0	46
Hay, full bloom	90	15.0	28	2.0	8.9	29.0	50
Bahiagrass							
Fresh	30	8.9	—	1.6	11.1	30.4	68
Hay, late vegetative	91	9.5	—	1.7	9.6	33.0	73
Bermudagrass, coastal							
Hay, early vegetative	94	16.0	—	2.5	6.1	26.8	68
Hay, late vegetative	91	16.5	—	1.8	7.7	27.3	70
Hay, mature	93	8.0	—	1.4	9.0	36.0	78
Bluegrass, Canada							
Fresh, early vegetative	26	18.7	—	3.7	9.1	25.5	—
Hay, late vegetative	97	—	—	—	—	—	—
Bluegrass, Kentucky							
Fresh, early vegetative	31	17.4	—	3.6	9.4	25.3	55
Fresh, early bloom	35	16.6	—	3.9	7.1	27.4	65
Fresh, mature	42	9.5	—	3.1	6.2	32.2	69

Brome							
Fresh, early vegetative	34	18.0	22	3.7	10.7	24.0	56
Fresh, mature	57	6.4	—	2.2	—	38.0	72
Hay, late vegetative	88	16.0	—	2.6	9.4	30.0	65
Hay, late bloom	89	10.0	35	2.3	8.4	37.0	68
Clover Alsike							
Fresh, early vegetative	19	24.1	—	3.2	12.8	17.5	—
Hay	88	14.9	—	3.0	8.7	30.1	—
Clover, Crimson							
Fresh, early vegetative	18	17.0	—	—	—	28.0	—
Hay	87	16.0	—	2.4	11.0	30.1	—
Clover Ladino							
Fresh, early vegetative	19	24.7	—	2.5	13.5	14.0	—
Hay	90	22.0	33	2.7	10.1	21.2	36
Clover, Red							
Fresh, early bloom	20	19.4	25	5.0	10.2	23.2	40
Fresh, full bloom	26	14.6	—	2.9	7.8	26.1	43
Hay	89	16.0	31	2.8	8.5	28.8	46
Corn, Dent Yellow							
Silage, stover	31	5.9	—	2.1	11.6	31.3	67
Silage, few ears	29	8.4	—	3.0	7.2	32.3	53
Silage, well eared	33	8.1	32	3.1	4.5	23.7	51
Fescue, Kentucky 31							
Fresh, vegetative	29	14.5	30	5.5	9.9	24.6	—
Hay, early bloom	91	20.2	30	6.6	9.8	23.6	59
Hay, midbloom	92	16.4	—	6.1	9.1	25.5	63
Hay, full bloom	92	12.1	—	5.3	7.9	27.4	67
Hay, mature	90	9.2	35	4.3	6.4	32.6	70

(continues)

TABLE 2.1 *(continued)*

Species	Acid detergent fiber (%)	Lignin (%)	Calcium (%)	Magnesium (%)	Phosphorus (%)	Potassium (%)	NEM (Mcal/lb)
List 1							
Alfalfa							
Meal dehy., 15% protein	41	12	1.37	0.31	0.24	2.48	0.58
Meal dehy., 17% protein	35	11	1.52	0.32	2.25	2.60	0.61
Meal dehy., 20% protein	31	8	1.74	0.36	0.30	2.73	0.63
Meal dehy., 22% protein	28	8	1.82	0.33	0.33	2.58	0.70
Hay, early vegetative	28	5	1.80	0.26	0.35	2.21	0.69
Hay, late vegetative	29	7	1.54	0.24	0.29	2.56	0.64
Hay, early bloom	31	8	1.41	0.33	0.22	2.52	0.60
Hay, midbloom	35	9	1.41	0.31	0.24	1.71	0.57
Hay, full bloom	37	10	1.25	0.31	0.22	1.53	0.52
Bahiagrass							
Fresh	38	7	0.46	0.25	0.22	1.45	0.50
Hay, late vegetative	38	6	0.28	0.27	0.21	1.80	0.34
Bermudagrass, coastal							
Hay, early vegetative	30	4	—	—	—	—	0.61
Hay, late vegetative	32	4	—	—	—	—	0.50
Hay, mature	43	7	0.26	0.13	0.18	1.30	0.33
Bluegrass, Canada							
Fresh, early vegetative	—	—	0.39	0.16	0.39	2.04	0.76
Hay, late vegetative	—	—	0.30	0.33	0.29	1.59	0.76
Bluegrass, Kentucky							
Fresh, early vegetative	29	3	0.50	0.18	0.44	2.27	0.77
Fresh, early bloom	32	4	0.46	0.17	0.39	2.01	0.73
Fresh, mature	40	6	0.26	0.16	0.27	1.52	0.54

Bromegrass (smooth)							
Fresh, early vegetative	31	3	0.50	0.18	0.30	2.30	0.80
Fresh, mature	44	9	0.20	0.18	0.26	1.25	0.55
Hay, late vegetative	35	4	0.32	0.18	0.37	2.32	0.71
Hay, late bloom	43	8	0.30	0.18	0.35	2.32	0.58
Clover, Alsike							
Fresh, early vegetative	—	—	1.29	0.41	0.26	2.46	0.69
Hay	—	—	1.29	0.41	0.26	2.46	0.57
Clover, Crimson							
Fresh, early vegetative	—	—	1.40	0.28	0.22	2.40	0.64
Hay	—	—	1.40	0.28	0.22	2.40	0.55
Clover Ladino							
Fresh, early vegetative	—	—	1.35	0.48	0.31	2.62	0.71
Hay	32	7	1.35	0.48	0.31	2.62	0.67
Clover, Red							
Fresh, early bloom	31	4	2.26	0.51	0.38	2.49	0.73
Fresh, full bloom	35	7	1.31	0.51	0.27	1.96	0.65
Hay	36	8	1.53	0.43	0.25	1.62	0.52
Corn, Dent Yellow							
Silage, stover	43	8	0.38	0.31	0.31	1.54	0.52
Silage, few ears	30	5	0.34	0.23	0.19	1.41	0.63
Silage, well eared	28	4	0.23	0.19	0.22	0.96	0.74
Fescue, Kentucky 31							
Fresh, vegetative	—	—	0.51	—	0.37	—	0.69
Hay, early bloom	32	3	—	—	—	—	0.65
Hay, midbloom	35	4	—	—	—	—	0.60
Hay, full bloom	39	5	—	—	—	—	0.57
Hay, mature	42	7	—	—	—	—	0.54

(continues)

TABLE 2.1 *(continued)*

Species	NEG (Mcal/lb)	NEL (Mcal/lb)	TDN (%)
Alfalfa			
Meal dehy., 15% protein	0.32	0.60	59
Meal dehy., 17% protein	0.35	0.63	61
Meal dehy., 20% protein	0.36	0.64	62
Meal dehy., 22% protein	0.43	0.69	67
Hay, early vegetative	0.42	0.68	66
Hay, late vegetative	0.38	0.65	63
Hay, early bloom	0.34	0.61	60
Hay, midbloom	0.31	0.59	58
Hay, full bloom	0.26	0.56	55
Bahiagrass			
Fresh	0.25	0.55	54
Hay, late vegetative	0.10	0.44	44
Bermudagrass, Coastal			
Hay, early vegetative	0.35	0.63	61
Hay, late vegetative	0.25	0.55	54
Hay, mature	0.09	0.42	43
Bluegrass, Canada			
Fresh, early vegetative	0.48	0.74	71
Hay, late vegetative	0.48	0.74	71
Bluegrass, Kentucky			
Fresh, early vegetative	0.49	0.75	72
Fresh, early bloom	0.45	0.71	69
Fresh, mature	0.28	0.57	56

Brome			
Fresh, early vegetative	0.51	0.77	74
Fresh, mature	0.29	0.58	57
Hay, late vegetative	0.44	0.70	68
Hay, late bloom	0.32	0.60	59
Clover, Alsike			
Fresh, early vegetative	0.42	0.68	66
Hay	0.31	0.59	58
Clover, Crimson			
Fresh, early vegetative	0.38	0.65	63
Hay	0.29	0.58	57
Clover, Ladino			
Fresh, early vegetative	0.44	0.70	68
Hay	0.40	0.67	65
Clover, Red			
Fresh, early bloom	0.45	0.71	69
Fresh, full bloom	0.37	0.66	64
Hay	0.26	0.56	55
Corn, Dent Yellow			
Silage, stover	0.26	0.56	55
Silage, few ears	0.36	0.64	62
Silage, well eared	0.47	0.73	70
Fescue, Kentucky 31			
Fresh, vegetative	0.42	0.68	67
Hay, early bloom	0.39	0.66	64
Hay, midbloom	0.34	0.61	60
Hay, full bloom	0.31	0.59	58
Hay, mature	0.28	0.57	56

(continues)

TABLE 2.1 *(continued)*

Species	Dry matters (%)	Crude protein (%)	Bypass protein (%)	Ether extract (%)	Total ash (%)	Crude fiber (%)	Neutral detergent (%)
List 2							
Lespedeza							
Hay, late vegetative	92	17.8	—	—	—	24.0	—
Hay, early bloom	93	15.5	—	—	—	28.0	—
Hay, midbloom	93	14.5	—	—	—	30.0	—
Hay, full bloom	93	13.4	—	—	—	32.0	—
Napiergrass							
Fresh, late vegetative	20	8.7	—	3.0	8.6	33.0	70
Fresh, late bloom	23	7.8	—	1.1	5.3	39.0	75
Oats							
Hay, boot stage	90	17.5	—	2.6	6.5	29.0	58
Hay, head emerging	90	14.0	30	3.3	8.3	32.0	62
Hay, late bloom	90	11.5	—	4.2	6.9	27.0	56
Orchardgrass							
Fresh early vegetative	23	18.4	25	4.9	11.3	24.7	55
Hay, early bloom	89	15.0	30	2.8	8.7	31.0	61
Hay, late bloom	91	8.4	30	3.4	10.1	37.1	72
Pangolagrass							
Hay, late vegetative	91	11.5	—	2.2	8.5	34.0	70
Hay, mature	91	5.5	—	2.0	7.6	38.0	77
Redtop							
Fresh	29	11.6	—	3.9	8.1	26.7	64
Hay	94	11.7	—	2.6	6.5	30.7	—

Ryegrass, Annual							
Hay, early vegetative	89	15.2	—	3.2	13.0	19.7	61
Hay, late vegetative	86	10.3	—	2.4	11.0	23.8	64
Hay, early bloom	83	5.5	—	0.9	8.4	36.3	69
Ryegrass, Perennial							
Hay	86	8.6	—	2.2	11.5	24.6	41
Sorghum, Grain							
Silage	30	7.5	32	3.0	8.7	27.9	—
Silage, dough stage	28	6.0	48	3.3	9.3	28.5	—
Sorghum, Johnsongrass							
Hay	89	9.5	—	2.4	8.2	33.5	—
Sorghum, Sudangrass							
Fresh, early vegetative	18	16.8	—	3.9	9.0	23.0	55
Fresh, midbloom	23	8.8	—	1.8	10.5	30.0	65
Hay, full bloom	91	8.0	—	1.8	9.6	36.0	68
Silage	28	10.8	—	2.8	9.8	33.1	68
Sweetclover, Yellow							
Hay	87	15.7	33	2.0	8.8	33.4	—
Timothy							
Hay, late vegetative	89	17.0	—	2.8	7.1	27.0	55
Hay, milk stage	92	7.0	—	2.3	6.3	33.9	71
Hay, early bloom	90	15.0	25	2.9	5.7	28.0	61
Hay, midbloom	89	9.1	—	2.6	6.3	31.0	67
Hay, full bloom	89	8.1	38	3.1	5.2	32.0	68
Hay, late bloom	88	7.8	—	2.8	5.4	32.5	70
Trefoil, Birdsfoot							
Fresh	24	21.0	—	2.7	9.0	24.7	—
Hay	92	16.3	—	2.5	7.0	30.7	47

(*continues*)

TABLE 2.1 *(continued)*

Species	Acid detergent (%)	Lignin (%)	Calcium (%)	Magnesium (%)	Phosphorus (%)	Potassium (%)	NEM (Mcal/lb)	NEG (Mcal/lb)	NEL (Mcal/lb)	TDN (%)
Lespedeza										
Hay, late vegetative	—	—	1.12	—	0.28	1.28	0.58	0.32	0.60	59
Hay, early bloom	—	—	1.23	0.26	0.25	1.00	0.52	0.26	0.56	55
Hay, midbloom	—	—	—	0.25	—	—	0.44	0.19	0.50	50
Hay, full bloom	—	—	—	0.24	—	—	0.39	0.15	0.47	47
Napiergrass										
Fresh, late vegetative	45	10	0.60	0.26	0.41	1.31	0.52	0.26	0.56	55
Fresh, late bloom	47	14	0.35	0.26	0.30	1.31	0.49	0.24	0.54	53
Oats										
Hay, boot stage	35	4	—	—	—	—	0.77	0.49	0.75	72
Hay, head emerging	39	6	—	—	—	—	0.60	0.34	0.61	60
Hay, late bloom	34	9	—	—	—	—	0.49	0.24	0.54	53
Orchardgrass										
Fresh early vegetative	31	3	0.58	0.31	0.54	3.58	0.77	0.49	0.75	72
Hay, early bloom	34	5	0.27	0.11	0.34	2.91	0.67	0.40	0.67	65
Hay, late bloom	45	9	0.26	0.11	0.30	2.67	0.50	0.25	0.55	54
Pangolagrass										
Hay, late vegetative	41	6	0.58	0.20	0.21	1.70	0.46	0.21	0.51	51
Hay, mature	46	7	0.38	0.14	0.18	1.10	0.27	0.03	0.39	40
Redtop										
Fresh	—	8	0.46	0.23	0.29	2.35	0.64	0.38	0.65	63
Hay	—	—	0.63	—	0.35	1.69	0.55	0.29	0.58	57
Ryegrass, Annual										
Hay, early vegetative	38	3	—	—	—	—	0.71	0.44	0.70	68
Hay, late vegetative	42	6	0.62	—	0.34	1.56	0.63	0.36	0.64	62
Hay, early bloom	35	9	—	—	—	—	0.50	0.25	0.55	54

Ryegrass, Perennial										
Hay	30	2	0.65	—	0.32	1.67	0.65	0.39	0.66	64
Sorghum, Grain										
Silage	38	6	0.35	0.29	0.21	1.37	0.60	0.34	0.61	60
Silage, dough stage	—	—	0.29	0.27	0.26	1.02	0.52	0.26	0.56	55
Sorghum, Johnsongrass										
Hay	—	—	0.84	0.35	0.28	1.35	0.49	0.24	0.54	53
Sorghum, Sundangrass										
Fresh early vegetative	29	3	0.43	0.35	0.41	2.14	0.74	0.47	0.73	70
Fresh, midbloom	40	5	0.43	0.35	0.36	2.14	0.64	0.38	0.65	63
Hay, full bloom	42	6	0.55	0.51	0.30	1.87	0.54	0.28	0.57	56
Silage	42	5	0.46	0.44	0.21	2.25	0.52	0.26	0.56	55
Sweetclover, Yellow										
Hay	—	—	1.27	0.49	0.25	1.60	0.50	0.25	0.55	54
Timothy										
Hay, late vegetative	29	3	0.66	0.14	0.34	1.68	0.69	0.42	0.68	66
Hay, milk stage	41	8	0.28	0.12	0.18	1.00	0.47	0.22	0.52	52
Hay, early bloom	32	4	0.53	0.14	0.25	1.62	0.61	0.35	0.63	61
Hay, midbloom	36	5	0.48	0.16	0.22	1.59	0.57	0.31	0.59	58
Hay, full bloom	38	6	0.43	0.14	0.20	1.64	0.54	0.28	0.57	56
Hay, late bloom	40	7	0.38	0.13	0.18	1.61	0.50	0.25	0.55	54
Trefoil, Birdsfoot										
Fresh	—	—	1.91	0.28	0.22	1.99	0.69	0.42	0.68	66
Hay	36	9	1.70	0.51	0.27	1.92	0.58	0.32	0.60	59

[a] Numbers represent average values.

Sources: *Nutrient Requirements of Dairy Cattle,* 6th Edition & Feedstuffs, November 1989 (as organized by Holland, C., W. Kezar, and Z. Quade (eds.), 1990.)

more common usuage—that is **available phosphorus, available magnesium, available calcium** and so on.

Apparent digestibility more properly refers to the balance of nutrients in the ingesta minus that in the feces, as described previously. **True digestibility** also requires that the metabolic products added into the feces from body sources be accounted for (Van Soest, 1982). Thus, the coefficient of true digestibility is always higher than that of apparent digestibility. Unfortunately, digestibility alone fails to account for the serious energy losses that occur in the fermentation and metabolism of forages. **Metabolizability** accounts for nutrient losses in the urine and fermentation gasses (principally methane) as well as fecal losses (i.e., **metabolizable energy**). The methane loss is entirely of microbial origin; this loss is generally calculated by formula in feedstuff evaluation rather than measured. Urinary energy losses include catabolism of body tissue and also substances absorbed from the digestive system (digested) but excreted in the urine with little or no alteration (Van Soest, 1982).

Net energy is the amount of energy used either for maintenance only or for maintenance plus production. [Metabolizable energy = net energy minus the **heat increment,** i.e., energy lost in the form of heat, this resulting routinely from fermentation and nutrient metabolism (Natl. Res. Counc., 1962).] Unless the air temperature is below the thermal neutrality zone of the animal, this heat loss represents total loss to the animal. Because TDN does not account for urinary and gaseous energy losses nor the heat increment, it overestimates the value of forages relative to the more concentrated energy feeds.

The total energy of a feedstuff (i.e., **gross energy**) can be determined by totally burning the sample and measuring the heat produced, but this provides no useful information in meeting an animal's energy requirements. The relationships of commonly used energy terms are shown in Fig. 2.1.

"True" nutrient levels in forages can be directly measured only by feeding to live animals—that is, under *in vivo* (in animal) conditions; but certain chemical analyses made under carefully controlled *in vitro* (in test tube) conditions in the laboratory are also useful in predicting "apparent" nutritional value. For example, dry matter disappearance in a specific period of time under artifical conditions simulating the rumen environment indicates how digestible a forage may be. *In vitro* analysis is usually a two-step procedure, both done in test tubes: (1) the forage sample is digested using rumen fluid from a donor animal to simulate rumen digestion; and (2) the sample is then further digested in an enzyme solution to simulate digestion in the small intestine.

In situ (in bag) describes an intermediate procedure in which a small nylon bag containing a forage sample is suspended in the rumen of live animals, and disappearance from the bag is used as a measure of digestibility. Both *in situ* and *in vitro* analyses are excellent techniques for forage

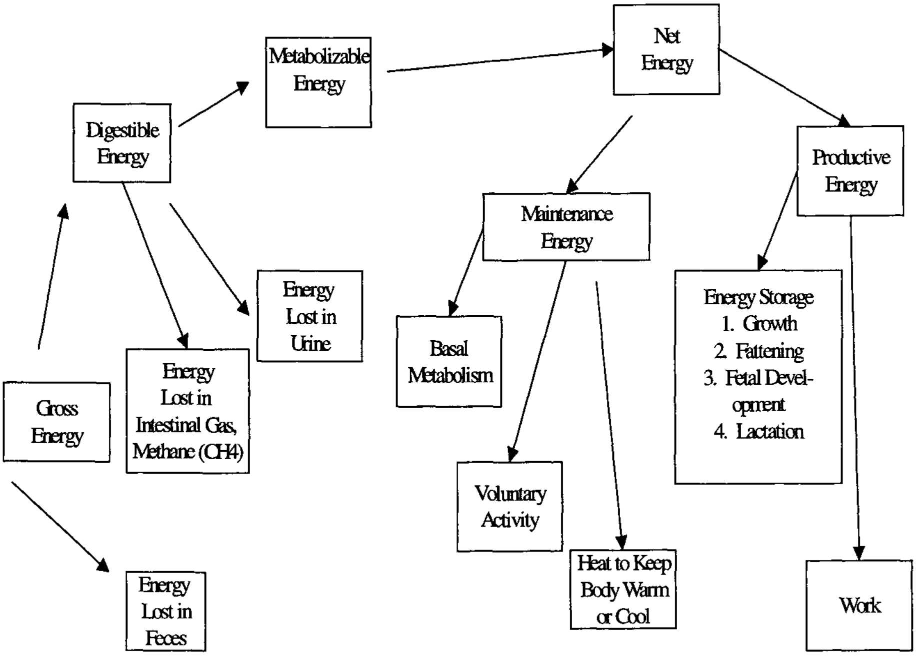


FIGURE 2.1 Energy digestion and metabolism. (Redrawn from Holland *et al.*, 1990).

evaluation when more expensive and time-consuming digestion trials are not possible. An understanding of the methodology used in measuring nutritive value assists in evaluating both average composition tables and laboratory analyses for specific forage lots.

B. PROXIMATE ANALYSIS

Proximate analysis, a system for analyzing forages and other feedstuffs, also referred to as the *Weende system,* utilizes wet chemistry laboratory procedures and has been in use since late in the 19th century. Although the system has definite limitations, portions of it are still widely used. In a complete proximate evaluation, analyses are made for (1) dry matter (DM) content (remainder after oven drying); (2) crude protein (CP) ($N \times 6.25$); (3) ether extract (EE) (a measure of lipids and fats); (4) ash (the residue after burning made up of mineral content); and (5) crude fiber (CF) (organic matter remaining after prescribed alkali and acid treatment). Utilizing these analyses, the following two feed energy components are estimated: (6) nitrogen-free extract (NFE) (calculated by subtracting CF, CP, and EE from total organic matter content) and (7) TDN (also by calculation).

Ash in proximate analysis is determined solely to determine the nonorganic matter component of dry matter—this required in calculating NFE—and has no nutritional significance per se. In many wet chemistry laboratories—in conjunction with both the proximate analysis and detergent systems—calcium and phosphorus are routinely analyzed. In NIRS analysis, potassium and magnesium may also be routinely analyzed. However, in conjunction with either wet or dry (NIRS) laboratory analyses, the content of any other mineral of concern can be provided on request.

Total digestible nutrients (TDN) is a summation of the estimated energy contributions from CP, EE, CF, and NFE:

$$\begin{aligned}\%\ \text{TDN} = {} & \%\ \text{digestible CP} + \%\ \text{digestible EE}\ (\times\ 2.25) \\ & + \%\ \text{digestible CF} + \%\ \text{digestible NFE}\end{aligned} \tag{2.1}$$

Percentages of the four components are on a dry matter basis but are corrected for digestibility. EE is multiplied by a factor of 2.25 because of higher energy contribution per unit of weight of lipids (fats); the energy contributions of CP, CF, and NFE are assumed equivalent and given a factor of 1. Coefficients of digestibility for deriving each component in the formula are taken from previous digestion trials with the feedstuff.

The dry matter and the CP procedures from the proximate system are still widely used in forage and analyses. Dry-matter content is important because all animal requirements are made on a dry-matter basis and it provides a common basis for comparing the nutritive value of forages. Also, the moisture content of a forage provides clues as to how it will preserve when stored dry or ensiled.

CP is measured by the standard Kjeldahl procedure in which total nitrogen is determined and multiplied by a factor of 6.25 (based on protein containing an average of 16% nitrogen). The nitrogen in forages is incorporated in both true protein and nonprotein nitrogen compounds, and the proportion of nitrogen in the nonprotein nitrogen form is substantially higher in immature, fresh forages than at more mature stages. However, ruminants are able to utilize both sources of plant nitrogen effectively in meeting their protein needs.

The CP analysis of harvested forages gives no indication that excessive heating may have rendered an additional portion of the protein unavailable to the animal. If heat damage is suspected, a special analysis can be requested and reported on the basis of ADF-N protein, bound protein, or insoluble protein. Many laboratories report a digestible protein value for forages, but this is most commonly only an estimate calculated as 70% CP or % CP − 4.4% (Holland *et al.*, 1990).

The most serious deficiency of the proximate analysis system is in estimating energy value. The determination of TDN utilizes a series of factors and estimates in its derivation with opportunities to accumulate errors; NFE is determined solely by subtraction. CF (containing cellulose and some lignin) was originally intended to represent the less digestible carbohydrate fraction, and NFE (containing sugars and starch but also hemicellulose and lignin) was to represent the more digestible carbohydrate fraction. However, their relative digestibility is often similar in forages, particularly in immature forages. The CF system has been criticized for often underestimating good-quality forage and overestimating poor-quality forage. Thus, the original CF analysis of forages has largely been replaced with the newer detergent analysis. Other alternatives include determining digestible dry matter or digestible organic matter utilizing *in vitro* artificial rumen techniques or *in situ* procedures.

C. CELL-WALL SIGNIFICANCE IN DIGESTION

Cell contents comprise most of the protein, starch, sugars, lipids, organic acids, and soluble ash of forages and are highly digestible to both ruminants and nonruminants (Table 2.2). The sugars, starch, pectin, and other soluble carbohydrates are almost completely digestible. The proteins, nonprotein nitrogen, lipids (fats), and other solubles have high digestibility to all animals. In contrast, cell walls make up a large portion of the forage (40–80%) and represent the less digestible portion of the plant cell.

Cell walls are a complex matrix of polysaccharides (cellulose, hemicellulose, and pectin), lignin, some protein lignified nitrogenous substances, waxes, cutin, and minerals that resist normal digestive processes (Van Soest, 1982; Hartfield, 1989). Cellulose and hemicellulose are major constituents of cell walls of forage plants; they are partially digestible to ruminants and horses but have low digestibility to most other nonruminants. Heat-

TABLE 2.2 Classification of Forage Fractions Using the Van Soest Method

		Nutritional availability	
Fraction	Components included	Ruminant	Nonruminant
Cell contents	Sugars, starch, pectin	Complete	Complete
	Soluble carbohydrates	Complete	Complete
	Protein, Nonprotein N	High	High
	Lipids (fats)	High	High
	Other solubles	High	High
Cell wall (NDF)	Hemicellulose	Partial	Low
	Cellulose	Partial	Low
	Heat-damaged protein	Indigestible	Indigestible
	Lignin	Indigestible	Indigestible
	Silica	Indigestible	Indigestible

(After P. J. Van Soest. 1967. Development of a comprehensive system of feed analyses and its application to forage. *J. Anim. Sci.* **26**(1):119–128.)

damaged proteins, lignin, and silica are mostly indigestible to reminants and nonruminants alike.

Animals that have the ability to utilize forages as the primary portion of their diet, such as ruminants and horses, do not have the enzymes necessary to digest the cellulose and hemicellulose of forages. They must rely on the microbial populations within their digestive systems to break down these components through fermentation before normal digestion can occur. The reticulorumen in ruminants and the cecum in horses provide the proper environment for the symbiotic activities of the microbes to occur.

A young forage plant cell has a single outer layer referred to as the *primary cell wall.* Later, as the plant matures, a second layer referred to as the *secondary cell wall* is laid down on the inside of the cell (Fig. 2.2). The secondary wall is thicker and gives the plant cell tensile strength. With advancing growth and maturity, forage cells insert a noncarbohydrate material known as *lignin* into the primary and secondary walls. This complex compound gives additional tensile strength and rigidity to the plant but has negative nutritional consequences. Not only is the lignin mostly indigestible, but its presence also inhibits the availability of the associated cellulose and hemicellulose.

D. DETERGENT ANALYSIS

In order to differentiate more accurately cellular and cell-wall fractions of forages and the components of the cell wall and thereby more accurately

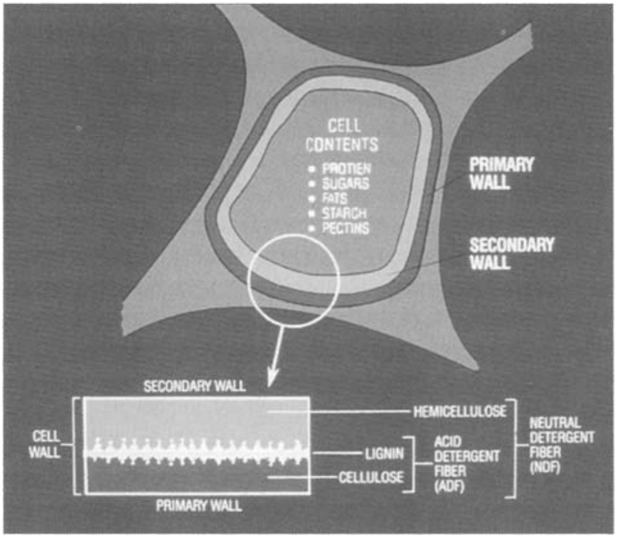


FIGURE 2.2 Diagram of a plant showing cell-wall structure (From Holland *et al.*, 1990).

estimate energy values, a newer wet chemistry method referred to as the *detergent method* or the *Van Soest method* was developed by the U.S. Department of Agriculture (USDA) (Van Soest, 1967). This system is now the most common method of partitioning the energy constituents of forages and is considered the primary standard of chemical evaluation of forages (Marten and Martin, 1986). A schematic drawing of this method is shown in Fig. 2.3, and a functional comparison of the proximate and detergent systems is provided in Fig. 2.4.

Cell contents, labeled **neutral detergent solubles** (NDS) in the detergent method, are removed by digesting with a special detergent at a neutral pH of 7.0. NDS contains the sugars, starch, pectins, lipids (fats), soluble carbohydrates, protein, nonprotein nitrogen, and water-soluble vitamins and minerals. The remaining insoluble portion, referred to as **neutral detergent fiber** (NDF), represents the cell-wall fraction and contains cellulose, hemicellulose, and lignin (also silica until ashed). When NDF is digested with acid detergent, the hemicellulose is removed and the remainder, consisting of cellulose and lignin (also silica unless ashed), is labeled **acid detergent fiber** (ADF). Last, digestion of ADF with 72% sulfuric acid removes the cellulose, leaving **lignin** as the remaining component after ashing. Table 2.2 is provided for clarification of the Van Soest or detergent methods of forage analysis.

ADF may be the most important determination in the detergent system.

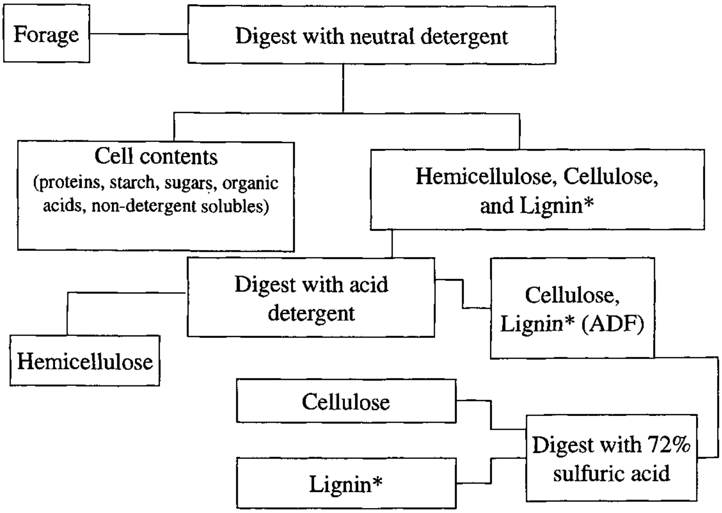


FIGURE 2.3 The detergent (Van Soest) procedure to partition the organic matter components of forages. Asterick (*) indicates matter that also contains silica unless corrected by ashing. (Redrawn from Holland *et al.*, 1990).

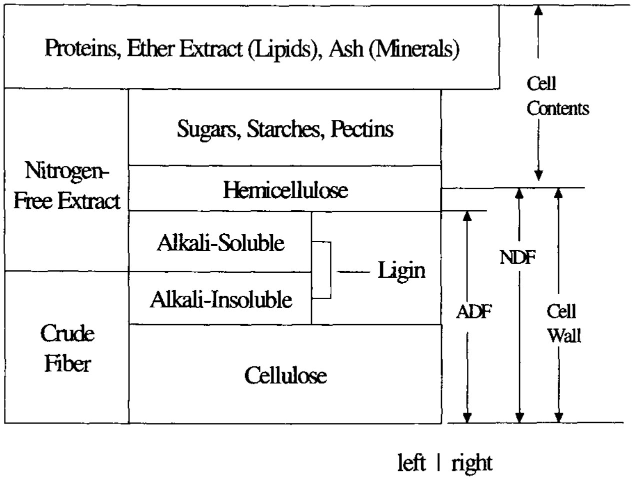


FIGURE 2.4 Forage analysis showing crude fiber (*left*) verses Van Soest (*right*). (Redrawn from Holland *et al.*, 1990).

It is important because it is negatively correlated with forage digestibility when the forage is fed. As ADF increases, the forage becomes less digestible. Laboratory digestibility and net energy values are not routinely measured in the laboratory because they require digestion or metabolism trials that are costly and time-consuming. Instead, energy values, estimates of digestibility, and relative feed values reported on laboratory analyses are calculated using the ADF and NDF content of the forage. The label *acid detergent fiber* is unrelated to the acid content of a forage; the name is derived solely from the chemical procedure.

Both lignin and silica are structural inhibitors to the digestion of other associated nutrients and are recognized as antinutritional factors. Grasses can contain silica in concentrations approaching 10% on a dry matter basis (Mayland, 1986). Silica reduces the digestibility of herbage by about 3 percentage units for each unit of silica. The mechanism is not known but may relate to silica acting as a varnish on the cell wall or to its precipitation with some trace mineral, limiting the latter's availability to rumen flora.

E. NEAR-INFRARED REFLECTANCE SPECTROSCOPY ANALYSIS

Near-infrared reflectance spectroscopy (NIRS) utilizes near-infrared light rather than chemicals to determine protein, fiber, energy, and mineral content. NIRS provides a rapid and low-cost computerized method for analyzing forage and grain crops for their nutritive value. This newer method of forage analysis involves drying and grinding samples, which are then exposed to infrared light in a spectrophotometer. The reflected infrared radiation is converted to electrical energy and fed to a computer for interpretation. Each major organic component of forages absorbs and reflects near-infrared light differently. By measuring these different reflectance characteristics, the NIRS unit and a computer determine the quantity of these components in the feed sample (Holland *et al.,* 1990). The typical forage analysis generated with NIRS is similar to that using proximate or detergent analysis. In addition, NIRS typically reports bound protein, available CP, and potassium and magnesium values. The detection of specific nutrients is possible because reflectance spectra from forage samples of known nutrient values—established by wet chemistry procedures—are programmed into the computer. When a similar feed sample is evaluated by NIRS, the computer compares the wavelength reflections caused by the sample and matches them to previously tested samples.

Proper calibration is all important in NIRS analysis. The calibration set that is used must be developed from an adequate number of wet chemistry samples similar to those being analyzed by NIRS. These samples must be carefully collected and stored and consistently dried, ground, and mixed prior to analysis. However, when properly done, the NIRS method of determining forage nutritional content is very rapid and less expensive than wet chemistry methods.

A distinct advantage of NIRS analysis of harvested forages is that the system is quite mobile. The necessary equipment can be put in a van and moved for on-site analysis. This permits an immediate quality evaluation for the livestock producer; it also permits both buyers and sellers of harvested forages to know the feed value before the sale.

IV. SAMPLING FOR NUTRITIVE ANALYSIS

Although average chemical composition has initial value in planning livestock rations, considerable variation exists in the composition of different lots of the same forage or roughage. These differences can be accurately evaluated only through chemical analyses. However, developing and following proper sampling procedures are required if forage analyses are to be meaningful and useful. Inaccurate sampling procedures may lead to greater error than relying solely on average analyses found in feed composition tables.

Samples must be taken to represent the average of the entire lot of harvested forage. A *lot,* as related to harvested forages, is defined as being taken from the same cutting, at the same stage of maturity, the same species (pure or mixture) and variety, from the same field, and at the same time of day. Lots can also be differentiated by amount of rain damage, amount of weeds present, distinct soil differences within the same field, or substantially different harvesting or handling methods after harvest. Separate samples should be taken when such differences are large enough to warrant forage being handled as different lots.

Feed samples of at least 0.5 lb and preferably 1.0 lb (dry matter basis) are adequate for most individual or combination of analyses. New plastic freezer bags are ideal containers for feed samples; the entire composite sample is immediately placed in the plastic bag and sealed to retain the same moisture level as when sampled. The moisture content of the original lot must be known for accurately determining market value and provides other indirect evidence of forage quality. Milk cartons or insulated paper bags are satisfactory as outer containers for shipping and handling. Freezing the sample may be required in special situations. Samples should be mailed or carried to the testing lboratory as soon as possible after being completely labeled. (If analysis is by NIRS procedures, the equipment may be brought to the sample collection site and the analyses made immediately.)

A. HAY SAMPLING

Hay can be sampled most accurately by using core-sampling tubes or probes used as boring devices on the end of a hand-operated brace or electric drill. With baled hay of the same lot, take adequate samples (10 minimal but 20 preferred, each from different bales) for compositing in a plastic bag, being sure to penetrate from 12 to 18 in. into small bales and to the center core of large bales. The sample should be taken from the center of the butt end. For loose or chopped hay in piles, take samples with the probe from random locations over the pile. Avoid dividing samples or other manual handling that results in the sifting out of fine leaves and stem parts. If the hay is in a windrow, cut hay samples into short pieces while avoiding the loss of dry leaves and composite into a single sample. For hay cubes, take enough cubes to provide the necessary quantity of sample.

B. SILAGE SAMPLING

Because most samples have to be taken from the top, bottom, or open face of different types of silos, it may be necessary to sample the silage several times during the feeding period. This is especially true if there is appreciable variation in the maturity, variety, or date of cutting of the silage when harvested. In silos that have been opened, take 10 to 20 double handfuls of silage from different locations, put these in a clean container, mix thoroughly, and then take out the necessary size of sample.

C. GRAIN SAMPLING

For grain and mixed feeds, sampling with a grain probe is the most convenient and most accurate method of obtaining samples. Take a minimum of five cores from various places in the bin or from different sacks of the same lot. Mix these thoroughly in a clean container. Then take the required amount for final sample.

D. PASTURAGE SAMPLING

Sampling standing forage in pasture is difficult because forage is often highly variable from place to place in the pasture unit. Grazing animals select only certain plant parts and, in mixtures, selectively choose between different plant species on a priority basis. Because grazing animals are more prone to select the finer, leafier, and more nutritious plants and plant parts, total clipping of standing forage plants to ground level underestimates the nutrient content of the actual diet. Thus, grazing animals must be carefully observed to determine what plants and plant parts are currently being ingested. While simulating what grazing animals are actually consuming, as nearly as possible, take 10 or more subsamples, consisting of several clips from several locations in the pasture; then composite subsamples, mix thoroughly, and portion out the required amount for analysis.

E. FEED ANALYSIS SERVICES

Feed analysis services are generally available in each state through the state department of agriculture, the state experiment station, the state extension service, or other laboratories at private or state universities. Alternative commercial laboratories are also available for analyzing feeds. Some feed companies offer free chemical analysis services to their patrons through their own laboratories or through commercial laboratories. Inquire locally about the availability of reliable feeds analysis laboratory services. Costs for analyzing each feed sample vary depending on the specific analysis or combination of analyses being requested and on the individual laboratory but are generally reasonable.

V. FACTORS THAT INFLUENCE NUTRITIVE VALUE

A. PLANT SPECIES AND PARTS

The forage plant species selected for use in an enterprise limits the range of quality that can be obtained from the various management practices. Legumes are often associated with higher daily animal response as a result of rapid digestion of consumed dry matter, a higher density of the rumen liquor, and a lower retention time in the animal. However, grasses may be favored in mixture with legumes or planted alone in meeting more stressful environments, enhanced stand longevity, and reducing agronomic or plant-animal management requirements. Except when grasses are fed as green chop, the choice between cool- and warm-season grasses for harvested forages is independent of when to be fed; adaptation to the latitude, seasonality of optimum growth, and other environmental factors are major decideing factors.

Many but not all weeds are deleterious to forage quality. Marten *et al.* (1987) noted that the forage quality of perennial weeds varied among species but was sometimes equal to that of alfalfa. This suggests that the decision on how rigorously to control herbaceous weeds might well be based on their potential effect on the quality and quantity of mechanically harvested forage.

Leaves make up the most digestible and nutritious parts of plants harvested as green crop, hay, or haylage and are very important nutritionally. Leafiness is also generally a very desirable characteristic of silages as well. Whereas alfalfa leaves at the 10% bloom stage may contain 24% CP, the stems generally contain only about 12% CP. Thus, selecting forage plant species or cultivars within species that have a high proportion of leaves to stems should be considered. Rapid-maturing cultivars of alfalfa or rapid growing conditions in the spring generally result in a lower percentage of leaves; harvesting at an earlier stage of maturity under these conditions can produce equivalent high-quality hay (James *et al.*, 1985).

B. STAGE OF PLANT DEVELOPMENT

The stage of maturity is a major factor affecting the nutritive value of forages. During rapid growth, forage plants normally contain enough nutrients to promote growth, weight gains, reproductive response, and milk production in livestock. However, as they begin to mature, the levels of many nutrients decline, forages become less able to meet livestock requirements, and the needs for supplemental feeding to prevent deficiencies increase. Synchronizing harvest cutting schedules with optimal stages of growth, rather than with calendar dates, to achieve maximum nutrient yields is a primary tool for producing high-quality forages.

Protein, phosphorus, and vitamin A (in the form of carotene) follow similar patterns throughout the plant growth cycle, being high when plants are immature and declining as the plant approaches maturity. The digestibility of the CP also declines as plants mature. Calcium levels tend to drop only slightly from immaturity to maturity on a dry-matter basis and are affected much more by calcium levels in the soil than by the stage of plant growth. The usable energy in the vegetative portions of forages generally remains relatively stable while the plants are green and growing; a drop in energy levels nearing maturity may be more than compensated for by increasing levels of grain on the forage plants, at least until dormancy is nearly complete. However, the advancing stem : leaf ratio and even decline in total leaf area in the standing crop, along with more rapid nutrient decline in the stems than in the leaves, suggest earlier cutting dates than have been historically common.

Early cut hay makes a more desirable feed because it contains more of the nutrients associated with high quality. Hay cut at an early stage of maturity is also more palatable and is consumed in larger quantities by livestock. Thus, using early cut hay improves animal performance and reduces the amount of hay needed.

C. SOIL FACTORS AND FERTILIZERS

Forage quality can be altered substantially by fertilizer application, particularly when nitrogen is applied to pure stands of grasses. It can generally be expected that a deficiency of a required mineral nutrient in the soil reduces forage yield and the concentration of that nutrient in the forage (Ward, 1959). Two related conclusions of general acceptance are: (1) additions of a mineral nutrient at high rates may cause its luxury consumption and result in higher concentration in herbage or in lower composition of other nutrients, and (2) a balanced mineral nutrient supply, whether at low or high levels, results in forage of approximately at the same mineral nutrient composition but in different yields.

Increased nitrogen levels in the soil nearly always increase the nitrogen and thus CP levels in forage from pure grass stands, but may have minimal effect on levels of these nutrients in grass-legume stands unless the legume component is substantially reduced. Enhancing levels of soil nitrogen generally will not alter cellulose or CF content, lignification, or digestible energy levels unless stage of growth at time of harvest its materially affected. In fact, from the agronomic point of view, addition of nitrogen fertilizer to a legume or a legume-grass stand is deleterious to maintaining the legume in the stand. (See Chapter 11 for further discussion and explanation.)

On phosphorus-deficient sites, phosphorus fertilization can be expected to greatly increase the phosphorus content of both grass and legume herbage providing other minerals and soil moisture are not greatly limiting. In fact, phosphorus application may alleviate the need for supplemental feeding of phosphorus to livestock consuming forage produced on phosphorus-depleted sites. Increasing fertilizer application rates of K, Ca, S, or Co on sites deficient in these plant nutrients can also be expected to increase their concentration in the forage harvested therefrom.

D. CLIMATIC FACTORS

Temperature and rainfall (both actually related to soil moisture) are the two environmental factors that are most important in altering forage quality. In general, when temperatures increase above the optimum for a particular species, the nutritive value is depressed. This occurs particularly in cool-season forages, such as smooth brome and the wheatgrasses, and to a lesser extent in alfalfa and warm-season grasses, such as Indiangrass and switchgrass. Rainfall or supplemental irrigation may have a greater effect on enhancing growth (quantity) than on quality of forage. Nevertheless, restoration of soil moisture following drought may have a profound effect on forage quality when rapid growth or regrowth is restored.

When alfalfa and other forage legumes experience moisture stress, older leaves on the stems dry and fall off before or during harvest, thus decreasing the percentage of leaves and reducing the quality of hay (James *et al.*, 1985). Irrigation practices should be regulated so that plants do not experience drought at any time during the growth cycle, but excessive irrigation can reduce both yield and quality of forage. (See Chapter 13 for further discussion of this relationship.)

E. WEATHER AND HARVESTING PRACTICES

Harvested forage that is initially of excellent quality can become very low in quality if it rains at the time of harvest or if the forage later becomes wet and moldy in storage. Weather, particularly precipitation and unsatisfactory drying conditions during harvest and field curing, can be a major deterrent to the production of high-quality hay. Field drying hay is the most energy-efficient preservation method, but forage may be exposed to rain while drying. Utah research has shown that 1 in. of rain on hay during field drying reduces hay quality more than does the reduction associated with a 1-week delay in harvest (James *et al.*, 1985).

The first rainfall causes the most damage because it removes the most soluble nutrients, thus reducing both the quality and the quantity of hay harvesting. Leaves become more fragile after a rain and are more readily lost during raking or packaging; leaf loss may reach 60% when hay is damaged by rain (Rohweder and Collins, 1980). Prolonged wet conditions or rewetting in the field encourages spoilage (mold), often rendering the forage unusable for feed. High humidity also increases time of field curing, thus increasing the loss of dry matter because of plant respiration and microbial decomposition and the potential for further rain damage. Hay conditioning, including crimping, crushing, or abrading as the forage is being cut in the field, reduces the field drying time of forages and thereby increases the chances of obtaining rain-free forage.

In the more humid areas, rainy weather makes it difficult to capture the full nutrient value of the forage crops in the form of hay. Delaying harvest beyond optimal growth stages to avoid rainfall results in advancing maturity and reduced hay quality. Alternatives in such situations for conserving high nutrient levels is to feed as green chop or conserve as silage.

Harvesting or defoliation schedules (stage of maturity and frequency of harvest) can greatly alter both quality and quantity of forage. Delayed harvesting may increase forage yields per unit area while reducing forage quality because it allows more advanced growth stages to be reached. Although frequent defoliation increases the quality of forage by maintaining more immature growth stages, it generally reduces the quantity of forage yield, particularly with erect-type forage plant species.

F. DISEASES AND INSECT DAMAGE

Disease and insect pests that prey on forage plants during growth cause severe reduction in quality as well as quantity of harvested forage. The damage to the leaves is often particularly evident, either removing parts of the leaves or cell contents or stunting the growth and forcing them into dormacy. Sharply reduced nutritive value, particularly protein and carotene, and often palatability as well, are often the major detriments. An integrated system of pest management can greatly reduce quality impairment from insects and diseases; selecting plant species and cultivars with genetic resistance to pest damage remains important. (For further discussion of these relationships, see Chapter 10.)

G. NUTRIENT ENHANCEMENT AGENTS

Plant growth regulators such as mefluidide, ethephon, and amidochlor appear promising in suppressing seedstalk production of grasses and legumes and thereby increasing forage quality (DeRamus and Bagley, 1984; Slade and Reynolds, 1985; Fritz *et al.*, 1987; Robert *et al.*, 1987). However, the use of plant growth regulators for manipulating nutrient composition is still mostly experimental, and promising chemicals may or may not be cleared for such use.

This Page Intentionally Left Blank

3

MARKETING HARVESTED FORAGES

I. MARKETING STANDARDS AND GRADES

In spite of the magnitude of hay sales, a single national hay-grading system has not been accepted and implemented. Market grades were not urgent when markets were mostly local. However, more hay is now being marketed over long distances, and the lack of uniform acceptance of hay standards has been critical in the development and servicing of national and international markets for hay.

Hay has traditionally been priced and sold on the basis of visual criteria alone. Classification systems based entirely on appearance of the hay have provided a rapid and helpful means of evaluating forage quality; they have been used in lieu of more direct chemical analyses that have a high cost in both time and resources. It was recognized that forage quality was related, at least indirectly, to parameters such as greenness, leafiness, small stems, and purity of content. It has also been recognized that, at times, the highest-quality forage did not always correlate well with the grading system (i.e., the performance provided by some hays grading lower would be equal to the higher-graded hays, and vice versa).

United States Department of Agriculture (USDA) hay grades, established in 1946 and last revised in 1949, provided for 11 hay groupings (comprising classes of species and mixtures) and four quality grades (based mainly on visual criteria) within each group. Grade criteria emphasize primarily leafiness, greenness, and content of foreign matter such as weeds, but are also based on moisture content, odor, and dustiness. Because the U.S. hay grades are determined subjectively, their accuracy and repeatability is open to question; they are now rarely used officially in hay marketing in the United States (Marble and Templeton, 1985).

Even more recent descriptive systems developed regionally have become so varied in nature that they are essentially unusable in terms of communicating market information and precisely describing hay available for sale or sought for purchase (Petritz, 1989). Prices are still being based on terms such as "premium-quality," "dairy-quality," "horse-quality," and "beef-quality" hay. Some locally used hay grades are more promotional than informational. Combining colloquial grade names with minimal quality descriptors is only slightly more useful, such as the following categories being used by one hay growers' association in Kentucky (Tietz, 1991):

Kentucky Pride: dairy-quality hay; described as the best hay based strictly on nutrient analysis; it tests at least 14% protein on a dry matter basis, and has a relative feed value (RFV)[1] of at least 124.
Triple Crown: horse-quality hay; described as fine-stemmed, has a green color, smells fresh, and is mold- and weed-free but not necessarily high in protein.
Kentucky Feeder: beef-quality hay; described as being at least 8% crude protein (CP) and 75 RFV.

Even though sampling and testing lots of harvested forages hold the key to intelligent buying/selling and management decisions, only a small fraction of the U.S. hay crop is evaluated for nutritive properties (Templeton, 1984). Failure to utilize nutritive value leads to undervaluing and underpricing the best quality hays rather then rewarding them with a premium price. Growers feeding their own livestock as well as hay buyers for commercial operations need to become more informed about the quality and nutrient content of forages in order to maximize animal performance.

Based on alfalfa sales data in Oklahoma during 1983–1984 and 1984–1985, Libbin *et al.* (1988) concluded that buyers were still basing pricing decisions and whether to buy a specific lot primarily on percentage protein, color, amount of foreign matter, and type of package. A preference survey by Petritz (1990) of southeastern hay buyers found that high preference was given to lack of mold, leafiness, immaturity, and low moisture content and less on color. CP was the most requested nutritive analysis by buyers.

The laboratory method usually considered to be superior for estimating the digestibility (primarily energy) of hay and other forage samples is the use of *in vitro* dry matter digestibility (IVDDM) (Marten and Martin,

---

[1] Calculated as follows: $\frac{(\mathrm{DDM} \times \mathrm{DMI})}{1.29}$. An RFV of 100 is equivalent to the feeding value of full-bloom alfalfa. DDM is digestible dry matter and DMI is dry matter intake.

1986). This IVDDM procedure, however, is not recommended for routine, commercial hay-quality testing because it is difficult to standardize and expensive to run. Thus, easier and more economical but still reliable estimates of digestibility and nutritive value have been needed.

The Hay Marketing Task Force, organized by the American Forage and Grassland Conference (AFGC) in 1972, undertook the challenge (1) to research and select the best practical methods of forage analysis suitable for the widest range of hay species and (2) then set up a system of standards with which forages of varying feed value could be classified. The AFGC Task Force proposed market grades separately for legume/legume-grass hays and grass hays, both hay classes being assigned four hay grades and one sample grade (unfit for marketing) (Rohweder *et al.,* 1978). Their proposed market hay grades were defined in terms of flowering and vegetative growth stages. Although physical descriptors were also employed in arriving at the respective grades, these proposed grades were backed up with "typical" chemical composition [CP; acid detergent fiber (ADF), a measure of digestibility of the forage; neutral detergent fiber (NDF), which correlates very closely with the rate of passage through the ruminant; dry matter intake (DMI); digestible dry matter intake (DDMI); and RFV].

Further refinement in the hay market grades proposed by the Hay Marketing Task Force (Rohweder *et al.,* 1983) maintained separate grades for legume/legume-grass and grass/grass-legume hays but combined both classes into one set of standards for predicting DMI and RFV within five grades and a sample grade. Marten and Martin (1986) utilized the Task Force findings to develop a hay grading system utilizing seven grades in a continuum from legume pre-bloom to grass headed and/or heavily weathered forage.

It is now becoming common to refer to hay as being in the following classes: Prime, No. 1, No. 2, No. 3, No. 4, and No. 5 (the last grade incorporating all stages below a minimum quality). These have been incorporated by Lacefield *et al.* (1988) in utilizing the guidelines developed by the Hay Marketing Task Force and are shown in Table 3.1. In this classification system, hay grades are based on minimum levels of CP and maximum levels of ADF and NDF, while also providing calculated values of DDM, DMI, and RFV. When coupled with visual information on each lot, it is hoped that this system will replace the present antiquated USDA federal grades.

These hay quality standards also incorporate the recommendations of the U.S. Hay Quality Committee, organized in 1984 by the AFGC and National Hay Association, on methods for determining and expressing feeding value of hay (Templeton, 1984). These recommendations were: (1) express energy values as digestible dry matter (DDM), this to be calculated from ADF, and (2) determine dry matter, ADF, and NDF on dry matter basis, NDF being used to estimate intake. The committee accepted any method for determining these factors that gives acceptable results. A

TABLE 3.1 Legume and Grass and Legume Mixture Quality Standards

	Laboratory analyses[a]			Calculated values		
Quality standard[b]	CP (% of DM)	ADF (% of DM)	NDF (% of DM)	DDM[c] (% of DM)	DMI[d] (% of BW)	RFV[e]
Prime	>19	<31	<40	>65	>3.0	>151
Grade 1	17–19	31–35	40–46	62–65	3.0–2.6	151–125
Grade 2	14–16	36–40	47–53	58–61	2.5–2.3	124–103
Grade 3	11–13	41–42	54–60	56–57	2.2–2.0	102–87
Grade 4	8–10	43–45	61–65	53–55	1.9–1.8	86–75
Grade 5	<8	>45	>65	<53	<1.8	<75

[a] Analysis associated with each standard: CP = crude protein; ADF = acid detergent fiber; NDF = neutral detergent fiber.

[b] Standard assigned by Hay Market Task Force of AFGC.

[c] Digestible dry matter (DDM%) = 88.9 − 0.779 ADF (% of DM).

[d] Dry matter intake (DMI, % of body weight) = 120 ÷ forage NDF (% of DM).

[e] Relative feed value (RFV) calculated from $\left(\frac{\text{DDM} \times \text{DMI}}{1.29}\right)$.

From "Alfalfa Hay Quality Makes the Difference." G. D. Lacefield, 1988. University of Kentucky, College of Agriculture, Coop. Ext. Ser., GR-137.

certifying association was set up to establish acceptable ranges in methodology and results.

In 1984, the National Alfalfa Hay Testing Association (NAHTA) issued a manual that incorporated the previously mentioned standards; NAHTA standards require expressions of DDM (based on ADF), CP, and dry matter as minimum value and recommend providing RFV calculations (Marten and Martin, 1986). RFV has been found useful in assigning various lots of harvested forage to specific animal groups based on needs and production potential; RFV includes expressions of both DDM and DMI and has been used effectively in forage evaluation, hay marketing, and ration-balancing systems (Marten and Martin, 1986).

The use of near-infrared reflectance spectroscopy (NIRS) has been developed and refined to replace the more costly chemical procedures required for nutritive evaluation of forages (proximate analysis). The NIRS techniques have proved to be reliable and inexpensive if the established guidelines are followed; thus, it was accepted by the U.S. Hay Quality Committee (Marten, 1984). Several states have shown success with on-site NIRS forage testing using mobile vans; such mobile units can be made available to hay producer groups locally or at hay market centers. (Refer to Chapter 4 for further details about the meaning and derivation of RFV.)

It is important to note that ADF is the basis for estimating forage digestibility (footnote of Table 3.1), and that nowhere does protein enter into these calculations. CP of forages, especially alfalfa, has long been considered to be of primary importance; so important, in fact, that all other factors may seem to have been ignored. As valuable as protein is to producing or growing animals, the digestibility of a forage as estimated by ADF and the rate of passage, as determined by NDF concentration, are more important. Protein concentration in a forage is subject to considerable variation due to environmental conditions, thus it is not useful as a predictor of quality. ADF and NDF are closely related to quality, and are, therefore, far more reliable as a predictor of forage quality. This is not to say that protein is not important—it is. It just says that protein is not a reliable predictor of quality. Questions as to the value of alfalfa protein, in that it may not be as valuable as was once thought, have been raised by Satter *et al.* (1989), who state that it is increasingly evident that high-quality alfalfa is not as good a protein source as once was thought. They base this on research that showed that cows in early lactation, receiving diets with high-quality alfalfa as the principal forage, sometimes show protein deficiency; thus, some supplementation may be required.

A hay sample sent to a certified laboratory usually contains the information in Table 3.2. Not all these analyses are included on reports from laboratories. The minimum is dry matter concentration, CP, and ADF. Others are provided on request for an additional fee at the time of sample submission. If, in addition to these three measurements, NDF is determined, all other calculated variables can be determined by individuals submitting the sample provided that the relationships are known (Holland *et al.*, 1990).

II. MARKETING METHODS

The basic alternatives available to the forage producer for selling harvested forages, primarily hay, are (1) direct sale to a local feeder, (2) direct sale to a dealer or hay company, (3) sale by advance contract, (4) sale through a broker, (5) sale through a growing/marketing association, or (6) sale by public auction. Each of these marketing techniques has advantages, and the hay producer often uses a combination of methods in selling hay.

Direct sales to livestock feeders in the local area or to dealers account for much of the hay sales in the United States; and nearly all of the silage sold off-farm is by direct sale to local feeders. A written description of the forage being offered for local sale is often not required because both seller and buyer usually have access to the forage and rely on experience and senses such as sight, smell, taste, and touch to judge the hay (Libbin *et al.*, 1988). Knowledge of local market conditions, bargaining skills, and the relative worth of various product characteristics largely determine price.

TABLE 3.2 Example of Forage Analysis Report Form

Analysis	Units	As received	Dry basis
	Analyses		
Crude protein	%	6.54	19.36
Unavailable	%	0.87	2.57
Available	%	6.45	19.11
Acid detergent fiber (ADF)	%	10.77	31.89
Neutral detergent fiber (NDF)	%	14.22	42.10
Crude Fiber	%	8.48	25.11
Lignin	%	2.09	6.18
Calcium	%	0.79	2.33
Phosphorus	%	0.10	0.31
Potassium	%	0.65	1.92
Magnesium	%	0.09	0.26
	Calculated Analyses		
Digestible protein	%	4.71	13.94
Digestible dry matter (DDM)	%	21.64	64.07
Total digestible nutrients (TDN)	%	20.15	59.68
Net energy—lactation (NEL)	Mcal/lb	0.21	0.61
Net energy—gain (NEG)	Mcal/lb	0.11	0.34
Net energy—maintenance (NEM)	Mcal/lb	0.20	0.60
Relative feed value (RFV)	—	—	142

Nutritive quality evaluation generally is not provided, but may be requested by the buyer.

Local buyers may pick hay up out of the field immediately after it is cut, cured, and baled, or the hay producer may remove the hay from the field and stack it at the roadside or other convenient place for pickup. Unsold hay may be "roadsided" and advertised for sale at set price or by requesting bids. Hay producers may opt for immediate removal of hay on sale, allow hay to remain in stack until needed and picked up, or even provide protected storage during an interim period.

Hay dealers or companies are middlemen that locate, buy, sell, and arrange for transporting the hay to the final buyer. Such hay is often handled and transported by independent companies or subhaulers (Tietz, 1990). Dealers, in contrast to brokers, make direct purchase from the grower and then sell on contract or offer "open" hay on truckload or stack lots. Large, intensive dairy industries located near population centers buy more hay through dealers and hay companies than directly from hay producers. Hay dealers may contract not only to deliver hay to dairies and cattle feedlots, but also provide temporary storage and even stack or line bales on mangers for feeding.

Advance contracts guarantee the hay producer a market and the price to be received. Contracts must specify kind of hay, minimal quality of hay, and packaging. As is true in all marketing techniques when hay is not sold to local markets and the buyer cannot see the hay lot for sale, precise nutritive analyses become very important in meeting quality standards and may be required as part of the advance contract. This places a greater burden on the producer to produce top quality hay—in fact, penalizing him if he does not—but should reward him for the higher quality.

Hay brokers do not take possession of the hay, but act as agents in bringing seller and buyer together and charge a commission for their services. Hay growing/marketing associations generally provide even more services, including hay description, quality testing, advertising, selling, and transportation for the producer. Producers are generally charged an annual fee and an additional commission by tonnage on each lot of hay sold by the association. The association normally guarantees payment for every lot sold and acts as mediator if any dispute arises.

Hay auctions have been successful in some areas where local buyers are plentiful. The auction is considered by many to be the optimal way of bringing sellers and buyers together to establish a fair market pricing system based on known characteristics important to the livestock feeder. Thus, hay at auctions should be fully described and quality tested before sale. Auctions require the seller pay a commission but have the advantage in that the auction firm is bonded so that payment to the hay producer is immediate and assured. The value of auctions in facilitating hay transactions is emphasized by the Wisconsin experience (Table 3.3) after the use of the new hay classification system was begun. The numbers change from year to year, but the relative positions and importance given to high-quality hay is maintained with respect to price received. Prime hay is always worth

TABLE 3.3 Hay Prices at Auction, 1983–1989, Wisconsin and Minnesota

Hay grade	Number of lots	Relative feed value	Price ($ per ton)	Relative value
Prime	340	>151	120.29	1.00
Grade 1	1836	125–150	106.92	0.89
Grade 2	3045	103–124	88.56	0.74
Grade 3	1837	87–102	73.29	0.61
Grade 4	528	75–86	58.92	0.49
Grade 5	180	<75	52.69	0.44

From "Hay Prices at Auctions." Anonymous. *In* G. D. Lacefield (ed.). *Forage News.* University of Kentucky, Coop. Ext. Serv., Lexington, KY, 1991.

more than lesser grades of hay. The last column, the relative price, remains quite constant, pointing out that grade 5 hay is only 44% as valuable as prime hay in generating economic returns.

Different auctions have different rules pertaining to weighing conditions, commissions, method of payment, and recourse if the hay purchased is not what was represented at the auction (Petritz, 1991). Hay is sold on-loaded at some auctions, but off-loaded at others. Some auctions offer free delivery within so many miles of the auction site and/or help in transferring hay from one vehicle to another. Most hay going through auction is sold directly by the producer to the livestock feeder, but hay dealers or hay companies may make substantial purchases.

III. PRICING AND LOCATING

Determining the price of harvested forage is a difficult task for both buyer and seller because there are no organized markets as there are for the grains. Most buyers, of course, consider not only kind and quality of hay but also transportation costs to where the forage is to be fed in the price they can afford to pay. Prices paid at local auctions or in local private treaty or included in local market reports are useful sources. Hay associations also make market information and sales offerings of their members available to potential customers. Both prices and availability of hay for sale can be located by checking advertisements in farm magazines or newspapers or with hay brokers.

Because only the dry matter of forage provides nutrients for animal growth and milk production, the price must be adjusted to compensate for different dry-matter levels. Moisture content is particularly important when buying or selling forage as silage, haylage, or green chop. However, because dry-matter content is only one of many factors affecting the value of forages, price comparison of different lots of a harvested forage on a dry-matter basis must assume no differences resulting from harvesting or storage or make appropriate adjustments for such value differences.

The basis of determining prices of forages of varying moisture levels is commonly 30 or 35% dry matter for silages and 90% dry matter for hay (approximate air dry); or price equivalents for different lots of harvested forage differing only in dry matter can be compared on a 100% dry-matter basis (oven dry). If the dry matter content of a forage lot deviates significantly from normal moisture levels, either very wet or very dry, additional evaluation should be made to determine if quality might have been lowered. If it has been lowered, then an additional price adjustment is appropriate.

The USDA's Hay Market News (USDA AMS Market News Service, P.O. Box 2437, Sioux City, IA, 51107; $40 per year subscription) is published weekly and lists prices of all grades and forms of hay in several states from coast to coast. The magazine *Hay and Forage Grower* (Webb Division, Intertec Pub. Corp., P.O. Box 5068, Hazlet, NJ, 07730) provide hay market updates in their issues by accumulating prices from various sources; it also includes an annual hay marketing directory that includes hay price reports and provides information for contacting hay growing/marketing groups, hay hotlines, computerized hay lists, hay auctions, and state forage councils. Another comparative source for hay information, including prices and sources, is the *Western Hay Magazine* (published by Pan-Ag Enterprises, P.O. Box 713, Tooele, UT, 84074).

Many state departments of agriculture, state extension services, and state forage councils compile and distribute hay market releases and reports, maintain hay directories and hotlines, or make available computerized listings of hay lots for sale. These service programs are generally locator and informational rather than brokerage in nature, leaving marketing agreements, price negotiations, and payments and delivery arrangements as the responsibility of buyers and sellers who use the list. With the importance of the Internet and the more common use of computers by hay growers, computer-based hay locator programs permit buyers and sellers of hay and straw to list specific information about forage to be bought or sold; these include HAYMARKET in Oklahoma (Gerrit *et al.,* 1983), HAYLIST in Wyoming (Gray, 1988), and HAY LOCATOR in Indiana (Johnson *et al.,* 1990). Once a person accesses one of these sites, it is usually just a matter of clicking on one of the many links to other sources for hay information. For example, accessing the Forage Information System, maintained by forage specialists at Oregon State University (www.forages.css.orst.edu) provides the user with entry to the following: Central Oregon Hay Growers Association, Hay Locator Service, The Haynet, The Hay Pages, Internet Hay Exchange, Minnesota Extension Service Haylot, Washington State Hay Growers Association, and Wyoming Hay Hotline, among others. From each of these sites, one can branch to other related topics. Other states or state hay growers associations also have websites, such as the Idaho Hay Growers Association (www.idahay.org). Many systems can be accessed directly for searching the listings; some charge fees that include chemical analysis and standardized visual appraisal, others have no fees being charged beyond the program telephone access charge.

It is important that the hay producer identify the market that is to be serviced, understand the buyers' wants and needs, and then strive to meet these requirements; maintaining continuing contacts with the buyer and following up at the feeding operation is suggested. It is important that the hay producer develop a reputation for consistency and quality, and developing a working relationship with a buyer may have long-lasting benefits to both the seller and the buyer. The needs of the buyer include not only quality criteria but also lot sizes; bale size, weight, and type; and method of tying. The type of package or form of the product affects handling, storage, and transportation facilities needed and associated costs. Heavy bales have less cost per ton in transporting hay long distances, but many local buyers are not equipped to handle very heavy bales and will pay less or refuse to buy at all. Round bales are much less conducive than rectangular bales to efficient long-distance transport, and may cause a load to exceed width restrictions.

International markets for hay produced in the United States presently account for only about 1% of the total forage production, but have much greater potential (Henry, 1990). The export market emphasizes alfalfa but also includes timothy, sudan, and other grass forages, originates principally from the West Coast states, but demands a clean and pure product. Hay planned for export or otherwise to be shipped long distances are advantageously prepared in the form of compressed bales, wafers or cubes, or compressed meal to reduce bulk and transportation costs. Compressing can reduce space requirements by a 3:1 to 5:1 ratio. Cubes have an even further freight advantage in that 27 to 28 metric tons of alfalfa cubes can be put into an overseas shipping container, compared to 24 to 25 metric tons of compressed alfalfa bales.

Some alfalfa hay packaged in big bales in the field is later shredded, compressed, and rebaled to specification. Shredding is preferred over grinding to provide compaction while maintaining some of the advantages of long hay, particularly in dairy rations. Shredded and compressed bales hold their shape well until the ties are removed and then fall apart readily. Stem lengths can be varied to work best in various mixer wagons. The National Hay Association's International Market Development Commission is suggested as a source of information for hay producers interested in foreign markets.

4

FORAGES AND ANIMAL NUTRITION

THE BASICS

I. ANIMAL DIGESTIVE SYSTEMS

Harvested forages are effectively utilized only by ungulate herbivores equipped with specialized digestive systems, either ruminant systems (e.g., cattle, sheep, goats, deer) or cecal digestive systems (e.g., horses, rabbits). (An **herbivore** is any animal species, including many insects and rodents, that subsists principally or entirely on plants or plants materials; an **ungulate** is any hoofed animal.) Both of these digestive systems enable ungulate herbivores to digest plant fiber, high in plant cell walls, by microbial fermentation. The fermentation process by bacteria and protozoa are similar in both systems, but the anatomy of the respective systems is substantially different.

Simple-stomached digestive systems (as found in monogastric species such as swine, dogs, mink, poultry, and even humans) have both limited total capacity and limited microbial action; this results in minimal fiber digestion capability and essential amino acid and vitamin B synthesis. Thus, such livestock are unadapted to the use of large quantities of forages and other roughages and are better adapted to the use of concentrated feeds such as grains and meat by-products. Only nutrient-rich forage components such as alfalfa leaf meal are generally suggested for including in rations for simple-stomached farm animal species. Because of the limited use of harvested forages in feeding simple-stomached animal species, only the two principal digestive systems found in ungulate herbivores are covered here in detail.

A. THE RUMINANT DIGESTIVE SYSTEM

A **ruminant** is any even-toed, hoofed mammal that chews the cud and has a four-chambered stomach. In addition to the domesticated farm animal species such as cattle, sheep, and goats, *Ruminantia* (the animal taxon including all ruminant families) also includes semidomesticated and wild animal species such as yak, buffalo, camel, llama, bison, muskox, reindeer, caribou, antelope, deer, elk, and moose. All ruminants have in common the addition of three chambers to the true stomach (e.g., rumen, reticulum, and omasum), these collectively sometimes referred to as the *paunch.*

The **rumen,** in combination with the smaller **reticulum,** commonly referred to as the **reticulorumen,** constitutes the anterior large compartment of the ruminant stomach. It functions as a holding tank in which fermentation can occur and from which the *ingesta*—the nutritive materials consumed by the animal—is regurgitated for rumination (rechewing). Here the symbiotic breakdown of cellulose and similar compounds occurs through fermentation, as does also amino acid and vitamin B synthesis.

Rumen fermentation converts much of the cell-wall material, not otherwise usable, and most of the soluble cellular contents into volatile fatty acids, the principal source of energy for the ruminant host. Extensive absorption of the resulting volatile fatty acids occurs in the reticulorumen and continues as the ingesta flows through the omasum into the fourth chamber, the **abomasum,** which is the true stomach and provides the site for digestive processes similar to that found in the nonruminant stomach.

The reticulorumen provides a favorable environment for microbial populations. Muscular contractions there increase the contact between microbes and food particles, and the by-products of fermentation are reused so that fermentation continues (Demment and Van Soest, 1983). Selective delay in the passage of ingesta through the reticulorumen results, with the probability of passage tied to particle size. Large particles that are recently ingested have a low probability of escape; the probability of passage increases as retention time increases and particle size is reduced to 1 mm or less.

Retarding the flow of the plant tissues from the ruminoreticulum is a means of extending the period of time available for chemical and physical degradation of fibrous plant tissues. The mean particle size escaping the rumen and appearing in the feces is remarkably constant across *ad libitum* fed or grazed forage diets (Ellis *et al.*, 1987). However, the increase in digestibility of the ingested forage resulting from delayed passage may not be of net benefit to the ruminant because of reduced feed intake.

Particle size reduction is a critical process determining digesta volume, rates of passage, and digestion of the food particles (Ellis *et al.*, 1987). These, in turn, largely determine the rate of forage intake by ruminants. Due to the finite capacity of the reticulorumen to harbor undigested forage residues and remove such residues by means of fermentation and passage, such retarded flow may limit the level of forage intake. Thus, advancing forage maturity reduces not only dry matter digestibility but also the rate and total amount of forage intake by prolonging retention time of large particles in the reticulorumen.

In combination with high salivary secretion, ruminants are set apart from other herbivores by their ability to masticate and remasticate their feed in order to reduce particle size (Ellis *et al.*, 1987). Ingested forages are fragmented into various sizes as the result of **ingestive mastication** (initial chewing) and **ruminative mastication** (rechewing the cud after regurgitation). Ingestive mastication reduces the ingesta to sizes that can be incorporated into a bolus (small, round lump or mass, as of chewed food) and swallowed. Ruminative mastication results in further particle size reduction and exposure to microbial attack. Further particle disintegration by digesta movements and microbial and chemical digestion aid only slightly in further particle size reduction (Pond *et al.*, 1987).

In addition to the reduction in particle size, mastication also benefits fermentation and digestion of forages by crushing and crimping the plant tissues, thereby releasing the soluble cell contents for microbial access (Pond *et al.*, 1984). The disruption of "barrier" tissues—the cuticle and vascular tissue within the blade and stem fragments—allows entry of the microflora. The main effect of mastication may well be the exposure of more potentially digestible tissues previously encompassed within indigestible barrier tissues.

In addition to greater efficiency of cell-wall digestion, other advantages result from the symbiotic relationships of microorganisms in the rumen of the ruminant digestive system over that of simple-stomached animals. Microbial synthesis in the functioning rumen can supply the full complement of required amino acids and B vitamins (Demment and Van Soest, 1983). More complete nitrogen conservation and recycling through the saliva takes place in the ruminant, thus reducing dietary nitrogen intake needed. The ruminant, in addition, has the ability to effectively use nonprotein nitrogen sources for microbial protein synthesis (Owens, 1988). Microbes passing from the rumen into the abomasum and small intestines are readily digested and absorbed, providing the host animal with an expanded if not the major source of protein.

The ability of the ruminant to convert organic substances not usable by humans and other monogastric animals, such as most forages, into human food of high quality and desirability is a truly great natural phenomena and benefit to humankind. It seems reasonable to anticipate that the ruminant in the future will be used primarily to convert low-quality biomass into useful production (Vallentine, 1990); but ruminant rations may continue to include some low-quality grain, grains bred specifically as "feed grains," and even food grains in surplus of market demands. Small amounts of grain or short concentrate feeding periods immediately prior to slaughter also improve carcass quality.

B. THE CECAL DIGESTIVE SYSTEM

The principal cecal-digesting, nonruminant, ungulate herbivore is the horse. The single-compartment stomach of the horse is relatively small and functions mainly for storage and regulation of ingesta reaching the small intestine (Burke, 1987). Feed moves rapidly through the stomach, and the digestive activity therein is limited. The small intestines are the primary site of digestion of soluble carbohydrates, fats, and proteins. The large intestine—comprised of the cecum, large colon, small colon, and rectum—is the most important segment of the equine digestive tract relating to the utilization of forages.

The **cecum** is the blind sac appended to the posterior end of the small intestines and forms the forepart of the large intestine of the horse. Although it comprises only about 10% of the digestive tract in the horse, it has some functional similarities to the rumen. The operational difference between them is that the rumen functions like a filter that selectively delays food particles, whereas the cecum provides less selective retention and functions more like a perfect mixer (Demment and Van Soest, 1983).

The equine large intestine contains large populations of bacteria, and here fermentation of the fibrous portions of feeds takes place, the end products being volatile fatty acids (VFA) as from the rumen of cattle and sheep (Burke, 1987). From the small intestines the ingesta passes into the cecum, where fermentation of the fibrous portions of the ingesta begins. Protein and vitamin B synthesis take place as in the rumen, but their utilization by the horse is apparently less efficient because the synthesis takes place posterior to the stomach and small intestines. Ample evidence of nitrogen recycling exists for nonruminants, but except for the horse where the evidence is probable, there is no evidence of the ability to absorb amino acids from the colon (Demment and Van Soest, 1983).

Presumably, the horse can subsist on even lower quality forage and/or roughage diets than can large ruminant species by increasing rate and amount of intake of fibrous feedstuffs (Hanley, 1982). The reduced fiber digestion resulting from faster and less restrictive/selective passage from the cecum compared to the rumen is compensated for by ingesting greater amounts of forage (Janis, 1976), a compensatory mechanism not available to ruminants.

II. NUTRITIVE REQUIREMENTS

The nutrient balance of animals on high-forage rations, whether grazed or penfed, is dependent on five basic factors: (1) the animal's nutrient requirements, (2) the nutrient content of the feedstuff(s), (3) the digestibility or availability of the feedstuff(s) and nutrients consumed, (4) symbiotic microbial synthesis in the digestive system, and (5) the amount of feed consumed. The nutrient requirements of farm animals are dependent on a number of factors including species of animal, age of animal, metabolic body size, body condition, physiological and reproductive state, and production levels.

Environmental factors such as ambient temperature, humidity, wind, and hide conditions (hair cover and dryness) affect nutrient requirements, particularly energy. The maintenance energy requirement of ruminants increases linearly during cold weather but nonlinearly during heat stress (Ames and Ray, 1983), based on a temperature range of 50° to 68°F minimizing maintenance expenditures of energy. The effects of environment on the nutrient requirements of domestic animals has been summarized by the National Research Council (NRC, 1981b). Increasing levels of voluntary and involuntary activity increase nutrient requirements. When fed in confinement, voluntary activity levels are generally minimized, in contrast to grazing, in which the search for forage and water may require substantial increase in voluntary activity. Only in the case of the horse does involuntary activity normally have substantial impact on nutrient requirements.

The nutrient requirements of domestic livestock have been provided in detail by various NRC publications, and these sources of information are highly recommended in planning appropriate livestock-forage systems:

Beef cattle; Pub. 4 (NRC, 1996)
Dairy cattle; Pub. 3 (NRC, 1988)
Environment (NRC, 1981a)
Goats; Pub. 15 (NRC, 1981b)
Horses; Pub. 6 (NRC, 1989)
Sheep; Pub. 5 (NRC, 1985)

III. FORAGE DRY MATTER INTAKE

Production by livestock from forages, within the bounds of animal genetic potential, is primarily a function of quantity and quality of forage consumed.

Both contribute directly to nutrient intake, the prime environmental basis of animal performance. Although diet quality is obviously important also, variation in voluntary forage intake has been deemed the most urgent factor determining level and efficiency of ruminant productivity (Demment and Van Soest, 1983). Maximizing the intake of forages relative to concentrates in animals diets results in maximizing profit from most but not all livestock-earning enterprises; exceptions may exist when very high levels of animal performance are desired and justified or when the price of forages is abnormally high relative to grains and other concentrated energy/protein feedstuffs.

Increasing total forage dry matter intake (DMI) is one way of correcting nutrient deficiencies in livestock diets. Although energy intake is closely related to digestible organic matter intake, nitrogen requirements for maximum microbial growth are primarily a function of digestible organic matter intake. Most diets satisfy protein requirements at 6 to 8% crude protein (CP), but 9 to 11% CP may be required for calves, lambs, and other herbivore offspring (NRC, 1987). Conceptually, if an animal could eat enough, it could satisfy its energy requirements from most low-quality forages. An understanding of the factors that limit forage intake suggest ways in which intake limitations can be overcome and the potential productivity of the animal more closely approached.

Control of feed intake is mostly indirect, except when high-nutrient-density rations that would exceed the animal's nutrient requirements if fed free choice are limit fed (NRC, 1987). However, **voluntary intake** of forage should be based on the level of consumption when more forage is offered than can be eaten, and this made available without substantially limiting access time (18 h or more each day) (Minson, 1990), thus eliminating the direct effects of restricted forage quantity on intake. Also, because the water content of forages is highly variable, values for voluntary intake should be expressed on a moisture-free (oven-dry) basis, usually g/kg body weight (W) or g/kg $W^{0.75}$ (Minson, 1990).

The intake of harvested forages by livestock is determined by a large number of animal, forage, and management factors. The control of feed intake, in any given situation, is apparently multifactorial because for any single treatment to suppress intake, it has to be administered at an artificially high level (Forbes, 1986). Those factors that increase the intake of harvested forages or at least maintain high levels, along with those that decrease forage intake, are listed in Table 4.1 and are discussed in the following section in more detail.

A. ANIMAL FACTORS

Feed intake is controlled by physiological demand due to maintenance needs and production demands, but only up to the limits of the gastrointes-

TABLE 4.1 Factors That Influence the Voluntary Intake of Harvested Forages

Factors increasing/maintaining high forage (dry matter) intake	Factors decreasing forage (dry matter) intake
I. Animal factors	
Large body size (actual or metabolic)	Small body size (actual or metabolic)
Low body condition	Excessive body condition
Large reticulorumen capacity	Limited reticulorumen capacity Distention of reticulorumen (fill) Undeveloped rumen in young
High physiological energy demand	Low physiological energy demand
Lactation, midgestation, work, high rate of growth	Maintenance or early gestation
High milk production; suckling twins or triplets	Internal parasites, disease, nutrient imbalances
Recovery from restricted feeding	Chemical factors contributing to satiety (in doubt) Temporary stress of estrus or parturition
II. Forage factors	
High forage digestibility and passage rate	Low forage digestibility and increased retention time (ruminants)
Unlimited forage access	Limited forage access
High leaf:stem ratio	Low leaf:stem ratio
Early stage of maturity	Late stage of maturity
Legume forage	Grass forage
Balanced diets (adequate N, P, Ca, Mg, NaCl, etc.)	Imbalanced diets (inadequate N, P, Ca, Mg, NaCl, etc.)
High forage palatability (in doubt)	Low forage palatability (in doubt)
Grinding and pelleting low-quality forages	Fecal contamination
Ammoniation or alkali treatment (low-quality forages)	Presence of toxicants or other contaminants
III. Management factors	
Forage ample, of high quality	Forage restricted, low quality, or toxic
Protein, minerals fed to balance deficiencies	Energy supplements fed at high levels; substitution
Drinking water unrestricted; high quality	Drinking water inadequate in quantity or quality
Medium to low ambient temperatures	High ambient temperatures, extreme body heat load
Providing shelter in inclement weather	Combinations of extreme cold, strong winds, heavy precipitation, muddy ground

Adapted from Vallentine (1990).

tinal tract capacity, and more particularly reticulorumen capacity in ruminants (NRC, 1987). Forbes (1986) concluded that forage intake is controlled primarily by animal physical factors, whereas the intake of more-concentrated diets is controlled mainly by energy requirements. Of course, high levels of internal parasites or sickness resulting from disease or severe nutrient deficiencies can be expected to reduce intake. Because increased genetic potential for growth in livestock likely stimulates intake as a result of a greater demand for production, selecting for increased relative growth rate can be expected to increase intake as well as efficiency in use of consumed nutrients (NRC, 1987).

Body size—including the effects of species, sex, and age differences—has a major effect in governing level of voluntary feed intake (Freer, 1981). Feed intake or energy intake is commonly described in relation to body weight$^{0.75}$, the index for general metabolism, or more simply as a percentage of body weight. Limited forage holding capacity in ruminants may be severe (1) in species with low rumen capacity : body size ratio (i.e., deer, pronghorn antelope, and probably small breeds of goats), (2) when the rumen is still developing in young offspring, and (3) during the last trimester of pregnancy. Most young calves begin rumen function around 2 to 3 months of age; milk and forage intake by calves are negatively correlated but augment each other in a nursing calf's diet (NRC, 1987).

Animals in thin body condition compared to animals of similar age and equivalent physiological stage but of high body condition consume more forage per liveweight (often 50% or more additionally, when other factors are not limiting) (Allison, 1985; NRC, 1987). When thin animals are fed *ad libitum,* they eat more forage and can be expected to grow at a faster rate. **Compensatory gains** (e.g., subsequent gains that are enhanced or depressed as a result of gains during a prior period) often result from changes in feed intake as well as changes in nutrient density in the ration.

The physiological status of the ruminant animal influences daily forage consumption. Lactation, growth, and fattening are all stimuli for increased feed intake. Forage intake of ruminant females increases slightly during midgestation over maintenance alone, declines late in pregnancy (in spite of increasing energy needs), is sharply reduced around parturition, but greatly increases during lactation (Forbes, 1986). The decrease in voluntary dry matter intake (VDMI) in late pregnancy probably results from rumen compression by the growing uterus and associated hormonal and discomfort factors (Wallace, 1984; Freer, 1981). Rumen compression from excessive abdominal fat seldom occurs in ruminants consuming medium- to low-quality forage diets (Forbes, 1986).

In both cows and ewes, energy demand increases more rapidly than intake early in lactation, often requiring that body reserves be mobilized (NRC, 1987). After the peak in lactation is reached, the level of voluntary intake often stays high while milk flow gradually decreases, and body reserves are replenished; then intake declines in late lactation (Forbes, 1986).

Lactating cows consume 35 to 50% more dry matter than do gestating cows of the same weight and on the same diet under conditions of high feed availability (NRC, 1987). Forage intake values reported in the literature for lactating cows commonly range from 1.6 to 3.2% of body weight per day, with lactation-associated increases of 25 to 35% commonly reported (Kronberg *et al.*, 1986). Lactating ewes or cows rearing twins increase feed intake over those rearing singles (NRC, 1985, 1987); intake averages approximately one-third higher when ewes are nursing one lamb (from birth to at least 10 weeks) and 50% more when nursing two lambs.

The digestibility and rate of ingesta passage and its association with reticulorumen fill (distention) appear to be the primary mechanisms regulating forage intake in large ruminants (Allison, 1985; Forbes, 1986; Freer, 1981; NRC, 1987). Freer (1981) concluded that within-day, short-term controls of feeding behavior seem more likely to be a response to rumen distension than to changes in local or circulating level of metabolites. The proposition that ruminants increase their forage intake when digestibility goes down (Moen, 1984) cannot be accepted (Holland *et al.*, 1990). When forage digestibility decreases with plant maturity, the ruminant cannot compensate by eating more because the ingested material does not move through the intestinal tract fast enough. For example, Mertens (1985, as cited by Holland *et al.*, 1990) predicted that when neutral detergent fiber (NDF, dry-matter basis) increased in forages from 38% to 54%, then daily DMI as a percentage of body weight would decrease from 3.16 to 2.22%.

The potential roles that VFA, metabolites, hormones, and brain factors play in the control of feed intake have been reviewed by the NRC (1987), but the quantitative implications of these effects remain in doubt and are not discussed here.

B. FORAGE FACTORS

The voluntary intake of harvested forages is affected by forage species, cultivar, stage of development, leaf:stem ratio, digestibility, soil fertility, climatic condition, and conservation process. Based on summarizing the voluntary forage intake by sheep of 1215 different forages worldwide, Minson (1990) found that the mean voluntary intake was about 60 g/kg $W^{0.75}$. However, intake levels varied from 20 to 100 g/kg $W^{0.75}$, and in 17% of the trials were outside the 40–80 range.

Altering the digestibility and consequently rate of passage of harvested forages in ruminants can be expected to cause parallel changes in VDMI. Highly fibrous, slowly digestible forage (high cell-wall content or NDF level) increases retention time, physical fill becomes limiting, and intake is reduced. As forages mature, decreasing levels of voluntary intake result from decreasing digestibility in both the leaf and stem segments, a reduction of the leaf:stem ratio, and possible nutrient deficiencies in relation to animal requirements. Leaf loss can be accentuated by drought or frost or by improper practices in field harvesting and handling.

Immature, highly digestible, slightly laxative forages decrease retention time and rumen fill and thus stimulate intake. However, with roughage diets of high digestibility, possibly 65 to 80%, voluntary intake may be controlled less by forage factors and reticulorumen capacity than by the energy requirements of the animals. Also, a satisfactory compromise must be maintained between voluntary intake, total forage or nutritive yield, and maintenance of the forage stand.

Walton (1983) provided rules of thumb for estimating daily forage intake by the ruminant animal based on forage quality (both palatability and digestibility): (1) 2.5% of the animal's live weight for top-quality forage, (2) 2% for good-quality forage, and (3) only 1.5% for low-quality forage. However, these can be considered as only rough averages because they assume no effect from the many other factors known to affect forage intake.

Grovum (1987) ranked low-forage palatability and an unfavorable protein:energy ratio (i.e., nitrogen status) over reticulorumen distension as the main factors limiting the intake of poor quality roughage (overmature, weathered, low-nutritive levels); with medium- and good-quality roughage, rumen distension was ranked as the priority factor. There is a consensus with dairy cattle that, at low digestibilities, the level of milk production is determined by the cow's capacity for feed, particularly undigested residues, and the rate at which undigested feed can be moved through the digestive system (NRC, 1987).

Voluntary intake is higher for legumes than for grasses and for temperate than for tropical forages (Minson, 1990). Legumes have a lower resistance to breakdown during chewing and rechewing, probably as a result of smaller quantity of cell-wall constituents. Where both the grass and the legume component in a mixture contain adequate levels of CP and minerals, voluntary intake is linearly related to the proportion of legume in the mixture. Leafy legumes and grasses are consumed in greater quantities than are their stemmy counterparts as a result of greater reduction in particle size from mastication and more rapid passage out of the reticulorumen.

Because of the relationship between digestibility and voluntary intake of forages, plant breeding and selection for digestibility provides a means of developing cultivars with increased potential animal-intake qualities. However, care must be taken when comparing intake levels of different cultivars that observed differences are not resulting from different harvest dates or stages of maturity.

Although desirable fermentation processes during ensiling does not normally reduce DMI, silage that is processed when unusually wet or dry often fails to ferment properly (NRC, 1987). In silages with greater than 65%

dry matter, the potential for molding increases, which is apt to reduce intake (Mertens, 1979). Slow feed-out may result in still further mold development. In silages with less than 30% dry matter, a pH of higher than 4.4 may be indicative of proteolytic fermentation and the development of amines and excessive butyric acid, which may reduce intake (Van Soest, 1982).

It has also been shown that direct-cut compared to unwilted silage and long-cut silage compared to fine-cut silage reduces voluntary intake (Minson, 1990), with the effect being greater with sheep than with cattle. These potential depressing effects of ensiling on voluntary intake can be reduced by fine chopping, wilting (or adding water to meet desired moisture levels when crop being ensiled is too dry), adding formic acid or formaldehyde as a preservative, or adding grain either prior to ensiling or as a feed supplement.

Pellets made from ground forage are usually eaten in larger quantities than is chopped forage. Grinding and pelleting can cause large increases in the voluntary intake of poor-quality forage (Minson, 1990; NRC, 1987), particularly in sheep. Although digestibility may be reduced slightly (5 to 10%), this is generally more than offset by the reduced wastage plus the greater rate of passage (NRC, 1987). Grinding results in smaller particle size and, thus, reduced reticulorumen retention time, whereas pelleting results in reduced time of mastication and puts fine, dusty feed in a more palatable form. Although this combination treatment is effective with both grasses and legumes, it has less beneficial effect with high-quality, immature forages.

Nitrogen deficiency in the diet can be a primary factor limiting feed intake while also reducing net utilization of metabolizable energy and thus animal performance. Diet digestibility and, thus, rate of passage, is reduced if the nitrogen requirements of rumen microflora are not met (NRC, 1987). Freer (1981) concluded that in senescent herbage or straw with a digestibility of less than 40%, advanced maturity is commonly associated with levels of nitrogen and minerals that are low enough to limit microbial activity in the rumen, and thus herbage intake. At moderate to high levels of dietary protein in forage diets, voluntary intake probably is not affected by protein content. The critical protein level is lower in ruminants than in monogastric species because the saliva of ruminants provides a substantial supply of urea for use in protein synthesis (Forbes, 1986).

Although not fully documented, deficiencies of salt (NaCl) or P and possibly other minerals in animal diets, if severe, may also reduce forage intake. When compared at equivalent stages of growth and where severe soil and, thus, forage deficiencies have not been present, fertilizing forage crops with N, P, Ca, S, and Mg have generally failed to increase voluntary intake even though levels of these minerals in the forage are increased (Minson, 1990). Treating low-quality forages with sodium hydroxide or ammoniation has been a means of improving digestibility and, thus, voluntary intake; this results in part from softening the fibrous constituents, expediting particle size reduction by mastication, and faster passage from the reticulorumen.

The NRC (1987) concluded that both taste and smell can influence the selection and consumption of various foods for most animal species, that olfactory cues (smell) can influence whether a meal will be initiated, and that taste may affect the length of the meal. Although palatability of a forage is generally assumed to be directly related to the level of intake of that forage, it is readily apparent that smell, taste, and appearance of a forage have less effect on the level of DMI when no alternative choice is offered (Forbes, 1986). Wallace (1984) questioned whether palatability alone always has a consistent influence on either forage intake or animal performance.

Reduced VDMI formerly was widely believed to result from high-moisture feedstuffs and associated limited rumen capacity. Allison (1985) has concluded that high forage moisture levels—whether from high internal water content or rainwater on the surface—generally does not affect forage DMI. He noted that ruminants seem to have the ability to consume forages as high as 85% moisture without affecting DMI, suggesting that excess water rapidly leaves the rumen and is subsequently voided.

Concern remains when high levels of excess water is not in the free state but rather trapped inside plant cells, as in some fresh forages and silages; Forbes (1986) concluded this may well reduce DMI, at least temporarily. Minson (1990) concluded that forages with water levels exceeding about 780 g/kg can be expected to have a detrimental effect on voluntary intake; with cattle he attributed this to their spending much more time ruminating very wet forage, probably because the forage was swallowed before maximum particle breakdown had occurred. In contrast, he found no evidence that voluntary intake differed substantially between low and moderate amounts of water in forage.

The following working hypothesis has been provided by the NRC (1987): "Voluntary free water intake plus water in the feeds consumed is approximately equal to the water requirements of cattle [seemingly would apply to other ruminants as well]. Thus, dietary water concentration *per se* would not be expected to influence dry matter intake until total expected water intake per unit of dry matter is exceeded." Nevertheless, the development of mold in wet forages must be prevented, or this alone can reduce forage intake.

C. MANAGEMENT FACTORS

Many management opportunities exist for increasing DMI of harvested forages. Keeping an ample supply of palatable, highly digestible, nontoxic forage available to livestock through all or most of each 24-h day is a primary management technique. In fact, VDMI, by definition, presumes that forage is made available in excess of the quantity that can temporarily be consumed. Although assuring that forage waste is realistically minimized, the excess over immediate consumption should be adequate to prevent limiting intake on high-appetite days and provide opportunity for the animals to select the more desirable and usually less fibrous parts of the forage. Care should be taken that forages fed are not contaminated by feces, mold, or other toxicants or antipalatability agents, or low levels of intake may result.

The kind and amount of supplements and concentrates can have a large influence on forage consumption. Minimal levels of protein and mineral and possibly even energy supplements necessary to balance high-forage rations should increase forage intake. However, grains or other high-energy supplements made available in liberal amounts (e.g., more than 3 lbs daily for cattle and 1 lb daily for sheep) are likely to cause only substitution of forage by the supplement, particularly with mature forages. When feeding high-forage diets to growing sheep, rate of passage and, thus, forage intake has been increased by feeding low levels of grain continuously, thereby avoiding the ruminal sensitive stretch receptors in sheep (NRC, 1987).

Substitution by high-energy concentrates in ruminants is greatest when the forage supply is high, the relative palatability of the forage is marginal, and the concentrate is fed in larger amounts. The substitution of grain for forage may be desirable when the objective is to stretch the forage supply or to enhance animal production levels by enriching the dietary energy levels, but undesirable when maximizing the relative use of forage is sought.

Drinking water should be provided free choice without attempts to limit intake levels. Restricting water consumption reduces DMI, and any factor that reduces water consumption below 75% of free choice consumption is apt to reduce animal performance as a result (NRC, 1987; Forbes, 1986). Unlimited time access to drinking water in contrast to infrequent or irregular access and assuring that water is of high quality should also have beneficial effects on feed intake.

Weather factors can materially affect forage DMI and animal performance generally, but can be controlled by management only in part, this more with pen-fed than with grazing livestock. Ambient temperature alone within the zone of thermal neutrality (14° to 68°F; −10 to 20°C) has minimal effect on VDMI. However, animals eat to keep warm and quit eating to prevent hyperthermia (Forbes, 1986). Temperatures above 68°F increase body temperature and associated heat stress; heat stress is further contributed to by the consumption of fibrous forages because of associated high heat increments. The resulting reduction in feed intake, particularly in the short run but with some acclimatization in the long run, represents a major cause of reduced productivity in heat-stressed ruminants (Robertshaw, 1987). High humidity further increases the stress of high temperatures; however, wind may reduce heat stress in hot environments, particularly when humidity is high.

Below ambient temperatures of 14°F, increased heat losses are compensated for by increasing the rate of heat production; this requires the conversion of productive energy to heat energy and often increases feed intake if readily available (Forbes, 1986). Sheep sheared and kept in a cold environment can also be expected to suffer increased body-heat loss and to increase feed intake to compensate. However, in very cold environments, and particularly in the absence of shelter, strong winds, heavy precipitation, and muddy ground may prevent livestock from ingesting the additional forage necessary to maintain body temperature and achieve acceptable performance. This problem can be expected to be even greater when the lowest quality forage is being fed.

D. PREDICTING FEED INTAKE

Prediction of DMI, or its measurement under controlled conditions, is a key component in assessing free-choice nutrient intake and needed dietary enhancements and in determining appropriate management practices. Valuable experience can be developed by the livestock manager in predicting feed intake by carefully observing and measuring voluntary feed intake and relating the differences found to the factors affecting voluntary feed intake. However, prediction equations may be required in planning livestock-forage programs.

Voluntary dry matter intake of forages has been predicted from a variety of measurable characteristics of the specific forages: leaf : stem ratios, bulk density, mechanical resistance to breakdown (i.e., grinding energy or leaf tensile strength), and resistance to chewing (i.e., artificial mastication). Intake predictions have also been based on a range of chemical analyses, near-infrared reflectance spectroscopy, and *in vivo* digestion techniques. Prediction of intake can be made using complex models including all animal, plant, and management factors known to control VDMI, but this is primarily a research rather than an applied management technique.

Because NDF has been shown to be negatively correlated with DMI, it is now commonly used to predict DMI. The formula based on NDF for the calculation of DMI potential as a percent of body weight is as follows (Holland *et al.,* 1990):

$$\text{DMI} = \left(\frac{120}{\%\text{NDF}}\right) \tag{4.1}$$

For example, assuming comparative NDF values in forages of 40% (high quality), 60% (medium quality), and 80% (poor quality), predicted DMI would be 3.0%, 2.0%, and 1.5% of body weight, respectively. (Refer to Table 4.2 for DMI values calculated for a selected list of harvested roughages.)

Relative feed value (RFV) is a measure of value that combines a forage's predicted intake and energy value. The equation for RFV requires both DMI (Eq. 4.1) and **digestible dry matter** (DDM) be determined. DDM can be determined by the following equation:

$$\%\text{DDM} = 88.9 - (\%\text{ADF} \times 0.779) \qquad (4.2)$$

(For example, if %ADF is 35, then %DDM is 61.6.) One equation for calculating RFV is as follows (Holland *et al.*, 1990):

$$\text{RFV} = \frac{(\%\text{DDM} \times \%\text{DMI})}{1.29} \qquad (4.3)$$

TABLE 4.2 Relationship of DMI, DDM, and RFV to ADF and NDF for Selected Forages (DMI, DDM, and RFV are Calculated Using Equations 4.1, 4.2, and 4.3 Respectively)

Forage	ADF (%)	NDF (%)	DDM (%)	DMI %	RFV (%)
Alfalfa, pre-bud	28	38	67	3.2	164
Alfalfa, bud	30	40	66	3.0	152
Alfalfa, mid-bloom	35	46	62	2.6	125
Alfalfa, mature	41	53	57	2.3	100
Alfalfa-grass, bud	30	45	66	2.7	135
Alfalfa-grass, mid-bloom	38	55	59	2.2	100
Bromegrass, late vegetative	35	63	62	1.9	91
Bromegrass, late bloom	49	81	51	1.5	58
Bermudagrass, early	32	70	64	1.7	85
Bermudagrass, late	43	78	55	1.5	66
Corn silage, well eared	28	48	67	2.5	130
Corn silage, few ears	30	53	66	2.3	115
Corn stalks	43	68	55	1.8	76
Fescue, late vegetative	36	64	61	1.9	88
Fescue, early bloom	39	72	59	1.7	76
Orchardgrass, early vegetative	31	55	65	2.2	110
Orchardgrass, early bloom	34	61	62	2.0	95
Sorghum-sudangrass, vegetative	29	55	66	2.2	112
Sorghum-sudangrass, headed	40	65	58	1.8	83
Wheat straw	54	85	47	1.4	51

Adapted from Holland *et al.* (1990).

RFV values calculated for selected forages using the Eq. 4.3 are recorded in Table 4.2. RFV values are only relative but do provide a means of comparing one forage with other forages or with a standard. For example, brome hay harvested in late vegetative stage (RFV = 91) can be compared with alfalfa hay harvested in the bud stage (RFV = 152) or with wheat straw (RFV = 51). When applied against a standard of 100 (represented by mid- to full-bloom alfalfa hay or a standard forage with NDF value of 53% and ADF value of 41%), the brome hay used in this example (medium value) falls slightly below the standard, whereas alfalfa hay (high quality) greatly exceeds the standard and wheat straw (low quality) is far below the standard. However, because RFV considers only DMI and energy value and not protein levels, the protein content of the forage must be evaluated separately from RFV.

More comprehensive equations and modeling suggestions for predicting feed intake with different animal species and for different feeds and feeding situations have been given in *Predicting Feed Intake of Food-Producing Animals* (NRC, 1987) and are referenced in *Forage in Ruminant Nutrition* (Minson, 1990; Chapter 2).

5

FEEDING HARVESTED FORAGES

I. FORAGE–ANIMAL SYSTEMS

Feed costs represent the largest single expenditure in most livestock operations, and providing pasture and producing, properly preserving, and feeding high-quality harvested forages can reduce dependence on concentrates and supplements, thereby reducing feed costs. **Forage–animal systems** may be defined as combined forage and animal management practices directed to meeting the nutritional needs of herbivores in specific production phases or throughout a production cycle (Matches and Burns, 1985). Nutritional requirements of the livestock should be given first consideration in planning a forage program. A priority objective is to match the nutritive value of different sources of forage with the nutrient requirements of different kinds and classes of livestock. Although all-concentrate rations are used sparingly to finish cattle and lambs, the breeding herds and backgrounding enterprises generally require large quantities of forage.

Another key principle in developing forage-livestock systems is to utilize advantageously the inherent differences among forages in their pattern of seasonal production and nutritive levels (Matches and Burns, 1985). An alternative to changing the forage quality to better meet the animals' changing needs is to change the livestock program to better coordinate with the changes that naturally occur seasonally in forage quality. This may require changing breeding seasons, shortening the breeding season, or changing weaning ages; changes that can be applied more readily to beef cattle than to sheep, goat, dairy cattle, and horse enterprises. However, supplemental feeding during critical, high-nutrient demand periods may still be required even with beef cattle.

Ruminant animals and horses have relatively low feed-conversion efficiency; even steers on finishing rations typically require 7.5 lb of feed (dry-matter basis) per pound of liveweight animal gain, this compared with 2.0 lb dry matter per pound of gain with broiler chickens. Nevertheless, pasturage and other forage rations generally provide satisfactory, lowest-cost rations for maintenance and production of herbivores. This requires that abundant forages and roughages be available at appropriate periods to sustain profitable ruminant and horse production.

Forage-livestock systems must be adapted to the changing nutritive requirements of animals as they move into different phases of production. The cyclic nature of reproduction in ruminant females and in the corresponding nutrient requirements result in the following critical periods: (1) development of the replacement females, (2) breeding and conception, (3) the last trimester of gestation, and (4) the postpartum period including lactation, and particularly during the female's first lactation (Bellows, 1985). High-quality forage is required during these periods, but also for young livestock at weaning and early postweaning or when being finished for slaughter. However, the addition of energy and protein concentrates may not only be required but may also be fully economical when strategically provided during these high-nutrient demand periods.

A principle in the applied nutrition of growing/finishing animals is continual improvement in dietary quality once the drive toward market condition begins; this begins at birth in some systems. In contrast, compensatory gains and losses tend to net out to zero in the annual weight/condition cycle of the mature reproductive animal; this allows loss of weight and body condition in noncritical reproductive periods to be restored in other periods. Mature, pregnant beef cows in good condition can lose 10% of body weight during early and midgestation and still produce 90% calf crops or more, providing they can gain weight after calving.

When livestock that was previously deprived nutritionally, but are otherwise healthy, are placed on higher quality or quantity of feed, their subsequent gains are generally greater than had they previously been fed on a higher plane of nutrition. These compensatory gains in the second period compensate or partially compensate for the prior period of reduced nutrition. Restricted drylot gains during overwintering usually enhance gains of growing animals subsequently placed on high-quality feedlot rations or pasture. These added compensatory gains following periods of marginal or underfeeding are largely dependent on compensatory increases in voluntary feed intake (Forbes, 1986). In contrast, lower subsequent gains (or even losses) may compensate for high previous gains. Thus, a step down in diet quality of livestock being prepared for slaughter should normally be avoided.

II. GRAZING/HARVESTED FORAGES INTERRELATIONSHIPS

A. COMPLEMENTAL ASPECTS

Most rangelands, excepting tallgrass prairies and native meadowlands, can be grazed to utilize only the standing crop. Characteristics commonly making rangelands unadapted to mechanical forage harvesting include (1) terrain is too rough; (2) the standing crop includes trees, brush, or other undesirable vegetation components; or (3) the site is too arid and forage yield too low to sustain the costs of mechanical harvesting. However, many planted forage crops can be either grazed or mechanically harvested or in some combination; such potential alternative uses of forage crops provides flexibility in meeting current needs on the farm and ranch or cash sale opportunities in the marketplace. Cutting part of the standing crop as hay or haylage on intensively managed, high-production pastures during flush growth is one means of meshing current animal demand and annual forage production cycles. However, pasturage provides a means of utilizing harvested forage crops or edible cash crops damaged by drought, frost, hail, or insect attacks.

Providing carrying capacity from a combination of rangeland, improved pasture, crop aftermath, and harvested forages is the basis of most livestock production enterprises. Annual deviations in forage production of 30% from the average on arid and semiarid rangelands are common, but 50% deviations below the average will probably require severe measures unless forage reserves in the form of harvested forages or pasturage from haylands or subirrigated pasture is available. Maintaining on hand a carryover supply of emergency feed such as hay, silage, or other harvested forages is the primary line of defense against severe reductions in pasturage yield caused by drought.

Rotation grazing, particularly short-duration and strip grazing, provides the opportunity to conserve or mechanically harvest as hay or haylage the surplus forage not needed for pasturage that might otherwise be wasted. With rotation grazing, excess forage can be harvested as hay or silage for feeding during periods of low forage production; losses due to herbage trampling, fouling, and senescence are reduced by more timely utilization through mechanical harvesting. Harvesting one regrowth cycle mechanically also reduces patch grazing caused by animal waste. A problem in grazing intensive cropland pasture is that cattle select against or even reject herbage around their droppings. However, when harvested along with regrowth as hay or haylage, the affected herbage is readily consumed by cattle. Thus, alternating grazing with mowing for conservation can promote more even grazing on intensively managed pastures (Simpson and Stobbs, 1981).

An increase in crop residues from monocultures aimed at intensive grain production in contemporary American agriculture has been achieved at the expense of cropland pasture (Wedin and Klopfenstein, 1985). Crop aftermath and residues in the form of regrowth, stubble, crop residues, chaff, lost grain, and weed and volunteer herbage can be a valuable secondary product after the primary grain crop is produced and harvested. This forage resource has been used primarily for maintaining breeding herds of beef cows or sheep during fall and winter or for putting weight on cull animals prior to sale; when properly supplemented, it can also be used for calves being maintained over winter. Crop aftermath and residue can be utilized through grazing or, if the quantity and quality of residue justifies, by making hay or ensiling. For example, even though of relatively low quality, stalklage can be made from the stalks remaining after harvesting corn or sorghums for grain. Also, crop aftermath or partial crop failures of grain crops can be mowed and windrowed or round baled and fed/grazed on the site where produced.

Fall or winter harvesting by grazing animals of the aftermath of herbaceous perennial plants on hayfields after dormancy is a common practice. In the western United States, this includes grazing subirrigated and irrigated hay meadows early in spring where soil conditions permit and in encouraging substantial regrowth after the last cutting for fall and early winter grazing. Leaving the last cutting of hay, either partial or full growth, in the field for grazing along with aftermath is practiced in many areas of the Midwest, particularly for beef cows (Wedin and Klopfenstein, 1985). Rake-bunched meadow hay (last crop) was found in Oregon to be a cost-effective strategy for overwintering pregnant beef cows (Angell *et al.,* 1987); rake-bunched hay was more nutritional than was the equivalent standing crop, and cows readily opened up the windrows.

A combination of grazing and round baling, based solely on the utilization of tall fescue, has been recommended by Ocumpaugh and Matches (1977) as a year-round forage program for beef cattle in the Midwest. A combination of grazing and round baling of the forage is carried out during spring and summer. From August 10 through October, part is grazed and part is left ungrazed for **stockpiling** (e.g., allowing the standing crop to accumulate during rapid growth stages and grazed near or after maturity). The stockpiled forage is then grazed during November and December, and the round bales are then fed/grazed during the winter until green-grass growth on the tall fescue is ample for grazing, thereby completing the year-round forage program.

B. UTILIZATION EFFICIENCY

Even though grazing is often the cheapest way per acre to harvest forage, it is almost never the most efficient way. Wedin (1976) estimated the relative inefficiency of utilizing tall, productive forage mixtures as follows (forage wasted): rotational grazing, 34%; daily rotational grazing, 25%; stored feeding, 10%; and green chopping, 5%. When dairy cows were grazed on alfalfa-smooth brome pasture during a 3-year study period, Van Keuren *et al.* (1966) found strip-grazing increased cow days per acre by 14% over regular rotation, but green chopping increased cow days per acre 53% over regular rotation. Larsen and Johannes (1965), studying the utilization of alfalfa-smooth brome stands with dairy cows, reported forage waste by cows on stored feeding (50:50 hay and silage) amounted to 8.5% of the dry matter of the forage fed, wastage that was reduced to 2% with green chopping, but increased to 33% of the forage dry matter under strip grazing.

When coastal bermudagrass in Georgia was utilized by steers from May 13 to September 17, green chopping produced 948 lb/acre of steer gains compared to 457 lb/acre under continuous grazing (Brown *et al.,* 1962). Gains were equal the first 28 days, but the gain differential widened thereafter. In other Georgia studies with steers utilizing coastal bermudagrass, green chop was favored over hay as follows: steer months per acre, 23.5 vs. 19.9; steer months per ton of forage dry matter, 2.03 and 1.42 (Hart *et al.,* 1976). Moderate stocking rate under grazing (3.24 yearling steers per acre) was compared to green chopping of irrigated orchardgrass-Ladino clover irrigated pasture at Davis, California (Hull *et al.,* 1961). The measured advantages of green chopping over grazing were as follows: forage consumption per acre, 7351 lb vs. 5700 lb; digestible energy consumption per acre, 9262 Mcal vs. 6950 Mcal; beef production per acre, 609 lb vs. 575 lb; and actual carcass yield per acre, 561 lb vs. 425 lb. The respective increases were 29%, 33%, 6%, and 32%.

The reasons for increased harvesting efficiency of green chopping—and most other forms of mechanical harvesting as well—over grazing has been reviewed by Blaser *et al.* (1959) and by Walton (1983) to be as follows: (1) more uniform utilization, (2) less unutilized residue, (3) reduced losses from fouling and trampling, (4) less trampling damage of forage plants and the soil surface, particularly where drainage is poor or irrigation is practiced, (5) reduced weed problems, (6) alternating growth and rest periods, and (7) harvesting at optimum growth stages for maximizing either dry matter or nutrient yield. However, it should be noted that these advantages of mechanical harvesting are accompanied by greatly increased utilization costs. The comparative economy of pasture results from the saving of labor, equipment use, and power in that the grazing animal gathers its own feed.

C. GRAZING EFFECTS ON HAYLANDS

Pasturage can often be obtained during emergencies or during normal seasons of insufficient grazing capacity from forage crops primarily planned for mechanical harvesting. When carefully managed to prevent deterioration of the perennial forage plants and the soil on which they grow, this practice has generally resulted in minimal or no hay yield reduction in future years or in stand deterioration.

Grazing alfalfa in West Virginia during a 3- to 4-week period only in the spring did not reduce total annual yields (Wolf and Blaser, 1981); this permitted the flexibility of grazing alfalfa in early spring for balancing seasonal grazing capacity. The spring grazing delayed the first hay cutting by about 3 weeks, thereby foregoing only about one-half cutting of hay for the season. In subsequent West Virginia studies (Allen *et al.,* 1986a), grazing, beginning in early spring, for 4 weeks for 2 consecutive years resulted in minimal influence on stand longevity and productivity, particularly when available forage was maintained at about 800 lb/acre (0.9 Mg/ha). However, extended grazing duration prior to early bloom and during the hot, dry conditions of summer was more detrimental to alfalfa regrowth and stand longevity than was spring grazing only (Allen *et al.,* 1986b). This was attributed to alfalfa being a C_3 plant, a vigorous and rapid grower, and being more competitive with weed species in the spring than in the summer.

During a 5-year study in Nevada with alfalfa grown under irrigation, dormant-season grazing of aftermath during November, January–February, or April did not reduce yields of the first hay cutting made in early May (Jensen *et al.,* 1981). The dormant-season grazing treatments did not significantly affect the number of plants per unit area or increase the incidence and severity of root and crown diseases; it did provide an additional half ton of forage when grazed in the fall, or about half that much if not grazed until winter. When little or no growth occurred from January to March on coastal California perennial ryegrass–white clover pasture, short, intensive grazing periods during the winter had little effect on growing-season yields (Jaindl and Sharrow, 1987).

Grazing tall fescue hay meadows in the fall in West Virginia resulted in more forage production than did an all-hay system (Baker *et al.,* 1988). The fall grazing not only utilized the aftermath not otherwise available, but also distributed manure and urine for productive purposes. Early spring grazing of the tall fescue hay meadows tended to reduce annual dry matter production. However, total annual yield expressed as metabolizable energy per acre for the spring and fall-grazed meadow management was similar to the all-hay treatment.

Spring grazing of native hay meadows may be a practical means of increasing spring grazing without seriously affecting subsequent wild hay production. Continuation of grazing into midspring on hay meadows near Big Piney, Wyoming, did not affect yield of the typical single cutting; continuation of grazing into late spring depressed hay yield only slightly (Table 5.1).

Although the grazing capacity of native and improved meadows is high, grazing on some meadows has been discouraged because of fragile soils. Prior to studies on grazing Sandhill meadows in Nebraska (Clanton and Burzlaff, 1966), it was the practice to graze only on aftermath or initial spring growth, and growing-season grazing was avoided. However, it was demonstrated that grazing every third year and haying the other 2 years resulted in no deterioration of range condition or productivity and in favorable livestock response. Nevertheless, grazing patterns on the meadows were often patchy, resulting from livestock preferences for regrowth of grazed plants and avoiding forage contaminated with manure and urine; grazing of meadows in any 2 consecutive years was not recommended.

Soil compaction may be a serious problem when fine-textured soils are grazed when very moist or wet, resulting in soil-surface compaction, an increase in bulk density, and reduced water penetration rates. Damage is much less where soils remain dry or are of coarser texture, unless wind erosion becomes a problem. New stands under which the soil is not covered by dense sod is particularly susceptible to trampling damage. However, such damage can also result from machinery and equipment during such periods. Severe defoliation near the end of the growing season should be avoided because energy reserves are then being replenished and new buds for next year's tillers are being developed (Waller *et al.*, 1985). A lack of spring vigor and early growth can result from depleted storage carbohydrates and lack of insulation to protect against frost damage to perennial plant bases.

Deep-treading damage, referred to as **poaching** in the British Isles, can result from grazing heavy soils even when at field capacity rather than only when saturated (Tanner and Mamaril, 1959). When clay or even loam soils

TABLE 5.1 Influence of Grazing in the Spring on Subsequent Hay Yields

When discontinued	AUD[a]/acre grazing	Hay yield (T/acre)	Total forage (T/acre)
Early (May 3 avg)	10.8	1.66	1.79
Mid (May 26 avg)	15.4	1.67	1.89
Late (June 8 avg)	38.7	1.46	1.93

[a] AUD, animal unit day.

From Stewart and Clark (1944).

are very wet following snow melt, rain, or irrigation or during periods of high water table, hooves are apt to penetrate deeply and disrupt the soil surface. Not only does this high-impact hoof action disrupt soil structure and soil surface, but the shearing action may also destroy foliage, growing points, and roots of the plants. Special effort should be made to avoid high cattle or horse densities—a greater problem than with sheep or goats—during sensitive periods; avoiding grazing altogether at such times may be the best approach (Wilkins and Garwood, 1986).

Livestock should not be held on perennial meadows or haylands during nongrowing seasons unless deep treading and associated damage to the perennial plant roots and crowns can be avoided. This may be a problem when livestock are fed harvested forages on haylands following complete use of the aftermath. The solution is to move livestock into drylot confinement after the aftermath has been consumed and before damage occurs. If this is not possible, frequently rotating the feeding site aids in the distribution of manure and urine, improving sanitary conditions, and lessens animal damage to the living sod (Taylor and Templeton, 1976). December–April grazing and hay feedings on alfalfa-bromegrass haylands in southwest Idaho were compared at zero, normal (25 head/acre), and high-stocking densities (100 head/acre) (Stephenson and Veigel, 1987). The high-stocking density resulted in higher April soil bulk density, a 92% recovery period 16 months after protection from grazing and trampling, and required 24 months for full recovery. Deep treading can permanently damage the sward, enable major weed invasions, and greatly curtail the productive life of the stand.

III. GRAZING/FEEDING MANAGEMENT PLAN

A balanced livestock enterprise requires sufficient quality and quantity of not only harvested but also grazable forages and other feedstuffs to promote continuous satisfactory maintenance and production of the livestock. Even "junk" forages such as quackgrass areas, stackyards with hay mats, weeds in wintering grounds or "go-back" lands temporarily out of crop production, and residues in corn or sorghum fields previously harvested for grain may play a useful role in maintenance rations. A comprehensive plan to secure the best practicable use of forage resources is a key management step in ruminant animal production enterprises. Providing the day-to-day carrying capacity from the combination of available sources to best match the quantitative and qualitative requirements of livestock is the basis of the *grazing/feeding management plan.*

When balancing the annual and seasonal carrying capacity with livestock needs, utilization of the grazing lands should often be considered first. The seasonal utilization of native range and other permanent, dryland pasture is generally the least flexible, except on year-long range found mostly in the central and southern Great Plains and Southwest. Croplands provide some flexibility through crop-rotation pasture, temporary pasture, and *crop aftermath* pasture (available after the main crop has been harvested) or *crop foremath* pasture (removed before the main crop is produced) in meeting seasonal grazing capacity deficits; if not needed for pasture, such lands can be utilized in producing cash crops. Lastly, the production of harvested forages and grain can be used to fill carrying capacity gaps that cannot be filled by the optimum combination of grazing resources, and even carried over into subsequent years.

It is common to replace part or all of the grazing resource with harvested forages and other feedstuffs on a regular basis for the more intensive livestock enterprises or when pasture standing crop is seasonally or temporarily inadequate in supply for production and growing enterprises, a practice preferably referred to as *maintenance feeding.* A related term, *emergency feeding,* refers to supplying such feedstuffs when the available standing forage crop is insufficient because of heavy storms, fires, severe drought, or other emergencies. A harvested forage reserve such as hay or silage serves as a means of bridging such emergencies as a severe winter, a late spring, a summer drought, or a partial crop failure in either pasture or harvested forages.

The term **supplement** more precisely refers to nutritional additives high in protein, phosphorus, salt, or energy and intended to remedy deficiencies in the grazing animal's diet or other basal ration, thereby balancing animal diets. Supplements are generally concentrates or less commonly nutrient-rich, harvested roughages such as alfalfa hay or even pasturage (as *supplemental pasture*). Supplemental pasture of exceptionally high quality can be employed to enrich nutrient intake and enhance livestock performance when grazed simultaneously with low-quality pasturage or when added to other low-quality roughages. When nutrient levels are marginal in pasture or harvested forages, any reduction in forage intake associated with low palatability, digestibility, or availability may cause dietary deficiencies not otherwise encountered. Thus, a feedstuff such as alfalfa hay may bring up dry-matter intake (DMI) while providing supplemental protein.

Forage plant species that can be maintained high in digestibility are good choices for animal responses requiring high energy intake. Forages that are lower in digestibility—but sometimes higher yielding—may be better choices where animal responses are less demanding. Paying an extra premium for the highest quality forage will probably not be economical when only a maintenance ration is needed. Most forages adequately meet the nutrient requirements of some kind and class of livestock. However, for those classes of livestock having high nutrient requirements, fewer forage sources meet their needs.

High-quality forage is probably more important for dairy cattle in lactation than for almost any other kind or class of livestock [minimum of 65%

total digestible nutrients (TDN) or relative feed value (RFV) of 125]. Excessive amounts of concentrated feeds in the diets of dairy cows depress the milk yield (Oldfield, 1986); it is generally recommended that silage not replace all of the hay in the forage component for best animal condition and health. High-quality alfalfa or other legume hay is expected not only to contribute substantially to the energy needs of lactation, but also most of the protein requirements. Such legume hays are also generally excellent sources of vitamins, minerals, and other essential nutrients. Although lactating dairy cows require additional energy concentrates and calves will not grow well on all-forage rations, high-quality alfalfa hay will meet most of the nutrient requirements for growing dairy heifers and nearly all of the requirements of nonlactating cows.

Another demand for high-quality hay is by horse owners, particularly owners of race horses and other high-value pleasure horses. However, other horse owners demand either grass or a mixed grass–legume hay. Because blister beetles are potentially highly toxic to horses, many horse producers want assurances that no blister beetles are present in the hay. Other outlets for high-quality hay include specialty markets such as zoos and emergency feeding of big-game animals during severe winters. Wild ruminants, like domestic ruminants, have microflora capable of digesting hay as well as browse and converting it to volatile fatty acids (VFA) (Nagy *et al.,* 1967; Urness, 1980), but hay feeding must begin before starvation sets in and rumen function has largely halted.

A greater variety of forage quality can be utilized in beef cattle than in dairy cattle rations, giving an opportunity to utilize large quantities of hay harvested too late or cured improperly, corn stover silage, stover of corn or sorghum, or even straw of wheat or other small grains. Both beef cow and stocker enterprises are almost totally dependent on forages (in various combinations of pasturage and harvested forages) for satisfying both energy and protein requirements. Pregnant beef cows being wintered without suckling calves by side can utilize medium-quality forages or even very low-quality forages when some higher-quality forage is added. However, lactating beef cows, growing beef heifers, and young bulls require good- to high-quality forages because energy concentrates are not generally economical. Bulls during nonbreeding can also utilize medium- to low-quality forage but require high-quality forage during active breeding seasons.

A much lower dependency on forages—but this normally of high quality—is commonly found in cattle-finishing enterprises in the United States than in most other countries. In the United States, high-grain rations are more commonly used, either throughout the feeding period or at least during the last few weeks. The advantages of high-grain rations commonly given by cattle feeders are shorter feeding periods associated with faster gains; carcasses of higher grade, less shrink in the cooler, white rather than yellowish color of fat, and better taste; and sometimes favorable low grain : forage price ratios.

Forage quality requirements with sheep are similar to those of beef cattle, and practically all feed for the mature ewe can come from forage. Some lower-quality forages can be fed during early gestation, while saving or providing the higher-quality forage for use from about 6 weeks before lambing through the lactation period. A higher proportion of high-quality hay is generally included in lamb- than in beef-finishing rations. The lowest-quality hay may have markets limited to mulch for gardeners or in mushroom growing.

This Page Intentionally Left Blank

6

ANTI-HEALTH FACTORS IN HARVESTED FORAGES

I. INTRODUCTION

Harvested forages may contain toxicants that directly harm the ingesting animals, antipalatability factors that reduce dry matter intake (DMI), or antidigestibility factors that reduce digestibility and often intake as well. Foreign material in harvested forages may be sorted out and remain unutilized or may be inadvertently consumed and then be harmful. Small metals consumed with the forage can cause a serious malady referred to as *hardware disease.* Dead rodents, rabbits, or birds may be bound up in hay bales and result in killing livestock by botulism if consumed. The botulism toxin can also occur in silage that spoils rather than properly ensiles during processing. Large masses of blister beetles killed during hay harvesting and included as contaminants in the hay have been found to be toxic to livestock because of an irritant chemical contained in the insect bodies. Insecticides with high toxicity to livestock can cause severe maladies when applied at excessive rates to the forage crop, when applied too soon before harvesting, or applied to hay after harvesting.

Even high-quality forages—those of high palatability and nutritive value—may cause or at least contribute to animal disorders. Thus, it is important to be alerted against and understand the basic anti-health aspects of harvested forages and how to prevent or reduce their consequences. Even potentially dangerous forages can often be used safely by knowing the danger and taking reasonable management precautions. The anti-health factors that may be associated with harvested forages are discussed under (1) metabolic disorders of livestock and (2) plant toxins produced by forage plants.

II. METABOLIC DISORDERS

Metabolic disorders may result from simple nutrient deficiencies or from complex interactions of soil, climate, physiological status of the animals, and fermentative reactions in the reticulorumen. Forage plants being utilized may produce components that indirectly contribute to the metabolic disorder or may passively accumulate toxic levels of minerals from the soil, such as nitrates and selenium. The resulting animal disorders may result in visual deficiency or toxicity symptoms, or even death, but may remain only marginal or "subclinical" in being difficult to detect while depressing animal performance.

A. LEGUME BLOAT

The consumption of succulent, immature growth of alfalfa, the clovers, or sweetclover has the potential for subacute or acute frothy bloat. This condition results in formation of a frothy, stable foam in the rumen, a retention of gas produced in normal rumen function, and an inhibition of belching or eructation (Reid and James, 1985). An affected animal initially shows signs of abdominal pain, and the left side of the animal becomes distended and swollen. In advanced cases the abdominal cavity becomes severely distended, breathing is labored, animals go down, and death is often the result.

Stable foam production in bloating ruminants is due to a complex interaction of animal, plant, and microbiological factors. It is generally accepted that soluble leaf proteins are the principal foam-causing agents in legumes, but marked differences exist among animals within a given herd in susceptibility to frothy bloat. Nonbloating legumes such as sainfoin, cicer milkvetch, birdsfoot trefoil, crownvetch, or lespedezas can be used, but yield and performance may be substantially less than for alfalfa or the clovers. The nonbloating characteristic is associated with high tannin levels, which are capable of precipitating the proteins found in bloat-causing foam. However, this advantage of high tannin levels—a characteristic that can be selected for in the bloating legumes—carries with it the probability of lower digestibility and intake.

Legume bloat is primarily a problem with grazing ruminants, particularly when alfalfa or clovers make up more than one-third of the standing crop (Vallentine, 1990). However, it can prove equally serious when they are fed in the form of green chop. Precautions must also be taken when feeding large amounts of legume hay, particularly harvested when immature or following a frost; however, when alfalfa is mowed, wilted, and stored as haylage, it is not likely to cause bloat (Holland *et al.,* 1990).

Poloxalene (trade name "Bloat Guard") is an effective water-soluble, detergent-type compound for preventing frothy bloat. This antifoaming agent is effective when continual daily intake is assured and feeding is begun prior to animals gaining access to hazardous legumes. Poloxalene can be provided in a liquid molasses-based supplement, mixed or included with the dry supplement, or incorporated into a composited ration. Animals should be removed from the legume ration when bloat symptoms appear; ruminal drenching with a concentrated poloxalene material should be administered if bloating is pronounced.

Because the intake of immature alfalfa or clover green chop or hay in drylot is more readily controlled than under grazing, limiting intake to no more than 40% of the ration circumvents most bloat-hazard potentials. Spreading the intake of green chop over the whole day through multiple feedings or feeding mixed with grain or other forage is suggested. More mature green chop or hay (mid- to late-bloom stage) is less bloat promoting but has reduced nutritive levels. Gradually accustoming drylot ruminants to higher levels of legumes in the ration may also help. (Note that a common but different form of gaseous bloat occurring in feedlots is associated with high-concentrate or all-concentrate rations, but is not discussed here.)

Because grazing animals are most susceptible to bloat from alfalfa or from clovers, precautions should be taken to minimize the risk. Suggested management practices are:

1. Gradually (over a 5- or 6-day period) increase the time that animals have access to legume pasture.
2. Observe animals at least twice a day when they are turned onto legume pasture. Some animals are chronic bloaters and should be watched especially close or removed from the pasture.
3. Once the animals are accustomed to alfalfa pasture, leave the animals on the pasture constantly, even at night.

4. Extra caution should be taken during wet, cloudy periods in the early spring, when alfalfa is making its most rapid growth. Do not put animals onto alfalfa pasture if a heavy dew is present.
5. More mature alfalfa is less likely to cause bloat. Minimize potential problems by initially turning them onto legume pastures that have reached the bloom stage.
6. Begin feeding poloxalene 2 to 5 days before turning animals onto legume pasture. Use higher dosages when animals are first placed on the pasture, and reduce the rate if no problems occur. Animals on lush alfalfa and clovers will require more poloxalene than will animals on more mature forage.
7. A very important reduction of risk can be attained by assuring that the legume in the pasture is between 35 and 50% of the total forage. If the legume is less than 35% of the total forage, dinitrogen fixation will be insufficient to maintain high production.

B. GRASS TETANY

Grass tetany potential in grazing animals can be a major antiquality factor associated with spring grain forage, crested wheatgrass, and other cool-season grasses in lush growth stages. Green chop from equivalent sources may also be a source of trouble. Grass tetany occurs most often in older, lactating cows recently turned onto cool-season pasture in the spring, but may also affect sheep and goats and other classes of cattle. However, it can also occur in animals maintained on poor-quality grass hay or field-crop aftermath (Reid and James, 1985; Grunes and Mayland, 1984).

Grass tetany is characterized by low blood serum magnesium concentrations (**hypomagnesemia**), which can result from a simple magnesium deficiency in the diet or more often from reduced availability and absorption of forage magnesium due to conversion to an insoluble form in the digestive system. The complete causal relationships of the latter are only partly understood (Rendig and Grunes, 1979). Symptoms include nervousness, muscular incoordination, staggering, and paralysis; death usually occurs within 2 to 6 h if affected animals are left untreated. When grass tetany cannot otherwise be prevented, feeding recommended levels of supplemental magnesium per head daily will do so; animals that have already incurred grass tetany can be treated by giving intravenous injections of magnesium sulfate or calcium–magnesium gluconate (Grunes and Mayland, 1984).

Grass hays from tetany-prone areas of northeastern Nevada were found to contain only about half as much magnesium as hays from other areas of the state where tetany from grass hays was not a problem (Bohman *et al.*, 1980). However, wet meadow hays comprising mostly broadleaf sedge and rushes were found to be tetany-prone regardless of where they were grown. Magnesium fertilization and introducing legumes into grass hay meadows are means of increasing magnesium levels in hay and, thus, reducing the incidence of grass tetany.

C. SILICA URINARY CALCULI (UROLITHIASIS)

Although minerals deposited within the urinary tract in the form of small stones (calculi) can occur in both males and females of all species of livestock, the problem is greatest in castrated males. These hard deposits collect in the urethra, thereby interfering with urine flow; kidney damage can also occur. Symptoms include tail twitching, uneasiness, kicking at the abdomen, dribbling urine, and straining in an attempt to urinate. In advanced stages the bladder may rupture and urine spills into the abdominal cavity, giving rise to an extended abdomen referred to as "water belly," and death follows.

Urinary calculi composed predominantly of calcium, magnesium, and ammonium phosphates are common in feedlots. Grain concentrates are high in phosphorus, and a high ratio of concentrate to roughage contributes to the formation of such phosphatic calculi. However, targeted for discussion here are the formation of siliceous calculi associated with the intake of forages high in silica.

Siliceous calculi formation is commonly associated with grazing forages. Range grasses commonly contain 2% silica (dry basis) in the spring months; levels reaching 7% by dormancy, or even more after weathering, are common. High levels of silica are similarly found in grass hays, particularly prairie hay, and in some straws. Low water intake enhances the formation of siliceous calculi. When in combination with low water intake, a forage silica content greater than 2% can be expected to cause urinary calculi problems in the more susceptible animal classes (Mayland, 1986).

Prevention of silica urinary calculi includes encouraging high water intake for diluting silicic acid and other interacting minerals in the urine by providing adequate supplies of clean water and even warming water on cold days. Force-feeding high levels of common salt or 1/10 lb of ammonium chloride daily in the diet will materially increase water intake (Emerick, 1987). Both ammonium chloride and phosphorus supplements aid in acidifying the urine and reducing the formation of silica stones. Feeding good-quality alfalfa hay or other legume forages up to as much as one-half of the ration greatly reduces the problem.

D. NITRATE TOXICITY

When plants accumulate high levels of nitrates (0.5 to 1.5% or even more), poisoning may occur in ruminants upon the conversion of nitrates to nitrite (James *et al.*, 1980). The nitrite causes the production of methemoglobin in the blood, a form of hemoglobin that cannot carry oxygen; the resulting oxygen starvation causes suffocation and death in advanced stages. Severely affected animals develop muscle tremors, lose coordination, and become weak. Sublethal levels of nitrate intake can cause abortion, reduce growth and milk production, and interfere with vitamin A utilization.

Forage-plant species especially adept at accumulating nitrates include Johnsongrass, sudangrass and other sorghums, sweetclover, smooth bromegrass, orchardgrass, tall fescue, oats, rape, barley, wheat, and corn. Weeds such as annual kochia, pigweed, Russian thistle, and nightshade are also important contributors. Livestock may be poisoned after eating either harvested or grazed forage. Although ensiling forages suspected of having high nitrate levels usually reduces the chances of problems, hay continues to be dangerous as the accumulated nitrates do not decrease over time. Avoiding the addition of nonprotein nitrogen sources such as urea or ammonia to silage made from stressed plants is suggested.

Excessive rates of nitrogen fertilization or stress in plants from drought, hail, or frost increase the accumulation of nitrates. Nitrate levels tend to be higher in the lower one-third of the plant vegetative tissue and accumulates more at night and on cloudy days (Holland *et al.,* 1990). Prevention includes diluting nitrates in the ration by mixing low-nitrate forage (25 to 75% of ration) with the high-nitrate forage and discontinuing the feeding of nitrate-accumulating forage when toxicity symptoms become evident. Avoiding mowing accumulator species closer than 10–12 in. from the ground and not cutting drought-stressed plants for several days after a rain also helps avoid problems. Samples of forage suspected of high-nitrate levels should be sent to a laboratory for analysis of nitrate levels.

E. SELENIUM TOXICITY

Although selenium is a naturally occurring mineral required in trace amounts in animal diets, its presence in excessive amounts in forages and grains is apt to cause animal poisoning (Anderson *et al.,* 1961). Soils of specific parent materials in the central and northern Great Plains and other areas of the western United States receiving less that 25 in. of precipitation annually are labeled seleniferous (i.e., they contain hazardous levels of selenium of 0.5 to 100 ppm or more). Animals consuming forage grown on these soils may be poisoned by consuming excessive levels of selenium in their diets. Nevertheless, selenium deficiency in ruminant rations is considered more widespread and of greater economic significance than selenium toxicity (Minson, 1990).

Some native plant species growing on seleniferous soils actively accumulate selenium in their tissues (50 to 3000 ppm), and acute symptoms, including death, may result in grazing animals. Most grasses and other forage species from which harvested forages are produced passively develop lower but potentially toxic levels (5 to 40 ppm). Animals consuming pasturage or hays and silages containing these reduced levels of selenium over a period of several weeks slowly become poisoned and develop the malady referred to as *alkali disease*. Symptoms of this chronic illness include emaciation; lack of vigor; stiffness of the joints; rough hair coats; loss of long hairs; and cracking of the hoofs, resulting in tender feet. All domestic livestock species are affected.

A wide array of forage-plant species grown for harvested forages appear prone to take up toxic levels of selenium when high levels occur in the soil. At lower soil levels of selenium, immature forage is generally higher in selenium levels than is more mature forage. Irrigation over several years aids in leaching selenium from the soils, thus reducing the hazard. Because alkali disease is a chronic form of poisoning resulting from accumulation of selenium in animal bodies over time, rotating animals biweekly between seleniferous and nonseleniferous forage may be a useful practice.

F. ESTROGENIC COMPOUNDS

Breeding failures in both cattle and sheep have resulted from ingesting estrogenic compounds found in legume pasturage from ladino clover, alfalfa, and subterranean clover (Cheeke and Shull, 1985). Although the problem appears to be restricted mostly to animal grazing these actively growing plants, similar problems should be expected when such forage is fed as green chop to breeding animals. Feeding such forages as hay or haylage are not known to be a major problem. Selection for cultivars low in plant estrogen content appears the most direct solution to this problem.

III. PLANT TOXINS

Toxins produced by plants may serve as defense mechanisms against herbivores or be secondary metabolites (side products of normal plant metabolism) that play no role in vital plant processes. Poisonous plants cause significant economic losses among grazing animals, particularly on rangelands where they are natural or invading constituents in the standing crop. Under grazing situations in which forage is consumed as pasturage, the relative palatability of the toxic plants must be given primary consideration; the regulation and manipulation of grazing is important in preventing the consumption of poisonous plants in harmful amounts (Vallentine, 1990). Avoiding thirst or hunger, keeping animals on an acceptable plane of nutrition, and providing ample quantities of palatable, nontoxic forage solves many poisonous plant problems under grazing; however, such practices should also be considered when harvested forages are being fed.

The first line of defense against plant toxins when harvested forages are fed is to assure that toxic materials are not made available to animals for consumption. Foreign materials such as toxic weeds inadvertently included with the forage crop when harvested are often the problem; animals consuming harvested forages often do not select against toxic foreign materials mixed with the primary forage materials. Mycotoxins produced by fungi either before or after harvest may provide toxicity. However, the primary forage species being harvested may itself be toxic under some situations. Because many forage-plant species otherwise well adapted for use as harvested forages are not entirely free of potentially harmful compounds, it is important to understand how both environment and management determine whether their use will be potentially hazardous.

A. PRUSSIC ACID

Cyanogenic glucosides, the precursors of prussic acid or hydrocyanic acid (HCN), are potentially hazardous toxicants in sudangrass, other sorghums, Johnsongrass, arrowgrass, and flax and less commonly in white clover, birdsfoot trefoil, and corn herbage. Their levels accumulate in new growth or regrowth following cutting or the return of good growing conditions in drought-stunted plants, or in damaged or stressed plants. Prussic acid is released from the cyanogenic glucosides in two ways: (1) by plant enzymes liberated when plant tissue is injured as a result of cutting, masticating, wilting, or freezing, or (2) by the action of rumen flora, thereby making ruminants more susceptible to the problem. High levels of nitrogen fertilizer also increase levels of cyanogenic glucosides.

Prussic acid poisoning is most commonly associated with sudangrass, the forage sorghums, or their hybrids. Minimum plant growth for safe grazing, green chopping, or silage making is 18 in. for sudangrass, 30 in. for sorghum–sudangrass, and headed out for forage sorghums (Holland *et al.,* 1990). Ensiling should be delayed for 3 days following frost at these growth stages or for 2 weeks if frosted in more immature growth stages; delaying feeding for at least 3 weeks after ensiling will also be helpful. A postensiling forage analysis for prussic acid potential can be obtained if hazardous levels are suspected. Harvested forages are generally safer than pasturage in that the total plant is consumed rather than the leaves being selectively consumed.

Neither green chopping nor ensiling decreases the prussic acid levels, but field curing or drying in hay production releases 50 to 70% of the toxicant. New cultivars of sorghum species have been and are being selected for low content of cyanogenic glucosides; Piper sudangrass is one example. Although substantial quantities of arrowgrass may be found in native meadow hay, the danger is minimal if the hay has been well cured. Chokecherry and other members of the *Prunus* genus are also potentially poisonous but are rarely found in harvested forages, and trimmings from such plant species should not be made available to livestock.

Important factors that influence the incidence of prussic acid poisoning are (1) cyanide content of the plant, (2) rate of consumption, (3) rate of release of cyanide from ingested plants, and (4) rate of absorption and detoxification. Because the animal's body can detoxify large amounts of HCN, poisoning occurs when excessive amounts of plant material are consumed in a short period of time (Reid and James, 1985). HCN is readily absorbed into the blood, is carried throughout the animal's body, and causes death by asphyxiation at the cellular level. All species of farm animals are subject to prussic acid poisoning, but horses and pigs are less susceptible than are ruminants. Symptoms of poisoning are nervousness, excessive salivation, muscle tremors, and blue coloration of mucous membranes. Spasms and convulsions follow, animals go down and become paralyzed, and death follows within 2 h of initial symptoms. Some animals can be saved by intravenous injections of a mixture of sodium thiosulfate and sodium nitrite if treatment is done early enough.

B. ALKALOIDS

Alkaloids (or nitrogen-based chemicals) occur naturally in plants, are found in a rather wide variety of vascular plants, and are associated with some fungal growths. Because alkaloids are a highly heterogenous group of chemicals, the symptoms they cause are also highly variable. Effective treatment of poisoned animals is seldom possible or practical, and death often results. Poisonous plants containing alkaloids may occur as foreign materials in hay or silage. The presence of high alkaloid content often sharply reduces palatability in plants, but some species high in total alkaloids are apparently palatable to livestock. However, when alkaloid-containing poisonous plants are intermixed in hay or silage crops, animals may not be able to avoid eating the hazardous materials even if unpalatable. Neither process of hay drying or ensiling reduces alkaloid levels.

Hays produced from wild meadows or from improved meadows subsequently invaded by poisonous plants may be hazardous. Resident problem plants found in meadows include water hemlock (*Cicuta* spp.), poison hemlock (*Conium maculatum*), tansy ragwort (*Senecio jacobaea*), nightshades (*Solanum* spp.), milkweeds (*Asclepias* spp.), and even houndstongue (*Cynoglossum officinale*). The narrow-leaf milkweeds are more poisonous than are the bloodleaf milkweeds, but all milkweed species are potentially poisonous; resenoids and glycosides may also be present in hazardous levels. Water hemlock grows in swampy, wet areas and is distinguished by tuberous roots and chambered, swollen rootstocks; although the rootstocks are highly poisonous, all parts of the plant are potentially poisonous. Tansy ragwort is an invading weed that has infested many haylands in the Pacific Northwest, but is found in eastern United States as well.

Annual kochia (*Kochia scoparia*) is an aggressive warm-season weed that grows abundantly over much of western United States. It is drought hardy, salinity tolerant, and readily reseeds itself. Although it produces abundant herbage, is readily grazed in vegetative stages, ranks relatively high in nutritive content, and has found substantial acceptance as a forage crop even under irrigation, it is potentially hazardous because of variable levels of alkaloids and possibly other toxicants, including nitrates and oxalates (Karachi *et al.,* 1988). Toxicity symptoms in cattle are thinness, lethargy, and self-isolation, excessive salivation, watery eyes, difficulty breathing, severe liver and kidney damage, and sometimes death (Kiesling *et al.,* 1984). Annual kochia should not comprise the major portion of diet for cattle or sheep, and caution should be used under grazing or when feeding as harvested forage.

Alkaloids are also problems in some recognized forage species, including reed canarygrass (*Phalaris arundinacea* L.) and tall fescue (*Festuca arundinacea* Schreb.), in which different forms of *staggers* are associated. Although the hazards of these grasses are greatest to animals grazing new growth, particularly new regrowth in the fall, poisoning can also result when these forage grasses are incorporated into hay or haylage. The problems associated with reed canarygrass can be substantially reduced by utilizing cultivars low in alkaloids; strains high in alkaloids are not only potentially hazardous but have low palatability, intake, and digestibility. High soil N levels and drought stress are also associated with increased alkaloid concentrations. Because alkaloid levels in tall fescue are not only natural but are also enhanced by fungal association, this problem is discussed more fully under mycotoxins.

C. MYCOTOXINS

Although mycotoxins (including aflatoxins) are most commonly associated with corn grain, peanuts, and cottonseed and less frequently with wheat, sorghum, and other oilseeds, problems with grazed and harvested forages do occur. Even though moldy hay and silage may not be toxic, mold is undesirable because the nutritive value is reduced and the feed is less palatable to livestock. Clouds of spores released when dry, moldy hay is being fed can be injurious to handlers as well as livestock. Ruminants appear to tolerate somewhat higher levels or longer periods of low-level intake of mycotoxins than do monogastric animals, and young ruminants are generally more susceptible than are older ruminants.

Mycotoxins are diverse, naturally occurring toxic metabolites (including alkaloids) produced by fungi, principally molds, and can result from the fungi invading feedstuffs during production, processing, or storage (Richard and Cole, 1989). Symptoms in ingesting animals are highly variable depending on the actual fungal-derived toxicant, but range from acute (including vomiting, diarrhea, prostration, and death) to chronic (including reduced growth and appetite, lower reproduction and milk production, liver necrosis, vascular changes, pinpoint hemorrhages, and gastric lesions). Excessive salivation or slobbering may be associated with feeding moldy red clover or alfalfa hay. The diagnosis of mycotoxicosis in its highly variable forms is difficult, and requires the services of a veterinary practitioner.

During processing and storage, preventing molds from growing is largely dependent on reducing either moisture or oxygen levels or both. Because oxygen penetration cannot be prevented in normal hay storage, keeping the hay dry (18% moisture or less) or adding chemical preservatives is effective. Management tools for preventing molding in hay include adequate drying before baling or stacking or subsequent barn drying, followed by reducing exposure of hay to rain or wet ground. Because ensiling is a wet process and ample moisture is present for mold growth, success depends on preventing or greatly reducing air (oxygen) penetration by using airtight structures, compacting the silage, keeping moisture moderately high, fine chopping, and sealing the surface. Once the surface seal is opened for feeding, ample depth of silage must be taken daily to prevent spoilage from molding and heating.

The deleterious effects of tall fescue toxicity has had a serious impact on animal production in the southeastern and midwestern United States and is now attributed primarily to alkaloid mycotoxins (Stuedemann and Hoveland, 1988). Three animal-impact syndromes have been recognized: (1) "fescue foot," a gangrenous condition of the feet associated with lameness, (2) bovine fat necrosis, and (3) the more common fescue toxicosis, or "summer slump." The last is characterized by low gains or even loss of weight, rough hair coat, general unthriftiness, low milk production, and impaired reproduction. The interrelationships of the fungi with the host plant, including apparent symbiotic relationships, and the actual toxic factors or combination of toxic factors involved in each syndrome are not yet fully understood.

The symptoms of tall fescue toxicity are most severe in grazing animals, but can also be a problem with cured hay or haylage. The solution to the problem of the tall fescue toxicity problem lies in destruction of contaminated plant stands and replacement through use of fungus-free seed (Pedersen and Sleper, 1988). Reinfestation may occur over time, apparently limited to the reintroduction of contaminated seed by animals, feeding fungus-contaminated hay on uninfested land, or other mechanical seed transport (West, 1989). Endophyte-free tall fescue appears to be less tolerant of environmental stress than is endophyte-infected grass—apparently because of the loss of symbiotic benefits—and may require more careful management, including less severe defoliation (Hoveland *et al.*, 1990).

Because there are no visual signs of the fungus on the tall fescue plants, laboratory tests must be relied on to determine its presence. The use of plant breeding and selection for resistance to the fungus also appears promising. Dilution of contaminated tall fescue hay is suggested, either by mixed seedings with legumes or other grasses in the field or mixing with noncontaminated hay or silage before feeding.

Ergotism is caused by alkaloid mycotoxins produced by specific fungi and is associated with the dark-colored, hard ergot bodies that replace the seeds in the seedheads of affected plants. Ergot primarily affects the cereal grasses (common rye, triticale, wheat, barley, and oats); it is also found in forage grasses such as wheatgrasses, ryegrasses, wildryes, Johnsongrass, dallisgrass, some cultivars of bahiagrass, smooth bromegrass, and bluegrasses, and in a variety of weedy grasses. Ergot is common in tall fescue, being similar or possibly even involved in some aspects of tall fescue toxicosis.

Ergotism may affect grazing animals but can also carry over into harvested forages when grasses with affected seedheads are utilized. Ergotism can take the nervous form of hyperexcitability, convulsion, muscle spasms, and temporary paralysis (more common in sheep and horses) or the gangrenous form that affects extremities of the animal body (most common in cattle). Only reduced weight gains and milk production, reproductive failures, and emaciation may be associated with milder forms. Because the presence of ergot bodies is readily apparent in the seedheads, avoiding the use of contaminated plants in harvested forages is the best solution where experience indicates potential problems exist. Harvesting before the development of seedheads or mowing to prevent seedhead development are preventatives that may prove useful. Rotating annual or other short-term forage crops with noninfectable crops is a helpful measure.

D. SWEETCLOVER POISONING

Sweetclover pasturage and properly processed and stored sweetclover forage is rarely toxic. Sweetclover does contain a harmless chemical **coumarin,** which gives the plant its characteristic odor, particularly noted when plants are cut or trampled. However, during heating or spoilage of sweetclover hay or silage, this chemical is converted to the toxic **dicoumarol.** This toxin prevents blood-clotting and may cause animals ingesting moldy sweetclover to bleed to death from minor wounds or from internal hemorrhaging; the problem is more common in ruminants than in horses. Early symptoms of abnormal bleeding can be noted around the nose and through the droppings; stiffness, lameness, dull attitude, and swellings beneath the skin become evident. The problem can be particularly troublesome in females around parturition, and the toxins are transferred to the unborn through the placenta or through milk to the newborn.

Toxic levels of dicoumarol result from poorly managed sweetclover silage or in sweetclover hay put up too wet or allowed to draw dampness when bales or loose hay, including that in windrows, remain in contact with moist ground. The stems of sweetclover are relatively thick and retain moisture after the small leaves have dried; care must be taken in attempting to retain a high proportion of leaves that the hay is not stacked or bailed before the stems are fully dried. Chopping during processing as hay or haylage should be helpful. Treatment of baled sweetclover hay with anhydrous ammonia but not propionic acid has greatly reduced the formation of dicoumarol (Sanderson *et al.,* 1984). Once toxic levels of dicoumarol are produced, they are retained in the affected forage, which is readily eaten by livestock.

Livestock should be carefully observed for several weeks after starting to feed sweetclover hay or silage that is moldy. If discovered in time, the condition can be cured by removal from the toxic forage and injecting with high doses of vitamin K to restore bloodclotting; adequate calcium intake should be assured through supplementation. Moldy sweetclover has to be fed for about 3 weeks before chronic bleeding occurs. Thus, intermittent feeding of suspected forage (i.e., alternating periods of 7 to 10 days with alfalfa or other dicoumarol-free forage) is more effective in neutralizing the toxicity than is feeding a mixture on a continuing basis. Some cultivars of sweetclover, such as Polara, have been selected to have low levels of coumarins; their use minimizes the risk to levels no greater than with other clovers. However, high-coumarin cultivars have out-yielded low-coumarin cultivars (Sanderson *et al.,* 1984).

E. OTHER PLANT TOXINS

Numerous other poisonous plants with the array of toxicants they present may occur as foreign materials in hay cut from upland or lowland native meadows, seeded forage crop stands invaded by weeds, and intermittent croplands. These potentially hazardous plant species include white snakeroot (*Eupatorium rugosum*), containing the alcohol tremetol; St. Johnswort (*Hypericum perforatum*), containing the photosensitizing compound hypericin; and bracken fern (*Pteridium aquilinum*), containing thiaminase, which inactivates vitamin B_1.

PART

III

GROWING AND PRODUCING FORAGE CROPS

7

PLANT GROWTH, DEVELOPMENT, LONGEVITY

I. PLANT DEVELOPMENT

A. GENERAL CONSIDERATIONS

Plant development is regulated by species, available water, soil nutrients, and ambient temperatures. Because of the importance of temperature in plant growth and development, forages are classified as cool- or warm-season crops. Examples of cool-season crops are the perennial forages used in temperate regions such as alfalfa, orchardgrass, bluegrass, the various clovers, and so on. Warm-season crops are represented by corn, sorghum, millet, bermudagrass, all tropical grasses, and many of the native grasses of the Great Plains of the United States.

If planted at the proper time, over a period of time, crops develop a canopy that provides the factory for optimum photosynthesis to occur. Development of this canopy is much slower in perennial forage crops (alfalfa, orchardgrass, clover, smooth bromegrass, etc.) than in annual forage crops such as corn or sorghum. However, if properly planted and cultured, a full canopy develops within 30 to 45 days. When a nurse or companion crop is used in the establishment of a forage crop, the rate and extent of development of the forage crop in the first season is delayed until the late summer or until the fall. Thus it may be that a full canopy is not developed until the next growing season.

B. THE CROP CANOPY

In established forage stands, both spring growth and regrowth after clipping occurs quite rapidly, and the complete canopy is formed within a short period of time if temperatures are favorable for plant growth. Fifteen to 30 days are usually required for canopy closure. For optimum production, it is essential that the crop stand be sufficient to intercept 95% of the incident radiation received at the top of the canopy; therefore, rapid regeneration of the canopy is essential.

It is desirable for the canopy to form as soon as possible because it is the full complement of leaves that allows maximum photosynthesis to occur and, consequently, maximum dry matter to accumulate. When the canopy is sufficient to intercept 95% of the incident radiation reaching the top of the canopy, it is at a stage that allows optimum dry matter production.

When a plant first begins to grow, it has a very low leaf area, but the amount of leaf area increases rapidly under proper temperature, soil nutritional status, and moisture conditions. If an individual plant is separated into its leaf and stem components, it is possible to measure the leaf surface available for photosynthesis. Only one surface of each leaf is measured. The photosyntheticly active stem tissues are not considered. This leaf area varies with the size of the plant and size varies with the number of plants per unit area. Therefore, rather than refer to leaf area per plant, leaf area per unit of surface soil is used. This is called the **leaf area index** (LAI). Thus, the LAI for a specific crop is determined by the total leaf area of several plants divided by the soil surface area from which the plants were produced. LAI is a dimensionless rating because in the division, the units used for measuring area in both the leaves and of the soil surface cancel each other. This concept was first introduced by D. J. Watson in 1947. It allows expression of yield to be put on a common basis, the LAI, and has proved to be quite useful in comparing the results from various research efforts. LAI is a physiologically important parameter and the influence of various environments and management treatments on it are directly reflected in a crop's yield.

Forage crops commonly have LAIs ranging from 3.5 for corn and white clover to about 6.3 to 7.1 for many of the cool-season grasses such as orchardgrass, perennial ryegrass, smooth bromegrass, and so on (Table 7.1). The critical leaf area is not necessarily the maximum leaf area that a species can achieve. It is, however, the canopy required for interception of 95% of the incident radiation. LAIs may be 20 to 100% greater than the optimum in some canopies (Davidson and Donald, 1958). In these canopies, however, growth and leaf production are inhibited.

It should be noted, however, that the LAI of a specific forage crop may not be the same during all periods of growth. For example, smooth bromegrass is used extensively for spring and fall grazing in the Midwest because of the higher production at that time that is favored by better precipitation patterns. Summer growth is limited. In Nebraska (Engel *et al.*, 1987), it was reported that the LAI was maximum during the spring growth period (6.8), somewhat less in the fall (5.2), and even lower during the summer (3.2).

Forage crops show a relatively good linear relationship between dry-matter yield and LAI. Brougham (1956) showed that an increase of one unit in LAI resulted in an increase of approximately 503 kg up to the highest LAI of 10 (Fig. 7.1).

C. LIGHT INTERCEPTION BY CROP CANOPIES

Light penetration within the canopy and to the soil surface is described by Beer's Law and is a logarithmic function of the LAI (e.g., it shows a logarithmic decrease as the LAI increases). Beer's Law is expressed as

TABLE 7.1 Critical Leaf Area Index (LAI) for Various Forage Crops

Species	LAI
Perennial ryegrass	7.1
Smooth bromegrass	6.9
Timothy	6.5
Red fescue	6.3
Alfalfa	4.6
White clover	3.5
Corn	3.5–4.0

Source: Walton, 1983.

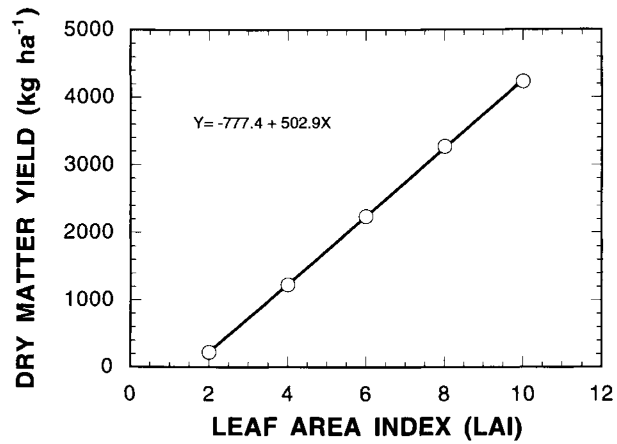


FIGURE 7.1 Relationship of leaf area index (LAI) and herbage yield. (Redrawn from Brougham, 1956).

$$I = I_0e^{-}kF \qquad (7.1)$$

where I is the incident radiation at a given height within the canopy, I_0 is the incident radiation at the top of the canopy, e is the base of the natural logarithm, k is the extinction coefficient, and F is the LAI from the top of the canopy to the height within the canopy in question.

The extinction coefficient is determined mainly by inclination and arrangement of leaves. *Leaf transmissibility,* or the ability of radiation to pass through leaves, is a minor factor in determining the extinction coefficient. Crops that have an upright leaf display generally have k values of 0.3 to 0.5, and crops that display leaves more or less horizontally usually have k values of 0.7 to 1.0 (Saeki, 1960).

There is a linear relationship between the proportion of the logarithm of relative light (I/I_0) intercepted and LAI or total leaf area (Fig. 7.2). Beer's Law is very accurate in describing radiation distribution within a canopy, but it is seldom used by anyone other than researchers because of the difficulty in measuring the leaf area of the various canopy strata. Instead, a less tight relationship between fraction of light beneath a canopy and crop height is often used (Fig. 7.3). Interception of light by a crop increases with age because of the increase in extent of the canopy. It also increases in a regular manner as time from solar noon increases, either morning or afternoon (Baker and Musgrave, 1964. The relationship of plant age, minutes from noon, and percentage of radiation intercepted is shown in Fig. 7.4.

The percentage of the incident radiation intercepted by the full canopy may be influenced by environmental factors such as temperature and avail-

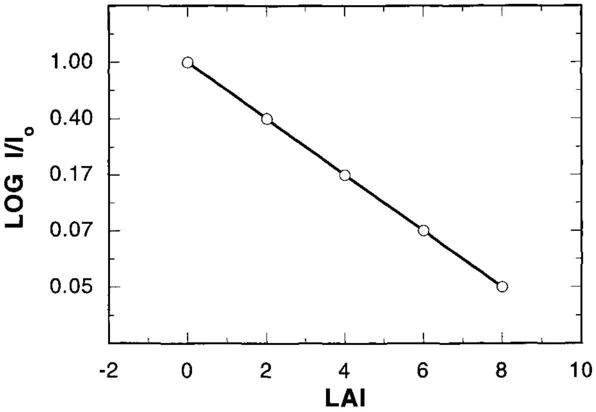


FIGURE 7.2 Leaf area and relative light intensity within a canopy. (Redrawn from Takeda, 1961).

able water. For example, in Nebraska, smooth bromegrass showed radiation interception values of 99% in the spring under optimum growing conditions with a LAI of 6.8. In the summer, when moisture is usually limited, light interception was only 73% and the LAI was 4.1, whereas in the fall, interception was 97% and the LAI was 5.2 (Engel *et al.*, 1987).

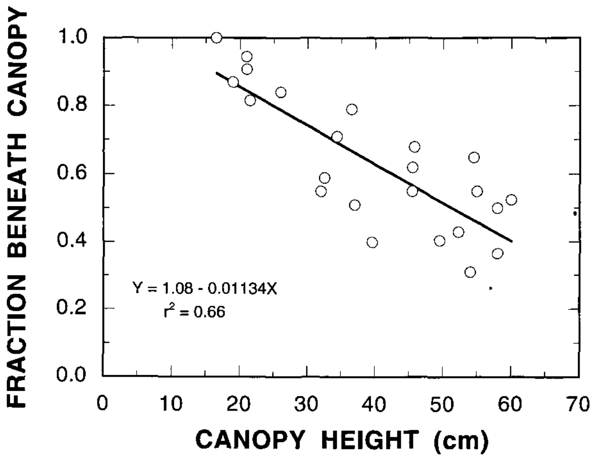


FIGURE 7.3 Crop height and fraction of solar radiation at ground level. (Redrawn from Stanhill, 1962).

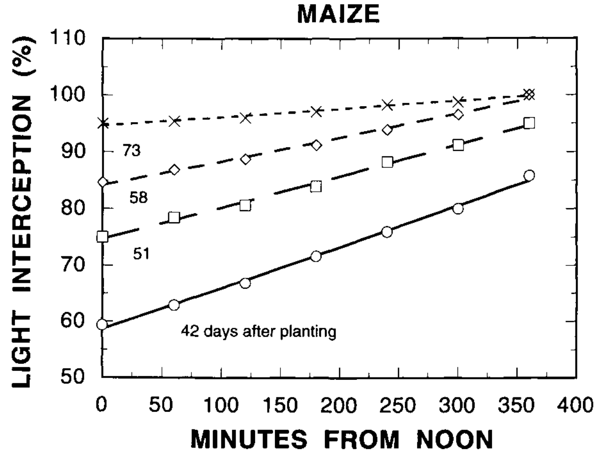


FIGURE 7.4 Light interception as influenced by time from solar noon and age of corn stand. (Redrawn from Baker and Musgrave, 1964).

II. RESPIRATION

All active or living cells exhibit the process of **respiration** (i.e., they usually utilize O_2 and release CO_2 in equal volumes). The process is an overall oxidation-reduction reaction in which CO_2 is oxidized and O_2 is reduced. Chemically, respiration is the reverse of photosynthesis, but the pathways and enzymes required to effect the process differ. Substrates of respiration may be sucrose, starch, fructans or other sugars, fats, organic acids, and, under some conditions, even proteins.

Utilization of energy derived from respiration is divided into two categories. The first is *maintenance respiration,* or that portion of respiration required to support constant turnover of materials and maintain cellular organization. The second is *growth respiration,* or that portion of intermediates and energy remaining after maintenance respiration is satisfied that is used for synthesis of new materials or production of growth.

The overall equation expressing the energy balance of this process is the reverse of photosynthesis, but it must be emphasized that the two processes do not follow the same pathway. The process is summarized as follows:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy} \qquad (7.2)$$

Most of the energy, 2870 kJ or 686 kcal per mole of glucose, is released as heat. However, far more important than this large amount of released heat is the energy trapped in adenosine triphosphate (ATP). The energy captured by this molecule is used to support many essential processes in the cell.

Respiration varies with age and with type of tissue. Younger leaves respire at a greater rate than do older leaves. Respiration rates of plant material range from a low of 0.003 for a resting seed to a high of 65 μmoles O_2 hr^{-1} g^{-1} of fresh material for a seedling (Table 7.2).

Respiration is the expression of an enzymatically driven process and rates are highly influenced by temperature. Within limits, the rates of these enzymatic reactions approximately double with each increase of 10°C in the temperature. This is referred to as the Q_{10} *value,* and is expressed as

$$Q_{10} = (\text{rate at } (t + 10)^\circ\text{C} \div \text{rate at } t^\circ\text{C}) \tag{7.3}$$

where Q_{10} is the ratio of growth at $t + 10^\circ$C and t° C, and t is temperature. Between temperatures of zero and 20°C, Q_{10} values are usually in the range of 2 to 3. Above this temperature, the Q_{10} often decreases. Above 35°C there is a progressively more rapid breakdown of respiration rate because

TABLE 7.2 Rates of Respiration for Some Plant Tissues

Tissue	Per g fresh wt.	Per g dry wt.
Barley seed	0.003	
Wheat seedling	65	
Wheat leaf		
5 days old	22	
13 days old	8	
Healthy laurel leaf	9	
Starved laurel leaf	1.3	
Barley root	50	
Carrot root	1	
Potato tuber	0.3	
Undeveloped apple fruit	10	
Mature apple fruit	0.5	
Whole potato plant	5	
Pea seed		0.005
Barley seedling		70
Tomato root tip		300
Beet slices		50
Sunflower plant		60

Source: Bidwell, 1979.

of heat destruction of enzymes. The enzyme systems of C_4 plants are adapted to higher temperatures than are those of C_3 plants. For example, the primary carboxylating enzyme in the temperate (C_3) crops is ribulose-1,5-bisphosphate carboxylase, which has an optimum operating temperature of 20 to 25°C (68–77°F). The C_4 grass enzyme, phosphoenol pyruvate, has an optimum operating temperature of 30 to 35°C (86–95°F).

Net photosynthesis (P_N), gross photosynthesis (P_G) minus respiration (R), provides an indication of the carbohydrates available for maintenance, growth, and storage. Thomas and Hill (1937) showed that respiration of alfalfa was 35 to 49% of its photosynthetic rate. As temperatures increase, photosynthesis (Fig. 7.5) and respiration (Fig. 7.6) also increase, but respiration increases more rapidly. Thus the net efficiency of photosynthesis decreases as temperatures increase above the optimum for a crop. As the temperature approaches 30°C for C_3 plants, respiration rates approach photosynthetic rates, and above that respiration exceeds photosynthesis. This is the reason for decreased alfalfa yields during the hot summer periods in the southwestern United States and similar areas.

III. PHOTOSYNTHESIS

The growth of plants is driven by the sun, which is key to their survival as it is to survival of all higher forms of life. The process of capturing and storing the radiant energy entering the earth's atmosphere from the sun is

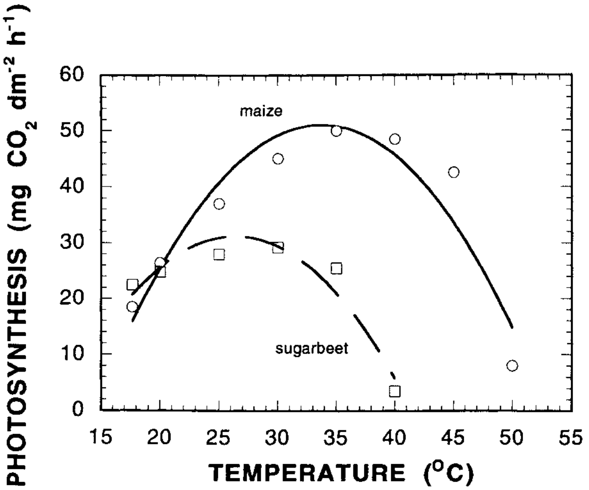


FIGURE 7.5 Relationship of photosynthesis in C_3 (sugarbeet) and C_4 (maize) plants to temperature. (Redrawn from Hofstra and Hesketh, 1969).

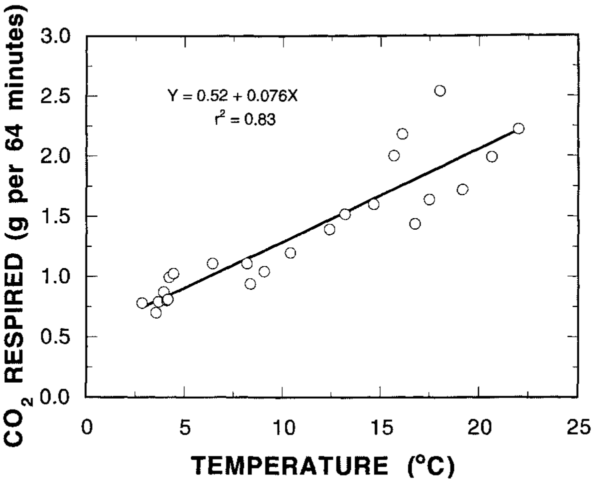


FIGURE 7.6 Temperature and respiration in alfalfa, 11 Sept. 1936, Logan, Utah. (Redrawn from Thomas and Hill, 1937).

called **photosynthesis.** This process requires the plant with its chlorophyll molecules in the leaves and stems, carbon dioxide, water, and proper temperature for the process to occur. Chemically, photosynthesis can be shown as follows:

$$6CO_2 + 12H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6\,O_2 \qquad (7.4)^1$$

The radiant energy from the sun is captured by the chlorophyll molecules and stabilized as electric potential in the electron transport system and in the form of ATP and reduced nicotianamide adenine diphosphate (NADPH). These compounds then provide energy to drive the previously mentioned reaction. The results of this reaction are then transported, largely as sucrose and galactose, to other parts of the plant, where they are used or converted to more complex carbohydrates, stored, and subsequently remobilized and utilized where needed in the plant. This is the basic process of all green plants.

[1] American scientists S. Reuben and M.D. Kamen demonstrated in 1941 that all the O_2 produced in photosynthesis comes from the water. They used isotopically enriched $^{18}O_2$ in their studies. This concept was related to the biological system in 1937 by English biochemist R. Hill, who was the first to obtain a partial reaction of photosynthesis to work on isolated chloroplasts. His preparation could simultaneously produce O_2 and reduce added electron acceptors in light. This process has been called the Hill reaction. Hill was not able to couple his reaction with the reduction of CO_2, but it was subsequently understood to represent the first step, or light reaction, in photosynthesis.

A. ENVIRONMENTAL EFFECTS ON PHOTOSYNTHESIS

1. Light

The response of various species to increased incident radiation varies. Most C_3 plants, represented by cotton and wheat, show an increase in the rate of photosynthesis from very low light to moderate light intensities, above which the rate plateaus. It is said that they saturate at the point where a significant increase no longer occurs. In contrast, the C_4 plants, such as maize, show a continued increase in photosynthesis as light intensity is increased (Fig. 7.7). The saturation point of the tissues in C_4 plants, with respect to photosynthesis, is not reached within the normal incident radiation received at the earth's surface.

2. Water

Studies on the direct effect of water deficit on the photosynthesis of alfalfa or other forage crops are few. However, there are numerous studies in which the effect of water deficit on stomatal opening have been studied. Because CO_2 must enter the plant through the stomata, anything that causes the stoma to close has a limiting effect on photosynthesis. As water deficits increase, the gradient between atmospheric CO_2 and cellular CO_2 continues to increase until the stoma completely close. At this point, photosynthesis ceases. In alfalfa, Murata *et al.* (1966) found that photosynthesis was reduced 40% by stress resulting from water deficit in the soil. Reducing soil moisture

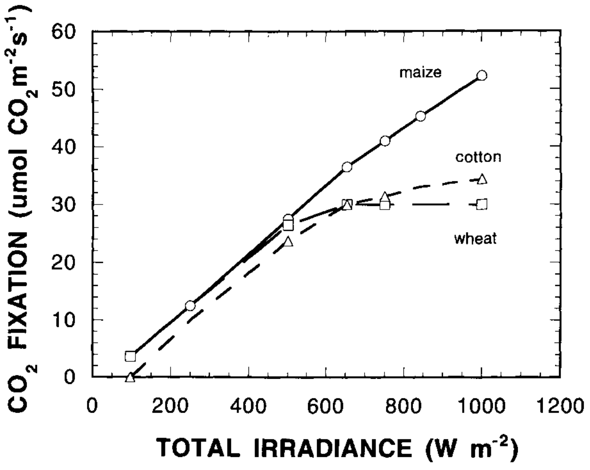


FIGURE 7.7 Effect of total solar radiation intensity at the top of the canopy on net photosynthetic rates in maize, wheat, and cotton plants. [Redrawn from Salisbury and Ross, 1992. Original data were from Baker and Musgrave, 1964 (maize); Puckridge, 1968 (wheat); and Baker 1965 (cotton)]. (From *Plant Physiology, 3rd edition* by Salisbury and Ross. Copyright 1985. Reprinted with permission of Brookes/Cole Publishing, a division of International Thompson Publishing. FAX 800 730-2215).

to 37 to 40% of field capacity for 10 days at the bud, flowering, and seed-filling stages of development reduced photosynthetic productivity by 22 to 35% (Redeva and Topchieva, 1979). Begg and Turner (1976) and Turner and Begg (1978), in a review of the effects of moisture stress on forage crops, concluded that the relative decrease in photosynthesis was greater than the decrease in dark respiration or photorespiration.

3. Carbon dioxide

The rate of photosynthesis in C_3 plants increases nearly twofold as concentration of CO_2 is increased above the ambient level of 0.03% to 0.13% (Fig. 7.8). In going from CO_2 concentrations of 800 ppm to approximately 2500 ppm, photosynthesis in alfalfa increases from an apparent rate of about 14.5 to approximately 42 g CO_2 (80 min.)$^{-1}$ (Thomas and Hill, 1949). The increased CO_2 concentration reduces the loss of fixed carbon in photorespiration; thus, the increase in net photosynthesis. Corn and other C_4 plants do not show this increase in photosynthesis with increased CO_2 concentrations (Carlson and Bazzaz, 1980). Corn grown at 350, 600, and 1000 ppm CO_2 produced, after 24 days, 7.0, 6.2, and 6.6 g dry matter, respectively. In contrast, soybean, a C_3 crop, produced 3.6, 4.7, and 6.4 g, respectively (Patterson and Flint, 1980). Note that at 350 ppm of CO_2, corn produced almost twice as much as soybean, but at 1000 ppm the production was approximately equal. This has also been reported by others (Jensen

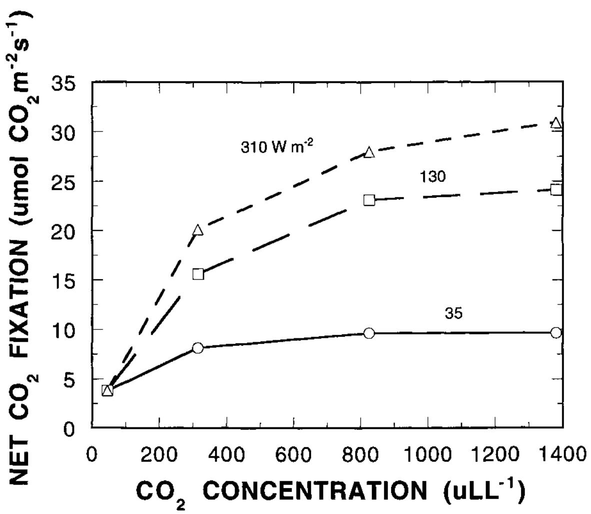


FIGURE 7.8 Atmospheric CO_2 enrichment and CO_2 fixation in sugarbeet leaves. Fixation rate for three solar radiation intensities is shown. (Redrawn from Salisbury and Ross, 1992. From *Plant Physiology, 3rd edition* by Salisbury and Ross. Copyright 1985. Reprinted with permission of Brookes/Cole Publishing, a division of International Thompson Publishing. FAX 800 730-2215).

and Bahr, 1977; Mortensen and Moe, 1983; Mortensen and Ulsaker, 1985; Raschke, 1986).

This large increase in yield of C_3 plants with increased CO_2 concentrations points to the positive affect of the predicted greenhouse effect. It does not, however, take into consideration the change in global climate that may occur and the effect that this will have on crop production areas. One school of thought is that the greenhouse effect will cause widespread desertification, and areas now considered to be the breadbasket of North America will become drier (Buol *et al.,* 1990) and warmer (Taylor and MacCracken, 1990) and the optimum area for wheat, corn, and soybean production will be shifted northward. The extent of the temperature rise is uncertain. Some have projected an increase in average global temperature of as much as 8°C, but Idso (1990a,b) is not convinced that increases of such magnitude will occur even if CO_2 concentration is doubled, as is expected. He feels that the increased yield and water use efficiency (King and Greer, 1986; Rogers *et al.,* 1983) and increased competitiveness (Marks and Strain, 1989) of C_3 plants will offset the deleterious effects.

For further information about the greenhouse effect and the predicted effects, the reader is referred to the references mentioned and to more recently published literature.

4. Temperature

At full light intensity and normal CO_2 concentrations, photosynthesis is influenced by temperature. This is because, as temperatures vary from the optimum, the enzymatic systems are not functioning at their optimum or maximum capacity. Typical of C_3 cool-season (potato) and warm-season (tomato, cucumber) is the CO_2 assimilation pattern that peaks at about 30 to 36°C, and thereafter declines very rapidly.

Temperature has a significant influence on leaf development of forage crops, providing other factors such as water and soil nutrient levels are not limiting. In alfalfa and many other cool-season forage crops, growth and leaf development is optimum at about 21°C (70°F). At temperatures above or below that optimum, growth and development are retarded. The further the growing conditions depart from the optimum, the greater is the retardation of growth. In the extreme cases, at 10°C (50°F) or 32°C (90°F), development of leaf area is only 1.05 and 1.3 to 1.5 $cm^2\ d^{-1}$, respectively. This is compared to 2.86 $cm^2\ d^{-1}$ at 21°C (Wolf and Blaser, 1971). These values are for individual plants over a 7-day period. At 32°C the rate of growth tails off after the fifth day, indicating that the high respiration rate is placing stress on the plant due to insufficient availability of carbohydrates.

B. C_3 VS. C_4 PLANTS

Until about 1968, the full degree of complexity of respiration in plants was not understood. Because of the confusing results obtained in respiration research, the wrong questions were often asked and interpretations varied. Total respiration could be measured, but the discrepancies reported in the various crop plants could not be explained. It was noted as long ago as 1920 that respiration of plants, such as alfalfa, snap bean, and other crops now classified as C_3 species, was suppressed by increased concentrations of O_2. This inhibition is called the *Warburg effect,* and occurs in all C_3 species. In contrast, respiration of C_4 plants such as corn do not exhibit this effect. During darkness, C_3 plants respire at a rate that is about 1/6 the rate of photosynthesis, yet in the light they respire much faster than in the darkness. It was eventually understood that the difference was caused by respiration that occurred only in the light. Respiration that occurs both in the light and in the dark is call *dark respiration,* and it is not dependent on light. Respiration occurring only in the light is called *light respiration.*

Wheat is a C_3 plant and its light and dark respiration patterns are similar to all C_3 plants. Carbon dioxide release, respiration, is three or more times higher in the light than in the dark (Table 7.3).

Because of the work of Hatch and Slack (1966, 1968), nonsucculant plants were eventually classified as C_3- and C_4-pathway plants. This designation refers to the first measurable product of the photosynthetic reaction. Those plants that form a 3-carbon acid are called C_3 plants. Examples are many of the perennial forages, such as alfalfa, birdsfoot trefoil, clovers, orchardgrass, smooth bromegrass, and so on, used in temperate regions. Plants such as corn, sorghum, millet, bermudagrass, and all tropical grasses are C_4 plants, and the first measurable product of photosynthesis is a 4-carbon acid. Some North American grasses such as the bluestems and others are in the C_4 classification.

Carbon-4 plants have the following common characteristics: (1) a second pathway and enzyme system for effecting photosynthesis, (2) more efficient photosynthetically, (3) generally show more drought tolerance than do C_3 plants, (4) water use efficiency is higher than in C_3 plants, and (5) *Kranz anatomy,* which is characterized by large rings of bundle-sheath cells separated by two or three mesophyll cells, small intercellular spaces, and fre-

TABLE 7.3 Uptake and Release of CO_2 by Wheat Leaves

		mg CO_2 hr^{-1} (g fresh wt)$^{-1}$	
Expt. no.	Experimental conditions	Uptake $^{14}CO_2$	Release $^{12}CO_2$
1	Dark	0.06 ± 0.37	0.06 ± 0.41
	Light	3.73 ± 0.29	0.95 ± 0.33
2	Dark	0.57 ± 0.23	0.64 ± 0.29
	Light	4.40 ± 0.18	1.67 ± 0.20

Source: Krafkau *et al.,* 1958.

quent veins. The bundle-sheath cells possess a high concentration of chlorophyll (Bidwell, 1979). This is in contrast to the leaf anatomy of a C_3 plant, which has loosely structured spongy parenchyma and palisade cell layers and the translocatory bundles (xylem and phloem) are separated by up to 20 mesophyll cells (Crookston and Moss, 1974). The palisade cells contain high concentrations of chlorophyll.

IV. PHOTORESPIRATION

Plants classified as belonging to the C_3 category exhibit a phenomenon called *photorespiration.* This phenomenon is not readily apparent in C_4 plants and is only measurable when intercellular CO_2 is limited by stress (Dai *et al.,* 1993). Photorespiration is a process that requires light (it occurs only in the light) and is defined as the respiration of the immediate products of photosynthesis. The carbon respired in this manner is lost to the atmosphere, and the process is of no apparent use to the plant. Approximately 30 to 35% of the carbon fixed by C_3 plants is lost in this manner, depending on the particular plant. Thus, yields of C_3 plants are reduced by about 30 to 35%. However, the C_4 crops such as corn, sorghum, and the tropical grasses, which have both the C_3 and C_4 pathways, do not exhibit photorespiration. The CO_2 that may be released in this process is evidently recaptured for further cycling by the plant; photorespiration is prevented by the increased concentration of CO_2 in the cells which carry out the C_3 photosynthetic process.

For further discussion of this subject, the reader is referred to any recently published plant physiology textbook.

V. CARBOHYDRATES

The fate of carbohydrates produced in the photosynthetic process is controlled by the plant's current stage of development. The products of photosynthesis may be disposed of in one or more of the following ways: (1) utilized in maintenance respiration, (2) translocated to actively growing sites and utilized in growth, or (3) translocated to storage organs such as developing fruits or seeds, stems, crowns, roots, or tubers, depending on the plant, for storage. There may be competition for carbohydrates from more than one or two of these sites at the same time.

A. PARTITIONING

Partitioning of the photosynthate is determined by the source–sink relationships existing at a given time in the development of the plant. The source is the photosynthetically active tissues of the plant. Sinks may be sites with active meristematic tissues or storage organs. During periods of early vegetative growth, much of the photosynthate produced is utilized to sustain growth, but as the leaf area increases to the point that assimilate production exceeds the demand by the immediate sinks, other sinks come into the picture. Actively growing red and white clover plants translocated much of the photosynthate to the roots regardless of whether the plants were nodulated or whether the N source was from the nutrient solution (Ryle *et al.,* 1981b). The growing leaves imported 4% of the shoot's assimilate in white clover, compared to 16% in red clover (Ryle *et al.,* 1981a). Branches in red clover and stolons in white clover were the strongest sinks for photosynthate, importing 39 and 63% of the labeled CO_2, respectively. Older leaves in these studies translocated more of their photosynthate to branches or stolons than did the younger leaves, an attestation of the strength and importance of sink proximity in source–sink relationships. Position of the leaf on the plant with respect to a fruiting body also controls destination of the photosynthate. For example, it is known that photosynthate from lower leaves translocates relatively more to the roots and underground storage organs (Salisbury and Ross, 1992). However, leaves in close proximity to developing fruits translocate more to that sink than to sinks farther away (Ryle, 1970; Cook and Evans, 1978; Horrocks *et al,* 1978; Boller and Heichel, 1983; Cralle and Heichel, 1985). The size of the sink also controls the amount of photosynthate received (Cook and Evans, 1978). The movement of ^{14}C-labeled assimilate from the youngest leaves of ryegrass plants was studied by Ryle (1970). During early vegetative growth, the terminal meristem, tillers, and roots received most of the labeled assimilate. With aging, less assimilate was translocated to the roots. As stems became important sinks for assimilate, less was transported to the tillers and much less to the roots. Thus, sink demand is important in determining the destination of carbohydrates. Transition from the vegetative to the reproductive stage of development marked an abrupt increase in ^{14}C moving to the stem from upper leaves. Immediately before ear or head emergence, export from the flag leaf to the stem declines, and there is an increase in transport to the developing kernels (Ryle, 1970). Water stress in alfalfa has been shown to increase partitioning of carbohydrates to the roots (Hall *et al.,* 1988).

It is known that when sink demand is low, sucrose accumulates in the leaves, causing an inhibition of photosynthesis (Wardlaw and Eckhardt, 1987). It is proposed that a buildup of sucrose in the cells leads to synthesis of fructose-2,6-bisphosphate, a regulator of sucrose synthesis and photosynthesis (Foyer, 1987; Stitt, 1986), which indicates that the enzyme is not being utilized at the time. For further discussion of this process, the reader is referred to a current text on plant physiology.

The rate of translocation from the leaves also varies with species. The warm-season, C_4 crops are reported to export 70% or more of the assimilated ^{14}C during the first 6 h after assimilation, whereas values for C_3 crops are in the range of 45 to 50% (Hofstra and Nelson, 1969). Gallaher *et al.* (1975) studied translocation rates from CO_2-fixing sites in C_4 and C_3 species of *Panicum* and found that the C_4 species, *P. maxicum* L., had a 100% greater translocation rate than did the C_3 species, *P. miloides.* They also reported that the C_4 species had 96% more cross-sectional area for translocation.

B. STORAGE

Carbohydrates are stored by all plants used as forage crops. For example, the grasses generally store carbohydrates in the stem bases and, to a degree, in the fleshier roots; alfalfa in the crown and in the roots; and corn and sorghum in the stems or stalks and the fleshier, shallow roots. Some corn and sorghum hybrids are known as high sugar cultivars, and sugar concentrations in the stems may reach approximately 15 to 18% (Van Reen and Singleton, 1952; Widstrom *et al.,* 1988).

The leguminous crops and warm-season or tropical grasses that have been studied generally store the majority of their carbohydrates as starch, whereas cool-season grasses (Hordeae, Aveneae, and Festuceae tribes) store their carbohydrates as fructosans (Walton, 1983; Smith *et al.,* 1986; Table 7.4).

C. UTILIZATION OF STORED CARBOHYDRATES

Height of clipping is more important for some forages than for others. For example, under normal hay-cutting schedules in which greater than 30

TABLE 7.4 Types and Concentrations of Stored Carbohydrates in Common Forage Crops

Plant carbohydrates	*Examples*
Monosaccharides ($C_6H_{12}O_6$)	Glucose, fructose
Disaccharides ($C_{12}H_{22}O_{11}$)	Sucrose, maltose
Polysaccharides ($(C_6H_{10}O_5)_n$)	Starch (glucose polymers), including amylose and pectin Fructosan (fructose polymers), including inulins and Levans
Type of forage	*Carbohydrates accumulated*
Tropical and subtropical grasses	Starch
Temperate cultivated grasses	Fructosans
Native North American grasses	Starch
Alfalfa	Starch

Sources: Walton, 1983; Smith, 1986.

to 35 days mark each regrowth interval, alfalfa is not seriously influenced by cutting height. Such cutting schedules encourage adequate production of crown buds. However, frequent cutting systems are deleterious to bud formation, and clipping height therefore has a significant effect on regrowth (Langer and Steinke, 1965). Higher clipping heights provide sites for more axillary buds as well as leaf area that can, although it will not be as efficient as newly formed leaves (Pearce *et al.,* 1968), begin immediate production of assimilate. In birdsfoot trefoil, a higher proportion of the regrowth comes from stem axillary buds. The removal of these axillary buds through defoliation thus retards regrowth.

Grasses are generally more susceptible than alfalfa to close defoliation. To maximize production of forage from grasses, the height of defoliation is critical because too much leaf area is removed by lower clipping heights and regrowth rates and yields are substantially reduced. In forage grasses, the height of cutting or grazing has a considerable effect on radiation interception and rate of regrowth. For example, 4 days after defoliation, Brougham (1958) demonstrated that perennial ryegrass defoliated at 12.7 cm (5 in.) was intercepting nearly 100% of the total incident radiation, whereas if defoliated at 7.6 cm (3 in.), approximately 70% was intercepted by the crop canopy, and at a 2.5 cm (1 in.) defoliation height, only about 16% was being intercepted (Fig. 7.9).

Reed canarygrass clipped at a stubble height of 10 to 13 cm (4–5 in.) regrew more rapidly than when clipped at 4 to 5 cm (1.5–2 in.; Davis, 1960). Leaving a shorter stubble height, if practiced over an extended period of time, results in reduced levels of stored reserves and less vigorous plants (Decker *et al.,* 1967). As the frequency of cutting orchardgrass increases,

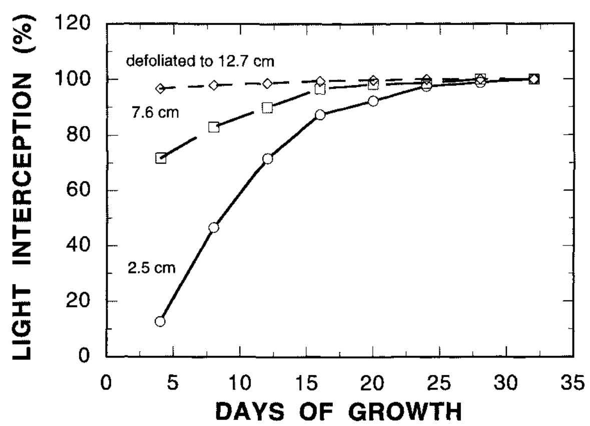


FIGURE 7.9 Percentage of light intercepted above the 2.54-cm level (above the soil and to the top of the canopy) in a grass canopy, harvested at three different cutting heights. (Redrawn from Brougham, 1958).

higher stubble heights are of increasing importance (Davidson and Milthorpe, 1965; Reynolds *et al.*, 1971).

Walton (1983) reported that the growth rate of forage grasses, smooth bromegrass and orchardgrass, was the same after clipping or grazing regardless of the clipping height. Biomass was produced at the same rate whether the clipping height was 2, 5, or 10 cm. At the end of a 25-day growth period, however, the total biomass produced was significantly more for plants clipped at a height of 10 cm than for plants clipped at a height of 2 cm (100% more for bromegrass and 25% more for orchardgrass). He also reported a similar response for each species if regrowth was begun from plants with a high level (23%) of stored carbohydrates compared to plants with a low level (10%) of stored carbohydrates. Regardless of the level stored, the growth rates for the 25-day growth period were identical for each species, but total biomass produced differed significantly (76% more for smooth bromegrass and 25% more for orchardgrass). Smooth bromegrass, orchardgrass, reed canarygrass, and meadow bromegrass respond similarly to clipping height, and they are representative of most cool-season perennial forage grasses.

In grasses, a high proportion of the carbohydrates used in regrowth after defoliation is stored in the lower stems and in the stem bases. The greater the tendency for a particular grass to store high concentrations of carbohydrates in the lower stems and stem bases, the more important it is to pay attention to clipping height. Low clipping heights retard growth initially, and the difference in resulting dry matter is maintained through the growth cycle. In comparison, alfalfa contains more than 50% of its nonstructural carbohydrates in the top 10 cm of the tap root (Escalada and Smith, 1972), and the majority of new stems are formed from root crown buds; thus, clipping height is not usually critical. However, birdsfoot trefoil regrowth comes largely from axial buds; thus, clipping height can greatly influence subsequent yields.

Growth conditions that favor storage of higher levels of carbohydrates in the lower stem or stem bases of grasses and in the crowns and roots of legumes result in more rapid rates of spring and aftermath growth and greater dry-matter production. Spring growth of alfalfa is retarded significantly if insufficient carbohydrates have been stored in the crowns and roots the previous autumn (Table 7.5). Grasses in temperate regions accumulate carbohydrates until growth ceases with the onset of winter. For example, timothy and orchardgrass grown in Pennsylvania, depending on the cutting management, will accrue up to 20% total nonstructural carbohydrates (TNC) by the first week in November (Mislevy *et al.*, 1978). In this study, if the aftermath was clipped at a height of 10 to 15 cm (4–6 in.) vs. 41 to 46 cm (16–18 in.), the TNC concentrations at the end of the season were 15% and 20%, respectively. Although orchardgrass maintained a signifi-

TABLE 7.5 Influence of Previous Season Fall Management on Spring Growth and First Harvest Yields of Alfalfa

	Year			
Date of final harvest	1987	1988	1989	Stand rating[a]
8/20 (3 cuts)	2.7	4.0	4.2	6.8
9/2 (4 cuts)	3.0	1.9	2.5	6.5
9/16 (4 cuts)	3.1	1.6	2.5	5.7*
9/30 (4 cuts)	3.2	2.0	2.7	6.4
10/13 (4 cuts)	3.3	2.9	3.2	6.8
10/27 (4 cuts)	3.6	3.0	3.4	6.9
Mean	3.3	2.6	3.1	6.5
LSD (0.05)		0.86[b]		0.8

Source: Horrocks and Zaifnejad, 1997.

LSD, Least significant difference.

[a] Visual score: 0 = no alfalfa cover of soil surface; 10 = 100% cover.

[b] Valid for comparison within the 1987–1989 fall treatment X year interaction.

cantly lower TNC concentration throughout the growing season, orchardgrass and timothy stored equal amounts going into the winter.

After harvesting alfalfa that is growing under normal conditions, approximately 20 days is required before the canopy is sufficient to begin rebuilding the storage of carbohydrates by the allocations of carbohydrates to the roots. From then until 47 days after harvest, carbohydrate storage accrues at approximately 1.4% per day (Escalada and Smith, 1972).

Growth in forages occurs in three phases. The first phase is very slow while the leaf area required for rapid growth is being developed. The second phase is a linear phase in which dry matter accumulation is very rapid. The third phase is after the linear phase has ceased, the genetic capacity of the crop has been reached, and the leaves are beginning to senesce.

D. CARBOHYDRATES AND STAND MANAGEMENT

Beginning in the 1920's, researchers in the northcentral United States showed that proper timing of cutting during the months of September and October is critical to maintaining vigorous, productive stands of alfalfa (Graber *et al.*, 1927; Grandfield, 1935). Graber and coworkers (1927) reported that continual cutting of alfalfa at immature stages of development lowers the productivity and vigor of plants, favors weed encroachment, and accelerates both winter and summer damage to stands. They also suggested that these deleterious effects were associated with depleted food reserves in the roots. Further work was done on this in the late 1950s (Smith, 1962) that emphasized the importance of maintaining plant health and vigor by allowing optimum fall storage of TNC in the crown and roots of alfalfa (Grandfield, 1935; Kust and Smith, 1961; Smith, 1962; Chatterton *et al.*, 1977).

Later work (Tesar and Yager, 1985; Sheaffer *et al.*, 1986) demonstrated that management during the season (i.e., the stage of development at which each crop is removed) and soil K^+ concentrations could ameliorate the effect of fall management. Adequate levels of K^+ reduced the deleterious effect of fall management. Allowing the crop to reach the beginning-flower stage once during the growing season also reduced the effect of fall management (Tesar and Yager, 1985; Horrocks and Zaifnejad, 1997).

The work of Smith (1962) is most definitive when it comes to the relationship of TNC storage, plant regrowth, and survival. The general pattern for TNC accumulation in an uncut stand of alfalfa shows a decline as spring growth begins, which lasts until the plant is 15 to 20 cm (6–8 in.) tall. This is followed by a continual increase until the plant reaches full bloom, and then a decline until the seeds are mature (Fig. 7.10). When alfalfa is harvested for hay, the increase in root–crown TNC ceases and there is a decline until the plant reaches 15 to 20 cm in height. With each harvest this pattern is repeated (Fig. 7.11).

Removing the last harvest of the season can be deleterious to subsequent yields and stand persistence and results in increased weed encroachment. The optimum time to take the last harvest in the fall is approximately 45

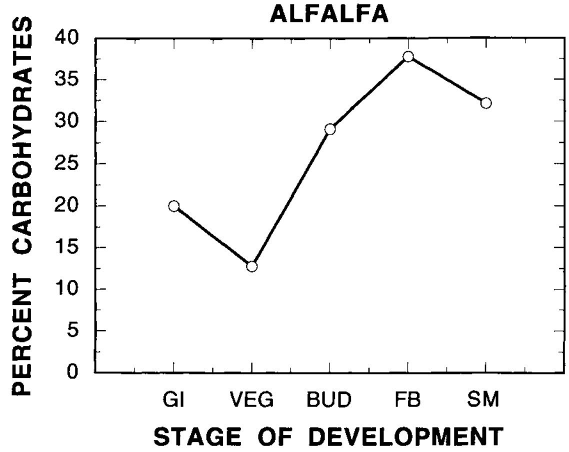


FIGURE 7.10 Changes in the percentage of total nonstructural carbohydrates (TNC) in the roots of alfalfa from the initiation of growth in the spring to the stage of seed formation. GI, growth initiation; VEG, vegetative, 15–20 cm height; BUD, bud stage; FB, full bloom; SM, seed mature. (Redrawn from Smith, Bula, and Walgenbach, 1986).

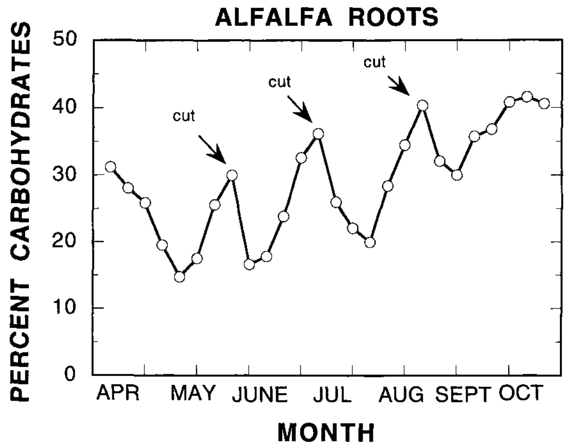


FIGURE 7.11 Changes in total nonstructural carbohydrates in the roots, crown (stubble), and top growth of alfalfa during a season with three early flower harvests—3 June, 16 July, and 25 August. (Redrawn from Smith, Bula, and Walgenbach, 1986).

days prior to the mean average-killing-frost date (Tesar and Yager, 1985; Sheaffer *et al.*, 1986, 1988; Welty *et al.*, 1988; Horrocks and Zaifnejad, 1997).

As one moves from the temperate areas that experience harsh winters to winter climates that are more mild, the effect of harvesting in the critical period is less pronounced. In fact, Sholar *et al.* (1983), in an Oklahoma study, reported that there were no significant differences in first-harvest or total yields regardless of the time of removal of the final harvest each year. Therefore, they concluded that harvesting could occur at any time during the fall period. Likewise, Reynolds (1971) in Tennessee and Brown *et al.* (1990) in Georgia, did not find a significant positive correlation between TNC at the end of the second year of production and yield during the third year. Reynolds did, however, find that yields during the third year of his Tennessee study were significantly lower with more frequent harvesting (5 or 6 harvests per season). Two, three, and four harvests per season treatments produced an average of 8.36 Mg ha^{-1} (3.73 t $acre^{-1}$), with a standard deviation of 0.49 Mg ha^{-1} (0.22 t $acre^{-1}$). The fact that there was little or no effect of fall harvest treatment may be due to the presence of green leaves during the late autumn and winter at these locations as well as the more mild temperatures. Similar reasons were suggested by Mays and Evans (1973) for stable carbohydrate concentrations in Alabama. Finally, Collins and Taylor (1980) reported that late harvesting in Kentucky was less detrimental to alfalfa than were similar treatments in more northerly areas of the United States. There appears to be ample evidence to support this conclusion.

This Page Intentionally Left Blank

8

CULTIVAR SELECTION

I. INTRODUCTION

Many crops used for hay production have received little attention when it comes to developing improved cultivars. Alfalfa (*Medicago* spp.) has received the most attention of all the perennial forage crops from plant breeders. The true clovers (*Trifolium* spp.) and the grasses, both perennial and annual types, have received limited attention from plant breeders. In general, however, where plant breeding work has occurred, the released cultivars are usually superior to cultivars used earlier, largely because of increased pest tolerance. Thus, it is to the grower's advantage to spend the time required to identify these improved cultivars, regardless of the crop being grown, because increased yield and stand longevity are the usual result.

The selection of a cultivar for forage production should consider several important criteria: (1) disease and pest resistance, (2) adaptation to environmental and soil conditions, (3) yield potential, (4) intended use (hay, pasture, etc.), and (5) stand longevity. A good description of cultivars of the various forage types is found in Heath *et al.* (1985). Birdsfoot trefoil (*Lotus* *corniculatus* L.) and its adaptation, characteristics, and uses are discussed by Seaney and Henson (1970).

II. LEGUMES

A. ALFALFA

Prior to 1955, there were only 33 alfalfa cultivars grown in the United States and Canada (Melton *et al.,* 1988). From 1956 through 1975 the number increased to about 160 cultivars (Barnes *et al.,* 1977). Even more dramatic increases in number of cultivars occurred between 1978 and 1983, when more than 400 cultivars or brands were offered for sale in the U.S. and Canadian seed markets (Miller and Melton, 1983). Passage of the Plant Protection Act in 1970 assured the entrance of private plant breeders into the arena, and the proprietary proportion of the cultivars released each year thereafter increased dramatically. Privately developed cultivars made up 20% of the total during the period from 1956 to 1960, and 92% during the period from 1981 to 1985. The Certified Alfalfa Seed Council listed 256 cultivars in 1998, of which only 15 (5.9%) were publicly developed (CASC, 1998).

Alfalfa cultivars have changed dramatically since the early to mid-1970s. Continued development work by plant breeders, both public (at universities and the USDA) and private, has improved pest tolerance and resistance. The net effect of this is a general increase in yielding ability of today's cultivars when compared to cultivars used before the 1970s. Hill and Kalton (1976) estimated that total genetic yield improvement in alfalfa between 1956 and 1974 was only 3%. Other researchers have estimated a similar rate of improvement for this period (Elliott *et al.,* 1972). Hill *et al.* (1988) estimated that improvements in alfalfa since 1971 have averaged about 0.25% per year over the standard check cultivar (Vernal). This is small when compared to crops such as corn, in which the estimated increase in yield between 1939 and 1970 was 1 bushel per year per acre due to fertilizer use and other such technology and 1.5 bushels per year per acre due to genetic improvement (Horrocks and Zuber, unpublished data, 1972). Tollenaar (1989) has demonstrated similar yield gain for maize during the period from 1959 to 1988 in Ontario, Canada.

There are a number of reasons for the slower rate of improvement in forage crops, among which is the perennial nature of most forages and the diversity with which a forage-plant breeder must work. Wheat breeders work on wheat or closely related cereal species, corn breeders work on corn (maize), but forage breeders may well be working on multiple forage species. The perennial nature of most forage crops contributes factors that must be considered that affect winter survival and storage of photosynthates for production of the next crop. Experimental strains must be evaluated for a number of years before decisions can be made in a selection program; this makes it virtually impossible to obtain gains per cycle equivalent to those attained in annual crops. The desirable portion of the crop is the vegetative material, and storage of carbohydrate cannot then be diverted by manipulation to the storage organ as in annual crops (Evans, 1980). Finally, much of the improvement effort has been directed at increasing pest resistance, which may indeed be counterproductive in producing greater genetic yield potential (Hill *et al.*, 1988). However, dramatic yield increases can be achieved by incorporating pest resistance into new cultivars. Annual losses to diseases and nematodes in the U.S. hay crop are approximately 10% annually, or about $500 million (Elgin *et al.*, 1988); thus, much of the breeding effort has been directed at pest resistance or tolerance.

In a successful management program, the selection of the proper cultivars for existing conditions is of major importance. Through the years, as alfalfa has been grown in more diverse areas, new pests have arisen. First it was bacterial wilt (Elling and Frosheiser, 1960; Elgin *et al.*, 1988) and alfalfa weevil, both of which were devastating to production each year. Others soon followed, such as phytophthora root rot, stem nematode, and verticillium wilt, to name those most important in the Intermountain West. In other parts of the United States, notably the Midwest and the Northeast, other pests have become problems: anthracnose, spotted alfalfa leaf aphid, pea aphid, and leafhoppers. The southeastern United States, in which more and more alfalfa is being grown, and the southwestern desert areas of New Mexico, Arizona, and California, have their unique pest problems. The net effect of all these pests is the weakening of the stand, nonvigorous growth, greater susceptibility to other pests, winter kill, lower yields, and generally poor performance.

Control of these pests is achieved in various ways: application of pesticides, cultivar resistance, and biological control in integrated pest-management systems. The best control, both from the economic and the environmental aspect, is achieved with cultivar resistance. Of the pests listed, cultivar resistance has been achieved, at least to some degree, in all cases except alfalfa weevil. Control of this pest is obtained by using a combination of biological predators, insecticide application, and management in which the time of the last fall harvest is varied.

It is quite difficult to bring all the information together so that one can make an intelligent decision, one based on reliable information, about which cultivar to grow. A good source of information about characteristics of alfalfa cultivars is published annually by the Certified Alfalfa Seed Council (CASC, 1998). This publication provides vital information about characteristics of alfalfa cultivars: cultivar name, developer and/or contact for marketing information, and information on fall dormancy (FD), bacterial

TABLE 8.1 Classification Codes Used in Characterizing Alfalfa Cultivars with Respect to Their Response to Fall Dormancy

Category	**Range of response**
Fall dormancy	1–10
Check cultivars	**Dormancy rating**[a]
Norseman	1
Vernal	2
Ranger	3
Saranac	4
DuPuits	5
Lahontan	6
Mesilla	7
Moapa 69	8
CUF 101	9

[a] 1 = most dormant; 9 = least dormant.
Source: CASC, 1998.

wilt (BW), verticillium wilt (VW), fusarium wilt (FW), anthracnose (An), phytophthora root rot (PRR), spotted alfalfa aphid (SAA), pea aphid (PA), blue alfalfa aphid (BAA), stem nematode (SN), and root knot nematode (RKN). Each cultivar is classified according to the information shown in Tables 8.1 and 8.2.

It is important to recognize that resistance (R) means that only 31 to 50% of the plants show resistance to a particular pest. The same is true, of course, for respective values in the other categories. This, however, provides good tolerance and control of a disease because of the planting rates. Even if half of the plants die because of infection or infestation with the pest, the half remaining will be more than sufficient to produce high yields. Once

TABLE 8.2 Definition of Codes Used to Indicate Cultivar Response to Various Diseases, Nematodes, and Insects

Resistance class	Resistant plants (%)[a]
S—Susceptible	0–5
LR—Low resistance	6–14
MR—Moderate resistance	15–30
R—Resistance	31–50
HR—High resistance	>50

[a] Ratings are rounded to the nearest percent.
Source: CASC, 1998.

a stand is established, even under conditions in which no pests are present, the number of plants per unit area will decrease by as much as 70% within 3 years. The size of the individual plants increases, with each plant producing more stems; thus, the effective population is relatively stable from the seeding year through the third, fourth, or fifth year of the stand.

Losses from disease, nematode, and insect pests of alfalfa are not always well documented. In cases in which the pest is endemic (never reaches epidemic proportions, but is always present), this uncertainty is especially so. The leaf and stem diseases, of which there are many, fall into this category. However, there is work that shows the impact of some endemic pests on yield. For example, Elgin *et al.* (1981) demonstrated that An decreased alfalfa yield, in the central and northern humid regions of the United States by about 10% on the average each year. Several studies have documented yield losses associated with potato leafhopper feeding. Infested plots showed a reduction in leaf area of 15 to 67%, and overall biomass was reduced by 27 to 61% (Hutchins and Pedigo, 1989; Hutchins *et al.*, 1989; Hower and Flinn, 1986; Faris *et al.*, 1981). Leaf protein concentration was down by about 8.2%; stem protein was enhanced by about 9%. Neutral detergent fiber (NDF) of the whole plant was not affected by leafhopper feeding. Verticillium wilt has also been shown to cause yield losses even in first- and second-year alfalfa, long before its devastating influence becomes obvious (Papadopoulos *et al.*, 1989; Arny and Grau, 1985; Christen and Peaden, 1981; Heale and Isaac, 1963). Fifty-six percent of the yield variation in infected plants was due to VW. Pennypacker *et al.* (1988) found VW markedly reduces flowering of alfalfa, and, consequently, predicted a reduction in seed yield. Until just recently, resistance to this disease has been insufficient to maintain desirable yield levels for the desired number of seasons (Busch and Smith, 1981). A number of new cultivars, that have been released during the past several years have good VW resistance (CASC, 1998). Plant-breeding activity has progressed at a significant rate in developing breeding lines with glandular hairs that have the potential for multiple pest resistance (Sorensen *et al.*, 1986).

Reid and coworkers (1989) showed that, in areas in which milder winters are the rule, the less winter-dormant cultivars harbored a greater number of alfalfa weevil larvae than did the winter-hardy types. An excellent publication summarizing the weevil story and providing tips on how to manage to control the weevil is available from the CASC (Wilson, 1984).

Cold tolerance or cold hardiness refers to the ability of a plant to survive the effects of freezing temperature stress. Winter hardiness, however, involves the ability of plants to survive all factors influencing survival during the winter. This includes freezing temperatures, diseases, insects, moisture, and so on. The total overwintering complex cannot be neglected, however, in discussions on cold tolerance because temperature stresses that are insufficient to kill the plant may still weaken it and make the plant more susceptible to other winter stresses.

Increases in the winter hardiness of alfalfa have been derived primarily from the hybridization of *M. sativa* with *M. falcata.* Although improved disease and pest resistance have significantly increased winter survival in many areas, resistance to cold temperature stress is by far the most important component of the winter-hardiness complex in northern latitudes. During midsummer, alfalfa cannot survive freezing temperatures below −2 to −5°C, but during the fall hardening period, changes occur within the plant, called *hardening,* to enable the roots and crowns to survive temperatures as low as −20°C. Alfalfa undergoes biochemical, biophysical, and morphological changes in the fall that increase tolerance to low temperature stresses. The overwintering behavior of plants is determined by factors such as time of initiation of hardening, rate of hardening, maximum midwinter-hardiness level, hardiness stability under widely fluctuating conditions in midwinter, and time that dehardening occurs in the spring. These parameters are under complex genetic and environmental control.

Fall dormancy is generally equated with winter hardiness by growers and researchers. However, dormancy and winter hardiness are not necessarily the same. Alfalfa cultivars may have a higher fall dormancy rating (i.e., less dormant) and still be as winter hardy as cultivars with a lower dormancy rating (Busbice and Wilsie, 1965). Some of the new cultivars may have a fall dormancy rating of 5 or 6 (Table 8.1) and still have considerable winter hardiness. This trait is highly variable and depends on the parentage of the cultivar. Thus, one should be careful in assessing this relationship because some cultivars with similar ratings will not have sufficient winter hardiness.

B. CLOVERS

Of the true clovers, red clover (*Trifolium pratense* L.) and white clover (*T. repens* L.) are the most important ones used for hay or silage. When considering both grazing and mechanical harvesting, red clover is one of the most important legumes in the world (Smith *et al.,* 1985). Prominent red clover cultivars used in the United States are ‘Arlington’ and ‘Kenstar’ (Smith *et al.,* 1985). Cultivars released by private companies are ‘Florie,’ ‘Florex,’ ‘Prosper I,’ ‘Redland,’ ‘Redmand,’ ‘Redmor,’ ‘Ruby,’ and ‘Tristan.’ Other cultivars adapted to northern areas of the United States are ‘Lakeland,’ ‘Ottawa,’ ‘Bytown,’ and ‘Norlac.’

White clover is widely distributed throughout the world, in the arctic, high elevations, and tropical sites, but grows best in humid sections of the temperate zone during cool, moist seasons. White clover is classified as small, intermediate, and large (Gibson and Cope, 1985). The large type is called *Ladino clover* and was introduced into the United States from Italy in the early 1900s. The number of white clover cultivars is far fewer than the number developed in alfalfa. The first large type released in the United States was 'Pilgrim.' Others followed from the U.S. program that were called 'Merit,' 'Regal,' and 'Tilman' (Gibson and Cope, 1985).

Often cultivars of both red and white clovers are simply referred to as 'common,' meaning that seed was grown locally or that the cultivar is not known.

Other clovers of importance in some areas are subterranean clover (Morley, 1961) and arrowleaf clover (Hoveland *et al.*, 1969). Kura clover (*Trifolium ambiguum* M. Bieb.) is a recent introduction that shows considerable promise in pastures (Sheaffer *et al.,* 1992).

III. GRASSES

Perennial grasses important as harvested forages have received a variable amount of attention with respect to developing superior cultivars. Genera receiving the most attention are those most used as hay or pasture crops: perennial ryegrass (*Lolium perenne* L.) in Western Europe, the British Isles, New Zealand, and, more recently the United States; orchardgrass (*Dactylis glomerata* L.); tall fescue (*Festuca arundinacea* Schreb.); and smooth bromegrass (*Bromus inermis* L.) in North America (Harlan, 1983). Bermudagrass (*Cynodon dactylon* (L.) Pers.) is the tropical grass to receive the most attention from plant breeders.

Smooth bromegrass cultivars are divided into three classes: northern, intermediate, and southern. They differ in many aspects: seedling vigor, stand establishment, aftermath and total forage yield, seasonal distribution of yield, disease resistance, persistence, forage quality, and seed yield and quality (Carlson and Newell, 1985). Smooth bromegrass is used for both hay, grown alone or in conjunction with a legume, and pasture. The northern type is adapted to the northern Great Plains, western Canada, and Alaska. Southern smooth bromegrass is best suited for conditions encountered in the central Great Plains, Corn Belt, and the northeastern United States and Canada.

Most cultivars of smooth bromegrass available in the United States have been developed in the northcentral states region of the U.S. The oldest developed cultivars are Lincoln (Nebraska) and Achenbach (Kansas). 'Lyon' was a later development from Lincoln. 'Sac' was developed in Wisconsin and is very high in resistance to brown leaf spot (*Helminthosporium bromi*). Efforts in forage improvement in Iowa have resulted in 'Baylor,' 'Blair,' 'Barton,' and 'Beacon' as proprietary releases (Carlson and Newell, 1985). 'Rebound' was developed in North Dakota by selecting in 'Saratoga,' a cultivar released in New York. The chief characteristic of 'Rebound' is enhanced aftermath production. 'Saratoga' also shows increased aftermath production, and for this reason it is the most important cultivar in the northeastern United States. ‘Carlton’ and ‘Magna’ were developed in Canada after selection for high forage and high seed production.

The key to cultivar selection in smooth bromegrass is to choose cultivars adapted to a specific area and to specific conditions. This is so because of the great deal of variability found in the cultivars representing smooth bromegrass. Carlton, a typical northern type that is well adapted to Canada, does not produce well in conditions encountered in Iowa (Carlson and Wedin, 1974).

Orchardgrass is used as pasture, hay, and silage, and it is grown alone with nitrogen application or with legumes—mainly alfalfa. It is a fast-growing, cool-season perennial that is referred to as ‘cocksfoot’ in Britain. Breeding efforts have concentrated on developing cultivars that flower later than common orchardgrass. Important cultivars are ‘Pennlate,’ ‘Potomac,’ ‘Napier,’ ‘Hallmark,’ and ‘Latar’ (Jung and Baker, 1985).

The genus *Festuca* contains more than 80 species that are adapted to cool or temperate zones (Willis, 1973). Tall fescue is adapted to most of the temperate United States east of the 100th meridian under natural rainfall conditions (Buckner, 1985). It is also well adapted to arid areas if irrigation is available, but its adaptation in the majority of the Intermountain areas is limited by insufficient precipitation (Burns and Chamblee, 1979). The most important cultivars are ‘Kentucky 31’ and ‘Alta’. Other cultivars are ‘Fawn,’ ‘Kenwell,’ ‘Kenmont,’ ‘Johnstone,’ ‘Missouri 96,’ and ‘Triumph.’ ‘Kenhy’ is a hybrid derived from a cross of annual ryegrass and tall fescue (Asay *et al.,* 1979).

Reed canarygrass is often used as hay, pasture, and silage. It is well adapted to temperate zones of the northern United States and it will grow on moist to wet sites in both humid and arid areas. In humid areas where irrigation is not practiced, if unexpected moderate drought is encountered, reed canarygrass adapts quite well. Among the few cultivars developed by plant breeders are ‘Superior’ (Oregon), which is adapted to upland sites, ‘Ioreed’ (Iowa), and ‘Auburn,’ released in Alabama in 1952. From Canada, one leafy cultivar, ‘Frontier,’ was released in 1959. ‘Rise,’ a proprietary cultivar, was released by Rudy–Patrick plant breeders in about 1970. ‘Vantage’ was released in 1972 by Iowa State University, and it possesses better seed retention than does ‘Rise’ (Marten, 1985).

Important cultivars of bermudagrass are ‘Coastal,’ ‘Suwanee,’ ‘Midland,’ and ‘Coastcross-1.’ All of these cultivars were developed in Georgia by G.W. Burton (Burton and Hanna, 1985). A bermudagrass development in Alabama is the cultivar ‘Russell’. It has superior early season yielding ability and is more winter hardy than is ‘Coastal’ (Ball *et al.,* 1996).

IV. CULTIVAR ADAPTATION

In choosing a cultivar, either legume or grass, it is important to match its characteristics with the moisture requirements and tolerance to the

TABLE 8.3 Relative Moisture Adaptation and Soil Tolerance for Selected Forage Species used for Harvested Forages[a]

	Moisture adaptation					Tolerance				
	Good moisture, poor drainage	Good moisture, good drainage	Semimoist	Semidry	Dry	Partial flooding	Severe flooding	Moderate salinity	Severe salinity	Moderate acidity
Legumes										
Alfalfa		X	X	X	X					
Alsike clover	X	X	X			X				
Red clover		X	X							X
Sweet clover		X	X	X	X			X		
Birdsfoot trefoil	X	X	X	X						X
Grasses										
Smooth bromegrass		X	X	X						X
Creeping red fescue	X	X	X							X
Orchardgrass		X	X							
Reed canarygrass	X	X	X			X	X			X
Russian wildrye			X	X	X					X
Tall fescue	X	X	X			X		X	X	X
Timothy	X	X	X			X				X
Crested wheatgrass			X	X	X			X		

Source: Adapted from Walton, 1983, p. 122; with permission from Reston Publishing Company, Inc., a Prentice Hall Company.

conditions in which it will be grown. If the soil is very wet and acid, the grass and or legume adapted to each situation would be quite different than for a site showing well-drained soil. For example, planting alfalfa in an area with poor soil drainage would not be an acceptable alternative, whereas birdsfoot trefoil would be the legume of choice. Likewise, reed canarygrass is well adapted to wet, poorly drained conditions, but smooth bromegrass is not. Environmental and soil adaptations of some of the cool-season forage grasses and legumes used for harvested forages are shown in Table 8.3.

9

ESTABLISHMENT OF FORAGE SPECIES[1]

[1] Recommendations in this chapter are primarily directed to establishing forage crops on mesic sites or irrigated lands. For making range and other dryland seedings in areas of limited precipitation—those receiving less than about 18 in. of average annual precipitation—but with some potential for harvesting for hay, reference to Vallentine (1989) is suggested. On such lands, only a single cutting of hay may be achieved in a given year, and then only in years of highest yields. Hay production on native prairie, mountain meadows, and flood plains may utilize only native vegetation and require no seedbed preparation or stand establishment, or sod seedings may be made of introduced grasses and legumes directly into the native vegetation to improve forage yields and quality.

V. Date of Seeding
VI. Stand Rejuvenation

I. SUCCESSFUL STAND ESTABLISHMENT—A CRITICAL STEP

To establish vigorous, high-producing stands, a forage crop requires significant inputs in the form of money, resources, and time. Economic reality associated with establishment and the necessity of survival dictates that sound management principals and practices be followed. Establishment of a forage stand, whether it is grasses, grass-legume mix, alfalfa, or other legumes, is an expensive proposition when one considers the costs incurred in land preparation, fertilization, liming in areas with acid soils, seed and seeding, weed control, and, in arid areas, irrigation. These costs, of course, vary from location to location and from season to season and according to fertilizer needs of the soil and the extent of seedbed preparation required. Nevertheless, it is expensive enough that the proved principals of successful stand establishment should be applied.

No other aspect of a forage program is so basic and so critical as successful establishment of a stand. Without it, there is no opportunity for high forage yields or production of high-quality forage. Once a stand is successfully established, then many other aspects of management come into play.

Establishing a strong, vigorous forage stand is often the point at which many producers fail, or at least perform inadequately. Because of forage plant seed size and the dynamics of seed germination and seedling establishment, it is critical that certain standards be met if success is to be realized. A prescribed set of procedures must be followed if these standards are to be met. These factors are discussed in the sections that follow.

A. GERMINATION

Three environmental conditions are required for successful seed germination: proper temperature for the crop or species, water, and oxygen. Temperature requirements can be met by planting at the time of year when the mean daily soil temperature is above the minimum cardinal temperature for the species (Chang, 1968). For cool-season species such as alfalfa, oat, wheat, barley, red and white clovers, orchardgrass, bromegrass, timothy, and many other species growing in the same areas as these crops, the optimum temperatures lie between 25 and 31°C (77–87.8°F). Minimum temperatures required for germination range between zero and 5°C (32–41°F). Warm-season grasses such as corn, sorghum, bermudagrass, and most of the forage species grown in subtropical or tropical areas require somewhat higher temperatures: minimum 15 to 18°C (59–64.4°F), optimum

31 to 37°C (87.8–98.6°F). In practice, strictly from the temperature standpoint, seeding may occur in the spring, summer, or autumn in temperate regions and practically any time of the year in the subtropical and tropical settings. However, water must be available through natural precipitation or irrigation; thus, the time of seeding must coincide with the time of season that supplies sufficient water for germination and emergence to occur. During extended dry periods, it is very difficult to meet the water needs of germinating seeds unless irrigation is available. In contrast, waterlogged soils deprive seeds of oxygen, cause failure of germination, and result in conditions that cause anaerobic rot and decay.

Germination begins with imbibition of water and ends with elongation of the radicle, which results in emergence of the radicle from the seed and eventual establishment of the primary root system. Imbibition is initially very rapid for 5 to 30 min, the amount of time depending on the species. After this initial uncontrolled period of water uptake, a linear phase follows that lasts 5 to 10 h (Parrish and Leopold, 1977).

Two patterns of germination and emergence are common among most forage crops. The first, called *epigeal* germination, is exhibited by legumes such as alfalfa, the clovers, the common bean (*Phaseolus* spp.) and soybean (*Glycine max* L.). The cotyledons are brought above ground, thus *epi,* in the emergence process. The second pattern is exhibited by all grasses. It is called *hypogeal* because the cotyledon remains below the surface of the soil (Copeland, 1976).

B. EMERGENCE

It is known that seed size is related to emergence of some small-seeded plants, but in alfalfa it is evident that seed size does not influence seedling stand density (Murphy and Arny, 1939; Cooper *et al.,* 1979). Murphy and Arny (1939) showed that there was no correlation between emergence and seed weight at recommended planting depths for a wide range of forage species. Large-seeded species appear to be able to emerge from deeper planting depths than do the smaller-seeded ones (Murphy and Arny, 1939). This may be related to the fact that larger seeds are capable of exerting more force (Williams, 1956) than are the smaller ones. Subterranean clover, a larger-seeded species, was capable of exerting a force 60× gravity, whereas alfalfa, the smallest-seeded species, was capable of exerting only 15.2× gravity during emergence.

Within a range to which the plants are adapted, plant processes are driven by temperature. Warm temperatures result in very rapid water imbibition, germination, and emergence. However, cool temperatures delay emergence considerably. At very low soil temperatures, or after being subjected to a freeze-thaw sequence and the subsequent cool temperatures, a major proportion of the emergence problems are caused by soil-borne pathogens.

If seeds can be protected from them in some fashion, good germination percentages, even under cool conditions, occur in a number of forage species (Laude, 1956). The major problem is that forage seeds are not routinely treated with fungicides as are corn, soybeans, and some other crops; thus, they are subjected to and not protected from the adverse soil conditions that encourage soil-borne pathogens. Laude (1956) showed that duration of the freeze to which the forage seed is subjected reduces germination. For example, germination of tall fescue was reduced from 80% to 56% when the seeds were subjected to a 6-hour period of freezing. Twelve hours of freezing reduced the germination to 33%. Greater damage occurs if the freeze occurs after water has been imbibed and the germination process has begun. Other small-seeded forage crops suffer similar consequences when subjected to prolonged freezing temperatures.

C. PRESCRIPTION FOR SUCCESS

Once the established root system is of sufficient magnitude to meet the water and nutrient needs of the seedling, one can consider that the establishment process has been successful. Exceptions to this would be cases of extended drought. To assure successful establishment, specific seedbed preparations and planting techniques are critical.

Two cardinal principals of good seedbed preparation are (1) a firm seedbed is a must and (2) soil-seed contact must be achieved for a significant proportion of the seeds planted. The better these two requirements are met, the better will be the established stand, and the lower the seeding rate will need to be. If these two principles are ignored or only given "lip service," the chances of success will be smaller and the required seeding rate will be higher to achieve a heathy, vigorous, competitive forage stand. Excellent forage stands may be established if the protocol discussed in the next section is followed.

II. FERTILIZER REQUIREMENTS

A. SOIL TEST

Before planting the new crop, a soil test should be obtained and the required fertilizer and lime added prior to preparation of the soil. If alfalfa is to be established in humid areas, the lime required to amend the soil to the proper pH should be plowed down. The soil P and K concentrations should be carefully evaluated and the required additions made prior to plowing. All perennial crops, ideally, should have the required lime, P, K, and other elements plowed down rather than applied to the surface after stand establishment or in subsequent years. The amount of fertilizer required for a 4- or 5-year period may be very large in soils that are low in P or K, and full applications may not be economically feasible or possible at the time. Surface application of these elements, especially K, has been shown to be effective if the plow-down alternative cannot be completely followed. Research in a number of places has demonstrated that P can also be applied to the surface to meet the needs of forage crops (Brown, 1935; Hanson and MacGregor, 1966; Hanway *et al.*, 1953; Lawton *et al.*, 1954; Midgeley, 1931; Kroth and Mattas, 1976).

The soil test results may be obtained by submitting the soil samples to any certified laboratory in the area. The report will contain the following information: (1) nutrient concentration of each element specified in the test request; (2) soil pH; (3) electrical conductivity (EC) of soils with a pH greater than 7.0 (if requested); (4) the name of the crop to be planted, as specified in the request; (5) the recommended amount of lime to be added for acid soils to amend the pH of the soil to the optimum range for the designated crop; and (6) the recommended amount of fertilizer to be added to produce optimum growth of the crop to be grown. The use of proper sampling techniques is extremely important if proper results and recommendations are to be achieved. Soil sampling techniques are suggested in Chapter 11.

B. STARTER NITROGEN

In direct or clear seeding, the question most often asked is, "Should nitrogen be used as a starter fertilizer to provide the germinating seedlings with an early boost in growth?" For pure grass stands the answer is yes, but for legumes the answer to this question appears to be mixed. A survey of the U.S. forage-growing areas conducted in 1978 (Hojjati *et al.*, 1978) shows that 28 states did not recommend N application as a starter for pure-legume or legume-grass stands, and 21 states recommended starter N for legumes or legume-grass mixtures (Table 9.1). The general recommendation for N on legumes or legume-grass mixtures ranged from 22 to 67 kg ha^{-1} (20–60 lb acre^{-1}) (Hojjati *et al.*, 1978). Work in Indiana (Rhykerd *et al.*, 1970), Michigan (Tesar, 1984), and Wisconsin (Lee and Smith, 1972) suggests that N is not required as a starter in these areas. Meyer *et al.* (1984) reported similar results in California. Ward and Blazer (1961) demonstrated that the percentage of all legumes in legume-grass mixtures was reduced by addition of N as a starter. After 56 days, however, they showed that seedling weights were significantly higher with greater amount of starter N—up to 90 kg ha^{-1} (80 lb acre^{-1}). The use of 90 kg ha^{-1} of N as a starter not only affected the mix during the seeding year, but also resulted in depressed ladino white clover and red clover yields during the second year (Ward and Blaser, 1961). The general conclusion out of California is that N is normally not required in establishing alfalfa (Marble, unpublished data,

TABLE 9.1 Summary of State[a] Recommendations for N Fertilizer at Planting Time for Legumes and Grass–Legume Mixtures

	Number of responses	
N	Pure legume	Grass–legume mixtures
kg ha-1		
0	19	9
0–22.4	10	5
0–33.6	—	8
0–44.8	7	2
0–56.0	—	4
0–67.3	4	2
No recommendation listed	3	12
Indefinite recommendations	2	3

[a] Data from 45 states responding to inquiry.
Source: Adapted from Hojjati *et al.,* 1978.

1984). Conversely, in the southeastern United States it has been shown that some soils are low enough in N-supplying power for a beneficial response in legume seedling establishment (Mueller *et al.,* 1984). Roth and coworkers (1983) demonstrated that N applied to alfalfa, through the irrigation system the year following seeding on a very fine sandy soil gave a large increase in each of the 10 harvests. Hallock (1976) has shown that NO_3-N applied to the surface of a sandy soil, above the root nodulation zone, resulted in improved growth. However, if applied in the root nodulation zone, at a 25-cm depth, growth was depressed. Munns (1968b) also demonstrated that nitrate was only inhibitive when it was applied to the nodulation zone.

If too much N is applied, however, the rapidity with which the legume establishes the symbiotic relationship with the N-fixing rhizobia will be delayed (Munns, 1968a). Soil NO_3-N concentrations of 50 parts per million (ppm) have been shown to reduce symbiotic N fixation in soybean (*Glycine max* L.) by more than 50% (Musselman, 1978). Percentage nodulation in alfalfa decreased from about 82% with no added N to 47% with 50 ppm, a decline of about 43% (Heichel and Vance, 1979). Nitrogen incorporated into amino acids and protein comes from the fixed-initrogen pool and other soil sources. The ratio ranges from approximately 43% (Heichel *et al.,* 1981) to 62% (Heichel *et al.,* 1984) from the fixed-N pool. Total N fixed during the seeding year ranges from 148 kg ha^{-1} (Heichel *et al.,* 1981) to 177 kg ha^{-1} (Heichel *et al.,* 1984), an amount that cannot be disregarded.

In establishing pure stands of grasses, under mesic conditions found in humid areas, or under irrigation, 56 to 112 kg N ha^{-1} (50–100 lb $acre^{-1}$)

should be applied because grasses cannot extract their own nitrogen from the atmosphere through the process of dinitrogen fixation. Additional N may be required on grasses if optimum yields are to be achieved in the seeding year. Grasses also require annual top dressing to maintain production (see Chapter 11 for further discussion.)

It appears that in situations in which soils are low in N-supplying power, legumes benefit from starter-N fertilizer. Such soils are found under the following conditions: sandy soils with a low cation exchange capacity (CEC); arid soils low in organic matter or high in $CaCO_3$; soils heavily leached by precipitation and highly oxidized (reduced organic matter), as occurs in the subtropic and the tropics; or soils with less than 15 ppm soil nitrate or organic matter concentrations less than 1.5% (Hannaway and Shuler, 1993).

If stand establishment in forage crops is with a companion crop, the N needs of the companion crop are met and the needs of the forage crop are incidental.

III. STAND ESTABLISHMENT

A. SEEDBED PREPARATION

Proper seedbed preparation is vital to successful forage stand establishment. The soil and the planting technique must assure that good soil–seed contact is achieved. If plowed, then the soil should be disked and compacted with a corregated roller before seeding occurs. If no-till planting is practiced, the tilling operation and compaction are applied in a limited area during the planting operation. Precipitation or irrigation of plowed, disked, and harrowed soils may negate the need for compaction prior to planting. In either case, the seedbed must be firm and compact to assure optimum seed–soil contact. A rule-of-thumb for soil surface firmness is to have the soil sufficiently firm that when a person stands on it, the indentation caused by the weight is about 1 cm (approximately 3/8 in.) deep.

B. BROADCAST SEEDING

Broadcast seeding requires that the soil be prepared by clean plowing, disking, harrowing, and (in some cases, but not all) compaction to produce a smooth, firm seedbed. The seed may then be broadcast on the surface using any one of a number of methods. When the seeding is completed, however, the surface must be rolled or compacted with a corregated roller for best results. Dragging a spike-tooth harrow over the field, either while seeding or after it is completed, causes some covering of the seed. Because firmness and a high degree of soil-seed contact may be lacking in this procedure, the percentage of the seeds that result in established seedlings will be reduced. This practice requires a higher seeding rate than do other methods to obtain an equivalent stand. A very good broadcast seeding system has been developed by the Brillion Company (Fig. 9.1) that combines the compacting and seeding operation. The machine is fairly costly, but in a situation in which large areas are being seeded annually, it may be an economical investment. The seed is dropped from the seed box, down between the two sets of corregated rollers. The first or forward set firms the soil originally, the seed is dropped on the surface, and the second set presses the seeds into the soil and firms it further. Broadcast seeding results are equally as good as other methods if this procedure is followed.

C. BAND SEEDING

Another form of seeding was pioneered by Haynes and Thatcher (1950) in Ohio. In this method, all the seed is concentrated immediately above a band containing starter fertilizer—usually phosphorus (P). In this system, the soil must be prepared by plowing, disking, and harrowing. However, unless it is very fine and loose (powdery) on the surface, the precompacting operation may be eliminated. The seed is dropped in a very shallow furrow and either covered with a drag chain or by a compacting wheel that follows each drill row, or a combination of both the drag chain and the compaction

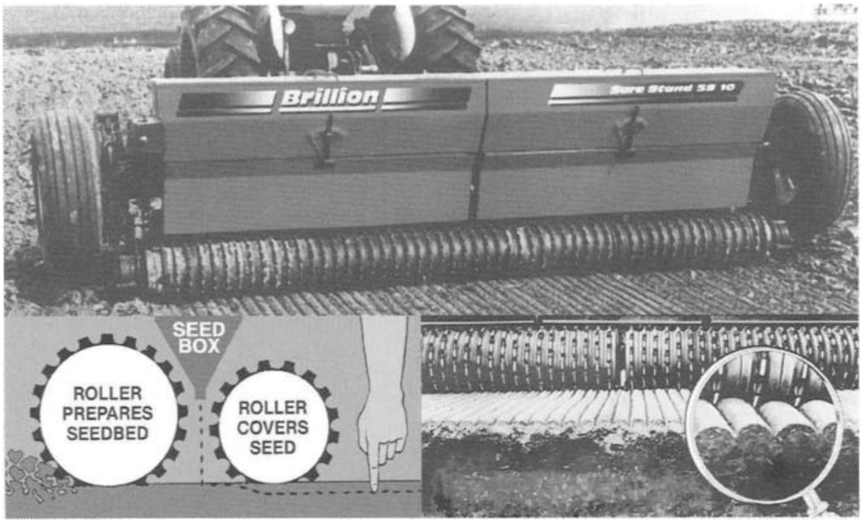


FIGURE 9.1 Use of a cultipacker seeder is an excellent method to establish small-seeded legumes and grasses. The seed is placed in contact with the soil between the front and the rear rollers and covered shallowly as it is pressed into the soil by the rear roller. Fertilizer must be applied with other equipment prior to seeding. (Courtesy of Brillion Iron Works, Inc.)

wheel (Fig. 9.2). Utilization of this technique is not necessary if the soils are high in P.

Because P is so insoluble and the majority of applied P is almost immediately fixed in an unavailable form, to be released slowly later (Brady, 1990), banding has been shown to be advantageous in establishing seedlings of all forage crops. Immediate access to available P for the grass or legume seedling provides rapid, more vigorous, and healthy growth of seedlings (Brown, 1959; Carmer and Jacobs, 1963; Haynes and Thatcher, 1950; Tesar and Marble, 1988). In a review article on alfalfa establishment, Tesar and Marble (1988) reported that band seeding results in more vigorous and rapidly growing seedlings than the seedlings obtained in comparable broadcast seedings. The advantage for banding over broadcasting on several soil types in Michigan ranged from 10% to 60% more seedlings per unit area (Tesar *et al.*, 1954).

The type of fertilizer in the band dictates how close it can be to the seed. If only P is involved, seed and fertilizer may be placed in the same band (Tesar *et al.*, 1954). Regardless of the components of the banded fertilizer, Tesar *et al.* (1954) showed that the fertilizer band, in order to be

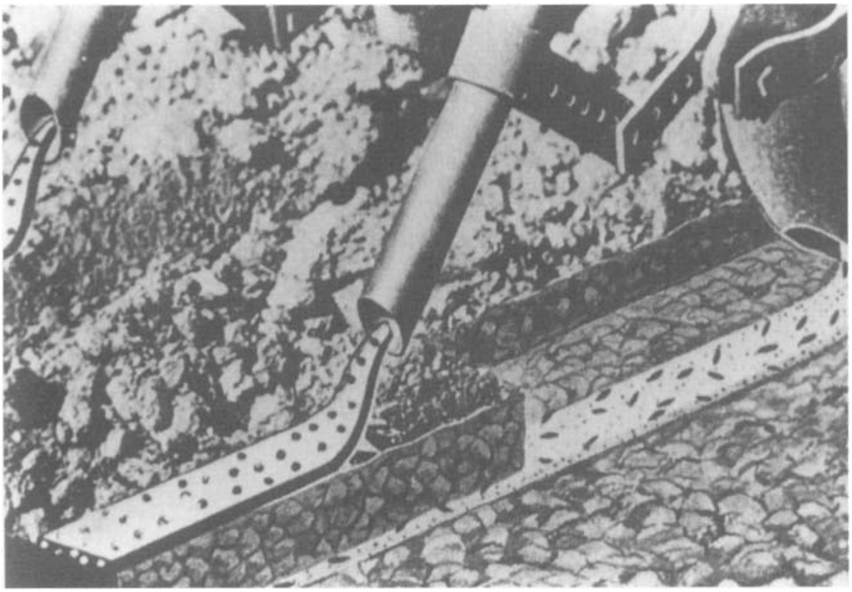


FIGURE 9.2 In band seeding, forage legume or grass seed is placed in a band on or near the surface (0–1.3 cm) directly over a band of fertilizer placed 2.5 to 5 cm deep. The P in the fertilizer stimulates rapid root and seedling growth. (From Tesar and Marble, 1988.)

effective in supplying nutrients to the seedling, however, should be as close as feasible. Seed placed immediately adjacent to a band of P obtained 100% of P from the band. When the band was moved to about 2.5 cm (1 in.) away, 70% of the P came from the band; 5.1 cm (2 in.), 17.5%; 7.6 cm (3 in.), 3%; and 10.2 cm (4 in.), 0%. In 2-month-old seedlings, the percentage of P from the band ranged from 78% at 0 cm to 8% at 10.2 cm (4 in.). This points to the critical nature of band placement with respect to the seed if the band of P is to achieve the purposes for which it was intended. In Connecticut, broadcast and banding showed large differences in favor of banding and in early seedling development, but no differences in later yields (Brown, 1959). When adverse environmental conditions were present, however, Carmer and Jacobs (1963) showed that band placement of seed and fertilizer increased yields, but not when favorable environmental conditions were encountered.

If the band contains N or K, in addition to the P, the fertilizer band should be approximately 2.5 to 3.8 cm (1–1.5 in.) away from the seed band because both N and K are quite soluble and, with water, they form acids that kill the seedlings (Haynes and Thatcher, 1950). For example, Tesar and coworkers (1954) demonstrated that seedling density was reduced significantly if banded fertilizer containing K was placed adjacent to the seed band; for example, alfalfa declined from 19.5 to 6.9 and trefoil declined from 27.2 to 2.9 seedlings per 0.1 m^2 (18.1–6.4 and 25.3–2.7 ft^{-2}, respectively). Haynes and Thatcher (1950) reported an apparently similar, but unquantified, experience.

D. COMPANION CROPS

A third seeding method, and the most common in many areas, is seeding the forage with a companion crop (Tesar and Marble, 1988). This involves preparing the soil for the planting of a small grain crop, and placement of the forage seed on the surface or in a small surface groove, and covering with a drag chain or a press wheel arrangement. A variation is to attach a corregated roller to the drill to assure seed-soil contact (Fig. 9.3). If the legume seed is broadcast on the surface, some additional activity to assure soil-seed contact is required. A common practice is to drag a spike-tooth harrow over the soil surface. However, the use of a corregated roller, behind the harrow is more effective to compact the soil.

Three common ways of reducing competition from the companion crops are (1) proper companion crop selection, (2) reduced planting rate, and (3) early removal of the companion crop. It is generally recommended that the seeding rate of the companion crop be reduced to about two-thirds the normal rate to reduce competition with the forage crop where soil moisture is not limiting (Martin *et al.,* 1976). Use of a companion crop effectively eliminates most weed problems, but it also eliminates any possibility of

FIGURE 9.3 Seeding small-seeded forage legumes and grasses with a drill is successful if the seed is covered after it falls to the ground. Methods of covering include drag chains, following the seeding operation with a roller compacter (above), or press wheels that push the seed into the ground immediately behind the drill. Drag chains by themselves are the least effective, but when used in conjunction with a roller compacter, excellent results may be obtained. (Photo by author.)

significant forage production during the seeding year, although some forage production, along with the grain stubble, will be available for late fall or winter grazing in some areas, particularly if planting occurred in the fall and the companion crop is removed early in the following growing season to reduce competition. In areas in which soil moisture is more limiting, the seeding rate of the companion crop should be adjusted downward.

Acceptable companion crops are oat (*Avena sativa* L.), flax (*Linum usitatissimum* L.), and pea (*Pisum sativum* L.). These three crops have common characteristics that make them superior companion crops: they mature early in the growing season, and the canopy structure is not so dense that suppressive shading results. Other small grains such as wheat, barley, rye, and triticale generally provide too much competition to be used as companion crops without altering some of the agronomic practices associated with them. Rapeseed (*Brassica napus* L.) has also been used as a companion crop in Canada (Waddington and Bittman, 1984). Yields of both alfalfa and bromegrass were reduced drastically by association with rapeseed in the seeding year; they averaged only about 13 to 14% of direct-seeded bromegrass and 9 to 10% of direct-seeded alfalfa. In the first year after seeding, yields compared to direct-seeded alfalfa and bromegrass were reduced by only 11 and 4%, respectively. Yields for the first harvest during the third year were 100 and 123%, respectively, of the direct-seeded yields. For such competitive crops to be economically viable as companion crops, the return must make up for the deficit, resulting from direct competition for light, water, and minerals, during the first and second years after seeding.

Alfalfa established with oat, which was harvested for forage, produced the most forage (composed of oat, alfalfa, and weeds) during the establishment year; alfalfa with weeds controlled by use of EPTC was second; the control plots (no weed control) were next; and oat for grain was last (Hansen and Krueger, 1973). In cases in which oat straw is of economic value, the returns may be greatest from oat for grain and straw (Schmid and Bahrens, 1972).

Winter wheat (*Triticum aestivum* L.), barley (*Hordeum pratense* L.), rye (*Secale cereale* L.), and triticale (*Triticum* × *Secale*) provide too much competition to allow consistent success in establishing forage crops (Bula *et al.,* 1954). Spring wheat (*T. aestivum* L.) is less competitive than the previously mentioned crops, but it is more competitive than oat, flax, or pea. If wheat, barley, rye, or triticale is to be used as the companion crop, the seeding rate must be reduced to approximate 60% of the normal rate, especially if the grain crop is to be grown to seed maturity. If the cereal crop is to be removed as silage at the dough stage of development, the planting rate can be as high as 70% of the normal planting rate. Oat grown on a course-textured soil should also be reduced to about two-thirds of the normal rate to reduce competition for water (Smith *et al.,* 1954; Tesar and Marble, 1988). However, on a fine-textured soil or under irrigated conditions in which competition for water is not a factor, the planting rate for the oat companion crop should not be reduced below the normal rate for the area (Smith *et al.,* 1954; Tesar, 1984). In the northcentral states, this is 72 to 103 kg ha^{-1} (64–92 lb $acre^{-1}$). Too much reduction in the companion crop planting rate may result in excessive incursion of weeds (Smith *et al.,* 1954). In the irrigated desert valleys of the southwestern United States, it is recommended that 30 to 40 kg ha^{-1} (27–36 lb $acre^{-1}$) of oat be planted with fall-seeded alfalfa, mainly as a winter protection to the alfalfa. As little as 8 kg ha^{-1} (7 lb $acre^{-1}$) have little negative effect on establishment and superior first-harvest and first-season yields result from this practice (Marble, 1974). The optimum rate under California management conditions is 18 kg ha^{-1} (16 lb $acre^{-1}$) (Lanini *et al.,* 1991).

Early removal of the companion crop as silage or hay at the late-boot to early-head stage of development is an effective way of reducing competition, especially when wheat, barley, and triticale are used as companion crops. The seedlings are well established at this point, and development is rapid provided that water and soil nutrients are available. Total biomass production, oat as forage plus the legume, may equal direct seeding of alfalfa using a herbicide to control weeds (Hansen and Krueger, 1973;

Schmid and Bahrens, 1972). Lanini *et al.* (1991) reported that total biomass exceeded forage received from direct-seeded alfalfa.

If a companion crop is used to control weeds in the seeding year, the amount of alfalfa produced will be reduced, but the total amount of dry matter produced (alfalfa, weeds, and companion crop) will not be affected. Data from the second year of production shows that establishment methods have no influence on alfalfa yields (Hansen and Krueger, 1973; Schmid and Behren, 1972). Other legumes, which are lesser competitors than alfalfa, may be affected significantly by companion crops. For example, companion crops have been noted to reduce trefoil stands significantly from 13.8 to 3.8 plants 0.1 m^{-2} (12.8 vs. 3.5 plant ft^{-2}) (Scholl and Staniforth, 1957). In concert with the reduction in stand, dry-matter yields in the seeding year were reduced by 98% because of competition from the companion crop (1630 to 17 kg ha^{-1}; 1455 to 15 lb $acre^{-1}$) and 85% (5382 to 793 kg ha^{-1}; 4805 to 708 lb $acre^{-1}$) the following year. Birdsfoot trefoil is a weak competitor (Scholl and Staniforth, 1957; McKee, 1962).

E. SEEDING DEPTH

Seeding too deep is the root of many failures in forage stand establishment. That and an unfirm seedbed combine to be responsible for a significant proportion of stand establishment failures in small-seeded legumes and grasses; seedbeds that have not been compacted or have not received recent precipitation or irrigation usually allow the seed to be covered too deeply; thus, emergence is not possible. Germination goes on as it should, but the crops in question, being very small seeded, have short hypocotyls (legumes) or coleoptiles (grasses); thus, they are unable to emerge from the soil.

Research has shown that small-seeded grasses and legumes must be planted from 0.6 to 1.3 cm (0.25-0.5 in.) deep (Moore, 1943; Sund *et al.*, 1966; Tesar *et al.*, 1954; Tesar and Triplett, 1960). The recommended planting depths range from 0.6 to 1.9 cm (0.25–0.75 in.) on most fine-textured soils (Smith, 1981). Sandy, course-textured soils may require a seeding depth of 1.3 to 3.9 cm (0.75–1.5 in.) (Smith, 1981; Sund *et al.*, 1966; Triplett and Tesar, 1960). The best depth of seeding for four species (alfalfa, birdsfoot trefoil, smooth bromegrass, and orchardgrass) was 1.3 to 2.5 cm (0.5–1 in.) on sandy soils and 1.3 cm (0.5 in.) or less on clay soils (Sund *et al.*, 1966). Supporting data are presented in Table 9.2. Planting greater than 3.9 cm (4 in.) deep results in almost no alfalfa emergence, whereas 0.6 cm (1/4 in.) depth results in greater than 90% emergence. Some species will emerge from greater depths, up to 2.5 cm (1 in.), but the seedlings are weaker and less vigorous (Murphy and Arny, 1939). Bromegrass, slender wheatgrass [*Agropyron trachycaulum* (Link) Malate], perennial ryegrass (*Lolium perenne* L.), and reed canarygrass all achieve good emergence

TABLE 9.2 Emergence[a] of Alfalfa Planted at Four Depths and Compacted at Four Levels in a Field in Michigan

	Compaction, 9 g dm-2 (psi)				
Depth, cm (in.)	0	213 (3)[b]	426 (6)	852 (12)	Average
0	10[c]	16	24	40	22
0.64 (0.25)	60	58	58	59	59
1.27 (0.50)	60	62	64	63	62
2.54 (1.0)	50	52	52	50	51

[a] Average of two soil types; irrigated and nonirrigated.
[b] Numbers in parentheses represent psi.
[c] Numbers are percentages.
Source: Tesar and Marble, 1988.

from as deep as 1 in. (Murphy and Arny, 1939). Surface planting of small-seeded legumes and grasses may result in successful stand establishment if conditions are ideal, but ideal conditions rarely, if ever, occur in the field due to drying of the surface.

Rate of emergence is influenced by planting depth and forage type. Murphy and Arny (1939) showed that all legumes planted at the 1.3 to 2.5 cm (0.5–1 in.) depth achieved 70% or more emergence within 15 days, whereas grasses reached 91 to 93% emergence in the same time.

F. SEEDING RATE

There is much less work done on seeding rates of forage grasses or clovers than on alfalfa. Presumably this is because (1) the grasses are less sensitive to variation in seeding rate and (2) they are less important from the economic point of view. However, recommended seeding rates for all important small-seeded grasses and legumes grown in North America have been established (Martin *et al.*, 1976; Table A-1). Best results are achieved by adhering to these rates and adjusting them only to meet local soil and environmental conditions.

A highly productive, mature alfalfa stand must have at least 4 to 6 mature plants 0.1 m^{-2} (1 ft^{-2})[2] (Tesar and Marble, 1988). The year following seeding, however, the number required to achieve optimum yield is approximately 15 to 25 0.1 m^{-2}. Thus, seeding rates should be targeted that assure such a population. As seeding rate is increased, seedling plants per unit area increase linearly (Hansen and Krueger, 1973; Kephart *et al.*, 1992), ranging from very low values to more than 600 plants m^{-2} at the highest planting

---

[2] 0.1 m^{-2} is approximately equal to 1 ft^{-2}.

rates. Two factors must be considered in this regard. First, one wants to achieve maximum production in the first 2 years of production when plants are quite small in size. The number of plants per unit area must be increased considerably to meet this objective. Second, planting rate must far exceed the mature stand requirements for optimum yields. Another factor also comes into play: the greater the seeding rate, the lower the emergence percentage. Percentage emergence and shoots per plant was negatively correlated with seeding rate (Kephart *et al.*, 1992). The higher the seeding rate, the lower the percentage survival of seedlings. Cooper *et al.* (1979) reported that at a seeding rate of 0.6 kg ha^{-1} (0.53 lb $acre^{-1}$), emergence was 100%, but at 20.2 and 22.4 kg ha^{-1} (18 and 20 lb $acre^{-1}$, respectively), stand establishment was 35% of the seeds planted.

Optimum seeding rate depends somewhat on the environment in which the crop is to be grown. Irrigated forages can support a higher seeding rate than can dry-land conditions (Hansen and Krueger, 1973). Research on alfalfa has shown that about 9 to 15 kg pure live seed (PLS) ha^{-1} (8–14 lb $acre^{-1}$) is optimum for maximum first-year forage yields (Cooper *et al.*, 1979; Kephart *et al.*, 1992). Greater seeding rates resulted in a decrease in yield during the seeding year (Cooper *et al.*, 1979). However, in California, under irrigation, a seeding rate of 22.4 to 33.6 kg ha^{-1} (20-30 lb $acre^{-1}$) is recommended (Marble, 1984). Research shows that optimum yields may be obtained by increasing the seeding rate from 9 to 18 kg ha^{-1} (8–16 lb $acre^{-1}$) in Maine (Brown and Stafford, 1970) and Michigan (Tesar, 1984). According to Tesar and Marble (1988), seeding rates in the northeast section of the United States have doubled in the 16-year period from 1972 to 1988. Recommended seeding rates in the western prairies of the United States and Canada ranged from 4.5 to 9 kg ha^{-1} (4–8 lb $acre^{-1}$) in 1962 (Heinrich, 1968). Work by Kephart *et al.* (1992) in South Dakota would suggest that seeding rates in these prairie areas also have the potential to nearly double, 9 to 15 kg ha^{-1} (8–13.4 lb $acre^{-1}$).

IV. PLANT DENSITY AND YIELD

Almost all the research on the effect of seeding rate on yields during the seeding year and the first year after seeding has been done on alfalfa. Thus, the following discussion relates most specifically to alfalfa.

A. SEEDING-YEAR YIELDS

Many things enter into seeding rate-yield relationships. To obtain optimum yields during the seeding year, seeding rates must reach a critical level. This level provides far more plants that the 4 to 6 per 0.1 m^2 (1 ft^{-2}) required for optimum production in a mature stand. In Montana, Cooper *et al.* (1979) showed that yields were 4.82 Mg ha^{-1} (2.15 tons acre^{-1}) at 0.6 kg ha^{-1} (0.5 lb acre^{-1}) seeding rate, and as high as 8.31 Mg ha^{-1} (3.7 tons acre^{-1}) at 15.7 kg ha^{-1} (14 lb acre^{-1}). When seeding rates were increased to 22.4 kg ha^{-1} (20 lb acre^{-1}), first-year yield was significantly decreased to 7.4 Mg ha^{-1} (3.3 tons acre^{-1}). Moline and Robison (1971) found no significant increase in yield when seeding rate exceeded 17 kg ha^{-1} (15 lb acre^{-1}). Graffis and Pardee (1968) reported increased first-year yields in Illinois with seeding rates up to 54 kg ha^{-1} (48 lb acre^{-1}). To relate the work of Cooper *et al.* (1979) in Montana to seedling stand density, it is important to note number of seedlings per meter should exceed 85 (8.5 ft^{-2}). All seeding rates greater than 6.7 kg ha^{-1} (6 lb acre^{-1}) provided such seedling density. In Indiana, which provides a more moderate climate, Volenec *et al.* (1987), demonstrated that yields in the seeding year increased with plant densities up to 172 plants m^{-2} (17.2 plants ft^{-2}). Thus, in areas with ample summer rainfall or where irrigation is practiced, seeding-year yields may be enhanced by seeding rates up to 25 to 30 kg ha^{-1} (22–27 lb acre^{-1}). However, in areas with limited or marginal summer precipitation, seeding rates should not exceed 15 kg ha^{-1} (13.4 lb acre^{-1}). In fact, in Montana the recommended seeding rate on irrigated lands is about 8 kg ha^{-1}, or approximately 7 lb acre^{-1} (Cooper *et al.,* 1979).

B. SECOND-YEAR YIELDS

In studies near Moscow and Sandpoint, Idaho, it was found that seeding-year harvest management, which refers largely to the stage of development at which each harvest was removed, had no effect on second-year yields (Hall and Eckert, 1992). Planting as late as 29 May did not influence second-year yields. Yields obtained in the year following the seeding year showed no significant differences among establishment methods; that is, companion crop vs. herbicides to control weeds (Schmid and Bahrens, 1972; Hansen and Krueger, 1979). Cooper *et al.* (1979) showed that regardless of seeding rate, 1.1 to 9.0 kg ha^{-1} (1–8 lb acre^{-1}) second-year yields did not differ significantly.

C. YIELDS AS STANDS MATURE

Under both irrigated and dry-land conditions in South Dakota, Hansen and Krueger (1973) showed that seeding at 4.5 kg ha^{-1} (4 lb acre^{-1}) produced significantly less forage than seeding at 9, 13.5, and 18 kg ha^{-1} (8, 12, and 16 lb acre^{-1}, respectively). However, none of the three higher planting rates differed significantly among themselves in yield once the stand matured. In work to evaluate the effect of seeding rate on yields in the fourth and fifth years of production, Kephart *et al.* (1992) showed, under North Dakota dry-land conditions (Brooking), that optimum yields were provided by the

13.4–kg ha^{-1} rate (12 lb acre^{-1}), but yields did not respond to seeding rate at Highmore. In general, seeding rates in the range usually used by growers have no effect beyond the seeding year.

D. FORAGE QUALITY AND RATE OF SEEDING

When emphasis is placed on forage quality, one may wonder what relationship exists between seeding rate and forage quality. This question reduces to the relationship between quality and stem diameter (Volenec *et al.*, 1987). As number of stems per unit area increase, stem diameter decreased ($Y_d = 2.12 - 0.0055x + 0.00002x^2$, $R^2 = 0.96$) and *in vitro* dry matter disappearance (IVDMD) increases ($Y_q = 603 + 0.334x - 0.0009x^2$, $R^2 = 0.99$). Figure 9.4 demonstrates this relationship as stem density increases from 11 to 172 plants m^{-2} f(1.1–17.2 plants ft^{-2}). Stems from plants grown at 172 plants m^{-2} contained 10 g kg^{-1} (1%) less lignin and were 30 g kg^{-1} (3%) more digestible than plants grown at 11 plants m^{-2} (1 plant ft^{-2}). The implications are that seeding rate can have an effect on forage quality. This potential should be viewed from the point of economic reality, however. Because yield does not vary above an effective planting rate of 9 to 10 kg ha^{-1} (8–9 lb acre^{-1}), seeding at a higher rate, especially if it is more than 20 kg ha^{-1} (18 lb acre^{-1}), to obtain higher-quality hay may be counterproductive in that the additional cost of seed may not be offset by the improved quality. (It should be remembered that the major determinant

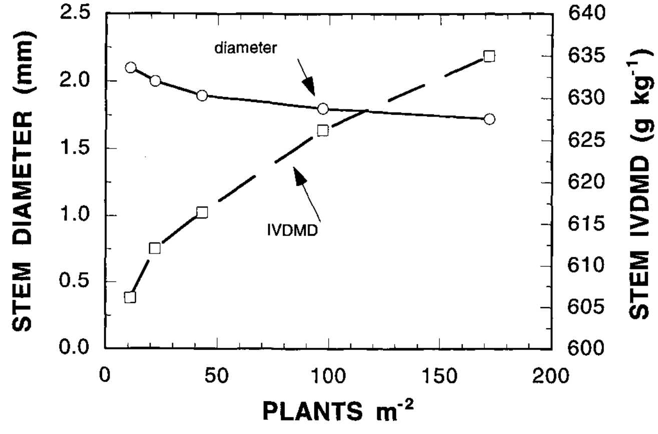


FIGURE 9.4 Relationship between plant population and stem diameter and *in vitro* dry matter disappearance (IVDMD) of alfalfa stems. Values are means of three cultivars and five harvests. The SEs from analysis of variance were 0.03 mm and 3 g kg^{-1} for stem diameter and digestibility, respectively. (Redrawn from Volenec, Cherney, and Johnson, 1987.)

of forage quality is the stage of development at the time of harvest.) In situations in which the seeding rate is not sufficient to obtain optimum forage yields, it follows that the amount of crude protein (CP) or IVDMD produced per unit area will decrease (Hansen and Krueger, 1973).

V. DATE OF SEEDING

Seeding date depends on the weather in a given area. Some areas may have winters that are too harsh for fall-established forages to survive. Thus, seeding in these areas must be done in the spring or early summer. Other areas have winters that are mild enough, although they are cold, for forage seedlings to survive. If germination and seedling establishment is dependent on natural precipitation, early summer may not be a good time to plant. An advantage to seeding in the fall, without a companion crop, is that no herbicide is required to control weeds, thus reducing establishment costs significantly.

Fall seeding requires that the forage be established early enough to develop a strong, vigorous plant capable of surviving the winter and taking advantage of the early growth periods the next spring. First-year production can range from 3 to 7 Mg ha^{-1} (1.3–3.1 ton $acre^{-1}$), depending on a number of factors such as fall planting date, soil fertility, and fall and spring temperature regimes favorable to growth (Tesar and Marble, 1988; Horrocks, 1989). Seeding alfalfa as early as 15 July results in significant yield increases during the first production year. A comparison of the planting dates 15 July, 15 August, and 15 September in Utah (irrigated) resulted in yields of 3.92, 3.75, and 2.72 Mg ha^{-1} (1.75, 1.67, and 1.21 tons $acre^{-1}$), respectively (Horrocks, unpublished data, 1997). There are numerous examples of the benefits of fall seeding throughout the medium latitude temperate zones.

Spring establishment of legumes without a companion crop requires some means of controlling weeds. To control weeds, three protocols may be followed: (1) mow the weeds to prevent too much competition, (2) use 2,4-DB (2,4-dichlorophenoxy butyric acid) as a postemergent herbicide for broadleaf weed control, or (3) apply a preemergence herbicide such as eptam, balan, and so on for weed control in legume seedings. The preemergence herbicides kill both dicotyledonous and grassy weeds; thus, they cannot be used when a grass is included with the legume. In that case, weed control is limited to mowing and postemergent use of 2,4-DB. In cases in which weed competition is left unchecked, alfalfa yields the following year are not usually affected (Hansen and Krueger, 1973; Schmid and Bahrens, 1972). However, in years with unfavorable environmental conditions, the effect can carry over into the first harvest of the next year (Peters, 1961). Competition from weeds during the seeding year results in severe decreases in yield of the desired forage (Scholl and Staniforth, 1957; Peters, 1961).

Applications of 2,4-DB should be made when the forage legume is in the 3- to 4-trifolioliate leaf stage of development (Schmid and Bahrens, 1972). If birdsfoot trefoil is to be established with mowing, clipping, or grazing to control weed competition, more frequent clipping, to simulate periodic grazing, is superior to less frequent clipping (Scholl and Staniforth, 1957). Mowing at the proper stage of weed development effectively controls tall-growing annual broadleaf weeds, but it does not control grassy weeds.

Not all legumes are resistant to 2,4-DB; thus, the label should be read carefully and the directions followed. Birdsfoot trefoil is resistant to 2,4-DB; thus, 2,4-DB can be used to control postemergent weeds (Peters and Lowance, 1971). It is also safe to use this postemergent herbicide on crownvetch (*Coronilla varia* L.), although some damage may result (Peters and Lowance, 1971), and on red clover (*Trifolium pratense* L.). Reduced plant vigor and stand density may be the result of using 2,4-DB on crownvetch. In severe cases of broadleaf weed infestations, the use of 2,4-DB would be justified, because the deleterious effect is not lasting.

Red clover is known as a short-lived perennial, and it appears that dry-matter harvest from it can be affected by the management treatments of the seeding year. Red clover yields were affected by seeding year management and spring seeding date (Hall and Eckert, 1992). Planting on 29 May vs. 29 April resulted in a yield reduction of 1.7 Mg ha^{-1} (0.76 tons $acre^{-1}$) in a two-harvest system. If seeding-year management included cutting 40, 60, or 80 days after seeding, progressively greater yields in the first harvest resulted, and dry-matter yields for a two-harvest system yielded from 2.5 to 3.3 Mg ha^{-1} (2.2–3.0 tons $acre^{-1}$).

Spring-seeded oat companion crops have long been used successfully for the purpose of controlling weeds. In addition to the benefit of the oat crop in weed control, the need for grain and straw may make this practice economically feasible. This method is especially useful on dairy farms, where bedding straw is needed. As farms came into being that had no animals and bedding material was not needed (this is particularly descriptive of commercial hay growers), direct seeding became a practice of some importance.

VI. STAND REJUVENATION

Often, one would like to reestablish a stand of alfalfa without killing or plowing the old one. Although this has merit from the economic point of view, it is not commonly done because of the high failure rate. It is not a matter of being mechanically impossible, because no-till seeding of small-seeded forages is routinely done throughout the United States. It is a matter of that alfalfa produces and releases into the immediate environment phytotoxic (toxic to plants) compounds that kill alfalfa seedlings (Miller, 1983; Hegde and Miller, 1992). This is called **allelopathy** (Chapter 10). However, such stand rejuvenation may be accomplished if the alfalfa stand is decimated to the point that there is 1 or less plants per m^2 (1 plant ft^{-2}; Asbil and Coulman, 1992).

In an attempt to rejuvenate a depleted alfalfa stand (10–11 plants m^{-2}; 1 plant ft^{-2}), Asbil and Coulman (1992) compared 4.0 and 12.3 kg ha^{-1} (3.6 and 11 lb $acre^{-1}$) seeding rates. Reseeding was without plowing, relying only on winter surface seeding with the accompanying late-winter freezing and thawing action to work the surface-applied seed into the soil. Under these conditions, the 12.3 kg ha^{-1} (11 lb $acre^{-1}$) rate produced significantly more alfalfa in the second year, but no differences in the seeding year. Seedling establishment from the 4.0-kg (3.6-lb) seeding rate did not yield significantly different from the check treatment, which had only 1 plant per square foot. Seeding rates, in such reestablishment efforts, should be similar to what one would use in establishing a new alfalfa stand. Asbil and Coulman (1992) suggest that at least 12.3 kg ha^{-1} (11 lb $acre^{-1}$) must be used to succeed. Comparing what is recommended for seeding in a well-prepared seedbed, it is evident that, if anything, the seeding rates should be equal to or greater than the normal rate.

Tesar has completed a large body of work on reseeding alfalfa into old stands (Tesar, 1993), and recommends that in attempting to rejuvenate an old alfalfa stand, one should treat with glyphosate or plow at least 3 weeks prior to seeding to kill all old alfalfa. In such attempts, whether a seedbed is prepared prior to seeding or no-till seedbed preparation is practiced at the time of seeding, the key to success is, as with establishment of a new stand, optimum soil-seed contact.

10

PEST CONTROL

WEEDS, INSECTS, PATHOGENS, AND RODENTS

I. INTRODUCTION

Similar to other classes of crops, forages are beset with a myriad of pests. Included are weeds and the associated competition, insects, diseases, rodents, and herbivorous animals. The mix of pest problems varies from locale to locale. Rarely are all classes of pests (i.e., weeds, insects, and diseases) important at a given location at the same time. However, it is the exception rather than the rule for an area, or even a field, to be entirely free from the effects of pests. Not all infestations are of epidemic proportions; most are simply endemic. Regardless of location or the crop grown, it behooves the grower to be aware of potential pest damage. To avert losses, a grower must know the potential pests, be able to identify them and their symptoms, know and practice the best control methods, and have a sense of when a pest becomes important from the economic point of view.

Since before the dawn of recorded history, people have been at war with crop pests such as weeds, insects, plant diseases, and rodents. For thousands of years endemic pest populations have caused significant amounts of crop loss. From time to time, these endemic populations have grown to epidemic proportions, and much havoc has been wreaked on the human population. Periodic insect plagues devastated crop production in the Mediterranean area, Africa, Asia, and Europe. The black or bubonic plague of 14th-century Europe, which killed more than half of the human population, was spread by rodents carrying the causal agent. Locust plagues have devastated areas of the Middle East and Africa regularly throughout recorded history. Plant diseases have rarely caused disasters of the same magnitude as have the insects. In Ireland, the potato famine of the mid-1840s was an exception to this. Weeds have always been present and they have been controlled to various degrees by "the sweat of the brow."

Over long periods of time, methods of averting the consequences of pest infestations evolved. These efforts involved selecting and practicing techniques best suited for control, including cultivar selection, rotation, and cultivation. Only recently has the use of chemical pesticides become an important part of this integrated control effort.

All crop and livestock production is affected by pests, and significant losses occur each year. It is estimated that world crop losses to weeds, insects, and pathogens are about 35% annually (Cramer, 1967). In reality, this estimate may be too low. Despite the use of modern pest-control strategies and technology in the United States, preharvest losses are estimated to be about 37% (USDA, 1965). It is estimated that weeds account for 12%, plant diseases 12%, and insects 13% of these losses. Postharvest losses are estimated to be an additional 9%, thus bringing the total to more than 45%. Forage crop losses associated with harvesting, preserving, and storage are discussed in Chapter 13.

Because forage crops have mostly been considered of lesser importance in the minds of producers, the extent of losses from pests have received little attention. Consequently, less data and information are available on estimated forage production losses that are the result of pests. In some cases, notably alfalfa weevil (*Hypera postica* Gall.), losses from pests have been of gigantic proportions; however, generally most pests have been of the endemic type—always present but not devastating; thus, the impact was not as obvious as with crops considered to be "money crops." Because of this attitude, limited efforts have traditionally been applied to solving these pest problems.

In the forage crops used for hay, breeding pest resistance into new cultivars has long been recognized as the first line of defense, and the efforts accumulated over time are impressive. Alfalfa, because of its economic importance, has received much attention, and the list of pathogens to which it is resistant has grown impressively since 1978. The Certified Seed Council currently lists more than 200 alfalfa cultivars and their response to diseases, insects, and some nematodes (CASC, 1998).

Pest-management strategies include basic knowledge, development of sources of information, and ready access to information on (1) the ecological basis for the pest problem, (2) pest and predator populations and life cycles, and (3) analysis of the costs and benefits of pest-control techniques. Subsequent sections of this chapter discuss the various types of pests that affect forage crops.

II. WEEDS

A. PHILOSOPHY REQUIRED FOR SUCCESSFUL WEED CONTROL

In order to successfully control weeds and prevent losses of forage dry-matter yield and quality, growers must have the attitude that the crop is important economically. Preventive measures must be taken at each stage of the crop's production cycle. For example, at time of seeding, soil-seed contact must be assured through proper seed bed preparation—plowing, disking, harrowing, and compacting. This is the primary factor in establishing excellent stands of small-seeded forage crops—both grasses and legumes—which then effectively suppress weed growth. Control of initial weed competition by mowing, fall planting, or application of pre- or post-emergence herbicides is a second important consideration. (This aspect of weed control is discussed in Chapter 9.) Another important aspect of weed control in forages is maintaining soil fertility at sufficient levels for a healthy, vigorous stand to be established and maintained. To accomplish this, proper management of N and adequate levels of P and K are essential. At times, other nutrient elements may be in short supply; thus, these needs should be determined through a soil test taken prior to seeding and corrected by applying the recommended rates of all elements determined to be deficient. (Further aspects of soil fertility are discussed in Chapter 11.) Finally, a grower must have the attitude that continuous education on the latest developments in the field is important in maintaining vigorous, high-producing stands of forage. In the dynamic situation found in crop-weed relationships, new information is continually being developed.

B. EXTENT OF CROP LOSSES DUE TO WEEDS

Losses due to weeds in forage crops are extensive, although they are only one-fourth of the losses experienced in field crops (Table 10.1). It is estimated that the dollar value of losses in all forage crops in the United States totals approximately $1.6 billion annually. Of these losses, 47% are in harvested hay, 50.6% in pasture and rangeland, and 2.4% are in the forage seed industry (Chandler, 1991). At the end of a 3-year study, Lamp *et al.* (1985) showed that alfalfa yields were reduced by as much as 83% by weeds.

C. FACTORS CAUSING LOSSES IN FORAGE CROPS

Losses caused by weeds come about because of several factors: reduced yield because of plant-to-plant competition for water, nutrients, and light; reduced overwintering ability of the desired forage; toxins produced by weedy species; reduced forage quality, which results in reduced value of the forage; and reduced quantity and quality of animal products. The scenario in competition for light, nutrients, and water was outlined by Donald (1963) as follows: a heavily shaded plant suffers reduced photosynthesis, leading to poorer growth, a smaller root system, and, ultimately, reduced capacity for water and nutrient uptake.

TABLE 10.1 All Crops: Estimated Average Annual Losses Due to Weeds, 1975–1979

Commodity group	Average annual monetary losses ($1000)[a]
Field crops	6,408,183
Vegetables	619,072
Fruits and nuts	441,449
Forage seed crops	38,126
Hay	772,107
Pasture and rangelands	778,805
Total	9,027,016

[a] To obtain value in today's dollars, multiply by 2.5%.

Source: Chandler, 1991.

1. Yield Reduction Caused by Competition

Most competition research comes from Australia and emphasizes the interrelationship of light, nutrients, and water. Intraspecific competition among annual pasture plants increases with density, stage of development, and decreased nutrient status (Donald, 1951). Because we are interested in harvesting the whole above-ground plant, forages in general, when provided with adequate water and nutrients, do not decrease in yield, stand, or vigor even in very dense populations. However, optimum yields are another matter, because they can be achieved at relatively low plant populations. The work of Donald (1954) shows the importance of proper plant density. Optimum yield was achieved by pastures of subterranean clover (*Trifolium subterraneum* L. 'Wimmora') and annual ryegrass (*Lolium rigidum* Gaudin.) at moderate densities of approximately 107 to 172 plants m^{-2}. These optimum yields were maintained at all higher densities (8000–10,000 plants m^{-2}).

Forage-weed plant competition is, however, a counterproductive situation. The production potential of a unit of land is set with respect to dry matter, and each unit of weed dry matter produced results in approximately a 1-unit decrease in the desired forage (Peters and Lowance, 1969). It is accepted that weeds in forage crops can be most easily controlled by maintaining vigorous, weed-free, competitive stand of these crops (Peters, 1973; Schrieber and Oliver, 1971). Vigor of forage stands can be maintained by practicing proper management with respect to fertilization. Addition of P and K, when limiting, increases growth of desirable species (Ward and Blaser, 1961; Carmer and Jacobs, 1963).

Broadleaf weeds suppress development of legumes more than they do grasses (Hollingsworth, 1958). Controlling broadleaf weeds may release annual grasses, which in turn cause less legume yield loss. The effect of yield loss in alfalfa production by competition from weedy species is best illustrated by the work of Schreiber and Oliver (1969, 1971). During the establishment year, alfalfa alone produced 5690 kg ha^{-1}. However, in competition with *Seteria faberii* L., alfalfa produced only 1165 kg ha^{-1}, and in competition with *Amaranthus retroflexus* L., production was even less, just 200 kg ha^{-1}. During the first year after establishment, three cuttings produced the following yields of alfalfa: alfalfa alone, 12,700; alfalfa and setaria, 10,400; and alfalfa and amaranthus, 3,800 kg ha^{-1}. A second study on birdsfoot trefoil showed the following results: trefoil alone yielded 5256 kg ha^{-1}; in competition with setaria, the yield was 935 kg ha^{-1}; and in competition with amaranthus, 125 kg ha^{-1} (Schreiber and Oliver, 1971).

Grassy weeds are at a competitive advantage when compared to legumes if synthetic sources of N are provided rather than letting the legume supply its own N. Considerable research has shown that growth of grasses, stimulated by added N, suppresses growth of associated legumes (Blaser and

Brady, 1950; Mouat and Walker, 1959; Stern and Donald, 1962; Thrasher *et al.*, 1963; de Wit *et al.*, 1966). This is so whether the grass is a desirable one in a binary mix or an undesirable weedy species encroaching into the legume stand. Response to sulfur (S) deficiency is similar to that of N deficiency. In a grass–clover association, grasses take up most of the S and clover growth was depressed (Walker and Adams, 1958). Addition of N increases the negative effects of competition. However, applications of S relieved clover suppression. In a situation in which a desirable combination of a grass–legume association is to be maintained, or in a situation in which a pure stand of a legume is desired, imbalance of nutrients such as S and N may result in an increase in the grass or grassy-weed component and a decrease of the legume. Grassy-weed encroachment thus can be abetted by soil fertility management.

The basis for weed takeover of a stand when K is limiting seems to be related to the weed species' inherent ability to extract K from a low-K soil. Deficiency in P results in severe stunting of desirable forages, but weeds appear to be insensitive to low-K soils (Buchanan and Hoveland, 1973; Hoveland *et al.*, 1976). Weeds, however, although they can grow in low soil-K concentrations, do respond to K fertilization.

2. Competition for Water

A plant's ability to compete for water depends on the rate and completeness with which it utilizes the soil water supply (Donald, 1963). Three factors are important for a species or cultivar: high relative growth rate, earliness of water demand, and a high rate of root extension. Alfalfa and annual medic, because of their quite different growth habits—one is a perennial and the other is an annual—show very different responses to soil water deficiency when competing with rush skeleton weed, *Chrondrilla juncea* (L.). With alfalfa, the competition is mainly for water, and alfalfa will dominate, but with annual medic it became more of a contest for light, and annual medic is unable to suppress skeleton weed as effectively (Wells, 1969). Water management in irrigated areas may be an important factor in weed populations. Thrasher *et al.* (1963) showed that Canada thistle (*Cirsium arvense* [L.] Scop.) in competition with forages increased in number with frequency of irrigation at 112 kg N ha^{-1} or less; but at 448 kg N ha^{-1}, weed numbers decreased. When flood irrigation is practiced, the lower ends of the field, where water usually accumulates and stands for lengthy periods of time, are quite susceptible to alfalfa stand loss and encroachment of adapted weedy grasses such as *Hordeum jubatum* (L.), commonly called foxtail or foxtail barley.

3. Competition for Light

Light is the key external variable in the photosynthetic process. Being able to obtain sufficient light to produce a vigorous plant is key to success of a species or cultivar in competition with other species in a forage mix or in competition with weeds. When the growth habit of a weed or a companion species is more vigorous in its top growth than the other species, shading will result and the shaded species will become less vigorous. Several factors such as stage of development, species, and season of the year affect this relationship (Brougham, 1958). Management of nutrients, especially N, and water may enhance or control the dominance of one species over another simply by reducing vigor of growth, and consequently increasing or reducing the competitive leaf canopy.

4. Inhibitors and Phytotoxins

Production of inhibitors by plants is a common phenomenon among weeds as wells as among crop plants. This effect, called *allelopathy,* is documented by a number of workers (Lawrance and Kichler, 1962; Liebl and Worsham, 1983; Miller, 1992; Tesar, 1993). The term *allelopathy* is derived from the Greek root words *allelon,* meaning "of each other," and *pathos,* meaning "to suffer". Thus, its meaning is the injurious effect of one plant upon the another plant.

Quackgrass (*Agropyron repens* L.), a common weed in forage stands, produces a phytotoxic compound that provides an advantage once it is established (Kommendahl *et al.,* 1959; Ohman and Kommendahl, 1960). Canada thistle has been shown to have allelopathic activity (LeTourneau and Heggeness, 1957; Stachon and Zimdahl, 1980; Wilson and Hardle, 1978). Other examples of weeds exhibiting allelopathic effects are *Ageratum conyzoides* (L.), *Imperata cylindrica* (L.) Beauv., and *Commelina benghaensis* (L.), all of which have a deleterious effect on the Nigeria savanna (Singh *et al.,* 1989). Both yellow (Drost and Doll, 1980) and purple (Friedman and Horowitz, 1971) nutsedge have been shown to exhibit allelopathic effects on other crops. In the mid-south and southern areas of the United States, johnsongrass (*Sorghum halapense* [L.] Pers.), which poses a serious problem in forage systems, also shows allelopathic activity (Lolas and Coble, 1982).

Once the weed is established in the forage stand, allelopathic compounds are introduced into the system by the following actions: (1) compounds are exuded from the roots, (2) compounds may be leached from plant litter, and (3) microbiological breakdown of plant litter. These compounds are water soluble and are also toxic to a wide range of other species (Lawrance and Kichler, 1962; Rice, 1974, 1979; Miller, 1992).

Although in a forage-hay production system alfalfa is not a weed, it is one of the better-known producers of allelopathic compounds (Miller, 1992). These compounds are mainly self-inhibitory in that they prevent establishment of alfalfa seedlings. (This aspect of allelopathy is discussed in Chapter 9.) One class of compounds in alfalfa that is allelopathic is the saponins (Oleszek *et al.,* 1992), which are mixtures of glycosides, and yield pentoses, hexoses, uronic acids, and aglycones, and the nonsugar parts of the saponin moity upon hydrolysis. The active agent, which results from hydrolysis of saponins, is the rare medicagenic acid that is found mainly in the genus *Medicago.*

Growth of weedy species that produce phytotoxic compounds is more likely to occur under conditions of poorer management, more with grasses than with alfalfa, and in unique situations in which a reserve of seed from the toxic species may be spread through the irrigation system and deposited in fields (Jeffery, unpublished data, 1993). The undesirable weeds prevent growth of other species, and thus they are able to spread and increase their influence over the entire stand. Thus, good management principles, including optimum soil fertility, proper cutting height and fall management, harvesting at the proper stage of development, and weed control, should be practiced.

D. LOSSES OF FORAGE YIELD AND QUALITY

1. Quality Reduction

Weeds generally reduce the quality of harvested forages; therefore, an effort to manage them in such a way that their incursion is prevented is of foremost importance.

As the proportion of weeds in a forage increase, the quality of the feed decreases. Cords (1973) and Marten *et al.* (1987) demonstrated this inverse relationship for a number of species. A list of the most prevalent weeds affecting forage quality of alfalfa has been published by the Certified Alfalfa Seed Council (Jordan, 1989; Table 10.2). Many of these weeds are also important in perennial forage grass hay production. Marten and Andersen (1975) determined the relative palatability of 12 common weeds in comparison to oat (*Avena sativa* L.) in a grazing study with sheep. Weeds reported to be as palatable as oat were yellow foxtail (*Setaria glauca* [L.] Beauv.), barnyardgrass (*Echinochloa crusgalli* [L.] Beauv.), green foxtail (*Setaria veridis* [L.] Beauv.), redroot pigweed (*Amaranthus retroflexus* L.), Pennsylvania smartweed (*Polygonum pensylvanicum* L.), and common lambsquarter (*Chenopodium album* L.). Four weed species—giant foxtail (*Seteria faberi* Herrm.), wild mustard [*Brassica kaber* (DC) L.C. 'Wheeler' var. pinnatifida [Stokes], giant ragweed (*Ambrosia trifida* L.), and common cocklebur (*Xanthium strumarium* L.)—were unpalatable. Two species, common ragweed (*Ambrosia artemisiifolia* L.) and velvetleaf (*Abutilon theophrasti* Medic.) were classed as interactors (i.e., some sheep found them palatable and others would not graze them). Palatability was not associated with nutritive value as measured by crude protein (CP) or *in vitro* dry matter digestibility (IVDMD).

In another study, Dutt *et al.* (1982) reported the effect of broadleaf weeds on alfalfa quality. Yellow rocket (*Barbarea vulgaris* R. Br.), white

TABLE 10.2 Weeds Affecting Quality of Alfalfa Hay

Common name	Scientific name
Common chickweed	*Stellaria media* (L.) Vill.
Common lambsquarter	*Chenopodium album* L.
Shepherdspurse	*Capsella bursa-pastoris* (L.) Medic.
Field pennycress	*Thlaspi arvense* L.
Yellow rocket	*Barbarea vulgaris* R. Br.
Redroot pigweed	*Amaranthus retroflexus* L.
Dodder	*Cuscuta* spp.
Prickly lettuce	*Lactuca serriola* L.
Common dandelion	*Taraxacum officinale* Weber
Common ragweed	*Ambroisia artemisiifolia* L.
Giant foxtail	*Seteria faberi* Herrm.
Green foxtail	*Setaria veridis* (L.) Beauv.
Large crabgrass	*Digitaria sanguinalis* (L.) Scop.
Quackgrass	*Agropyron repens* (L.) Beauv.
Downy bromegrass	*Bromus tectorum* L.

Source: Jordan, 1989.

cockle (*Lyncnis alba* Mill.), and dandelion (*Taraxacum officinale* Weber.) were weeds in the harvested area. Portions of the area were treated with herbicides to provide differences in quantity of weeds in the harvested area. Differences in intake, digestibility, and nutritive value index between weedy and weed-free forages were determined by feeding goats in stall trials. Dandelion and white cockle were palatable and yellow rocket was unpalatable, in that the intake of forage infested with the first two weeds was not reduced whereas the intake of forage with the last weed was. Voluntary intake (g/kg$^{0.75}$/day) were as follows: alfalfa-grass infested with dandelion: weed-free, 66.2, weedy, 67.9; alfalfa-grass infested with white cockle, weed-free, 61.2, weedy, 58.5; alfalfa-grass infested with yellow rocket, weed-free, 58.5, weedy, 53.6.

In 1979, Temme *et al.* compared clean and weedy alfalfa hay and weed forage quality. Quality was measured by animal intake (sheep) and *in vitro* digestible dry matter (IVDDM). The range in IVDDM was from 58.1% to 79.3%, with the weed forage being lowest and the weed-free hay being the highest. With the addition of weeds to alfalfa hay, dry matter intake was reduced from 1.7 to 1.3 kg d^{-1}. Chemical analyses of the weeds in this study indicated that Pennsylvania smartweed, shepherdspurse [*Capsella bursa-pastoris* (L.) Medic.], and yellow foxtail had the greatest influence on lowering forage quality. These three weeds composed 25% of the untreated alfalfa forage.

The stage at which weeds are harvested, just as in the case of forages, regulates apparent quality (Temme *et al.,* 1979). For example, common lambsquarter showed 21.8% CP on 2 July (bud stage) and 18.3% CP on 7 July (flower stage); shepherdspurse, 19.4% CP on 2 July (green seed) and 15.5% on 7 July (seed); Pennsylvania smartweed, 17.9% CP on 2 July (flower) and 15.0% on 7 July (late flower); redroot pigweed, 18.0% CP on 2 July (flower) and 14.8% on 7 July (early seed); yellow foxtail, 16.5% CP on 2 July (early seed) and 13.7% on 7 July (seed); and common ragweed, 26.3% CP on 2 July (vegetative) and 20.9% on 7 July (vegetative). In comparison, alfalfa CP concentration may range from 22% at late bud to 15% at mid-bloom (Marten *et al.,* 1987). Acceptability to animals is not, however, always predicated on CP concentration. For example, in a 3-year study (Marten and Anderson, 1975), giant foxtail, Pennsylvania smartweed, common lambsquarter, common ragweed, giant ragweed, and common cocklebur, had CP concentrations greater than 24%, which is very similar to alfalfa in the bud stage, but all were only partially accepted or totally unacceptable to animals.

Marten *et al.* (1987) evaluated a number of common weeds, perennial forage grasses, and alfalfa at various stages of development for IVDMD and the results are shown in Table 10.3. In this study, a comparison was

TABLE 10.3 Herbage *In Vitro* Dry Matter Digestibility (IVDMD) Concentration of Two Perennial Forages and Ten Weeds[a]

	IVDMD					
Species	Stage	g kg^{-1}	Stage	g kg^{-1}	Stage	g kg^{-1}
Alfalfa	Early bud	782	Late bud	682	Mid-bloom	658
Smooth bromegrass	Boot	771	Head	662	Anthesis	633
Quackgrass (common)	Joint	766	Boot	688	Head	630
Quackgrass (biotype)	Joint	783	Boot	710	Early head	641
Dandelion	Mid-bloom	798	Seed	801	—	736[b]
White campion	Veg.	802[b]	Late bud	747[b]	Mid-bloom	665[b]
Jerusalem artichoke	Veg.	833	Veg.	811	Veg.	692[b]
Curly dock	Veg.	766[b]	Veg.	644[b]	Veg.	495[b]
Hoary alyssum	Early bud	888[b]	Mid-bloom	762[b]	Late bloom	644[b]
Canada thistle	Veg.	792[b]	Veg.	781[b]	Bud	741[b]

[a] Average of two years, 1981 and 1982.

[b] One year only.

Source: Marten *et al.,* 1987.

made between alfalfa and smooth bromegrass with a host of weedy species [quackgrass, white campion (*Siline alba* (Mill.) E.H.L. Krause), perennial sowthistle (*Sonchus arvensis* L.), dandelion, swamp smartweed (*Polygonum coccineum* Muhl. ex Willd.), Jerusalem artichoke (*Helianthus tuberosus* L.), curly dock (*Rumex crispus* L.), hoary alyssum (*Berteroa incana* (L.) DC.), and Canada thistle] at various stages of development. The measure of acceptability was the amount of material rejected by the animals. From 20% to 30% of the alfalfa was rejected; quackgrass and smooth bromegrass from 30% to 50%; perennial sowthistle, dandelion, and swamp smartweed were all about 80% rejected; and hoary alyssum and Canada thistle showed a rejection rate of 100%.

E. CONTROL OF WEEDS IN PERENNIAL FORAGE STANDS

Control of weeds at the time of stand establishment is extremely important. A set of good management practices exists to assure successful establishment of a vigorous, rapidly growing, and competitive stand of alfalfa, clovers, or perennial grasses. (These factors are discussed in Chapter 9, Stand Establishment, and are not reviewed further here).

1. Maintaining Healthy Stands

Once a forage stand is established and growing vigorously, the primary factor in controlling weeds is keeping the stand healthy and vigorous. Several factors are important in maintaining a stand's health: maintaining soil fertility at optimum levels; harvest management, especially with alfalfa (i.e., taking harvests at such frequency and time that the plants have time to replenish their root-crown reserves in legumes and stem-base reserves in grasses); and height of cutting. The best solution is to maintain a healthy stand in which weeds cannot invade and thrive. Factors to consider are: (1) correct pH (this is important east of the 100th meridian in North America), (2) proper fertility of the soil, (3) apply herbicides as needed, and (4) management that does not cause a decline in plant health and vigor, such as cutting at improper and inopportune times, with respect to plant development (see Chapter 11).

2. Mechanical Control

Mechanical control of weeds in forages consists of two practices: mowing or clipping the weeds, which is done regularly as each harvest is mowed, and mechanical treatment when the stand is dormant. Dormant treatment works only if a stand becomes dormant because of cool or hot weather. The procedure applies mainly to hardiness caused by winter dormancy, and is particularly applicable to alfalfa in irrigated areas. Mechanical control of winter annuals may be accomplished by cultivation with a spring-tooth harrow or a heavy drag that disturbs the seedling weeds. This procedure may also be used after cutting and before regrowth starts to control grassy weeds, and has traditionally been practiced in dryland alfalfa production. It is obvious, that other deleterious effects may occur in this procedure: mechanical damage is likely to crowns of the forage plants, especially alfalfa, which makes them more susceptible to invasion by pathogens.

3. Herbicides

In the use of herbicides, the important management principal is to obtain a weed-control guide that outlines the use of chemicals, crops for which they have been cleared, rates and times of application, and safety precaustions. As part of their extension and research programs, most states in the United States produce such manuals that can be obtained from local extension offices. Also available are such annual publications as *Farm Chemicals Handbook* (Meister, 1999a) and *Weed Control Manual* (Meister, 1998), which are available from the publisher. A second principal practice is to always read the label and follow the instructions contained thereon. Field representatives of the commercial products are also good sources of information. In addition, professional consultants are becoming more important as a source of information, as are representatives of regional and local cooperatives. (On the web contact www.Ag-consultants.com.)

Dormant periods are effective times to control weeds. Paraquat, a contact herbicide, may be applied to kill newly germinating winter annual weeds. Paraquat is light activated; thus, it should not be sprayed in the late evenings because it may injure the plant because of translocation before light activation occurs.

Residual control of winter annual weeds may be effected by use of any of the following herbicides: Karmex, Velpar, Sinbar, Sencor (Lexone), or Kerb. Kerb at times will have some effect on the control of quackgrass. The effectiveness of these herbicides depends on the environmental conditions; thus, local recommendations as to the most effective herbicide for an area should be obtained. Some herbicides have some affect on perennial grasses that may be included in the forage mix; thus, care must be taken to follow recommendations contained on the herbicide label or in a weed-control guide.

If it is desired to use residual control means on new stands of alfalfa, several precautions should be followed: do not apply Karmex, Velpar, Sinbar, or Sencor (Lexone) until the stand is at least 1 year old. Kerb may be applied in the winter following a spring seeding without deleterious effects.

If weed control is needed on actively growing alfalfa, two things should be considered. If a legume is part of the mixture and broadleaf weeds are the problem, then 2,4-D,B rather than 2,4-D should be used, because the former does not kill alfalfa and many other legumes used in legume-grass mixes. (Read labels for specific legumes on which it is safe to use 2,4-D,B.)

If the stand is pure alfalfa, then Poast can be used to eliminate annual and perennial grassy weeds.

Because there is an economic cost to use of herbicides, or any other "after-the-fact" weed-control effort, one should incorporate sound management principles to eliminate, or at least reduce to a minimum, the need for mechanical or herbicidal weed control efforts.

F. CONTROL OF WEEDS IN SILAGE CROPS

Control of weeds in silage corn, grain sorghum, millets, and so on is effected in the same manner it is when these crops are grown for grain: long-term management practices that reduce the number of weed seeds produced and deposited in the fields, mechanical cultivation, and use of appropriate herbicides. Again, the suggested practice of obtaining information on use of herbicides from proper authoritative experts and reading and following the labels is of utmost importance. Without proper practices in this respect, it is impossible to do an acceptable job of controlling weeds and unproductive economical cost may occur. Because recommended herbicides change from time to time, it is important to keep up on the latest developments. New and more effective herbicides may be released or labels may be withdrawn from old, very commonly used herbicides because usage was not sufficient to maintain the label or ecological concerns outweighted the benefits.

III. INSECTS

A. IMPORTANCE OF CONTROL AND EXTENT OF LOSSES

Of the nearly 60 major agronomic insect pests listed by Higley *et al.* (1989), five are important problems on alfalfa, six on corn, three on sorghum, and three on grasses used for hay, pasture, and range (Table 10.4). Due to high yields and mechanization, value of agronomic crops per unit of area are rather low. One need only recall the price received for a ton of hay produced to know that this is so. Therefore, rather large losses can be tolerated before they are of economic importance. However, losses are significant when everything is placed in the proper context.

1. Extent of Losses

Lamp and coworkers (1991) predicted, based on scout-generated population data for alfalfa weevil and potato leafhopper for the period 1983 to 1988, that weevil-induced damages ranged from $4.25 per ha in 1985 to $23.80 per ha in 1988. Leafhopper-induced damages ranged from $32.11 per ha in 1988 to a maximum of $66.12 per ha in 1987.

TABLE 10.4 Major Insect Pest of Forage Crops in the United States

Forage crop	Common name	Latin name
Alfalfa		
	Alfalfa weevil	*Hypera postica* (Gylh.)
	Blue alfalfa aphid	*Acyrthosiphon kondoi* (Shinji)
	Pea aphid	*Acyrthosiphon pisum* (Harris)
	Potato leafhopper	*Empoasca fabae* (Harris)
	Spotted alfalfa aphid	*Therioaphis maculata* (Buckt.)
	Threecornered alfalfa hopper	*Spissistilus festinus* (Say)
Corn		
	Chinch bug	*Blissus leucopterus* (Say)
	Corn earworm	*Heliothis zea* (Boddie)
	Northern corn rootworm	*Diabrotica longicornis barberi* (Smith & Lawrence)
	Western rootworm	*Diabrotica virgifera virgifera* (LeConte)
	Black cutworm	*Agrotis ipsilon* (Hunagel)
	Dingy cutworm	*Feltia ducens* (Walker)
	Variegated cutworm	*Peridroma saucia*
	European cornborer	*Ostrinia nubilalis* (Hubner)
Forage grasses		
	Chinch bug	*Blissus leucopterus leucopterus* (Say)
	Clear winged grasshopper	*Camnula pellucida* (Scudd.)
	Grasshopper	*Aulocara elliotti*
	Grasshopper	*Melanoplus* spp.
Sorghum		
	Chinch bug	*Blissus leucopterus* (Say)
	Corn earworm	*Heliothis zea* (Boddie)
	Sorghum midge	*Contarinia sorghicola* (Coq.)
	Green bug	*Schizaphis graminam*

Sources: Dicke and Guthrie, 1988; Higley *et al.,* 1989.

Further studies on the effect of alfalfa weevil, in combination with weeds, on declining alfalfa stands was reported by Latheef *et al.* (1992). Use of an improved cultivar, compared to Oklahoma common, resulted in 5.4 Mg ha^{-1} more alfalfa production during the 6th and 7th production years. At the end of the 7th production year, only the herbicide plus insecticide treatment of the improved cultivar (WL 318) had sufficient plant numbers to continue production. Summers and Gilchrist (1991) showed that alfalfa subjected to insect stress averages 18% less forage production over a 5-year period. The productive life of the stand was not influenced by insect stress. In this study, the effect of the Egyptian weevil (*Hypera brunneipennis* Boheman), pea aphid (*Acyrthosiphon pisum* Harris), and blue aphid (*A. kondoi* Shinji)—these three being the most destructive of the insects studied—on yield continued to be measured in second and third cuttings, even though the pests were not biologically active during that period. The physical injury was done prior to the first harvest. Water-stressed alfalfa has been shown to be unfavorable for leafhopper population growth (Hoffman *et al.*, 1991). The cause for the decline is not known, but speculation suggests that it may result from lower N content of water-stressed alfalfa or to changes in other components of host quality.

2. Method of Injury

Insects inflict two types of injury: direct and indirect. *Direct injury* refers to feeding on yield-producing organs, and, therefore, they have a greater effect on yield than does *indirect injury,* which refers to injury to nonyield-producing portions of the plant. The insects most detrimental to forage crops are mostly in the direct-injury class because they all feed on the leaves of grasses and legumes used for forage. For example, alfalfa weevil, blue alfalfa aphid, pea aphid, potato leafhopper (*Empoasca fabae* Harris), and spotted alfalfa aphid (*Therioaphis maculata* Buckton) all feed on the leaves of the plants. Pests of grass hay and pasture-range grasses, such as chinch bug (*Blissus leucopterus* Say), grasshoppers (*Aulocara elliotti, Camnula pellucida,* and *Melanoplus* spp.), and black grass bugs (*Labops* and *Irbisia* spp.) also feed on the economically important vegetative aerial portions of the plant. Some insects are more devastating year-in and year-out than are others, but all insects at one time or another across the vast area used in forage production have an economic effect on forage crops.

3. Important Insects in Perennial Forages

There are a number of insects that infest perennial forages (Table 10.4). The most serious and most persistent of these insect pests is alfalfa weevil. Without treatment every year, and in some locations from two to three times each year, the losses would constitute a significant proportion of the crop. There are two species of the weevil important in the United States—*Hypera postica* in all the temperate and humid areas, and Egyptian weevil, which is important in the desert southwest areas.

Potato leafhopper is an important insect on alfalfa throughout the northeast and the midwest sections of the United States. It feeds on the vascular fluids and at the same time it injects a toxin (Medlar, 1941) that induces cell formation that disrupts the vascular tissue and, consequently, photosynthesis and transpiration (Womack, 1984; Flinn *et al.,* 1990). Flinn *et al.* reported that feeding by *E. fabae* reduced photosynthesis by 60 to 80% (four and eight adult females, respectively, per plant), whereas Womack showed the reduction was approximately 34%. Yellow or red tips, called *hopperburn,* are visible signs of significant potato leafhopper damage (Ball, 1919). Retardation of growth is associated with reduced alfalfa yield (Hutchins and Pedigo, 1989; Flinn *et al.,* 1990) and total nonstructural carbohydrate accumulation (Onstad *et al.,* 1984; Flinn *et al.,* 1990). Kitchen *et al.* (1990) reported a 17% decline in shoot weight and a 30% decline in plant height as a result of potato leafhopper infestation. One of the premises of this study was that increased levels of soil K might result in reduced potato leafhopper damage to alfalfa. However, damage was not compensated for by increased fertilization with potassium. Delayed maturity has also been reported to result from potato leafhopper feeding (Kitchen *et al.,* 1990; Wilson *et al.,* 1979; Oloumi-Sedeghi *et al.,* 1988). In this same area, the pea aphid is an important problem. The spotted alfalfa aphid is important in the drier areas of the central United States—Missouri, Kansas, and Oklahoma. The threecornered alfalfa hopper is important in localized areas, as is the blue alfalfa aphid (CASC, 1993).

The threecornered alfalfa hopper (*Spissistilus festinus* [Say]) is recognized throughout the world as an important pest of alfalfa (Leath, 1990). This pest is particularly important because it girdles the stem and blocks translocation (Hicks *et al.,* 1984; Wilson and Quisenberry, 1987). In alfalfa, nymphas of the threecornered alfalfa hopper can reduce root carbohydrate reserves and stem regrowth after harvesting or after dormancy (Moellenbeck and Quisenberry, 1991).

Epidemics of grasshoppers are important in the Western United States, where vast areas of government-held range lands harbor a latent population that may explode when environmental conditions are favorable. It is evident from Table 10.4 that the perennial grass forages have no serious insect pests other than grasshoppers. The chinch bug prefers corn and sorghum to the perennial grasses or the small grains; however, it can cause localized damage when hot, dry conditions prevail. Heavy precipitation and low temperatures greatly increase egg and nymphal mortality (Hill, 1987).

4. Important Insects in Annual Silage Crops

The European corn borer, corn earworm, and chinch bug all have a direct effect on the production of silage corn. The effect of corn rootworms (northern rootworm and western rootworm) and cutworms (black cutworm, dingy cutworm, and variegated cutworm) is the result of indirect injury (Table 10.4). As for grain sorghum, the effect of chinch bug, corn earworm, green bug, and sorghum midge is direct (Table 10.4).

B. METHODS OF CONTROL

1. Cultivar Resistance

Unlike plant diseases, cultivar resistance to insect pests in perennial forage crops has been more difficult to attain. The major insect pest, alfalfa weevil, has blunted all efforts to develop resistance. Although efforts have been monumental (Barnes and Ratcliffe, 1969; Barnes *et al.,* 1969; Ratcliffe and Elgin, 1987, 1990), progress has been modest in this area with only two cultivars, Team (Barnes *et al.,* 1970) and Arc (Devine *et al.,* 1977), showing some tolerance to alfalfa weevil feeding. Unfortunately, Team and

Arc have been bypassed in their production capacity by new cultivars released in the 1980s and the early 1990s. New cultivars possessing more alfalfa weevil resistance may be near, but as yet have not been marketed.

Resistance in alfalfa to alfalfa weevil and potato leafhopper is found in erect glandular-haired *Medicago* species. Hybrid populations have been developed that possess a high degree of resistance to these two pests (Lenssen *et al.*, 1989). Both mechanical and chemical factors appear to be involved (Shade *et al.*, 1975; Johnson *et al.*, 1980a,b, 1981). Resistance in the larval stage is primarily mechanical (Shade *et al.*, 1975; Thompson *et al.*, 1978). Research has shown that the factor imparting resistance of *Medicago rugosa* (Desr.) to alfalfa weevil feeding may not be the lactone [(z)-oxacyclotridec-10-en-2-one] as was earlier reported (Doss *et al.*, 1989). Although this compound does inhibit weevil feeding, the concentration in the leaves of *M. rugosa* does not appear sufficient to result in the resistance to feeding exhibited by the plant (Doss and Johnson, 1991).

Other major alfalfa pests, notably blue alfalfa aphid, pea aphid, and spotted alfalfa aphid, have lent themselves to the development of cultivars with a high degree of resistance (CASC, 1998). No alfalfa cultivar should be selected for use that does not have resistance to these pests. Only recently has effective resistance to potato leafhopper in alfalfa been developed (Anonymous, 1997). These lines, in the first year of production trials, produced yields equal to conventional cultivars under conditions in which leafhoppers are controlled. Under noncontrolled conditions, their yields may be twice that of the conventional cultivars. Further research is required to assess the economic benefits of this development. Resistance in alfalfa to other chewing insects such as grasshopper has not been achieved. Other perennial legumes such as birdsfoot trefoil (*Lotus corniculatus* L.), crownvetch (*Coronilla varia* L.), and sainfoin (*Onobrychis viciifolia* Scop.) contain tannins, a natural inhibitor of insect predation.

The *Trifolium* spp. show a long list of pests. Elliott (1952) lists 14 species found to be a problem in red clover. Surveyed fields of red clover in Rhode Island and Michigan showed 37 and 67 species, respectively, of injurious insects (Kerr and Stuckey, 1956; Niemczyk and Guyer, 1963). An excellent review on insect pests of clover was published in 1985 (Manglitz). Perennial forage grasses, unlike these legumes, seem not to be inflicted with serious insect pests. The exception to this is grasshoppers in semiarid and arid areas, where hoards of these insects can occasionally cause significant losses.

2. Insecticide Use

Insecticide use has been prevalent since the end of World War II when DDT first became readily available. Identification of the pest causing the problem is a key to successful use of insecticides. Two particularly useful publications, with respect to insecticide use, are *Farm Chemicals Handbook* (Meister, 1999a) and *Insect Control Guide* (Meister, 1999b). These publications are updated and published annually. Their focus, like the *Weed Control Guide* (Meister, 1998), is on chemicals that may be used to control the various pests on specific crops. Other publications are available also, particularly from state extension services in the United States and Canada's agricultural research and extension arm, Agriculture Canada. Specifically, if a particular insect is a problem in a section of the country, published information provided by the State Extension Services is available. In addition, where pests are important over a wide area or a crop is of particular significance, useful regional publications are available through the state extension services of states within the region. For example, a key for identifying armyworms and cutworms that attack corn in the northcentral United States has been developed by Rings and Musick (1976). Rings (1977) also published a reference for common cutworm, armyworms, and looper moths in the northcentral states. Knutson *et al.* (1983) provided a key to the identification of grasshoppers.

3. Integrated Pest Management

Control of alfalfa weevil is effected in a number of ways: natural environment; use of pesticides solely; use of pesticides coupled with insect scouting; and pesticides, scouting, and use of natural predators and pathogens (Hornby *et al.,* 1987). There are a number of good guides to production and integrated pest management of alfalfa (Edwards, 1986; Anonymous, 1985), but none are available for the perennial legumes and the perennial grasses.

The alfalfa weevil is a serious pest of alfalfa in almost all parts of the United States and southern Canada. In some areas such as the northeast and the northern portions of the United States (north of 30°N), there is one well-defined oviposition period that gives rise to one generation of larvae (Horn, 1988). The autumn-laid egg seldom survives the winter in this area (Wilson, 1984), but throughout the alfalfa-growing areas south of this latitude, survival is possible. This provides an early generation of larvae that can cause significant damage to young, vegetative growth. Spring-laid eggs provide a second generation, and a third generation may even occur. It is extremely important to know the time at which the eggs are laid for each cycle and the relationship of development and the environment so that insecticides may be used in conjunction with the buildup in population. In the northern areas of the United States and southern areas of Canada, weevil population buildup may not become a problem until the herbage growth is 30 to 50 cm (12–20 in.) high, and the best management is to cut the alfalfa. Exposure to the sun and wind often kills the larvae. However, under wet, humid, and overcast conditions this may not occur and failure to apply an insecticide can cause significant damage or loss of the stand in extreme cases. Areas in which the fall-laid eggs survive experience problems earlier and require application of an insecticide before the herbage is ready to harvest. In these cases, a second application may also be required.

When alfalfa weevil damage potential is high, monitoring of the fields is a primary part of good management. This includes sampling the field using an M-shaped pattern (Wilson, 1984), which includes at least five samples. The sampling steps are as follows:

1. Enter the field, collect an initial random sample of alfalfa, and shake the larvae from the foliage into a bucket. The very young larvae will not be dislodged in this manner and the young terminal leaves must be unfolded to release them. Count the number and measure the length of each stem and record this information. Consider this the bottom of the left leg of a letter "M." From this point, move to the top of the left leg of the "M" and take a second sample, then to the bottom of the "M" for third sample, to the top of the right leg of the "M" for the fourth sample, and finally to the bottom of the right leg for the fifth sample. After each sample, shake the larvae into the bucket as described previously. Count the larvae and average the number per stem.
2. Examine each stem and record the presence or absence of feeding in the stem tip. Tiny pinholes are evidence of larval feeding, but other signs may be present also. Determine the percentage of infested stems from these observations.
3. Measure the length of each stem to the nearest inch. Total these lengths and determine the average length of the stems collected.

With this information, the control decision can be made. The *economic threshold* is dynamic, and changes with the height of the alfalfa. As mass of material present increases, the amount of infestation required to reach the economic threshold increases. Once this economic threshold is reached, it signals the need for control if loss is to be prevented (Table 10.5).

Lamp and coworkers (1991), working in Maryland with scout-generated data from 1983 to 1987, reported that the cost, with respect to costs and returns, were lowered by \$3.11 ha^{-1} if insecticide application to control alfalfa weevil and potato leafhopper was coordinated with insect scouting. In comparison, the scouting–insecticide program cost \$20.91 and \$17.80 per ha^{-1} less than common insecticide application programs not coupled with scouting.

Examples of natural predators are *Bathyplectes curculeonis* (Thompson) and *Peridesmia dicus,* both parasitic wasps, and *Erynia phytonomis* (Arthur), a pathogen. Goh *et al.* (1989a) found that the pathogen *Erynia* is pathogenic to both alfalfa weevil and bathyplectes. However, even though for a short period of time, 1983 to 1986, they showed that the pathogen reduced survival of the parasitic wasp by more than 90%, they were not willing to say that it has had a long-term effect on the bathyplectes population. Goh *et al.* (1989b) did show that *Erynia* reduces alfalfa weevil populations.

TABLE 10.5 Economic Thresholds for Alfalfa Weevil Pest Management Decision Making

Heat units[a]	Plant height (inches)		Stem tips with feeding (%)	Decision
300	<6		25[b]	Reevaluation in 7 days. If the number of weevil larvae average at least one per stem and damage is increasing, spray with a long residual insecticide.
400	9		50	Spray with a long residual insecticide if weevil larvae average one or more per stem.
500	12		75	Spray with a short residual insecticide. If field is cut at this time, reevaluate field after cutting and treat within 7 days if weevils are still active.
600	15+	or	75–100	Best to cut and remove crop; spray stubble at the bud stage, within 7 days if weevil are still active.
750	Short or regrowth		50 on regrowth	If no regrowth within 4–5 days of cutting and weevils are present, feeding on "bark" of old stems, spray immediately.
800				Beyond need for control measures. Weevil population gone or declining rapidly.

[a] Heat unit accumulation above a base temperature of 48°F from January 1.

[b] Counts of larvae in addition to feeding are advised because mortality of winter-hatching larvae frequently occurs, and treatment at this stage may be too early.

Source: Wilson, 1984.

Larvae infections often exceeded 60% and the number of insecticide applications was often reduced. *Peridesmia* was first released in the United States in 1972 (Dysart and Day, 1976). The wasp is now reported in 41% of the surveyed fields in New Jersey, Pennsylvania, Delaware, Maryland, Virginia, and West Virginia (Dysart, 1989). Recovery-site data from North Carolina, South Carolina, Georgia, and Tennessee also show that 5.3 to 16.7% of the overwintering weevil eggs were destroyed by *Peridesmia* (Dysart, 1988).

Management and dormancy of cultivars may also influence the alfalfa weevil population. For example, Reid *et al.* (1989) reported that less-dormant alfalfa cultivars, because they did not cease growth in the autumn, provided a more suitable habitat for alfalfa weevil egg and larvae populations. The more dormant cultivars harbored egg populations of 69 eggs per 0.025 m^2, whereas the less-dormant ones had 117.5 eggs per 0.025 m^2. Larval populations were 99 and 120 larvae per 25 stems, respectively. In Oklahoma, Dowdy *et al.* (1992) demonstrated that removal of alfalfa by either late fall harvesting or grazing held the potential to delay occurrence of peak larval numbers up to 10 days if most eggs were laid in the fall. Larval number per stem was not changed with changing stem density and various intensities of weed infestation, but larval numbers per unit area increased with greater stem densities. Incidentally, these management treatments tend to promote stand longevity. Grazing after autumn frost, which has been shown by work in Nevada (Jensen *et al.*, 1981) to not be detrimental to alfalfa stand longevity, would provide two benefits: reduced stems for overwintering of alfalfa larvae, and feed for cattle with low maintenance requirements.

The use of the environmentally friendly *Bacillus thuringiensis* exotoxin had been tried in Georgia (Wilson *et al.*, 1984) with encouraging results. In these laboratory tests, a dipping technique was used in which solutions of 0.2, 0.02, 0.002, and 0.0002% active ingredient (a.i.) were applied. Mortality was comparable to field rates of carbofuran at the third stage larvae within 48 h and with adults in 5 to 9 days at the rate of 0.2%.

The burning of alfalfa stubble to control weevil populations in areas where the weevil overwinters has been studied by Schaber and Entz (1991). Response depended largely on the season. They reported that immature alfalfa weevil populations were significantly reduced by the burn-every-autumn treatment in 3 of the 8 years; in 2 out of 8 years in the burn-every-spring treatment; and by the alternate-year-burn treatment in 1 out of 4 years. Although burning is sometimes effective in controlling some insects, it is reported to have little or no effect on pea aphid populations (Schaber and Entz, 1991).

In the latter years of a stand it is important to control weevil and weeds if the stand is to remain reasonably productive. Without such control, Latheef *et al.* (1992) showed that first-harvest yields were reduced approximately 52% (3.72 to 1.79 Mg ha^{-1}). Buntin (1989) reported that stubble defoliation by weevil increased survival of annual weeds such as large crabgrass, redroot pigweed, and common lambsquarter. Furthermore, defoliation decreased stored carbohydrates in the roots. Severe defoliation of stubble by weevil apparently reduces competitiveness of alfalfa. In a short-term greenhouse study, defoliation of alfalfa by yellow striped armyworms (*Spodoptera onithogalli* (Guenée) reduced plant height (18%) and yield (33%), but root carbohydrate reserves were not affected. Defoliation in this study did not increase severity of *Fusarium* crown-rot in alfalfa (Lee *et al.*, 1990).

C. FORAGE YIELD AND QUALITY

1. Yield

Yield reductions occur when forages are infested by insects such as alfalfa weevil and grasshoppers that cause direct damage by removal of all or a portion of the leaves. Insects that suck fluids from the leaves or stems cause, through enzymatic reactions, a loss of chlorophyll and leaf senescence, which also results in reduced yields. Although Wilson and Zajac's work (Wilson, 1982) does not provide quantitative data on alfalfa yield reduction caused by potato leafhopper infestations, they do show a very significant decrease in plant height as leafhoppers per sweep increased from 5 to 100. Plant height decreased from 40 cm when 5 leafhoppers were collected per sweep to 12 cm at 100 insects per sweep. Eight nymphs attacking a stem, in a field study, resulted in a 56.6% reduction in dry weight (Hower and Flinn, 1986).

2. Quality

Quality of forages can be altered significantly by insect infestation. For example, Moellenbeck *et al.* (1992), in a greenhouse study of threecornered alfalfa hopper showed that this insect reduced CP and IVDDM (up to 17.5 and 4%, respectively, in some harvests). Acid detergent fiber (ADF) and neutral acid fiber (NDF) were increased by feeding of the threecornered alfalfa hopper by approximately 6 and 14%, respectively. This is typical of what one would expect from leaf-feeding insects because forage quality is closely related to the proportion of leaves in the legume forage. Hower and Flinn (1986) reported that protein was reduced by up to 29.5% when eight nymphs were present per stem. Under moderate potato leafhopper infestation, Hutchins *et al.* (1989) concluded that potato leafhopper feeding had no affect on total forage quality.

IV. DISEASES

A. IMPORTANCE OF CONTROL AND EXTENT OF ANNUAL LOSSES

It was emphasized in the beginning of this chapter that accurate estimates of losses due to diseases are difficult to obtain. However, with approximately 50% of the total land area of the United States used for forage crop production, it is safe to assume that total losses are significant. This is emphasized by the 1953 estimate of losses to all crops in the United States of $3 billion (Wood, 1953) and by the estimate for white clover losses in North Carolina of $42.2 million or more in 1986 (Main and Byrne, 1986). Total loss to diseases for all forage crops in the United States has been estimated at $834 million annually (based on 1965 data). This figure represents about one-fourth of the loss for all crops (James *et al.,* 1991). It is interesting to note that 24% of the losses from diseases in forage crops is recorded by alfalfa (Table 10.6).

B. IMPORTANT DISEASES

Diseases that significantly affect alfalfa production vary from one place to another because of environmental conditions. Temperature, precipitation, and humidity are all factors that influence pathogen development.

TABLE 10.6 Estimated Losses Due to Diseases of Hay and Pasture Crops in the United States

	Annual losses	
Crop	Percent	($ millions)[a]
Alfalfa (hay)	24	389
All other hay	15	226
Forages for seed	4–52	24
Cropland pastures	9	77
Forestland pastures	3	16
Grassland	5	102
Total		834

[a] Based on 1951 to 1960 values. To adjust the dollar values to 1998 values multiply by 5.4%.

Source: James *et al.*, 1991.

Diseases important in various sections of North America are presented in Table 10.7. Sampson (1954) discusses diseases of grasses and legumes grown in Britain.

Other diseases of alfalfa are of localized importance. For example, fusarium crown rot (*Fusarium oxysporum* [Say]) is an important alfalfa pest in Louisiana (Lee *et al.*, 1990).

C. EFFECT ON YIELD AND QUALITY

1. Yield

Yield decreases may result from pathogen infection. Richard *et al.* (1980) showed that significant alfalfa stand decline and yield reduction resulted from fusarium crown-rot. Greater damage has been shown to occur, however, when fusarium crown-rot is combined with plant stress caused by foliar diseases, untimely harvests, severe winter conditions, or insects (Leath, 1990; Leath and Byers, 1977). Leath and Byers (1977) reported that fusarium root-rot increased in alfalfa plants stressed by the pea aphid (*Acyrthosiphon pisum* [Harris]). Godfrey and Yeargan (1987) demonstrated similar effects for root-rot fungus and clover-root curculio, *Sitona hispidulus* (F.). Anthracnose (*Colletotrichum trifolii* Bain) reduces alfalfa yield by an average of 7% in the United States (Elgin *et al.*, 1981). Verticillium wilt (VW) is related to 20 to 56% of the variation in alfalfa herbage yield (Papadopoulos *et al.*, 1989).

Verticillium was first reported in alfalfa fields in Oregon and Washington

TABLE 10.7 Important Diseases of Alfalfa, Clovers, and Birdsfoot Trefoil

Common name	Scientific name	Area of distribution
Alfalfa		
Bacterial wilt	*Cornebacterium insidiosum* (McCull.) H. L. Jens.	All continental United States except for the south: Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina, North Carolina, Tennessee, Virginia, Arkansas, and Oklahoma. (Mountainous regions of Georgia, South Carolina, North Carolina, Kentucky, Virginia, and Arkansas are affected by the disease.)
Phytophthora root rot	*Phytophthora megasperama* sp. *medicaginis*	All continental United States except northeast states.
Fusarium wilt	*Fusarium oxysproum* f. sp. *medicaginis*	All continental United States
Crown rot	Caused by one or more species of *Fusarium, Rhizoctonia, Phoma, Staganospora,* or *Colletetrichum*	All continental United States
Schlerotinia stem rot	*Sclerotinia trifoliorum* Eriks.	Pacific states, intermountain region, and the area east of the 100th meridian with the exception of the Floridian peninsula.
Verticillium wilt	*Verticillium albo-atrum* Reinke & Berth	Pacific northwest, intermountain area to approximately the 30th parallel, and southern half of Wisconsin.
Anthracnose	*Collototrichum trifolii*	Pacific states, southwest states, north from the Mexican border to central Nebraska, southern Minnesota, and central Wisconsin and New York.
Rhizoctonia stem and root canker	*Rhizoctonia solani*	All continental United States
Common leaf spot	*Pseudopeziza medicaginis*	All continental United States, with infestation in the southwest and intermountain states less of a problem.
Lepto leaf spot	*Leptosphearulina briosiana*	Great Plains (except for Texas) and prairie states and all states east of the Mississippi River. Most serious infestation is in the northcentral and northeast states.
Stemphylium leaf spot	*Stemphilium botryosum*	All continental states except for the intermountain area, Nebraska panhandle, western half of South Dakota, and all of North Dakota and Montana, and northern one-fourth of Minnesota. Most serious in the southeast and along the Pacific Coast.
Spring black stem	*Phoma medicaginis*	All continental United States. Less serious in the intermountain and southwest states and southern two-thirds of California.

Summer black stem	*Cercospora medicaginis*	Continental United States with the exception of V-shaped corridor extending from northwest New Mexico to northwest Washington on the west and to northcentral North Dakota on the east, and the northeastern states. Most serious infection is in the Midwest and southeast.
Bacterial leaf spot	*Xanthomonas alfalfae*	All states east of a line drawn from southwest Arizona to northwest Wisconsin, with the exception of northern New York, and states north and east of there. Most heavily infected area is Missouri and contiguous states.
Downey mildew	*Peronospora trifoliorum*	All continental United States.
Alfalfa mosaic virus		All continental United States
Red clover		
Crown rot	*Sclerotinia trifoliorum* Eriks.	One of the more destructive diseases in the southern part of the clover belt.
Root rot	*Fusarium oxysporum* Schl.; *F. roseum* Link.	Temperate, humid regions.
Northern anthracnose	*Kabatiella caulivora* (Kirch.) Karak.	Occurs from Massachusetts to Minnesota and south to Delaware and Missouri; most destructive in wet weather at temperatures of 20–25°C.
Southern anthracnose	*Colletotrichum trifolii* Bain	Southeastern United States; reported as far north as Canada, but not of significant consequence.
White clover		
Stolon and root rot	Species of *Fusarium, Rhizoctonia, Colletetotrichum, Leptodiscus,* and *Curvularia.*	All white clover growing areas.
Pepper spot	*Leptosphaerulina trifolii* (Rostr.) Petr.	During cool weather.
Cercospora leaf and stem spot	*Cercospora zebrina* Pass.	Throughout the season.
Curvularia leaf spot	*Curvularia trifolii* (Kauff.) Boed.	During warm, humid weather.
Sooty blotch	*Cymadothea trifolii* (Pers. ex Fr.) Wolf	During cool seasons.
Rust	*Uromyces trifolii* var. *trifoliirepentis* (Liro) Arth.	In late summer and fall.
Birdsfoot trefoil		
Crown and root rot complex	Species of *Fusarium, Verticillium, Macrophomina, Mycoleptodiscus, Rhizotonia,* and *Sclerotinia.*	Of greater importance in the south.
Leaf and stem lesions	*Stemphylium loti* Graham	Most widespread disease of leaves and stems; causes reddish-brown leaf and stem lesions and results in premature leaf drop.
Crown and stem rot	*Sclerotinia trifoliorum* Eriks.	Under heavy snow in late winter or early spring.

Sources: CASC, 1993; Heath *et al.,* 1973; Kreitlow, 1953.

in 1976. It was at first thought that this pest would not spread out of the northwest, but it has now been reported in 13 states and two Canadian provinces. The effect of VW on dry-matter production becomes progressively more important as the stand ages. Yield of susceptible cultivars will not be affected during the seeding year; in the second year, yield of susceptible cultivars will be reduced by about 7 to 15%; and in the third year, dry matter production will be reduced from 22 to 33%. In the third year, comparative figures were 22% and 33%. In Wyoming, a 1990 survey (Page *et al.,* 1990) revealed that most of the irrigated alfalfa fields in the state are infected with VW. It is estimated that infected fields lose, on the average, approximately \$71.18 ha^{-1} (\$28.82 acre^{-1}). This translates to statewide losses of \$1,990,308 annually, and an average of 1 Mg ha^{-1} (0.45 t acre^{-1}) of dry matter in infected fields.

2. Quality

Because an important component in forage quality is the proportion of leaves retained in the hay sample, diseases that tend to reduce the number of leaves have an adverse affect on alfalfa quality. Diseases that do not alter the leaf-stem ratio do not affect forage quality. An example of the latter is fusarium crown-rot (*Fusarium oxysporum* Schlecht.), which was reported by Moellenbeck *et al.* (1992) to not alter number of harvestable stems, ADF, CP, NDF, and IVDDM.

D. TYPE OF CONTROL

1. Cultivar Resistance

In forage crops, the most important factor in avoidance of losses from diseases is cultivar resistance. Great strides have been made since the late 1970s, and it behooves the grower to know about and use cultivars that carry resistance to diseases important in their area. Lists of crops and the diseases for which they are wholly or partially resistant are available (Shaner, 1991; Stevenson and Jones, 1953) and show resistance in a widely divergent group of forage crops, including corn, sorghum, bahiagrass, bermudagrass, bromegrass, orchardgrass, tall fescue, alfalfa, red clover, white clover, and white sweetclover. Some very important steps were taken when resistance to bacterial wilt, phytophthora root-rot, lepto leaf spot, and VW, among many others, was introduced into alfalfa in the late 1940s. Since the early 1980s, remarkable progress has been made in disease resistance in alfalfa. The response of more than 220 alfalfa cultivars to the major diseases is provided in the annual Certified Alfalfa Seed Council (CASC, 1998) publication. The levels of tolerance and their descriptions are shown in Table 10.8.

When alfalfa is seeded, far more seeds are sown than are required to provide optimum yields from a mature stand. This practice is followed to assure an adequate stand because of the uncertainty associated with seeding

TABLE 10.8 Indications of Tolerance/Resistance

Code	Meaning	Description
S	Susceptible	0–5% of the plants are resistant
LR	Low resistance	6–14% of the plants are resistant
MR	Moderately resistant	15–30% of the plants are resistant
R	Resistant	31–50% of the plants are resistant
HR	Highly resistant	>50% of the plants are resistant

Source: CASC, 1998.

of small-seeded forage crops. Plants that die during the first year of production will likely be the most susceptible ones; thus, concentrating the percentage of resistant plants in the final, mature stand.

Disease resistance, incorporated into new cultivars in plant-breeding programs, is the most important means of control of diseases in all perennial forage crops. Cultivars also have specifically bred resistance to diseases in a specific area; thus, they may not perform well in other areas in which other diseases are prevalent. For these reasons, information should be obtained from local extension and research agencies about adapted cultivars.

2. Diseases of Grasses used for Forage

Although perennial grasses make a large proportion of crop acreage, the amount of research done on them is limited. This is related to the relatively low return per unit of production and the lack of economic incentive for proprietary breeders to develop new disease-resistant lines. The most important diseases of grasses are presented in Table 10.9. The annual forage crops, especially corn and sorghum, have been researched extensively largely because they are so important as producers of feed grains. Their utility as silage crops has benefitted from this research when it comes to yield and disease management. Resistance to important diseases largely comes about because of plant breeding efforts or because of inherent resistance resulting from selection.

3. Fungicide Use

Fungicides are seldom used on forage crops, other than corn and sorghum, because they produce very little economic return.

V. OTHER PESTS

A. NEMATODES

Nematodes are important pests of alfalfa. Stem nematode (*Ditylenchus dipsaci* [Kuhn] Filipjev) is a major pest in areas under irrigation in the

TABLE 10.9 Important Diseases of Perennial and Annual Grasses Used for Forage

Forage crop	Disease (common and scientific names)	Comments
Temperate grasses		
Orchardgrass	Brown stripe (*Scolecotrichum graminis* Fckl.)	
	Leaf scald (*Rhynchospurium orthosporum* Cald.)	
	Rust (*Puccinia* spp.)	A significant number of rust diseases, representing a number of species, infect the leaves and stems.
	Leafspots	
	(*Mastigosporum rubricosum*)	Northwest United States
	(*Staganospora maculata*)	Northeast United States
Smooth bromegrass	A bacterial disease (no common name given; *Pseudomona coronafaciens* var. *atropurea*)	
	Brown stripe (*Scolecotrichum graminis* Fckl.)	
	Septoria leaf spot (*Septoria bromi*)	
Timothy	Stem rust (*Puccinia graminis* var. *phlei-pratensis* (Eriks. & E. Henn.) Stakman & Piem.	Controlled by use of resistant cultivars.
Perennial ryegrass	Leaf scald (*Rhynchospurium orthosporum* Cald.)	
	Brown rust (*P. dispersa* Eriks. & E. Henn.)	
Tall fescue	Leaf scald (*Rhizoctonia solani*)	All of these diseases are a problem mostly in the south.
	Net blotch (*Helminthosporium dictyoides*)	In the temperate zones no disease problems are listed.
	Leaf spot (*Cercospora festucae*)	
Bluegrass	Powdery mildew (*Erysiphae graminis* DC)	
	Leaf and stem rust (*Puccinia* spp.)	
	Stripe smut (*Ustilago striiformis* (West.) Niessl.)	
	Eye leafspot (*Helminthosporium vagans* Drechsl.)	
	Anthracnose (*Colletotrichum graminicola* (Ces.) G. W. Wils.)	
Warm-season grasses		
Bermudagrass	No serious diseases.	
Bahiagrass	Leaf blight (*Helminthosporium micropus* Drechsl.)	Relatively free of diseases.

Sources: Heath *et al.*, 1973; Kreitlow, 1953.

western United States and in areas of high rainfall and heavy spring rains (Graham *et al.,* 1979). It is usually associated with heavy soils. Infected stems enlarge and are often discolored, nodes swell, and the internodes are shortened. Stem nematode is the most economically devastating of the nematodes to infest alfalfa. Stands may become economically nonviable within 2 to 3 years after infestation (Faulkner and Bolander, 1966).

Root-knot nematode (*Meloidogyne* spp.) is the most widely disseminated plant parasitic pest in the world. It is usually favored by sandy soils, although it is present in all soils. Large populations build up on alfalfa, but more damage is caused to crops that follow alfalfa. Thus, care should be exercised to understand the consequences of planting certain crops after alfalfa. A scenario exists in which *M. incognita* apparently increases the incidence and severity of fusarium wilt (Graham *et al.,* 1979). Roots of plants infested with root-knot nematode become knotted and deformed and plant growth is stunted (Chapman, 1960).

There are three species of root-knot nematode that are of economic importance on alfalfa: northern root-knot nematode (*M. hapla* Chitwood), southern root-knot nematode (*M. incognita* [Kofoid & White] Chitwood), and Javanese root-knot nematode (*M. javanica* [Treub] Chitwood). The northern root-knot nematode is most frequently found in areas in which dormant or hardy alfalfa cultivars are grown. The southern and Javenese root-knot nematodes are primarily adapted to areas in which nondormant or semidormant alfalfa cultivars are grown (Elgin *et al.,* 1988).

Nematode infestation and severity of economic consequences have not been well established for other perennial forages. A survey by McGlohon and coworkers (1961) suggests that nematode prevalence among forage crops probably warrants greater attention. Alfalfa cultivars have been developed with low to high resistance to the stem nematode. Most new cultivars have this resistance; thus, they should be used because they yield as well as or better than older cultivars that do not possess resistance (CASC, 1998). Root-knot nematode (*Meloidogyne* spp.) resistance has not been incorporated into as many cultivars. Cultivars that do possess some resistance are rated as moderately resistant (CASC, 1998).

B. VIRUSES

1. Alfalfa

Twelve viruses have been described on alfalfa, but the biology, distribution, and importance of only three of them, alfalfa mosaic virus (AMV), alfalfa enation virus (AEV), and transient streak virus (TSV), have been investigated (Graham *et al.,* 1979).

AMV was first described in 1931 and occurs worldwide. Infection can range from mild to very severe because of the variation within both the pathogen and the host. Classic symptoms are interveinal light green or yellow mottle accompanied by stunting (Graham *et al.,* 1979; Plate 41). The AMV complex is composed of many strains differing in infectivity and several other characteristics. Strains of this virus are reported to infect at least 220 plant species representing approximately 73 genera. Use of virus-free seed is the first line of defense against AMV. Insect control, especially aphids, also assists in control of AMV by reducing its rate of spread. All alfalfa cultivars are susceptible to AMV, but about 20% of the plants in most cultivars may show resistance to specific strains.

The other two virus, AEV and TSV, have been described in Europe and Australia, respectively. No control methods have been established for either virus (Graham *et al.,* 1979).

2. Clovers

Trifolium sp., especially red clover and white clover, are infected by viruses. In a review of clover viral diseases, Barnett and Diachun (1985) listed 41 viruses that afflict the clovers.

Bean yellow mosaic virus (BYMV) is the most common virus of red clover. It has also been known by a host of other names (Barnett and Diachun, 1985). It is worldwide in distribution, and also causes important diseases in crimson, subterraneum, and arrowleaf clovers, in addition to bean and pea. Less prevalent are red clover vein mosaic virus (RCVMV) and AMV. From 25% to 35% of randomly sampled red clover plants in Pennsylvania were infected with viruses. Approximately 70% were BYMV, and RCVMV and AMV were encountered much less frequently (Leath and Barnett, 1981). Wisconsin surveys showed that BYMV was most commonly found in red clover, although RCVMV infected one-third of the plants surveyed (Hanson and Hagedorn, 1971). Evidence suggests that BYMV isolates that infect pea but not bean are most commonly found in red clover (Barnett and Diachun, 1985).

White clover is generally infected with clover yellow vein virus (CYVV), RCVMV, white clover mosaic virus (WCMV), pea streak virus (PStrV), and AMV (Barnett and Diachun, 1985). Nineteen randomly sampled pastures in the southeastern United States showed that 37% of the white clover plants sampled were infected with viruses (Barnett and Gibson, 1975). Greater than 85% of the plants in some pastures were infected, but younger pastures showed far less infection and newly seeded pastures showed no viral infections. Viruses present were AMV (7 pastures), CYVV (15 pastures), pea stem virus (PSV, 14 pastures), and WCMV (5 pastures). The greatest infection in any one pasture by a given virus was PSV, 74%; WCMV, 53%; AMV, 47%; and CYVV, 47%. PSV is very frequent in the eastern United States, but is rarely isolated in western fields of white clover (Barnett and Diachun, 1985). More common in western fields are WCMV and CYVV.

C. RODENTS

Rodents can cause considerable damage in alfalfa fields and in other forage crops. Most reports of control, however, refer to alfalfa, especially in irrigated areas. Some irrigated areas experience severe infestations of pocket gophers. The Nevada Department of Agriculture indicates that pocket gophers are the worst problem that alfalfa growers face in Nevada (Behling, 1993). Primary among control measures are:

1. Mechanical burrow builder-bait applicators, which are available in three-point hitch or pull-type models. These machines apply bait while making an artificial burrow. Grain, laced with a poison, is used as bait. Soil moisture must be high enough so that the artificial burrows do not cave in. Use the burrow builder-bait trap in both autumn and early spring. Followup each baiting operation with hand-baiting and trapping between harvests. Fresh bait such as alfalfa or carrots works best because it is difficult to get the pocket gophers to eat grain when they have fresh alfalfa available.
2. Gas cartridges may also be used, especially if the infestation is low. They look like firecrackers, are 5 cm (2 in.) long and about 4 cm (1.5 in.) in diameter. They are lit and placed in the burrows, where the emitted smoke suffocates the gophers.
3. Rotation from alfalfa to small grains helps control the gopher population because small grains cannot support the population an alfalfa field can.

Guidelines for gopher control include: (1) One gopher is too many gophers. Control immediately so that population explosions do not occur. (2) The best time to control gophers is now. (3) Use every control technique available. The more you work at it the better gopher control will be. (4) Be systematic by eliminating gophers from your farm one field at a time. Another excellent source of information on rodent control is published by the University of California (Orloff and Carlson, 1995).

11

SOIL FERTILITY AND FORAGE PRODUCTION

- I. Introduction
- II. Determinants of Soil Fertility
  - *A. Parent Material*
  - *B. Geologic Classification of Parent Material*
- III. Soils
  - *A. Soil Acidity*
  - *B. Lime Requirements of Acid Soils*
  - *C. Nutrient Availability and Soil pH*
  - *D. Response to Lime Application*
- IV. Nutrients and Plant Growth
  - *A. Nitrogen*
  - *B. Phosphorus*
  - *C. Potassium*
  - *D. Calcium and Magnesium*
  - *E. Sulfur*
  - *F. Micronutrients*
- V. Soil Nutrients and Dinitrogen Fixation
  - *A. Nitrogen*
  - *B. Potassium*
  - *C. Calcium*
  - *D. Sulfur*
  - *E. Boron*
  - *F. Molybdenum*
- VI. Aluminum Toxicity
- VII. Soil Sampling and Testing

I. INTRODUCTION

Soil fertility refers to the power or ability of soil to supply nutrients required for optimum growth of crops. *Soil productivity* refers to the ability of the soil to sustain and produce a crop; low productivity equals a poor crop or low yield and high productivity means a good crop or high yield. To maintain a high-producing forage stand, nutrient removing power of the crop, especially P and K for legumes and N, P, and K for grasses, must be considered. Remedial actions must replace nutrients removed, especially on soils with low nutrient supplying power.

When the United States was first settled the soils were very fertile. However, by the 1930s, soils in many temperate humid areas of the United States were depleted of their native fertility, and economical production of crops was impossible. This was particularly true throughout much of the area east of the Mississippi River. Agronomists at the time, under the leadership of Emil Truog, rallied to the call and began promoting the use of fertilizers to enhance and restore production capabilities of the soils (Truog, 1938). Sixty years later, however, the great need for use of massive amounts of fertilizer in these areas may not exist because fertilizer practices have built up the nutrient-supplying power of many of these soils (Thomas, 1989).

In the arid west, many soils are high in their ability to supply P and K; thus, neither have ever been applied as a fertilizer in some areas. However, after 75 to 150 years of such practices, some of these soils are beginning to show deficiencies of P and K (James *et al.,* 1995). Whether in arid, semiarid, or in temperate, humid regions, economic discretion requires that fertilizer be used only where required, but not to excess. It is, therefore, important to recognize these potential nutrient-supplying differences of various soils and to use soil tests to establish a baseline for each element and then manage accordingly.

Knowledge of the amount of a nutrient available to plants in a soil is important. A quantitative estimate may be obtained through accepted soil-sampling and laboratory procedures. These measures must be correlated with yield response (Fisher, 1974) in a given area to be reliable. The technique and protocol followed in taking the soil sample from the field is as important as the chemical analyses performed in the laboratory. Improper soil sampling techniques will invalidate laboratory results. Soil testing protocol is discussed in the last section of this chapter.

II. DETERMINANTS OF SOIL FERTILITY

Soil fertility is determined by (1) parent material; (2) climate, particularly temperature and precipitation; (3) living organisms (native vegetation, microbes, soil animals, human beings); and (4) duration of time the parent materials are subjected to soil formation (Brady, 1990).

A. PARENT MATERIAL

Parent material, along with climate, determines the kind and quality of soil and, with the exception of N, the majority of the elements in a soil are inherited from the parent material (Jenny, 1980). The chemical and mineral composition of parent material can influence weathering directly, and at the same time can affect naturally occurring vegetation. Parent material can also influence quantity and type of clay minerals present in the soil profile (Brady, 1990). Quartz-rich rocks are acid igneous rocks (silicon forms very weak acids) and rock low in quartz is basic igneous rock, and in the extreme it is low in Al, Ca, K, and Na, but high in Mg. In basic igneous rock, the profusion of black biotite, blackish horneblende and augite, and green olivine results in dark soils. Their high base and P concentrations favor the genesis of productive soils (Jenny, 1980). The difference between soils formed from acid igneous and basic igneous rocks is shown in Table 11.1. Soils in humid, temperate regions formed from basic rocks are usually more fertile when compared to soils formed from acid rocks. They are commonly higher in organic matter, P (much of it fixed), clay, silt, montmorillonite, and reddish-brown "chroma and hue" (color) (Buol *et al.*, 1989).

Igneous rock has an average P_2O_5 concentration of 0.37%, or 162 mg kg^{-1} P (Clarke, 1924). Phosphorus is present mostly in the mineral apatite. Basic igneous soils average 0.89% P_2O_5 (390 mg kg^{-1} P) (Jenny, 1980). Sedimentary rocks have P associated with Al and Fe oxides, which lower

TABLE 11.1 Mean Composition of Soils Formed from Acid and Basic Igneous Rock

Soil properties	Acid igneous soils	Basic igneous soils
Clay (%)	11.6	21.2
Silt (%)	21.2	33.0
Sand (%)	58.0	34.5
C (%)	1.74	2.88
N (%)	0.074	0.121
Bases (me/100g)	5.33	10.86
1st principle components of clays	Vermiculite Illite Quartz Montmorillonite	Montmorillonite Illite Gibbsite Haloysite

Source: Jenny, 1980, p. 254.

solubility. Shales average 0.27% P_2O_5 (87 mg kg^{-1} P) and limestones average 0.04% P_2O_5 (17 mg kg^{-1} P). As $CaCO_3$ weathers, P concentration in the residual increases, thus benefitting plant growth (Jenny, 1980). In the prefertilizer era, soils from limestones were valued for their high productivity. Such soils may have as much as 5.34% P_2O_5 in the B2 horizon. The bedrock of this soil has 2.76% P_2O_5 (Jenny, 1980). However, not all carbonate-derived soils are endowed with lasting fertility, as the Ozark highly weathered cherty limestone soils showed (Jenny, 1980). In Scotland, basaltic soils have almost twice the P as the granitic soils (Jenny, 1980). Quartzite, a metamorphic, acid, pure quartz, is essentially infertile. Ultrabasic rocks, such as serpentine, give rise to "barrens," soils with an imbalance of nutrients and a higher than normal Mg concentration (Buol *et al.,* 1989).

The high annual precipitation and temperatures in the humid tropics provide ideal conditions for weathering, and soils will likely be thoroughly oxidized and low in organic matter, leached, and comparatively low in Ca and Mg (i.e., the primary silicates have weathered and only highly weathered material remains). Products of intense weathering, oxides of Fe and Al, dominate these soils (Brady, 1990). Order of resistance of silt and sand-sized particles to weathering in tropical conditions is as follows: quartz > muscovite and potassium feldspars > sodium and calcium feldspars > biotite, horneblende, and augite > olivine > dolomite and calcite > gypsum. This order accounts for the absence of dolomite, calcite, and gypsum in tropical areas, and for the predominance of quartz in the courser fraction of tropical topsoils (Barshad, 1955).

In cooler, drier climates, weathering is much less drastic; oxidation and hydration of Fe are hardly noticeable, and Ca content is much higher, especially in drier regions. These types of soils are found in the Great Plains, the western United States, and other semiarid and arid areas of the world. Areas with sufficient precipitation to support lush plant growth will, over long periods of time, produce the richest soils. An example of such an area is the tallgrass prairie of North America. The interaction of the moderate summer temperatures, precipitation, high organic-matter levels from the decaying grass roots, and the teeming micro- and macro-organisms living in these soils combined to produce very deep, high organic-matter soils with high water-holding capacity and a high initial level of fertility.

B. GEOLOGIC CLASSIFICATION OF PARENT MATERIAL

There are two groups of inorganic parent material: sedentary (formed in place) and transported. The latter are divided according to means of transport: gravity (colluvial), water (alluvial), ice (glacial), and wind (eolian). Water-transported soils are further divided into marine (ocean) and lucustrine (lake) origin (Brady, 1990). Residual or sedentary parent materials have experienced long and intense weathering.

Three types of alluvial parent material exist: flood plains, alluvial fans, and deltas. *Flood plain* soils are usually rich in nutrients and are sometimes poorly drained. *Alluvial fans* are generally gravelly and stoney, somewhat porous and well drained. They may be very productive even though they may be quite course in texture. *Delta* soils consist of the finer sediments carried by streams into lakes, reservoirs, or oceans. They are a continuation of a flood plain and are usually clayey in nature and quite likely to be swampy (Brady, 1990).

Soils of arid regions are remarkably similar to their parent materials because primary minerals are more prominent. This is due to dominance of physical rather than chemical forces in the weathering process. Minerals requiring water for formation are not formed as readily as they are in a humid climate. In humid areas, the forces of weathering are more varied, and vigorous chemical change accompanies the physical changes. Thus, new minerals, such as silicate clays and oxides of Fe and Al, are more abundant in the soil. These processes are intensified and accelerated by large quantities of organic matter (Brady, 1990).

Glaciation is important agriculturally in much of the United States because of the "leveling" effect. This made agricultural operations more easily accomplished, and the fact that the parent material is "young" or less leached leads to greater inherent fertility. In eastern Canada and New England, however, near the glaciation center, the moving ice picked up and transported much of the weathered parent material southward, leaving shallow, unproductive soils (Brady, 1990).

III. SOILS

A. SOIL ACIDITY

Acidic soils have a pH of less than 7.0 and basic soils have a pH of greater than 7.0. Soil acidity in humid regions develops as water percolates through the soil, removing Ca, Mg, and other basic cations, replacing them with hydrogen (H) ions. The measure of acidity, pH, is the logarithm of the inverse of the hydrogen concentration [i.e., log $(1/[H^+])$]. Thus, as the H^+ ion concentration increases, the pH is reduced.

Neutral and alkaline soils lack extensive leaching. Thus, the concentration of base-forming cations is usually high with a pH higher than 7.0. Positively charged Al^{+3} and $AlOH^{+2}$ ions are absent and H^+ is extremely low. Absorbed Ca^{+2} and Mg^{+2} dominate and Na^{+1} and K^{+1} are also higher than in acid soils. Organic matter is usually low. According to their proper-

TABLE 11.2 Properties of Different Kinds of Soils as Dictated by Their Chemical Constituents

Soil	pH	Ec (dS/m)	SAR
Normal	6.5–7.2	<4	<13–15
Acid	<6.5	<4	<13–15
Saline	<8.5	>4	<13–15
Saline–Sodic	<8.5	>4	>13–15
Sodic	>8.5	<4	>13–15

Source: Brady, 1990.

ties, soils are classified as normal, acid, saline, saline–sodic, and sodic (Table 11.2).

Tolerance of most crops to salt is low; thus, saline–sodic and sodic soils present challenges in determining crops that are adapted to such conditions. Relative tolerance of some crop plants to salty soils is presented in Table 11.3.

B. LIME REQUIREMENTS OF ACID SOILS

pH is used as an indicator of the need for lime in soils; however, no one pH level is indicative of the lime needs for all soils (Foy, 1964; Pearson

TABLE 11.3 Relative Tolerance of Certain Plants Used as Forages to Salty Soils

Tolerant	Moderately tolerant	Moderately sensitive
Barley, grain	Barley, forage	Clover, alsike, Ladino, red, strawberry
Bermudagrass	Bromegrass	Corn
Bougainvillea	Clover, berseem	Cowpea
Mutall alkaligrass	Orchardgrass	Cucumber
Rescuegrass	Oat	Pea
Sugarbeet	Rye, hay	Soybean
Saltgrass	Ryegrass, perennial	Sweetclover
Wheatgrass, crested	Sorghum	Timothy
Wheatgrass, fairway	Sudangrass	
Wildrye, Altai	Trefoil, birdsfoot	
Wildrye, Russian	Wheat	
	Wheatgrass, western	

Source: Brady, 1990; modified from Carter, 1981.

and Hoveland, 1974). As Ca^{+2} and Mg^{+2} ions are removed from the soil by the growing crop, by leaching, or by a combination of both, the percentage of base saturation decreases and eventually another application of limestone is required (Fig. 11.1). Thus, the purpose of liming is twofold: (1) increase the base saturation and (2) adjust the soil pH so that the availability of essential nutrients is maximized and elements that may be toxic at high concentrations are minimized. Lime requirements of soils depend on several factors: (1) magnitude of the pH change required, (2) buffering capacity of the soil, (3) chemical composition of the limestone, and (4) fineness of the liming materials (Brady, 1990).

The range of pH optimum for the crop being considered dictates the magnitude of the pH change required. Grasses and most clovers can be grown at a lower pH (more acidic conditions) than can alfalfa. **Buffering capacity** refers to the resistance to change in pH of the soil solution (Brady, 1990). It is explained in terms of equilibrium existing among the active, salt-replaceable, and residual acidity of H^+ and Al^{+3} of a given soil. (The reader is referred to a basic soil text for further discussion of these relationships.) The general relationship of buffering to limestone requirements as a function of soil texture are shown in Fig. 11.2. Fine-textured soils require several times the amount of limestone to raise the pH to 7.0 as do sandy soils. Some soils have particularly high buffering capacities and enormous amounts of limestone are required to adjust the soil pH. This buffering capacity occurs largely between soil pH values of 5.5 and 8.0, and can be attributed to organic matter and the hydroxy-aluminum interlayers or surface coatings. A soil with a very large buffer capacity indicates the presence

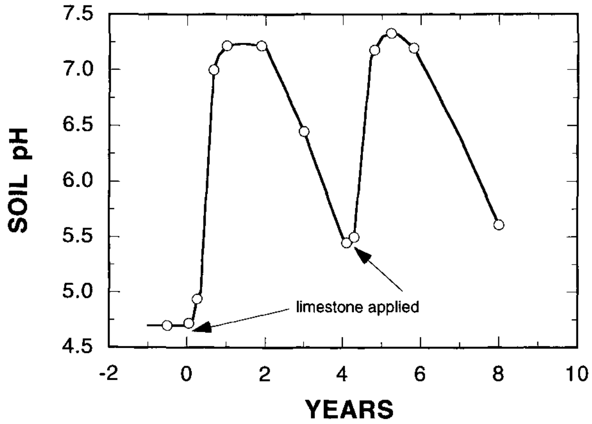


FIGURE 11.1 Influence of limestone on pH of a cropped soil. The initial rate of limestone application was assumed to be 3.5–4.5 tons/acre. It takes about 1 year for most of the limestone to react, and crop use and leaching requires 3–4 years to deplete the calcium and magnesium to a point at which additional limestone is needed. (Redrawn from Brady, 1990. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.)

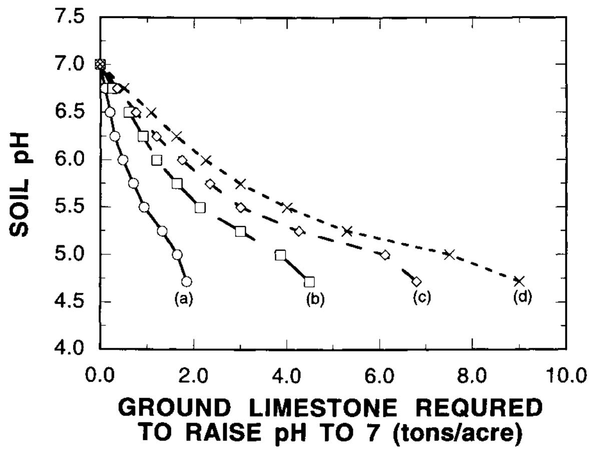


FIGURE 11.2 Relationship between soil texture and the amount of limestone required to raise the pH of New York soils to 7.0. Representative organic matter (O.M.) and cation exchange capacity (CEC) levels are shown. (a) sands; (b) sandy loams; (c) loams, silty loams; (d) silty clay loams. (Redrawn from Brady, 1990; from Peech, 1961.)

of layer silicate-hydrous sesquioxide[1] complexes (Coleman and Thomas, 1967).

The chemical composition of limestone regulates the long-term effect on soil pH. In humid areas, these changes are so important to successful crop production that laws governing sale of liming materials have been passed by state legislatures. These laws require guarantees of chemical composition of liming materials. Their content may be listed in one or more of the following ways: (1) concentration of elemental Ca and Mg; (2) percentage of oxide (CaO and MgO); (3) CaO equivalent (e.g., neutralizing ability of all compounds expressed in terms of CaO); (4) total carbonates, which is the sum of the calcite and dolomite forms; or (5) $CaCO_3$ equivalent or total neutralizing power in terms of $CaCO_3$ (Brady, 1990). The first two methods are important because the concentration of Mg is indicated. In some areas, soils are low in Mg and the most effective method of correcting this deficiency is through the application of dolomitic limestone (i.e., limestone containing significant concentrations of Mg).

Fineness of grind in the liming material regulates the rate with which the material reacts with the soil and causes a change in pH. Three months after application of calcitic limestone, Schollenberger and Salter (1943) showed that in 20-mesh material, less than 20% of the limestone had reacted with the soil. For dolomitic limestone, about 10% had reacted with the soil. If the material was ground to pass a 30-mesh screen, the relative percentages

---

[1] An oxide in which three atoms or equivalents of oxygen are combined with two atoms of some other element or radical.

reacting with the soil were about 30 and 12%, and grinding the material to pass a 100-mesh screen resulted in approximately 70 and 47% of the limestone and dolostone, respectively, reacting with the soil after 3 months. The work of Adams (1971) clearly shows the relationship of limestone fineness and its effectiveness. Material passing through a 60- to 100-mesh screen has a relative value of 100%, whereas 4- to 10-mesh material has a relative value of 8 to 10% (Fig. 11.3).

When applied to in-place forage crops, calcium neutralizes residual acidity near the soil surface by forming Ca and Mg nitrates. These are residually basic, and when the plant preferentially absorbs the NO_3^- ion from such salt solutions, the Ca^{+2} and the Mg^{+2} are left, making the solution more basic (Pearson and Hoveland, 1974).

C. NUTRIENT AVAILABILITY AND SOIL pH

Soil pH plays an important role in availability of nutrients essential for plant growth. In general, optimum availability occurs between a soil pH of 6.0 and 7.0 (Brady, 1990). Low pH results in lower rates of N mineralization, a process dependent on active, viable microbial populations in the soil. Thus, ammonium accumulation has been shown at low soil pH (Cornfield, 1952). Rhizobium populations usually increase after liming (Pearson and Hoveland, 1974; Van Keuren, 1980).

Time required to correct soil pH to one favorable for plant growth depends on the initial pH, liming material used, fineness of grind, and extent of mixing with the soil (Barber, 1984). Most situations require application only 2 or 3 weeks before seeding. No-till planting would require surface application at least 26 weeks prior to seeding.

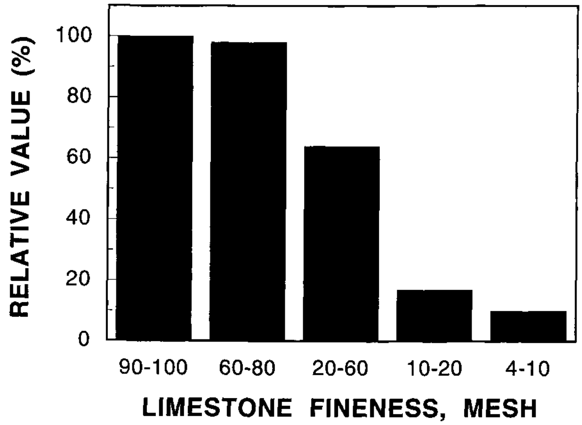


FIGURE 11.3 Relationship of limestone fineness to its relative value in neutralizing soil acidity. (Redrawn from Adams, 1971.)

Standard recommendation for a large lime requirement application is to plowdown half of the limestone and apply the remaining half after plowing but before planting, so it can be incorporated into the soil.

D. RESPONSE TO LIME APPLICATION

Acidity of soil is generally detrimental to plant growth because of the following factors: (1) increased solubility of toxic elements, (2) lowered availability of essential nutrients, and (3) repressed activity of desirable soil microorganisms (Follett and Wilkinson, 1985; Pearson and Hoveland, 1974).The amount of limestone applied should be geared to reflect the initial soil pH and the crops being grown. If alfalfa is in the rotation, soil pH values > 6.0 should be maintained. If, however, the crops being grown in the rotation are all tolerant of pH values in the range of 5.5 to 6.0, there is no reason to apply additional limestone.

1. Legumes

There is a difference among forage crops in the ability to grow, survive, and produce acceptable yields under acidic soil conditions. Crops most sensitive to acid soils are alfalfa, sainfoin, and sweet clover, each of which responds well to lime application (Whyte *et al.*, 1953; Rorison, 1958; Adams and Pearson, 1967). Relative tolerance of major forage legume crops to acid soils is as follows: alfalfa < white clover < arrowleaf and ball clover < red and crimson clover < birdsfoot trefoil < alsike and subterranean clover (Hoveland *et al.*, 1969; Weeks and Lathwell, 1967; Ozanne and Howes, 1970; Pearson and Hoveland, 1974). The last two may not respond to liming, except in extreme cases of soil acidity. Fergus and Hollowell (1960) reported no response of red and crimson clover to liming at soil pH values > 5.5. Morley (1961) showed that subterranean clover flourishes at pH 4.5 if N is provided. The rhizobia required for symbiotic dinitrogen fixation do not function at this pH.

Birdsfoot trefoil is generally considered to be acid tolerant (Seany and Henson, 1970), although Canadian research has shown optimum yields were obtained on various soils with pH values ranging from 5.2 to 7.5 (Dione, 1969). Crownvetch does not respond with increased yields to lime on soils with a pH > 5.5. However, a pH of 6.5 to 7 is required for rapid growth and stand persistence (McKee and Langille, 1967). Brazilian research has shown a clear response by *Stylosanthus* and *Phaseolus* on eight latosolic[2] soils at pH 4.0 to 5.2, with maximum yields occurring at pH 6.1 to 6.4 (de Freitas and Pratt, 1969). Mean response for the two afore-

---

[2] A latosolic soil is one with a lateritic layer or iron-rich subsoil layer found in some highly weathered humid tropical soils that, when exposed and allowed to dry, becomes very hard and will not soften when rewetted. When erosion removes the overlaying layers, the laterite is exposed and a virtual pavement results (Brady, 1990).

mentioned forages was 146 and 93%, respectively. Yields of forages decreased above pH 6.4. Other tropical legumes such as kudzu, centro, Townsville stylo[3] (*Stylosanthus humilis* Kunth.), and phasey bean have given only a slight response to lime according to Norris (1958, 1970) and Hutton (1970). This disparity, with respect to Townsville stylo and phasey bean, points to the importance of understanding the characteristics of specific soils, before it is decided that limestone, and how much, is or is not needed.

Mahler (1983) reported that alfalfa yield response to liming was curvilinear between pH 4.8 and 7.4. The yield response was described by this equation: $Y = 0.009x^{3.71}$, $r^2 = 0.981$. Maximum alfalfa yield in six western Oregon soils was achieved at pH 6.0 (Janghorbani *et al.,* 1975). Addition of limestone resulted in acceptable yields only after the soil pH was amended to at least 6.6 from 4.8. The highest alfalfa yield was achieved at pH 7.4 (Mahler, 1983).

Application of limestone has been noted to reduce yields of subterranean clover and white clover (Helyer and Anderson, 1971). When adequate N was applied, however, Al toxicity depressed growth of alfalfa and phalaris. The other species (subterranean clover, white clover, and perennial ryegrass) were resistant to Al toxicity.

2. Grasses

Grasses are generally more capable of performing satisfactorily in acid soils than are alfalfa and sweet clover (*Melilotus* sp.). Forage crops most able to grow under acid soil conditions of 4.5 to 6 pH are red top, bentgrass (excepting creeping), and red and sheep's fescue (Brady, 1990). In a 7-year study in Georgia, bermudagrass produced maximum yields at pH 4.8 (Adams *et al.,* 1967) and the minimum or optimum pH was set at 5.5 by Sanford *et al.* (1968), who found that roots of bermudagrass are capable of extending deep into the soil, even though the subsoil pH values are 4.0 to 4.5. Other tropical grasses—napiergrass, guineagrass, and pangolagrass, have shown similar adaptation to low soil pH. A coastal bermudagrass-arrowleaf clover sward showed a response to liming (Cripps *et al.,* 1988). Application of limestone, 17.9 Mg ha^{-1} (8 ton acre^{-1}), resulted in yield increases of 11, 26, and 33% in the second, third, and fourth years after application. Pearl millet is relatively tolerant to acid soils, providing only a 20% increase in yield to applications of lime on a sandy soil of pH 5.1 (Adams, 1968). Contrasted to this, sorghum-sudangrass hybrid yields were tripled on the same soil with application of limestone. Johnsongrass has been reported to give responses to liming similar to the sorghum–sudangrass hybrids (Adams, 1956). Cool-season grasses show similar adaptation (e.g., tall fescue is tolerant of soil pH values of 4.6 to 4.7; Follett and Wilkinson, 1985). A general

---

[3] Commonly called Townsville lucerne prior to 1970, but since changed to Townsville stylo to avoid confusion with the *Medicago* species.

rule to follow is that most crops produce best in the range of pH 6.0 to 7.0 (Wilkinson and Mays, 1979). Low yield in persisting stands of these species is often related to low nutrient availability. Thus, liming usually provides a favorable response (Pearson and Hoveland, 1974).

3. Soil Microorganisms

Application of lime can also influence survival of native and introduced species of rhizobium (Mahler, 1983; Mulder and Van Veen, 1960). An important reason for reduced growth of some legumes in acid soils may be that they grow less favorably in acid media because of less N availability due to less N fixation. Under such conditions, addition of N has resulted in increased plant growth, even though the soil pH was not changed (Virtanen, 1928; cited by Mulder and Van Veen, 1960). Dinitrogen fixation is affected by such factors as nodulation (Andrew, 1976; Munns, 1970), nodule effectiveness (Munns *et al.,* 1977), and nodule occupancy (Dughri and Bottomly, 1983; Jones and Morley, 1981). Each of these factors can be influenced by soil acidity–increased when pH is in the normal or favorable range compared to the acid (less than 6.0) range (Doerge *et al.,* 1985).

According to Munns (1965), most yield response in alfalfa from addition of limestone is due to increased nodulation. In solution culture studies, a pH < 5.5 reduced nodule numbers and a pH < 4.5 prevented nodulation (Munns, 1968a). Root-hair curling, a precursor to infection, and infection did not occur below pH 5.4. Studies have shown that low pH, or acid soil conditions, are detrimental to *Rhizobium melilotii* (Mahler, 1983). At pH adjustment time, the number of organisms per gram of soil was approximately 2.5×10^4. At the time of planting, the number of *R. melilotii* at pH 7.0 had increased to 5×10^4 per gram of soil. After 3 months, the number had risen to more than 35×10^4 per gram of soil (Fig. 11.4). Doerge et al. (1985) also studied the response of N fixation to soil pH. At soil pH values of 5.3, 5.8, and 6.5, the nodules per plant were 33.2, 62.3, and 67.3, respectively, a 203% increase as the pH changed from 5.3 to 6.5. Total N uptake by the plants was as follows (g pot^{-1}): 0.052, 0.127, and 0.286 (550% increase) at pH 5.3, 5.8, and 6.5, respectively. Other work by Andrew (1976) showed that compared to the reduced nodulation at pH 4.0, *Desmodium uncinatum* and *T. repens* exhibited reduced nodulation at soil pH values of 4.0 and 5.0, respectively (de Freitas and Pratt, 1969). All *Medicago* spp., including alfalfa, showed reduced nodulation at soil pH < 6.0. pH had little effect on growth of plants well supplied with N, regardless of the source.

Red clover grown in acid soils, both under field conditions and in greenhouse pot experiments, was poorly nodulated or lacked nodules. Thus, red clover suffered severely from N deficiency and provided low yields (Mulder and Van Veen, 1960). Although addition of limestone in quantities sufficient to reduce the Al concentration to subtoxic levels restored yield potential of a soil in which alfalfa was grown, additional inoculum resulted in in-

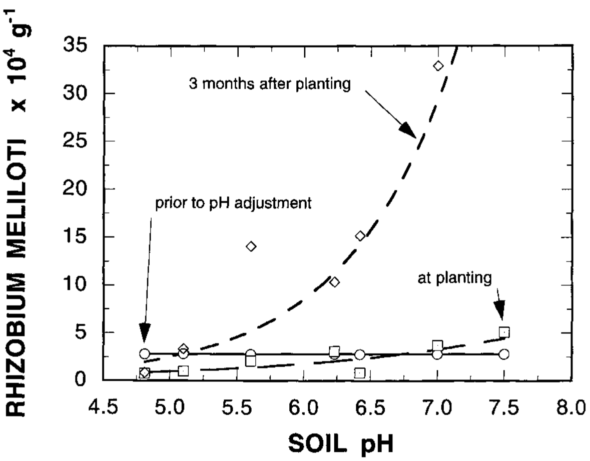


FIGURE 11.4 Relationship between soil pH (X) and populations of *Rhizobium meliloti* (Y) to soil pH adjustment at planting and 3 months later. (Redrawn from Mahler, 1983.)

creased yields (Rice, 1975). This points to the importance of using inoculum when planting a legume crop, even though a resident rhizobial population may be in the soil.

Without pH amendment, inoculation of acid soils with *Rhizobium trifolii* resulted in nodulated plants that grew vigorously. However, greater than 60,000 rhizobium cells had to be introduced per 500 g of acid soil to attain normal nodulation (Mulder and Van Veen, 1960).

4. Effect of soil

The response of plants to pH also differs from soil to soil. "Buffalo" alfalfa yield was maximum at about pH 5.0 on a Bladen clay loam, but increased on a Leon fine sand until the soil pH had reached at least 7 (Fig. 11.5). Plant symptoms and soil analyses indicated that Al toxicity was chief among the reasons for limited growth on the Bladen soil. On the Leon fine sand, Ca deficiency was the primary cause. For a third soil, Rains sandy loam (not shown in Fig. 11.5), Ca deficiency, Mn toxicity, and Al toxicity were all likely involved in reduced alfalfa yield on unlimed soil. The response to liming may simply be one of making nutrients available to the plant that were unavailable before. For example, increased yields of alfalfa to lime application were found to be associated with increased P and Mn availability (Janghorbani *et al.*, 1975).

The lime requirement in acid soils is absolute if alfalfa stands and yields are to be maintained. The importance of lime to acid-sensitive crops like alfalfa is shown in the work of Moscher *et al.* (1961). Stand survival at the end of three seasons of growth ranged from 0 to 95% for 0 to 36 Mg ha^{-1}

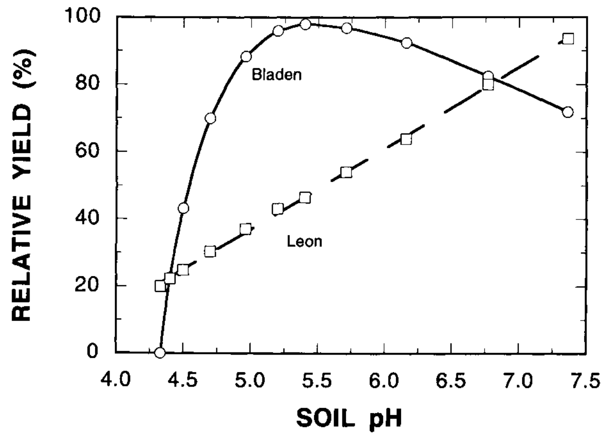


FIGURE 11.5 Alfalfa yield response to pH in a Bladen clay loam and Leon fine sand. (Redrawn from Foy, 1964.)

(0 to 16 ton acre^{-1}) of lime applied. Yields ranged from 0.25 to 8 ton acre^{-1} for three cuttings.

5. Stand Establishment

Seeding success is also related to soil pH. For example, Schulte *et al.* (1982) found that as the soil pH was increased from 4.9 to 7.1, the number of alfalfa crowns per m^2 in August increased from 54.7 to 118.4. In June 1981, the counts were 1.1 vs. 39.8, which was a 2 and 33.6% survival over the intervening period. Yields (2-year average) were 2.1 and 5.9 Mg ha^{-1} (0.94–2.63 ton acre^{-1}), respectively.

IV. NUTRIENTS AND PLANT GROWTH

Two facts with respect to soil fertility and nutrient concentration in plants are important when considering whether a plant produces at an optimum level. First, the soil must have adequate supplies of each of the essential elements; second, the critical concentrations within the plant for each element must be met. If the former matter is taken care of in a soil fertility program, the latter item will automatically be met. However, there are times when the nutrient concentration in a plant may help diagnose whether a problem is due to nutrient insufficiency or to some other problem. Much variability in nutrient concentrations in plants exists because of uncontrolled factors: species, cultivar, time of sampling, position sampled on plant, weather, and so on. Thus, it is difficult to make a hard-and-fast assessment. Nutrient concentrations in plant tissue deemed to be critical for two forage crops (maize and alfalfa) are given in Table 11.4. Generally, grasses contain a lower nutrient concentration than do legumes. These crops may be somewhat indicative of legume and grass species in general; however, it should be recognized that there is variability among the various grass forage crops as well as among the various legume forage crops. An extent of this variation is provided in plant analysis handbooks published in 1991 (Jones, Wolf, and Mills) and 1996 (Mills and Jones). These works list survey and/or sufficiency ranges for many forage crops.

Nutrients are removed from soils by forage crops in much larger quantities than by row crops. The reason is obvious—the entire top growth is removed as the harvestable portion of the crop in forages, but only the grain or seed is removed in most agronomic row crops. Of course, corn removed for grain plus removal of the stalks as fodder has the same effect on soil nutrient status as does removal for silage. In the United States, harvest of the alfalfa crop alone removes approximately 1.7 million tons of K annually. This is approximately 40% of all the K applied annually for all purposes (Lanyon and Griffith, 1988). In the Pennsylvania Alfalfa Growers Program, uptake of 11 nutrients is given at yield levels from 9 to 18 Mg ha^{-1} (4.0–8.0 ton $acre^{-1}$; Table 11.5).

TABLE 11.4 Sufficiency Range in Plant Tissues for Nutrient Concentrations of Several Elements in Alfalfa and Corn

Nutrient	Corn[a] <30 cm tall	Corn[b] prior to tasseling	Corn[c] at silking	Alfalfa[d]
N(%)	3.00–3.50	3.00–3.50	2.70–4.00	4.50–5.00
P(%)	0.30–0.50	0.25–.045	0.25–0.50	0.26–0.70
K(%)	2.50–4.00	2.00–2.50	1.70–3.00	2.00–3.50
Ca(%)	0.30–0.70	0.20–0.50	0.21–1.00	1.80–3.00
Mg(%)	0.15–0.45	0.13–0.30	0.20–1.00	0.30–1.00
Fe (mg kg^{-1})	50–250	10–200	20–250	30–250
B (mg kg^{-1})	5–25	4–25	5–25	30–80
Cu (mg kg^{-1})	5–20	3–15	6–20	7–30
Zn (mg kg^{-1})	10–60	15–60	25–100	21–70
Mo (mg kg^{-1})	0.10–10.00	0.10–0.30	0.10–0.20	1.00–5.00
Mn (mg kg^{-1})	20–300	15–300	20–200	31–100

[a] Sample whole tops.

[b] Sample leaf below the whorl.

[c] Sample leaf subtending the ear.

[d] Sample top 15 cm of new growth.

Source: Mills and Jones, 1996.

TABLE 11.5 Removal of Eleven Elements from the Soil by an Alfalfa Crop Yielding from 9 to 18 Mg ha^{-1}

Yield group	Nutrient (kg ha^{-1})										
	N	P	K	Ca	Mg	S	B	Cu	Zn	Mn	Fe
Mg ha^{-1}											
≤9	227	25	205	99	17	18	0.22	0.06	0.18	0.40	1.09
9–11.2	253	32	270	121	21	22	0.28	0.07	0.24	0.53	1.16
11.2–13.4	351	38	315	148	27	28	0.34	0.08	0.29	0.57	1.58
13.4–15.7	418	45	379	162	29	32	0.37	0.09	0.31	0.74	1.76
15.7–17.9	480	53	451	187	34	38	0.41	0.10	0.34	0.90	1.80
>17.9	559	61	524	226	39	47	0.48	0.12	0.40	0.87	2.15

Source: Lanyon, Baylor, and Waters, 1983.

A. NITROGEN

Nitrogen in soil solutions exists in the reduced, stable form as ammonium (NH_4^+) or in the oxidized form as the NO_3^- ion. The NO_3^- form is very mobile and is readily leached by percolating water; thus the general concern for degradation of the environment through groundwater contamination by leached NO_3^-. Ammonium is adsorbed as an exchangeable cation on soil colloids, and is therefore not readily leached by percolating water, but it is readily replaced, under soil temperatures conducive to plant growth, by potassium. The NH_4^+ form, under normal soil temperatures, is converted readily to the nitrate form (Follett and Wilkinson, 1985). Plant roots absorb N from the soil solution as inorganic NH_4^+ and NO_3^- ion (Mengel and Kirkby, 1982). Ammonium-N accumulation in soils at low pH has been shown to occur, indicating that the microbes that effect nitrate production are inhibited at low pH values (Cornfield, 1952). Organic matter is the major source of soil N. Thus, a great reservoir exists when the organic matter concentration is high (Follett and Wilkinson, 1985).

Nitrogen is an integral part of all amino acids and proteins in plants. It is also part of the puric and pyrimidic bases, which makes it and essential component of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Nitrogen is also a component of the tetra-pyrole ring of chlorophyll, nicotinamide dinucelotides (NAD+, NADH, NADPH), choline, and indolacetic acid, a growth regulator (Mills and Jones, 1996).

Nitrogen fertilizers, because they can form nitric acid in the soil, will under some conditions result in soils becoming more acid (Adams and Pearson, 1967). For example, after 4 years of fertilizing tropical grasses with 896 kg N ha^{-1} annually, a response to lime application was reported, whereas at the beginning of the study no response was measured. The initial soil pH was 4.0 (Vicente-Chandler *et al.*, 1964).

Forms of N fertilizer include urea, 46% N; NH_4NO_3, 33% N; NH_4SO_4, 21% N; $Ca(NO_3)_2$, 15.5% N; $NaNO_3$, 16.5% N; anhydrous ammonia (NH_3), 82% N; and N solutions, 27 to 53% N (Follett and Wilkinson, 1985). Some crops such as legumes have the ability to fix, convert dinitrogen to nitrate, in a symbiotic relationship with various *Rhizobium* species. Alfalfa has been identified as a crop than can fix 50 to 200 kg N ha^{-1}. Nitrogen uptake may range from 90 to 211 kg N ha^{-1}, with yields ranging from 1.9 to 10.5 Mg ha^{-1} (Nuttall, 1980; Nuttall *et al.,* 1980). Very high yields of alfalfa under intensive management (18 Mg ha^{-1}) may remove as much as 500 kg N ha^{-1} (Table 11.4) indicating that under high-yield management, earlier estimates of N fixation are too low (Griffith, 1974). Other legumes fix lesser amounts of dinitrogen.

Attempts to augment the symbiotically fixed N in an alfalfa field with the application of N have not proved to be successful, however. It has been demonstrated that N application is deleterious, causing stand reduction, decreased longevity, and greater invasion of weeds (Markus and Battle, 1965; Gerwig and Ahlgren, 1958). In postemergence studies, application of 100 kg N ha^{-1} tended to increase weeds and decrease alfalfa plants when weeds were present (Kunelius, 1974). When up to 363 kg N ha^{-1} as NH_4NO_3 per year was applied, it did not affect protein concentration over a 3-year period (Rhykerd *et al.,* 1970). Therefore, there is no need to apply N to legume crops, because this practice is simply counterproductive. In addition to the deleterious effects listed previously, N concentration in the soil of more than 25 to 50 mg kg^{-1}, causes inefficiencies in N fixation, and eventual shutdown of the N-fixing mechanism as 50 mg kg^{-1} is approached (Musselman, 1978).

The extent of volatilization of applied N depends on placement, soil, and environmental conditions. Ammonium nitrate usually has the highest recovery rate or uptake of applied N by the crop. Urea surface application results in considerable N loss to volatilization. Liquid N sources result in some loss when surface applied. Anhydrous ammonia, which is the least expensive source of N, results in very low N volatilization losses if it is properly injected into the soil; otherwise, losses are extensive (Follett and Wilkinson, 1985). However, injection of anhydrous ammonia into soils planted to forage crops is not a practical option.

Nitrogen required to maintain production of forage crops must be geared to production goals, crop type, soil organic matter concentration, inorganic N in the soil, and soil-test results. Grasses on inorganic soils always require additions of N fertilizer, either in the commercial or organic manure form. Carbon-4-pathway grasses appear to be more efficient users of N that do C_3 grasses. Legumes fix sufficient N for their needs and the needs of grasses grown in association with them if the legume makes up at least 40% of the plants in the sward.

B. PHOSPHORUS

Phosphorus deficiency in crops occurs worldwide. Sanchez and Salinas (1981) reported that deficiency symptoms occur in 82% of the tropical soils in the Western hemisphere. Depending on parent material and amount removed, reserves can accumulate if overapplication is practiced (Thomas, 1989).

Roots absorb P mainly as $H_2PO_4^{-1}$. Soil P concentrations are very low (0.007–1 mg kg^{-1}) and are maintained by dissolution of inorganic P and mineralization of organic P. Uptake is thus influenced or regulated by fixed P in the soil, organic matter, and pH. Critical levels for soil extractable P concentration is between 17 and 37 mg kg^{-1} in humid regions and 6 to 10 mg kg^{-1} in less humid and arid regions. Desirable levels in the soil are crop dependent (Follett and Wilkinson, 1985). In the plant, minimum P concentration for alfalfa growth is 0.25% at the 1/10-bloom stage of development. Similar concentrations (0.23–0.29%) (Van Riper and Smith, 1959) are common for other legumes in the humid temperate zones (Reid *et al.*, 1970; Nelson and Barber, 1964).

Phosphorus is important in plants as integral components of enzymes, proteins, nucleic acids, adenosine triphosphate (ATP), lipids, and esters. In photosynthesis, light energy absorbed by the chlorophyll reduces nicotine adenine diphosphate (NADP) and synthesizes ATP. These two compounds serve as energy donors in energy transfer processes and numerous biosynthesis processes. Phosphorus enhances cell division, fat formation, flowering, fruiting, seed formation, and development of lateral and fibrous root systems (Follett and Wilkinson, 1985).

Phosphorus is readily fixed or made unavailable to the plant in some soils. Fixation depends on soil texture and acidity. Addition of P in extremely acid soils may not be profitable because a large share of the applied P is fixed by Fe and Al compounds. Application of lime usually improves this situation. The response of phosphate application increased as the level of applied lime increased; pointing to the positive effect of P availability at high soil pH values (Helyar and Anderson, 1971). Species used in this study were *Phalaris tuberosum,* alfalfa, white and subterranean clovers, and perennial ryegrass, indicating that both grasses and legumes respond similarly.

The finer the soil texture and the more acid the soil, the greater is the fixation of P (Griffith, 1974). Movement of inorganic P in the soil, because of this fixation, is rather limited. The affect of soil pH on P uptake is linear in the pH range of approximately 4.8 to 7.4 ($Y = -101.71 + 22.83X$, $r^2 = 0.983$, where X = soil pH and Y = P uptake). This study showed uptake amounts of 8.5 mg pot^{-1} at pH 4.8 to 65 mg P pot^{-1} at pH 7.4 (Mahler, 1983). Dry-matter production is also linearly related to P uptake, ranging from 2.3 g pot^{-1} at a soil P concentration of 7 mg P pot^{-1} to 13 g pot^{-1} at 65 mg of soil P pot^{-1} (Fig. 11.6). Soils planted to alfalfa are depleted of P

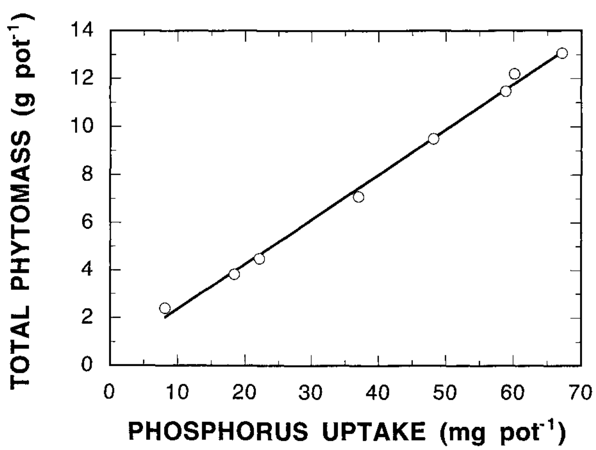


FIGURE 11.6 Relationship between total P uptake (X axis) by alfalfa and total phytomass production (Y axis). (Redrawn from Mahler, 1983.)

at a more rapid rate than if the soil was planted to other crops. The greatest depletion is in the 15- to 30-cm zone, which, in one study (Lipps and Fox, 1956), was reduced 60.8%. The 30- to 45-cm zone was reduced 54%; 45 to 60, by 37%; 60 to 75, by 24%; and 79 to 90, by 16%. The zone 0 to 15 cm was reduced by 43%.

Phosphorus, as a fertilizer, is available in the following sources: (1) superphosphate, which contains 9% water-soluble P (derived from rock phosphate treated with H_2SO_4); (2) triple superphosphate, 20% water-soluble P (from rock phosphate treated with phosphoric acid); (3) ammonium phosphates, 7 to 33% watersoluble P (made by reacting ammonia and phosphoric acid); and (4) less soluble forms of P (e.g., basic slag or ground rock phosphate; Follett and Wilkinson, 1985).

Phosphorus is very immobile, causing concern about surface-applied P and its effectiveness. Hanson and MacGregor (1966) demonstrated, in a 10-year study in which surface application was practiced, that P had moved below the 7.5 cm level in a Port Byron silt–loam soil. Jacobs *et al.* (1970) found that there was a slight advantage with respect to production over a 4-year period, if P was incorporated. In a study where P was applied at 0, 48, 98, and 195 kg P ha^{-1} on ladino clover at planting time, annual surface supplemental application of 24 kg P ha^{-1} on the 98-kg treatment over a 7-year period was superior (Woodhouse, 1964). The 7-year average yield was not better than the 7-year average from plots receiving 195 kg P ha^{-1}. However, by the time the seventh year was reached, the annual P treatment was yielding significantly more ladino hay. Similar results in a four-state alfalfa study were reported by Terman *et al.*, (1960). In their Australian research, Ozanne and Petch (1978) found that the P fertilizer requirement for 90% maximum yield for subclover was 49 kg P ha^{-1} if the soil surface was cultivated to a depth of 20 cm, but only 28 kg P ha^{-1} if the P was surface applied. Wolfe and Lazenby (1973), working in Australia, reported tall fescue seedlings to be less dependent than white clover seedlings on banding of superphosphate. Banding has proved superior in seeding establishment (see Chapter 9). Because of high fixation and the deep alfalfa rooting patterns, at least part of the requirement should be plowed down, with the remainder being placed on the surface (Griffith, 1974).

It is important to keep the P : K ratio of soils in balance. For soils testing low in both P and K, it appears that a P:K ratio of 1:4 should be applied to maintain fertility (Griffith, 1974). The removal ratio is, however, from 1:10 to 1:12.

C. POTASSIUM

Much has been written about potassium (K) and it role in forage production. The primary role of K in the plant is nutritional and metabolic (Follett and Wilkinson, 1985). Potassium is not a constituent of any plant component, although it is vital to plant functions such as formation and translocation of sugars and starches, protein synthesis, stomatal action, and the cations associated with organic anions (Epstein, 1972). Mengel and Kirkby (1980) wrote an excellent review article on the role of K. They list the various roles of K^+ as transport across membranes, cell turgor and water economy of plants, energy metabolism, long-distant transport, and enzyme activation.

Potassium is in three general forms in the soil (Follett and Wilkinson, 1985): (1) soluble K, which is free to move with soil water; (2) exchangeable K, held on soil colloids in equilibrium with soluble K; and (3) nonexchangeable K, held within the clay lattice or in primary minerals, which is thus not readily available to plants. Soluble and exchangeable K make up a very low percentage of total K in most soils. A limited amount of the total soil K is available annually in most soils. This amount may be adequate for relatively low-yielding forages, but crops such as alfalfa, a high-K requiring crop, or higher yields in all crops, require more K than can be released by the soil.

All K salts used as fertilizer are water soluble and have little effect on soil pH. Potassium chloride (KCl) is 40 to 52% K; $KMgSO_4$ is 19 to 25% and may be used where Mg is also required; KNO_3 is 37% K and is an excellent source of both K and N for grasses, but cost limits its use (Follett and Wilkinson, 1985).

Potassium deficiency in orchardgrass was reported to be severe at a plant concentration of 1% (Kresge and Younts, 1962). In conjunction with N fertilization, the concentration of K required for optimum growth and yield increased as the amount of applied N increased. For example, at 56 kg N

ha^{-1}, K was 2.15% and at 112 kg N ha^{-1} application, 2.68% K was required for optimum yields. In ladino clover (Brown, 1957), plant concentrations below 0.7% K resulted in deficiency symptoms. Other work (Blaser *et al.,* 1958) showed that deficiency symptoms were expressed by plants with less than 1.0% K. Optimum yields were achieved if K percentage was greater than 2.6%. Near maximum growth was attained in experiments by McNaught (1958) when plant K was at 1.81% in the leaves (all of them) and optimum concentrations of K in grasses is reported to be about 1.6% (McNaught, 1958). Blaser and Kimbrough (1968) reported that maximum yield of alfalfa could be achieved if plant K was between 2% and 2.5%.

There is a tendency for some plants to absorb far more K than is required for its metabolic processes. It is particularly a problem with legumes, especially alfalfa. From 2% to 3% K is usually sufficient for forages such as alfalfa, ladino clover, orchardgrass, and smooth bromegrass. Yet it is common for these plants to have K concentrations from 3.5% to 4.5%. Thus, fertilization of pure stands should not exceed that level required to raise the soil K concentration to the medium to high level, depending on the yield (Follett and Wilkinson, 1985). Annual summer applications of K greatly reduce the trend toward luxury consumption by alfalfa, which is a particular problem in spring growth (Blaser and Kimbrough, 1968). When soils not needing fertilizer are fertilized, no increase in yield occurs; but luxury consumption is prevalent. Thus, economical considerations and common sense must dictate fertilizing practices.

Stand longevity and yield of alfalfa is closely tied to K nutrition. At rates of K ranging from 0 to 1792 kg K ha^{-1}, residual yields and stand maintenance among treatments receiving either KCl or K_2SO_4 did not differ (Rominger *et al.,* 1976). Compared to the check, zero K applied, residual yields and stands after 2 years of treatment were significantly greater if K was applied. Residual stands ranged from 50% (check) to 64 to 81% for the K treatments. Residual yields ranged from 3.43 Mg ha^{-1} (check) to 4.89 for the highest K treatment. Proper soil liming and K application (179 kg K ha^{-1} annually) increased the stand life of alfalfa grown in imperfectly drained soil. In the fifth year, plots receiving the K application produced 4.0 Mg ha^{-1} more than those receiving no K (Brown, 1963). If a soil is low to medium in exchangeable K, maintenance of a vigorous, high-producing stand of alfalfa requires fertilizer applications high in K (Blaser and Kimbrough, 1968). In this 9-year study, they showed that maintaining a pure stand of alfalfa that was productive required 186 kg K ha^{-1} annually. With no K applied, 2.5 Mg ha^{-1} was produced from a stand that included 0.75 alfalfa plants m^{-2}. Applying 186 kg K ha^{-1} resulted in dry-matter production of 8.1 Mg ha^{-1} from a stand of 4.5 plants m^{-2}. At 280 kg K ha^{-1}, K accumulated in the surface soil layer. Parks and Safley (1961) reported increases in dry-matter production with annual applications of up to 279 kg K ha^{-1}. Initial soil tests showed K at 178 kg ha^{-1}. Soil K depletion did not occur at annual K application rates above 279 kg K ha^{-1}.

In humid areas, K depletion may occur within 2 to 3 years without addition of fertilizer. Initial application of 135 kg K ha^{-1} was not sufficient to maintain soil fertility because annual removal of K averaged 164 kg ha^{-1} yr^{-1} (Peck *et al.,* 1969). In two northwestern Pennsylvania soils prone to wetness, (Alva *et al.,* 1986), K application resulted in an increase in alfalfa dry-matter production. Economic rates for the 3-year period ranged from 137 to 263 kg K ha^{-1}. Herbage K concentrations of 16 to 19.5 g kg^{-1} were necessary to produce 90% of the maximum yield the first harvest year. Response of bermudagrass to K applications of 140 kg ha^{-1} was 36 and 129% in 1983 and 1984, respectively, but above 280 kg ha^{-1} no significant response to K application was measured (Cripps *et al.,* 1988).

In arid, irrigated soils, Barberick (1985) showed that even though the soil K was high, small but significant responses could be attained from application of K in Colorado. However, the economics related to fertilization would dictate that one should not practice K application on such soils. He postulated that K addition suppressed Na uptake, which possibly resulted in greater dinitrogen fixation and dry-matter production. This postulation is supported by the work of Huffaker and Wallace (1959), who reported K inhibition of Na uptake in corn, soybean, and radish in solution culture. Inhibition was greater when Na concentration was at its highest concentration.

Whether to use KCl or K_2SO_4 is a question that is sometimes asked. Both are equally effective in supplying K needs of crops. Deleterious effects of high concentrations of Cl in soils have been shown to result in lowered dry-matter yields (Eaton, 1972; Griffith, 1974; Hall, 1971; Smith, 1971; Smith and Peterson, 1975). Concentrations of chlorine greater than 1.5% in the first harvest weakened alfalfa by killing young stems and resulted in a slight decrease in yield (Smith and Peterson, 1975). Concentrations this high may be reached with applications of KCl of more than 675 kg K ha^{-1} (603 lb $acre^{-1}$); therefore, if large levels of K are required to amend the soil K status, it may be wise to split the application among 2 years (Smith and Peterson, 1975). Application of up to 111 kg Cl ha^{-1} (100 lb $acre^{-1}$) from KCl had no negative affect on alfalfa or birdsfoot trefoil yields over a 3-year period. In the third year, a significant increase in yield was shown by alfalfa (Moyer *et al.,* 1994), indicating that under normal conditions Cl toxicity is not a problem. In association with harsh winters, similar to those that occur in the northcentral states of Wisconsin, Minnesota, and Michigan, an increase in plant death has been reported to occur in association with high Cl applications (LeCroix, 1969). In a study by Rominger *et al.* (1976), in which the two forms were compared, it was shown that at rates above 448 kg K ha^{-1} yr^{-1} (400 lb $acre^{-1}$) as KCl resulted in a reduction in yield. This is a response by the plants to the higher concentrations of Cl in the soil, but it only influenced yields during the application year. Soils containing 205 kg ha^{-1} of exchangeable K that received 672 kg K ha^{-1} (600 lb acre^{-1}) as KCl resulted in damage to the alfalfa. In the sulfate form, however, equivalent amounts of K did not damage the stand, presumably because of the absence of Cl in the second case (Smith, 1971). Movement of the chloride ion (Cl^-) in soils is rapid. Thus, the effect of high Cl concentration in the soil does not affect alfalfa in the second year, or the first year after application of large amounts of KCl (Smith and Peterson, 1975). When K was applied as K_2SO_4, however, modest yield increases continued to occur at 896, 1344, and 1792 kg K ha^{-1} yr^{-1} (800, 1200, and 1600 lb K acre^{-1} yr^{-1}; Rominger *et al.,* 1976).

Potassium may be lost through leaching, particularly in sandy soils. Kilmer (1974) concluded that although such losses probably do not exceed 10 to 12 kg ha^{-1} (8.9–10.1 lb acre^{-1}), Truog and Jones (1938) reported that K leaching losses from cultivated soils may exceed 27 to 41 kg ha^{-1} (24–37 lb acre^{-1}).

If adequate amounts of K are supplied for growth, time of application is generally not important (Griffith, 1974). In the fall after the last harvest is an ideal time because of weather, work load, and price received from industry, to apply K. On soils low in K, at least annual applications of K are required to maintain production (Overdahl, 1972; Hanson and MacGregor, 1966) and assure stand longevity (Markus and Battle, 1965). If high rates of K are required, split applications after the first and last harvests may be advisable. Rhykerd and Overdahl (1972) showed some temporary injury to the plants when very high rates of K are applied early in the spring. Legumes grown on light, sandy soils, under irrigation, or with extended growing seasons require more than one K application for sustained crop growth (Griffith, 1974). Kresge and Younts (1962) and Brown (1957) have shown that for soils requiring regular application of K, improved yields result from more than one application per year. Benefits of such practices must, however, be weighed against added cost of application. There is some advantage to applying the annual application after the first harvest (Blaser and Kimbrough, 1968). For example, spring application resulted in only 8.5 Mg ha^{-1} (3.8 ton acre^{-1}); spring and after second cutting produced 8.6 Mg ha^{-1}; after the first harvest, yield was 9 Mg ha^{-1} (4.0 ton acre^{-1}). This concept is illustrated by Fig. 11.7. Soils with low cation exchange capacity (CEC) and low release rates of residual and nonexchangeable K require frequent, relatively small K applications, (i.e., sandy soils). Soils with high CECs and high release rates of residual and nonexchangeable K can be fertilized less frequently (Follett *et al.,* 1985).

In grass-legume mixtures, it is important to keep the K concentration in the soil at adequate levels. In situations in which soil K is low, grasses dominate and legumes are lost from the stand because they are not able to obtain sufficient K (Fig. 11.8). Legumes and grasses require similar

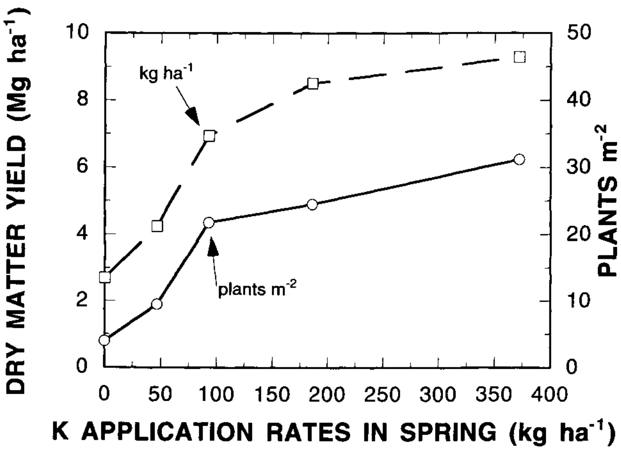


FIGURE 11.7 Relationship between hay yields and alfalfa stands with K fertilization during the seventh year of harvesting. Lime, P, and B were applied uniformly and K was applied each year to the alfalfa–orchardgrass mixture on a Cecil loam in Virginia. (Redrawn from Blaser and Kimbrough, 1968.)

concentrations of K for proper growth, but when they are grown in a mixture, grasses can more easily extract the needed K than can the legumes. As K supplying power decreases, the differences become more pronounced; thus, greater K levels may be needed in mixtures (Table 11.6). This has implications for stand longevity. If soils are lower in K, more difficulty is experienced in maintaining a stand of alfalfa. This point is well illustrated

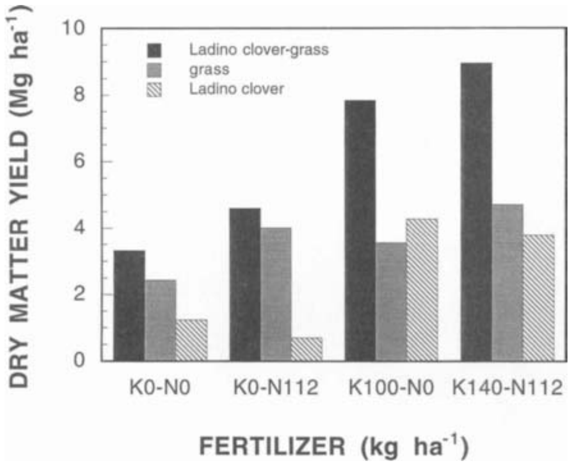


FIGURE 11.8 Total mixed herbage yield (16% moisture) and botanical components as influenced by N and K fertilization. (Redrawn from Blaser and Kimbrough, 1968.)

TABLE 11.6 Percentage of K in Orchardgrass–Alfalfa Stands

	K (% of DW)		
K applied	Grass	Alfalfa	% K in alfalfa relative to grass
0	2.71	0.70	26
46.5	3.46	1.21	35
93	4.01	1.78	42
372	3.85	3.53	92

Source: Blaser and Kimbrough, 1968.

by the work cited by Griffith (1973; Table 11.7). For mixed stands of grasses and legumes, split application of fertilizer, generally in the fall and after first grazing or harvest in the spring, improve overall yield and quality (Griffith, 1973).

D. CALCIUM AND MAGNESIUM

Humid area soils are generally low in Ca because leaching has occurred over the years. Liming readily corrects this problem. Plant concentration is usually far in excess of the metabolic needs (0.2 to several percent; Epstein, 1972), whereas the requirement is only 2 mg kg^{-1} (Wallace *et. al.*, 1966). Arid region soils are high in Ca.

Calcium is the major cation of the middle lamella of cell walls and calcium pectate is a principal constituent of cell walls. Calcium is required for normal growth in the growing points of plants; without it they cease proper growth and, in extreme cases, die. General disorganization of cells

TABLE 11.7 Influence of K Application on Maintaining a Legume in a Grass–Legume Stand

Forage mixture	Fertilizer rate (kg ha^{-1})	Yield (Mg ha^{-1})	Legume (%)
Alfalfa–bromegrass	0	4.45	73
	279	9.15	90
Alfalfa–orchardgrass	0	4.60	27
	279	6.25	46
Ladino–orchardgrass	0	4.19	7
	279	6.79	12
Ladino–tall fescue	0	4.57	8
	279	5.96	28

Source: Griffith, 1973.

and tissues showing Ca deficiency suggest that Ca promotes membrane functions and likely maintains cellular organization (Epstein, 1972).

Magnesium is a constituent of chlorophyll. It activates enzymes and plays a major role in metabolism. In addition, it is contained in the plastids and is a cofactor in the majority of enzymatic reactions occurring in plants that act on phosphorylated substrates, thus serving a major role in energy metabolism (Epstein, 1972).

Deficiencies of Mg may develop in the soil (Brady, 1974) and therefore use of dolomitic limestone (sometimes called *dolostone*), in areas where it is available, correct this problem. Use of dolomitic limestone is the preferred way to alleviate Mg deficiencies, but in areas where it is not readily available, fertilizers containing Mg are available.

At times, even though the soil pH is maintained at 6 to 7, Mg deficiency develops in animals consuming the forage—usually lush grasses. The condition is called **hypomagnesemia** and appears to result from an imbalance of K, Mg, and Ca (see Chapter 6).

E. SULFUR

The essential nature of S was discovered late in the 19th century. Until recently, however, little attention has been paid to it because of the use of S-containing N and P fertilizers (Follett and Wilkinson, 1985) and acid rain. Over the years, incidental S carried in fertilizers has undoubtedly been an important factor in maintaining fertility of the soil with respect to S (Follett and Wilkinson, 1985). To illustrate this incidental application, important sources of S are single superphosphate and sulfate of ammonia. The most common materials applied to correct S deficiencies are elemental S, gypsum, potassium sulfate, and potassium-magnesium sulfate (Griffith, 1974). Bardsley and Jordan (1957) reported that approximately 5 kg S ha^{-1} yr^{-1} are added through acid rain in Mississippi. The amount would be less in semiarid and arid climates because of reduced precipitation. The amount would also be somewhat dependent on the amount of S spewed into the atmosphere by industry. Hester (1978) reported S fallout from the atmosphere to range from 6 to 22 kg S ha^{-1} yr^{-1}, depending on closeness to industrial sites and prevailing wind patterns. When fallout from the atmosphere exceeds 11 kg S ha^{-1} yr^{-1}, it is unlikely that S deficiencies in the soil occur (Whitehead, 1964). Some S is made available in the soil from decaying organic matter. Higher-analysis fertilizers (i.e., of more pure analysis) have resulted in increased S deficiency reports (Griffith, 1973; Tisdale, 1977; IFDC, 1979). Since 1948, reports of S deficiency and response to S application have become widespread across the United States.

Total S in soils varies widely (Peverill and Briner, 1974) and is related to the variable nature of primary minerals in the soil. Sulfur may be in the following forms: soil solution sulfate (SO_4^{-2}) ions, adsorbed SO_4^{-2} ions, organically bound ester SO_4^{-2}, and organic S compounds (Follett and Wilkinson, 1985). In warmer areas (subtropics and tropics), soil-adsorbed S is higher and temperate regions show a predominance of organic S and esters (IFDC, 1979; Laughlin *et al.,* 1981). Surface soils (plow layer) in the southeastern United States are commonly low in extractable S (Bardsley and Jordan, 1957). A regional study has shown that most soils release approximately 6.7 kg S ha^{-1} or less with extraction by sodium acetate-acetic acid (Morgan's solution). However, just below the plow layer in most of these soils, S accumulates. Sulfur deficiencies often occur in grasses grown in southcentral Alaska (Laughlin *et al.,* 1981). Deficiencies have also been reported in Nebraska on highly leached, sandy, and low organic-matter soils (Fox *et al.,* 1964). Six years of continuous alfalfa also resulted in development of S deficiencies in other soil types. Griffith (1974) stated that although many soils appear to have sufficient S, they may be expected to show S deficiency when managed for high-forage yields.

Sulfur is taken up by plants in the sulfate (SO_4^{-2}) form (Follett and Wilkinson, 1985). Most legumes are particularly high users of sulfur (S) when compared with grasses (Bardsley and Jordan, 1957). Alfalfa and clovers cut for hay remove 22 to 28 kg S ha^{-1} annually.

Expression of deficiency is usually expressed as leaf chlorosis (Bardsley and Jordan, 1957). Deficiency results in incomplete N assimilation and, consequently, affects protein metabolism (Bardsley and Jordan, 1957). The main effect of S appears not to be on nodulation of legumes or N supply, but on N assimilation (Cairns and Carson, 1961). Nutrient deficiencies affect plant yield and forage quality through changes in the synthesis of the amino acids, the building blocks of proteins, cystine, cysteine, and methionine. Chlorophyll formation and synthesis of vitamins such as biotin, thiamine, and vitamin B are also affected by S deficiency (Follett and Wilkinson, 1985). Soils low in S provide greater yield and increased quality in response to S application.

Conrad *et al.* (1948) reported a fourfold increase in alfalfa dry matter with application of S in California. On two soils that gave a positive response to S application in Nebraska, it was shown by Sorenson *et al.* (1968) that N percentage also increased when compared to the control. Plants were at the 1/10-full bloom stage of development. Bardsley and Jordan (1957), in a study including seven soils on the effects of S application, found that whiteclover produced without added S was lower in S and N concentrations, and the concentration of methionine and cystine in the forage was lower. Soils considered to be sufficient in S have been shown by Caldwell *et al.* (1969) and Seim *et al.* (1969) to yield twice as much alfalfa when S was applied as elemental S or gypsum (4.0 vs. 9.5 Mg ha^{-1}).

A survey of soils in Wisconsin revealed a response of alfalfa to S application on 6 of 9 sandy loam soils (Hoeft and Walsh, 1970; Rand *et al.,* 1968). The sulfate form of S was more effective than was the elemental form in eliciting a response. In Minnesota, soils with less than 7.0 mg kg^{-1} usually show S deficiency; 7 to 12 mg kg^{-1} concentrations in the soil may possibly show S deficiencies; and more than 12 mg kg^{-1} shows no deficiencies (Grava, 1971; Beaton *et al.*, 1968). Beaton indicates that no response to S application may be expected when the soil S is in the 10 to 12 mg kg^{-1} range.

Losses of S from soils can be rather large. Sandy soils and soils low in organic matter need more frequent S fertilization than do heavier-textured soils. Soils low in S but capable of high yields may respond more favorably, and more efficiently, to annual S applications. Incorporation of S into the soil has not been found to be important (Griffith, 1974).

An in-plant S concentration of approximately 0.16% is considered to be the critical level (Martin and Matocha, 1973). Rominger *et al.* (1976) suggested that a plant concentration of 0.2% could serve as a guideline for S needs. In whiteclover, the seventh harvest, without S application, showed tissue concentrations of 0.08 to 0.14% and 0.20 to 0.30% with S application (Bardsley and Jordan, 1957). Bear and Wallace (1950) and Harward *et al.* (1962) suggest that S concentration should be between 0.20% and 0.22% of dry weight. Sorenson *et al.* (1968) and Caldwell *et al.* (1969) have identified the favorable concentration to be higher—0.3% or more. Westerman (1975), on 13 sites in southern Idaho, found only one site produced optimum alfalfa with an S concentration in the tops of less than 0.20%. This indicates that there is some soil-dependent variability in response to S required for optimum yield. However, the majority of the soils held to the 0.20% dictate. In this study, the maximum forage yields were obtained when the tops of alfalfa plants contained 0.15 to 0.20% S. Alfalfa also showed a similar increase in yield as the S in the tops increased from 0.05 to 0.211%. At the lower S concentration yield was 40% of the yield at the higher concentration. Relative yield is expressed in the following equation:

$$RY = -190.73 - 1310.85(\%\mathrm{S}) + 1233.14\sqrt{\%\mathrm{S}} \qquad (11.1)$$

where *RY* is relative yield. The coefficient of determination (R^2) was 0.934.

The N:S ratio in the plant could be used in conjunction with the soil test to make a more accurate prediction of S requirements of alfalfa. There are times when soil S tests indicate a deficiency, but no response to applied S is observed; vice versa, a soil test may indicate that S is not needed, but a response is observed (Nuttall, 1985b). A N:S ratio of 12 in the plant tops produced optimum yields of dry matter; but no response of alfalfa to S fertilization was measured unless the N:S ratio was greater than 17 (Westerman, 1975). Under very severe S stress, the N:S ratio increased to 30 in this study. The work of Westerman (1975), Dijkshoorn *et al.* (1960), and Stewart and Porter (1969) indicates that the N:S ratio for legume tissues is near 17.5:1, above which a response to S fertilization can provide a yield increase, but below which no increase generally is realized. Nuttall (1985a,b) showed that a range of 14:1 to 21:1, in plant N:S ratio, was the range in which plants showed deficiency to S. To ensure maximum production, N : S ratios of 14 : 1 to 16 : 1 should be maintained in the forage (Tisdale, 1977). Martin and Matocha (1973) reported that S deficiencies often occur when plant N : S ratios ranged from 14 : 1 to 21 : 1. In a different study, Pumphrey and Moore (1965b) reported that N : S ratios of less than 11 indicate that yield increases are not very likely, and the need for S fertilization was predicted with accuracy of 96% with the following relationship:

$$Y = 1.00834 - 0.00179X - 0.00103X^2, \qquad (11.2)$$

where Y is predicted percentage of full yield and X is the N : S ratio. No significant yield increase was achieved when the N : S ratio was less than 11, but in 20 of 21 experiments where the N : S ratio was more than 11, significant yield increases from S fertilization resulted (Fig. 11.9). Bardsley and Jordan (1957) showed that typical N : S ratios for nine soils ranged from 20 to 30 without application of S and 10 to 17 with application of S.

F. MICRONUTRIENTS

Micronutrient deficiencies are not common in forage crops. However, in some environmental conditions and on some soils, the additions of specific nutrients may be critical to achieving optimum yields. General guidelines

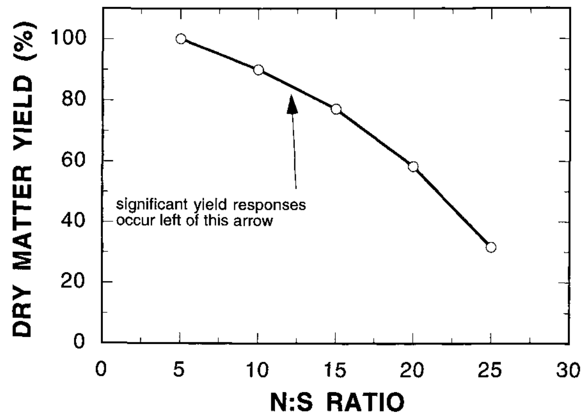


FIGURE 11.9 Relationship between percentage yield and N : S ratio in the forage of "non-sulfur-fertilized" first-cutting alfalfa (X = significant yield increase; • = no significant increase in yield.). (Redrawn from Pumphrey and Moore, 1965a.)

for deficient, normal, and toxic levels of six micronutrients are presented in Table 11.8.

In general, deficiency of micronutrients can be corrected by applying salts of the deficient nutrient to the soil or chelates sprayed on the plant. Rate of application must be watched carefully because an overdose will result in severe toxicity problems. Micronutrients should not be added unless their need can be clearly established (Follett and Wilkinson, 1985).

1. Boron

Boron (B) is frequently deficient in some soils and expresses itself in legumes in abnormal growth of the growing point. This is especially true for crops grown on light-colored, sandy soils in humid regions. Deficiency is sometimes associated with soil type, areas of moderate to heavy precipitation, neutral or alkaline soils, dry weather, and high light intensity (Lucus and Knezek, 1972). In general, among forage crops only the legumes consistently show B deficiencies. Mahler *et al.* (1985) reported that a rotation rich in leguminous crops such as alfalfa, beans, and clover required more B than did a rotation high in cereal crops. Legumes, but especially alfalfa, are sensitive to low concentrations of B in the soil. Use of B in alfalfa fertilizers is a common practice, and B deficiency is easily corrected with application of 1 to 3 kg ha^{-1} of actual B (0.9-2.7 lb acre^{-1}). Application with other fertilizers is preferable in both preplant and maintenance operations. Light-textured, permeable soils should receive annual applications of B because of the danger of leaching losses when large amounts are applied (Griffith, 1974).

Availability of B to plants is related to the decomposition of organic

TABLE 11.8 Essential Trace Elements and Important Parameters for Soils, Plants, Deficiency, and Toxicity

Element	Soil (mg kg^{-1})^{a}	Plant (mg kg^{-1})	Deficient (mg kg^{-1})	Toxic (mg kg^{-1})	Comment
Boron	10 (2–100)		5–30	>75	Wide species difference
Cobalt	8 (1–40)	0.05–0.5			Legumes require <0.02
Copper	20 (2–100)	4–15	<4.0	>20	
Manganese	850 (100–4000)	15–100			Toxicity depends on Fe:Mn ratio
Molybdenum	2 (0.2–5)	1–100	<0.1		Low toxicity
Zinc	50 (10–300)	8–15		>200	

[a] Desirable (range) concentration in soils.

Source: Allaway, 1968.

matter, soil texture, and soil pH (Griffith, 1974). Boron is held by the organic fraction of the soil and is released as decomposition occurs. Low pH inhibits activity of microorganisms and reduces the rate of B release. Clay fractions of soils also hold some B, but it is easily leached unless it is used by the plants. Excess lime may also reduce B availability (Wear and Patterson, 1962).

It is recommended that 21 to 80 mg kg^{-1} is a sufficient range in the top 7.5 cm of alfalfa sampled before flowering begins (Ohio State University, 1972). Generally, healthy alfalfa contains approximately 35 mg kg^{-1} B, and a response to B application is expected when B concentration drops below 20 mg kg^{-1} (Nelson and Barber, 1964). Boron is relatively immobile in the plant, and the youngest growth generally first show deficiency symptoms. Thus, in alfalfa and other legumes, it is expressed in the terminal bud. To correct B deficiency, the most commonly used material is borax, which contains 11% B. More concentrated forms, with up to 20% B, are also available.

2. Zinc

Alfalfa is capable of absorbing zinc (Zn) from soils considered to be Zn deficient for other crops (Brown *et al.*, 1964). Thus, Zn deficiency has rarely been reported in alfalfa or clover (Nelson and Barber, 1964). Shitao and Reisnauer (1968) showed no response to Zn addition when plant-leaf Zn concentrations exceeded or equaled 6 mg kg^{-1}. Their work caused them to conclude that alfalfa has a lower Zn requirement than do other crops. The range for Zn sufficiency in alfalfa is reported to be 21 to 70 mg kg^{-1} in the top 7.5 cm of growth when sampled prior to initial flowering (Ohio State University, 1972; Mills and Jones, 1996). Zinc deficiency in other legumes and in grasses other than corn and grain sorghum is not well documented.

3. Molybdenum

Normal alfalfa plants contain about 2 mg kg^{-1} of molybdenum (Mo), and deficiency occurs at about 0.5 mg kg^{-1} or less (Nelson and Barber, 1964; Mills and Jones, 1996). Deficiency symptoms appear similar to N deficiency in legumes. Molybdenum is required in N fixation and in protein formation; thus, Mo deficiency results in N starvation of the plant. Yield increases, in response to addition of Mo, of 482, 141, 25, and 6% at pH levels of 5.0, 5.3, 5.7, and 6.0, respectively, were reported in Virginia (Jones and Moschler, 1966), thus, showing the effect of pH on Mo availability. Nitrogen concentration of alfalfa also increased as pH increased. This suggests that the soil contained sufficient Mo for normal alfalfa growth, but Mo, due to the pH, was not available. This is a common circumstance in many acid soils for Mo. Thus, most Mo deficiency symptoms appear in crops grown on acid soils.

The effect of Mo deficiency on dry-matter yields and N uptake are dramatic (Doerge *et al.,* 1985). Dry-matter yields of tops and roots were, respectively, 1.78 and 1.18 g pot^{-1} without Mo and 6.52 and 3.35 with Mo. Nitrogen concentration of the tops (g kg^{-1}) was 20.6 and 26.5, or a 127% change, for minus and plus Mo, respectively. Total N uptake was similar, but even more dramatic: 0.049 g pot^{-1} without Mo and 0.216 g pot^{-1} with Mo, a 441% increase (Doerge *et al.,* 1985). Response to N and Mo, especially at lower soil pH levels, suggests that growth response to lime is due primarily to increased nodule efficiency, resulting from greater Mo availability as soil pH is raised (Doerge *et al.,* 1985). Molybdenum primarily affects the N-fixation process, but has only a slight effect on development of nodules (Mulder 1948). The result of liming is to increase the N percentage in the shoots of alfalfa and white clover with increased soil pH, in plants grown in a soil pH of 4.8 to 7.2 (Munns *et al.,* 1977). The increase was particularly pronounced for alfalfa. For example, alfalfa and white clover increased from 2.25% N at a pH of 4.8 to 3.8 and 3.0, respectively, at a pH of 7.2.

Correction of Mo deficiency can usually be achieved by application of limestone, but if correction of soil acidity is not needed, it is appropriate to apply Mo salts, usually at time of seeding (Mengel and Kirkby, 1982).

4. Copper

If the concentration of Cu in alfalfa falls below 10 mg kg^{-1} at 1/10 bloom, Cu deficiency symptoms may occur (Nelson and Barber, 1964; Mills and Jones, 1996). Mineral soils with known Cu deficiencies may be amended with application of 11 to 17 kg ha^{-1} of copper sulfate. Organic soils may require at least double this amount (Rhykerd and Overdahl, 1972).

The expected response of various forage crops to micronutrient application when grown in soils that predispose them to nutrient deficiencies is presented in Table 11.9. The common perennial forage grasses show little response, alfalfa shows a low to medium response to all micronutrients except for B, and the large annual grasses such a corn, sorghum, and sudangrass show a high response to Zn, Fe, Mn, and Cu.

V. SOIL NUTRIENTS AND DINITROGEN FIXATION

Fixation of atmospheric N by legumes is a unique and valuable trait for reducing N fertilizer costs in forage production and in generally enriching the productivity of the soil. Legumes commonly used as forages fix differing amounts of dinitrogen during the growing season (Table 11.10). Alfalfa and Ladino clover typically fix from 200 to 225 kg ha^{-1} (180–200 lb $acre^{-1}$). The efficiency of dinitrogen fixation is closely tied to the mineral nutrient

TABLE 11.9 Response of Forage Crops to Micronutrients under Soil or Environmental Conditions Favorable to a Deficiency

Crop	Zn	Fe	Mn	Mo	Cu	B
Alfalfa	L[a]	M	M	M	H	H
Barley	M	H	M	L	H	L
Clover	M	—	M	H	M	M
Corn	H	M	L	L	M	L
Grass (Kentucky bluegrass)	L	H	L	L	L	L
Oat	L	M	H	M	H	L
Pea	L	—	H	M	L	L
Rye	L	—	L	L	L	L
Soybean	M	H	H	M	L	L
Sorghum	H	H	H	L	M	L
Sudangrass	H	H	H	L	H	L

[a] L, low; M, medium; H, high.
Source: Lucas and Knezek, 1972.

TABLE 11.10 Amounts of N Typically Fixed by Forage Legumes in Temperate Climates

Legume	Typical amounts of N fixed per year (kg ha^{-1})
Alfalfa	224
Crimson clover	140
Ladino clover	202
Sweet clover	134
Red clover	129
Kudzu	123
White clover	112
Cowpeas	101
Lespedeza (annual)	95
Vetch	90
Pea	78
Soybean	112
Birdsfoot trefoil	105

Source: Tisdale *et al.,* 1993.

status of the soil in which the legume is grown. The elements most critical are discussed in the following section.

A. NITROGEN

Nitrogen application rates greater than 25 to 50 kg ha^{-1} (22.5–45 lb acre^{-1}) applied to alfalfa prior to stand establishment did not enhance yield during the first year (Kunelius, 1974). Nodule weight and number decreased significantly if more than 25 kg ha^{-1} was added. There were 1.6 nodules per plant at 0 N to 1.4 at 25 N and 0.3 at 50 and 100 kg N ha^{-1} (45–90 lb acre^{-1}). Weight per nodule declined 35% when 25 kg N ha^{-1} was applied. Further significant decreases occurred with application of 50 or 100 kg N ha^{-1} over two experiments (Kunelius, 1974). A report by Munns (1968b) indicates that nitrate concentrations of 2 m*M* in the growth solution reduced the number of root hairs by 95%, curled root hairs by 99%, and nodules by 98% per plant.

B. POTASSIUM

Potassium concentration of the soil has a major effect on dinitrogen fixation. Collins *et al.* (1986) demonstrated that dinitrogen fixation was increased 2.8 times with the addition of 224 kg K ha^{-1} (200 lb acre^{-1}) on a sandy soil and 1.7 times on a loam soil. Over the K treatments of another study, Duke *et al.* (1980) demonstrated that a linear correlation ($P \leq 0.01$) resulted between nodule number and N fixation (acetylene reduction rate) as K availability was increased. They also showed that high rates of K, as either sulfate or chloride, increased nodulation and dinitrogen fixation when compared to the control plants (approximately 2.5 times). On a per-plant basis, increases were shown to be due to increased nodule mass instead of greater activity per unit of nodule mass.

C. CALCIUM

Evidence suggests that the most calcium-demanding factor in dinitrogen fixation is infection initiation. It is also the most acid-sensitive stage of nodulation (Munns, 1970). In support of this, Mulder and Van Veen (1960) showed that addition of $CaCO_3$ (1 to 2 g) to 500 g of acid soil, after an incubation period of about 4 weeks, resulted in normal nodulation of red clover plants. This suggests that *R. trifolii* are unable to grow in acid soils.

D. SULFUR

Dinitrogen fixation may not respond to S application alone, but when combined with other elements such as P or K, a significant response may be realized. Collins *et al.* (1986) showed that there was no response in nodule number when S was applied alone. However, when applied with 56 kg P ha^{-1} (50 lb $acre^{-1}$), the nodule number per core increased from 18.5 to 32.9—a 1.7-fold increase. High K application rates (448 kg K ha^{-1} or 400 lb $acre^{-1}$) in conjunction with S at 28 kg S ha^{-1} (25 lb S $acre^{-1}$) resulted in significantly higher dinitrogen fixation than did other treatments in which K application was one-half the previously mentioned rate (Collins *et al.*, 1986). The increase was from 372 to 644 nmol $core^{-1}$ hr^{-1}.

E. BORON

Boron deficiency inhibits dinitrogen fixation by preventing the growth of nodule tissue (Munns, 1977).

F. MOLYBDENUM

Molybdenum serves an essential role in N fixation (Mulder, 1948; Postgate, 1985), and it is the only micronutrient that becomes more available as soil pH increases. As pH decreases, the decrease in Mo in the soil solution is due to absorption by acid, hydrated haloysite (Stout *et al.*, 1951). Molybdenum deficiencies are associated with soil acidity or high free Fe (Lucus and Knezek, 1972). Rhizobium survival (Rice, 1975) and Mo (Mortvedt, 1981) deficiency at pH less than 6 can restrict symbiosis; thus, yield increases could be expected with application of either lime or N (Munns *et al.*, 1977).

VI. ALUMINUM TOXICITY

It is impossible to ascribe poor plant growth to one factor in an acid soil. For example, it may be that the plant or crop is suffering from each of the following simultaneously: Al and Mn toxicity and Mo and Ca deficiency. However, deleterious effects of soil acidity on plant growth are commonly due to excessive soil solution concentrations of exchangeable Al and Mn. In strongly acid soils, excess soluble or exchangeable Mn and Al produce toxicity in many crops (Jackson, 1967). There is considerable variability in crops in response to these elements. Aluminum and Mn in the soil solution in increased amounts is usually of major importance in reduced plant growth in highly acid soils (Jackson, 1967). All soils have the potential for Al toxicity because Al is always present, making up 15 to 20% by weight of dry soil and it is an important part of clay mineralogy. The concentrations required for inhibition of plant growth are very low (Adams and Pearson, 1967; Pearson and Hoveland, 1974). Symptoms of Al toxicity are generally restricted root development—both rooting depth and fineness of root development are affected. Thus, liming, improves root–soil contact and better exploitation of available nutrients in the soil profile (Pearson and Hoveland, 1974). Aluminum toxicity has no evident leaf symptoms. However, Mn toxicity has striking leaf symptoms (Adams and Pearson, 1967), but Mn varies greatly in soils, so toxicity problems vary accordingly (Follett and Wilkinson, 1984; p. 313). When the soil pH is ≤ 4.5, dry-weight production of alfalfa is reduced, and Mn uptake, as measured in the plant tops, is increased (Table 11.11). There is a close relationship between exchangeable Al in the soil and alfalfa yield and longevity of stand. Maximum alfalfa yield of 18 Mg ha^{-}1 (8 ton acre^{-1}) was achieved with application of 2.2 Mg ha^{-1} (2 ton acre^{-1}) of dolomitic limestone. With this rate, exchangeable Al was reduced to less than 0.2 meq Al/100 g of soil. Without limestone application, the value was 0.8 meq Al/100 g (Fig. 11.10).

Exchangeable Al decreases in soils as pH increases from 4.8 to 6.0 (Adams and Lund, 1966). At the same time, root length increases dramatically. Noble *et al.* (1988) showed that soybean root length decreased dramatically as Al^{+3} ion activity increased. In andic (volcanically derived) soils, Al toxicity is a problem (Janghorbani *et al.*, 1975).

Plant growth can be expected to decline or decrease in rate when pH is < 5.2 in the presence of Al and/or Mn (Helyar and Anderson, 1971; Rice, 1975). Good production levels of alfalfa may be achieved as long as the Al level is less than 20% of the CEC (Helyar and Anderson, 1971); thus, it is evident that differing conditions provide varied results.

Thus, alleviating Al toxicity is closely tied to changing the pH of the soil through liming. Correcting the subsoil pH is much more challenging than is correcting the surface soil pH. The only practical way to increase the pH of the subsoil zone is through the application of $Ca(NO_3)_2$ to the surface, and then relying on movement of part of the applied material into the acid subsoil, where the roots preferentially take up the NO_3^-, leaving

TABLE 11.11 Effects of Lime on the Soil Solution and on the Yield and Mn Content of Alfalfa

	Soil solution				
	Al	Mn			
Calcium added (kg/ha)	$\mu g\ L^{-1}$	$\mu g\ L^{-1}$	Water pH	DW g	Mn $\mu g\ g^{-1}$
0	307	146	4.1	0.27	8.14
628	84	90	4.5	0.42	5.33
1255	9	34	4.5	0.58	3.09
1883	4	14	4.7	0.61	1.86
2511	3	8	4.87	0.66	1.51

Source: Helyar and Anderson, 1971.

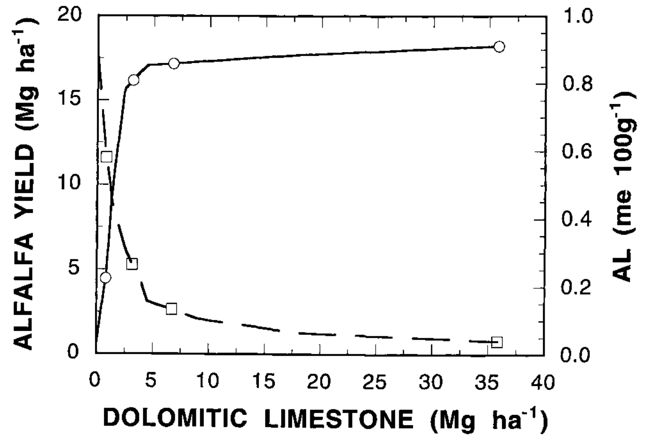


FIGURE 11.10 Relationship between applied lime, reduction in exchangeable Al, and alfalfa yields on a Tatum silt loam. (Redrawn from Moschler *et al.*, 1960.)

the Ca or Mg, which will increase the pH of the soil. After 4 years of such treatment on bermudagrass, the soil pH at 30- to 45-cm depths had changed from 5.2 to 6.0 and at 60- to 75-cm depths the pH had changed from 5.2 to 5.5 (Adams and Pearson, 1969). Injecting liquid lime and deep plowing may be feasible in some situations, but the economics of these practices are suspect if the pH change is desired at the deeper levels within the soil profile.

VII. SOIL SAMPLING AND TESTING

The fertility level of a field varies considerably from side to side and from one end to the other. This variability is due to variations in soil type, the soil forming processes, cropping patterns, and previous fertilization levels and patterns. Banding of fertilizers (James and Dow, 1972) can cause variability in soil samples simply because banded fertilizers such as phosphorus may not move very far from the original placement position.

A soil sample is intended to represent the fertility status of the field. Thus, the sample must consist of soil from numerous places in the field. The sample submitted to the soil testing laboratory must provide an accurate representation of the field's fertility variability and status. A poorly collected sample is essentially useless in assessing the fertilizer needs of the crop to be grown on the field.

The best protocol for sampling a field is disputed by the experts, largely because of insufficient and conflicting research. It is suggested by some researchers that the sample, representing a uniform field, should consist of approximately 20 to 30 cores taken randomly from the field. Once the cores have been collected, they should be thoroughly crushed and mixed, subdivided to reduce the sample to a manageable size, and air dried before sending it to the laboratory. Others, however, suggest that systematic sampling may be superior to random sampling (Reuss *et al.*, 1977). LeClerg *et al.* (1962) drew two general conclusions from analysis of previously published uniformity trials: (1) variations in soil fertility are not distributed randomly, but to a degree they are systematic; and (2) soil fertility variability is not so systematically distributed that it can be described mathematically. In nonuniform fields, a nonrandom, systematic sampling procedure is recommended. In nonrandom sampling, the objective is to understand both the average field conditions and the extremes encountered in the field (James and Wells, 1990). This requires placement of grid marks at regular intervals throughout the field and collecting the cores from the grid intersections. Spacing between the grids varies with the degree of detail required. At each grid intersection point, 8 to 10 cores should be taken within a 1-m radius. A soil analysis is then performed on each sample from each grid-intersection point. This procedure, however, becomes prohibitively expensive if the grids are too close together.

The practical approach, based on the premise that a random soil sample is a better indication of the field's fertility status than no soil sample at all, suggests that approximately 30 soil cores be taken from a field. Large fields or fields that show obvious nonuniformity should be divided into smaller units that represent the most obvious differences.

Generally, sampling the soil to the depth of the plow layer is sufficient.

12

WATER RELATIONS AND IRRIGATION

I. INTRODUCTION

All aspects of plant growth and development are influenced by water. Water functions as a hydraulic agent in maintenance of *turgor* or *turgor pressure* (cell pressure, equal to the pressure of water in the cell) in the plant's cells, allows for expansive growth, is a biochemical reactant in photosynthesis and other important metabolic reactions, a solvent and an agent of transport for all substances moving into and through the plant, and is the primary structural filler of plant-cell protoplasm. Water also functions as a thermal buffer and, through transpiration, as an evaporative cooling agent (Dainty, 1963; Meidner and Sheriff, 1976).

Water is the factor that most limits plant growth in many parts of the world. Soils may be high in nutrients and salts may be below the critical range for plant growth, but without sufficient water, crop growth is reduced or prevented. As water becomes limiting, photosynthesis is reduced and, in turn, growth and development of plants are affected. Eventually, respiration is also reduced. To alleviate or eliminate water stress in crop production, many arid and semiarid areas of the world have developed extensive and elaborate irrigation systems. For example, in the Central Valley of California, the desert southwest, and the intermountain valleys of the western United States, extensive irrigation systems are found, without which no crop production could occur. In temperate regions such as the Midwestern, northeastern, and southeastern United States, drought may limit plant growth even though precipitation is ample to maintain either grass or forest cover. In these areas, irrigation is often a significant supplemental practice that assures higher crop yields.

Important terms used in referring to water relations in plants are transpiration, evaporation, evapotranspiration, water use efficiency, and water potential (of both plants and soil). *Transpiration* is the loss of water from an actively growing plant. It is lost as a vapor through the stomata of the leaves. *Evaporation* is defined as the change of water from the liquid to the gaseous state, and it can occur from any wetted surface. Because a crop canopy, as a whole, exhibits both transpiration and evaporation, the loss of water from the canopy is termed *evapotranspiration.* Other terms used in describing soil and plant water relations are *soil matric potential,* which is the tenacity with which a soil holds water; and *water potential,* a measure of the energy available for reaction or movement of water. Water potential is the expression of chemical potential of the water. Under normal biological conditions, the water potential is usually high enough not to limit the rates of reaction involving water. Water will always move from a region of higher potential to a region of lower potential (Bidwell, 1988). *Osmotic potential* is a measure or expression of cell turgor and it is a function of solute concentration. *Osmoregulation* or *turgor regulation* is the regulation of osmotic potential within a cell by the addition or removal of solutes from solution until the intracellular osmotic potential approximately equals the potential of the medium surrounding the cell (Turner and Jones, 1980). *Osmotic adjustment* in higher plants refers to the lowering of osmotic potential arising from the net accumulation of solutes in response to water deficits or salinity (i.e., the net solute increase or active accumulation of solutes). *Water use efficiency* is the ratio of the amount of water used (evapotranspiration) to the amount of dry matter produced.

To understand the effect of water stress on yield of forage plants, we must evaluate water potential of both plants and soils, stomatal control, water movement in the plant, and transpiration. These topics are discussed in the next section.

II. WATER POTENTIAL

The water status of plants is described in terms of water potential (ψ_w). The components of water potential are the *solute contribution,* expressed as osmotic potential (ψ_π), and the *pressure potential* (ψ_p). The relationship is described as follows: $\psi_w = \psi_p + \psi_\pi$. In the protoplasm, ψ_p is the turgor potential, and is usually assumed that $\psi_p \geq 0$. In the absence of water flux across the plasmalemma, ψ_w of the wall and protoplasm are equal. Because ψ_w in the wall is much less than that in the protoplasm, in the wall ψ_p is ≤ 0, except during guttation. A third component, the *matric potential* (ψ_r), is often added (e.g., $\psi_w = \psi_p + \psi_\pi + \psi_r$). In reality, the macroscopic measurements of water potential components include matric effects in ψ_π or ψ_p (Passioura, 1980); thus, the matric potential (ψ_r) is usually not included in the water potential expression.

When a plant or crop is subjected to drought stress, an increase in solute concentration within the cell is a means for partial or even complete turgor maintenance as ψ_w decreases. Benefits from turgor pressure maintenance are delayed stomatal closure, thus allowing photosynthesis to continue despite reduced ψ_w, and in cases in which active vegetative growth is occurring, continued leaf, stem, and root growth may continue. Williams and Stout (1981) presented evidence that such osmotic adjustments may occur in alfalfa and, in general, osmotic adjustment is evident in many plants (Turner and Jones, 1980).

III. STOMATAL REGULATION

Transpiration by crops is regulated by stomatal opening and closing. Water loss and CO_2 uptake are reduced with closing of the stomata. Research shows that daily stomatal conductance of irrigated alfalfa decreased from 0900 h to about 1400 h, and then remained nearly constant until 1900 h (Baldocchi *et al.,* 1981).

Under optimum growth conditions, soil at field capacity and the plant canopy with a leaf area index (LAI) of 3 or more, alfalfa sustains very high transpiration rates. Measurements have shown transpiration rates up to 14 mm d^{-1}, and a maximum rate during the day of 1.6 mm h^{-1} (Rosenberg and Verma, 1978). Transpiration from such a canopy is determined by the day's heat supply and availability of water in the soil. Plants with a limited available water supply in the soil and a high heat load can experience wilting during the warmest part of the day. Wright (1982) listed the following plant factors as important in maintaining high rates of transpiration: (1) high stomatal conductance (1.5–3 cm s^{-1}), (2) small leaves with high boundary layer conductances, (3) high stem densities, and (4) high root densities. Because forage crops possess all of these characteristics, high rates of transpiration are maintained as long as the soil water supply is adequate.

When a forage crop is removed through harvesting, transpiration becomes negligible, but evaporation under conditions favorable to high evapotranspiration (a wet soil) reach approximately 70 to 80% of the preharvest transpiration. With a dry soil surface, evaporation is approximately 20% (Wright, 1982). The ratio of transpiration or evapotranspiration to maximum T or ET is shown in Fig. 12.1.

IV. EFFECT OF WATER STRESS ON PHOTOSYNTHESIS AND RESPIRATION

When plants are subjected to water stress, observed net photosynthesis often decreases (Tenhunen *et al.*, 1984; Wong *et al.*, 1985). Murata *et al.* (1966) reported decreases in photosynthesis and respiration of 40% in seedlings of various forage crops. The soil matric potential (ψ_s) was −0.45 MPa in these studies. Two extensive reviews of the literature on water relations in forage plants (Begg and Turner, 1976; Turner and Begg, 1978) show that photosynthesis and respiration decline whenever water deficits are low enough to close stomata, but the relative decrease in respiration is less than in photosynthesis. Even though the intercellular CO_2 concentration remains

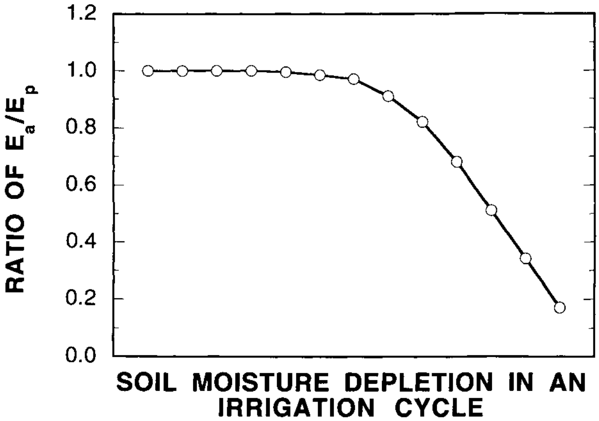


FIGURE 12.1 Ratio of actual transpiration (T) or evapotranspiration (ET) to potential maximum T or ET and canopy resistance with increasing soil moisture depletion. (Redrawn from van Bavel, 1967, with permission of Elsevier Science.)

relatively constant, photosynthesis decreases. This response is attributed to the stomata closing in "patches" rather than uniformly across the whole leaf surface (Farquhar *et al.,* 1987; Downton *et al.,* 1988; Terashima *et al.,* 1988). Antolin and Sanchez-Diaz (1993) demonstrated that drought stress significantly influences chloroplast metabolism; thus, resulting in a significant inhibition of net photosynthesis in alfalfa.

V. ROOT MASS AND ROOTING DEPTH

The extent of root development in forage crops varies with species and age of the stand. An unirrigated stand of alfalfa developed roots to a depth of 11 m (36 ft) in Nebraska (Kiesselbach *et al.,* 1929). Perhaps the deepest penetration of alfalfa roots reported was at 39 m (128 ft) in a mine shaft that underlayed an alfalfa field (Meinzer, 1927). Extensive studies near Greeley, Colorado of a number of crops showed that unirrigated alfalfa roots penetrated to a depth of approximately 1.5 m (5 ft) during the first year of growth and 2.7 m (9 ft) by the end of the second year. Irrigated plants reached a depth of just more than 2.7 m the first year and about 2.9 m (9.5 ft) at the end of the second growing season (Jean and Weaver, 1924).

Root distribution in the top 22 cm (8.7 in.) of soil for alfalfa ranges from 78 to 89% of the root mass, depending on moisture regime and type of alfalfa (Bennett and Doss, 1960). In this same study, Ladino and intermediate whiteclover (*Trifolium repens* L.) produced from 67 to 85% of the roots in the same zone, and red clover (*T. pratense* L.) ranged from 77 to 92% of the roots in the top 22 cm. Ladino tended to send its roots deeper than intermediate whiteclover. After seeding, alfalfa roots have been reported to penetrate to depths of 1.2 m (3.9 ft) in a clay loam soil and 1.8 m in a sandy loam soil (Upchurch and Lovvorn, 1951) after 304 days of growth. The interesting aspect of this work is that after 6 years of growth, the penetration depth in the sandy loam was 2.1 m (6.9 ft) and in the clay loam it was still only 1.2 m. In a line-source irrigation system (in which amount of irrigation water ranged from optimum at the center of the line-source to none just outside the area of influenced by the sprinkling pattern), Abdul-Jabbar *et al.* (1984) reported that the total root mass and rooting depth of alfalfa was highest under optimum irrigation (Fig. 12.2). Also, evapotranspiration was greatest at the highest or optimum irrigation level. Others (Carter and Sheaffer, 1983a) showed that nonirrigated alfalfa, in which the soil matric potential reached −0.3 to −1.5 MPa, had greater root length and mass in the top 0.6 m (2 ft) of the soil profile than irrigated alfalfa (soil matric potential of −0.1 to −0.06 MPa). Evidence supports the idea that dryland alfalfa has greater primary and secondary branching than do roots of irrigated alfalfa (Jean and Weaver, 1924; Weaver, 1926, 1968). It appears

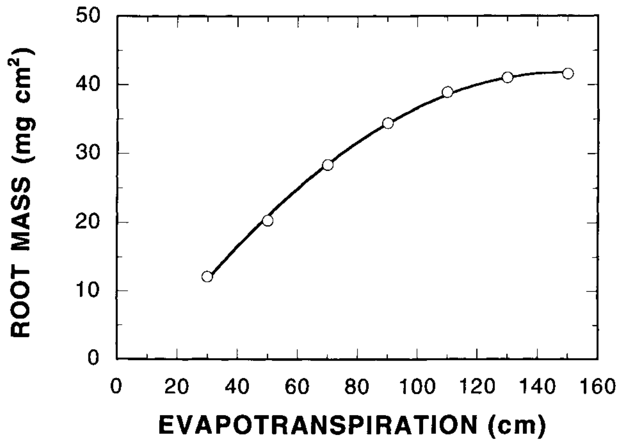


FIGURE 12.2 Root mass and ET of alfalfa. (Redrawn from Abdul-Jabbar *et al.*, 1982.)

that root growth is also a function of cultivar in alfalfa, and that within the crop, greater root growth under drought conditions occurs in cultivars that are more winter hardy (Bennett and Doss, 1960). The ability to withstand water stress is apparently related to winter hardiness (Rumbaugh, 1982).

Grasses produce a more fibrous, less depth-penetrating root system, but the total root mass in the rooting zone can be rather high. Probably the classic example of the extent of crop rooting systems is the report for rye (*Secale cereale* L.), which showed a total measured root length from one plant, growing without competition from other plants, of 380 miles (Dittmer, 1937). In grasses, 55 to 70% of the root mass, depending on species, is in the top 22 cm (8.7 in.) of soil (Bennett and Doss, 1960). This work, however, showed that rooting depth for common tall pasture grasses reached a depth of 1.2 m when 80% of the soil moisture from the root zone had been removed before irrigation occurred. If irrigation occurred when 30 to 65% of the soil water had been removed by crop growth, root mass was reduced by 10%. Warm-season grasses have from 55 (*Paspalum notatum* Flugge) to 78% (*P. urvellei* Steud.) of the roots in the top 22 cm (8.7 in.) of the soil profile (Burton, 1943). Annual grasses such as sorghums [*Sorghum bicolor* (L.) Moench.] and corn (*Zea mays* L.) show a deeper rooting pattern, but the distribution in the soil profile is quite similar with 78% in the top 22 cm (8.7 in.) 80 days after planting (Foth, 1962; Heatherly, 1975). For sorghum, the increase in root weight in the profile was completed within 5 weeks of planting (Heatherly, 1975), but that did not mean that root growth ceased. The mass of roots in the soil profile 5 weeks after planting was maintained throughout the remainder of the season. Cultivation resulted in reduced root mass, but root growth soon returned root mass to the former level (Heatherly, 1975).

VI. CROP PRODUCTIVITY AND WATER USE

Taylor (1952) reported a linear decrease in dry matter production on a loam soil as the soil matric potential decreased from −0.1 to −0.4 MPa. Others have reported decreases in canopy growth rate of 60 to 70% when soil matric potential of a silty clay loam soil decreased to less than −0.25 MPa at the 25- to 50-cm soil depths (Kemper and Amemiya, 1957). The number of stems, stem diameter, and internode number and length all decrease with increased moisture stress (Cowett and Sprague, 1962; Donovan and Meek, 1983; Gindel, 1968; Vough and Marten, 1971). The effects of moisture stress on internode number and length were greater for nonhardy than for hardy alfalfa cultivars (Perry and Larson, 1974). In contrast to this is the report of Field *et al.* (1987), indicating that nondormant alfalfa in New Mexico yielded as well under water stress as did dormant types without water stress.

Crop yield is linearly related to evapotranspiration (Fig. 12.3). Each unit increase in ET from 20 to 80 cm results in an increase in yield of approximately 159 kg ha^{-1} (Bauder *et al.*, 1978). This figure emphasizes the importance of maintaining adequate soil moisture to ensure optimum photosynthesis and growth. Analyzing data from several states, Sammis (1981) concluded that production of 1 Mg ha^{-1} of alfalfa dry matter required 8.3 cm of water. Another summary, by Heichel (1983), of alfalfa production

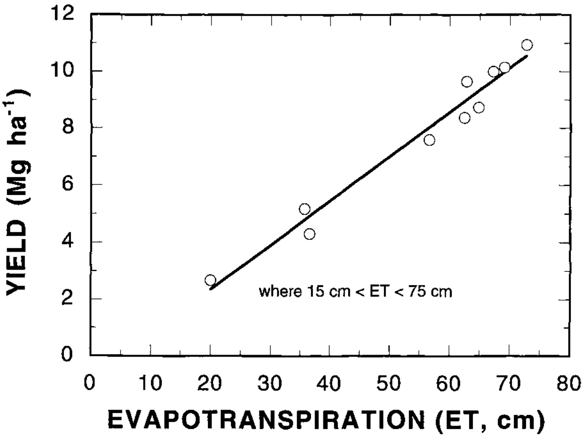


FIGURE 12.3 Alfalfa dry matter yield as related to growing season ET. (Redrawn from Bauder *et al.*, 1978.)

in many diverse climates, showed that 5.6 to 7.3 cm of water were required to produce 1 Mg ha^{-1} of dry matter, the range being dependent on the various climatic factors encountered in each location. Water requirements of various crops range from about 136 kg (300 lb) of water per pound of dry matter produced for corn, sorghum, and millet to 377 kg (830 lb) for alfalfa (Briggs and Shantz, 1914; Shantz and Piemiezel, 1927).

VII. EXCESS WATER AND STAND PERSISTENCE

Growers have a tendency to emphasize the effects of too little water on forage crop production, especially alfalfa in the arid areas, but often overlooked is the deleterious effects of too much water, either from irrigation or naturally high soil water tables. Adaptation of crops to wet conditions dictates whether they will be planted on a given soil. Some legumes, notably alfalfa, cannot withstand excess soil moisture for any length of time, whereas others, such as birdsfoot trefoil (Grant and Marten, 1985), are better adapted to wetter conditions. Similarly, among the grasses timothy and reed canarygrass are well adapted to wet soils, but orchardgrass and smooth bromegrass are less tolerant of excess water.

Alfalfa root growth and stand persistence is reduced by excess water (Kemper and Amemiya, 1957; Perry and Larsen, 1974; Wahab and Chamblee, 1972). Alfalfa may endure short-term flooding for 16 days at cooler temperatures (16°C), but survival is shortened to 6 days at 32°C (Thompson and Fick, 1981). In the warmer arid areas of the southwestern United States, the combination of high soil temperatures and high soil moisture result in "scalding," which results in plant death within 3 to 4 days (Donovan and Meek, 1983; Graham *et al.,* 1979; Meek *et al.,* 1980). Excess soil water has more severe consequences immediately after cutting (Barta, 1980; Christain, 1977). Some legumes, such as birdsfoot trefoil and crownvetch (*Coronilla varia* L.), are not as adversely affected by excess water as is alfalfa (McKee and Langille, 1967).

VIII. IRRIGATION SCHEDULING

Judicious irrigation scheduling is important in maintaining crop yields. If irrigation is practiced when there is no need, two things occur: first, additional and unnecessary production costs occur; and second, stress associated with too much water is applied to the crop (see section on excess water). When practicing irrigation, a balance between too much and too little water must be maintained. The severity of the consequences is generally greater in arid zones, where no or only sporadic precipitation falls during the growing season, than it is in temperate, humid areas, where natural precipitation is generally adequate for production of most forage crops. Failure to schedule irrigation properly in arid zones can result in very significant yield decreases. A number of methods may be used successfully to properly schedule irrigation during the growing season.

A. SOIL

Three conditions of the soil are important in assessing soil water status and its relationship to crop needs and growth. These are measured by determining soil water content, soil water potential, and soil water diffusivity or conductivity. The first two relate to soil water status and the last to soil water movement. All three of these are important in determining when to irrigate a crop.

Soil water potential is the potential energy per unit quantity of water (Campbell and Mulla, 1990). It is useful for describing the amount of water available to plants and assessing the movement of water in the soil. The most important components of soil water potential are matric potential and osmotic potential. The sum of these two potentials is an important indicator of availability of water to plants. Matric potential is the driving force for water movement in the soil—both direction and magnitude of flow.

According to Warrick (1990) soils are porous material composed of a skeleton of solids, with air and water filling the interspaces. The amount of water held by a soil is dependent on its structure and composition. The greater the amount of pore space, the greater is the water holding capacity of the soil. The greatest capacity to retain water is found in soils high in clay and silt and the lowest capacity in sandy soils. The smaller the particle size, the greater the amount of space.

Water content is often described as the amount of water (mass) per unit of soil dry mass. This is referred to as *gravimetric water content.* It is simple to measure, requiring the wet weight of the sample, its dry weight, and weight of the water lost in drying. Sampling, however, is very labor intensive. Thus, when many samples are desired or continuous monitoring of soil water content throughout the growing season is required, other methods of estimating soil water content are preferred.

Monitoring neutron scattering provides a means of measuring many samples throughout the growing season with the least amount of physical labor. Installation of the neutron probe access tubes is labor intensive, but once they are in place, probe readings can be made quite easily. Generally, neutron scattering measurements are precise even if they are not accurate; thus, this is a good method for measuring relative changes in water content. These changes are effective indicators that may be used in timing of irrigation (Campbell and Mulla, 1990).

Another popular method involves use of tensiometers, which measure the soil water potential (Cassell and Klute, 1986). The tensiometer consists of a sealed, water-filled tube with a porous cup attached to the end that is placed in the soil. The other end has a gauge that provides a reading of the water pressure inside the tensiometer, which, once equilibrium is attained, is equal to the matric potential of the soil (Campbell and Mulla, 1990). The range over which tensiometers function is only a small portion of the range over which plants can extract water from the soil, but this is the range in which plant growth can critically be affected. Thus, tensiometers have become excellent indicators of soil water status and a means of efficiently scheduling irrigation.

B. SOIL WATER STATUS AS A CRITERION

Estimation of soil water depletion in the rooting zone can be done directly, using gravimetric techniques, or indirectly, with calibrated tensiometers or calibrated neutron probes (Bell, 1976; Haise and Hagan, 1967; Nakayama and Reginato, 1982). In addition, estimates of water use by a crop can be made using pans or climatic-based formulas for indirectly estimating evapotranspiration (ET). In the first method, a pan coefficient, which is a ratio of maximum ET from a full-cover, well-watered crop to pan evaporation, is determined. The pan coefficient may vary depending on exposure and site because convective heat transfer at the pan is larger relative to radiation than it is for the surface of a crop such as alfalfa or grass (Pruitt, 1966). Calibration of the coefficient is required, but estimating with respect to a reference surface may be satisfactory (Doorenbos and Pruitt, 1977). The variation of pan evaporation is more severe in arid or semiarid than in humid climates; thus, it may be less favorable as a means of estimating ET in arid areas. Typically, the ratio in arid or semiarid areas will be as low as 0.75, whereas in humid areas it usually ranges from about 0.90 to 0.95 (Donovan and Meek, 1983). Another problem is loss of water from the pan during heavy rain storms due to splash out.

Depletion of soil water below a critical level results in rapid and precipitous declines in critical plant functions. In general, a good rule of thumb is to irrigate when approximately 50% of the available water in the soil has been depleted (Table 12.1). Once this critical level is reached, plants are subject to reduced photosynthesis, and movement of CO_2 into the leaf is highly restricted because of closure of the stomates. If this state is prolonged, eventual and serious loss of yield will result.

Available soil water in the crop rooting zone is usually defined as the difference between the soil matric potential (ψ_m) at -1.5 MPa and field capacity of the soil. Fractional depletion of the moisture is allowed, usually 40 to 50% for most forage crops, before irrigation is again practiced. Monitoring of the water in the root zone is required on a regular basis.

TABLE 12.1 Estimates of Available Water and Allowable Depletion for Different Soil Types

Soil type	Available water (in./ft)	Allowable depletion (in./ft)	Four-foot root zone[a] Available water (in.)	Four-foot root zone[a] Allowable depletion (in.)
Course sand	0.5	0.25	2.0	1.0
Fine sand, loamy sand	1.0	0.50	4.0	2.0
Sandy loam	1.5	0.75	6.0	3.0
Fine sandy loam, loam, silt loam	2.0	1.00	8.0	4.0
Clay loam, silty clay	2.2	1.10	8.8	4.4
Clay	2.3	1.15	9.2	4.6
Organic clay loam	4.0	2.00	16.0	8.0

[a] A 4-foot root zone is a typical effective rooting zone for most forage crops.
Source: Orloff *et al.*, 1995.

C. PLANT WATER STATUS AS A CRITERION

The water potential (ψ_w) of the crop is used effectively to assess the need for irrigation (Brown and Tanner, 1981). The problem with this type of measurement is that it is time-consuming and producers rarely, if ever, have access to the equipment. Visual correlation of ψ_w, with plant color or leaf shape or size may provide a quick indicator of a plant's water status (Haise and Hagan, 1967). It has been reported by Brown and Tanner (1981) that alfalfa subject to water stress (ψ_w, −1.5 MPa) was wilted and gray-green when the relative growth rate had dropped to 50%. Although a change in color or cupping of the leaves of alfalfa or rolling of grass leaves are visual indicators of crop water stress, these indicators may not appear until the plant has been subjected previously to considerable physiological stress, as indicated by Brown and Tanner (1981), and if repeated a number of times yields may be reduced significantly. Other factors such as cultivar, disease, and soil fertility may influence these visual symptoms, and they are thus difficult to quantify (Jones, 1979; Wilde and Voigt, 1952).

D. WEATHER-DRIVEN METHODS—ESTIMATING EVAPOTRANSPIRATION

Estimating ET from selected weather parameters has received much effort over the years. Penman (1948) developed an equation for estimating ET that combined the equations for convection transfer of heat (sensible and latent) with the energy balance. This original relationship was subsequently modified by Penman and Schofield (1951) and Penman (1953) so that the status of a crop canopy surface was more closely mimicked. Kanamasu *et al.* (1979) and Monteith (1981) published excellent reviews of the historical development of these concepts.

Researchers and growers in California commonly use the Jensen–Haise equation (1970) to schedule irrigation for a wide variety of crops. It differs somewhat from the Penman method in detail, but is also based on measurable weather parameter. Potential ET is estimated as a function of daily maximum air temperature and the average solar radiation curve for a given location. Use of these various formulae should be calibrated for a particular crop and climate (Pruitt and Doorenbos, 1977; Tanner, 1967).

Services that provide estimates of ET for a given crop usually provide both the Penman and the Jensen–Haise estimates. There are other variations of these methods, but there is no need to discuss them here. Readers who may be interested can further research these techniques in the abundant literature.

Because the previously mentioned techniques (pan evaporation and ET estimates from empirical formulae) make the assumption that ET is progressing at a maximum rate, ET is overestimated following cutting or in the spring until the LAI reaches 1.5 to 2. To avoid this problem, it is standard to use a variable crop coefficient that accounts for the fractional reduction in ET associated with less than a full canopy. This concept is illustrated in the work of Wright (1982; Fig. 12.4). The coefficient is defined as K_c = ET/ETmax, where K_c is determined by measurement of ET at various stages of development after cutting (Doorenbos and Pruitt, 1977; Jensen, 1973, 1974; Stegman *et al.*, 1977).

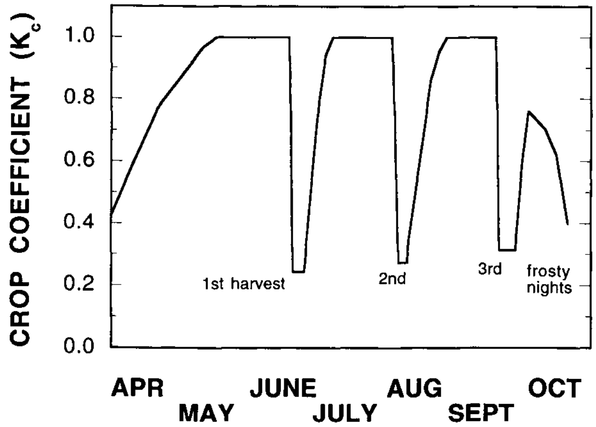


FIGURE 12.4 Average seasonal basal crop coefficient curve for alfalfa, Kimberly, Idaho. (Redrawn from Wright, 1982.)

E. WATER BUDGETS

Irrigation scheduling can also made by of a water budget method (Jensen, 1973, 1974; Stegman *et al.,* 1977). These methods all deduct daily soil water depletion, as estimated by calculation of ET over a given crop, and add water inputted into the system by irrigation or precipitation. When the soil reaches 50% depletion of the available water, the crop should be irrigated (see Table 12.1).

F. CROP TEMPERATURE

This method is based on the fact that an increase in temperature is the natural result of increased water stress. As the water stress increases, the stomata begin to close, transpiration is reduced or even ceases, and, consequently, the temperature of the leaf surface increases (Tanner, 1963; Walker and Hatfield, 1983). This method is called *infrared (IR) thermometry.* Small, hand-held units have been developed that have greatly increased the efficiency with which IR thermometry can be used. Useful reviews of the literature are provided by Jackson (1982), Nielsen *et al.* (1984), and O'Toole and Real (1984). Because leaf temperature is a function of several factors, discretion must be used. To address these problems, the reader is referred to additional sources (Clawson and Blad, 1982; Fuchs and Tanner, 1966; Gardner *et al.,* 1982; Idso *et al.,* 1981; Jackson *et al.,* 1981; O'Toole and Hatfield, 1983; Tanner, 1963; van Bavel, 1967).

IX. WATER QUALITY

In arid and semiarid regions where irrigation is practiced as a matter of necessity for crop production, quality of the water has a significant influence on yield and longevity of the stand. Prime hay crops such as alfalfa can be produced successfully in saline soils (those high in cations, but without excessive sodium), even when the soil pH exceeds 8.0, but saline-sodic or sodic soils (those high in sodium) prevent good growth of the crop. In worst-case scenarios, stand maintenance and even establishment is rendered impossible by highly saline-sodic soils.

Plants extract water from soils by exerting a force (absorptive) greater than the force that holds the water to the soil. As the salt concentration in the soil increases, the force required to remove the water from the soil increases, and eventually it can become so great that water stress develops and yield is reduced. Two otherwise identical soils that are at different salt concentrations—one salt-free and the other salty—will yield differently because of this difference in osmotic potential (Fig. 12.5). Yield reduction

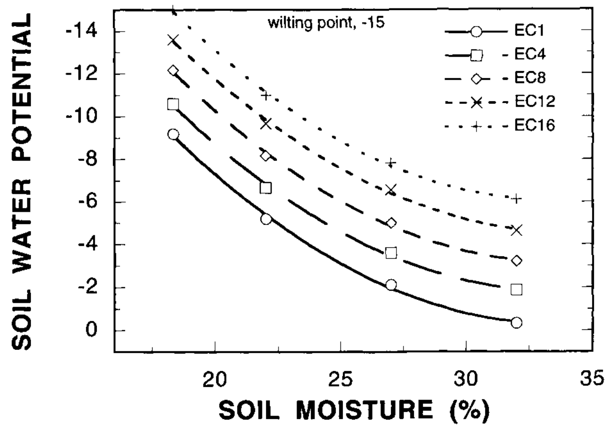


FIGURE 12.5 Soil moisture retention curves for a clay–loam soil at varying degrees of soil salinity (ECê). (Redrawn from Ayers and Westcot, 1985, p. 20; with permission of the Food and Agriculture Organization of the United Nations.)

is less than 5% when the electrical conductivity (EC) is 4, but at 8 yield loss is 7.6%, at 12 it is 12.4%, and at 16 it is 18.8% (Ayers and Westcott, 1985).

Another aspect of this soil-salt-yield equation is that high sodium or low calcium content in the soil or water reduces the rate at which irrigation water infiltrates into the soil to such an extent that the soil water content is not sufficient to meet the needs of the crop. Also associated with soils or water high in salts may be toxicity caused by certain ions (e.g., sodium, chloride, boron). These ions may accumulate to the point at which sensitive crops are damaged and the yield is reduced. Water quality guidelines are presented in Table 12.2. The reader who is concerned about water quality is referred to the FAO publication, *Water Quality for Agriculture* (Ayers and Westcot, 1985).

All irrigation water carries salts. High-quality water is low in salts, and as the salt concentration increases, the quality of the water declines. Thus, with each irrigation, salts are being added to the soil. In time, if the salt load is too high, percolation through the soil profile is poor, and evaporation from the soil surface is high, salts build up in the soil until the soil becomes so saline that crop plants can no longer grow or survive.

X. CROP RESPONSE TO SALINITY

All crops do not respond to increased salinity in a similar manner. Some crops can withstand considerably higher soil salinity than can others and still maintain their potential to yield (Ayers and Westcot, 1985). The effect of soil and water salinity on selected field and forages crops is presented in Table 12.3. It is interesting to note that the prime forage legumes such

TABLE 12.2 Guidelines for Interpretation of Water Quality for Irrigation

		Degree of restriction of use		
Potential irrigation problem	Units	None	Slight to moderate	Severe
Salinity (affects crop water availability)[a]				
EC_w	dS/m	<0.7	0.7-3.0	>3.0
TDS	mg/L	<450	450-2000	>2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)[b]				
SAR = 0-3 and EC_w =		> 0.7	0.7-0.2	< 0.2
= 3-6 and EC_w =		> 1.2	1.2-0.3	< 0.3
= 6-12 and EC_w =		> 1.9	1.0-0.5	< 0.5
= 12-20 and EC_w =		> 2.9	2.9-1.3	< 1.3
= 20-40 and EC_w =		> 5.0	5.0-2.9	< 2.9
Specific Ion Toxicity (affects sensitive crops)				
Sodium (Na)[c]				
Surface irrigation SAR		< 3	3-9	> 9
Sprinkler irrigation	me/L	< 3	> 3	
Chloride (Cl)[c]				
Surface irrigation	me/L	< 4	4-10	> 10
Sprinkler irrigation	me/L	< 3	> 3	
Boron (B)[d]				
Surface irrigation	mg/L	< 0.7	0.7-3.0	> 3.0

[a] EC_w, electrical conductivity, a measure of the water salinity, reported in deciSiemens per meter at 25°C (dS/m) or in units millimhos per centimeter (mmho/cm). Both are equivalent. TDS, total dissolved solids, reported in milligrams per liter (mg/L).

[b] SAR, sodium adsorption ratio. SAR is sometimes reported by the symbol Rna. See Ayers and Wescot (1985, Fig. 1) for the SAR calculation procedure. At a given SAR, infiltration rate increases as water salinity increases. Evaluate the potential infiltration problem by SAR as modified by EC_w.

[c] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive; use the salinity tolerance tables found in Ayers and Wescot (1985; Tables 4 and 5). With overhead sprinkler irrigation and low humidity (< 30%, sodium and chloride may be absorbed through the leaves of sensitive crops. For crop sensitivity to absorption, see Ayers and Wescot (1985; Tables 18, 19, and 20).

[d] For boron tolerances, see Ayers and Wescot (1985; Tables 16 and 17).

Source: From Ayers and Westcot, 1985, p. 8; with permission of the Food and Agriculture Organization of the United Nations.

TABLE 12.3 Crop Tolerance and Yield Potential of Seclected Crops as Influenced by Irrigation Soil Salinity (EC_e) and Water Salinity (EC_w)

	Yield potential[a]									
	100%		90%		75%		50%		0%[b]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Field crop										
Barley (*Hordeum vulgare* L.)[c]	8.0	5.3	10.0	6.7	13	8.7	18	12	28	19
Sugarbeet (*Beta vulgaris* L.)[d]	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16
Sorghum [*Sorghum bicolor* (L.) Moench.]	6.8	4.5	7.4	5.0	8.4	5.6	9.9	16.7	13	8.7
Wheat (*Triticum aestivum* L.)[c,e]	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Corn (*Zea mays* L.)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Forage crop										
Barley, forage (*Hordeum vulgare* L.)[c]	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20	13
Ryegrass, perennial (*Lolium perenne* L.)	5.6	3.7	6.9	4.6	8.9	5.9	12	8.1	19	13

Trefoil, birdsfoot (*Lotus corniculatus* L.)[f]	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15	10
Fescue, tall [*Festuca arundinaceae* (L.) Schrieb]	3.9	2.6	5.5	3.6	7.8	5.2	12	7.8	20	13
Sudangrass (*Sorghum sudanense* L.)	2.8	1.9	5.1	3.4	8.6	5.7	14	9.6	26	17
Alfalfa (*Medicago sativa* L.)	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16	10
Corn, forage (*Zea mays* L.)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15	10
Orchardgrass (*Dactylis glomerata* L.)	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18	12
Foxtail, meadow (*Alopecurus pratensis* L.)	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Clovers (*Trifolium* spp.)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6

---

[a] EC_e average root zone salinity as measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per meter (dS/m) at 25°C. EC_w electrical conductivity of the irrigation water in deciSiemens per meter (dS/m). The relationship between soil salinity and water salinity is $EC_e = 1.5EC_w$.

[b] The zero yield potential or maximum EC_e indicates the theoretical soil salinity (EC_e) at which crop growth ceases.

[c] Barley and wheat are less tolerant during germination and seedling stage; EC_e should not exceed 4 dS/m in the upper soil during this period.

[d] Beets are more sensitive during germination; EC_e should not exceed 3 dS/m in the seeding area for garden beets and sugarbeets.

[e] Semidwarf cultivars may be less tolerant.

[f] Broadleaf birdsfoot trefoil seems less tolerant than does narrowleaf birdsfoot trefoil.

Source: Adapted from Ayers and Westcot, 1985, pp. 31–32; with permission of the Food and Agriculture Organization of the United Nations. These data should serve only as a guide and not as absolutes because the values will vary depending on soil, climate, and cultural practices.

as alfalfa and the clovers are very sensitive to EC of the water or the soil. To obtain maximum yields, the EC of the water for alfalfa must be ≤ 1.3. The clover species tolerate ECs between 1.0 and 1.5. Orchardgrass tolerances also fall into this same range, whereas other forage grasses can be produced successfully at somewhat higher EC values. The range grasses are more tolerant to higher ECs, with western wheatgrass being the most tolerant. This is expected, however, because these range grasses are native to arid regions where the soils are often high in salts.

PART

IV

HARVESTING AND STORING FORAGE CROPS

13

FIELD-HARVESTING HAY

I. INTRODUCTION

Two important components regulate forage quality: fiber [acid detergent fiber (ADF) and neutral detergent fiber (NDF)] and crude protein (CP). Both are related to the age or stage of development of the crop. For example, as the crop ages, fiber increases and protein decreases (on a dry-matter basis). Forage quality then declines with age because fiber becomes a predominant component (Fig. 13.1). Thus, it is important that procedures and protocol be followed in a haymaking system such that quality or quantity (yield) can be optimized. To achieve both maximum quality and quantity is not a feasible option because of the nature of forage plant growth and development. There are, however, a number of steps that can be taken to

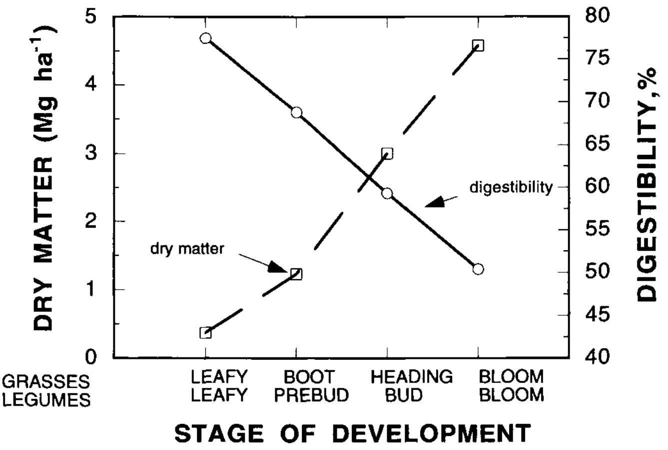


FIGURE 13.1 Relationship between forage yield and quality at different stages of development for grasses and legumes. (Redrawn from Blaser, 1985).

maintain acceptable dry-matter yields and enhance forage quality. Drying and curing hay is also inextricably tied to realization of quality in the final product (Sullivan, 1973).

II. HARVESTING SCHEDULES

There is no question that hay quality declines with maturity of the forage. Because of this fact, it is important to cut frequently enough that forage is at an optimum level of maturity at each harvest. The typical relationship is presented in Fig. 13.1. As forage growers have become more aware of this relationship between maturity and forage quality, and as the need for high-quality forage has become more evident, the practice has evolved of harvesting either on a fixed interval (e.g., every 30 days, etc.) or at a specific stage of development.

A. FIXED INTERVAL

Fixed-interval harvests are made based on a calendar date. Sufficient time must have elapsed before the first harvest is removed to provide optimum dry-matter yields of high-quality forage. Depending on the area in which one lives, an arbitrary date coinciding with the approximate date the desired stage of development is reached is chosen for the first harvest. In areas where winter dormancy in perennial forages occurs, that date will depend on altitude and latitude, and may range from early April through mid-June in the northern hemisphere. It also depends on the forage crop being grown, and even the cultivar within a given crop because of differences in rate of development. After the first harvest is made, subsequent harvests may occur at uniform intervals of 28 to 40 days, depending on the quality of forage desired.

Such fixed intervals were chosen because work in the northeastern United States showed that quality declined in a linear fashion after a selected base date in the spring (Conrad *et al.,* 1962; Kane and Moore, 1959; Mellin *et al.,* 1962; Reid *et al.,* 1959; Richards *et al.,* 1962; Troelsen and Campbell, 1969). For example, forage digestibility declined an average of 0.24 to 0.48% per day after base dates ranging from 30 April through 12 May. Such relationships can be judged to hold in most other temperate areas. However, the daily rates of decline and the base dates would differ. Slope of the CP decline for first, second, and third cuttings ranges from 0.20 to 0.38% per day in Utah (Gale, 1988) during the period May through August.

Advantages of harvesting on a fixed schedule come mostly from being able to plan work during a given period of time, thus coordinating essential activities in the many phases of a farm operation. The disadvantage of such a system is largely in being locked into a scheduled date and not being able to adjust if the weather is not conducive to making high quality hay. Obviously, the dryer environments of the western United States would not face so serious a problem as is encountered in the more humid portions of the country. Some areas may require more flexibility than a fixed-schedule system allows.

B. STAGE OF DEVELOPMENT

For years it has been commonly recommended that alfalfa hay be harvested at first flower or 1/10 bloom. Likewise, it is commonly recommended that grasses be harvested at head emergence to early anthesis to optimize both quantity and quality of the forage. This compromise has provided production of optimum quantities of high-quality forage. Nevertheless, a few problems are encountered when harvests are made that depend on the stage of development. First and foremost is the difficulty of determining if a forage is at a given stage of development. For example, what is commonly referred to as "1/10 bloom" by growers is more akin to ½ bloom because alfalfa does not bloom from the top down, but instead from within the canopy upward. The plant is described as growing indeterminately; that is, the top of the plant is the youngest and new flower buds are produced there, and they flower after the older ones, which are borne at successively lower nodes. The older flowers are not visible, so by the time top-of-the-canopy flowers are seen, at least two or three other flowers are fully developed on the plant. (Techniques for identifying stages of development are discussed later in this chapter.) Second, it is common to wait for the forage to reach a specific stage of development, then find that the weather has turned bad. The dilemma now is, "Should I wait until the weather is good?" or "Should I go ahead and harvest on the chance that the weather will not be too detrimental to making high-quality hay?" The fact that harvesting was delayed through a rather extended period of good weather while waiting for a specific stage of development can be rather disconcerting and costly.

Identification of specific stages of development has received considerable attention from researchers since the late 1970s. Kalu and Fick (1981) proposed a system for alfalfa and clover and Moore *et al.* (1991) developed a comprehensive system for grasses that meets the needs of researchers very well. Each system is described in the following sections.

1. Alfalfa

Kalu and Fick (1981) proposed the rating system shown in Table 13.1. Such a system is good as a references and in research, but it requires that one identify specific characteristics that relate to each numeric stage of development. In trying to develop a quick and reliable means of identifying

TABLE 13.1 A System for Identifying Stage of Development in Alfalfa

Number	Definition
0	Early vegetative; stem length ≤ 15 cm; no buds, flowers, or seed pods
1	Midvegetative; stem length 16–30 cm; no buds, flowers, or seed pods
2	Late vegetative; stem length > 30 cm; no buds, flowers, or seed pods
3	Early bud; 1 to 2 nodes with buds; no flowers or seed pods
4	Late bud; 3 or more nodes with buds; no flowers or seed pods
5	Early flower; 1 node with one open flower (standard open); no seed pods
6	Late flower; 2 or more nodes with open flowers; no seed pods
7	Early seed pod; 1 to 3 nodes with green seed pods
8	Late seed pod; 4 or more nodes with green seed pods
9	Ripe seed pod; nodes with mostly brown, mature seed pods

Source: Kalu and Fick, 1981.

stage of development, researchers at Utah State University (Gale, 1988) extended Kalu and Fick's method. Study of the morphology of the alfalfa plant showed that late bud stages (the stage of development judged to be most advantageous for producing maximum quantities of high-quality forage) could quickly be identified by studying the peduncle development during the bud stage and prior to flowering. The *peduncle* arises from the axil of the second, third, and fourth branches from the top of the stem and bears the flower. When peduncles of the three topmast potential flowering branches have begun elongation, the plant is at the late bud stage of development. To identify this requires a periodic walk through alfalfa fields and observation of the status of a number of stems.

The total effect of the environment is integrated by the growing plant, and is then expressed at each morphological stage of development. Quality factors change in concert with change in morphological stage of development in alfalfa (Kalu and Fick, 1981, 1983). *In vitro* digestibility of dry matter (IVDDM) decreased about 43 g kg^{-1} of dry matter (DM), or 4.3 percentage points,[1] with each unit change in the 10-stage maturity rating system. Others have reported that digestible dry matter (DDM) decreased by 2.8 g kg^{-1} d^{-1} and CP declined 2 g kg^{-1} d^{-1} during spring growth (Anderson *et al.*, 1973). Jung *et al.* (1969) and Richards *et al.* (1962) found similar values for alfalfa.

2. Grasses

Moore *et al.* (1991) patterned a system for consistently identifying the stage of development of forages grasses after Kalu and Fick's (1981) alfalfa

---

[1] To convert g kg^{-1} to percent, divide by 10.

system. The grass system has five phases or stages of development: germination, vegetative, stem elongation, reproductive, and seed development and ripening (Table 13.2). For the purpose of making hay from perennial grasses, only the last four stages are important. This system is more amenable for use by researchers than by growers. Fortunately, identifying the stage of

TABLE 13.2 Primary and Secondary Growth Stages and Their Numerical Indices and Descriptions for Staging Growth and Development of Perennial Grasses

Stage	Index	Description
Germination		
G0	0.0	Dry seed
G1	0.1	Imbibition
G2	0.3	Radicle emergence
G3	0.5	Coleoptile emergence
G4	0.7	Mesocotyl and/or coleoptile elongation
G5	0.9	Coleoptile emergence from soil
Vegetative—leaf development		
V0	1.0	Emergence of first leaf
V1	$(1/N) + 0.9$[a]	First leaf collared
V2	$(2/N) + 0.9$	Second leaf collared
Vn	$(n/N) + 0.9$	Nth leaf collared
Elongation—stem elongation		
E0	2.0	Onset of stem elongation
E1	$(1/N) + 1.9$	First node palpable/visible
E2	$(2/N) + 1.9$	Second node palpable/visible
En	$(n/N) + 1.9$	Nth node palpable/visible
Reproductive—floral development		
R0	3.0	Boot stage
R1	3.1	Inflorescence emergence/first spikelet visible
R2	3.3	Spikelets fully emerged/peduncle not emerged
R3	3.5	Inflorescence emerged/peduncle fully elongated
R4	3.7	Anther emergence/anthesis
R5	3.9	Postanthesis/fertilization
Seed development and ripening		
S0	4.0	Caryopsis visible
S1	4.1	Milk
S2	4.3	Soft dough
S3	4.5	Hard dough
S4	4.7	Endosperm hard/physiological maturity
S5	4.9	Endosperm dry/seed ripe

[a] Where n equals the event number (number of leaves or nodes) and N equals the number of events within the primary stage (total number of leaves or nodes developed). General formula is $P + (n/N) - 0.1$, where P equals primary stage number (1 or 2 for vegetative and elongation, respectively) and n equals the event number. When $n > 9$, the formula $P + 0.90(n/N)$ should be used.

Source: Moore *et al.,* 1991.

development of grasses is somewhat easier than in legumes, because it is keyed to stem elongation (grand phase of growth), head emergence, and flowering (anthesis)—all quite visible processes in most forage grasses.

Grasses are reported to decline in feeding value with considerably more rapidity (Lema *et al.,* 1977; Troelsen and Campbell, 1969) than do legumes.

C. COMBINATION OF HARVEST SCHEDULING METHODS OFFERS FLEXIBILITY

The best schedule for harvesting may be a combination of the fixed-interval and the stage-of-development methods. In each case, the decision to harvest would be based on a fixed interval, knowing that a specific stage of development would be reached on approximately the same date for each harvest within each year. However, the beginning date each year would vary because of the environment. The first harvest date for alfalfa can vary by as much as 10 to 15 days because of variation in temperature and precipitation patterns. The fixed-interval method thus provides for general, overall planning, but use of a combination of fixed-interval and stage-of-development methods allows the flexibility required to avoid bad weather, either delaying or taking the harvest earlier than planned. Smith *et al.* (1968) provide an extensive study comparing fixed-interval vs maturity-scheduling in Iowa, Minnesota, Missouri, and Wisconsin. Winch *et al.* (1970) also studied various forage types extensively. These works indicate that combined fixed-interval and stage-of-development considerations provide the highest-quality hay.

III. DRYING AND CURING HAY

A. DRYING AND CURING TIME

The drying rate of hay depends on a number of important, and usually uncontrolled, environmental factors: moisture content of the crop, wind speed, temperature, relative humidity (Sullivan, 1969), and formation of morning dew. Normal field conditions may require from as little as 2 to 3 days in arid areas to up to 14 or more days in humid areas.

During the drying and curing process, a forage is subject to significant dry matter loss through respiration and leaf loss (Wolf and Carson, 1973; Collins, 1983b). Leaf shattering begins in alfalfa at 30 to 40% moisture, resulting in extensive leaf loss (Zink, 1936). In grasses, stem and leaf losses begin at about 50% dry matter and increase drastically thereafter (McGechan, 1988). From hay that is at 20 to 50% DM losses are from 2 to 3%, but may increase under certain environmental conditions to as much as 40 to 45% at 80% DM. Respiration rate, which is positively correlated with

DM concentration of the forage, declines as the forage matures and as the DM content of the forage increases (Fig. 13.2). Shorter drying times associated with lower moisture content of the forage can result in significant reductions in respiration.

When frequent storms arise, reducing the number of days from mowing to baling may mean a significant increase in quantity and quality of hay. Thus, a number of practices have developed in which the rate of drying can be increased. These practices consist of mechanical and chemical conditioners; and in some cases both may be practiced. In addition, preservatives are also used.

B. RESPIRATION

Respiration is the oxidation of water soluble carbohydrates (hexose) as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + H_2O. \qquad (13.1)$$

It yields 1.47 g of CO_2 for the loss of each gram of hexose (McGechan, 1989).

After the herbage is cut, respiration continues until it is inhibited by low moisture conditions in the cured hay. The substrate for this respiration, nonstructural or water-soluble carbohydrates (WSC) such as starch, sucrose, glucose, fructose, and other sugars (plant hexose sugars), can conceiv-

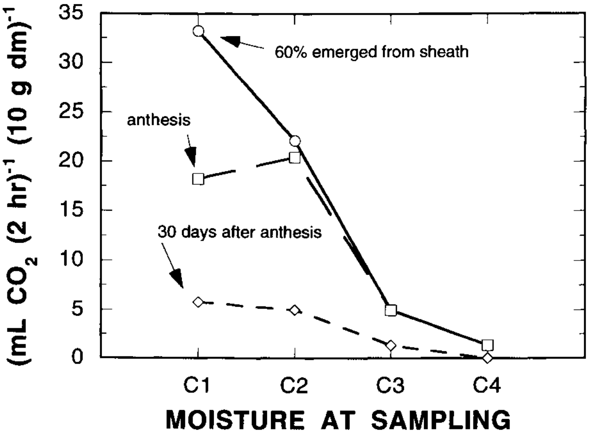


FIGURE 13.2 Interaction of stage of development and herbage moisture concentration and their effect on respiration. Moisture concentrations are: 60% emerged from the sheath —C_1 = 83.48, C_2 = 69.54, C_3 = 45.93, C_4 = 29.61; anthesis — C_1 = 77.78, C_2 = 58.60, C_3 = 36.00, C_4 = 18.37; 30 days after anthesis — C_1 = 65.25, C_2 = 58.60, C_3 = 25.95, C_4 = 18.39. (Redrawn from Pizarro and James, 1972).

ably be used up during prolonged periods when the herbage is wetted, dried, re-wetted, and re-dried several times. Thus, it is possible, but not very likely, that the rate of respiration could be reduced by the diminished amount of substrate. Apparently, because of the kinetics of the reaction (a very small Michaelis–Menten constant, K_m), the respiratory reaction continues at its full rate until the substrate concentration drops to a very low level (Thornley, 1976).

The effect of temperature and moisture concentrations on production of CO_2 and the loss of DM has been measured (McGechan, 1989) from small samples of perennial ryegrass (*Lolium perenne* L.). Samples held at temperatures from 20 to 30°C and moisture contents from 35 to 71% for a period of 120 h showed a decline in rate of respiration. Other workers (Wood and Parker, 1971), over a 30-hour period, measured CO_2 production from small samples of perennial ryegrass. They observed higher respiratory rates at higher temperatures and higher moisture concentrations. However, there was little increase in CO_2 evolution when the temperature exceeded 25°C (Fig. 13.3). Wilkinson and Hall (1966) reported similar results for alfalfa (i.e., loss at 25°C was the same as the loss at temperatures greater than 25°C). Others have also shown that respiration decreased as the moisture concentration of the herbage was dropped from about 75% at mowing (McGechan, 1989). McGechan (1989) demonstrated that respiration rate increased almost linearly with temperature and quadratically with increased moisture concentration. Losses ranged from 0.1% DM per hour at 30% moisture to 0.18% DM per hour at 90% moisture.

McGechan (1989) cites evidence that, as well as oxidizing sugars, respira-

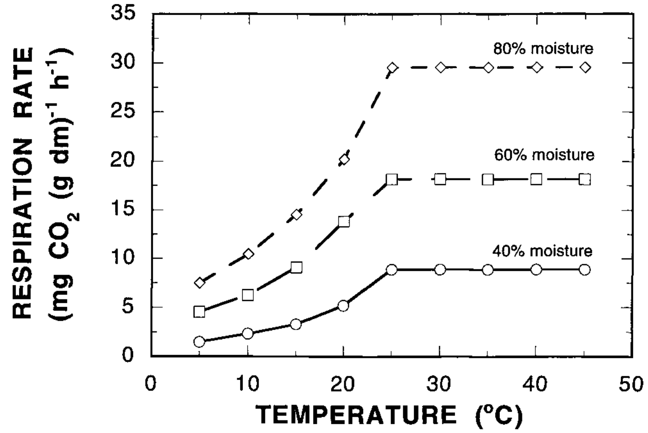


FIGURE 13.3 Respiration rate of three different hay moisture levels as a function of temperature. (Redrawn from Wood and Parker, 1971).

tion degrades proteins to amino acids. The amino acids have a similar feed value for ruminants as the original protein, but are more water soluble and more susceptible to leaching loss during times of precipitation. Murdoch and Bare (1963) and Collins (1983b; 1985a), however, have reported that under field conditions, the changes in nitrogenous components of forage are insignificant; thus, one could assume that no change in CP occurs with leaching losses, except perhaps under the most extreme environmental situations.

Wood and Parker (1971) developed the following relationship for respiratory CO_2 loss (R) and temperature (T) dependent on moisture in the hay (M): $R = 0.177(0.0.56M - 1.53)\exp(0.069T)$. Solution of this equation provides estimates of respiratory CO_2 loss at 80% moisture ranging from 1.66 at 30°C to 0.79 mg CO_2 (g dry matter)$^{-1}$ h^{-1} at 20°C. These values are similar to those reported by Wilkinson and Hall (1966) for alfalfa. Greenhill (1959) worked with grass, clover, and alfalfa and also reported similar losses, suggesting that this relationship may hold for a number of forage crops. Greenhill (1959) found that respiration decreased as moisture content of perennial ryegrass was reduced, completely ceasing at 35%. Wolf and Carson (1973) found that respiration was inactivated by desiccation to about 60% DM. Temperature up to 55°C for a 15-min period had little affect on respiration of alfalfa, but above that temperature, and if exposed beyond the 15-min period, the respiratory enzymes were destroyed.

Pizarro and James (1972) showed that respiration of perennial ryegrass decreased with age (later stage of development). The higher respiration rates are associated with the younger tissue. At these times, however, the WSC concentration is much lower, suggesting that in herbage at a young stage of development, respiration might be relatively more important. Cutting grasses at 60% inflorescence resulted in respiration losses of 12.8 g kg^{-1} (1.28%), whereas cutting at anthesis and at 30 days after anthesis resulted in DM losses of 9.0 and 2.6 g kg^{-1} (0.9 and 0.26%). These figures indicate that respiration losses, at least in perennial ryegrass, are only about 1%.

The average WSC concentration in perennial ryegrass at various stages of development shows that young herbage has only about 1/4 to 1/3 of the concentration of older forage; for example, at 60% head emergence from the sheath, 5.56%; at anthesis, 15.28%; and at 30 days after anthesis, 21.56%. This data, coupled with the measured loss of WSC of 1.78%, showed that in the younger material, 20% of the WSCs was lost to respiration. Alfalfa harvested at beginning bloom contains about 14.6% WSC. Enzymatic activity, even during rapid drying in an oven, can result in a 22.6% loss. In field conditions, drying may require considerably longer and losses of WSC may be even more significant. Coupled with precipitation and redrying, it is not difficult to imagine that perhaps 50% of the WSC would be lost.

IV. ENHANCEMENT OF DRYING RATE

A. MECHANICAL CONDITIONING

Mechanical conditioning by crushing, breaking, and abrading have long been used to speed up the drying process in forages. Mechanical conditioning serves to break the waxy cuticular layer that covers the stems and leaves of forage plants, allowing the moisture to escape at a more rapid rate. The majority of the effect is on the stems. These actions result in up to 30% greater rate of drying (Sorenson and Person, 1967).

Use of mechanical conditioning results in an increase in DM losses over what would be expected under ideal drying conditions in which mechanical conditioning is not practiced. The idea of ideal drying conditions, however, is a moot point because they seldom, if ever, exist. The net effect of mechanical conditioning, in light of weather encountered in almost all haymaking situations, is less loss because of avoidance of precipitation and re-wetting and re-drying cycles.

At times it may be expedient to turn[2] the windrow to accelerate drying. This is a very common practice in the temperate, humid areas where grass hay is predominant. It is sometimes practiced in the United States also, especially after inclement weather events. Michigan researchers (Rotz *et al.,* 1987; Davis *et al.,* 1989), however, reported that inverting or **tedding** does not increase the drying rate in alfalfa, inverting may or may not increase losses, and tedding always increases losses.

B. CHEMICAL DRYING AGENTS

1. Potassium and Sodium Carbonates

Chemical drying enhancers were first investigated by Shepherd (1959), but their acceptance has been limited. The major products in this area are potassium and sodium carbonates (K_2CO_3 and Na_2CO_3). These compounds, when applied to the stems at the time hay is mowed and windrowed, in conjunction with the newer conditioners, reduce drying time considerably. Their mode of action is to disperse the waxy cutin on the plant's surface, which increases rate of moisture loss. This increase in rate of moisture loss has been explained by the chemical disarrangement of the cuticular layer, allowing greater rates of transpiration (Radler, 1965; Grncarevic and Radler, 1967). They are most effective when environmental drying conditions are favorable (Mullahey *et al.,* 1988).

Treating alfalfa herbage with K_2CO_3 solutions reduces curing time (Sheaffer and Clark, 1975; Tullberg and Angus, 1978; Tullberg and Minson,

---

[2] Turning the windrow is commonly practiced in areas where accelerated drying of hay is desired. Tedding, which also turns the windrow, is also common, especially in areas where grass hays predominate. See glossary for definition of tedding.

1978; Wieghart, *et al.,* 1980; Fenn, 1981; Wieghart *et al.,* 1983; Valentine *et al.,* 1983; Rotz and Thomas, 1983; Rotz *et al.,* 1982, 1987; Arledge and Melton, 1984b; Rotz and Davis, 1985; Nocek *et al.,* 1986, 1988; Mullahey *et al.,* 1988; Oellermann *et al.,* 1989). Such additives are especially effective in significantly reducing drying time in arid regions; thus, allowing irrigation to begin sooner. This in turn stimulates rapid regrowth. In humid areas, with more frequent precipitation events, use of a drying agent may provide sufficiently more rapid drying rates to allow avoidance of precipitation. In general, the drying rate was doubled, or time was reduced by one-half (Wieghart *et al.,* 1983) with the application of drying agents. Other research (Jones, 1991) has shown the rate of drying can be increased by 40 to 63% over and above the mechanical increase.

Field studies have shown that increased amounts of K_2CO_3 have increased drying rates almost proportionally to the increased volume (Rotz and Davis, 1985). Mullahey *et al.* (1988) reported in North Carolina that treating alfalfa at mowing time with K_2CO_3 reduced field drying time by as little as 3 and as much as 22 h (29 to 72%), depending on the weather conditions. They also found that increasing the concentration of K_2CO_3 from 3.5 to 14 kg Mg^{-1} (0.35–1.4%)[3] of DM resulted in a small, but statistically significant, reduction in drying time. The decrease in time, however, would not be economically or biologically significant. Increasing the spray volume from 35 to 166 L Mg^{-1} of DM treated did not affect drying time (Mullahey *et al.,* 1988).

Arledge and Melton (1984b) compared drying agents in proprietary formulations and K_2CO_3 and found them all equally effective in reducing water content of alfalfa hay. Nocek, *et al.,* (1988) reported that a surfactant had little effect on drying rate, either by itself or with the drying agent.

Even after rain, the same rate of drying and the differential is maintained by K_2CO_3-treated hay (Vough, 1983). The rate of application was 8.5 lb of commercially available drying chemical applied in 15–18 gal. of water per ton of hay, which was at 20% moisture. A rate of 17 lb gave no additional advantage.

Nothing works better than K_2CO_3. Na_2CO_3 is about half the cost, but may not be as effective. A 50:50 mix, however, of K_2CO_3 and Na_2CO_3 is just as effective as K_2CO_3 (Annexstad, 1988). Supposedly, the additives are effective on alfalfa and other legumes, but not on grasses. Jones (1991) investigated the effect of K_2CO_3 on the drying rate of alfalfa and grasses under controlled laboratory conditions. He found that drying of alfalfa was accelerated, but that treatments of grasses with a 2% K_2CO_3 had little effect.

2. Comparison of Formic Acid on Grasses and Legumes

Formic acid has also been used as to enhance drying in forages (Jones, 1990). It initially enhances the drying rate in grasses, but later it retards it

---

[3] To convert kg Mg^{-1} to percent, divide by 10.

because of rapid desiccation of laminae (leaf blades), thus reducing their effectiveness in providing a pathway for water loss from the stem. In Jones' (1990) work, the rate of water loss from the surface of the stems was not enhanced at all, probably because the enveloping leaf sheaths acted as a protective layer. In contrast, drying of alfalfa was enhanced because the stems have no such layer. However, the enhancement of the drying rate in alfalfa by formic acid was not as great as that provided by K_2CO_3.

3. Effect on Digestibility

It is possible that drying agents, such as the carbonates and the surfactants sometimes used in concert with them (supposedly to enhance the effectiveness of the carbonates), may also influence digestibility of the forage. Nocek *et al.* (1988) suggest that, because cutin poses a barrier to microbiological assimilation of plants in the animal's rumen (Van Soest, 1982), drying agents might increase rumen fermentation rate. Second, they postulated that surfactants may decrease the surface tension of rumen fluid, which might speed the penetration rate of rumen microorganisms into the plant tissue. Either of these mechanisms would enhance extent and rate of ruminal nutrient digestion. They found that drying agents alone did not influence *in situ* DM or NDF digestibility, but addition of surfactant did increase rates of digestion for both DM and NDF.

Wieghart (1979) treated alfalfa in the laboratory with various combinations of K_2CO_3, a surfactant (Tween), and oleic acid. No differences were found in *in vitro* dry matter digestibility (IVDMD). Valentine *et al.* (1983) also reported no affect on IVDMD. However, all treatments increased ruminal CP, NDF, and ADF digestibility. Oellermann *et al.* (1989) showed that there were no significant differences in feed composition parameters or in IVDMD between treated and untreated third-cut hay. However, dairy cows fed the Na_2–K_2CO_3–citrate had a higher mean daily milk yield, adjusted for feed intake (33.0 versus 32.5 kg d^{-1}; 72.8 vs. 71.7 lb d^{-1}). There was no significant difference in the milk composition.

Van Horn *et al.* (1988) compared a control (no treatment), K_2CO_3, and Conservit[4] and showed that no differences existed among treatments for NDF or ADF. However, *in vivo* digestion trials showed that Conservit applied to hay that was packaged in loosely packed bales, 198 kg m^{-3} (12.4 lb ft^{-3}) resulted in a significantly higher DM disappearance rate (62% vs. a mean value for other treatments of 54.3% DM disappearance) after 24 h than Conservit applied to hay packaged in densely packed bales, 237 kg m^{-3} (14.8 lb ft^{-3}).

---

[4] Trade name of a hay-drying chemical that is a product of Fenn Products, Inc., Cottage Grove, OR. It consists of alkaline N silicates, alkaline salts of linear carboxylic acids, alkaline carbonates, wetting agents, and antifoaming agents.

C. APPLICATION OF DRYING AGENTS

To apply drying agents successfully, a spray bar mounted on the mower–conditioner ahead of the reel may be used (Vough, 1983; Rotz *et al.,* 1984; Anderson *et al.,* 1988). An alternative is to use a push bar, or a crop deflector bar in conjunction with the spray bar. The push bar is located at the front of the header, about 20 to 25 cm (8–10 in.) above the cutting level. This bar pushes plant tops over so chemical spray is directed primarily at the stems and it should be adjustable so that it can be placed at one-half the crop's height. The nozzle spacing should be approximately 15 cm (6 in.).

V. PRESERVATIVES

A. UTILITY OF PRESERVATIVES

Effective hay preservatives must be capable of preventing growth of aerobic microbes (mainly fungi and bacteria) in order to conserve quality of high-moisture hay during storage. As the concentration of moisture in the hay increases, the rate of aerobic microbial activity increases (Lacey, 1980) and higher rates of active preservative are required (Lacey and Lord, 1977). Failure to control these processes may result in spontaneous combustion of the hay (Roethe, 1937), which results in a fire that destroys the stack and storage facility. Benham and Redman (1980), in a review article, suggested that an ideal effective preservative should (1) inhibit the growth of fungi, actinomycetes, and bacteria in hay at moisture concentrations significantly above 20%; (2) be acceptable under the appropriate feeding stuffs legislation with no undesirable effect on the livestock receiving the treated hay (i.e., leave no residues in the meat or milk); (3) be simple, safe, and acceptable for use by operators; (4) eliminate storage losses and in addition have a nutritive value; (5) cause no corrosion or damage to machinery; (6) have a noncritical distribution with high mobility, high wetting power, and minimum volatility; (7) have no residual effect on crop growth; and (8) be readily available and economic to use in practice.

In areas of high summer precipitation, growers desiring to make high-quality hay may find use of preservatives advantageous. In arid areas, in addition to quality, growers may find them of value for an additional reason—quick removal of hay after cutting so that postcutting irrigation, which enables rapid plant regrowth, can begin as quickly as possible. This practice may result in a minimum of 25% increase in seasonal DM production (Wallentine, 1986), in addition to decreased harvest and storage losses and higher-quality forages. Growers in the more humid areas may also realize some yield increase, but data is not available to define its extent. Research has shown that producers in both areas can realize an increase in quality of the harvested forage, provided that a proper and effective preservative is applied, the rate used is sufficient, and the proper techniques are used to assure complete coverage of the herbage.

Three types of preservatives are available: organic acids such as propionic or acetic acids, which are usually used as a mixture of 80% propionic and 20% acetic (80P : 20A), ammonia and urea, and microbial agents. Propionic and acetic acid mixes may sometimes be buffered with ammonium butyrate or other chemicals.

B. ORGANIC ACIDS

Organic acid compounds containing high percentages of propionic acid, applied at baling, are the most reliable preservatives. To be effective these chemicals must be applied at the proper rate, which depends on moisture in the hay at time of application (i.e., at baling). It is extremely important that the material be uniformly distributed through the hay mass (Arledge and Melton, 1983). Arledge and Melton (1983, 1984a) reported that baling alfalfa hay at higher than normal moisture concentrations reduced harvest losses by 48%, resulting in nearly a 100% yield increase and 8% higher protein than hay baled at the normal moisture concentration. Liquid propionic acid compounds were more efficient at preserving hay quality in the bale. These compounds were efficient up to a bale moisture of 25%. The biotic compounds appeared to be efficient up to a bale moisture of 23%. In a followup study Arledge and Melton (1984a) evaluated liquid and granular sodium diacetate hay preservatives. They found that the liquid or granular formulations were equally effective in preventing hay spoilage when applied in the proper manner. They also found that no differences existed between two application rates. In their studies, all untreated bales were totally spoiled, whereas bales treated with preservatives were rated as good 95 to 100% of the time.

The organic acids preserve the high-moisture hay by maintaining the pH of the forage at less than 6.0. Deleterious aerobic microbial growth is suppressed by acid conditions, just as it is in the silage ensiling process. The combination of low moisture of the forage and the low pH provide excellent curing conditions: specifically, lower temperatures and low pH values. The pH of wet alfalfa is between 5.5 and 6.0 when baled at 20 to 35% moisture.

Propionic acid or a mixture of propionic and acetic acids (80P : 20A, respectively) are commonly used as preservatives. This mixture is capable of maintaining the pH below 6.0. Without microbial growth, the temperature is maintained at a low level [usually between 35°C (95°F) at the time of baling and 24°C (75°F) after 2 to 3 weeks of storage]. These two factors thus minimize aerobic respiration and DM loss. Untreated hay, or ineffectively treated hay, baled at these moisture contents, invariably shows an increase in temperature to about 43°C (110°F). After about 30 days of storage, temperatures fall to the approximate ambient temperature in the storage area. In hay treated with 80P:20A at the proper rate, temperature does not rise after baling even though the hay moisture content may be as high as 35% (Baron and Greer, 1988; Crawford *et al.,* 1986; Kersbergen and Barton, 1986; Walgenbach and Massingill, 1986).

A number of workers have shown that high-moisture hay (25 to 30%) treated with organic acids at rates of 1 to 2% of the forage weight at 25% moisture can be stored successfully (Nehrir *et al.,* 1978; Vough, 1983;). Nihrer *et al.* (1978) demonstrated that small rectangular bales were of quality comparable to heat-dried hay and gave increased DM yield when compared to field-cured hay. When hay contains more than 30% moisture, 2 to 2.5% rate of organic acid is recommended (Vough, 1983). Sheaffer and Clark (1975) successfully preserved 31% moisture hay with propionic acid and ammonium isobutyrate at rates of 1.5 to 2.0% (wt/wt) in the field. Applications of less than 1% are generally ineffective in preventing heating, mold growth, and dry-weight loss (Walgenbach and Massingill, 1986).

Experimentally, in laboratory models, it can be shown that lesser rates (0.3 to 0.6%) are effective in controlling aerobic microbes (Lacey and Lord, 1977) when the moisture concentrations of the forage range from 25 to 50%. However, practice and field experiments show that because of uncertainty in application procedures and inability to control environmental factors in the field, rates must be about 1.5% of an 80P:20A mix. Atwal and Heslop (1987) reported that concentrations of propionic acid in excess of 0.3% were necessary to conserve large round bales with more than 17% moisture.

Disadvantages in using organic acid preservatives include (1) danger in handling the organic acids and corrosion of the equipment, (2) reduced selling price because treatment with organic acids discolors the hay and gives it a rain-damaged look, (3) hauling extra weight when hay is to be transported long distances, and (4) unfavorable cost–benefit ratios.

C. AMMONIA AND UREA

Ammonia has been used as an effective preservative for high-moisture alfalfa hay (Atwal et al., 1986; Johnson *et al.,* 1981; Thorlacius and Robertson, 1984; Knapp *et al.,* 1975). Henning (1990) has also looked at urea as a preservative of wet or high-moisture baled hay. Ammonia is readily absorbed by wet material and is lethal to fungi (McCallon and Weedon, 1940). Thus, it is effective although not commonly used, like many of the corrosive agent treatments, because of the difficulty of handling and detrimental effect on equipment. Production balers may be retrofitted with an ammonia tank and injection needles on the face of the plunger (Roepnack, 1980). At moisture concentrations of 18 to 28%, treated uncovered bales were effective in preserving alfalfa in small rectangular and in large round bales. Treated bales enclosed in plastic bags were adequately preserved at higher-moisture concentrations of up to 50% (Koegel *et al.,* 1985). These treatments, in addition to acting as a preservative, result in increased N content in the hay and greater cell wall digestibility. Thus, they have the potential to enhance the quality of low-value feed such as straw and corn stalks and cobs. Rates range from 1.5 to 2% ammonia per ton of wet material (Knapp *et al.,* 1975). When high-quality hay was being fed to dairy cows, Weiss *et al.,* (1982) showed that treating the hay with ammonia did not affect DM intake or milk production.

D. MICROBIAL AGENTS

The first microbial agents were developed initially for use in preserving high moisture (50 to 70% moisture) silage. Thus, these agents were anaerobic bacterial inoculants such as *Lactobacilli, Pedioccocci,* and *Streptococci* that produce lactic acid. Their effectiveness on high-moisture hay (20 to 35%), however, is questionable because of the relatively low moisture levels in the hay (low in comparison to silage conditions under which these organisms flourish). Research by Baron and Greer (1988) has shown them to be ineffective, and also showed that pH of control (nontreated) hay, hay treated with 80P:20A live bacterial culture of protease and cellulose enzymes, or 12% lactic acid and fermentation extract responded differently over time. The only treatment to effectively prevent change in pH was the propionic acid–acetic acid treatment, with which at day 0 pH was 5.7; day 2, 5.6; day 9, 5.6; and day 21, 5.6. In contrast, the control and the two biological agent treatments were quite similar in their response and the results were quite unsatisfactory. Research in more arid areas has shown some success (Holland *et al.,* 1990).

Aerobic bacterial inoculants for use on hay were developed long after the role of bacteria in silage fermentation was understood. The only example is that by the company Microbial Genetics,[5] which introduced a hay inoculant in 1988. The product is composed of living strains of *Bacillus pumulus* selected from samples of alfalfa hay, and were thus well adapted to moisture conditions in the range of 20 to 30%. This product offers advantages that the organic acids do not possess. It is noncorrosive and easily handled. Pioneer research (Holland *et al.,* 1990) shows that it allows for greater leaf retention, palatability, and improved quality of the hay. Treatments costs are approximately $3.00 per ton.

Three factors are of prime importance in deciding to use microbial agents to enhance the preservation of high moisture hay. First, the material must have been proved effective through repeatable research. Second, the bacteria, to be effective, must have been developed from microbes found natu-

[5] A division of Pioneer Hi-Bred International.

rally on dry hay rather than in silage. Third, the specific product must be applied at the rate recommended by the manufacturer.

E. APPLICATION OF PRESERVATIVES

It is essential that preservatives be applied properly. Of foremost importance is uniform coverage of all hay because the preservatives work as inhibitors of mold growth. The forage is normally cut and allowed to wilt to a moisture concentration of 17 to 35%, and then preservative is applied at the time of baling. The procedure and protocol differ somewhat, depending on type of preservative—organic acid or microbial agent—to be applied. Organic acids must be sprayed on the herbage as it enters the baler or forced into the bale under pressure, whereas the microbial agents may be metered on with a Gandy box attached to the baler just ahead of the baling chamber.

Quality of hay is largely preserved and even enhanced by inhibition of respiration of the WSC stored in the stems and leaves. Table 13.3 shows representative values for WSC in grasses and legumes. Kersbergen and Barton (1986) showed that IVDMD was significantly better with the use of a preservative when compared to the control (61.5 vs. 62.2%) for red clover–timothy hay.

VI. FIELD CURING OF HAY AND NUTRIENT LOSSES

A. EXTENT OF PROBLEM

In humid areas of the world, the greatest impediment to making good hay is the weather experienced during the period between cutting and the completion of the curing process. Relative humidity, cloudy weather, wind, precipitation, and formation of morning dew, often in a repeated sequence, and moisture content of the crop all combine to extend the drying period. Losses of DM which are a natural but unwelcome part of the curing process, are increased by deleterious environmental conditions (Wilkinson, 1981).

Losses during the haymaking process are estimated to range from 2 to more than 50%. In legumes, in which most of the work has been with alfalfa, curing losses range from approximately 8% under ideal conditions to more than 50% under adverse conditions. Under similar conditions losses in grasses range from 2 to 25%. Summarized data, under U.S. conditions, indicate that loss of DM is higher in field-cured hay than in silage, and barn-dried hay losses are slightly less than those experienced in silage (Carter, 1960).

TABLE 13.3 Comparative Water Soluble Carbohydrate Concentrations in Various Forage Crops at Differing Stages of Development

	Stage of development (g kg^{-1} DM)[a]		
Forage	Vegetative	Early flower	Mature
Alfalfa[b]	160–200	111–150	108–113 (TNC)[c]
Red clover[b]	150–200	150–190	135–175 (TNC)
Ladino clover[b]	150–225	160–185	140–150 (TNC)
Birdsfoot trefoil[b]	200–215	130–160	110–113 (TNC)
Orchardgrass			
Smooth bromegrass			
Timothy[d]		16–309	
Alfalfa[d]		39–82	
Tall Fescue			
Corn[e]			74–286[f]
Corn[e]			350–32[g]
Corn[d]			254–428
Sweetcorn[d]			260–380
Sorghum[d]			253–384
Perennial ryegrass[h]	182–192	—	—
Italian ryegrass[h]	186–243	—	—

[a] To convert g kg^{-1} to percent, divide by 10.
[b] Raguse and Smith (1966).
[c] TNC, total nonstructural carbohydrates.
[d] Smith (1971).
[e] McAllan and Phipps (1977)
[f] Soluble sugars.
[g] Starch.
[h] Haigh (1990).

B. DRY MATTER LOSSES

On the average, hay baled at 15% moisture loses 22% of DM in harvesting and in storing for 6 months (Crawford *et al.,* 1986). It has been reported, however, that treatment with preservatives, which allows hay removal from the field at a high moisture content, can result in significant reductions of DM losses (Nehrir *et al.,* 1978; Crawford *et al.,* 1986; Baron and Greer, 1988). Rectangular-baled alfalfa lost 14.9% and 29.7% of the dry matter when treated with acid and field cured, respectively (Nehrir *et al.,* 1978). Baron and Greer (1988) showed that the control lost 11.8% of DM in the first 21 days after baling, propionic acid + NH_3, 5.3%, and two bacterial or bacterial extract treatments lost an average of 10.2%, a value that was not significantly better than the check or control.

Dry matter losses in other species, however, have also been shown not to differ with various preservative treatments. For example, Van Horn *et al.* (1988) reported that control (no treatment) losses averaged 22.4%, Conservit (dense bales, 255 kg m^{-3} or 15.94 lb ft^{-3}), 20.1%, Conservit (loose bales, 198 kg m^{-3} or 12.4 lb ft^{-3}), 18.4%, and $K2CO^3$ (dense bales, 241 kg m^{-3} or 15.1 lb ft^{-3}), 19.6%. These differences were not statistically different. Thus, the advantage of using the additives was in being able to remove hay from the field in about half the normal time required for drying and field curing.

The percentage of leaves in baled hay declines as percentage moisture in the bale decreases. For example, Crawford and coworkers (1986) reported that herbage baled at 30 to 35% had 58.3% leaves if treated and 61.7% if untreated. These leaf percentages do not differ statistically. When baled at 15% (sun-dried), leaf percentage was 43.7%. The leaf: stem ratio was 1.4, 1.6, and 0.8, for the untreated, treated, and sun-dried hay, respectively.

C. TYPES OF DRY MATTER LOSSES

Nutrient losses in haymaking are caused by plant respiration, mechanical damage, leaching by precipitation, and adverse storage conditions. A summary of research shows the relative losses in each category Table 13.4. These figures are typical of what is reported by researchers and experienced

TABLE 13.4 Losses in Harvesting and Preserving Forages

	Losses (%)		
	Field loss	Storage loss	Total
Direct cut grass silage	2–3	18–22	20–25
Haylage—65% moisture	11–13	8–12	19–25
Haylage—50% moisture	11–13	3–8	19–25
Baled alfalfa—raked at baling	30–35	2–4	14–19
Baled alfalfa–direct windrowed or raked at 50–60% moisture	12–15	2–4	14–19
Legume–grass—raked at baling	18–23	2–4	20–27
Legume–grass—windrowed or or raked at 50–60% moisture	12–18	2–4	14–22

Source: Martin, Leonard, and Stamp, 1976, p. 226; with permission of Macmillan Publishing Company.

by growers everywhere. They are at first rather shocking because most growers are not aware that losses are this great.

1. Mechanical

Conditioning machinery may be used to further accelerate the rate of drying (Murdoch and Bare, 1963; Shepperson *et al.*, 1962) in order to reduce the probability of exposure in the field to inclement weather. Mechanical losses represent a combination of two processes: true shatter loss, which takes the form of particles breaking off whenever forage is disturbed, and pickup loss, which takes the form of particles of unshattered material dropping between pick-up tines (McGechan, 1988; Rotz and Davis, 1986). In grasses there is ample evidence that shattering loss is related directly to the moisture content of the forage (e.g., to its brittleness). However, there is no evidence that this is the case for pick-up losses, because these have been shown to be very similar for both silage and hay (McGechan, 1988). However, pick-up losses are proportional to the net area of ground cleared by the operation (e.g., the area under the swath). This initial value for grasses is 0.15 Mg ha^{-1} of dry matter.

Klinner and Wood (1981) showed that this loss could be best described by this relationship: $L_p = 0.1 + 0.0025t_w$, where L_p is pick-up loss, Mg dm ha^{-1} of area cleared, and t_w is throughput of wet material, in Mg ha^{-1}. McGechan (1988) reports pick-up losses in grasses to range from 1 to 1.5%. Mayne and Gordon (1986) reported that pick-up losses ranged from 0.9 to 3.7% (0.04 to 0.14 Mg dm ha^{-1}) for a precision harvester; for a flail-type chopper, losses ranged from 0.7 to 1.1% (0.03 to 0.04 Mg dm ha^{-1}).

Losses during mowing have been reported to range from 0.7 to 1.9% for timothy (Savoie, 1988) from a mower fitted with a crimper. Honig (1979) reported that cutting losses were from 0.2 to 0.5 Mg dm ha^{-1} with drum or disc mowers and mower conditioners. Whitney (1966) identified 7.4 to 12.8% losses in the baling process alone, including losses from pick-up, forward and rear chamber, and rake and mower losses.

Mechanical shattering losses during normal handling (turning or tedding during drying) resulted in 25 to 50 kg dm ha^{-1} (22.3–44.6 lb acre^{-1}) losses when dm content ranged from 60 down to 20%. At moisture concentrations below 20%, loses increased sharply to as much as 130 kg dm ha^{-1} (116 lb dm acre^{-1}; Honig, 1979). In an attempt to simulate tedding in the laboratory, McGechan (1988) demonstrated that first-cut grass crops showed a low level of loss per treatment until a breakpoint moisture content of about 45% was reached, after which loss levels rose sharply to as much as 45% at about 80% DM.

Vincent (1983) carried out stress-strain experiments to determine the stiffness and fracture properties of individual grass leaves at a range of moisture contents. Stiffness increased markedly as the moisture content dropped below 50%, with a further steep rise as the moisture concentration dropped below 20%. He explained his results in terms of the engineering theory of composite materials; a comparison of changes in stiffness in transverse and longitudinal directions indicated that a change in stiffness of the cells between the fibers, rather than the fibers themselves, accounted for changes in properties of grasses with change in moisture content.

Quoting unpublished work by Spencer *et al.,* McGechan (1988) reported losses behind big-bale balers to range from 0.6 (0.071 Mg dm ha^{-1}) after wilting to 1.2% (0.126 Mg dm ha^{-1}) after wilting in a spread swath with regular tedding and windrowing before baling. After wilting in the windrow with regular tedding, losses were 0.163 Mg dm ha^{-1} (1.55%). Losses during baling operations decrease as moisture content of the forage increases. In working with high-moisture hay (ensiling in a bale), Koegel *et al.* (1985b) report that baling losses range from 7 to 8.5% at 34% to 2.8 to 4.1% at 50% moisture concentration. If losses are that high at 34%, it is not difficult to imagine that they would be much higher at moisture concentrations at which hay is usually made—10 to 18%.

Banthien (1970) measured losses in grasses associated with the use of various mower and mower-conditioner systems followed by tedding. He noted particularly high losses from tedding a crop cut with a flail mower, 5.3% when tedded at 46% moisture content plus 16% when tedded a second time at 31% moisture content.

Losses in legume hay, especially alfalfa, are considerably greater than for grass hay. The presence of grass in hay apparently provides a consistent advantage to hay-drying rate for red clover, but alfalfa and birdsfoot trefoil are unaffected (Collins, 1985a). Smith (1981) has suggested that grasses mixed with alfalfa increase the drying rate, and there is evidence (Klinner, 1975) that while curing, alfalfa loses more DM (38.9%) than does grass (19.1%). Shattering losses for mowing and raking in alfalfa was four times greater than for grasses. This is related to alfalfa morphology—extending of the leaves on a slender petiole that is much more subject to abscission than are grass sheaths and blades (Savoie, 1988). Other than the extent to which they differ, leaf losses in grasses and legumes have little relationship to each other as they interact with the environment. However, mowing, raking, tedding, and turning windrows results in increased loss of nutrients, particularly when coupled with significant amounts of precipitation. Thus, one faces a dilemma—increased drying rate on the one hand and greater physical losses on the other from use of mechanical conditioning devices.

In humid areas that experience frequent precipitation events during the summer, hay is often dried in barns to reduce the losses. Although nutrients are preserved more efficiently in barn-dried hay and silage than in field-cured hay during periods of inclement weather, Shepherd *et al.* (1954) showed that there were small differences in losses among the three methods during periods of good weather.

2. Leaching

Precipitation during field curing can reduce yield and quality of hay (Carter, 1960; Collins, 1983b). These losses can be reduced by hastening field drying or through use of preservatives to allow baling at higher moisture contents (lower DM concentrations), or both. Collins (1985a,b) reported that precipitation increased field-drying losses by as much as 15.4% for alfalfa, but did not affect birdsfoot trefoil–smooth bromegrass mixtures. Wetting reduced digestibility (IVDMD) by 1.3% for birdsfoot trefoil–grass and 6.4% for alfalfa.

Losses during field curing for legume forage exposed to precipitation during drying result from excess respiration, leaf loss, and leaching (Murdoch, 1964). Shepherd *et al.* (1954) recorded field losses as high as 33% of the DM for alfalfa, and Carter (1960) in a review article noted that DM losses during field curing and barn drying of hay ranged from 3.5 to 40%. Collins (1983a, 1985b) showed similar effects of precipitation on alfalfa.

Multiple wetting during curing of alfalfa and red clover hay reduced total nonstructural carbohydrates (TNC) by 34 and 67%, respectively (Collins, 1983a). In the same study, Collins (1983a) showed that alfalfa hay exposed to 2.5, 4.2, and 6.1 cm of precipitation lost an average of 17% of its DM (vs 8.1% for the unwetted check) in 1980 and 10.5, 43.4, and 53.0% of the original DM (check, 4.2–, and 6.1–cm treatments, respectively) in 1981. In 1980, red clover lost 25% of its DM. IVDMD was reduced both years: 1980, 70.8 (check) to 67.4% when exposed to 2.5 cm (1 in.) of precipitation; 1981, 65.2 to 47.9% when exposed to 4.1 cm (1.6 in.) of precipitation. NDF was increased by wetting. Prolonged wetting in 1981 reduced the yield of N and TNC by 40.3 and 71.5% respectively.

Loss of DM and starch from leaching is reduced considerably if mechanical damage to the hay is avoided. Mechanical damage without rain falling on the hay increased the loss of starch equivalent by 16%, and there was a further 16% increase in starch loss when the hay was subjected to frequent showers (Murdoch, 1964.) Leaching losses of hay in the windrow show a negative relationship to moisture content of the swath at the time of precipitation. For example, McGechan (1989) showed that leaching losses when the windrow was at 20% moisture, from 5 mm of precipitation, was 5% of DM, whereas at 60% windrow moisture, the loss was 2 to 2.5%. Ten millimeters of precipitation results in losses of 6 to 10% of the dryer forage and 3 to 5% of the wetter forage. If precipitation reached 20 mm, losses were 12 to 13% and 6 to 6.5%, respectively, for windrow moisture concentrations of 20 and 60%.

Denedde and Wilmschen (1969) studied relationships of losses in fully cured hay from 10 cm of artificial rain under both good and poor curing conditions. By analyzing the water that ran off, they measured DM losses due to leaching of 1% for hay made from uncrimped grass and 2% for crimped grass hay. Overall losses during wetting and drying ranged from 4 to 16%. Mechanical losses are not included in these totals. McGechan (1988) points out that all sources agree that respiration and leaching represent losses mainly of the WSC fraction of the forage material. Because this is the readily digestible portion of the forage, a reduction in digestibility occurs if hay is wetted by rain.

Evidence strongly suggests that both mechanical damage and leaching losses reach serious proportions in grasses when DM content of the herbage drying in the field is high (Watson and Nash, 1960). Collins (1983a) also supports this conclusion for alfalfa. WSC concentration at two moisture concentration and in the rewetted and nonrewetted grass were shown by Pizarro and James (1972) to be 9.9 at 75% moisture vs 8.0 at 36% moisture—a significant difference. Rewetted vs nonrewetted grass showed losses of 10.4 vs 7.5%, a nonsignificant difference (alpha = 0.05).

D. FORAGE QUALITY LOSSES

Wetting did not change forage N concentration either year, but N yield was reduced 40% (Collins, 1983a). Later work (Collins, 1991) showed that N concentration was unaffected by curing or soaking in water. Ash declined from 6.8 to 5.0% for herbage vs water-soaked hay. Other factors for herbage and water-soaked hay showed the following respective values: ADF, 46.6 vs 49.7%; IVDMD, 51.4 vs 50.5%; and NDF disappearance, 38.2 vs 36.5% (Collins, 1991). Hay exposed to simulated precipitation showed that 60% of the losses in DM, N, ash, and digestibility were associated with respiration and shatter of leaves (Collins, 1991). Leaves were responsible for 75% of DM and digestibility losses in rain-soaked forage, and stems were responsible for 14% of the losses. Alfalfa decreased from 11.3% ash in the standing herbage to 10.9% in the dried hay to 7.2% in the rain-soaked hay. NDF increased from 23.4% in the herbage to 30.9% in the rain-soaked hay. Comparative figures for ADF were 14.2 vs 18.0fF%. IVDMD declined from 78.3 to 72.9%. *In vitro* digestibility for herbage and water-soaked hay was 66.2 and 68.4%, respectively.

E. MINERAL LOSSES

Some research (Collins, 1985a) suggests that more than just DM is lost when hay curing in the windrow is drenched with rain. Calcium concentration was reduced by precipitation in the final dried hay.

VII. DIURNAL VARIATION IN NUTRIENTS

A. DIURNAL VARIATION IN WATER-SOLUBLE CARBOHYDRATES

Because photosynthesis is a light-driven process, it occurs only during the day. Dark respiration goes on at all times in living plants. It follows that in a mature, forage stand carbohydrates would probably accumulate from morning to evening and that, because of respiration, they would decline at night. These carbohydrates that are produced and stored on a diurnal basis are a source of readily digestible energy for ruminant animals. The obvious question is whether there is sufficient accumulation of additional carbohydrates during the day to justify harvesting hay during the afternoon rather than in the morning, when this soluble pool is depleted.

Curtis (1944) reported considerable diurnal variation in the labile carbohydrate pool in alfalfa. Over all sets of data (10, with 7 to 9 replicates) he showed that carbohydrate percentage was higher in the afternoon than in the morning. Overall percentage concentrations were 4.3% (dry weight basis) in the morning-harvested forage and 6.1% in the late afternoon-harvested forage, a gain of 42%. Generally, all work on diurnal carbohydrate variation shows that there is indeed an increase in WSC from morning until evening. Allen *et al.* (1961) showed that reducing sugars peaked at 10 AM at 3.24%, and thereafter they were 3.1% at 2 PM, and 2.56% at 6 PM. At 6 AM, they were at 2.38%. Others (Holt and Hilst, 1969) showed that alfalfa followed a similar quadratic pattern in WSC concentration during the day. For example, in 1964, concentrations ranged from 7.8% at 6 AM to 8.9% at 12 PM, and decreased slightly by 6 PM. The following year, similar results were reported for herbage in early, medium, or late stages of development: 7% at 6 AM, 8.1% at 12 PM, and 7.9% at 6 PM. Lechtenberg *et al.* (1971) demonstrated a similar pattern for alfalfa for glucose and fructose during the day. Sucrose comprised less than 3% of the DM but generally increased from 6 AM to 6 PM. TNC in first- and second-growth alfalfa increased from 6 AM to 6 PM. (Lechtenberg *et al.*, 1971). For example, in the first harvest, TNC concentration was 17.4% at 6 AM and 20.4% at 6 PM. Second harvest showed an increase from 15.0% at 6 AM to 18.3% at 6 PM, and concentrations then declined thereafter because respiration exceeded photosynthesis. They showed that WSC followed a similar pattern: first harvest, 11% at 6 AM, 12.1% at 6 PM, and 11.3% at midnight; second harvest, 6.5, 8.0, and 7.0%, respectively.

Alfalfa showed a quadratic diurnal change in WSC, but response of grasses was linear. Bluegrass, smooth bromegrass, and tall fescue all followed a linear pattern of increase from early morning to late evening, ranging from a mean of 5.4% at 6 AM to 6.4% at noon to 7.8% at 6 PM (Holt and Hilst, 1969).

B. DIURNAL VARIATION OF DRY MATTER PRODUCTION

When the carbohydrate concentration increase is considered in conjunction with DM increase of 19% from morning until afternoon, the question arises as to whether late-afternoon harvesting would result in higher field-harvested yields. Curtis (1944) showed that approximately one-fifth of the daily DM increase was accounted for by increased carbohydrate concentrations and the remainder would be attributed to growth and development.

Adolph *et al.* (1947) attempted to evaluate whether there were daily variations in DM yield as reported by Curtis (1944) and whether these variations were significant enough to provide an incentive for growers to alter time of harvesting during the day. They showed that total DM increased from morning to evening by 77 kg ha^{-1} (69 lb $acre^{-1}$) if DM was measured at time of cutting and by 92 lb when field cured. None of these differences were large enough to justify delaying harvesting until the afternoon to take advantage of the higher carbohydrate concentrations.

Adolph *et al.* (1947) did show that dry matter digestibility (DMD) was increased by about 2.8% from morning until evening in oven-dried samples. This was greater than the sample variation, 1.2 to 1.5%; thus, the difference is probably significant. However, differences did not exist in the field-cured hay (53.3% in the morning and 53.7% in the afternoon). Protein digestibility actually decreased from 73.3 to 72.8%. This was undoubtedly due to loss of leaves, which are the most digestible portion of the herbage, during the field-curing process. Their work showed that approximately 7 to 8% of the dry matter, largely the leaves, was lost during field curing.

There is evidence that soluble carbohydrates increase from morning until evening in forages. In actively growing forage, DM, as expected, also increases. However, field losses during curing are greater for afternoon-harvested forage, so there is no advantage for harvesting hay in the afternoon to take advantage of the higher carbohydrate concentrations. If one is making low-moisture silage (haylage) or direct-cut greenchop, in which field losses are much reduced, there may be an advantage to harvesting in the afternoon over harvesting in the morning. The data of Adolph *et al.* (1947), in which they show increased DM yields and greater digestibility from afternoon-cut forage, support this conclusion. Otherwise, worrying about diurnal variation of WSC concentration flies in the face of a much greater problem—avoiding the huge losses that occur because of precipitation and extended drying time. To make hay in a day, the grower must cut hay early in the day to take advantage of the best drying time and to minimize respiration losses, that is, reduce drying time (Fallon *et al.*, 1989).

VIII. ENVIRONMENTAL INFLUENCES ON FORAGE QUALITY

It is known that environmental variability causes changes in forage quality. Dairymen have decided, based on their experience, that alfalfa hay produced under hotter summer days and nights is of inferior value. Whether this assumption is true, however, is questionable. Like many things, it depends on circumstances or environment. It is a fact, however, that forage quality is affected indirectly by the weather because of delays in harvest that occur during periods of inclemency. Of all factors related to forage quality, stage of development is the most important. Aside from the effect on maturity, however, the purpose of this section is to provide information, based on published research, that can be used as a general guide in evaluating the effects of temperature, light intensity, and moisture stress on forage quality.

Although it has been recognized for some time that forage quality seems to decline in hot weather, it has not been clear whether this decline is due to a greater amount of fibrous materials being formed at comparable stages of development or whether it is simply a matter of more rapid development. There are those who claim that the primary effect of increased temperature on quality of alfalfa is hastened maturity and the normal associated decline (Jensen *et al.,* 1967; Marten, 1970). This is quite likely true in the field, or at least it is a major component responsible for the change observed in the field. Yet there are those who have not come to this conclusion, simply because their controlled-temperature growth-chamber experiments showed definite changes in quality as temperature changed even though stages of development were held constant (Smith, 1970a,b,c).

Field observations and research suggest that quality is more related to temperature after alfalfa begins to bloom (Hidiroglou *et al.,* 1966). Prior to that time there must be other factors that impinge on quality more than temperature. After blooming begins, the general trend is that as temperature increases, CP decreases and crude fiber (CF) increases. Digestibility of 1/10-bloom alfalfa declined at the rate of 0.55% per degree increase in the previous week maximum mean temperature ($r^2 = 0.978$). At 1/3-bloom, the decrease was 1.04% per degree change ($r^2 = 0.800$) and 1.07% at full bloom. IVDDM concentration also showed a decline (42.6 vs 39.6% at 15°C and 30°C, respectively).

A. TEMPERATURE

1. Protein

In general, from field studies where temperature could not be controlled but only observed and measured, the relationship between CP and temperature appears to be negative; for example, as temperature increases within the range that cool-season forages are adapted, CP percentage decreases (Garza *et al.,* 1965; Hiridoglou *et al.,* 1966). However, not all forages respond the same. For example, this negative relationship appears to hold for alfalfa (Hiridoglou *et al.,* 1966; Smith, 1970b), timothy (Hiridoglou *et al.,* 1966), and yellow sweetclover (Smith, 1970b). Smith (1970c), in a controlled-temperature study, showed the opposite response for timothy and smooth bromegrass (e.g., higher protein levels were associated with higher temperatures). Controlled-temperature studies (Smith, 1970b) show that in alfalfa at first bloom, CP concentration was negatively related to increased temperatures. Smith (1970b) has shown that red and alsike clover demonstrate a parabolic response as day temperature is increased from 15 to 32°C, being about 16% at 15°C, rising to 24% at 26°C, and then declining to about 20% at 32°C. Alsike follows a similar pattern. Birdsfoot trefoil, however, shows an increase in percentage of CP as temperature increases.

These studies support the conclusion that CP is not a good predictor of expected quality at the same stage of development over changing environmental conditions (Marten, 1970).

2. Fiber Development and Digestibility

The general response of most forage crops to increased temperature is increased fiber production (Hiridoglou *et al.,* 1966; Marten, 1970; Smith, 1970b,c). Smith (1970b) demonstrated that all legumes do not respond in the same manner, however. For example, alfalfa and red and alsike clovers increased in fiber as temperature was increased from day/night temperatures of 15/10 through 21/15 to 27/21°C. However, all three decreased in concentration of CF when grown at 32/27°C. Yellow sweetclover declined and trefoil increased in CF as temperature was increased. All evaluations were made at first flower.

Because of the close relationship of digestibility to ADF ($r = -0.72$ to -0.94; Vough and Marten, 1971), digestibility drops as expected as temperature is increased (Garza *et al.,* 1965; Hidiroglou *et al.,* 1966; Vough and Marten, 1971; Smith, 1969). Greenfield and Smith (1973) also demonstrated that at first flower, alfalfa grown under controlled conditions at 33/24°C (day/night temperatures) had considerably lower IVDDM than did alfalfa grown at 21/12°C (66.6 and 73.3%, respectively). Walgenbach *et al.* (1981) showed that leaf-stem ratios for alfalfa declined by about 23% (0.95 to 0.72) as temperature was increased from 18/10 (day/night) 26/18°C.

3. Water Soluble Carbohydrates

Large differences occur in starch concentration in alfalfa leaves, depending on the temperature at which they are grown. In a 32/24°C regime, leaves show only half as much starch at first flower as at 30/30°C (0.45 mg/leaf vs 0.94 mg/leaf). However, when the temperature is lowered to 21/12°C, the mg of starch per leaf increased to 4.83 in the vegetative stage and to 6.61 at first flower (Smith and Struckmeyer, 1974). This of course, is, partially, a reflection of the physiological processes occurring in the vegetative (growth of the plant and development of new tissues and organs) and reproductive stages (carbohydrate storage and accumulation) of development in preparation for seed development or winter survival. The much larger differences, however, are due to differences in respiration at the various temperatures (Figs. 13.2 and 13.3). This means that alfalfa and other forages produced under lower temperatures will have as much as 10 times more WSC than forages grown at warm temperatures. These carbohydrates are readily digestible when ingested by the animal. Thus, because of the lower WSC concentration, there may be some substance to the accepted idea that hay produced during the hot summer months is of inferior quality for dairy cattle.

B. LIGHT INTENSITY

Intensity of light apparently does not affect digestibility because Garza *et al.* (1965) showed only a slight, but nonsignificant, increase with greater light intensity (40.12 vs 41.45%). The light intensities were 1000 and 4000 foot-candles. CP decreased from 25.9 to 20.0% under the higher light regime. Photoperiod was a constant 12 h each day. Soluble carbohydrates in the plant were greater under the higher light intensity.

C. MOISTURE STRESS

When one thinks of moisture stress, it is usually with the effects of insufficient moisture or drought in mind. However, too much moisture in the soil can be as deleterious to the plant as too little. In fact, when one considers the effect of too much water on plant growth and stand longevity of some perennial forage plants, it is evident that this type of stress is more devastating than is too little moisture. This is especially so with alfalfa. Some other species, such as birdsfoot trefoil, the various clovers, timothy, reed canarygrass, and so on, are more tolerant of excess water than is alfalfa. The effect of excess moisture on forage plants is discussed in a later section.

Researchers have evaluated the effects of drought on forage quality (Vough and Marten, 1971; Wilson and Ng, 1975; Walgenbach *et al.,* 1981; Carter and Sheaffer, 1983b; Wilson, 1983; Halim *et al.* 1989). A higher percentage of leaves, higher IVDMD and lower percentages of ADF and acid detergent lignin (ADL) were reported by Vough and Marten (1971). They, along with many other researchers (Carter and Sheaffer, 1983; Snaydon, 1972; Jensen *et al.,* 1967) have reported that soil moisture status did not, however, affect CP concentration in a consistent manner. In fact, CP varied from 24.2% at 0.2 atmospheres of tension (atm) to 25.5 at 0.6 atm to 23.5 at 2 atm (Vough and Marten, 1971). In a greenhouse study, Walgenbach *et al.* (1981) found that CP concentration of alfalfa leaves increased from 26.6 to 30.6% as soil moisture concentration decreased. The inconsistent response may be due to the fact that dinitrogen fixation varies from study to study (Carter and Sheaffer, 1983). Hsiao (1973) has shown that N accumulates in the tissues of plants that do not fix nitrogen when they are subjected to water stress. Percentage of leaves, however, increased steadily from 48% at 0.2 atm to 62% at 2 atm (Vough and Marten, 1971). Digestibility also increased: 68.6% at 0.2 atm, 73.6% at 0.6 atm, and 77.7% at 2 atm. ADF decreased at the same soil moisture tensions from 30.8 to 25.7 to 21.9%, respectively. Data from Halim *et al.* (1989) indicate that the leaf-stem ratio increased from 0.62 in well-watered alfalfa to 0.72 in the most severely stressed treatment. Carter and Sheaffer (1983) did not find an increase in leaf material. Apparently, as greater moisture stress was applied, growth ceased to an ever-increasing degree, thus stopping the development of fibrous materials. Although evidence indicates that forage digestibility is associated with leafiness, based on Vough and Marten's (1971) growth chamber study, this is apparently not always the case. In this study, the increase in herbage digestibility was due primarily to increased digestibility of the stems (rather than the leaves).

Because moisture can be controlled by judicious irrigation, this data on moisture stress (deficiency) and its affect on forage quality may have some practical significance. First, it is not a tool that one would want to apply to increase the quality of the hay because the amount of DM produced may be affected much more, leaving a net negative return. However, under irrigated conditions in which water supply is limiting in the second or third cutting, this technique should be useful. Water could be applied to obtain rapid vegetative growth early in the growth period and then withheld, not by design but by necessity because of insufficient supply or delivery system (a common occurrence in the arid western United States), as the plant nears the late vegetative stage of development. The harvest should be made before too much damage to the forage has occurred. The resulting hay will be of higher quality (i.e., more digestible) because of less lignification of the stems (Halim *et al.,* 1989).

IX. WHEEL TRAFFIC

A. YIELD LOSSES

With the use of modern harvesting equipment, it has been estimated that from 65 to 75% of a forage stand receives wheel traffic each cutting (Jensen *et al.,* 1982; Sheesley *et al.,* 1974;Grimes *et al.,* 1978). Thus, during the course of a growing season, especially a growing season during which more than two harvests are made each season, it is unlikely that any plants will escape wheel traffic. Many plants may be run over multiple times, particularly near exits to fields.

The damage is done not so much to the crown itself, but to the new crown buds and stems. The more developed the buds or stems are the greater is the potential damage and the reduction in hay yield. A 10-ton bale wagon passing over an area of the field the day after cutting alfalfa can result in an 8 to 10% decline in yield for that area the next harvest (Jensen *et al.,* 1982). If the wagon traverses an area 7 days after cutting, the reduction in yield may be as high as 31%. On the average, wheel traffic resulting from normal harvesting reduces alfalfa yields by 10 to 26% (Meek *et al.,* 1988; Rechel *et al.,* 1991). Compacting all the soil surface results in an average 17% yield loss (Meek *et al.,* 1988). This effect is increased with time. For example, Rechel and coworkers (1991) showed no difference in yield between the uncompacted and the compacted areas in the first year, a 17.8% decrease the second year, and a 19.1% decrease the third year. A single traffic event can have lasting effects. Rechel *et al.* (1991) reported that covering the entire area just once can reduce DM yields as follows: first year, 20%; second year, 16.5%; third year, 14%; fourth year, 0%.

On a new or first-year stand of perennial ryegrass grown on a clay loam soil in Scotland, DM production was reduced 64% by heavy compaction in the spring growth period, 32% during the second growth period, and 12% in the third (Douglas and Crawford, 1991). During the second year of growth, the reductions in yield for the three growth periods were 46, 0, and 30%, respectively. Nitrogen concentration in the forage also decreased with increased compaction from wheel traffic during both years of the study. The most severe compaction treatment, which was comprised of seven passes of a 6-ton tractor over a 21-month period, resulted in an overall loss of 32% DM in this experiment.

Wheel traffic patterns with corn have been shown not to affect yields for a 4-year period (Bicki and Siemens, 1991). This is presumably so, at least in part, because of the annual disturbance of the soil by tillage.

Soils at or near moisture saturation show little or no compaction from wheel traffic, but considerable damage due to shearing within the soil profile results at depth 1.5 to 2 times the width of the wheel (Kirby, 1989).

B. STAND REDUCTION

Wheel traffic in an area with winter freezing and thawing may not experience a reduction in stand density or longevity (Jensen *et al.,* 1982), but an area without the freezing-thawing action, such as the San Joaquin Valley of California, may result in a diminished stand (Sheesley *et al.,* 1974). This may be due to the increased and prolonged effect of soil compaction on root growth, because this was found to be a much more important factor in the San Joaquin Valley (Sheesley *et al.,* 1974) than near Reno, Nevada (Jensen *et al.,* 1982). At the latter site, increased crown rot incidence did not occur due to wheel traffic. Both studies agreed, however, that the effect of wheel traffic was much more pronounced on new stands than on well-established stands of alfalfa. Other studies in California show that in order to minimize the affect on the stand and on hay yields, the tap root should be 35 to 45 cm (14 to 18 in.) in length before the first harvest. Root growth is enhanced by delaying the first harvest (Grimes *et al.*, 1978). Very heavy and repeated wheel traffic always results in a diminished stand, but normal field traffic in the harvesting operation provides variable results (Rechel *et al.*, 1991).

It is likely that less damage would be done on a grass crown than on alfalfa, but new growth would probably be damaged to a similar degree. However, a tractor and slurry tank, commonly used in grassland agriculture of Ireland, exerting a total force on the soil of 139 kN (kilo Newtons), reduces the net harvest yields of grasses (Frost, 1988b), and traffic each year may result in 9% loss with one pass and 13% loss with two passes (Frost, 1988a). Thus, precautions taken with alfalfa are equally important with other perennial forage crops, whether they are grasses or legumes.

Water infiltration rates are decreased to some degree by postplant traffic. Preplant compaction, however, may significantly increase water infiltration rates throughout the life of the stand (Meek *et al.*, 1989). As stands age, plants die and roots decay, providing a path for water infiltration. Therefore, despite traffic treatments, increases of water infiltration rates with age of stand can be expected because of root channels, resulting from root death and decay, which allow the water to bypass the compacted soil.

Generally, root penetration is impeded because of greater bulk densities in the soil (De Roo, 1961). Soil bulk densities in a California alfalfa study (Meek *et al.*, 1988) ranged from 1.6 to 1.7 Mg m^{-3} for nontrafficked soil to 1.8 to 1.9 for trafficked soil. Penetrometer resistance measurements, under alfalfa, are increased significantly by traffic (Rechel *et al.*, 1991), generally approximately 3 to 6%. Fine-root development may be affected as early as the second growing season (Rechel *et al.*, 1990). Normal traffic reduced fine-root development down to a depth of 0.45 m and heavy traffic to 1.8 m. These reductions decreased the plant's ability to exploit the soil for nutrients and water, resulting in lowered yields. Root length density may be reduced by as much as 60% in the 15- to 30-cm zone (Rechel *et al.*, 1991).

X. SUMMARY

One may wonder, "What is the importance to me in my haying operation of all this information? I cannot control the weather." Of course, the person who asks this is correct. Temperature or precipitation patterns cannot be controlled. However, managers can control when hay is harvested by carefully assessing, based on experience, reason, and available data, probability of specific events occurring. Deciding when to harvest should be couched in the following: (1) higher temperatures mean more rapid plant development; (2) development of plants (i.e., moving from one stage of development to another, such as late bud to 1/10-bloom, etc.) usually results in a rapid increase in concentrations of ADF and NDF; (3) digestibility is related to ADF and feed intake is inversely related to NDF; and (4) despite all the things a manager can do, the stage of development at which a harvest is made is the most important criteria in determining forage quality; therefore, one should concentrate on this factor.

To avoid the negative effects of temperature, as expressed in increased ADF and NDF concentrations, one must harvest at an earlier stage than would be practiced under cooler conditions. It must be recognized that higher temperatures speed up development and that the window for harvesting at the optimum stage of development is more narrow. Instead of having 3 to 5 days, as is common in the early or late portions of the growing season, there may be only 1 day on which the optimum DM and forage quality can be obtained.

This Page Intentionally Left Blank

14

FIELD-HARVESTING SILAGE

I. INTRODUCTION

A. DEFINITIONS

Silage has been defined in various ways, but all the definitions have a common element. For example, silage is forage preserved in succulent conditions by partial fermentation in a tight container (Martin *et al.,* 1976). Walton (1983) says that it is feed preserved by acid-producing action of fermentation. Cullison and Lowry (1987) indicate that **silage** is a feed resulting from the storage and fermentation of green or wet crops under anaerobic conditions. This is the definition we will use because it incorporates all important elements from the other definitions. **Haylage** is a silage product made from forage grasses and legumes containing 40 to 60% moisture (Walton, 1983). Elsewhere its definition is given as a product resulting from ensiling forage with about 45% moisture in the absence of oxygen

(Heath *et al.*, 1973). For the purposes of this chapter, haylage is defined as silage made from forage crops—grasses (such as orchardgrass, smooth bromegrass, etc.) or legumes (such as red clover, alfalfa, etc). We do this without placing a moisture content restriction on forage because the making of quality silage requires that the material to be ensiled have a specific range of moisture. This is discussed later in the chapter. **Fodder** is course grasses such as corn, sorghum, and pearl millet harvested whole (with grain intact), cured in the upright position in the field, and used for animal feed.

B. PURPOSE AND VALUE OF SILAGE

Silage is a means of preserving succulent roughage and high-quality feed for later feeding. Its main uses are that it (1) saves surplus forages during a given season that would otherwise be wasted, damaged, or lost because insufficient numbers of livestock are available to utilize standing forage; (2) assures a minimum loss of nutrients in the harvesting and conserving processes; and (3) weather conditions or patterns are sometimes factors that dictate the need for preserving forage and fodder as silage. This means that principles of good management, proper technique, and timeliness must be followed (Takano *et al.*, 1983). Making and preserving fodder as silage is more expensive than preserving it as hay, but a greater portion of the nutrients contained in the fodder can be retained using proper ensiling techniques and procedures (Martin *et al.*, 1976).

II. FACTORS DETERMINING YIELD AND QUALITY

A. TYPE OF FORAGE CROP

Silage is made from many different crops. Any green crop material that can be brought down to the proper moisture range or any organic material that can be brought up to the proper moisture range can be successfully ensiled. One need only to go to the literature to find examples of silage being made from the succulent stems and leaves of many domesticated plants. However, because of their ready availability, quality after ensiling, and yield per unit area, most silages in the United States are made from just a few common crops.

The best silages are made from carbohydrate-rich crops (e.g., crops that have more than two parts of carbohydrate for each part of protein). Corn is nearly ideal for silage because it can provide maximum nutrient value and the largest yield of carotene (McCullough, 1970; Goodrich and Meiske, 1974). Wilkinson *et al.* (1983) show that carbohydrate level is the single most important factor in predicting high-energy silage quality, providing that proper ensiling procedures and protocol are followed.

Crops such as sorghum (all types) also have a high concentration of soluble carbohydrates that are readily fermentable, and they are thus good silage crops (Nevens *et al.,* 1946; Nevens and Kendall, 1954). Both corn and sorghum also contain a low concentration, compared to legumes and forage grasses, of basic elements such as Ca, K, Mg, and so on, so a pH of 4.0 or less required to produce high-quality silage is more readily reached. Annual forage grasses such as sudangrass, sudangrass–sorghum hybrids, sorghum hybrids (all related to grain sorghum, but that grow much taller), or pearl millet (cattail millet) are also commonly used. They all make good silage with relative ease because of the high soluble carbohydrate concentration present in their grain.

Many other crops and some weeds make acceptable silage.[1] Included are legumes such as alfalfa, red clover (Thomas *et al.,* 1985; Lippke, 1990), white clover (Stewart and McCullough, 1985), birdsfoot trefoil, fababean (Murphy *et al.,* 1984; Faulkner, 1985), soybean, mungbean, and cowpea (Baxter *et al.,* 1984; Morris *et al.,* 1988) to name a few. Among the perennial grasses commonly used for silage are orchardgrass, smooth bromegrass, timothy, perennial ryegrass, and so on (Nevens *et al.,* 1946; Thomas and Thomas, 1988; Hammes, 1966; Langston, 1958; Lippke, 1990). Sunflower (Justin and Jackson, 1985; Valdez *et al.,* 1988a,b), small grains (Jaster *et al.,* McClaugherty and Carter, 1960; Read and Jones, 1986; Whitlow, 1987), and millets (VanKeuren and Heineman, 1959) are also commonly used.

The sunflower has the advantage that it is very high in energy because of the oil contained in the seed, and is therefore quite attractive for dairy rations. A successful option is to grow corn and sunflower in the same field — two rows of corn and then two rows of sunflower, repeated throughout the field (Valdez *et al.* 1988a,b). Silage yields from this arrangement have been found to be equal to yields obtained from corn grown by itself. Dairy cow performance on rations containing such silage is equivalent to rations with only corn silage (Valdez *et al.,* 1988a,b; Kellems *et al.,* 1990). The advantage of sunflower-laced silage may be that less high-energy concentrate may be needed. A disadvantage is that field corn and sunflower cultivars that mature or at least dry out at approximately the same time may be difficult to find (Kellems *et al.,* 1990). Care should be taken and this point addressed in determining whether to grow this crop combination. Part of the problem is that the sunflower dries down considerably slower than does the corn. By the time the sunflower stalks have lost sufficient moisture to assure proper ensiling, a large number of seeds will have shattered. These in turn may become a significant weed problem in the next crop. A possible solution to this problem is seeding the sunflowers at an early date and then seeding the corn when the sunflower is 30 to 40 cm

---

[1] The few references provided here are only a very small portion of those available for each crop.

(12–16 in.) tall. The maturity class of the corn could also be extended to assure a better mesh of sunflower and corn maturity. No information is available on this scenario; thus, a producer wishing to try it should spend at least two seasons evaluating the alternatives available.

On occasion, weeds may be used as a silage. Some weeds may provide high-quality silage that is acceptable to certain classes of animals, but others are of very marginal value. Examples of pernicious weedy species being made into silage can be found. Russian thistle (*Salsola iberica* Senen) can have high feed value and has been made into silage on occasions (Cave *et al.,* 1936; Donaldson and Goering, 1940). It should be harvested when the spines start to feel prickly but are still soft. It is equal to alfalfa in protein and fat content and superior in carbohydrate–crude protein (CP) ratio. It also has a high mineral content of 8% potash (K_2O). Kochia (*Kochia scoparia* L.) has also been evaluated for use as silage in a beef cattle ration (Grimson *et al.,* 1989). Substitution of kochia silage, either 35 or 70%, for alfalfa silage resulted in a depression of dry matter (DM) intake of 23.3 and 50.1%, respectively. Average daily gain and final body weight were also less when kochia was fed in the place of alfalfa silage. DM conversion to live-weight gain ratios were 13.91, 8.42, and 7.15 when the diets contained, on a DM basis, 70, 35, or 0% kochia, respectively. In a 42-day period following feeding with kochia, calves gained at a more rapid rate than did calves fed continually on the basal diet. Hinojosa *et al.* (1985) reported similar results when yearling cattle were fed diets containing 50 or 100% kochia hay. Mir *et al.,* (1991) also reported similar results for sheep (e.g., wethers showed a linear decrease in DM intake as the proportion of kochia substituted for alfalfa, in 25% increments, increased from 0 to 75%). Kochia has more problems associated with its use than being a weed (i.e., antihealth factors). This suggests that weeds are usually an expensive source of silage, contrary to first appearances and impressions (Donaldson and Goering, 1940; Hageman *et al.,* 1978,1988; Nelson *et al.,* 1970). Under specific circumstances, however, it may be economical to make silage from these types of plants.

Grain-type crops are superior to late-maturing corn or sorghum silage types because the nutritive value of silage is closely associated with the proportion of the grain it contains (Wilkinson *et al.,* 1983). Late-maturing types may yield more silage (wet weight), but produce less DM per acre (Perry *et al.,* 1968; Perry and Caldwell, 1969). The best silage crops are those that utilize the growing season to full advantage in production of DM but at the same time reach, at least in 3 out of 5 years grown, a stage of maturity described as the *dough stage* (Martin *et al.,* 1976). The ideal growth stage for highest quality silage is physiological maturity. This is the late dough stage for corn and sorghum (also called the *black-layer-formation stage,* which is an indication that DM accumulation has ceased) or the time that corn kernels begin to show the dent (McCulloch, 1978; Goodrich and Meiske, 1974). In corn, this is also called the *glazed stage.*

Total DM yield of the various crops differ because of their morphology. Corn and sorghum, and millet to some degree, are quite tall. All are C_4 plants, which are inherently more efficient than are the C_3 types (Salisbury and Ross, 1992), both with respect to DM production and water use efficiency. This relationship is shown in Table 14.1.

Yield of silage is, among other things, crop dependent. Corn, because of its high biomass production under various environmental conditions and its favorable ratio of grain to vegetative material, is the standard. If silage yields are expressed on the basis of 30% DM, 45 to 90 Mg ha^{-1} (20 to 40 t ac^{-1}) may be expected from adapted hybrids. Even higher yields may be achieved with superior management and optimum growing conditions. Under less favorable conditions, lower yields will be realized (Johnson *et al.,* 1997; Whitesides *et al.,* 1990). Even within a crop, the range in DM yield is considerable among cultivars or hybrids. For example, Vattikonda and Hunter (1983) show that among recommended corn hybrids the range in yield is from 83% to 112% of the trial average. *In vitro* dry matter digestibility (IVDMD) in this same study ranged from 81.5% to 77.2%. Evaluation trials conducted by each state show similar results with respect to each crop grown.

B. STAGE OF DEVELOPMENT

The various crops used for silage each have their own optimum time for harvesting. As a general rule, the stage of development at harvest for silage should be when optimum or maximum DM production has been reached (Wiggins, 1937). The same criteria to determine the proper stage of development are not used for the high-carbohydrate crops (corn, sorghum, small grains, and millets) as for the perennial forage crops (alfalfa, clovers, and grasses).

In Indiana, Caldwell and Perry (1971) showed that maximum silage yield

TABLE 14.1 Relative Dry Matter Production of Various Crop Types[a]

	Photosynthesis pathway	Dry matter (%) of corn[b]	Water use efficiency[c]
Corn silage	C_4	100.0	250–350
Sorghum silage	C_4	91.5	250–350
Hay (all kinds)	C_3	50.8	450–950

[a] Values based on average yields in the United States.

[b] Source: Zelitch, 1971.

[c] Source: Salisbury and Ross, 1992. Units of water used per unit of dry matter produced.

of corn was achieved 143 days after planting. Harvesting 2 weeks earlier or 2 weeks later resulted in 12 and 6% lower yields, respectively. The optimum time to harvest corn and sorghum for silage is at the beginning of the "black-layer-formation" period (Daynard and Duncan, 1969; Rench and Shaw, 1971; Eastin *et al.,* 1973). This is the time that maximum DM accumulation has been achieved in the grain. This relationship held across years and hybrids; thus, this research established that the position of the kernel milk line was a reliable and useful field indicator of when to harvest corn for silage. The recommended range of fodder moisture concentration at harvest required to make high quality silage is 61 to 68% (Jorgensen and Crowley, 1972). Thus, silage should be made from corn when the kernel shows the milk line to be from one-half to one-quarter the distance from the bottom of the kernel (i.e., at 63 to 69% moisture concentration in the fodder).

Rench and Shaw (1971) showed that weight loss by kernels from initial black-layer development to completed black-layer development was significant; thus, harvest should be at the beginning of black-layer formation. They also showed that different hybrids had significantly different moisture concentrations at black-layer formation. Crookston and Kurle (1988) further refined the definition for the best time to harvest corn for silage. They showed that chopping the fodder when the kernels showed one-quarter of the kernel (bottom part) with milky endosperm, whereas the remainder of the kernel was solid and a glazed-yellow color, was a reliable way to determine harvest time. The milk line is quite evident on the kernels as they reach this stage of development. The relationship of fodder moisture content and stage of development is shown in Table 14.2.

The moisture content of chopped corn can be estimated by a squeeze test (Martin *et al.,* 1976, quoting an anonymous source). Squeeze a handful into a ball, hold it for 20 to 30 sec, and then release the grip quickly. The

TABLE 14.2 Relationship of Visible Stages of Kernel Maturity and Corn Fodder Moisture Concentration

Stage	Full-season hybrids (% moisture)	Short-season hybrids (% moisture)
Full dent[a]	73.0	74.0
Half milk	68.5	69.0
One-quarter milk	63.5	65.5
No milk	55.0	61.5

[a] All kernels dented.

Source: Crookston and Kurle, 1988.

TABLE 14.3 Approximate Moisture Content as Indicated by the Squeeze Test

Moisture content (%)	Condition of ball
75+	Holds shape; considerable free juice
70–75	Holds shape; little free juice
60–70	Falls apart; no free juice
<60	Falls apart readily; no free juice

Source: Martin *et al.*, 1976, p. 237; with permission of Macmillan Publishing Company.

condition of the ball at release indicates the approximate moisture content (Table 14.3).

Sorghum matures in a similar manner, and the formation of a black layer also provides an indication that physiological maturity has been reached (Eastin *et al.*, 1973). In the grain type or the forage sorghum types that produce grain, the optimum or maximum production is realized when the grain maturity is between the hard-dough stage and the physiologically mature stage of development (Vanderlip, 1972,1979). This is approximately a 5- to 10-day period for most hybrids.

Silage yields from perennial forage crops such as cool-season legumes and grasses are somewhat lower than yields from corn and sorghum. It is also more difficult to make quality silage from these crops, although it can be done. Estimated silage-yield range for a number of perennial forage crops is shown in Table 14.4.

Stage of development for making silage from perennial forages is not, of course, dependent on formation of seeds or grain because by that time the herbage has declined in feeding value. It is more dependent on when

TABLE 14.4 Silage Yields for Various Perennial Forages

Crop	Mg ha^{-1} (30% DM)	Tons ac^{-1} (30% DM)	Source
Alfalfa	29–74	13–33	Kephart *et al.* (1990)
Red clover	23–53	10–24	McBratney (1984)
Birdsfoot trefoil	16–22	7–10	Kephart *et al.* (1990)
Cicer milkvetch	13–25	6–11	Kephart *et al.* (1990)
Orchardgrass	22–52	10–23	Hammes (1966); Sollenberger *et al.* (1984)
Bromegrass	20–34	9–15	Horrocks and Washko (1968)
Perennial ryegrass	8–39	3.5–17	Sollenberger *et al.* (1984); Davies *et al.* (1985)
Bermudagrass	36–80	16–36	Monson and Burton (1982)

the plant reaches the optimum vegetative DM production and the digestible dry matter (DDM) is at a maximum. This is identical to the optimum stages of development for hay production (see Chapter 13). Because the water concentration in forages can range from 70 to 85% at harvest, they should be cut and wilted to 65% moisture or less. Perennial forages ensiled at greater than 65% moisture result in moderate to excessive seepage losses, depending on the moisture concentration, and poor quality silage (Hoglund, 1964; Shepherd *et al.*,, 1953).

Several excellent general references on growth and development of crops used for silage are available: corn (Hanway, 1963; Hanway and Thompson, 1967; Ritchie and Hanway, 1982), sorghum (Vanderlip, 1972,1979), oat (Reeves and Sraon, 1976), and soybean (Hanway and Thompson, 1967).

C. HARVESTING LOSSES

Field-harvesting losses for hay were discussed in Chapter 13. Major losses in field curing of forages are associated with two factors: inclement weather and drying the forage too much or too long. In making silage, much of the loss can be avoided because of the nature of the major silage crops (corn, sorghum, etc.), which are direct cut. Also, crops commonly grown for hay are only wilted and do not remain in the field, in the curing condition, for extended periods of time when made into silage. Because the two types of silage crops differ considerably in the way they are handled and in the problems encountered, they are discussed independently.

Harvesting losses from corn, sorghum, millet, direct-cut small grains, and so on are mostly associated with spills. Standing material that is too dry, either from dry-down or frost, and subsequent drift loss during the time the silage is being blown from the chopper to the conveyance vehicle is an exception. On windy days, these losses can be substantial. However, assuming that harvesting is done at the proper stage of development, such losses can be minimized, if not eliminated. Field-harvesting losses have been estimated at approximately 4% of the chopped material (Fig. 14.1).

Harvesting losses for forage crops such as alfalfa, clovers, legume–grass mixtures, and grasses can be considerably more. These losses, however, when compared to losses experienced by crops made into hay, are drastically reduced. Work by Hoglund (1964) suggests that the following harvesting losses should be expected: direct-cut silage (moisture concentrations of 70 to 80%), losses range from 4 to 5%; wilted silage (60 to 70% moisture concentration), losses of 5 to 6%; and haylage (40 to 60% moisture concentration), losses of 6 to 12% (Fig. 14.1). British work on grasses shows harvesting losses of 9.5% for silage, whether wilted or unwilted, under ideal conditions (Mayne and Gordon, 1986). DM losses in making hay range from 12 to 35% for alfalfa hay, depending on the process used and the weather encountered (LeClerc, 1939; Martin, *et al.,* 1976; Shepherd *et al.,*

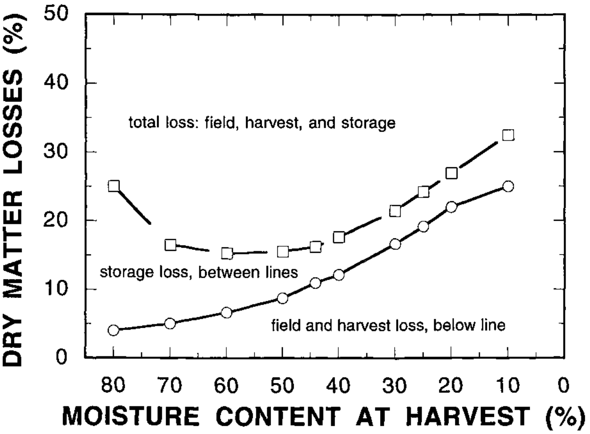


FIGURE 14.1 Estimated total field and harvest loss and storage loss when legume–grass forages are harvested at varying moisture levels and by alternative harvesting methods. (Redrawn from Hoglund, 1964).

1954). These same reports provide reported grass hay losses to range from 12 to 23%.

D. LENGTH OF CHOPPED PARTICLES

To make the best quality silage from forage crops such as alfalfa, clovers, perennial grasses, or annual cereal crops, the length of chop should be within the following range: unwilted material should be 6 to 25 cm (2.5–10 in.) in length and wilted material 6 to 12 cm (2.5–5 in.) in length (Noller, 1973). A fine chop allows proper compaction and exclusion of air pockets, resulting in high-quality silage.

Annual crops such as corn, sorghum, and millet should also be chopped finely, about 1.2 to 2.0 cm (0.5–0.75 in.), so that compaction in the silo can reach about 721 kg m^{-3} (45 lb ft^{-3}) at a depth of 5.2 to 5.5 m (17–18 ft) in an upright silo (Martin *et al.*, 1976). The density ranges from about 320 kg m^{-3} (20 lb ft^{-3}) at 0.9 to 1.5 m (3–5 ft) to as much as 1154 kg m^{-3} (72 lb ft^{-3}) at depths of 15.2 m (50 ft) (Fig. 14.2).

E. MISCELLANEOUS CONSIDERATIONS

In growing corn for silage, other questions come up that must be addressed. For example: What is the effect of low or high planting densities? What about high-oil corn? What about stage of development with respect to occurrence of frost? What about male sterile vs. nonsterile corn?

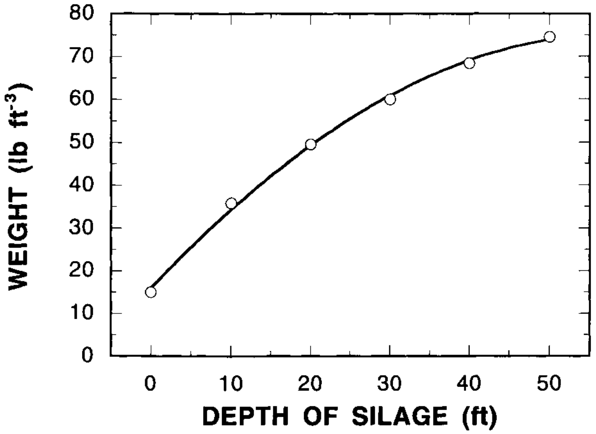


FIGURE 14.2 Weight per cubic foot of silage at different depth. Multiply lb ft^{-3} by 16 to convert to kg m^{-3}. (Redrawn from Martin *et al.,* 1976. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ).

1. Low or Moderate vs. High Planting Densities

Valdez *et al.* (1989) reported in the Pacific Northwest that silage quality was generally quite similar, regardless of planting population (75,000 vs. 150,000 plants ha^{-1}; 30,360 vs. 60,730 plants acre^{-1}) when planted early. However, if planted late, they suggest that it may be advantageous to plant a late-maturing hybrid. This suggestion was based on the fact that dairy cows consuming the late hybrid ingested 11% (27.3 vs. 24.3 kg d^{-1}; 60.2 vs. 53.6 lb d^{-1}) less DM to produce the same amount of 4% fat-corrected milk (35.2 vs. 35.0 kg d^{-1}; approximately 77.4 lb d^{-1}). Under somewhat shorter seasons, Flipot *et al.,* (1984) showed that planting densities of 86,000 vs. 129,000 plants per ha^{-1} resulted in DM yields that were quite similar. The significant effect of increased plant population was to decrease the percentage of the plants that had reached maturity (hard dough or dent) from 91.3 at the low planting density to 66.5 at the higher rate. Also, the ear yield (cob plus grain) was reduced from 4344 to 3053 kg ha^{-1} (3879–2726 lb acre^{-1}) when the planting rate was increased from 86,000 to 129,000 plants ha^{-1} (34,820–56,230 plants acre^{-1}). pH of the silage, which averaged about 3.75, was not influenced by planting density or N fertilizer PM fertilization rate (150 vs. 200 kg ha^{-1}; 134 vs. 179 lb acre^{-1}).

Animal performance, in the study by Flipot *et al.* (1984), was somewhat mixed in that at low N fertilizer rates DM intake increased from 6.21 to 6.52 kg d^{-1} (13.7–14.4 lb d^{-1}) as planting density increased; however, at high N the response was the opposite [e.g., 6.82 vs. 6.05 kg d^{-1} (15.1 vs. 13.3 lb d^{-1})]. When animal gain is considered, the response was similar within each planting density to increased N application. For example, at a low planting rate, gain was 0.47 and 0.62 kg d^{-1} (1.04 and 1.38 lb d^{-1}) as N rate was increased from 150 to 200 kg ha^{-1} (134-179 lb $acre^{-1}$); at the higher planting rate, the increase was from 0.47 to 0.56 kg d^{-1} (1.04–1.13 lb d^{-1}).

In another study, daily gain did not differ, but estimated beef production rose from 1976 to 2651 kg ha^{-1} (1765–2367 lb $acre^{-1}$) as the planting rate was increased from 60,000 to 200,000 kernels ha^{-1} (Nicholson *et al.,* 1986). DM yield was also increased by a significant amount, 28.7%, with greater planting density [9342 vs. 12,045 kg ha^{-1} (8342 vs. 10,756 lb $acre^{-1}$)]. Apparent digestibility of DM (65.5 vs. 62.7%) and digestibility of N (55.1 vs. 52.4%) decreased as planting rate increased. These data indicate that responses to plant population vary considerably from area to area and with agronomic management treatments applied. Undoubtedly the soil fertility enters in here, but definitive data is not available.

2. High-oil Corn

Atwell *et al.* (1988) demonstrated that silage or corn grain from high-oil corn did not provide a significant advantage in performance of lactating cows when compared to silage from conventional corn hybrids.

3. Male-Sterile vs. Regular Hybrids

Analyses of the chemical characteristics of silage from male-sterile vs. regular hybrids (Burgess and Nicholson, 1984) showed that silage made from male-sterile corn hybrids had no advantage over conventional corn hybrids. The generally lower DM yields of the sterile hybrids contributed significantly to their conclusion. When these silages were fed *ad libitum* along with a grain mixture, no differences resulted in animal performance due to silage. Perry and Caldwell (1969) reported that the high-sugar, male-sterile hybrids were higher in DM, CP, and crude fiber (CF). However, digestible energy was similar (64.1 vs. 64.6%, high-sugar and regular hybrids, respectively).

4. Frost

St. Pierre *et al.* (1987) reported an increase in NDF (59.0 to 65.9%) and DM concentration (20.8 to 45.9%) as the corn crop advanced in maturity from the milk stage through the occurrence of five sequential frosts. ADF and acid detergent lignin (ADL) remained fairly constant at about 28 and 2.8%, respectively. Animal performance showed that optimum harvest time was after the second frost because dry matter index (DMI) was maximal at that point, improving greatly the intake of DM.

Narasimhalu *et al.,* (1986) showed that silage made after the forage was frosted results in higher pH (4.3 vs. 3.8) and lower digestibility in all components (i.e., DM, NDF, ADF, DE, and N), lower intake, and lower relative feed value. When prefrost silage is rated as 100, postfrost silage is rated as 84 and 66% in these studies with sheep.

Again, environmental conditions—especially length of season and hardness of frost events—dictate the conclusions drawn. Severe frosts result in very rapid drying and loss of leaves, which may affect silage quantity and quality.

5. Brown-Midrib Maize

Brown midrib-maize (bm_3) refers to a mutant that shows a brown midrib in the leaf. Trials in the United States have shown that incorporating the bm_3 gene into conventional corn hybrids reduces lignin synthesis (Colenbrander *et al.,* 1973). This reduced lignin results in higher digestibility and greater animal performances (Barnes *et al.,* 1971; Rook *et al.,* 1977). Agronomically, it has been shown by Weller *et al.,* (1985) that the bm_3 gene delays silking by 3 days, decreases whole-plant DM concentration by 20 g kg^{-1} (2%), and the proportion of the ear in the total silage by 4 to 6 percentage points. However, comparable yields of DM were obtained from normal and bm_3 crops. The yield of digestible organic matter was 14% greater from the bm_3 hybrids. Lodging potential was presumably increased by the bm_3 gene because stalk strength decreased.

6. Sugary-Brawn2 Maize

In 1984, Brink reported on specific endosperm mutants of maize in which starch is partially replaced by sugars and water-soluble polysaccharides. The question has been raised about using the sugary-brawn2 (*su-Bn2*) maize as an energy additive in alfalfa silage. In Wisconsin, Tracy and Coors (1990) evaluated 20 *su-Bn2* hybrids, all experimental, for total ear yield and other agronomic characteristics. They found that the total ear yield of these hybrids ranged from 7.26 to 9.41 Mg ha^{-1} (3.24–4.20 ton $acre^{-1}$) compared to 7.96 to 9.40 Mg ha^{-1} (3.55–4.19 ton $acre^{-1}$) for the regular starchy hybrids. Silage trials performed by Woolford (1987) showed that alfalfa-*su-Bn2* plus a bacterial inoculant had a lower pH and less acetic acid and ethanol than did alfalfa silage with no additives. Feeding these two silages to 30 lactating cows, which were at the end of their lactating cycle, resulted in no difference in DM intake or milk production. However, body weight gain of the cows fed silage with the *su-Bn2* was significantly greater (0.32 vs. 0.03 kg d^{-1}, or 0.71 vs. 0.07 lb d^{-1}). The conclusion of this research on *su-Bn2* corn hybrids is that under relatively short growing seasons it is possible to use the *su-Bn2* hybrids if the logistics of making the two silages and mixing them can be worked out. The economics of this may be another matter, and must be answered by each potential grower.

III. SUMMARY ON MAKING QUALITY SILAGE

Noller (1973) provides guidelines to making quality silage from perennial grasses and legumes that applies equally well to small grains:

1. Use a crop of high quality.
2. Harvest forage at the proper stage of development.
3. Fine-chop. Length of cut for unwilted material should be 6 to 25 cm (2 1/3 to 10 in.) in length; for wilted material, 6 to 12 cm (2 1/3 to 5 in.) in length.
4. Field-dry to 65% moisture or less to produce either a wilted or low-moisture silage, or use an additive.
5. Use a silo that excludes air and water.
6. Fill the silo rapidly and pack thoroughly.
7. Use a suitable seal to exclude air.
8. Leave silo undisturbed until ready to use the feed.

These guidelines also serve when making silage from energy-rich annual crops such as corn, sorghum, and pearl millet, but the length of chop should be reduced to about 1.2 to 2 cm (0.5–0.75 in.). These crops do not need to be wilted to 65% moisture because they drop below that moisture concentration by the time they are ready to ensile. If, however, they are harvested prior to reaching the proper stage of development (physiological maturity or, roughly, the dough stage), wilting to 65% or less moisture should be practiced to prevent silo losses. Because they are high energy, they do not require an additive containing an energy source.

Stoneberg *et al.* (1968) suggest the following advantages and limitations to using high-energy silage (corn, sorghum, or pearl millet):

Advantages

1. Maximum yields of nutrients are obtained when a crop is harvested as silage.
2. Crops may be harvested for silage at several moisture contents; thus, the silage harvest season may be extended. In addition, silage harvest is earlier than for grain, which further extends the harvest period for a given crop.
3. Silages allow maximum flexibility in the cropping program. Decisions as to the amount of a crop to harvest as silage can be made late in the season. Also, if drought or early frost occurs, much of the value of the crop can be salvaged by harvesting it as silage.
4. Silage harvesting, storing, and feeding are easily mechanized.
5. Silages are highly palatable feeds.
6. Silages may be stored for long periods after they are properly ensiled and protected from spoilage loss.
7. The feeding rations that contain silage may reduce problems such as off-feed and founder.

Limitations

1. Silages do not have a ready market. Thus, once stored, they usually need to be fed on the farm where they were produced.

2. Silage is bulky to store and handle.
3. Storage, handling, transportation, and equipment costs are high in relation to its value.
4. Silage must be fed soon after it is removed from storage to prevent spoilage.
5. Losses may be high if silage is not stored properly.
6. Rates of gain are reduced and amounts of feed used for maintenance are increased when high levels of silage are fed.
7. With beef cattle, the length of feeding time to reach a given grade is increased and dressing percentages are lower than are values for cattle fed high-grain rations.

15

FORAGE-HARVESTING EQUIPMENT

I. INTRODUCTION

One of the many important decisions made by forage and livestock producers is selection of a forage-handling system. The system must be geared to meet needs of the current operation. Just as important, however, is that it must also match future plans. To make this decision intelligently, a number of questions must be asked and the proper information must be obtained in order to analyze each of the alternatives. The number of possible alternatives may be reduced by carefully considering the needs of a particular operation. Two factors are crucial in planning: (1) Will the system provide the proper quality in the stored feeds? (2) Does it match the labor and capital resources available on the ranch or farm?

II. CAPACITY AND COSTS

This section presents data important in making management decisions with respect to the economics of forage-harvesting-handling equipment. Data presented in Tables 15.1 through 15.4 are from Rider (1985). This information is dated in the sense that it expresses values in term of 1985 dollars, but by applying the consumer price index, 1.49[1], which is relative to 1985, the costs can be estimated satisfactorily. The tables include field capacity and corresponding labor requirements, costs to own and operate the machines, and management techniques to maximize performance of each system. It should be noted that capacity values of machinery presented in Tables 15.1 and 15.2 are significantly lower than actual values presented by manufacturers. These data, however, are based on actual field capacity, including time lost in the field in maintenance (routine), repair of minor malfunctions, and shutdown for breaks (lunch, dinner, etc.). Capacity of most operations should be within 25% of the tabular value when field conditions, crop and crop yield, operator skill, and machine condition are considered.

The relative cost of owning and operating a forage-harvesting-handling system can be estimated from the data presented in Tables 15.1 to 15.4. Once a potential system is identified that matches the needs and economic capacity of the operation, the potential cost of ownership and operation should be determined. For example, a large rectangular baler with the capacity to produce 1800-lb bales is not economically feasible or competitive with the traditional rectangular balers unless the amount of hay to be baled annually is in excess of 1000 tons (Table 15.3). An operation in which approximately 200 tons of hay are baled annually shows a cost per ton of owning and operating a traditional rectangular baler of from $8.67 to $9.97 per ton per year, compared with $12.44 per ton per year for a large rectangular baler used to bale 1000 tons.

To determine the potential cost for a forage-harvesting-handling system, estimate the annual tonnage to be handled by the system, list the equipment required, identify the associated cost for owning and operating each machine at that tonnage, and sum to obtain the total cost. The costs for owning and operating silage harvesting and handling equipment is presented in Table 15.4, and a similar procedure should be followed in deciding on the equipment appropriate for a given operation. Additional information helpful in choosing the proper components in a forage handling system is provided in Rider *et al.* (1993) and Roth and Undersander (1995).

---

[1] If 1985 is equal to 1, then 1997 is equal to 1.49, or a 49% increase in the consumer price index during the 1985–1997 period.

TABLE 15.1 Capacity and Labor Requirement for Hay Equipment on Beef Cattle Ranches[a]

	Capacity (tons/hr)[b]	Labor requirement (man-hours/ton)[b]
Bale handlers (SP—3 men)	5.0	0.60
Bale mover (roll)—tractor mounted		
Haul—500 lb	1.0	1.00
Feed—500 lb	1.3	0.77
Haul—800 lb	1.7	0.59
Feed—800 lb	2.0	0.50
Haul—1200 lb	2.5	0.40
Feed—1200 lb	3.0	0.33
Haul—1800 lb	4.2	0.24
Feed—1200 lb	5.0	0.20
Bale mover (roll—1200)—truck towed		
5 mi one-way haul	6.5	0.15
10 mi one-way haul	3.7	0.27
Bale wagon (PTO—83 bale)—automatic	6.9	0.14
Bale wagon (PTO—104 bale)—automatic	8.0	0.13
Bale wagon (SP—160 bale)—automatic	13.7	0.07
Baler (big rectangular—1750 lb)	12.2	0.08
Baler (medium duty)—14″ × 18″	6.4	0.16
Baler (heavy duty) std 14″ × 18″	8.0	0.13
Baler (round—500 lb)	5.0	0.20
Baler (round—800 lb)	5.2	0.19
Baler (round—1200 lb)	7.5	0.13
Baler (round—1800 lb)	9.2	0.11
Feed bales with pickup	1.0	1.00
Hand-haul bales (3 men)	2.7	1.11
Mower (7 ft)	2.9	0.34
Mower–conditioner (PTO—9 1/4 ft)	4.1	0.24
Mower–conditioner (PTO—12 ft)	4.9	0.20
Mower–conditioner (SP—12 ft)	5.3	0.19
Rake (single—9ft)	5.2	0.19
Rake (tandem—18 ft)	10.0	0.10
Stack wagon (loose hay—3 ton)	6.5	0.15
Stack wagon (loose hay—6 ton)	7.5	0.13
Stack mover (loose hay—3 ton)	5.0	0.40
Stack mover (loose hay—6 ton)—farm	10.0	0.10
Stack mover (loose hay—8 ton)—farm	15.0	0.07
Stack mover (loose hay—6 ton)—highway		
5 mi one-way haul	15.0	0.07
10 mi one-way haul	7.0	0.14
25 mi one-way haul	3.3	0.30

(*continues*)

TABLE 15.1 (*continued*)

	Capacity (tons/hr)[b]	Labor requirement (man-hours/ton)[b]
Windrower (SP—14 ft)	6.1	0.16
Windrower (SP—16 ft)	8.5	0.12

[a] Capacities presented are based on typical field operations but may vary by 25% depending on actual field conditions, crop yield and variety, operator skill, machine conditions, etc.

[b] To determine capacity in tonne/hour and labor requirement in man-hours/tonne, multiply by 0.907.

Source: Rider, 1985, p. 323; with permission of Westview Press, Inc.

TABLE 15.2 Capacity and Labor Requirements for Haylage Equipment[a]

	50% Moisture content		Dry hay equivalent	
	Capacity, ton/hr[b]	Labor requirement, man-hours/ton[b]	Capacity, ton/hr[b]	Labor requirement, man-hours/ton[b]
Feed haylage (belt feeder)	6.0	0.17	3.8	0.26
Feed haylage (chuck wagon or mixer-feeder wagon)	12.0	0.08	19.2	0.05
Forage blower	20.0	0.05	12.5	0.08
Forage harvester (PTO—small) w/pickup	7.7	0.13	4.8	0.21
Forage harvester (PTO—medium) w/pickup	10.0	0.10	6.3	0.16
Forage harvester (PTO—large) w/pickup	15.0	0.07	9.4	0.11
Forage harvester (SP) w/pickup	20.0	0.05	12.5	0.08
Haul haylage (w/forage wagon—1 mile)	6.7	0.15	4.2	0.24
Haul haylage (w/forage wagon—5 miles)	16.0	0.06	10.0	0.10
Unload trench silo (w/tractor and front-end loader)	16.0	0.06	10.0	0.10
Unload trench silo (w/tractor-mounted unloader)	12.0	0.08	19.2	0.05

[a] Capacities presented are based on typical field operations. They may vary by 25% depending on actual field conditions, crop yield and variety, operator skill, machine conditions, etc.

[b] To convert to tonnes/hour or man-hours/tonne, multiply by 0.907.

Source: Rider, 1985, p. 324; with permission of Westview Press, Inc.

TABLE 15.3 Total Cost per Ton of Owning and Operating Hay Equipment[a]

			Tons per year[b]					
Machine	Size	New cost ($)	100	200	400	600	800	1000
			Cost per ton[b]					
Bale mover (round)								
Three-point hitch mounted—2 moves	500 lb	500	$21.22[c]	$21.13	$20.98	$20.93	$20.91	$20.89
	800 lb	500	14.23	14.09	14.06	14.04	14.02	14.00
	1,200 lb	500	11.53	11.30	11.24	11.22	11.21	11.20
	1,800 lb	500	8.57	8.30	8.21	8.19	8.18	8.17
Baler (big rectangular)	1,800 lb	65,300	76.77	40.78	22.92	17.04	14.15	12.44
Baler (round)	500 lb	9,600	14.96	9.73	7.17	6.36	6.25	6.13
Baler (round)	800 lb	12,200	17.73	11.07	7.81	6.77	6.43	6.33
Baler (round)	1,200 lb	14,700	19.97	11.90	7.92	6.63	6.00	5.63
Baler (round)	1,800 lb	22,500	28.33	15.96	9.84	7.84	6.86	6.28
Baler (traditional), medium-duty	14″ × 18″	10,500	15.73	9.97	7.14	6.23	5.79	5.78
Baler (traditional), heavy-duty	14″ × 18″	12,400	17.73	8.67	7.56	6.46	5.93	5.62

(continues)

TABLE 15.3 (*continued*)

Machine	Size	New cost ($)	Tons per year[b]					
			100	200	400	600	800	1000
Bale wagon (PTO)	83 bales	12,300	16.13	9.39	6.07	5.00	4.48	4.30
Bale wagon (PTO)	104 bales	20,700	25.25	13.89	8.27	6.45	5.56	5.04
Bale wagon (SP)	160 bales	64,800	73.40	37.67	19.91	14.05	11.17	9.46
Mower–conditioner (PTO)	9 ft	9,700	14.93	9.67	7.11	6.48	6.40	6.33
Mower–conditioner (PTO)	12 ft	13,900	19.04	11.47	7.77	6.59	6.43	6.34
Rake (single)	9 ft	3,500	6.34	4.43	3.50	3.20	3.10	3.10
Rake (tandem)	18 ft	8,200	10.42	5.91	3.68	2.94	2.58	2.37
Stack mover (loose hay)	3 ton	4,500	8.81	6.36	5.16	4.78	4.73	4.69
Stack mover (loose hay)	6 ton	11,500	15.05	8.72	5.59	4.56	4.06	3.76
Stack wagon (loose hay)	3 ton	19,700	25.16	14.37	9.07	7.35	6.52	6.25
Stack wagon (loose hay)	6 ton	31,000	37.87	20.86	12.48	9.75	8.42	7.98
Windrower (SP)	16 ft	45,100	51.97	27.18	14.94	10.94	8.99	7.85

[a] All costs were calculated with the most recent cost data available in 1984–85. New costs were sourced from hay and forage equipment manufacturers. Ownership and operating costs were calculated using techniques from the American Society of Agricultural Engineers Machinery Management Standard.

[b] To convert to tonnes/year and cost/tonne, multiply by 0.907.

[c] If the consumer price index was 1.00 in 1985, then the index for 1997 is 1.49. Multiply these values by 1.49 to obtain today's values.

Source: Adapted from Rider, 1985, p. 326; with permission of Westview Press, Inc.

TABLE 15.4 Total Cost per Ton of Owning and Operating Forage Equipment for Haylage[a]

		Tons per year of dry hay equivalent[b]					
		100	200	400	600	800	1000
		Tons of haylage[b]					
Machine/size	New cost ($)	160	320	640	960	1280	1600
		Cost per ton[b]					
Forage blower	3,900[c]	$ 6.32	$ 4.17	$ 3.10	$ 2.75	$2.58	$2.48
Forage harvester							
Small PTO	13,300	19.71	12.47	8.94	7.81	7.66	7.50
Medium PTO	17,100	24.03	14.67	10.07	8.58	8.18	7.86
Large PTO	30,000	37.80	21.22	13.01	10.33	9.01	8.24

[a] All costs were calculated with the most recent cost data available in 1984–1985. New costs were sourced from hay and forage equipment manufacturers. Ownership and operating costs were calculated using techniques from the American Society of Agricultural Engineers Machinery Management Standard.

[b] To convert to tonnes/year and cost/tonne, multiply by 0.907.

[c] If the consumer-price index was 1.00 in 1985, then the index for 1997 is 1.49. Multiply these values by 1.49 to obtain today's values.

Source: Rider, 1985, p. 327; with permission of Westview Press, Inc.

III. HAY HARVESTING EQUIPMENT

A. MOWERS

Forage crops have been utilized since humans first domesticated animals. Just in the time since the late 1840s, the procedure for harvesting progressed from the labor-intensive age-old process in which a sickle or scythe was used to horse-drawn mowers and, finally, to tractor-powered mowers (Fig. 15.1). During the 20th century, mowers have been the standard, but sales of mowers declined steadily since 1970. The number of units sold in the United States in 1970 was approximately 25,000, and by 1982 that number had declined to about 11,000 units (Pauli *et al.,* 1988). Further declines have probably occurred since 1982, but the number of units sold is not available. These declines in sales of mowers have, partially, resulted from the increased popularity of mower-conditioners.

Tractor-powered mowers may be pull type, mounted via a three-point hitch or mounted on the side. Mower width varies from approximately 2.1 to 2.7 m (7–9 ft). Miller (1960) indicates that the predominant cutter type since the end of the 19th century has been the sickle-bar, but since 1970, rotary-disc types have become increasingly popular. The two types are contrasted in Fig. 15.2.

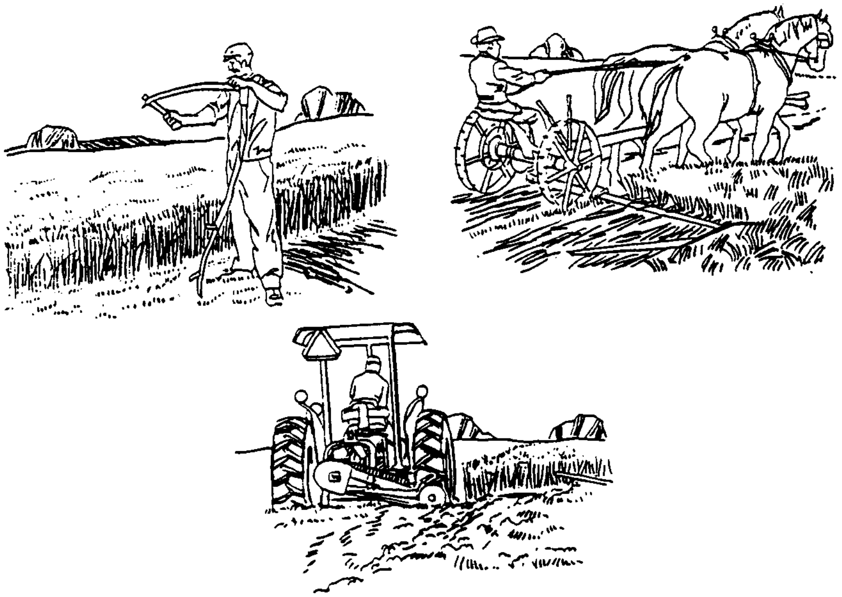
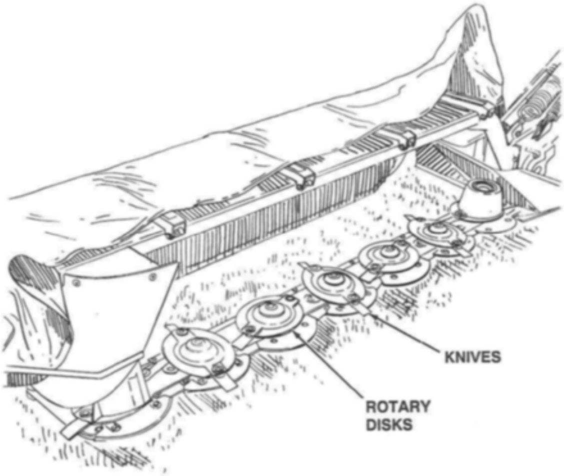


FIGURE 15.1 Changes in hay-mowing methods. (Courtesy of Deere and Company.)

Rotary cutting has been the major means of harvest for grasses in Europe for a number of years. Rotary mowers were introduced in the United States during the 1970s. In 1982, rotary-disc mowers accounted for 40% of all mowers sold in the United States (Pauli *et al.*, 1988). The principle by which these mowers work is a series of rapidly rotating knives. Drum-type (driven from the top through a vertical shaft) or disc-type cutting assemblies (belt driven below the knife mechanism) are available. The initial cost of rotary-cutting mowers is higher than for sickle-bar types. Rotary-type mowers have some advantages, however. More rapid field speeds are possible without plugging and less trouble is encountered with lodged forage, rodent mounds, and uneven terrain. Mower widths are from about 1.8 to 2.7 m (6–9 ft). However, rotary-disc mowers are more expensive to operate on a per unit basis—approximately 16% when 60 hectares (150 acres) are harvested three times per year (Harrigan, 1988)—and losses are greater—5.9% for the rotary-disc mowers vs 3.9% for the cutter-bar types (Koegel *et al.*, 1985b).

FIGURE 15.2 (*Top*) Rotary-disc mower. (Courtesy of AGCO Corporation.) (*Middle*) Drawing showing the stylized arrangement of the rotary discs and knives in a typical rotary-disc mower. Free-swinging reversible knives on each disc are brought in cutting position by centrifugal force. (*Bottom*) Sickle-bar pull-type mower–windrower. (Middle and bottom illustrations are courtesy of Deere and Company.)


HESSTON 1006


KNIVES
ROTARY DISKS

B. RAKES

Leaving the forage in the initial swath for a period after mowing allows for more rapid moisture loss because the hay is not piled so deeply and densely. Raking consolidates the hay into a narrower, more compact row (windrow) in preparation for final drying and baling. Raking of hay has progressed from the early use of horse-drawn dump and side-delivery rakes to tractor-drawn rakes (Fig. 15.3). The most common type rake is the side-delivery rake, either the parallel-bar or wheel type.

Parallel-bar rakes accounted for 80% of rake sales in 1982 (Pauli *et al.*, 1988). This type of rake has a series of parallel bars that form an oblique reel. The teeth attached to the bars move the hay forward and to the center as the reel rotates and the equipment progresses through the field. These rakes are generally ground-driven and they may be used singly or in pairs. An increasingly popular development in these rakes is the hydraulically driven models in which two independent, hydraulic cylinders drive the raking mechanisms. The rakes are driven by hydraulic motors that provide relatively constant raking or reel velocity, and the windrow size can be controlled from the tractor. Windrows may be formed from hay in a 10-m (33 ft) wide swath.

The wheel-type side-delivery rake consists of a series of wheels, each equipped with spring teeth along the circumference. The wheels are posi-

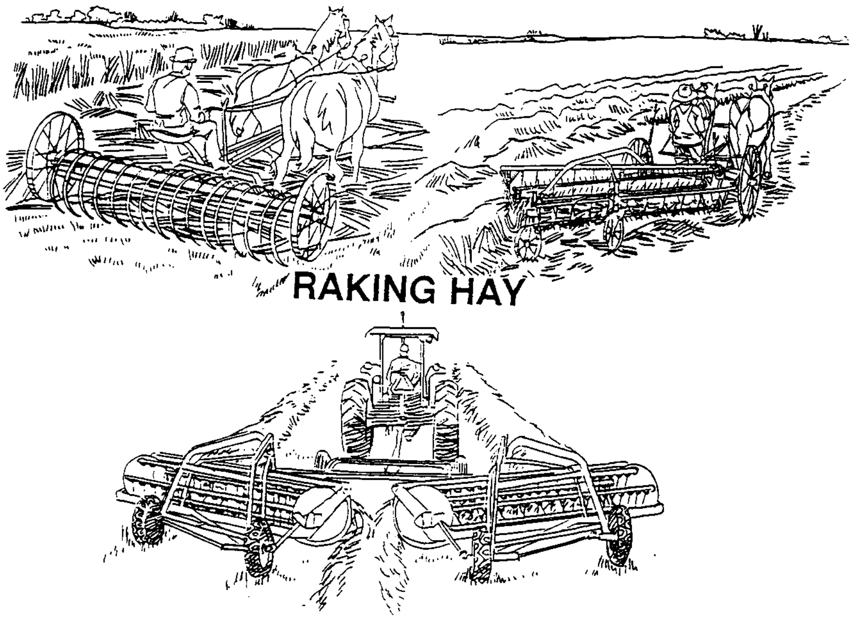


FIGURE 15.3 Changes in hay-raking methods. (Courtesy of Deere and Company.)

tioned along a diagonally oriented frame, with respect to the tractor's axis. The raking wheels are ground-driven and the windrow is deposited behind the last wheel. These wheels are mounted individually and they are thus particularly well adapted to raking over uneven terrain.

C. TEDDERS

Tedders (Fig. 15.4) are in common use in Europe, where the majority of the hay is made from forage grasses such as perennial ryegrass and orchardgrass (cocksfoot). Their purpose is to enhance drying rate and reduce losses due to prolonged exposure to inclement weather. They work effectively in grass hay to reduce the drying time significantly without excessive mechanical losses occuring. They are conducive to increased leaf loss in alfalfa and are thus not recommended for this crop (Rotz and Savoie, 1991). These researchers found that tedding reduced drying time on alfalfa by about 13 h in Michigan in the first cutting and 6 h in later cuttings. However, the mechanical losses, especially of leaves, caused by tedding were greater than the average rain-induced losses avoided by using the process.

FIGURE 15.4 A tedder is commonly used to turn grass–hay windrows to enhance drying. (Courtesy of New Holland North America, Inc.)

D. MOWER–CONDITIONERS AND WINDROWERS

Conditioners were developed in the 1950s to mechanically crimp the stems of the plants to accelerate loss of water. Their use in conjunction with mowers has increased since the late 1960s. The common pull-type mower–conditioner combines the functions of the pull-type mower and pull-type conditioner. Sickle-bar and rotary-cutting types are available. Cutting widths are from about 2.1 to 4.3 m (7–14 ft) for sickle-bar types and 2.1 to 3 m (7–10 ft) for rotary-cutting types.

Self-propelled windrowers were first available in the 1950s, and were especially popular in the irrigated alfalfa production areas of the United States (Fig. 15.5). Their initial cost is high; thus, the tonnage harvested annually required to justify their purchase is large. In the western irrigated areas of the United States, they have been popular because of the large acreages available for cutting, larger fields, and the prevalence of custom harvesting that spreads the initial investment over a larger number of acres. These machines have cabs that are air-conditioned. The cutting widths range from about 3.7 to 4.9 m (12–16 feet). The cutting mechanism is mounted on the front of a platform and the conditioning rolls are at the rear of the same platform. Adjustable deflector shields form the windrow as the hay leaves the conditioning crimping or crushing rolls. Windrow height and width can be manipulated by adjusting the shields.

E. BALERS

Balers have evolved from stationary machines when they were first introduced in the last part of the 19th century to highly mobile machines of today (Fig. 15.6). These first stationary balers produced bales of low density consisting of a series of compressed flakes. Initially, bales were rectangular, of varying lengths and density, but of a size a man could handle. Round balers were later introduced, followed by large rectangular balers. Balers in common use today in the United States form bales that are one of the following types: small rectangular, large rectangular, small round, and large round.

1. Small Rectangular Balers

Since the introduction of the self-tying baler in the 1940s, small rectangular balers have been the most popular type. However, with the introduction of the large-bale packaging systems, sales of balers that produce the small rectangular bales have declined from 30,000 in 1970 to 8000 in 1984 (Pauli

FIGURE 15.5 (*Top*) Tractor-drawn mower–conditioner. (Courtesy of New Holland North America, Inc.) (*Bottom*) Self-propelled windrower. (Courtesy of Case Corporation.)


8840

FIGURE 15.6 Progression of baler technology. (*Top*) An early John Deere Power Press stationary baler. (*Bottom*) A pull-type baler which makes small-rectangular bales. (Courtesy of Deere and Company.)

et al., 1988). Part of the reason for the decline in sales of these balers is associated with the reduced number of small farms.

The most common method of tying is with twine, although wire-tie machines are available and in use. In the 1980s, approximately 95% of the balers used twine (Pauli *et al.,* 1988) and presently that figure is even higher. Common bale sizes are 35 × 45 cm (14–18 in.) cross-section and from 80 to 90 cm (32–35 in.) in length. Another popular size in the western United States is 45 × 55 cm (18–22 in.) cross section and 115 cm (45 in.) long.

These balers are pull-type, which generally gain their operating power from the tractor power take-off (PTO). Some have baler-mounted engine power sources. Baler capacity ranges from 9 to 11 t h^{-1} (10–12 tons h^{-1}). Balers in the eastern United States may average about 91 t (100 tons) per season compared to 545 to 636 t (600–700 tons) in the western United States. Custom operators in the western United States, may bale from 2000 to 3000 t yr^{-1} (2200–3300 tons yr^{-1}).

Large Rectangular Balers

Large rectangular balers (Fig. 15.7) were commercially available in the United States in 1978 (Pauli *et al.,* 1988). The bales are tied with heavy-duty plastic twine and weigh approximately 700 to 900 kg (1540–1980 lb). These balers can produce 18 t h^{-1} (20 tons h^{-1}) and are typically used in

FIGURE 15.7 Large rectangular baler with a bale accumulator. (Courtesy of AGCO Corporation.)

the irrigated west, largely by commercial hay producers. The bales, because of their size and stability, are particularly amendable to transporting long distances. Their large size reduces the rate of moisture loss; thus the moisture content at the time of baling required for storage is lower than for the small rectangular balers. Western United States hay-producing conditions are ideal, because of the low humidity and favorable drying conditions, for use of these types of bales.

3. Small-Round Balers

Small-round balers were particularly popular in the 1950s and 1960s, but they are no longer manufactured. However, there is still demand for and a brisk trade of refurbished machines in the lower Midwest—Missouri, southern Illinois, Kentucky, northern Arkansas, and parts of Oklahoma. They are well adapted to low-labor harvesting, storing, and feeding systems. In areas where winter snow cover is not heavy and does not occur over long periods of time, the small-round bale is left in the field for consumption by the animal during the winter, greatly reducing handling and feeding costs. These savings offset the losses from being left in the field. Grasses baled and handled this way suffer far less spoilage than does alfalfa (see Chapter 16). Their low capacity, difficulty experienced in mechanized handling, and the development of large-round balers have reduced or totally eliminated their use in other areas.

4. Large-Round Balers

Balers that produce large-round bales, first introduced into the United States in the early 1970s, have been extensively adopted, especially in the humid areas of the country (Fig. 15.8). By 1982, approximately 60% of the balers sold in the United States were of this type (Pauli *et al.,* 1988). The cost per ton of hay produced is significantly lower for these large-round balers when compared to large rectangular balers (Table 15.3).

There are two types of large-round balers—fixed-size and variable-size chambers. In fixed-chamber balers, hay is compressed less in the center than toward the outer part of the bale. Variable-chamber balers continuously compress all hay into the bale as it enters the chamber, thus more uniform bale density results. The operator can vary bale size in the fixed-chamber balers.

From the array of large-round balers currently available, bale diameter from 1.2 to 1.8 m (4–6 ft), width of 1.2 to 1.5 m (4–5 ft), and weights of 300 to 900 kg (660–1980 lb) can be made. Bale size thus depends on the baler purchased and the chamber type.

The large-round bales, especially when made of grass hay, tend to shed precipitation better and weather less than the small or large rectangular bales (see Chapter 16).

FIGURE 15.8 Large-round baler. (Courtesy of Case Corporation.)

IV. BALE-HANDLING EQUIPMENT

Moving hay from the field to the storage area has always been a physically demanding, labor-intensive, and costly operation. Each package, whether it is loose piled hay cocks or small bales, either rectangular or round, requires individual handling two or three times during this operation—loading onto conveyance vehicle, unloading from conveyance vehicle, and placing in the stack, storage shed, or barn. The process, even with the advances in development of mechanical, labor-saving devices, still is often a labor-intensive process. During the 20th century, mechanization of hay-handling equipment, however, has taken tremendous strides that reduce the labor requirements of handling hay significantly (Harrington, 1997; Baumheckel and Borghoff, 1997; Rider *et al.,* 1993).

Bale ejectors, which toss the small rectangular bales directly from the baler into a trailing wagon can eliminate the hay-loading crew. If the bale is dropped in the field, three kinds of bale loaders are generally available to farms where small rectangular bales are used. The first is a bale loader that attaches to the conveyance vehicle, usually a truck; the second is a tractor front-end fork loader, which will handle multiple small rectangular bales, depending of their individual size; and the third is a self-propelled bale wagon (Fig. 15.9). Various means of handling and stacking large rectangular bales are available. One method consists of a bale wagon that picks up the bales in the field, then transports them to a designated area for stacking and storage (Fig. 15.9).

Large-round bale loaders usually consist of a three-point hitch unit on the back of the tractor or a front-end loader. These units usually consist of two or three tines that penetrate the bale. Large round bale movers may consist of a truck-mounted unit, a tractor-towed unit, or a truck-towed multibale mover.

V. SILAGE–FORAGE HARVESTERS

Different types of heads are required on silage-forage harvesters to harvest various crops for silage. For example, row crops such as corn and sorghum require a corn head. Direct cutting of the solid-seeded forages such as alfalfa, clovers, and grasses requires a head that removes a solid swath of forage. A windrow-pickup head is used to chop wilted alfalfa, clovers, or grasses to make silage (Fig. 15.10).

Forage harvesters have either precision-cut or flail-type cutting devices. The machines are also either pull-type or self-propelled. The type and size of farm operation dictates the most suitable type. Generally, the pull-type harvester, because of a lower investment requirement and need for lesser capacity, is used on smaller farms. The largest pull-type machines have the same capacity as the self-propelled harvesters. Dehydrators, custom operators, and the larger dairy farmers generally use the self-propelled harvesters because they provide greater tonnage capacity, and the larger number of hectares to be harvested make them economically competitive.

The precision-cut machines have various numbers of knives on a rotating cutterhead. These knives revolve against a fixed shear head; thus, chopping the forage into various lengths, depending on the width of the gap between the end of the knives and the fixed shear head. The length can be regulated by the operator to match the particular forage. The flail-type cutter accomplishes the cutting or chopping of the forage by slinging knives attached to a revolving shaft. The knives are set to miss the shear plate and provide the desired length in the chopped material. This type of harvester is most commonly used in direct-cutting of forages, either grasses or legumes, in which the length of cut is of lesser importance.

VI. FORAGE WAGONS

Associated with silage harvesters are trucks or wagons to transport the freshly chopped material from the field to the storage area. As the forage is chopped, it is blown into a forage wagon, which is often called a *bunk-*

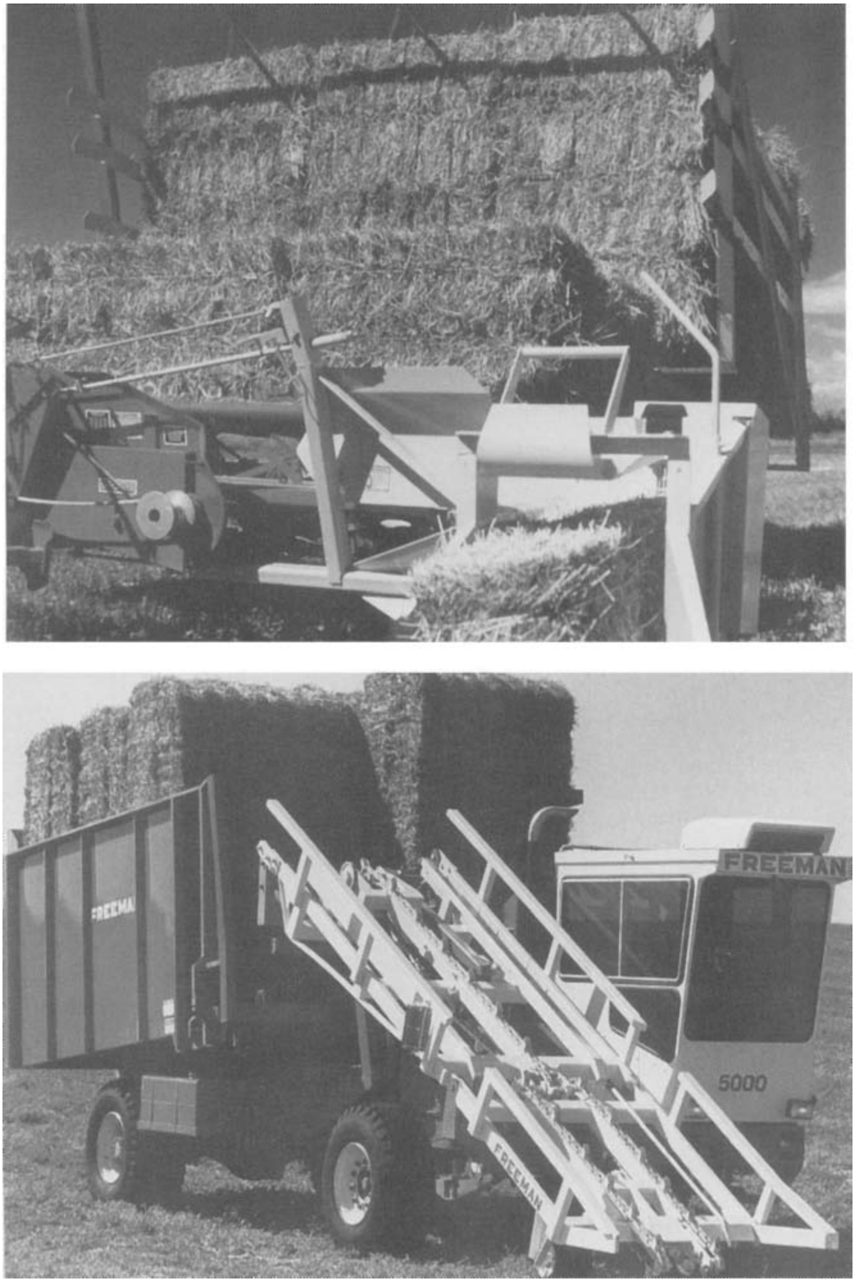


FIGURE 15.9 (*Top*) Bale wagon for handling small rectangular bales. (Courtesy of New Holland North America, Inc.) (*Bottom*) Bale wagon for handling large rectangular bales. (Courtesy of J. A. Freeman & Son, Inc.)

FIGURE 15.10 Forage choppers have contrasting heads, depending on the type of forage to be chopped. (*Top left*) Direct-chop head. (*Top right*) Swath pickup head. (*Bottom*) Corn head. (Courtesy of New Holland North America, Inc.)

feeder wagon (Fig. 15.11) or a *high-dump wagon* (Fig. 15.12). According to Rider *et al.* (1993), high-dump wagons offer two main advantages: (1) the number of transport vehicles is reduced because the silage transfer into higher-speed vehicles (trucks) for road transport; and (2) the transfer can be done at the edge of a field when soil conditions are such that the transport trucks cannot enter the field.

Depending on the type of storage system used, further equipment for unloading, placing, and packing the material is required. The simplest sys-

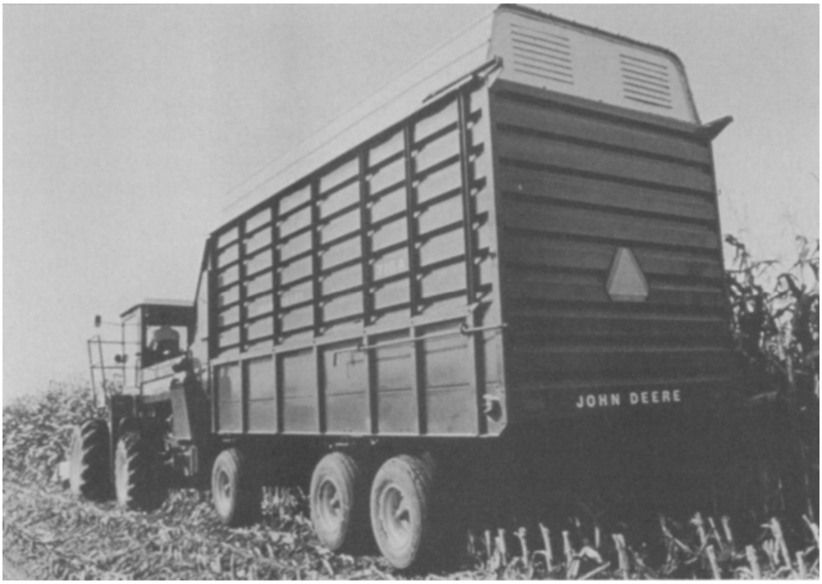


FIGURE 15.11 Forage wagons are used to transport freshly chopped forage from the field to the silo. (Courtesy of Deere and Company.)

FIGURE 15.12 High-dump wagon. (Courtesy of Deere and Company.)

FIGURE 15.13 Bagging unit for placing silage in long plastic bags. (Photo taken by author.)

tem is the pit or bunker silo, which requires some kind of dumping device on the transport vehicle and a means of spreading and compacting the silage once it is in the silo. A tractor with a blade attached to the rear or a front-end load attachment can be used both for spreading and compacting the silage in these types of storage systems. Tower silos require conveyer units to move the silage from the unloading hopper into the silo. Storing the silage in long, loaf-like white plastic bags (horizontal storage) requires special unloading and bagging units (Fig. 15.13). This type of system is quite expensive because of the cost of the bagger, but it almost eliminates storage losses. Park and Wallentine (1986) showed that storage losses were reduced to approximately 3%. Depending on the amount of the initial investment to purchase the system, approximately 200 acres of alfalfa, corn, sorghum, or a combination of these crops, to be chopped for forage, was needed to make this system economical in a dairy operation.

16

PROCESSING AND STORING HAY

I. INTRODUCTION

Storage facilities are an important part of a successful hay-handling system, especially in humid areas. In these areas, large, multipurpose barns in which animals could be sheltered and hay could be stored were built. At first the hay was stored in a loose form, but with the invention of balers, baled hay replaced almost all other types. Barns and sheds are still an important component of the humid-area farmstead.

Producers living in humid areas are faced with a particularly difficult challenge when it comes to curing and storing hay without suffering excessive weather damage. Table 16.1 identifies the major problems encountered by these producers. Hay must be dried to less than 30% moisture before it can be placed in a barn. The time required for hay to reach that moisture content in the field ranges from 48 h to as much as 2 weeks (Raymond *et al.*, 1986). The probability of receiving significant amounts of precipitation during that extended drying period is rather high.

In the semiarid and arid regions, building such elaborate storage facilities never caught on, mostly because the need was not so apparent. In these areas, stacks of loose hay were shaped so that water would run off. The

TABLE 16.1 Moisture Content at Which Hay Can Be Removed from the Field

Treatment	Moisture content limits (%)	Swath exposure time (hours)
Barn hay-drying, using some heated air	45–60	8–72
Baled, chopped, or loose hay dried in a barn or tunnel without supplementary heat	35–40	24–96
Storage conditioning of baled or chopped hay	30–35	48–130
Hay treated with a chemical additive, e.g., propionic acid	25–35	48–120
Baling followed by field conditions and barn storage	20–30	48 up to 2 weeks or more

Source: Raymond *et al.,* 1986, p. 23; with permission of Farm Press, Ltd.

advent of baled hay brought the recognition that considerable spoilage occurred as moisture seeped down through the stack along the lines between bales. Two solutions were implemented: (1) building of storage sheds or (2) use of a tarpaulin to cover the upper surface of the stack. In semiarid and arid areas, however, it is common to see uncovered stacks of hay. The questions remain those of economics, failure to recognize the extent of storage losses, and a lingering of the attitude that hay is not a crop of economic consequence.

II. STORAGE LOSSES

To appreciate the utility and economics of hay storage structures, it is important to understand the extent of loss with use of various types of storage facilities. The general range of storage loss for baled hay is given as 2 to 4% (Martin *et al.,* 1976). Hay stored outside in loaf stacks can lose greater than 12% of the dry matter (DM) in the first 7 months of storage and more than 29% after 29 months (Mader *et al.,* 1990). Hay baled at 10 to 15% moisture showed a 2.2% DM loss, whereas hay baled at 40 to 50% moisture lost 18.5% DM over the first 30 days of storage (after baling). Hay stored inside loses approximately one unit of DM for each unit of moisture lost (Lechtenberg and Petritz, 1982). This loss is not related to weathering, but instead to respiration (metabolic activity) going on in the hay during the drying process. Thus, hay baled at 20% would likely lose 7 to 8% of its DM as it dries to its final weight. Hay baled at greater than 20% will be subject to accelerated metabolic loss as well as spoilage from excessive microbial activity and heat damage. Hay that is too wet when

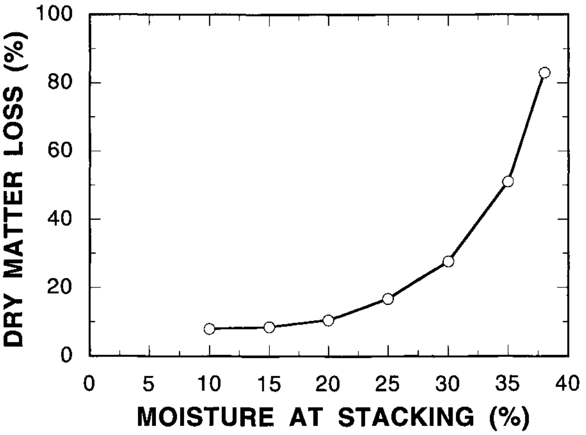


FIGURE 16.1 Dry matter loss due to spoilage in alfalfa stacks made at different moisture levels. (Redrawn from Drew *et al.*, 1974.)

stored, or that becomes too wet because of exposure to the elements, loses as much as 60% of its DM (Fig. 16.1; Drew *et al.*, 1974; Swanson, 1919). Generation of heat is most strongly correlated with baling moisture and bale density (Fig. 16.2), and has the potential to become an extreme fire hazard through spontaneous combustion (Browne, 1928; Roethe, 1937).

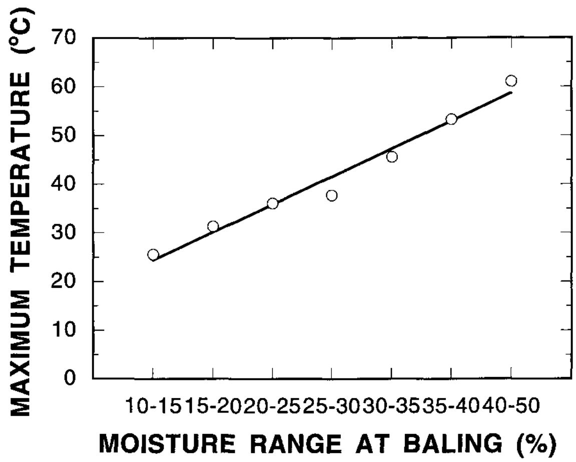


FIGURE 16.2 Relationship of bale temperature after storage and moisture content at time of baling. (Redrawn from Buckmaster *et al.*, 1989.)

III. HAY STORAGE FACILITIES

A. OUTSIDE STORAGE

Outside storage is initially the least expensive, and thus it is often used by default, especially in arid areas. Storage for any length of time in open stacks results in significant DM and quality losses, regardless of whether the hay is in loose or baled form. These losses in DM and quality can become significant over extended storage periods of 6 to 18 months. DM loss (shrinkage) of stacked hay (small, bread-loaf shaped stacks) during storage can result is as much as 15% when stored in the open for a period of 6 to 7 months (Johnson *et al.,* 1984). In this Minnesota study, small round bales stored in the open lost only 2.4% and large round bales showed a shrinkage percentage of 1.6% over a 6- to 8-month period. Thus, it is evident that round bales have an advantage over square bales in reducing outside storage losses. It also holds that grass hay is less susceptible to loss from weather than is legume hay, regardless of the type of bale system used. If round bales are placed on a gravel-based storage area, the weathering losses are reduced even further. In areas with less severe winters, such as the lower midwest in the United States, this storage method is commonly practiced.

If the precipitation to which the stack is exposed is significant, either as snow or rain, the loss in DM may be significantly higher. A measure of the loss that can be expected in stack-storage by hay that is exposed to significant precipitation can be gained by looking at the work of Collins (1983a). Mown alfalfa hay exposed to various amounts of precipitation in the drying process lost as much as 53% of its DM. Others have reported similar losses. *In vitro* digestibile dry matter (IVDMD) may be reduced 48 to 61%. The soluble carbohydrates, the primary energy component, of hay exposed to repeated wetting and drying is reduced significantly, and is the primary loss measured as storage shrinkage. Respiration and leaching represent losses mainly of the water soluble carbohydrate (WSC) fraction of the forage material (McGechan, 1988).

B. COVERED STORAGE

Covered storage has costs associated with it that the open-stacking system does not experience. The range of costs depends of the type of storage. Tarpaulin and plastic-wrapped bales (used commonly with the large round bale systems) are the least expensive and sheds and barns are the most expensive. In order to justify these systems, one must determine whether the cost can be recouped in the prevention of losses. A hay producer who sells most of his or her hay immediately after baling would not find the use of these protection systems beneficial. However, a grower who feeds hay, especially in the humid areas, should consider their costs and benefits.

1. Tarpaulins and Plastic Coverings

Tarpaulins, commonly called *tarps,* are a convenient way to protect hay from the weather. They are quite inexpensive, but in areas where wind is a problem, keeping the tarps anchored and in the proper position can become a serious problem. Loose ends may result in complete destruction of the covering. If a sturdy tarp is used and it is kept in place, the losses from weathering caused by precipitation and exposure to the sun can be reduced to a minimum.

Losses of alfalfa DM have been reported at 9, 40, and 30%, respectively, for hay stored inside, outside, and partially protected with plastic covering (Atwal *et al.,* 1984). In this same study, digestible dry matter (DDM) for each of the storage conditions was 50.0, 32.3, and 36.2%, respectively, and protein values were 8.38, 6.12, and 6.68%, respectively. Brasche and Russell (1988) showed that large round bales, uncovered and covered, stored outside differed in DM recovery by greater than 10% (78.5 vs 89.1%). Alfalfa hay harvested in large round bales and then stored in various manners were evaluated in Missouri (Belyea *et al.,* 1985). Large bales were stored in a barn, outside in single rows and uncovered, outside in two-high stacks and covered, and outside in three-high stacks and covered. DM storage losses were 2% for inside storage, 6% for covered outside storage, and 15% for outside uncovered storage. Rain penetration in the uncovered bales was from 10 to 25 cm, resulting in about 40% loss of the original bale dry weight in the weathered area.

Plastic coverings are less durable and are more susceptible to winds, but when anchored properly good temporary protection from the elements can be obtained from its use. Baling the forage at a higher moisture content, 35 to 60%, and placing the bales in large, heavy-duty plastic bags, which treats the forage as silage, results in high-quality silage that can be fed in an on-farm operation. This method almost entirely eliminates storage loss. Specialized equipment, which is available from forage equipment dealers and can be found advertised in forage production magazines, is required to "stuff" the bales into large plastic bags.

2. Wrapped Bales

Because losses in unprotected stored hay are usually excessive, a more economical and convenient means of protection was needed. Northern Europeans pioneered the use of plastic wrapping for protection of baled hay (Borcherding and Wanner, 1992). The large round bales, in particular, have been particularly well suited to this technology. Wrapping has been shown to result in comparable quality and DM recovery to hay stored inside.

Considerable research has shown that significantly less storage loss results when large round bales are stored outside after being baled with plastic (9.6% loss) compared with net binding (16.3%) and twine binding (16.5%) (Harrigan and Rotz, 1994). Wrapping round bales of fescue (*Festuca arundinaceae* Schreb.) with two layers of mesh or solid self-adhesive plastic wrap resulted in DM losses after 1 year of storage of 10.6% for the double mesh–wrapped bales and 3.6% for the solid-plastic–wrapped bales. Inside storage resulted in DM losses of 5.7%. Twine-tied, outside-stored bales lost 18.2% DM (Collins *et al.*, 1995). Weathered hay from twine-tied and mesh-wrapped bales fell approximately 20 percentage units in IVDMD during storage.

3. Hay Sheds

Because successful hay storage is largely a matter of protecting it from precipitation, buildings do not need to contain any particular environmental controls. Because only a roof is required to keep precipitation off the hay, several types of construction are adaptable. Two constraints are imposed on the system. First, the structure must be large enough to hold the projected amount of hay, and second, protected hay must be accessible to hay-handling equipment. Therefore, pole-frame and metal-frame buildings with at least one side open are the most popular types. The roof often represents the major cost in these buildings; the sidewalls are often 16 to 22 ft high (Phillips, 1981). Buildings of this type are frequently susceptible to damage from strong winds; thus, in areas with excessive amounts of wind, particular attention to wind direction, extra wind bracing, and tie down of both rafters and poles or metal frames may be required.

Storage capacity of these types of buildings depends largely upon the volume within the shelter. Table 16.2 provides information on storage for buildings of various size.

TABLE 16.2 Baled Hay Storage Capacity in Tons per Foot of Length for Several Sizes of Buildings

	Sidewall height (ft)					
Building width (ft)	12	14	16	18	20	22
24	1.1	1.3	1.5	1.7	1.9	2.1
28	1.3	1.5	1.7	2.0	2.2	2.4
30	1.4	1.6	1.9	2.1	2.4	2.6
36	1.7	2.0	2.3	2.5	2.8	3.1
40	1.9	2.2	2.5	2.8	3.2	3.5
48	2.3	2.6	3.1	3.4	3.8	4.2
60	2.8	3.3	3.9	4.3	4.8	5.2

Source: Phillips, 1981.

Shed storage of small or large round bales can present structural challenges that, if ignored, may result in collapse of the structure. An economical way to protect against sidewall pressure imposed by round bales is to install retainer posts at each end of each row of bales. These posts should be at least 5 in. in diameter and be set at least 3 ft in the ground (Phillips, 1981). Square bales do not require such considerations because they do not place pressure on the sidewalls when stacked properly. Randomly stored small square bales may present the same hazard. Another way to avoid this sidewall pressure is to stack the large round bales on end. Lechtenberg and Petritz (1982) questioned whether a grower could afford to store large round bales inside. Losses from outside storage must generally exceed 15% before pole barn storage will pay for itself.

Buckmaster (1993) has shown that some advantage is usually gained from storage protection for large round bales, stacked three bales high, if the hay is valued at more than \$61 t^{-1} (\$55 ton^{-1}) and experiences at least 15% loss during outside storage. The breakeven barn costs for hay valued at \$83 t^{-1} (\$75 ton^{-1}) was about \$26.90 m^{-2} (\$2.50 sq ft^{-1}) of floor surface if 10% outside storage loss is experienced, \$75.25 m^{-2} (\$7.00 sq ft^{-1}) at 15% loss, \$126.63 m^{-2} (\$11.50 sq ft^{-1}) at 20% loss, and \$161.25 m^{-2} (\$15.00 sq ft^{-1}) at 25% loss (Fig. 16.3).

Plans for hay storage barns are available from various sources. One readily available source is from the Midwest Plan Service (Bell, 1984). Costs for such buildings must be estimated by determining the supplies needed and then pricing them at a local building supply store. Labor for construction would be an additional cost. Economic considerations dictate

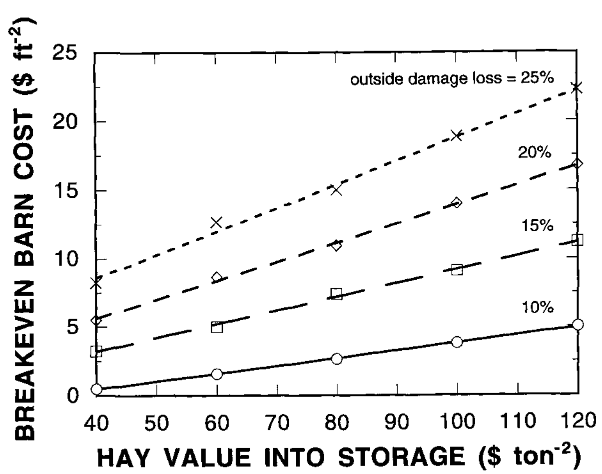


FIGURE 16.3 Breakeven barn cost for various levels of storage loss and varying hay value at harvest. (Redrawn from Buckmaster, 1993.)

that the hay preserved in hay storage units, that would be lost in outside storage, must be valued at more than the annual cost of ownership. Lechtenberg and Petritz (1982) calculated that losses in excess of 15% above usual storage losses must be valued at least $15 to $16 per ton of stored hay to justify building a pole storage barn if bales are stacked at a density of 1 ton per 30 ft^2 of storage space.

In the western United States, where much hay is grown for sale, it is common for hay buyers to refuse to accept the top weather-damaged tier of bales. With small square bales, the second layer, or even the third, may also be refused by buyers. This means that with small square bales, approximately 11 to 15% of the bales in the top layer may be rejected (Willett, 1983). If damage is substantial because of extraordinarily wet conditions, up to 34% of the bales in the stack may be rejected (first three tiers).

The premium paid by buyers for hay stored under cover varies from season to season. The amount of premium hay available, weather conditions, and demand are all determining factors in the price paid. It is common for hay stored under cover to sell for a premium of $10 to $40 per ton. If hay is covered, it will usually bring a better price in years when there is a surplus of hay, because the producer can hold it until the price is more in his favor.

In a profitable business with taxable income, tax benefits will be realized from the following: (1) deductions of depreciation, (2) interest on the debt, (3) insurance premiums, (4) property taxes, and (5) investment tax credits (Willett, 1983). For a storage shed costing $20,000 to $50,000, the savings from these tax advantages can be substantial.

A hay producer should ask the following questions: (1) Will a hay shed be profitable? (2) Will the cash flow handle the payments? (3) Will my operation handle the risk? (4) What are the benefits of hay storage? (5) What will be the reduction of spoilage and loss? (6) What are the summer/fall price premiums for covered hay? (7) What are the winter price premiums for covered hay? (8) What are the tax benefits? (9) What are the fixed costs—depreciation, interest on investment, taxes, insurance? (10) What are the variable costs—repairs, hay insurance, shrinkage during storage, high stacking of bales, interest on hay held? (11) What are the alternatives to building a hay shed—covering with straw bales, tarps, plastic covering? To evaluate the cost and benefits of this type of storage, the reader is referred to the work of Willett (1983) as an example. He provides a discussion of annual fixed costs, including depreciation, interest, repairs, taxes, and insurance; and the annual variable costs, including high stacking of bales, hay insurance, shrinkage, and interest on the hay investment. In addition, two examples are provided, along with worksheets, to help a grower evaluate the pros and cons of providing this type of covered storage. Spreadsheets to aid in this evaluation are available from extension specialists in some states; thus, growers should contact the local county extension office.

According to Willett (1983), there are three potential advantages to storing hay under shelter: (1) less spoilage during the fall and winter months (see previous discussion), (2) receipt of a premium price during the storage period, and (3) tax advantages.

4. Barns

Because of the high cost of such structures, few barns are built strictly for the purpose of storing hay. Protection of animals in areas where winters are severe is a primary reason for constructing such units. Hay storage is an auxiliary function.

C. OTHER MEANS OF PRESERVATION

Ammonia has been used as a preservative in storing high-moisture hay (Weiss *et al.,* 1982) and as an enhancer of quality for straw (Horton and Stacey, 1979). When high-moisture alfalfa hay was treated with anhydrous ammonia (used to prevent the formation of mold) and used as a feed for dairy cattle (Weiss *et al.,* 1982), animal performance was similar to lower-moisture untreated hay. Koegel *et al.,* (1985a) reported that alfalfa baled at 18 to 28% moisture, treated with ammonia, and stored uncovered and outside could be readily preserved. At greater than 28% moisture, they found that the hay was discolored, often caramelized, and musty. Approximately 1.1 to 2.5% NH_3 by weight was required to attain the desired effect.

Liquid materials have been developed and sold with the idea that they will, when sprayed on the outer surface of the hay bale, protect the hay from the elements. Such a system of spray-on coating, called Nutri-Shield, was evaluated by Huhnke *et al.,* (1992). They compared its effectiveness in reducing losses from hay stored outside. Bales were stored on pallets and exposed to three levels of precipitation from both artificial and natural rainfall. After 5 months of storage, no difference was evident in DM, moisture content, or quality of bales treated with Nutri-Shield and those left untreated.

This Page Intentionally Left Blank

17

Processing and Storing Silage

I. INTRODUCTION

The modern practice of ensiling green forages can be traced directly to the process of making "sour hay" in Germany in the 19th century. The green grasses, clovers, and vetches were stored in pits, salted at the rate of 1 kg of salt per 100 kg (1 lb per 100 lb) of freshly cut forage, thoroughly trampled, and covered. Maize was ensiled in Germany in 1865 (Carrier, 1920). The first American attempt to make silage was in Maryland in 1876, and subsequently the use of ensiling as a means of conserving forages spread to all part of the country (Carrier, 1920; Martin *et al.*, 1976).

II. SILAGE STORAGE STRUCTURES

Silage is stored in a structure called a **silo,** which is a semi-airtight to airtight structure designed for use in the production and storage of silage (Cullison and Lowry, 1987). Martin *et al.* (1976) indicated that it is a tight-walled structure for making and preserving silage. Other pertinent definitions of terms used in discussing silage are found in Chapter 14 and in the Glossary. The types of silos vary considerably.

The type of structure may be what is generally called *horizontal* or *upright storage.* In the first category is the pit or surface bunker, covered silage piles, and bagged storage. In the second category is the tower silo (McCalmont 1939, 1960). The more airtight the system is, the better will be the quality of the silage formed. Also, the more rapidly the silo is filled and covered to reduce oxygen in the system, the higher will be the quality and the lower will be the losses (Takano, 1983).

A. PIT AND BUNKER SILOS

The most simple storage structures are pit or bunker silos (Fig. 17.1). The pit, also called a *trench silo,* is dug into the ground, usually on a gently sloping hillside with the open end facing toward the down slope to provide for easy access in filling the silo and removing the silage for feeding. This arrangement also provides good drainage. A bunker silo is quite similar, except it is above ground and the side and end walls are made of concrete or wood.

The size of pit and bunker silos can vary according to need, but they are typically from 6 to 18 m (20–60 ft) wide and 12 to 60 m (40–200 ft) long. The storage capacities of such silos range from 36 to 1450 t (40–1600 tons) of dry matter (Roth and Undersander, 1995). These silos are filled, via wagon or truck from the field, through the open end. To reduce respiration losses, it is important that these silos are filled quickly and that proper packing techniques and procedures are practiced. At the end of the filling process, the silage must be covered and sealed to avoid further respiration loss of dry matter (DM) during storage. DM losses during storage are usually in the range of 12 to 16%. Silo size has a significant influence on DM loss, ranging from about 16% in a 91-tonne–DM capacity silo (100-ton) to 11.5% in a 455-tonne (500-ton) unit (Roth and Undersander, 1995).

After opening the silo for feeding, DM losses due to wastage and spoilage can be reduced if a smooth face is maintained and material to be fed each day is sheared from the entire face in a downward, rather than an upward,

FIGURE 17.1 Bunker (shown) or pit silos are effective in storing large amounts of silage. Their drawback is that they require greater care in filling and packing to assure quality silage. (Photo taken by author.)

motion, with a front-end loader. Removing silage in this manner at the rate of 10 to 15 cm (4–6 in) each day from the whole exposed face reduces losses. To accomplish this, the size of the silo must be matched to the size of the herd. An example of how to calculate this is found in the publication authored by Roth and Undersander (1995). Silage that is exposed to the elements for 4 days, after the silo is opened for feeding, suffers reduced feeding value because of fungus and yeast growth. Feeding such silage to dairy cattle results in up to 38% reduction in DM intake (Roth and Undersander, 1995).

B. TOWER SILOS

Tower silos are circular and are vertically upright (Fig. 17.2). They range in size from 4.9 to 9.1 m (16–30 ft) in diameter and 15.2 to 24.4 m (50–80 ft) in height and their capacity may range from approximately 77 to 468 t (85–515 tons). Tower silos are of the following types: oxygen limiting, constructed of metal, concrete staves, or poured concrete; those silos that are not oxygen limiting or may also be constructed of concrete staves or poured concrete (Ishler *et al.,* 1991). The exclusion of oxygen from the upright silos makes them superior to the pit and bunker types because DM losses are reduced considerably.

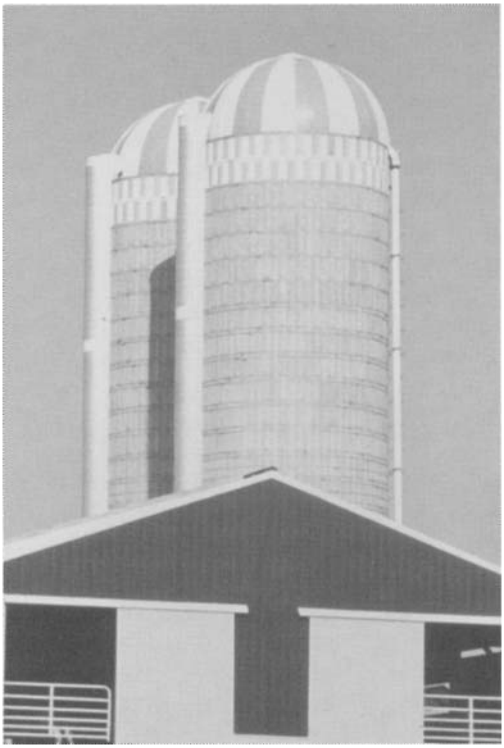


FIGURE 17.2 Tower silos are effective in storing and maintaining quality silage without excessive losses. (Courtesy of Pioneer Hi-Bred International, Des Moines, IA.)

C. BAGGED STORAGE

Another storage protocol now being used is bagging the silage in large, white plastic bags (Fig. 17.3). Storage losses in these units are approximately 1 to 3%. The cost of bagging equipment for such systems may be prohibitive in smaller- to medium-size operations (see Chapter 15). They are most likely to be economically viable in a dairy operation, where high-quality silage is required and where at least 80 ha (200 acres) of silage is to be harvested and stored annually (Park and Wallentine, 1986).

D. SILAGE PILES

The least expensive silage storage system is piles of silage covered with plastic, which is usually held in place with used automobile tires. The only annual storage costs are associated with this method are the area used, the plastic that covers the pile, and the used tires. Losses are usually highest from this type of storage, but an analysis comparing the various systems

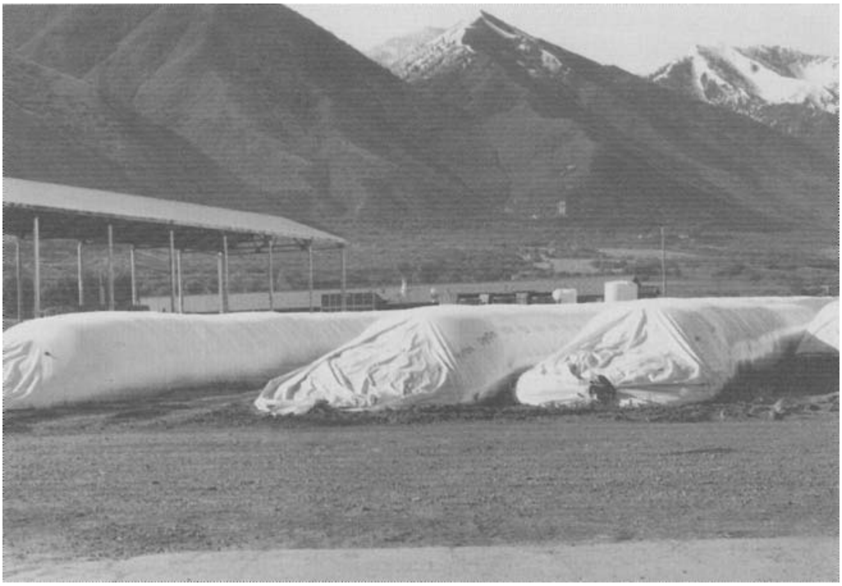


FIGURE 17.3 Horizontal storage in airtight plastic bags is one of the most effective ways to store and maintain high-quality silage. In this system, dry matter losses are only about 3% and the quality of the silage, whether it is from the high-sugar crops such as corn or sorghum or alfalfa or grasses, is superb. (Photo taken by the author.)

may show that this is the most economical. Typical DM losses usually exceed 20 to 25%. The DM losses are high because of the large amount of exposed surface area and the difficulty encountered in packing properly.

III. DRY MATTER LOSSES

Losses of DM during fermentation range from 5 to 20%, with the average being about 10 to 11%. Gaseous losses range from 5 to 10% and in 72 to 82% moisture silage, seepage losses range from 5 to 10% also. In silage that is less than 72% moisture, seepage losses are reduced, and below 65% they are negligible. Spoilage losses can be 1 to 2% in well-sealed silos and as high as 40% in uncovered pits or bunkers (Gordon, 1957, 1961). Experience has shown that in large bunker silos, even though the proper precautions have been taken to compact the material well and to exclude entrance of oxygen by covering, can lose up to 35% of the ensiled dry matter (Horrocks, unpublished data, 1978). Typical DM losses, averaged over all types of silos are presented in Table 17.1. Total losses in an airtight system (anaerobic conditions) can be kept below 2%, which is largely the respiration of the initial aerobic oxidation and the fermentation bacteria themselves.

Poor-quality silage usually has much of the protein and amino N broken down into less digestible NH_3 products (Gordon, 1957, 1961).

IV. KEYS TO MAKING QUALITY SILAGE

A. CARBOHYDRATE CONTENT OF ENSILED FORAGES

The carbohydrate content of the material placed in the silo is critical in formation of quality silage. The higher the sugar content, the more rapidly the anaerobic bacteria multiply; and the more bacteria there are, the more rapidly the pH of the silage drops to the desired level. This action can reduce DM and protein losses, thus resulting is higher-quality silage. Silage crops such as corn and sorghum are naturally high in soluble carbohydrates, and they are thus superior for making silage because no additives are required to provide additional energy for the fermentation bacteria.

The forage grasses, especially those highly fertilized with N, grass–legume mixtures, and all legumes, have a low concentration of soluble carbohydrates (sugars), the energy source for the fermentation bacteria, and high concentrations of basic elements such elements such as K, Ca, and Mg. These two factors combine to make it more challenging to produce quality silage.

B. LENGTH OF CUT AND TIGHTNESS OF PACKING

The length of cut should from 1.27 to 2.54 cm (0.5–1 in.) for corn, sorghum, forage sorghum hybrids, sudangrass–sorghum hybrids, sudan-

TABLE 17.1 Expected Dry Matter Losses, as a Function of Initial Silage Moisture, in Storage and Feeding

Corn silage moisture (%)	Storage	Feeding	Total
70+	13.7	4.0	17.7
60–69	6.3	4.0	11.3
<60	6.3	4.0	11.3

Source: Roth and Undersander, 1995.

grass, and pearl millet (Martin *et al.*, 1976). The British and the Scandinavians have had more experience with ensiling forage grasses and legumes because their growing seasons are generally too short and too cool to grow corn and sorghum. They have found that the length of cut for successfully ensiling these materials is critical. Raymond *et al.* (1986) indicate that length of cut depends on the DM content of the forage. If DM is less than 20%, the maximum length can be as long as 20 cm (8 in.). Material to be ensiled with 30% or more DM requires a maximum length of cut of 2.5 cm (1 in.).

The pack should be thorough with about 721 kg m^{-3} (45 lb ft^{-3}) of silage (Martin *et al.*, 1976). The density, however, varies with moisture content and depth of silage [320 kg m^{-3} at a depth of 0.61 m, (e.g., 20 lb ft^{-3} at 2 ft), and 1120 kg m^{-3} at a depth of 15.2 m, (e.g., 70 lb ft^{-3} at 50 feet)].

C. WILTING

Problem crops, such as the perennial pasture and hay grasses and legumes, will not ferment properly because they are too wet. The low sugar concentration in these crops exacerbates the fermentation problem. Thus, the first step required in achieving acceptable fermentation is the reduction of the moisture content of the forage. This can be accomplished by cutting the crop and allowing it to wilt before ensiling. For example, less sugar is needed to stabilize and preserve a crop at 30% DM (stable at pH 4.2) than to stabilize and preserve the same crop at 20% DM, which must be acidified to well below 4.0 before it will store safely (Martin *et al.*, 1976; Neidig, 1914). Wilting also reduces effluent (seepage from the silo) generated and DM solids lost in this effluent, and thus increases the effective feeding value of the silage. In addition, wilting reduces the weight or mass of material that must be moved from the field to the storage unit.

Storing silage in tower-type silos requires DM to be at least 30%. This requirement is related to maintaining structural integrity and balance in the silo itself as well as the items discussed in the previous paragraph. At such moisture levels, only a moderate amount of fermentation is needed for the silage to reach a pH of 4.5 to 5.0. Nevertheless, all silage should be at 30 to 35% DM or more for highest quality, reduced losses, and efficiency and effectiveness of ensiling and storage. Silages stored at 45% or more DM are difficult to pack and to expel the entrapped oxygen.

When compared with nonwilted perennial pasture and hay grasses and legumes, wilting results in a superior silage. If the moisture content is reduced by wilting to less than 70%, preferably 65%, and if proper exclusion of oxygen is practiced, as occurs in airtight storage units, no additive is required. Some field losses do occur during the wilting process (Martin *et al.*, 1976; Walton, 1983), but the improvement in silage quality and acceptability far exceeds the value of the lost material. Decreasing moisture content from 80 to 50% (conversely, increasing DM content from 20 to

50%) results in greater quantities of lactic acid being formed, less total acid formation (but not necessarily higher pH), and lower amount of butyric acid and ammonia being formed. In storage structures that are not airtight, the smell (butryic acid) is rather rank, but the silage is still acceptable to animals.

D. AEROBIC RESPIRATION

Under good silage-formation conditions, aerobic microorganisms (largely molds and bacteria) respire ever more rapidly as the temperature of the silage increases, using up the oxygen entrapped in the material within a few hours. These organisms then die because they are aerobes (require free oxygen to survive) and cannot live in anaerobic (no free oxygen) and acid conditions. The time required for this step depends on the tightness of pack, fineness of cut, and the precautions taken to reduce access of oxygen into the system.

If the oxygen in a mass of silage is not expelled or reduced by tight packing of the fodder, and if an airtight seal is not placed on the silo to prevent more oxygen from entering, aerobic respiration continues for a longer period of time. Aerobic respiration in the silage is undesirable because it causes the following deleterious effects: (1) readily digestible carbohydrates are converted to heat because they are an energy source for the aerobic microorganisms, thus resulting in excessive DM losses; (2) protein nitrogen is denatured; (3) silage quality is lowered because the acid-forming bacteria (anaerobes) cannot develop rapidly enough to lower the pH to a desirable level; (4) generation of heat causes the undesirable chemical reactions to proceed at a faster rate; and (5) the rising warm air, as it escapes from the silo, draws in fresh oxygen-rich air, like a draft in a stove, and incites even faster chemical reactions (Martin *et al.,* 1976).

Even after access by oxygen to the ensiled forage has been prevented, by covering or by another manner, the huge number of aerobic molds and bacteria that are usually present in the crop can rapidly multiply and decompose the forage into a putrefying and foul-smelling mass (or mess), similar to a garden compost pile. This is prevented in silage formation, however, by acidification because these organisms cannot survive in anaerobic, acid-forming conditions.

E. TEMPERATURE

Temperatures in silage rise after ensiling for about 15 days, then subside and fluctuate with the ambient air temperature. Usually the high temperature is about 38 to 60°C (100–140°F). Temperatures greater than 60°C result in carmelization of the silage, and brown and black pockets result if such temperatures persist or higher temperatures are reached. These conditions occur when oxygen continues to move into the system and the aerobic microorganisms continue to flourish.

F. FERMENTATION AND ACIDIFICATION

Fermentation begins as acid-forming bacteria multiply rapidly, O_2 declines, and CO_2 increases. A rapid drop in pH to 4.6 or less follows. Carbon dioxide increases rapidly for 2 to 3 days. In the final product, CO_2 makes up about 60 to 70% of the gaseous atmosphere in the silage. The remaining gases are largely dinitrogen (N_2).

Successful production of silage depends on formation of acid in the silage (pH 3.5 to 4.5). Because pH is expressed on a logarithmic scale, to reduce the pH of forage from 6.8 to 5.8 needs only one-tenth the amount of acid as is required to reduce it from 5.8 to 4.8. Thus, the ability to continue to produce acid is a requisite to good silage formation. Excess water in the silage dilutes the acid and makes it more difficult to achieve the desired pH. Low water-soluble carbohydrate concentrations in the fodder make it impossible for enough acid to be formed to lower the pH to the desired level of 3.5 to 4.5. However, Shockey and Barta (1987) showed that alfalfa silage only reached a pH of about 5.0 after 56 days. The fresh forage pH was about 5.9. Acidification of most silage depends on the fact that forages carry a natural population of bacteria (lactobacilli), which, in the absence of oxygen, ferment the sugars to produce lactic acid.

High quality silage contains more lactic acid than any other acid (Table 17.2). However, there are considerable amounts of acetic, propionic, succinic, and sometimes butyric acids as well as ammonia in silage. The last two are responsible for the bad odors and low palatability of poor-quality silages; thus, they must be kept to a minimum. High butyric acid concentration occurs when silage has (1) too much moisture, which dilutes the liquid and the pH cannot be reduced to the proper level; (2) too little soluble carbohydrates in the forage; and (3) high levels of basic elements, especially Ca as in most legumes, are present (Raymond *et al.,* 1986; Smith 1969, 1970a,b,c). Forage grasses, small grains without grain, and legumes present special challenges with respect to these points. However, the research of Shockey and Barta (1987) has shown that these basic nutrients do not seem to have the high deleterious buffering capacity in the silage fermentation systems as would be expected.

Soluble carbohydrates (sugars and some pentosans and starch) in the forage are converted to alcohols, which in turn are converted to acids—principally lactic acid (Neidig, 1914; Woodward, 1939). Under specific conditions, the molds and putrefying bacteria (when O_2 is not rapidly excluded or diminished) begins to decompose the lactic acid itself. As lactic acid disappears, the damaging process of secondary fermentation sets in (Neidig, 1914). Butyric acid, which is foul-smelling, then predominates (Barnett,

TABLE 17.2 Typical Fermentation Profile for Well-Fermented Whole Plant Corn Silage

Profile	Analysis
Silage pH	3.6–4.0
Fermentation end products	
Lactic acid	4–6%
Acetic acid	<2%
Butyric acid	<0.1%
Propionic acid	<0.5%
Ethanol	<0.5%
Nitrogen fractions	
Ammonia nitrogen	<5% of total N
Bound N	<12% of total N
Microbial assay	
Yeast	<100,000 CFU[a] g^{-1} of silage
Molds	<100,000 CFU[a] g^{-1} of silage
Total aerobes	<100,000 CFU[a] g^{-1} of silage

[a] CFU, colony forming units.

Source: Roth and Undersander, 1995.

1954; Gordon *et al*, 1961; Langston, 1958; Martin *et al.*, 1976; McDonald, 1981; McHan, 1984).

Sugars are fermented to acid only if no oxygen is present. Thus, it places even greater importance on limiting access of O_2 to the ensiled material. The longer the oxidation and fermentation processes go on, because oxygen was not expelled from the system, too much water is present, or soluble carbohydrate concentrations are low, the greater will be the DM losses. Protein and amino N are also degraded in greater proportion. Making good silage from grasses, legumes, and preheaded small grains requires more than efficient sealing to prevent oxygen entry. The moisture content of the material also must be brought down to less than 70% before it is placed in the silo.

V. ADDITIVES

Direct-cut grass or legume silage can be made. The moisture content, however, ranges from 72 to 85%, and therefore seepage losses are usually very high. Poor-quality silage also results because of reasons previously discussed (e.g., formation of butyric acid, which is associated with a high

TABLE 17.3 Suggested Amounts of Various Additives Required to Improve Quality of Silage

Material	kg t^{-1}	lb ton^{-1}
Ground shelled corn or dried beet pulp	50–75	100–150
Ground ear corn	87.5–100	175–200
Liquid molasses	30–50	60–100
Sodium metabisulfite	4–5	8–10
Calcium formate–sodium nitrate mix	2.5–5	5–10
Formic acid	1.75–2.5	3.5–10 80% liquid

Source: Martin *et al.,* 1976, p. 236; with permission of Macmillan Publishing Company.

pH). Such silages can be amended at the time they are ensiled with the materials listed in Table 17.3. These amendments can supply sugar for the fermentation process as well as DM in some cases, to reduce the moisture concentration of the whole silage. In addition, it has been shown that the addition of urea at the rate of 5 kg t^{-1} (10 lb ton^{-1}) can increase nutritive value of sorghum silage (Martin *et al.,* 1976); presumably, the quality of other low-protein crops would also be enhanced by adding urea.

In situations in which forage grasses and legumes are commonly used for silage, and wilting the crop prior to ensiling is not practical, other methods are used to ensure good silage. These include addition of acids and other additives.

At one time, acids such as sulfuric or hydrochloric acid were added to enhance acidification, particularly in Scandinavia, where the process was developed by A. I. Virtanen in Finland in the 1930s (Raymond *et al.,* 1986). Disadvantages to the use of these acids are that the user must be very careful when handling such corrosive materials. In addition, the acceptability or palatability of the silage is decreased.

By 1986, more than 60 different additives were being sold in Great Britain. They are represented by the following classes: (1) *Inorganc acids,* such as H_2SO_4 and HCl, which are used in the 45% concentration form. Eight percent of the acid used as a silage preservative in Ireland is 45% H_2SO_4 (Raymond *et al.,* 1986). The corrosiveness of these acids is an extreme drawback to their use. (2) *Organic acids,* such as formic, acetic, lactic, and propionic, are also used. These are less corrosive, but care still must be practiced in their use. (3) *Mixtures of acids and formalin*[1] are commonly used. Formalin is usually used in combination with H_2SO_4. The mixture requires less of each ingredient than when they are used alone. (4) *Soluble carbohydrates* provide an excellent alternative (see Table 17.3). (5) *Biologi-*

---

[1] An aqueous solution of formaldehyde that is 37% formaldehyde by weight.

cal inoculants are also becoming more popular. They are being developed mostly in the United States, and are composed of bacteria that are purported to improve fermentation. All of the biological inoculants contain *Lactobacillus planarum* as a major component, as well as other strains (Fishman, 1983).

Formic acid has been the most effect additive in Great Britain and Scandinavia (Raymond *et al.*, 1986). Woolford and Sawczyc (1984a,b) have stated that formic acid is the only additive that provided a positive impact on silage quality. Addition of formic acid at the time of ensiling has been shown to entirely prevent the deterioration of silage quality caused by imperfect or improper conditions (Fishman, 1983; Hoffman and Bradshaw, 1937; Shockey and Conrad, 1984). It is added at a rate of 1.75 to 5 kg of liquid additive (80% formic acid) per tonne (3.5–10 lb ton^{-1}) of fresh weight. The higher rate should be used with wet grasses or with clovers. pH of the chopped forage quickly falls to 5.0 because of the addition of acid, and aerobic oxidation is prevented. With the absence of oxygen, the lactobacilli then lower the pH to a safe range for storage. The final pH is no lower than it would be without formic acid, but the rate at which it drops at first is much more rapid, thus reducing oxidative losses (i.e, DM and breakdown of the protein).

Biological inoculants are commonly promoted as a secondary measure to assure additional quality. Their use is based on the premise that the forage material does not contain sufficient amounts of the desirable lactobacilli in the natural condition. Some reports indicate that they do indeed have a positive effect (Fishman, 1983; Moon, 1981, 1983). Others, however, question the veracity of the claims when it comes to making silage from corn (Roth and Undersander, 1995), because the corn has a natural population of the desirable bacteria on the leaves and stalks of the plant. In the silage formation process, the number of bacteria increases from 2000 to 4000 per gram to more than 1 billion per gram in just a few hours after ensiling (Martin *et al.*, 1976). Kung *et al.* (1984) showed a positive effect of inoculant on alfalfa fermentation, but Shockey *et al.* (1985) reported no advantage in fermentation of either alfalfa or corn silage with the addition of biological inoculants.

These mixed results are not too surprising when the research of Woolford and Sawczyc (1984a,b) are considered. They found in laboratory tests that only 3 of 21 microbial strains tested appeared to have potential as possible inoculants (Woolford and Sawczyc, 1984a). The three strains were *Streptococcus durans* strain 1024, *Lactobacillus planarum* strain 6, and *L. acidophilus* strain 2356. Further evaluation of these three strains under actual silage-making conditions showed that none of the cultures had any noticeable influence on microbial development, rate of acidification, or promotion of fermentation; instead, they tended to exacerbate loss of insoluble N and deamination. All silages in this study, including the nontreated check, were well preserved with no butyric acid being detected.

VI. SUMMARY

Silage formation consists of the following: (1) Oxygen trapped in the forage is utilized within a few hours by aerobic microorganisms. (2) Anaerobic bacteria (lactobacilli) increase from 2000 to 4000 up to 1 billion per gram of silage very early in the process. (3) Sugars are the principal food for anaerobic fermentation bacteria, but pentosans and starch are also used to a small degree. (4) Principal organic acids formed are lactic, acetic, succinic, and a trace of formic (McCulloch, 1978; McDonald, 1981; Neidig, 1914). Lactic acid is the desired acid (Woodward, 1939). (5) Poor silage fermentation breaks down much of the protein and amino acid N to form less digestible ammonia forms (Gordon *et al.,* 1957,1961; McHan, 1979). (6) Silage development is usually completed within about 12 days (Langston, 1958). (7) Losses of DM during fermentation range from 5 to 20%; gas losses range from 5 to 10%; seepage losses from 0 to 10%, depending on the water content of the initial fodder. Spoilage losses can range from a low of 1% (airtight silos) to a high of 40% (silage piles and poorly covered bunker or pit silos) (Guilbert, 1931; LeClerc, 1939; Martin *et al.,* 1976; Takano, 1983; Walton, 1983).

This Page Intentionally Left Blank

APPENDIX

TABLE I Useful Relationships and Conversion Factors

Metric system reference

The metric system is decimal with a power base of 10. Quantities are specified by prefixes to the three basic units measuring length, mass, and volume.

The basic units:

Meter:	Measures length and is equivalent to 39.37 in., or 1.0936 yards.
Gram:	Measures mass (weight) and is equivalent to 0.03527 ounces, or 1/454 pounds.
Liter:	Measures volume and is equivalent to 61.02 cubic in., or 0.2442 gallons.

Prefixes:

mega	1,000,000	deci	0.1
kilo	1,000	centi	0.01
hecto	100	milli	0.001
deca	10	micro	0.000001

The measure of temperature under the metric system is the Celcius scale, sometimes referred to incorrectly as the Centrigrade scale. The following relationships allow conversion from the Fahrenheit to the Celcius scale and vice versa.

Fahrenheit to Celcius: °C = (°F − 32) × 5/9

Celcius to Fahrenheith: °F = °C × 1.8 + 32

TABLE I (*continued*)

Conversion factors[a]

To convert column 1 into column 2, multiply by	Column 1	Column 2	To convert column 2 into column 1, multiply by
Length			
0.621	kilometer, km	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
0.394	centimeter, cm	inch, in.	2.54
0.039	millimeter, mm	inch, in.	25.4
Area			
0.386	kilometer, km	mile, m	2.590
247.1	kilometer, km	acre, ac	0.00405
100.0	kilometer, km	hectare, ha	0.010
2.471	hectare, ha	acre, ac	0.045
Volume			
0.00973	meter, m	acre-inch	102.8
2.38	hectoliter, hl	bushel, bu	0.352
0.0284	liter, l	bushel, bu	35.24
1.057	liter, l	quart (liquid)	0.946
Mass			
1.102	ton (metric)	ton (English)	0.9072
2.205	kilogram, kg	pound, lb	0.454
0.035	gram, g	ounce (avdp), oz	28.35
Pressure			
14.22	kg/cm	lbs inch, psi	0.0703
0.968	kg/cm	atmosphere, atm	1.033
0.9807	kg/cm	bar	1.0197
Yield			
0.446	ton (metric)/ha	ton (English)/ac	2.240
0.891	kg/ha	lb/acre	1.12
264.2	kiloliter/min	gal/min, gpm	0.00379
0.87	hectoliter/min	bu/acre	1.15
2.119	liters/sec, l/sec	ft/min, cfs	0.472
0.625	bushels/ac, bu/ac	quintals/ha, q/ha	1.6
0.01	kg/ha	q/ha	100.0
62.5	bu/ac	kg/ha	0.016

[a] Source: Buxton *et al.,* 1988.

TABLE I (*continued*)

Rules for computing circumference, area, and volume

Area of rectangle: (length) × (width)
Circumference of circle: (3.1416) × (diameter)
Capacity of rectangular container: (length) × (width) × (depth)
Volume of a cylinder: (0.7854) × (diameter) × (diameter) × (height)

Weights and measures

Avoirdupois weight

1 dram = 27 11/32 grains
1 ounce = 16 drams
28.35 grams
437 1/2 grains
1 pound = 16 ounces
7000 grains
453.59 grams
0.45 kilogram

Volume measure

1 pint = 2 cups
1 quart = 2 pints
1 gallon = 4 quarts
8 pints
1 peck = 8 quarts
1 bushel = 4 pecks

Linear measure

1 inch = 2.54 centimeters
1 foot = 12 inches
30.48 centimeters
1 yard = 3 feet
0.91 meter
1 rod = 5 1/2 yards
16 1/2 feet
1 mile = 320 rods
1,760 yards
5,280 feet

Area measure

1 sq ft = 144 sq in.
1 sq yd = 9 sq ft
1 sq rod = 30 1/4 sq yd or
272 1/4 sq ft
1 acre = 160 sq rods
4,840 sq yd
43,560 sq ft
1 sq mi = 640 acres
1 section = 1 sq mi

TABLE I (*continued*)

Commodity weights of various crops

Commodity	lb/bu	kg/hl	lb/hl	kg/hl
Corn, shelled	56	25.40	159.0	72.14
Corn, ear	70	31.75	198.8	90.18
Oats	32	14.97	93.7	42.49
Grain sorghum	56	25.40	159.0	72.14
Wheat	60	27.22	170.4	77.29
Rye	56	25.40	149.0	72.14
Rice, rough	45	20.41	128.7	57.97
Barley	48	21.77	136.3	61.83
Alfalfa	60	27.22	170.4	77.29
Alsike clover	60	27.22	170.4	77.29
Sweet clover	60	27.22	170.4	77.29
Red clover	60	27.22	170.4	77.29
Timothy	45	21.41	127.8	57.97
Rape	50	22.58	142.0	64.41
Bluegrass	14	6.35	39.8	18.04
Redtop	14	6.35	39.8	18.04
Field beans (dry)	60	27.22	170.4	77.29
Soybeans	60	27.22	170.4	77.29
Field peas	60	27.22	170.4	77.29
Millet	50	22.68	142.0	64.41
Sudangrass	40	18.14	113.6	51.53
Buckwheat	50	22.68	142.0	64.41
Flaxseed	56	25.40	159.0	72.14
Potatoes	60	27.22	170.4	77.29
Apples	44	19.96	125.0	56.68
Pears	48	21.77	136.3	61.83

TABLE I (*continued*)

Estimating volume of hay in stacks

The following formulae provide an estimate (within ±10%) of the volume, in cubic feet (ft^3), of a haystack.

Dt = distance over the top (ft)
W = width (ft)
L = length (ft)
H = height (ft)
C = circumference at base (ft)
V = volume (ft^3)

To obtain an estimate of the hay in the stack, divide the volume V by the cubic feet per ton (see following).

Type of stack, loose hay

Low round-topped stack:

$$V = ((0.52 \times Dt) - (0.44 \times W)) \times (W \times L)$$

High round-topped stack:

$$V = ((0.52 \times Dt) - (0.46 \times W)) \times (W \times L)$$

Square flat-topped stack:

$$V = ((0.56 \times Dt) - (0.55 \times W)) \times (W \times L)$$

Type of stack, rectangular baled hay

Square or rectangular stack:

$$V = W \times L \times H$$

Whenever possible, it is best to weigh feed and hay rather than estimate its weight.

Estimating grain in bins or cribs

B = bushels of grain
H = height of leveled grain (ft)
D = diameter of bin (ft)
L = length of bin (ft)
W = width of bin (ft)

Round bin or crib:

$$B = (0.7854 \times D^2) \times (H/1.25)$$

Square bin or crib:

$$B = (W \times W \times H)/1.25$$

TABLE I (*continued*)

Cubic feet per ton of animal feed

Type	30–90 days	90+ days
Alfalfa hay	485	470
Wild hay	600	450
Clover–timothy hay	580	515
Alfalfa hay (mobile stack machine)	640	625
Chopped alfalfa hay (1-in length)		360
Chopped alfalfa hay (2-in length)		300
Silage, corn (bunker silo)		60
Silage, corn (upright silo)		50
Haylage (bunker silo)		85
Haylage (upright silo)		65
Regular baled hay		100
Right baled hay		133
Concentrates, typical		45
Alfalfa meal		134
Barley meal		72
Barley, whole		53
Corn meal		53
Corn, shelled		46–51
Corn, ground ear		50–52
Oats, ground		106
Oats, whole		78
Rye, whole		45
Wheat, ground		46
Wheat, bran		154
Wheat, middlings		100
Wheat, whole		34
Grain sorghum, whole		45–50
Soybean meal		48
Linseed meal		88

TABLE I (*continued*)

Estimation of per-acre population

Inches between each plant in row	Row width (in.)					
	10	20	30	36	38	40
6	104,540[a]	52,270	34,850	29,040	27,540	26,130
7	89,600	44,800	29,870	24,890	23,630	22,410
8	78,400	39,210	26,140	21,780	20,640	19,600
9	69,700	34,850	23,230	19,360	18,340	17,420
10	62,720	31,360	20,910	17,420	16,510	15,680
12	52,280	26,140	17,420	14,520	13,750	13,070
14	44,800	22,400	14,930	12,540	11,790	11,200
16	39,200	19,600	13,010	10,890	10,320	9,800
18	34,840	17,420	11,620	9,680	9,170	8,710
20	31,360	15,680	10,450	8,710	8,250	7,840

[a] Plants per acre.

TABLE II Seeding, Seed, and Plant Characteristics

		Seeding rate per acre		Seeds per							
Crop	Botanical name	Close drills (lb.)	Rows (lb.)	Pound (thousands)	Gram (no.)	Weight per bushel (lb.)	Germination time (days)	Temperature type	Growth habit	Chromosome number	Photoperiodic reaction
Alfalfa	*Medicago sativa* L.			220	500	60	7	C	P	16	L
Humid areas		10–20									
Irrigation		10–20									
Semiarid		8–10									
Bahiagrass	*Paspalum notatum* Flügge	10–12		150	336		21	W	P	20	
Barley	*Hordeum vulgare* L.	72–96		13	30	48	7	C	A, WA	7	L
Bermudagrass	*Cynodon dactylon* (L)	6–8		1,800	3,900	40 (14)	21	W	P	15; 18	
	(unhulled)	10–15		1,300	2,900						
Big trefoil	*Lotus ulginosus* Schkuhr.	4–6		1,000	1,900	60	7	C	P	7	
Birdsfoot trefoil	*Lotus corniculatus* L.	8–12		375	800	60	7	C	P	12	
Black medic	*Medicago lupulina* L.	10–15		300	600	60 (hulled)	7	C	A	8	L(?)
Bluegrass											
Canada	*Poa compressa* L.	15–25		2,500	5,500	14	28	C	P	21; 28	L
Kentucky	*Poa pratensis* L.	15–25		2,200	4,800	14	28	C	P	14; 28; 35	N
Bluestem											
Big	*Andropogon furcatus* Muhl	15–20		150	340		28	W	P	35; 20	S
Little	*Andropogon scoparius* Michx	12–20		260	560		28	W	P	20	L
Buffalograss	*Buchloë dactyloides* (burs) Engelm.	15–20		50	110		28	W	P	28; 30	
Buffalograss (caryopses)		5			330		738				
Clover											
Alsike (alone)	*Trifolium hybridum* L.	6–8		680	1,500	60	7	C	P	8	L
Crimson	*Trifolium incarnatum* L.	15–25		150	330	60	10	C	WA	7; 8	L
Egyptian (berseem)	*Trifolium alexandrinum* L.	15–20		210	460	60	7	C	WA	8	L
Hop	*Trifolium agrarium* L.	8–12		830	1,800	60			WA	7	L
Ladino	*Trifolium repens* L.	5–7		860	1,900	60	10	C	P	8; 12; 14; 16	L
Large Hop	*Trifolium procumbens* L.	3–4		2,500	5,400	60	14	C	WA	7	L
Low Hop	*Trifolium dubium* (minus) L.	4–5		860	1,900	60	14	C	WA	14; 16	L

Persian	*Trifolium resupinatum* L.	4–8	640	1,400	60	7	C	WA	8	L
Red	*Trifolium pratense* L.	8–12	260	600	60	7	C	P	7; 14	L
Rose	*Trifolium hirtum* All.	15–20	160	360						
Strawberry	*Trifolium fragiferum* L.	4–6	290	640	60	7	C	P	8	L
Sub	(subterranean) *Trifolium subterraneum* L.	20–25	55	120	60	14	C	WA	8	L
White	*Trifolium repens* L.	5–7	700	1,500	50	10	C	P	8	L
Corn										
Field (for grain)	*Zea Mays* L.	6–18	1, 2	3	56	7	W	A	10	S
Crownvetch	*Coronilla varia* L.	5–10	140	300				P	12	
Dallisgrass	*Paspalum dilatatum* Poir	8–25	340	485	12–15	21	W	P	20; 25	S
Fescue										
Chewings	*Festuca rubra* var. *commutata* Gaud	15–40	615	1,400	14–30	21	C	P	21	
Hair	*Festuca capillata* Lam.		1,500	3,200		28	C	P	7	
Meadow	*Festuca elatior* L.	10–25	230	500	14–24	14	C	P	7; 14; 22; 35	
Red	*Festuca rubra* L.	15–40	400							
Sheeps	*Festuca ovina* L.	25	530	1,167	10–30	21	C	P	7; 21; 28; 35	
Tall	*Festuca arundinacea*	10–25	225	500			C	P	21	
Field pea										
(Large seeded)	*Pisum arvense* L.	120–180	4	8	60	8	C	A	7	L
(Small-seeded)		90–120								
Austrian winter	*Pisum arvenu* L.	30–90	5	11		8	C	WA		
Gramagrass										
Black	*Bouteloua eripoda* Torr.	7–9	560	1,200			W	P	21	
Blue	*Bouteloua gracilis* (H.B.K.) Lag.	8–12	900	1,980		28	W	P	20; 21; 14	N; S
Hairy	*Bouteloua hirsuta* Lag	10–15	980	2,200					21	
Side oats	*Bouteloua curtipendula* (Torr.)	15–20	200	442		28	W	P	21; 28; 35	S; I
Lespedeza										
Chinese (Sericea)	*Lespedeza cuneata* (Dum, De Cours) G. Don	30–40	372	820	35	28	W	P	10	S
(Scarified)		15–20	335	820	60					
Common and Tenn. 76	*Lespedeza striata* Hook Arn	20–30	343	750	25	14	W	A	10	S
Kobe	*Lespedeza striata*	30–35	185	750	30	14	W	A	10	S
Korean	*Lespedeza stuoykaceae* Maxim	20–25	240	525	45	14	W	A	10	S
Meadow Fescue (see Fescue)	*Alopecurus pratensis* L.	15–25	540	1,200	6–12	14	C	P	14	L

(*continues*)

TABLE II (*continued*)

		Seeding rate per acre		Seeds per							
Crop	Botanical name	Close drills (lb.)	Rows (lb.)	Pound (thousands)	Gram (no.)	Weight per bushel (lb.)	Germination time (days)	Temperature type	Growth habit	Chromosome number	Photoperiodic reaction
Milk vetch	*Astragalis cicer* L.										
Millet											
Browntop	*Panicum ramosum* L.	10–20	4–10	140	300		14	W	A	18	
Foxtail	*Setaria italica* (L) Beauv.	20–30		220	470	50	10	W	A	9	S
Japanese (barnyard)	*Echinochloa crusgalli frumentacea* W. F. Wight	20–25		155	320	35	10	W	A	18; 24; 28	
Pearl (cattalil)	*Pennisetum glaucum* L.	16–20	4–6	85	190		7	W	A	7	S
Proso	*Panicum miliaceum* L.	15–35		80	180	56	7	W	A	18; 21; 36	S
Napiergrass	*Pennisetum purpureum* Schumach.	Veg.		1,402	3,100		10	C	P	14	
Oats											
Common	*Avena sativa* L.	48–128		14	30	32	10	C	A; WA	21	L
Red	*Avena byzantina* C. Koch	48–128		14	30	32	10	C	A; WA	21	L
Orchardgrass	*Dactylis glomerata* L.	20–25		590	1,440	14	18	C	P	14	
Redtop	*Agrostis alba* L.	10–12		5,100	11,000	14	10	C	P	14; 21	
Reed canarygrass	*Phalaris arundinacea* L.	8–12		550	1,200	44–48	21	C	P	14	L
Rescuegrass	*Bromus catharticus* Vahl	25–30		70	145	8–12	35	W		14; 21	
Rhodesgrass	*Chloris gayana* Kunth	10–12		1,700	4,700	8–12	14	W	P	10; 21	
Rye	*Secale cereale* L.	28–112		18	40	56	7	C	A; WA	7	L
Ryegrass											
Italian	*Lilium multiflorum* Lam	25–30		227	500	24	14	C	B	18	L
Perennial	*Lolium perenne*	25–30		330	500	24	14	C	P	7	L
Sainfoin	*Onobrychis viciaefolia* Scop	30–35		23	50	55	10		P	11	
Sorghum	*Sorghum bicolor* L. Moench						10	W	A	10	S
Feterita			3–6	13	33	56	10	W			
Hegari			3–6	20	44	56	10	W			
Kafir		15–45	3–6	20	55	56	10	W			
Milo			2–5	15	33	56	10	W			

Sorgo		15–75	4–8	28	50	50	10	W			
Sorgo (Sumac)		15–75	3–6	40	88	50	10	W			
Soybean											
(Small-seeded)	*Glycine max* Merril (*Soja max* Piper)	60	15–20	8	18	60	14	C	WA	8	
(Medium-seeded)		90	20–30	2–3	6–13	60					
(Large-seeded)		120	30–45	1	2	60					
Sudangrass	*Sorghum vulgare Sudanense* (Piper) Hitchc	20–35	4–6	55	120	40	10	W	A	10	S
Sweetclover											
White	*Melilotus alba* Med. (Hulled)	12–15		250	570	60	7	C	B; A	8	L
Yellow	*Melilotus officinalis* Lam. (unhulled)	30–45		250	570	60	7	C	B	8	L
Switchgrass	*Panicum virgatum* L.			370	815		28	W	P	18; 36; 35; 28	S
Timothy											
(Alone, spring)	*Phleum pratense* L.	8–12		1,230	2,500	45	10	C	P	7; 21	L
(Alone, fall)		3–4									
(With clover)		4–6									
Vetch, Common	*Vicia sativa* L.										
(Alone)		40–80		7	19	60	10	C	A; WA	6; 7	L
(With grain)		20									
Vetch, Hairy	*Vicia villosa* Roth.	20–40		21	36	60	14	C	WA; B	7	
(With grain)		20									
Vetch, Hungarian	*Vicia pannomica* Crantz	40–80		11	24	60	10	C	A; WA	6; 7	L
Wheat, Common	*Triticum aestivum* L.	30–120		12–30	35	60	7	C	A; WA	21	L
Wheatgrass (CrestedFairway)	*Agropyron cristatum* (L.) Gaertn.	12–20	4–6	320	714		14	C	P	7	
Crested (Standard)	*Agropyron desertorum* Fisch.	12–20	4–6	190	425	20–24	14	C	P	14	
Slender	*Agropyron Trachycaulum* Malte (*pauciflorum*)	12–20		150	320		14	C	P	14	
Western	*Agropyron smithii* (Rydb.)	12–20		110	235		35	C	P	12; 28	L

Temperature type: C, cool-weather growth; W, warm-weather growth.
Growth habit: A, annual; WA, winter annual; B, biennial; P, perennial; P(A), perennial but grown as annual.
Chromosome number: reduced (gametic) number (N).
Photoperiodic reaction: L, long day; S, short day; N, day neutral or indeterminate; I, intermediate.
Adapted from: Martin *et al.*, 1976.

TABLE III Common Combining Forms Used in Latin Binomials

Following are the Latin and Greek roots that are used to form many scientific terms. Referring to this list one can often clarify the meaning of new and unfamiliar words. For example, biology is compounded from *bio* and *logy,* meaning *life* and *study or science,* respectively. Thus, biology is the study or science of life or living things.

a:	without
ab:	from, from off, away from, down from
aer (o):	air
angi (o, um):	vessel or covering, covered
annul:	a ring
ante:	before
anth (o):	flower
anti:	against, opposed to
arch (i):	beginning, primitive
asc (o):	bladder, sac
auto:	self
basi:	base
bi:	two
bio:	life
carp (o):	fruit
cary (o):	kernel, nucleus
center (i, o):	toward the center
chem (i, o):	chemical
chlor (o):	green
chrom (o):	color
circum:	around
coleo:	sheath or covering
crypt (o):	hidden
cycl (e, o):	circle
cyt (e, o):	cell
dend (i, o, on):	tree
derm (a, o):	skin
di:	two, twice
diplo:	double
dors (i, o):	back
eco or oec (i, o):	environment, house
enchym (a):	tissue
endo:	within
entom (o):	insect
eo:	primitive, early
epi:	on, upon, above
eu:	true
ex (o):	out from, away
fasc (a, i, o):	bundle
fil (a, i, o):	thread
flor (i):	flower
foli (o):	leaf
fruct (i, o):	fruit

gam (o):	marriage, union
gen (e, o):	birth, origin
geo (or geal):	earth
gymn (o):	uncovered, naked
gyn (e, o):	female
halp (o):	single
haust (o):	drink, suck up
hemi:	half
hetero:	different
hisce:	open
hist (o):	tissue
homo:	like
hort (i):	cultivated, garden
hydr (o):	water
hyper:	above, beyond
hypo:	under
in:	in, not
infra:	below, beneath
inter:	between
intra:	within
is (o):	like, equal
lab (i):	lip
leuc (i, o):	white, colorless
lign (i, o):	wood
log (i, y):	subject, study, science
ly (s, t):	dissolving
macro:	large
medi (o):	middle
mega:	large
meio (or mio):	fewer, less
merist (o):	dividing, divisible
mes:	middle
meta:	among, after
micro:	small
mono:	one
morph (o):	shape, form
multi:	many
myc (e, o):	fungus
necro:	dead
nem (o):	thread
neo:	recent
nom (e, iy):	name, subject
oec (i, o):	house or dwelling, environment
oid:	like, similar

TABLE III (*continued*)

ont (o):	being	som (a, e):	body
oo:	egg	sperm (a, o):	seed, germ
ortho:	straight	spot (e, o):	seed
ose:	full of	stel (e, o):	column
ov (i):	egg	stom (a, e, o):	opening
para:	beside, near	styl (e, i, o):	piller
path (o, y):	disease	sub:	below
ped (i):	foot	super:	over
pent (a, o):	five	supra:	more than
peri:	around	sym:	with, together
pheno:	appear, appearance	syn:	with, together
phil (i, o):	loving	tax (i, o, y):	arrangement
phob (i, o):	opposed to, hating	terr (i):	of the earth
phor (e, o):	bearing	tetra;	four
phot (o):	light	theo (a, i):	case
phyco:	alga	therm (o):	heat
phyl (o):	race, tribe	thigno:	touch
phyll (i, o):	leaf	tot (i):	entire
phyt (e, o)	plant	trans:	across
pinn (i, a):	feather, featherlike	tri:	three
plasm (i, a):	anything formed	trich (o):	hair
plast (o):	formed	trop:	turning
poly:	many	troph (o, y):	pertaining to nutrition
pro:	before	ult (i):	last
pyl (o, i):	gate, opening	ultra:	beyond
quadra;	four	uni:	one
ret (e, i):	net	vacu:	empty
rhiz (o):	root	vas (cul, i, o):	vessel
sapro:	rotten	vit (a):	life
scalar (i):	ladder	xyl (e, o):	wood
schiz (o):	split	zo (a, o):	life, animal
scler (o):	hard	zyg (o):	pair
semi:	half	zym (e, o):	yeast
set (i,o):	bristly, forest		

GLOSSARY

A Horizon, the surface and subsurface soil that contains most of the organic matter and is subject to leaching.

Abomasum, the fourth compartment of a ruminant's stomach. Sometimes called the true stomach.

Acceptability, readiness with which animals select and eat a forage or feed; sometimes used interchangeably to mean either palatability or voluntary intake. See *Palatability.*

Acetic acid, one of the volatile fatty acids with the formula CH_3COOH. Commonly found in silage, rumen contents, and vinegar.

Acid detergent fiber (ADF), this forage constituent is insoluble in acid detergent. ADF differs from crude fiber in that ADF contains silica. Silica and lignin in plants are associated with low digestibility. The lower the ADF, the more feed an animal can digest.

Acid soil, a soil with a pH reaction of less than 7.0 (from the practical viewpoint, it is 6.6). An acid soil has a preponderance of hydrogen ions over hydroxyl ions. Litmus paper turns red in contact with moist acid soil.

Ad libitum, where animals are permitted to eat daily as much as they desire. See *Orts* and *Voluntary intake.*

Additive, an ingredient or a combination of ingredients added, usually in small quantities, to a basic feed mix for the purpose of fortifying the basic mix with certain essential nutrients and/or medicines.

Aerobic, requiring free oxygen to function, as opposed to anaerobic, requiring no free oxygen.

Aftermath, recovery growth of forage plants; also harvesting by either animal or machine.

Agronomy, the science of crop production and soil management. The name is derived from the Greek words *agros* (field) and *nomos* (to manage).

Albedo, ratio of visible light reflected by a surface to that received by a surface.

Alkali soil, a soil, usually above pH 8.5, containing alkali salts in quantities that usually are deleterious to crop production.

Alkaline soil, soil with pH above 7.

Allelopathy, the process by which a plant affects other plants by producing and releasing biologically active chemicals into the soil either by exudation or leaching, or as a result of decay of the plant residues. The effects are usually negative, but may also be positive.

Ambient temperature, air temperature at a given time; not radiant temperature.

Amino acid, organic acid containing one or more amino groups ($-NH_2$) and at least one carboxyl group ($-COOH$). Some amino acids such as cystine and methionine contain sulfur. Many amino acids linked together in a definite pattern form a molecule of protein.

Ammoniated, combined or impregnated with ammonia or an ammonium compound.

Ammonification, formation of ammonia or ammonium compounds in soils.

Amylase, any one of several enzymes which effect a hydrolysis of starch to maltose. Examples are pancreatic amylase (amylopsis) and salivary amylase (ptyalin).

Amylopectin, one of the products (80%) resulting from hydrolysis of starch at 60 to 80°C. The other is amylose.

Amylose, one of the products (20%) resulting from hydrolysis of starch at 60 to 80°C. The other product is amylopectin.

Anabolism, metabolic process by which simple substances are synthesized into complex materials of living tissue.

Anaerobic, living in the absence of free oxygen; the opposite of aerobic.

Animal day, one day's tenure on range or pasture by one animal.

Animal starch, see *Glycogen.*

Animal unit, one mature cow, approximately 454 kg (1000 lb), or the equivalent in other classes of animals, based on average daily forage consumption of 12 kg (26.5 lb) dry matter per day.

Annual, plant that completes it life cycle from seed in one growing season.

Anther, the pollen-bearing part of the stamen; usually composed of two pollen sacks.

Anthesis, stage of floral development when pollen is shed; the period during which the flower is open; in grasses, the period when the anthers are extended from the glumes.

Anus, the posterior end and opening of the digestive tract.

Arginine, one of the essential amino acids.

Arid climate, a dry climate with an annual precipitation usually less than 25 cm (10 in) and not suitable for crop production without irrigation.

Articulate, provided with joints or made in segments that may be readily separated.

Artificially dried, dried by other than natural means. See *Dehy* and *Dehydrated.*

Ash, the incombustible residue remaining after incineration at 600°C for several hours.

Aspartic acid, one of the nonessential amino acids.

Astringent, tending to draw together or constrict tissue; contracting.

Available water, soil water available to plants; between field capacity and the permanent wilting point.

B Horizon, the subsoil layer in which certain leached substances (e.g., iron) are deposited.

Backgrounding, growing of replacement cattle, usually on high-forage systems. Backgrounding may take place anytime during the postweaning period until the animal goes into the feedlot or the breeding herd.

Balanced ration, such a combination of feeds as will provide the essential nutrients in the proper proportions.

Band seeding, placing crop seed in rows directly above but not in contact with a band of fertilizer.

Biennial, plant that normally requires 2 years to reach maturity. It produces leaves the first year, blooms and produces seed the second year, and dies at the end of the second growing season.

Biochemistry, the chemistry of living things.

Biomass, the part of a given habitat consisting of living matter, expressed either as weight of organisms per unit area or a volume of organisms per unit volume of habitat.

Biosynthesis, the formation of chemical substances from other chemical substances in a living organism.

Bloat, excessive accumulation of gases in the rumen of animals.

Boiling point, the temperature at which the vapor pressure of a liquid equals the atmospheric pressure.

Bomb calorimeter, an instrument used for determining the gross energy content of a material. See *Calorimeter.*

Boot stage, stage of development of grasses at which the head is enclosed in the sheath of the uppermost leaf.

Broadcast, a method of seeding by randomly distributing seed on the soil surface.

Browse, that part of leaf and twig growth of shrubs, woody vines, and trees available for animal consumption; the act of consuming browse.

Buffer, any substance that can counteract changes in free acid or alkali concentration.

Buffering capacity, the ability of a soil to resist changes in pH. Commonly determined by the presence of clay, humus, and other colloidal materials.

Butyric acid, four-carbon organic acid found in rancid butter and aerobically formed in grass silage, C_3H_7COOH. It gives butter the rancid smell.

C Horizon, the layer of weathered parent rock material below the B horizon of the soil but above the unweathered rock.

Calcareous soil, an alkaline soil containing sufficient calcium and magnesium carbonate to cause visible effervescence when treated with hydrochloric acid.

Calcification, process by which organic tissue becomes hardened by a deposit of calcium salts.

Caloric, pertaining to heat or energy.

Calorie (gram calorie), unit for measuring chemical energy, defined as the heat necessary to raise the temperature of 1 g of water from 14.5 to 15.5°C at standard pressure; 1 kilocalorie (kcal) raises the temperature of 1 kg of water 1°C. Thus, 1 kcal = 1000 cal, and 1000 kcal = 1 megacalorie (Mcal).

Calorimeter, an instrument for measuring heat. See *Bomb calorimeter.*

Cambium, the growing tissue lying between the wood and the bark of a shrub or tree.

Carbohydrate, compound of carbon, hydrogen, and oxygen in the ratio of one atom each of carbon and oxygen to two of hydrogen, as in sugar, starch, and cellulose.

Carbohydrates, nonstructural, photosynthetic products existing in plant tissue as a solute or as stored insoluble material; functions as readily metabolizable compounds, not as structural components of the tissue. Examples are fructose, glucose, sucrose, starch, fructosans, and hemicellulose.

Carotene, yellow compound of carbon and hydrogen that occurs in plants; a precursor of vitamin A. Alpha, beta, and gamma carotenes may be converted into vitamin A by animals.

Caryopsis, a one-celled fruit with a thin, adherent pericarp or covering; a wheat kernel is an example.

Catabolism, the conversion of complex substances into more simple compounds by living cells.

Catalyst, a substance that speeds up the rate of a chemical reaction, but is not itself used up in the reactions.

Cecum, an intestinal pouch located at the junction of the large and small intestine. Also called caecum.

Cellulose, (1) major skeletal material in the cell wall of plants; chemically, an anhydride of beta-D glucose units. A cellulose molecule may contain between 1600 and 2700 beta-D glucose units. (2) A carbohydrate having the general formula $(C_6H_{10}O_5)_n$.

Celsius (C), a thermometer scale in which water freezes at 0°C and boils at 100°C. Same as *centigrade,* but under the International System (SI) of measurement, *celsius* is the proper term.

Centigrade (C), same as *celsius.* (Use of *celsius* is preferred in the SI System.)

Cereal forage, cereal crop harvested when immature for either hay, silage, or green chop or as pasturage.

Chlorophyll, the green coloring matter of plants that takes part in the process of photosynthesis. It occurs in the chloroplasts of the plant cell.

Chlorosis, the yellowing or blanching of leaves and other chlorophyll-bearing plant parts.

Chopped, reduced in particle size by cutting.

Chromatography, a technique for separating complex mixtures of chemical substances.

Coenzyme, a partner required by some enzymes to produce enzymatic activity.

Combustion, the combination of substances with oxygen accompanied by the liberation of heat.

Commercial feed, any material produced by a commercial company and distributed for use as a feed or feed component.

Companion crop, crop sown with another crop, usually a small grain with which a forage crop is seeded. Preferred to the term *Nurse crop.*

Compensatory gains, weight gains in animals that are either enhanced or depressed depending on the conditions experienced during a prior period.

Complete ration, a single feed mixture that includes all of the dietary essentials, except water, of a given class of livestock.

Compound leaf, a leaf consisting of a central axis or rachis and several leaflets. It may also possess tendrils and stipules.

Concentrate, (1) any feed low (under about 20%) in crude fiber and high (over about 60%) in total digestible nutrients on an air-dry basis. Opposite of roughage; (2) also, a concentrated source of one or more nutrients used to enhance the nutritional adequacy of a supplement mix.

Congenital, existing at birth.

Conserved forages, See *Harvested forages.*

Consumptive use, the use of water in growing a crop, including water used in transpiration and evaporation.

Continental climate, climate typical of the interior of large land masses having wide extremes of diurnal and seasonal temperatures.

Cool-season grass, grass species adapted to rapid growth during the cool, moist periods of the year; usually dormant during hot weather or injured by it. Often referred to as *C_3 grasses* also, because the first measurable product of photosynthesis is a 3-carbon acid.

Corm, bulblike, short, fleshy, solid stem, exhibited by timothy at the base of the main stem or culm.

Correlation, a relation between two variable quantities such that an increase or decrease of one is associated (in general) with an increase or decrease of the other.

Correlation coefficient (r), the degree of correlation or interrelationship between two variables, which ranges from +1 to −1. A correlation coefficient of zero means that the two variables are not interrelated. An *r* value of −1 or +1 indicates complete association. A positive (+) correlation means that high values of one variable are associated with high values of the other. A negative (−) correlation means that as one variable increases, the other variable tends to decrease.

Cortex, the outer portion of the stem or root in plants; specifically, the bark of trees or the rind of fruits.

Coumarin, white crystalline compound ($C_9H_6O_2$) with a vanilla-like odor; gives sweetclover its characteristic odor.

Cover crop, a crop grown to protect the soil from erosion or nutrient leaching.

Crimped, having been passed between rollers with corrugated surfaces (e.g., hay).

Crop residue, portion of plants remaining after seed harvest; refers mainly to grain crops such as corn stover or of small-grain straw and stubble.

Crown, in plants, the top of a root, or base of a stem, where buds and new shoots arise; alfalfa growth and regrowth is initiated in the crown.

Crown buds, differentiated cells on the crown capable of initiating new shoot growth.

Crude fat, that part of a feed which is soluble in either. Also referred to as *ether extract.*

Crude fiber (CF), course portions of plants such as cellulose, partially digestible and relatively low in nutritional value. In chemical analysis, it is the residue obtained after boiling plant material first with dilute acid and second with dilute alkali.

Crude protein (CP), total ammoniacal nitrogen × 6.25, based on the fact that feed protein on the average contains 16% nitrogen. The inverse of 0.16 is 6.25 $\left(\frac{1}{0.16}\right)$. Crude protein indicates the capacity of the feed to meet an animal's protein needs.

Cubing, process of forming hay into high-density cubes to facilitate transportation, storage, and feeding.

Culm, jointed stem of a grass plant.

Cultivar, derived from the term *cultivated variety;* international term denoting an assemblage of cultivated plants that is clearly distinguishable by any characters (morphological, physiological, cytological, chemical, or others) and that when reproduced (sexually or asexually) retains its distinguishing characters. In the United States, variety is synonymous with cultivar, but the latter is preferred.

Cutin, outer covering of plants composed of waxes and waxy polymers.

DDM, see *Digestible dry matter.*

Decumbent, reclining or lying on the ground, but with the tip ascending.

Dehiscence, the opening of a seed pod or anther sack to emit its contents.

Dehy, usually alfalfa that has been chopped, dehydrated, and cubed.

Dehydrated, having had most of the moisture removed through artificial drying. See *Artificially dried.*

Denitrification, biological reduction of nitrate or nitrite to gaseous N (molecular N or the oxides of N).

Desiccant, compound that promotes dehydration or removal of moisture from plant tissue.

Determinate growth, the flowering of plant species uniformly within certain time limits. See *Indeterminate growth.*

Determinate infloresence, flowers arise from the terminal bud and cause cessation of the growth of the axis.

Dextrose, see *Glucose.*

Dicoumarol, chemical compound produced microbiologically from coumarin; found in spoiled sweetclover hay.

Digestibility, apparent, refers to the balance of feed ingested less that matter lost in the feces; usually expressed as a percentage; obtained by multiplying the digestion coefficient for a nutrient by its content in the feed.

Digestibility, true, actual digestibility or availability of a feed, forage, or nutrient as represented by the balance between intake and fecal loss of the same ingested material.

Digestible dry matter (DDM), estimate of the percentage of the feed or forage that is digestible. Based on feeding trials with animals and also estimated from ADF concentration.

Digestible dry matter intake (DDMI), an estimate of how much DDM an animal will consume. DDMI also estimates digestible energy intake (DEI). DDMI is calculated by the equation DDM × DMI/100.

Digestible energy (DE), the part of the gross energy of a feed that does not appear in the feces. The difference between feed and feces expressed in calories.

Digestible nutrients, portion of nutrients consumed that are digested and taken into the animal body. This may be either apparent or true digestibility; generally applied to energy and protein.

Digestion, the processes involved in the conversion of feed into absorbable forms.

Digestive tract, the passage from the mouth to the anus through which feed passes following consumption as it is subjected to various digestive processes. Primarily the stomach and intestines.

DMI, see *Dry matter intake.*

Disaccharide, any one of several so-called compound sugars that yield two monosaccharide molecules on hydrolysis. Sucrose, maltose, and lactose are the most common.

Dormancy, an internal condition of a seed or bud that prevents its prompt germination or sprouting under normal growth conditions.

Drill, (1) a machine for sowing seeds in furrows; (2) to sow seeds with a drill.

Dry matter (DM), total amount of matter in a feed or a plant less the moisture it contains.

Dry matter intake (DMI), amount of dry matter from feed or forage ingested by an animal.

Dry matter percent, plant substance less water; found by oven-drying a weighed sample, weighing, and determining percent lost. See *Moisture, dry basis; Moisture, wet basis.*

Duodenum, the upper portion of the small intestine that extends from the stomach to the jejunum.

Element, any one of the fundamental atoms of which all matter is composed.

Emergence, Coming out of a place, as a seedling from the soil or a flower from a bud.

Emulsify, to disperse small drops of one liquid into another liquid.

Endemic, occurring in low incidence but more or less constantly in a given population.

Endogenous, originating from within the organism.

Energy, the capacity to perform work.

Ensilage, see *Silage.*

Ensile, to store forage as silage.

Ensiled, having been subjected to anaerobic fermentation to form silage.

Enzyme, specialized protein compound occurring in both plant and animal bodies capable of producing chemical transformations without itself being changed or destroyed; functions as a biochemical catalyst.

Epidemic, when many individuals in a given region or population are attacked by some disease at the same time.

Epiphytotic, characterizes a sudden or abnormally destructive outbreak of a plant disease, usually over an extended geographic area.

Eructation, act of belching or giving off gas from the stomach.

Esophagus, the passageway leading from the mouth to the stomach. Sometimes called the *gullet.*

Essential amino acid, any one of several amino acids required by animals but that cannot be synthesized by them in the amount needed.

Ether extract, fats, oils, waxes, and similar plant components that are extracted with dry ethyl ether in chemical analysis.

Etiology, the causes of a disease or disorder.

Exchange capacity (soil), measure of the total amount of exchangeable cations that can be held by the soil, expressed in terms of milliequivalents per 100 g of soil at neutrality (pH 7) or at some other stated pH value.

Excreta, the products of excretion; primarily feces and urine.

Exogenous, originating from outside of the organism.

Extrinsic factor, a factor coming from or originating from outside an organism.

Extruded, as applied to feed—having been forced through a die under pressure.

Fahrenheit (F), a thermometer scale in which water freezes at 32°F and boils at 212°F.

Fat, product formed when a fatty acid reacts with glycerol. The glyceryl ester or a fatty acid; a glyceride. Stearic and palmitic acids are examples.

Fat soluble, soluble in fats and fat solvents but generally not soluble in water.

Fatty acid, any one of several organic compounds containing carbon, hydrogen, and oxygen that combine with glycerol to form fat; a glyderide.

Fauna, the animal life present. Frequently used to refer to the overall protozoal population present.

Fecal index, indirect method of estimating indigestibility of dry matter by determining concentration of an indicator in feces.

Feces, the excreta discharged from the digestive track through the anus.

Feed, any material eaten by an animal as a part of its daily ration.

Feed grade, suitable for animal but not for human consumption.

Feeding value, see *Forage quality* and *Nutritive value.*

Feedstuff, material or materials consumed by animals that contributes nutrients to the diet.

Fermentation, anaerobic chemical changes brought about by enzymes produced by various microorganisms.

Fertility (plant), the ability to reproduce sexually.

Fertility (soil), the ability to provide the proper compounds in the proper amounts and in the proper balance for the growth of specified plants under suitable environments.

Fertilization (plant), the union of male (pollen) nucleus with the female (egg) cell.

Fertilization (soil), the application to the soil of elements or compounds that aid in the growth and nutrition of plants.

Fibrous, high in content of cellulose and/or lignin.

Field capacity (water), amount of moisture remaining in soil after free water (gravitational) has drained away.

Finish, (1) to fatten a slaughter animal; (2) also, the degree of fatness of such an animal.

Fistula, surgically established opening between a hollow organ and the skin for experimental purposes, such as an esophageal fistula.

Flag leaf, the uppermost leaf on a fruiting culm; the leaf immediately below the inflorescence or the seed head.

Flagging, drying of the central leaf in grasses while other leaves stay green.

Flaked, rolled or cut into flat pieces.

Flood meadows, usually refers to river-bottom areas that are flooded during the early part of the growing season; used for hay and grazing after flooding recedes. These meadows are sometimes found in high mountain valleys, but are more commonly found in drier, more arid river valleys.

Flora, the plant life present. In nutrition, it generally refers to the bacteria present in the digestive tract.

Floret, individual, small flower such as one floret of a grass spikelet; one of a dense cluster.

Fodder, coarse grasses such as corn and sorghum harvested with the seed and leaves intact, and cured for animal feeding.

Foggage, British term meaning forage for winter pasture.

Forage, crops used as pasture, hay, haylage, silage, or green chop for feeding purposes.

Forage-animal systems, combined forage and animal management practices directed at meeting the nutritional needs of herbivores in specific production phases or throughout a production cycle.

Forage crops, plant crops of mostly cultivated plants or plant parts, other than separated grain; produced to be grazed or harvested for use as feed for animals.

Forage quality, characteristics that make forage valuable to animals as a source of nutrients; the combination of chemical, biochemical, physical, and organoleptic characteristics of forage that determine its potential to produce animal meat, milk, wool, or work. Considered by some as synonymous with feeding value and nutritional value.

Forage testing, laboratory evaluation of a given forage or feed in terms of intended use.

Forb, any herbaceous, non-grasslike plant on which animals feed.

Formula feed, a feed consisting of two or more ingredients mixed in specified proportions.

Fortify, nutritionally, to add one or more nutrients to a feed.

Fouled, pasture spots or areas made unacceptable to the grazing animal by presence of urine or dung.

Fractionation, the laboratory separation of natural materials into their component parts.

Free choice, free to eat two or more feeds at will.

Fructosan, polysaccharide yielding primarily fructose on hydrolysis; the primary form of carbohydrate storage in certain forage crops (mainly grasses).

Fructose, a hexose monosaccharide found especially in ripe fruits and honey. Obtained along with glucose from sucrose hydrolysis. Commonly known as *fruit sugar.*

Fruit, the structure or parts that enclose the seeds.

Galactose, a hexose monosaccharide obtained along with glucose from lactose hydrolysis.

Gastric, pertaining to the stomach.

Gastric juice, a clear liquid secreted by the wall of the stomach containing hydrochloric acid and the enzymes rennin, pepsin, and gastric lipase.

Genotype, group of organisms with the same genetic makeup. See *Phenotype.*

Germ, embryo of a seed.

Glabrous, smooth or free of hairs.

Glucose, a hexose monosaccharide obtained on the hydrolysis of starch and certain other carbohydrates. Also called *dextrose.*

Glume, the chaff or bract enclosing the seed of grasses, most commonly referring to one of the two empty bracts of the base of the spikelet.

Glutamic acid, one of the nonessential amino acids.

Glycerol, an alcohol containing three carbons and three hydroxy groups.

Glycine, One of the nonessential amino acids.

Glycogen, a polysaccharide with the formula $(C_6H_{10}O_5)_n$ found in the liver and depolymerized to glucose to serve as a ready source of energy when needed by animals. Known also as *animal starch.*

Grain, (1) a caryopsis; (2) a collective term for the cereals; (3) cereal seed in bulk.

Grass, (1) botanically, any plant of the family Gramineae; (2) generally, in grassland agriculture the term does not include cereals when grown for grain but does include forage species of legumes often grown in association with grasses.

Grass silage, designating silage from grasses, legumes, or mixtures. Terms such as *alfalfa silage, clover silage,* and *alfalfa–timothy silage* are definite expressions that should be used where applicable. See *Silage.*

Grassland, land on which grasses and/or legumes constitute the dominant vegetation.

Grassland agriculture, farming system that emphasizes the importance of grasses and legumes in livestock and land management.

Grassland farmer, one who plans his row crop and livestock production around his grassland acreage.

Green chop, forage harvested and fed in the green-chopped form.

Green soiling, See *Green chop.*

Green manure, any crop or plant grown and plowed under to improve the soil by addition of organic matter.

Groat, grain from which the hull has been removed.

Gross energy, the total heat of combustion of a material as determined by the use of a bomb calorimeter.

Harvested forages, forage crops harvested via mechanical means and fed fresh, or fed after conserving as hay or silage.

Hay, the aerial part of finer-stemmed forage crops stored in the dry form for animal feeding.

Haylage, product resulting from ensiling forages in the absence of oxygen. See *Grass silage; Silage.*

Heat increment, the heat that is unavoidably produced by an animal incidental to nutrient digestion and utilization. Originally called *work of digestion.*

Heat labile, unstable to heat.

Hemoglobin, the oxygen-carrying, red-pigmented protein of the red corpuscles.

Herbaceous, plant growth that is relatively free of wood tissue.

Herbage, leaves, stems, and other succulent parts of forage plants on which animals feed. See *Forage.*

Herbivore, any animal species, including many insects and rodents, that subsists principally or entirely on plants or plant materials.

Hexosan, a hexose-based monosaccharide having the general formula $(C_6H_{10}O_5)_n$. Cellulose, starch, and glycogen are the most common.

Hexose, a 6-carbon monosaccharide having the formula $C_6H_{12}O_6$. Glucose, fructose, and galactose are common examples.

Histidine, one of the essential amino acids.

Homogenized, the fat within a liquid having been reduced to globules so small they remain in suspension for an extended period of time (e.g., homogenized milk, etc).

Hormone, (1) a chemical substance secreted into the body fluids by an endocrine gland that has a specific effect on other tissues; (2) a growth regulator in plants.

Hulls, the outer protective covering of seeds.

Husks, usually refers to the fibrous covering of an ear of corn.

Hybrid, product of a cross between individuals of unlike genetic constitution or makeup (within the same genus).

Hydraulic process, a process for the mechanical extraction of oil from seeds, involving the use of a hydraulic press. Sometimes referred to as the *old process.*

Hydrocyanic acid (HCN), poison produced as a glucoside by several plant species, especially sorghum. Same as prussic acid.

Hydrogenation, the chemical addition of hydrogen to any unsaturated compound.

Hydrolysis, the splitting of a substance into smaller units by it chemical reaction with water.

Hydroxyproline, one of the nonessential amino acids.

Hyper, a prefix meaning in excess of the normal.

Hypo, a prefix meaning less than the normal.

Hypomagnesemia, an abnormally low level of magnesium in the blood.

Ileum, the lower portion of the small intestine extending from the jejunum to the cecum.

Impermeable, not capable of being penetrated.

In vitro, in glass; in test tubes; outside the organism, as digestion *in vitro.*

In vivo, in a living organism such as in the animal or in the plant.

Incidence, the frequency of occurrence of a situation or a condition.

Indehiscent, not dehiscent, or not splitting open at maturity.

Indeterminate growth, continuing growth, particularly at the apex.

Indeterminate inflorescence, flowers arise laterally and successively as the floral axis elongates. There is no terminal floret.

Inert, relatively inactive.

Inflorescence, the flowering parts of a plant; a group of flowers on a common axis.

Ingest, to eat or take in through the mouth.

Ingestive mastication, initial chewing prior to swallowing.

Inoculate, to add effective rhizobia to legume seed prior to planting for the purpose of promoting N fixation.

Inorganic, denotes chemical compounds that do not contain carbon in a chainlike structure.

Integrated pest management, the multifaceted approach of controlling pests in cultivated and forage crops that includes sanitation, crop rotation, biological controls, disease forecasting, use of pesticides, and genetic resistance.

Internode, that part of the stem between two nodes.

Intestinal juice, a clear liquid secreted by glands in the wall of the small intestine. It contains the enzymes intestinal lactase, maltase, sucrase, and several peptidases.

Intestinal tract, the small and large intestines.

Intestine, large, the tubelike part of the digestive tract lying between the small intestine and the anus. Larger in diameter but shorter in length than the small intestine.

Intestine, small, the long, tortuous, tubelike part of the digestive tract leading from the stomach to the cecum and large intestine. Smaller in diameter but longer than the large intestine.

Introduced wheatgrass grazing lands, grazing lands in arid areas that have been converted to dryland pasture by seeding introduced species of crested wheatgrass.

Irradiation, the act of treating with ultraviolet light.

Isoleucine, one of the essential amino acids.

Jejunum, the middle portion of the small intestine that extends from the duodenum to the ileum.

Joint, (1) a node; (2) the internode of an articulate rachis; (3) to develop distinct nodes and internodes in a grass culm (e.g., to joint is the process of primary stem elongation in grasses).

Keratin, a sulfur-containing protein that is the primary component of epidermis, hair, wool, hoof, horn, and the organic matrix of the teeth.

Kernel, (1) the matured body of an ovule; (2) a dehulled seed.

Kilo, prefix meaning 1000.

Kilocalorie (kcal), 1000 calories.

Labile, unstable or easily destroyed.

Lactose, a disaccharide found in milk having the formula $C_{12}H_{22}O_{11}$. It hydrolyzes to glucose and galactose. Commonly known as *milk sugar.*

Lamina, the blade of a leaf.

Leaf area index (LAI), ratio of leaf area (one side of leaf) to the ground surface.

Leaflet, one leaflike portion of a compound leaf.

Leghemoglobin, from leg (leguminous) and hemoglogin, a complex respiratory pigment of red corpuscles; a hemoprotein similar to blood hemoglobin.

Legume, (1) plant member of the family Leguminosae (also called Fabacae) with the characteristic of forming nitrogen-fixing nodules on its roots, in this way making use of atmospheric N possible; (2) the pod of a leguminous plant.

Lemma, the lower of the two bracts enclosing a grass flower; the flowering glume.

Leucine, one of the essential amino acids.

Ley, a British term designating the biennial or perennial hay or pasture portion of a rotation that includes cultivated crops.

Lignin, complex noncarbohydrate strengthening material in the thickened cell walls of plants; practically indigestible.

Line, group of individuals from a common ancestry; more narrowly defined group than a strain or cultivar.

Longevity, length of life, usually referring to seeds or plants of longer than average life.

Lysine, one of the essential amino acids.

Maltose, a disaccharide having the formula $C_{12}H_{22}O_{11}$. Obtained from the partial hydrolysis of starch. It hydrolyzes to glucose.

Manure, the refuse from animal quarters consisting of excreta with or without litter or bedding.

Matrix, the intercellular framework of a tissue.

Maturation, the process of coming into full development, as to mature or ripen.

Meadow, an area covered with finestemmed forage plants, wholly or mainly perennial, and used to produce hay.

Megacalorie, 1000 kilocalories or 1,000,000 calories.

Metabolic body size$^{0.75}$, weight of animal raised to three-fourths power. Used in reference to the energy and nutrient requirements of the animal.

Metabolism, the sum of all the physical and chemical processes taking place in a living organism.

Metabolite, any substance produced by metabolism.

Metabolizable energy, digestible energy minus the energy of the urine and fermentation gases.

Methionine, one of the essential amino acids; contains sulfur and may be replaced in part by cystine.

Microbe, see *Microorganism.*

Microbiological, pertaining to microorganisms.

Microflora, the gross overall bacterial population present. Sometimes used to include the protozoa as well as the bacteria.

Microgram, one-millionth of a gram or one-thousandth of a milligram.

Micromineral, see *Trace mineral.*

Micronutrient, a mineral nutrient element that plants need only in trace or minute amounts.

Microorganism, minute living organism such as bacteria, fungi, or protozoa.

Microsymbiont, one of the organisms (bacteria) in a symbiotic relationship.

Milk sugar, see *Lactose.*

Milligram, one-thousandth of a gram.

Moisture, dry basis, a basis for representing moisture content of a product as parts of water per part of dry matter (DM); when multiplied by 100, it equals a percentage that may be more than 100%. In SI units, it is expressed as g kg^{-1} or mg g^{-1}.

Moisture, wet basis, used for commercial designation. Obtained by dividing the weight of water present in the material by the total weight of material, including water and dry matter. May not be more than 100%. In SI units, it is expressed as g kg^{-1} or mg g^{-1}.

Molasses, a thick, viscous, usually dark colored, liquid product containing a high concentration of soluble carbohydrates, minerals, and certain other materials.

Mole, amount of a substance that has a weight in grams numerically equal to the molecular weight of the substance; also called *gram-molecular weight.*

Monocotyledon, plant having one cotyledon, as do grasses.

Monosaccharide, any one of several simple, nonhydrolyzable sugars. Glucose, fructose, galactose, arabinose, xylose, and ribose are examples.

Mountain meadows, areas in mountainous regions that consist of grasses and forbs and appear ordinarily without trees; soils are generally moist to wet, but they usually dry out later in the summer and the forage is then harvested as hay.

Mow, (1) mō—to cut with a mower or scythe; (2) mau—a place for indoor hay storage; (3) to place hay in a mow.

Native prairies, grasslands, mostly nearly level to rolling, originally treeless, and characterized by fertile soils, that are still in native species—mostly grasses—but also includes forbs.

Necrosis, death of a part of the cells making up living tissue.

Net energy (NE), difference between metabolizable energy and heat increment; includes the amount of energy used either for maintenance only or for maintenance plus production. That part of metabolizable energy over which the animal has complete control. See *Heat increment.*

Neutral detergent fiber (NDF), percentage of cell wall material or plant structure in a feed. This constituent is insoluble in neutral detergent and is only partially available to animals. The lower the NDF percentage, the more an animal will eat. NDF includes acid detergent fiber, and is negatively correlated with rate of passage of feed through the animal.

Neutral soil, neither acid nor alkaline, with a pH of 7, or, from the practical viewpoint, 6.6 and 7.3.

Nitrate poisoning, conditions sometimes resulting when ruminants ingest nitrate (NO_3) that rumen bacterial convert to nitrite (NO_2); the nitrites compete with oxygen, tying up the oxygen-carrying mechanism in the blood and causing the animal to suffocate.

Nitrification, formation of nitrates and nitrites from ammonia (or ammonium compounds), as in soil by microorganisms.

Nitrogen fixation, the conversion of atmospheric dinitrogen to nitrogen compounds, brought about chemically by soil organisms, or by organisms living in the roots of legumes.

Nitrogen-free extract (NFE), the unanalyzed substance of a plant (consisting largely of carbohydrates) remaining after the protein, ash, crude fiber, ether extract, and moisture have been determined. Obtained with the proximate system of feed analysis. See *Proximate analysis.*

Node, the joint of a culm to which a leaf is attached.

Nodule, tubercle, particularly such as is formed on legume roots by the symbiotic nitrogen-fixing bacteria of the genus Rhizobium. See *Inoculate.*

Nonessential amino acid, any one of several amino acids that are required by animals but that can be synthesized in adequate amounts by an animal in its tissues (endogenously) from other amino acids.

Nonprotein nitrogen (NPN), broad class of nitrogenous substances not comprising protein such as glutamine, glutamic acid, asparagine, aspartic acid, and gamma-amino butryic acid.

Nonruminant, a simple-stomached animal that does not ruminate. Examples are swine, horses, dogs, and humans.

Nurse crop, see *Companion crop.*

Nutrient, any chemical compound having specific functions in the nutritive support of animal life.

Nutritive value, characterizes a forage or feed as to its chemical composition, digestibility, and nature of digested products. See *Forage quality.*

Omasum, the small third chamber of the stomach of the ruminant that connects the reticulorumen to the abomasum.

Oospore, fertilized and fully developed egg cells.

Organic, refers to chemical compounds that contain carbon in chain structure.

Organic acid, any organic compound that contains a carboxyl group (COOH).

Organic matter, chemical compounds of carbon combined with other chemical elements and generally manufactured in the life processes of plants and animals.

Orts, the portion of an animal's feed that it refuses to eat.

Osmosis, the passage of a solute or a solution through a semipermeable membrane, the result of which is an equalization of the concentration of the fluids on opposite sides of the membrane.

Osmotic pressure, the pressure exerted by the movement of a solvent through a semipermeable membrane toward equalizing solution concentration on opposite sides of the membrane.

Paddock, small fenced field used for grazing purposes.

Palmitic acid, a long-chain, saturated fatty acid (ester of glycerol, called a *glyceride*) that, along with stearic acid, is the most common acid in fats. It formula is $CH_3(CH_2)_{14}COOH$.

Palatability, plant characteristics eliciting a choice between two or more forages or parts of the same forage, conditioned by the animal and environmental factors that stimulate a selective intake response. See *Acceptability.*

Panicle, a branching raceme, as in the head of oat (*Avena sativa* L.).

Pasturage, vegetation on which animals graze, including grasses or grasslike plants, legumes, forbs, and shrubs.

Pasture, fenced area of domesticated forages, usually improved, on which animals are grazed; to graze. See *Range.*

Pasture, carrying capacity, number of animals a given pasture or range will support at a given time or for a given period of time.

Pentosan, a pentose-based polysaccharide having the general formula ($C_5H_8O_4$); araban and xylan are examples. Not nearly as abundant as the hexosans.

Pentose, a 5-carbon monosaccharide having the formula $C_5H_{10}O_5$. Arabinose, xylose, and ribose are examples. Not abundant in the free form in nature.

Pepsin, the proteolytic enzyme present in the gastric juice. It acts on protein to form proteoses, peptones, and peptides.

Perennial, of three seasons duration or more.

Permeable, capable of being penetrated.

Petiole, the leaf-stalk by which a stem is supported.

pH, the pH scale is the measure of acidity and alkalinity; pH 7 is neutral; pH above 7 represents alkalinity, and below 7 represents acidity. The scale is logarithmic (e.g., log $(1/H)$, where H is the hydrogen ion concentration); a solution with a pH of 4 is 10 times as acid as one with a pH of 5 and 100 times as acid as one with a pH of 6.

Phenotype, group of organisms identifiable by their appearance regardless of genetic or hereditary makeup. See *Genotype.*

Phenylalanine, one of the essential amino acids.

Phloem, the portion of a vascular bundle containing the sieve tubes, which transport the food materials manufactured in the plant leaves.

Photoperiod, period of daily exposure to light.

Photoperiodism, response of a plant or animal to the relative length of day and night (light and dark), particularly in plants with respect to floral initiation.

Photosynthesis, process by which carbohydrates are produced from carbon dioxide (CO_2) and water (H_2O) in the chloroplasts or chlorophyll-bearing cell granules, and the energy of sunlight.

Physiological, pertaining to the science which deals with the functions of living organisms or their parts.

Pick-up, an attachment for a combine or other implement to gather cut crops from a windrow and convey them to the machine.

Plant, (1) any organism belonging to the plant or vegetable kingdom; (2) to set plants or sow seeds.

Poaching, a British term referring to deep treading damage to the soil, crowns, and roots of forage plants by the hooves of grazing animals.

Pollen, the grains borne by the anther, containing the male sex cells.

Polysaccharide, any one of a group of carbohydrates consisting of a combination of a large but undetermined number of monosaccharide molecules, such as starch, dextrin, glycogen, cellulose, inulin, and so on.

Preservative, silage, material added to the forage crop at ensiling to quickly develop the acidity essential for preservation.

Proline, one of the nonessential amino acids.

Propionic acid, one of the volatile fatty acids with the formula $CH_3CH_2 \cdot COOH$, commonly found in rumen contents but not in silage.

Protein, complex combination of amino acids, always containing carbon, hydrogen, oxygen, and nitrogen and sometimes phosphorus and sulfur; essential part of all living matter and the feed rations of animals.

Protein, crude, all nitrogenous substances contained in feedstuffs (% crude protein = % N × 6.25; 6.25 = 1/0.16; the average protein percentage for feeds is 16%). In SI units, it is expressed as g kg^{-1} or mg g^{-1}. See *SI System.*

Proximate analysis, analytical system that includes the determination of ash, crude fiber, crude protein, ether extract, dry matter, and nitrogen-free extract.

Prussic acid, see *Hydrocyanic acid.*

Pubescent, covered with hairs.

Pure live seed (PLS), percentage of the content of a seed lot that is pure and viable; determined by multiplying the percentage of pure seed by the percentage of viable seed and dividing by 100.

Put-and-take animals, used in grazing experiments to graze excess forage beyond that needed for tester animals and to accumulate animal days on pasture. See *Tester animals.*

Putrefaction, the decomposition of proteins by microorganisms under anaerobic conditions.

Rachis, the central axis of a spike in grasses or the axis of a compound leaf.

Rancid, a term used to describe fats that have undergone partial decomposition.

Range, land and native vegetation that is predominantly grasses, grasslike plants, forbs, and shrubs suitable for grazing and browsing. Includes lands revegetated naturally or artificially to provide a forage cover managed like native vegetation. See *Pasture.*

Relative feed value (RFV), a measure of a forage's intake and energy value. It compares one forage to another according to the relationship DDM × DMI/100 divided by a constant. RFV is expressed as percentage compared to full bloom alfalfa which has a value of 100 percent RFV. RFV value increases as forage quality increases. See *DDM; DMI.*

Resorption, a return of the nutritive components of a partially formed fetus and fetal membrane to the system of the mother.

Respiration, the process evident in all living organisms in which complex carbohydrates are degraded and energy derived therefrom is used to support the living system. The act of breathing.

Reticulum, the second chamber of the stomach of the ruminant.

Reticulorumen, the anterior compartment of the ruminant stomach, including the large rumen and the smaller reticulum.

Rhizobia, species of bacteria that live in symbiotic relationship with leguminous plants (within nodules on the plant's roots); they carry out the fixation of atmospheric dinitrogen (N_2) into forms used as nutrients by the host legume.

Rhizome, underground stem, usually horizontal, capable of producing new shoots and roots at the nodes.

Rhizosphere, interfacial layer of soil between the root and soil bulk that is under the influence of the plant root.

Rolled, grain compressed into flat particles by having been passed between rollers; examples are rolled oats, barley, corn, or sorghum.

Roughage, any feed high (over about 20%) in crude fiber and low (under about 60%) in TDN, on an air-dry basis. Opposite of concentrate.

Rumen, first compartment of the stomach of a ruminant or cud-chewing animal.

Ruminant, any of a group of hoofed mammals that have a four-compartment stomach and that ruminate or chew a cud. Examples are cattle, sheep, goats, and deer.

Ruminate, to regurgitate previously eaten feed for further chewing. To chew a cud.

Ruminative mastication, chewing the cud after regurgitation.

Saline soil, soil containing an excess of soluble salts, but not excessively alkaline; pH less than 8.5.

Saliva, a clear, somewhat viscid solution secreted by the salivary glands into the mouth. It contains the enzymes salivary amylase and salivary maltase.

Saponifiable, having the capacity to react with alkali to form soap.

Saponification, the formation of soap and glycerol from the reaction of fat with alkali.

Saponin, any of various plant glucosides that form soapy colloidal solutions when mixed and agitated with water.

Saturated fat, a fat formed from the reaction of glycerol with any one of several saturated fatty acids; contains no double bonds. Stearic and palmitic acids are examples.

Savanna, grassland with scattered trees, either as individuals or clumps; often a transitional type between true grassland and forest.

Scarification, procedure of mechanically or chemically scraping the seed coat of hard or impermeable seed to permit the rapid imbibition of water to make germination possible.

Seed, breeder, seed or vegetative propagation of material directly controlled by the originator (or, in certain cases, the sponsoring plant breeder or institution) that provides the source for the initial and recurring increases of foundation seed.

Seed, certified, progeny of foundation, registered, or certified seed that is so handled as to maintain satisfactory genetic identity and/or purity and that has been approved and certified by the certifying agency.

Seed, foundation, seed stocks so handled as to most nearly maintain specific genetic identity and purity, such as may be designated or distributed by an agricultural experiment station. Foundation seed is the source of certified seed, either directly or through registered seed.

Seed, registered, progeny of foundation or registered seed so handled as to maintain satisfactory genetic identity and purity; has been approved and certified by the certifying agency.

Serine, one of the nonessential amino acids.

Sessile, without a stalk, as spikelet attachment in a wheat head.

Sheath, the lower part of the leaf in grasses enclosing the stem.

Shorts, a by-product of flour milling consisting of a mixture of small particles of bran and germ, the aleurone layer, and coarse flour.

SI System, le Systeme International d' Unites of reporting measurements. Developed by the French and used worldwide, except for the United States. Includes the metric system.

Silage, the feed resulting from the storage and fermentation of green or wet crops under anaerobic conditions.

Silage additive, material added to forage at the time of ensiling to enhance either its preservation or feeding value.

Silage preservative, material added to silage at time of ensiling to enhance the favorable fermentation process.

Silo, a semiairtight to airtight structure designed for use in the production and storage of silage.

Soluble carbohydrates, completely digestible; includes glucose, fructose, sucrose, fructosan, and amylose starch.

Specific gravity, the ratio of the weight of a body to the weight of an equal volume of water.

Specific heat, the heat-absorbing capacity of a substance in relation to that of water.

Spike, an unbranched elongated flower cluster with sessile or nearly sessile flowers or spikelets.

Spikelets, the unit of inflorescence in grasses consisting of two glumes and one or more florets.

Spontaneous combustion, self-ignition of material by the chemical action of its constituents; most often results from high moisture hay storage.

Stalklage, crop residues, primarily stalks, remaining in corn or sorghum fields after harvest of the grain.

Starch, main storage carbohydrate $(C_6H_{10}O_5)_n$ in many plants, particularly seed, roots, and tubers. Yields glucose on hydrolysis.

Stele, meaning column. Conceived by Van Tieghem as a morphologic unit of the plant body; central cylinder of the axis (stem and root) comprising the vasuclar system (phloem, xylem, and associated ground tissue.

Stearic acid, a long-chain, saturated fatty acid (ester of glycerol, called a glyceride) that, along with Palmitic acid, is the most common acid in fats. Its formula is $CH_3(CH_2)_{16}COOH$.

Sterile, (1) free from living microorganisms; (2) not capable of producing young.

Stipule, a small structure or appendage found at the base of some leaf petioles; usually present in pairs; they are morpholically variable and appear as scales, spines, glands, or leaflike structures.

Stocker, beef animal being backgrounded prior to finishing or entering the breeding program.

Stockpiling, standing accumulated growth of a forage plant or plants. Used by animals after the growing season has ended.

Stolon, a modified propagating, creeping above-ground stem that produces roots.

Stoloniferous, bearing stolons. See *Stolon.*

Stomach, that part of the digestive tract lying between the esophagus and the small intestine. A four-compartment organ in ruminants; a single compartment organ in nonruminants.

Stover, mature, cured stalks of such crops as corn or sorghum from which grain has been removed; a type of roughage.

Straw, that part of the mature, small-grain plant remaining after the removal of the seed by threshing or combining.

Stress, any circumstance that tends to disrupt the normal, steady functioning of a microorganism, plant, or animal.

Substrate, a substance upon which an enzyme acts.

Sucrose, a disaccharide having the formula $C_{12}H_{22}O_{11}$. It hydrolyzes to glucose and fructose. Commonly known as cane, beet, or table sugar.

Sun-cured, dried by exposure to the sun.

Supplement, a semiconcentrated source of one or more nutrients used to enhance the nutritional adequacy of a daily ration or a complete ration mixture.

Sward, the grassy surface of a pasture.

Swath, a strip of cut herbage lying on the stubble.

Sweat, to emit moisture as does damp hay or grain, usually with some heating taking place at the same time.

Symbiosis, the living together of dissimilar organisms in a mutually advantageous partnership.

Symbiotic nitrogen fixation, fixation of atmospheric N by *Rhizobia* growing in nodules on roots of legumes. See *Rhizobia.*

Syndrome, a medical term meaning a set of symptoms that occur together.

Synthesis, the bringing together of two or more substances to form a new material.

Tannin, broad class of soluble polyphenols with a common property of condensing with protein to form a leather-like substance that is insoluble and of impaired digestibility; thus, causing lower digestibility in some sorghums, birdsfoot trefoil, sainfoin, and so on. Its astringent properties tend to enhance this indisgestibility. See *Astringent.*

Tap root, the main root extending vertically downward, other roots being secondary to it, without appreciable branching at the crown; a single central root.

TDN, see *Total digestible nutrients.*

Tedder, an implement for stirring hay in the swath or windrow to enhance the rate of drying.

Tendril, a long, slender, coiling, modified leaf (or rarely stem), by which a climbing plant attaches to its support.

Tester animal, used in grazing experiments to measure animal performance or pasture quality. See *Put-and-take animals.*

Tetany, a syndrome involving sharp flexion of the wrist and ankle joints, muscle twitching, cramps, and convulsions.

Threonine, one of the essential amino acids.

Total digestible nutrients (TDN), sum total of all digestible organic nutrients (i.e., proteins, nitrogen-free extract, fiber, and fat). Fat is multiplied by 2.25 to put its energy on the same basis as the other nutrients. On the average for all feeds, 1 g of TDN = 4.4 kcal.

Toxic, of a poisonous nature.

Trace element, mineral element essential to plant growth and development; needed only in minute quantities.

Trace mineral, any one of several mineral elements that are required by animals in very minute amounts. Same as micromineral.

Tracer element, a radioactive element used in biological and other research to trace the fate of a substance.

Transpiration, the evaporation of moisture through leaves of plants.

True protein, a nitrogenous compound which hydrolyzes completely to amino acids.

Tryptophan, one of the essential amino acids.

Tyrosine, one of the nonessential amino acids.

Ungulate, any hoofed animal.

Unsaturated fat, a fat formed from the reaction of glycerol with any one of several unsaturated fatty acids. Olein and linolein are examples.

Unsaturated fatty acids, any one of several fatty acids containing one or more double bonds. Oleic, linoleic, linolenic, and arachidonic acids are examples.

Urea, a white, crystalline, water-soluble substance with the formula $CO(NH_2)_2$. It is the most extensively used source of nonprotein nitrogen for animal feeding.

Valine, one of the essential amino acids.

Vector, the means whereby a disease is spread (e.g., insects, wind, machinery, etc.).

Vegetative, term used to designate stem and leaf development in contrast to flower and seed development.

Vitamins, organic compounds that function as parts of enzyme systems essential for transmitting energy and regulating metabolism.

Voluntary intake, ad libitum intake achieved when an animal is offered an excess of a single feed or forage.

Warm-season grass, a grass species that makes its major growth during the warmer part of the year. Also generally now called C_4 grasses because the first measureable product of the photosynthetic pathway is a four-carbon acid.

Weed, a plant that in its location is more harmful than beneficial.

Windrow, (1) curing herbage dropped or raked into a row; (2) to cut or rake into windrows.

Xylem, the woody part of a fibrovascular bundle containing vessels, which are the water conducting tissue.

Zero grazing, See *Green chop.*

REFERENCES

Abdul-Jabbar, A.S., T.W. Sammis, and D.G. Lugg. 1982. Effect of moisture level on the root pattern of alfalfa. *Irrig. Sci.* **3**(3):197–207.

Abdul-Jabbar, A.S., D.G. Lugg, T.W. Sammis, and L.W. Gay. 1984. A field study of plant resistance to water flow in alfalfa. *Agron. J.* **76**(5):765–772.

Adams, F. 1956. Response of crops to lime in Alabama. Auburn University, Alabama Agr. Exp. Sta. Bull. 301.

Adams, F. 1968. Relative responses of grain and annual forage crops to lime, phosphorus, and potassium on Norfolk sandy loam. Auburn University, Alabama Agr. Exp. Sta. Circ. 161.

Adams, F. 1971. Soil, crop and economic benefits from lime use. *In Increasing Lime Use in the Tennessee Valley Region.* Bulletin Y-20, National Fertilizer Development Center, Tennessee Valley Authority, Muscle Shoals, AL.

Adams, F., and Z.F. Lund. 1966. Effect of chemical activity of soil solution aluminum on cotton root penetration of acid subsoils. *Soil. Sci.* **101**(3):193–198.

Adams, F., and R.W. Pearson. 1967. Crop response to lime in the southern United States and Puerto Rico. pp. 161–206. *In* R.W. Pearson and F. Adams (eds.) *Soil Acidity and Liming.* Agron. Monogr. 12. ASA, Madison, WI.

Adams, F., and R.W. Pearson. 1969. Neutralizing soil acidity under bermudagrass sod. *Soil Sci. Soc. Amer. Proc.* **33**(5):737–742.

Adams, W.E., A.W. White, Jr., and R.N. Dawson. 1967. Influence of lime sources and rates on 'coastal' bermudagrass production, soil profile reaction, exchangeable Ca and Mg. *Agron. J.* **59**:(2):147–149.

Adolph, W.H., H.A. Macdonald, Hui-Lan Yeh, and G.P. Lofgreen. 1947. Content and digestibility of morning and evening cuttings of alfalfa. *J. Anim. Sci.* **6**(3):348–351.

Allaway, W.H. 1968. Agronomic controls over environmental cycling of trace elements. *Advan. Agron.* **20**:235–274. Academic Press, New York and London.

Allen, G.C., and M. Devers. 1975. Livestock-feed relationships—National and state. USDA Stat. Bul. 530 (Supp.). 101 pp.

Allen, R.S., R.E. Worthington, N.R. Gould, N.L. Jackson, and A.E. Freeman. 1961. Diurnal variation in composition of alfalfa. *J. Agric. Food Chem.* **9**(5):406–408.

Allen, V.G., L.A. Hamilton, D.D. Wolf, J.P. Fontenot, T.H. Terrill, and D.R. Notter. 1986b.

Yield and regrowth characteristics of alfalfa grazed with sheep. II. Summer grazing. *Agron. J.* **78**(6):979–985.

Allen, V.G., D.D. Wolf, J.P. Fontenot, J. Cardina, and D.R. Notter. 1986a. Yield and regrowth characteristics of alfalfa grazed with sheep. I. Spring grazing. *Agron. J.* **78**(6):974–979.

Allison, C.D. 1985. Factors affecting forage intake by range ruminants: A review. *J. Range Mgt.* **38**(4):305–311.

Alva, A.K., L.E. Lanyon, and K.T. Leath. 1986. Production of alfalfa in Pennsylvania soils differing in wetness. *Agron. J.* (**3**):469–473.

Ames, D.R., and D.E. Ray. 1983. Environmental manipulation to improve animal productivity. *J. Anim. Sci.* **57**(Supp.2):209-220.

Anderson, M.J., G.F. Fries, D.V. Kopland, and D.R. Waldo. 1973. Effect of cutting date on digestibility and intake of irrigated first-crop alfalfa hay. *Agron. J.* **65**:(3):357–360.

Anderson, M.S., H.W. Larkin, K.C. Beeson, F.F. Smith, and E. Thacker. 1961. Selenium in agriculture. *USDA Agric. Handbook.* 200. 65 pp.

Anderson, P.M., J.W. Garthe, and R.F. Stevenson. 1988. Application techniques for chemical hay conditioners. Am. Soc. Agric. Eng. Microfiche Colect. St. Joseph, MI.

Andrew, C.S. 1976. Effect of calcium, pH and nitrogen on the growth and chemical composition of some tropical and temperate pasture legumes. I. Nodulation and growth. *Aust. J. Agric. Res.* **27**(5):611–623.

Angell, R.F., H.A. Turner, and M.R. Haferkamp. 1987. Ramifications of strip grazing harvested or standing flood meadow forages for wintering cattle. *Soc. Range Mgt.,* Abst. Papers. **40**(1):33.

Annexstad, J. 1988. Alfalfa review: How to boost quality and profit. *Dairy Herd Manage.* **25**(2):28–29, 32–33.

Anonymous. 1984. Round bale silage perhaps a valuable addition. *Crops & Soils* **36** (8):12–13.

Anonymous. 1985. Integrated pest management for alfalfa hay. Pub. 3312. Univ. California, Statewide Integrated Pest Management Project, Div. of Agric. and Natural Resources, Berkeley, CA.

Anonymous. 1991. Hay prices at auctions. *In* G.D. Lacefield (ed.). *Forage News.* University of Kentucky, Coop. Ext. Serv., Lexington, KY.

Anonymous. 1997. Potato leafhopper resistant alfalfa: An update. *The Haymaker,* pp. 2–3. W-L Research, Inc. 8701 W. US Hwy. 14, Evansville, WI 53536.

Antolin, M.C., and M. Sanchez-Diaz. 1993. Effects of temporary droughts on photosynthesis of alfalfa plants. *J. Exp. Bot.* **44**(265):1341–1349.

Arledge, J.S. and B. Melton. 1983. Alfalfa hay preservative trial in the Pecos Valley. New Mexico State University, Agric. Exp. Stn. Res. Rpt. 509.

Arledge, J.S. and B.A. Melton. 1984a. Effects of method and rate of application of hay preservatives on hay quality after storage in southeastern New Mexico. New Mexico State University, Agric. Exp. Stn., Res. Rpt. 526.

Arledge, J.S., and B.A. Melton. 1984b. Effects of chemical drying agents on curing time of alfalfa in southeastern New Mexico. New Mexico State University, Agric. Exp. Stn. Res. Rpt. 531.

Arny, D.C., and C.R. Grau. 1985. Importance of verticillium wilt of alfalfa in North America. *Can. J. Plant Pathol.* **7**(2):187–190.

Asay, K.H., R.V. Frakes, and R.C. Buckner. 1979. Breeding and cultivars. pp. 111–139. *In* R.C. Buckner and L.P. Bush (eds.). *Tall Fescue.* Monograph 20, ASA, CSSA, SSSA. Madison, WI.

Asbil, W., and B.E. Coulman. 1992. Improving alfalfa stands with early-spring broadcast seeding. *J. Prod. Agric.* **5**(1):57–63.

Atwal, A.S. and L.C. Heslop. 1987. Effectiveness of propionic acid for preserving alfalfa hay in large round bales. *Can. J. Anim. Sci.* **67**(1):75–82.

Atwal, A.S., L.C. Heslop, and K. Lievers. 1986. Effectiveness of anhydrous ammonia as a preservative for high-moisture alfalfa hay in large round bales. *Can. J. Anim. Sci.* **66**(3):743–753.

Atwal, A.S., F.D. Sauer, and J.D. Erfle. 1984. Effects of storage conditions for large round bales on recovery and quality of alfalfa hay. *Can. J. Anim. Sci.* **64**(2):487–490.

Atwell, D.G., E.H. Jaster, K.J. Moore, and R.L. Fernando. 1988. Evaluation of high oil corn and corn silage for lactating cows. *J. Dairy Sci.* **71**(10):2689–2698.

Ayers, R.S. and D.W. Westcot. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Food and Agriculture Organization of the United Nations. Rome.

Baker, D.N. 1965. Effects of certain environmental factors on net assimilation in cotton. *Crop Sci.* **5**(1):53–56.

Baker, D.N., and R. B. Musgrave. 1964. Photosynthesis under field conditions. V. Further plant chamber studies of the effects of light on corn (*Zea mays* L.) *Crop Sci.* **4**(2):127–131.

Baker, M.J., E.C. Prigge, and W.B. Bryan. 1988. Herbage production from hay fields grazed by cattle in fall and spring. *J. Prod. Agric.* **1**(3):275–279.

Baldocchi, D.D., S.B. Verma, and N.J. Rosenberg. 1981. Seasonal and diurnal variation in the CO_2 flux and CO_2-water flux ratio of alfalfa. *Agric. Meteorol.* **23**(3):231–264.

Ball, D.M., R. A. Burdett, Jr., and M.M. Eichhorn, Jr. 1996. Russell bermudagrass. Alabama Agric. Exp. Stn. Circ. 316.

Ball, E.D. 1919. The potato leafhopper and its relation to the hopperburn. *J. Econ. Entomol.* **12**(2):149–155.

Balwani, T.L., R.R. Johnson, K.E. McClure, and B.A. Dehority. 1969. Evaluation of green chop and ensiled sorghums, corn silage and perennial forages using digestion trials and VFA production in sheep. *J. Anim. Sci.* **28**(1):90–97.

Banthein, P. 1970. Experiments with new crops conditioning machines of differing design for haymaking (in German). Ber. 136 Jurat. Tech. Bauw. Landw.

Barbarick, K.A. 1985. Potassium fertilization of alfalfa grown on a soil high in potassium. *Agron. J.* **77**(3):442–445.

Barber, S.A. 1984. Liming material and practices. pp. 125–160. *In* R.W. Pearson and F. Adams (eds.) *Soil Acidity and Liming,* Monogr. 12, Amer. Soc. Agron., Madison, WI.

Bardsley, C.E. Jr., and H.V. Jordan. 1957. Sulfur availability in seven southeastern soils as measured by growth and composition of white clover. *Agron. J.* **49**(6):310–312.

Barmington, R.D. 1964. Trends in Colorado's mountain meadow hay harvesting and handling. Colo. Agric. Expt. Sta. Gen. Ser. 806. 24 pp.

Barnes, D.K., and R.H. Ratcliffe. 1969. Evaluation of annual species of *Medicago* as sources of alfalfa weevil resistance. *Crop Sci.* **9**(5):640–642.

Barnes, D.K., R.H. Ratcliffe, and C.H. Hanson. 1969. Interrelationship of three laboratory screening procedures for breeding alfalfa resistant to the alfalfa weevil. *Crop Sci.* **9**(1):77–79.

Barnes, D.K., C.H. Hanson, R.H. Ratcliffe, T.H. Busbice, J.A. Schillinger, G.R. Buss, W.V. Campbell, R.W. Hemken, and C.C. Blickenstaff. 1970. The development and performance of team alfalfa: A multiple pest resistant alfalfa with moderate resistance to the alfalfa weevil. ARS no. 34-115.

Barnes, D.K., E.T. Bingham, R.P. Murphy, O.J. Hunt, D.F. Beard, W.H. Skrdla, and L.R. Teuber. 1977. Alfalfa germplasm in the United States. Genetic vulnerability, use improvement, and maintenance. USDA-ARS Tech. Bull. 1571.

Barnes, R.F. 1982. Grassland agriculture—Serving mankind. *Rangelands* **4**(2):61–62.

Barnes, R.F., and G.O. Mott. 1970. Evaluation of selected clones of *Phalaris arundinacea* L. I. *In vivo* digestibility and intake. *Agron. J.* **62**(6):719–722.

Barnes, R.F., L.D. Muller, L.F. Bauman, and V.F. Colenbrander. 1971. *In vitro* dry matter disappearance of brown midrib mutants of maize (*Zea mays* L.). *J. Anim. Sci.* **33**(4):881–884.

Barnett, A.J.G. 1954. *Silage Fermentation.* Academic Press, New York.

Barnett, O.W. and P.B. Gibson. 1975. Identification and prevalence of white clover viruses and the resistance of *Trifolium* species to these viruses. *Crop Sci.* **15**(1):32–37.

Barnett, O.W. and S. Diachun. 1985. Virus diseases of clovers. pp. 235–268. In N.L. Taylor (ed.) *Clover Science and Technology.* Agron. Monogr. 25. ASA, CSSA, SSSA, Madison, WI.

Baron, V.S., and G.G. Greer. 1988. Comparison of six commercial hay preservatives under simulated storage conditions. *Can. J. Anim. Sci.* **68**:(4):1195-1207.

Barshad, I. 1955. Soil development. pp. 1–52. *In* F.E. Bear (ed.). *Chemistry of the Soil.* Reinhold, New York.

Barta, A.L. 1980. Regrowth and alcohol dehydrogenase activity in waterlogged alfalfa and birdsfoot trefoil. *Agron. J.* **72**(6):1017–1020.

Bauder, J.W., A. Bauer, J.M. Ramirez, and D.K. Cassel. 1978. Alfalfa water use and production on dryland and irrigated sandy loam. *Agron. J.* **70**(1):95–99.

Baumheckel, R., and K. Borghoff. 1997. Hay and forage harvesting machinery: Mechanizing ancient drudgery. pp. 284–301. *In* International Harvester farm equipment: Product history, 1831–1985. American Society of Agricultural Engineers, 2950 Niles Road, St. Joseph, MI.

Baxter, H.D. M.J. Montgomery, and J.R. Owen. 1984. Comparison of soybean–grain sorghum silage with corn for lactating cows. *J. Dairy Sci.* **67**(1):88–96.

Bear, F.E. and A. Wallace. 1950. Alfalfa—Its mineral requirements and chemical composition. New Jersey and Agr. Exp. Stn. Bull. 748.

Beaton, J.P., G.R. Burns, and J. Platou. 1968. Determination of sulfur in soils and plant material. Tech. Bull. No. 14, Sulfur Inst., Washington, DC.

Begg, J.E., and N.C. Turner. 1976. Crop water deficits. *Adv. Agron.* **28**:161–217.

Behling, A. 1993. Pocket gophers: Plan your attack. *Hay For. Grow.* **8**(3):24.

Bell, D.B. 1984. *Handbook of Building Plans,* 3rd ed. MWPS-20. Midwest Plan Service, 122 Davidson Hall, ISU, Ames, IA 50011.

Bell, J.R. 1976. Neutron probe practice. Inst. Hydrol. Rep. 9. Natural Environment Research Council, Wallingford, UK.

Bellows, R.A. 1985. Integration of beef cattle reproduction and the range resource. *Amer. Soc. Anim. Sci., West. Sec. Proc.* **36**:1–3.

Belyea, R.L., F.A. Martz, and S. Bell. 1985. Storage and feeding losses of large round bales. *J. Dairy Sci.* **68**(12):3371–3375.

Benham, C.L. and P.L. Redman. 1980. Preservation of moist hay—A review. *Agric. Devel. Advisory Serv. (ADAS) Q. Rev.* **39**(winter):212–225.

Bennett, O.L., and B.D. Doss. 1960. Effect of soil moisture level on root distribution of cool-season forage species. *Agron. J.* **52**(4):204–207.

Bicki, T.J., and J.C. Siemens. 1991. Crop response to wheel traffic soil compaction. *Trans. ASAE* **34**(3):909–913.

Bidwell, R.G.S. 1979. *Plant Physiology,* 2nd ed. Macmillan Publ. Co., Inc. New York, NY.

Blaser, R.E. 1986. Forage–animal management systems. Virginia Agric. Exp. Stn, Bul. 86–87, Virginia Polyechnic Institute and State University, Blacksburg, VA.

Blaser, R.E. and N.C. Brady. 1950. Nutrient competition in plant associations. *Agron. J.* **42**(3):128–135.

Blaser, R.E., C.Y. Ward, and W.W. Moschler. 1958. Hidden hunger in grasses and legumes. *Better Crops with Plant Food* **42**(5):42–50.

Blaser, R.E., H.T. Bryant, C.Y. Ward, R.C. Hammes, Jr., R.C. Carter, and N.H. MacLeod. 1959. Symposium on forage evaluation: VII. Animal performance and yields with methods of utilizing pasturage. *Agron. J.* **51**(4):238–242.

Blaser, R.E., and E.L. Kimbrough. 1968. Potassium nutrition of forage crops with perennials. pp. 423–445. *In* V.J. Kilmer *et al.* (eds.) *The Role of Potassium in Agriculture.* ASA, CSSA, SSSA, Madison, WI.

Bohman, V.R., D.M. Stuart, and E.I. Hackett. 1980. Nevada hays and grass tetany. Nev. Agric. Expt. Sta. Bul. 46. 12 pp.

Boller, B.C., and G.H. Heichel. 1983. Photosynthate partitioning in relation to N_2 fixation capability of alfalfa. *Crop Sci.* **23**(4):656–659.

Borcherding. J.R., and D, Wanner. 1992. Baleage in a plastic wrap. *Success. Farm.* **90**(9):45.

Brady, N.C. 1974. *The Nature and Properties of Soils,* 8th ed. Macmillan, New York, NY.

Brady, N.C. 1990. *The Nature and Properties of Soils,* 10th ed. pp. 351–368. Macmillan Pub. Co., New York, NY.

Brasche, M.R., and J.R. Russell. 1988. Influence of storage methods on the utilization of large round hay bales by beef cows. *J. Anim. Sci.* **66**(12):3218–3226.

Briggs, L.J., and H.L. Shantz. 1914. Relative water requirement of plants. *J. Agric. Res.* **3**(1):1–64.

Brink, R.A. 1984. Maize endosperm mutant affecting soluble carbohydrate content as potential additives in preparing silage from high protein forages. *Maydica* **29**:265–286.

Britton, C.M., J.E. Cornely, and F.A. Sneva. 1980. Burning, haying, grazing, and non-use of flood meadow vegetation. Ore. Agric. Expt. Sta. Spec. Rep. 586, pp. 7–9.

Brougham, R.W. 1956. Effect of intensity of defoliation on regrowth of pasture. *Aust. J. Agric. Res.* **7**(5):377–387.

Brougham, R.W. 1958. Interception of light by the foliage or pure and mixed stands of pasture plants. *Aust. J. Agric. Res.* **9**(1):39–52.

Brown, A.L., B.A. Krantz, and P.E. Martin. 1964. The residual effect of zinc applied to soils. *Soil Sci. Soc. Amer. Proc.* **28**(2):236–238.

Brown, B.A. 1957. Potassium fertilization of ladino clover. *Agron. J.* **49**(9):477–480.

Brown, B.A. 1959. Band versus broadcast fertilization of alfalfa. *Agron. J.* **51**(12):708–710.

Brown, C.S. 1963. Speed alfalfa adoption with fertilizer. *Better Crops Plant Food* **47**(2):5–13.

Brown, C.S., and R.E. Stafford. 1970. Get top yields from alfalfa seedings. *Better Crops Plant Food* **54**(1):16–18.

Brown, L.A. 1935. A study of phosphorus penetration and availability in soils. *Soil. Sci.* ***39***(1):277-287.

Brown, L.G., C.S. Hoveland, and K.J. Karnok. 1990. Harvest management effects on alfalfa yield and root carbohydrates in three Georgia environments. *Agron. J.* **82**(2):267–273.

Brown, P.W., and C.B. Tanner. 1981. Alfalfa water potential measurement: A comparison of the pressure chamber and leaf dew point hygrometers. *Crop Sci.* **21**(2):240–244.

Brown, R.H., E.R. Betay, R.A. McCreery, and J.D. Powell. 1962. Coastal bermudagrass utilization: Soilage vs. continuous grazing. *J. Range Manage.* **14**(6):297–300.

Browne, C.A. 1928. The spontaneous combustion of hay. USDA Tech. Bul. 141. U.S. Government Printing Office, Washington, DC.

Buchanan, G.A., and C.S. Hoveland. 1973. Soil phosphorus and potassium levels on growth of warm season weed and crop species. *Weed Sci. Soc. Amer.* Abst 120.

Buckmaster, D.R. 1993. Evaluator for round hay bale storage. *J. Prod. Agric.* **6**(3):378–385.

Buckmaster, D.R., C.A. Rotz, and D.R. Mertens. 1989. A model of alfalfa hay storage. *Trans. ASAE* **32**(1):30–36.

Buckner, R.C. 1985. *The Fescues.* pp. 233–240. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.) *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Press, Ames, IA.

Bula, R.J., D. Smith, and E.E. Miller. 1954. Measurements of light beneath a small grain companion crop as related to legume establishment. *Bot. Gaz.* **115**(3):271–278.

Buntin, G.D. 1989. Competitive interaction of alfalfa and annual weeds as affected by alfalfa weevil (*Coleoptera: Curculionidae*) stubble defoliation. *J. Entomol. Sci.* **24**(1):78–83.

Buol, S.W., F.D. Hole, and R.J. McCracken. 1989. Site factors: state factors, initial material, and relief. pp. 135–149. *Soil Genesis and Classification,* 3rd ed. Iowa State University Press, Ames, IA.

Buol, S.W., P.A. Sanchez, and S.B. Weed. 1990. Predicted impact of climatic warming on soil properties and use. pp. 72–82. *In* B.A. Kimball, N.J. Rosenberg, and L.H. Allen, Jr. (eds.) *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture.* ASA Special Pub. No. 53. Amer. Soc. Agronomy, Madison, WI.

Burgess, P.L., and J.W.G. Nicholson. 1984. Comparison of male sterile corn and regular corn as silage for dairy cows. *Can. J. Anim. Sci.* **64**(2):427–434.

Burke, D.J. 1987. The role of forages in the horse program. Forage and Grassland Conf. 1987:36–41.

Burns, J.C., and D.S. Chamblee. 1979. Adaptation. pp. 89–90. *In* R.C. Buckner and L.P. Bush (eds.) *Tall Fescue.* ASA, CSSA, SSSA, Madison, WI.

Burroughs, W., P. Gerlaugh, and R.M. Bethke. 1950. The influence of alfalfa hay and fractions of alfalfa hay upon the digestion of ground corncobs. *J. Anim. Sci.* **9**(2):207–213.

Burton, G.W. 1943. A comparison of the first year's root production of seven southern grasses established from seed. *J. Amer. Soc. Agron.* **35**(3):192–196.

Burton, G.W., and W. W. Hanna. 1985. Bermudagrass. pp. 247–254. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Press, Ames, IA.

Burzlaff, D. F., and D. C. Clanton. 1971. The production of upland hay in the sandhills of Nebraska. Neb. Agric. Expt. Sta. Bul. 517. 13 pp.

Busbice, T.H. and C.P. Wilsie. 1965. Fall growth, winterhardiness, recovery after cutting and wilt resistance in F2 progenies of Vernal × DuPuits alfalfa crosses. *Crop Sci.* **5**(5):429–432.

Busch, L.V., and E. Smith. 1981. Susceptibility of Ontario-grown alfalfa cultivars and certain *Medicago* species to *Verticillium albo-atrum. Can. J. Plant Pathol.* **3**(2):169–172.

Cairns, R. R., and R.B. Carson. 1961. Effect of sulphur treatments on yield and nitrogen and sulphur content of alfalfa grown on sulphur-deficient and sulphur-sufficient Grey Wooded soils. *Can. J. Plant Sci.* **41**(4):709–715.

Caldwell, A.C., E.C. Seim, and G.W. Rehm. 1969. Sulfur effects on the elemental composition of alfalfa. *Agron J.* **61**(4):632–634.

Caldwell, D.M., and T.W. Perry. 1971. Relationships between stage of maturity of the corn plant at time of harvest for corn silage and chemical composition. *J. Dairy Sci.* **54**(4):533–536.

Campbell, G.S., and D.J. Mulla. 1990. Measurement of soil water content and potential. pp. 127–142. *In* B.A. Stewart, and D.R. Nielsen (eds.). *Irrigation of Agricultural Crops.* Agron. Monogr. 30, ASA, CSSA, SSSA, Madison, WI.

Carlson, I.T. and W.F. Wedin. 1974. Iowa State Univ. Coop. Ext. Serv. AG90.

Carlson, I.T., and L.C. Newell. 1985. Smooth bromegrass. pp. 198–206. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Press, Ames, IA.

Carlson, R.W., and F.A. Bazzaz. 1980. The effects of elevated CO_2 concentrations on growth, photosynthesis, transpiration, and water use efficiency of plants. pp. 609–661. *In* J. Singhjab and A. Deepek (eds.). *Proceedings of the Symp. on Environmental and Climatic Impact of Coal Utilization.* Academic Press, NY.

Carmer, S.G., and J.A. Jackobs. 1963. Establishment and yield of late-summer alfalfa seedings as influenced by placement of seed and phosphate fertilizer, seeding rate and row spacing. *Agron. J.* **55**(1):28–30.

Carrier, L. 1920. The history of the silo. *J. Am. Soc. Agron.* **12**(5):175–182.

Carter, P.R., and C.C. Sheaffer. 1983a. Alfalfa response to soil water deficits. I. Growth, forage quality, yield, water use, and water-use efficiency. *Crop Sci.* **23**(4):669–675.

Carter, P.R., and C.C. Sheaffer. 1983b. Alfalfa response to water deficits. III. Nodulation and N_2 fixation. *Crop. Sci.* **23**(5):985–990.

Carter, W.R.B. 1960. A review of nutrient losses and efficiency of conserving herbage as silage, barn-dried hay and field-cured hay. *J. Brit. Grassl. Soc.* **15**(3)220–230.

CASC. 1993. *Alfalfa Analyst.* Certified Alfalfa Seed Council. P.O. Box 2023, Woodland, CA 95695.

CASC. 1998. *Alfalfa Varieties.* Certified Alfalfa Seed Council. P.O. Box 2023. Woodland, CA 95695.

Cassell, D.R., and A. Klute. 1986. Water potential: Tensiometry. pp. 563–596. *In* A. Klute (ed.). *Methods of Soil Analysis, Part 1,* 2nd ed. *Agron. Monogr.* 9, ASA, CSSA, SSSA, Madison, WI.

Cave, H.W., W.H. Riddell, and J.S. Hughes. 1936. The digestibility and feeding value of Russian thistle hay. *J. Dairy Sci.* **19**(4):285–290.

Chandler, J.M. 1991. Estimated losses of crops to weeds. pp. 53–65. *In* D. Pimentel (ed.). *Handbook of Pest Management in Agriculture,* 2nd ed. Vol. I. CRC Press, Boca Raton, FL.

Chang, J.-H. 1968. *Climate and Agriculture: An Ecological Survey.* Aldine Publishing Company. Chicago, IL.

Chapman, R.A. 1960. The effects of *Meloidogyne Incognita* and *M. hapla* on the growth of Kenland red clover and Atlantic alfalfa. *Phytopathology* **50**(3):181–182.

Chatterton, N.J., S. Akaso, G.E. Carlson, and W.E. Hungerford. 1977. Physiological components of yield and tolerance to frequent harvests in alfalfa. *Crop Sci.* **17**(6):918–923.

Cheeke, P.R., and L.R. Shull. 1985. *Natural Toxicants in Feeds and Poisonous Plants.* AVI Publishing Co., Westport, CT.

Christen, A.A. and R.N. Peaden. 1981. Verticillium wilt in alfalfa. *Plant Dis.* **65**(4):319–321.

Christian, K.R. 1977. Effects of the environment on growth of alfalfa. *Adv. Agron.* ***29***:183–227.

Clanton, D.C., and D.F. Burzlaff. 1966. Grazing cattle on subirrigated meadows. *J. Range Mgt.* **19**(3):151–152.

Clarke, F.W. 1924. *Data of Geochemistry,* 5th ed. U.S. Geol. Surv. Bull. 330.

Clawson, K.L., and B.L. Blad. 1982. Infrared thermometry for scheduling irrigation of corn. *Agron. J.* **74**(2):311–316.

Coleman, N.T., and G.W. Thomas. 1964. Buffer curves of acid clays as affected by the presence of ferric iron and aluminum. *Soil Sci. Soc. Amer. Proc.* **28**(2):187–190.

Colenbrander, V.F., V.L. Lechtenberg, and L.F. Bauman. 1973. Digestibility and feeding value of brown midrib corn stover silage. *J. Anim. Sci.* **37**(1):294–295.

Collins, M. 1983a. Wetting and maturity effects on the yield and quality of legume hay. *Agron. J.* **75**(3):523–527.

Collins, M. 1983b. Changes in composition of alfalfa, red clover, and birdsfoot trefoil during Autumn. *Agron. J.* **75**:(2):287–291.

Collins, M. 1985a. Wetting and maturity effects on mineral concentrations in legume hay. *Agron. J.* **77**(5):779–782.

Collins, M. 1985b. Wetting effects on the yield and quality of legume and legume–grass hays. *Agron. J.* **77**(6):936–941.

Collins, M. 1991. Hay curing and water soaking: Effects on composition and digestion of alfalfa leaf and stem components. *Crop Sci.* **31**(1):219–223.

Collins, M., and T.H. Taylor. 1980. Yield and quality of alfalfa harvested during autumn and winter and harvest effects on the spring crop. *Agron. J.* **72**(5):839–344.

Collins, M., D.J. Lang, and K.A. Kelling. 1986. Effects of phosphorus, potassium, and sulfur on alfalfa nitrogen-fixation under field conditions. *Agron. J.* **78**(6):959–963.

Collins, M., L.D. Swetnam, G.M. Turner, J.N. Hancock, and S.A. Shearer. 1995. Storage method effects on dry matter and quality losses of tall fescue round bales. *J. Prod. Agric.* **8**(4):507–514.

Conrad, E.C. 1954. Effect of time of cutting on yield and botanical composition of prairie hay in southwestern Nebraska. *J. Range. Mgt.* **7**(4): 181–182.

Conrad, H.R., J.W. Hibbs, A.D. Pratt, and R.R. Davis. 1962. Relationships between forage growth stage, digestibility, nutrient intake and milk production in dairy cows. Ohio Agr. Exp. Stn. Bul. 914.

Conrad, J.P., H.L. Hall, and B.A. Chaugule. 1948. Sulfur fertilization of legumes in the upper Ojai Valley, California and the resulting effects on the following nonlegumes. *Soil Sci. Soc. Amer. Proc.* **12**(1):275–277.

Cook, M.G. and L.T. Evans. 1978. Effect of relative size and distance of competing sinks on the distribution of photosynthetic assimilates in wheat. *Aus. J. Plant Physiol.* **5**(4):495–509.

Coon, R.C., and F.L. Leistritz. 1974. Costs of native hay harvesting systems in North Dakota. N. Dak. Agric. Expt. Sta. Agric. Econ. Rep. 98. 26 pp.

Cooper, C.S. 1956. The effect of time and height of cutting on the yield, crude protein content, and vegetative composition of a native flood meadow in eastern Oregon. *Agron. J.* **48**(6):257–258.

Cooper, C.S., R.L. Ditterline, and L.E. Welty. 1979. Seed size and seeding rate effects upon stand density and yield of alfalfa. *Agron. J.* **71**(1):83–85.

Copeland, L.O. 1976. *Principles of Seed Science and Technology.* Burgess Publishing Co., Minneapolis, MN.

Cords, H.P. 1973. Weeds and alfalfa hay quality. *Weed Sci. Soc. Amer.* Abst. 17.

Cornfield, A.H. 1952. The mineralization of the nitrogen of soils during incubation: Influence of pH, total nitrogen, and organic carbon contents. *J. Sci. Food Agr.* **3**(8):343–349.

Cowett, E.R., and M.A. Sprague. 1962. Factors affecting tillering in alfalfa. *Agron. J.* **54**(4):294–297.

Cralle, H.T., and G.H. Heichel. 1985. Interorgan photoshynthate partitioning in alfalfa. *Plant Physiol.* **79**(2):381–385.

Cramer, H.H. 1967. Plant protection and world crop production. *Pflanzenschutz-Nachrichten* **20**(1):482–95.

Crawford, R.J., Jr., R.L. Belyea, B.J. Stevens, and F.A. Martz. 1986. Using organic acids in harvesting and storing alfalfa hay containing 30% moisture. pp. 182–186. *In Proc. Grassl. Coun.,* 15–17 Apr. 1986. Holiday Inn, Athens, GA. Amer. for Grassl. Coun. Lexington, KY.

Cripps, R.W., J.L. Young, T.L. Bell, and A.T. Leonard. 1988. Effects of lime and potassium application on arrowleaf clover, crimson, clover, and coastal bermudagrass. *J. Prod. Agric.* **1**(4):309–313.

Crookston, R.K., and J.E. Kurle. 1988. Using the kernel milk line to determine when to harvest corn silage. *J. Prod. Agric.* **1**(4):293–295.

Crookston, R.K., and D.N. Moss. 1974. Interveinal distance for carbohydrate transport in leaves of C_3 and C_4 grasses. *Crop Sci.* **14**(1):123–125.

Cullison, A.E., and R.S. Lowry. 1987. *Feeds and Feeding,* 4th ed. A Reston Book. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Curtis, O.F. 1944. The food content of forage crops as influenced by the time of day at which they are cut. *J. Am. Soc. Agron.* **36**(5):401–416.

Dai, Z., M.S.B. Ku, and G.E. Edwards. 1993. C_4 photosynthesis. The CO_2-concentrating mechanism and photorespiration. *Plant Physiol.* **103**(1):83–90.

Dainty, J. 1963. Water relations of plant cells. *Adv. Bot. Res.* **1**:279–326.

Davidson, J.L., and C.M. Donald. 1958. The growth of swards of subterranean clover with particular reference to leaf area. *Aust. J. Agric. Res.* **9**(1):53–73.

Davidson, J.L., and F.L. Milthorpe. 1965. Carbohydrate reserves in the regrowth of cocksfoot (*Dactylis glomerata* L.). *J. Brit. Grassl. Soc.* **20**(1):15–18.

Davies, D.A., E.L. Jones, and T.E.H. Morgan. 1985. Comparison of the relative performance of perennial ryegrass varieties under upland and lowland conditions. *Grass For. Sci.* **40**(3):323–330.

Davis, R.J., C.A. Rotz, and D.R. Buckmster. 1989. Effect of swath manipulation in losses and drying of alfalfa. pp. 329–333. *In* Proc. 1989 for Grassl. Conf., 22–25 May 1989. University of Guelph, Guelph, Ontario, Canada. Amer. For. Grassl. Coun. R.D. 1, Box 129, Belleville, PA.

Davis, W.E.P. 1960. Effect of clipping at various heights on characteristics of regrowth in reed canarygrass. *Can. J. Plant Sci.* **40**(3):452–456.

Daynard, T.B. and W.G. Duncan. 1969. The black layer and grain maturity in corn. *Crop Sci.* **9**(4):473–476.

Decker, A.M., G.A. Jung, J.B. Washko, D.D. Wolf, and M.J. Wright. 1967. Management and production of perennial grasses in the Northeast. I. Reed canarygrass. W. Va. Agric. Exp. Stn. Bull. 550T.

deFreitas, L.M.M., and P.F. Pratt. 1969. Responstat de tres leguminosas a calcario am diversos solos acidos de Sao Paulo. *Presq. Agropec. Bras.* **4**(1):39–95.

Delaney, R.H., and J. Borelli (eds.). 1979. *Management of Intermountain Meadows: Symposium Proceedings.* Wyo. Agric. Expt. Sta. Res. J. 141. 221 pp.

Demment, M.W., and P.J. Van Soest. 1983. *Body Size, Digestive Capacity, and Feeding Strategies of Herbivores.* Winrock International, Morrilton, Ark. 66 pp.

DeRamus, H.A., and C.P. Bagley. 1984. The effect of mefluidide treatment on Bahia and bermudagrass and nutrient utilization. *For. Grassl. Conf.* 1984:152–156.

Dernedde, W., and R. Wilmchen. 1969. Heuwerbungsverlkuste durch Niederschlage bei gequetschten Grass. (Hay making losses due to rain on lacerated grass.) *Landbauforschung Volkenrode* **19**(1):39–42.

DeRoo, H.C. 1961. Deep tillage and root growth: A study of tobacco growing in sandy loam soil. Connecticut Agric. Exp. Stn., Bul. 644, New Haven, CT.

Devine, T.E., R.H. Ratcliffe, T.H. Busbice, J.A. Schillinger, L. Hoffmann, G.R. Buss, R.W. Cleveland, F.L. Lukezic, J.E. McMurtrey, and C.M. Rincker. 1977. Arc, a multiple pest-resistant alfalfa. USDA Tech. Bull. 1559.

deWit, C.T., P.G. Tow, and G.C. Ennik. 1966. Competition between legumes and grasses. Ag. Res. Rpts. 687. Inst. Biol. and Chem. Res. on Field Crops and Herbage. Wageningen, Netherlands.

Dicke, F.F. and W.D. Guthrie. 1988. The most important corn insects. pp. 767–867. *In* G.F. Sprague and J.W. Dudley (eds.). *Corn and Corn Improvement,* 3rd ed. Agron. Monogr. 18. ASA, CSSA, SSSA, Madison, WI.

Dijkshoorn, W., J.E.M. Lampe, and D.F.J. Van Burg. 1960. A method of diagnosing the sulphur status of herbage. *Plant Soil* **13**(3):227–241.

Dione, J.L. 1969. Comportement differentiel du lotier en regard du chaulage (French). *Can. J. Soil Sci.* **49**(1):111–119.

Dittmer, H.J. 1937. A quantitative study of the roots and root hairs of a winter rye plant (*Secale cereale*). *Amer. J. Bot.* **24**(7):417–420.

Doerge, T.A., P.J. Bottomley, and E.H. Gardner. 1985. Molybdenum limitations to alfalfa growth and nitrogen content on a moderately acid, high-phosphorous soil. *Agron. J.* **77**(6):895–901.

Donald, C.M. 1951. Competition among pasture plants. I. Intra-specific competition among annual pasture plants. *Aust. J. Agric. Res.* 2(4):355–376.

Donald, C.M. 1954. Competition among pasture plants. II. The influence of density on flowering and seed production in annual pasture plants. *Aust. J. Agric. Res.* **5**(4):585–597.

Donald, C.M. 1963. Competition among crop and pasture plants. *Adv. Agron.* 15:1–118.

Donaldson, F.T., and K.J. Goering. 1940. Russian thistle silage. *J. Am. Soc. Agron.* **32**(3):190–194.

Donker, J.D., G.C. Marten, R.M. Jordan, and P.K. Bhargava. 1976. Effects of drying on forage quality of alfalfa and reed canarygrass fed to lambs. *J. Anim. Sci.* **42**(1):180–184.

Donker, J.D., G.C. Margen, and P.K. Bhargava. 1982. A comparison of grass and legume hays fed to Holstein heifers and lambs. *J. Anim. Sci.* **66,** Suppl. 1:307 (Abstr.).

Donovan, T.J. and B.D. Meek. 1983. Alfalfa responses to irrigation treatment and environment. *Agron. J.* **75**(3):461–464.

Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. Irrigation and drainage paper 24 (revised). FAO, Rome.

Doss, R.P., S.J. Gould, K.J.R. Johnson, R.A. Flath, and R.L. Kohnert. 1989. (Z)-oxacyclotridec-10-en-2-one, an alfalfa weevil feeding deterrent from *Medicago rugosa. Phytochemistry* **28**(12):3311–3315.

Doss, R.P., and K.J.R. Johnson. 1991. (Z)-oxacyclotridec-10-en-2-one does not appear to be responsible for resistance to adult alfalfa weevil feeding exhibited by *Medicago rugosa. J. Chem. Ecol.* **17**(3):535–542.

Douglas, J.T., and C.E. Crawford. 1991. Wheel-induced soil compaction effects on ryegrass production and nitrogen uptake. *Grass For. Sci.* **46**(4):405–416.

Dowdy, A.K., R.C. Berberet, J.F. Stritzke, J.L. Caddel, and R.W. McNew. 1992. Late fall harvest, winter grazing, and weed control for reduction of alfalfa weevil (Coleoptera: Curculionidae) populations. *J. Econ. Entomol.* **85**(5):1946–1953.

Downton, W.J.S., B.R. Loveys, and W.J.R. Grant. 1988. Non-uniform stomatal closure induced by water stress causes putative non-stomatal inhibition of photosynthesis. *New Phytol.* **110**(4):503–509.

Drew, L.O., H.M. Keener, R.W. Van Keuren, H.R. Conrad, and W.E. Gill. 1974. Preservatives for hay? *Ohio Rep. Res Develop.* **59**(2):38–39.

Drost, D.C., and J.D. Doll. 1980. The allelopathic effect of yellow nutsedge (*Cyperus esculentus*) on corn (*Zea mays*) and soybeans (*Glycine max*). *Weed Sci.* **28**(2):229–233.

Dughri, M.H., and P.J. Bottomley. 1983. Effect of acidity on the composition of an indigenous soil population of *Rhizobium trifolii* found in nodules of *Trifolium subterraneum* L. *Appl. Environ. Microbiol.* **46**(5):1207–1213.

Duke, S.H., M. Collins, and R.M. Soberalske. 1980. Effects of potassium fertilization on nitrogen fixation and nodule enzymes of nitrogen metabolism in alfalfa. *Crop Sci.* **20**(2):213–219.

Dutt, T.E., R.G. Harvey, and R.S. Fawcett. 1982. Feed quality of hay containing perennial broadleaf weeds. *Agron. J.* **74**(4):673–676.

Dysart, R.J. 1988. Establishment in the United States of *Peridesmia discus* (Hymenoptera: Pteromalidae), and egg predator of the alfalfa weevil (Coleoptera: Curculionidae). *Environ. Entomol.* **17**(2):409–411.

Dysart, R.J. 1989. New distribution records for the alfalfa weevil egg predator *Peridesmia discus* (Hymenoptera: Pteromalidae) in the eastern United States. *J. Entomol. Sci.* **24**(1):92–95.

Dysart, R.J., and W.H. Day. 1976. Release and recovery of introduced parasites of the alfalfa weevil in eastern North America. U.S. Dept. of Agric. Prod. Res. Rep. 167.

Eastin, J.D., J.H. Hultquist, and C.Y. Sullivan. 1973. Physiologic maturity in grain sorghum. *Crop Sci.* **13**(2):175–178.

Eaton, F.M. 1942. Toxicity and accumulation of chloride and sulfate salts in plants. *J. Agric Res.* **64**(7):357–399.

Eckert, Richard E., Jr. 1975. Improvement of mountain meadows in Nevada. USDI, Bur. Land Mgt., Washington, D.C. 45 pp.

Edwards, C.R. (ed.). 1986. Alfalfa: A guide to production and integrated pest management in the Midwest. North Central Regional Extension Publication 113.

Elgin, J.H., Jr., D.K. Barnes, T.H. Busbice, G.R. Buss, N.A. Clark, R.W. Cleveland, R.L. Ditterline, D.W. Evans, S.C. Fransen, R.D. Horrocks, O.J. Hunt, W.R. Kehr, C.C. Lowe, D.A. Miller, M.S. Offutt, R.C. Pickett, E.L. Sorensen, C.M. Taliaferro, M.B. Tesar, and R.W. Van Keuren. 1981. Anthracnose resistance increases alfalfa yields. *Crop Sci.* **21**(3):457–460.

Elgin, J.J., Jr., R.E. Welty, and D.B. Gilchrist. 1988. Breeding for disease and nematode resistance. pp. 827–858. *In* A.A. Hanson, D.K. Barnes, and R.R. Hill, Jr. (eds.) *Alfalfa and Alfalfa Improvement.* Agron. Monogr. 29. ASA, CSSA, and SSSA, Madison, WI.

Elling, L.J., and F.I. Frosheiser. 1960. Reaction of twenty-two alfalfa varieties to bacterial wilt. *Agron. J.* **52**(4):241–242.

Elliott, E.S. 1952. Diseases, insects and other factors in relation to red clover failure in West Virginia. West Virginia Agric. Exp. Stn. Bull. 351T.

Elliott, F.C., I.J. Johnson, and M.H. Schonhorst. 1972. Breeding for forage yield and quality. pp. 319–333. *In* C.H. Hanson (ed.). Alfalfa Science and Technology. Agron. Monogr. 15, ASA, CSSA, SSSA, Madison, WI.

Ellis, W.C., J.H. Matis, C. Lascano, M. Mahloogi, and K. Pond. 1987. Size reduction, fermentation, and passage of forage particles and forage intake by cattle. *Okla. Agric. Expt. Sta. Misc. Pub.* **121**:81–95.

Emerick, R.J. 1987. Answer to silica stones. *S. Dak. Farm & Home Res.* **38**(1):10–12.

Engel, R.K., L.E. Moser, J. Stubbendieck, and S.R. Lowry. 1987. Yield accumulation, leaf area index, and light interception of smooth bromegrass. *Crop Sci.* **27**:(2):316–321.

Epstein, E. 1972. *Mineral Nutrition of Plants: Principles and Perspectives.* John Wiley, New York, NY.

Escalada, J.A., and D. Smith. 1972. Changes in nonstrutural carbohydrate fractions at intervals down the tap root bark and wood of alfalfa (*Medicago sativa* L.) during regrowth. *Crop Sci.* **12**(6):745–749.

Evans, L.T. 1980. The natural history of crop yield. *Am. Sci.* **68**(4):388–397.

Fallon, J.B., G.A. Aspenall, and J.E. Nocek. 1989. Making hay in a day program work on Northeast farms. pp. 10–17. *In* Proc. 1989 for Grassl. Conf., 22 May 1989. Univ. Guelph, Guelph, Ontario, Canada. Amer. For. Grassl. Count., R.D. 1, Box 129, Belleville, PA.

Faris, M.A., H. Baenziger, and R.P. Terhune. 1981. Studies on potato leafhopper (*Empoasca fabae*) damage in alfalfa. *Can. J. Plant Sci.* **61**(3):625–632.

Farquhar, G.D., K.T. Hubrick, I. Terashima, A.G. Condon, and R.A. Richards. 1987. Genetic variation in the relationship between photosynthetic CO_2 assimilation rate and stomatal conductance to water loss. pp. 209–212. *In* J. Biggins (ed.). *Progress in Photosynthesis Research,* Vol. 4. Martinus Nijhoff Publishers, Dordrecht.

Faulkner, J.S. 1985. A comparison of faba beans and peas as whole-crop forages. *Grass For. Sci.* **40**(2):161–169.

Faulkner, L.R. and W.J. Bolander. 1966. Occurrence of large nematode populations in irrigation canals of south central Washington. *Nematologica* **12**(4):591–600.

Fenn, G.S. 1981. Drying windrowed alfalfa with chemicals. pp. 5–8. *In* Proc. 11th California Alfalfa Symp., 11th. 8–10 December, Fresno, CA. Univ. Calif. Coop Ext., Davis, CA.

Fergus, E.N., and E.A. Hollowell. 1960. Red clover. *Advan. Agron.* **12**:365–436.

Field, L., B. Melton, and C. Currier, 1987. Effect of fall dormancy of alfalfa cultivars on forage yield under different rates of irrigation. New Mexico State University Agric. Exp. Stn. Res. Rpt. *607*:1–4.

Fisher, T.R. 1974. Some considerations for interpretation of soil tests for phosphorus and potassium. Univ. of Missouri Agric. Exp. Stn. Res. Bull. 1007.

Fishman, M.L., F. McHan, and D. Burdick. 1983. Effect of formic acid–formaldehyde treatments on the nitrogenous constituents in annual ryegrass silage. pp. 636–639. *In* J.A. Smith and V.W. Hays (eds.) Proc. Int. Grassl. Cong. 14th 15–24 June, 1981. Lexington, KY. Westview Press, Boulder, CO.

Fitzhugh, H.A., J.J. Hodgson, O.J. Scoville, T.D. Nguyen, and T.C. Byerly. 1978. The role of ruminants in support of man. Winrock International Livestock Research and Training Center, Morrilton, AK. 136 pp.

Flinn, P.W., A.A. Hower, and D.P. Knieval. 1990. Physiological response of alfalfa to injury by *Empoasca fabae* (Homoptera: Cicadellidae). *Environ. Entomol.* **19**(1):176–181.

Flipot, P.M., W. Mason, and J. Genest. 1984. Effect of nitrogen fertilization and plant population on the value of corn silage fed to beef steers. *Can. J. Anim. Sci.* **64**(2):453–458.

Follett, R.F., and S.R. Wilkinson. 1985. Soil fertility and fertilization of forages. pp. 304–317. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalf (eds.). *Forages: The Science of Grassland Agriculture.* Iowa State University Press, Ames, IA.

Forbes, J.M. 1986. *The Voluntary Food Intake of Farm Animals.* Butterworths, London. 206 pp.

Foth, H.D. 1962. Root and top growth of corn. *Agron. J.* **54**(1):49–52.

Fox, R.L., A.D. Flowerday, F.W. Hosterman, H.F. Rhoads, and R.A. Olson. 1964. Sulfur fertilizers for alfalfa production in Nebraska. Univ. of Nebraska Res. Bull. 214.

Foy, C.D. 1964. Toxic factor in acid soils of the southeastern United States as related to the response of alfalfa to lime. USDA Prod. Res. Rep. 80, U.S. Govt. Printing Office, Washington, DC.

Foyer, C.H. 1987. The basis for source-sink interaction in leaves. *Plant Physiol. Biochem.* **25**(5):649–657.

Freer, M. 1981. The control of food intake by grazing animals. pp. 105–124. *In* F.H.W. Morley (ed.). *Grazing Animals.* Elsevier, Amsterdam.

Friedman, T., and M. Horowitz. 1971. Biologically active substances in subterranean parts of purple nutsedge. *Weed Sci.* **19**(4):398–401.

Fritz, J.O., K.J. Moore, and C.A. Roberts. 1987. Chemical regulation of quality and botanical composition of alfalfa–grass mixtures. *For. Grassl. Conf.* 1987:166–170.

Frost, J.P. 1988a. Effects on crop yields of machinery traffic and soil loosening. Part 1. Effects on grass yield of traffic frequency and date of loosening. *J. Agric. Eng. Res.* **39**(4):301–312.

Frost, J.P. 1988b. Effects on crop yields of machinery traffic and soil loosening. Part 2. Effects on grass yield of soil compaction, low ground pressure tyres and date of loosening. *J. Agric. Eng. Res.* **40**(1):57–69.

Fuchs, M. and C.B. Tanner. 1966. Infrared thermometry of vegetation. *Agron. J.* **58**(6):597–601.

Gale, J.A. 1988. A simple model to predict optimal harvest time of alfalfa using near infrared reflectance spectroscopy, environmental, morphological, and growth parameters. M.S. Thesis, Utah State University, Logan, UT.

Gallaher, R.N., D.A. Ashley, and R.H. Brown. 1975. ^{14}C-photosynthate translocation in C_3 and C_4 plants as related to leaf anatomy. *Crop Sci.* **15**(1):55–59.

Gardner, B.R., B.L. Blad, and D.G. Watts. 1981. Plant and air temperatures in differentially-irrigated corn. *Agric. Meteorol.* **25**(3):207–217.

Garza, T.R., R.F. Barnes, G.O. Mott, and C.L. Rhykerd. 1965. Influence of light intensity, temperature and growing period on the growth, chemical composition and digestibility of Culver and Tanverde alfalfa seedlings. *Agron. J.* **57**(5)417–420.

Gerrit, C., L. Rommanns, and C. Ward. 1983. HAYMARKET: A computerized alfalfa marketing system. Okla. State. Univ. OSU CR-465.

Gerwig, J.L., and G.H. Ahlgren. 1958. The effect of different fertility levels on yield, persistence and chemical composition of alfalfa. *Potash Rev. Subj.* 7. 4th Suite, 1–10.

Gibson, P.B., and W.A. Cope. 1985. White clover. pp. 471–490. *In* N.L. Taylor (ed.). *Clover Science and Technology.* Monograph 25. ASA, CSSA, SSSA, Inc., Madison, WI.

Gindel, I. 1968. Dynamic modifications in alfalfa leaves growing in subtropical conditions. *Physiol. Plant.* **21**(6):1287–1295.

Godfrey, L.D., and K.V. Yeargan. 1987. Effects and interactions of early season pests on alfalfa yield in Kentucky. *J. Econ. Entomol.* **80**(1):248–256.

Goh, K.S., R.C. Berberet, L.J. Young, and K.E. Conway. 1989a. Mortality of the parasite *Bathyplectes curculionis* (Hymenoptera: Ichneumonidae) during epizootics of *Erynia phytonomi* (Zygomycetes: Entomophthorales) in the alfalfa weevil. *Environ. Entomol.* **18**(6):1131–1135.

Goh, K.S., R.C. Berberet, L.J. Young, and K.E. Conway. 1989b. Mortality of *Hypera postica* (Coleoptera: Curculionidae) in Oklahoma caused by *Erynia phytonomi* (Zygomycetes: Entomophthorales). *Environ. Entomol.* **18**(6):964–969.

Goodrich, R.D., and J.C. Meiske. 1974. High-energy silage. pp. 569–680. *In* M.E. Heath, D.S. Metcalfe, and R.F. Barnes (eds.). *Forages: The Science of Grassland Agriculture,* 3rd ed. Iowa State Press, Ames, IA.

Gomm, F.B. 1979. Management alternatives for native meadowlands. Ore. Agric. Expt. Sta. Spec. Rep. 532. 35 pp.

Gordon, C.H., H.M. Irvin, C.G. Melin, H.G. Wiseman, and J.R. McCalmont. 1957. Some experiments in preservation of high moisture hay–crop silage. *J. Dairy Sci.* **40**(11):789–799.

Gordon, C.H., J.C. Derbyshire, W.C. Jacobson, E.A. Kane, C.G. Melin, and J.R. McCalmont. 1961. Comparisons of unsealed and plastic sealed silages for preservation efficiency and feeding value. *J. Dairy Sci.* **44**(6):1113–1121.

Graber, L.F., W.A. Luekel, N.T. Nelson, and W.B. Albert. 1927. Organic food reserves in relation to the growth of alfalfa and some other perennial herbaceous plants. Wisconsin Agric. Exp. Stn. Res. Bull. 80.

Graffis, D.W., and W.D. Pardee. 1968. Effect of seeding rates of spring-seeded *Medicago sativa* (alfalfa) without companion crops in Illinois. *Agron. Abst.* 44. ASA, CSSA, SSSA, Madison, WI.

Graham, J.H., F.I. Frosheiser, D.L. Stuteville, and D.C. Erwin. 1979. A compendium of alfalfa diseases. Amer. Phytol. Soc., 3340 Pilot Knob Road, St. Paul, MN.

Grandfield, C.O. 1935. The trend of organic food reserves in alfalfa roots as affected by cutting practices. *J. Agric. Res.* **50**(8):697–709.

Grant, W.F., and G.C. Marten. 1985. Birdsfoot trefoil. pp. 98–108. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Univ. Press, Ames, IA.

Grava, J. 1971. The sulfur picture in Minnesota. *Sulfur Inst. J.* **7**(1):12–14.

Gray, A.M. 1988. Wyoming Haylist: A hay evaluation and listing service. *For. Grassl. Conf.* 1988:121–125.

Gray, A.M. 1989. Hay quality and marketing improved with Wyoming hay evaluation and listing service. *Proc. Intern. Grassland Cong.* **16**:1007–1008.

Greenfield, P.L., and D. Smith. 1973. Influence of temperature change at bud on composition of alfalfa at first flower. *Agron. J.* **65**(6):871–874.

Greenhill, W.L. 1959. The respiration drift of harvested pasture plants during drying. *J. Sci. Food Agric.* **10**(9):495–501.

Griffith, W.K. 1973. Soil fertility and its relationship to yield and quality of forages. pp. 1–12. *In* W.E. Barksdale (ed.). Proc. 6th Research-Industry Conference, Amer. For. Grassl. Coun., Louisville, Ky.

Griffith, W.K. 1974. Satisfying the nutritional requirement of established legumes. pp. 147–169. *In* D.A. Mays (ed.). *Forage Fertilization.* ASA, CSSA, SSSA, Madison, WI.

Grimes, D.W., W.R. Sheesley, and P.L. Wiley. 1978. Alfalfa root development and shoot regrowth in compact soil of wheel traffic patterns. *Agron. J.* **70**(6):955–958.

Grimson, R.E., G.E. Riemer, R.P. Stilborn, R.J. Volek, and P.K. Gummeson. 1989. Agronomic and chemical characteristics of *Kochia scoparia* (L.) Schrad. and its value as a silage crop for growing beef cattle. *Can. J. Anim. Sci.* **69**(2):383–391.

Grncarevic, M., and F. Radler. 1967. The effect of wax components on cuticular transpiration. Model experiments. *Planta* **75**(1):23–27.

Grovum, W.L. 1987. A new look at what is controlling food intake. *Okla. Agric. Expt. Sta. Misc. Pub.* **121**:1–40.

Grunes, D.L., and H.F. Mayland. 1984. Controlling grass tetany. USDA leaflet 561. 8 pp.

Guilbert, H.R., S.W. Mead, and H.C. Jackson. 1931. The effect of leaching on the nutritive value of forage plants. *Hilgardia* **6**(1)13–26.

Hageman, J.H., J.L. Fowler, and D.A. Schafer. 1978. Nitrogen fertilization of irrigated Russian-thistle forage. II. Some nutritional qualities. *Agron. J.* **70**(6):992–995.

Hageman, J.H., J.L. Fowler, M., Suzukida, V. Salas, and R. LeCaptain. 1988. Analysis of Russian thistle (*Salsola* species) selections for factors affecting forage nutritional value. *J. Range Manage.* **41**(2):155–158.

Haigh, P.M. 1990. Effect of herbage water-soluble carbohydrate content and weather conditions at ensilage on the fermentation of grass silages made on commercial farms. *Grass For. Sci.* **45**(3):263–271.

Haise, H.R., and R.M. Hagan. 1967. Soil, plant, and evaporative measurements as criteria for scheduling irrigation. pp. 577–604. *In* R.M. Hagan *et al.* (eds.). *Irrigation of Agricultural Lands. Agron. Monogr.* 11, ASA, CSSA, SSSA, Madison, WI.

Halim, R.A., D.R. Buxton, M.J. Hattendorf, and R.E. Carlson 1989. Water-stress effects on alfalfa forage quality after adjustment for a maturity differences. *Agron. J.* **81**(2):189–194.

Hall, M.H., C.C. Sheaffer, and G.W. Heichel. 1988. Partitioning and mobilization of photoassimilate in alfalfa subjected to water deficits. *Crop Sci.* **28**(6):964–969.

Hall, M.H., and J.W. Eckert. 1992. Seeding year harvest management of red clover. *J. Prod. Agric.* **5**(1):52–57.

Hall, R.L. 1971. Some implications of the use of potassium chloride in nutrient studies. *J. Aust. Inst. Agric. Sci.* **37**(3):249–252.

Hallock, B.G. 1976. Nitrogen fixation: A consideration of factors which affect root nodule efficiency in *Medicago sativa* L. Ph.D. dissertation. Univ. of Calif., Davis (Diss. Abstr. 77-6338.

Hammes, R.C. 1966. The value of alfalfa–orchardgrass silage and hay cut at different maturities. Virginia Polytechnic Institute, Virg. Agric. Exp. Stn. 14 pp. Blacksburg, VA.

Hanley, T.A. 1982. The nutritional basis for food selection by ungulates. *J. Range. Mgt.* **35**(2):146–151.

Hannaway, D.B., and P.E. Shuler. 1993. Nitrogen fertilization in alfalfa production. *J. Prod. Agric.* **6**(1):80–85.

Hansen, L.H., and C.R. Krueger. 1973. Effect of establishment method, variety, and seeding rate on the production and quality of alfalfa under dryland and irrigation. *Agron. J.* **65**(5):755–759.

Hanson, E.W., and D.J. Hagedorn. 1961. Viruses of red clover in Wisconsin. *Agron. J.* **53**(1):63–67.

Hanson, R.G., and J.M. MacGregor. 1966. Soil and alfalfa plant characteristics as affected by a decade of fertilization. *Agron. J.* **58**(1):3–5.

Hanway, J., G. Stanford, and H.R. Meldrum. 1953. Effectiveness and recovery of phosphorus and potassium fertilizers topdressed on meadows. *Soil Sci. Soc. Amer. Proc.* **17**(4):378–382.

Hanway, J.J. 1963. Growth stages of corn (*Zea mays,* L.). *Agron. J.* **55**(5):487–492.

Hanway, J.J. 1966. How a corn plant develops. Spec. Rpt. No. 48. Iowa State Univ., Coop. Ext. Serv., Ames, IA.

Hanway, J.J., and H.E. Thompson. 1967. How a soybean plant develops. Spec. Rpt. 53. Iowa State University, Coop. Ext. Ser., Ames, IA.

Harlan, J.R. 1983. The scope of collection and improvement of forage plants. pp. 3–14. *In* J.G. McIvor and R.A. Bray (eds.). Genetic Resources of Forage Plants. CSIRO, 314 Albert Street, East Melbourne, Australia.

Harrigan, T.M. 1988. Rotary disk mower–conditioners. Coop. Ext. Serv., Ext. Bul. E-2116, Michigan State University, East Lansing, MI.

Harrigan, T.M. and C.A. Rotz. 1994. Net, plastic, and twine-wrapped large round bale storage loss. *Appl. Eng. Agric.* **10**(2):189–194.

Harrington, R. 1997. How John Deere tractors and implements work. American Society of Agricultural Engineers, 2950 Niles Road, St. Joseph, MI.

Hart, R.H., W.H. Marchant, J.L. Butler, R.E. Hellwig, W.C. McCormic, B.L. Southwell, and G.W. Burton. 1976. Steer gains under six systems of coastal bermudagrass utilization. *J. Range Mgt.* **29**(5):372–375.

Hart, R.H., H.R. Haise, D. D. Walker, and R.D. Lewis. 1980. Mountain meadow management: 12 years of variety, fertilization, irrigation, and renovative research. USDA ARR-W-16. 29 pp.

Harward, M.E., T.T. Chao, and S.C. Fang. 1962. The sulfur status and sulfur supplying power of Oregon soils. *Agron. J.* **54**(2):101–106.

Hatch, M.D., and C.R. Slack. 1966. Photosynthesis by sugar-cane leaves. A new carboxylation reaction and the pathway of sugar formation. *Biochem. J.* **101**(1):103–111.

Hatch, M.D., and C.R. Slack. 1968. A new enzyme for the interconversion of pyruvate and phosphopyruvate and it role in the C_4 dicarboxylic acid pathway of photosynthesis. *Biochem. J.* **106**(1):141–146.

Hatfield, R.D. 1989. Structural polysaccharides in forages and their degradability. *Agron. J.* **81**(1):39–46.

Haynes, J.L., and L.E. Thatcher. 1950. Band seeding method for meadow crops. *Ohio Farm Home Res.* **35**(262):3–5.

Heale, J.B., and I. Issac. 1963. Wilt of lucern by species of *Verticilium.* IV. Pathogenicity of

V. albo-atrum and *V. dahliae* to lucerne and other crops: Spread and survival of *V. albo-atrum* in soil and in weeds; Effect upon lucern production. *Ann. Appl. Biol.* **52**(3):439–451.

Heath, M.E., R.F. Barnes, and D.S. Metcalfe. 1973. *Forages: The Science of Grassland Agriculture,* 3rd ed. The Iowa State Press, Ames, IA.

Heath, M.E., D.S. Metcalfe, and R.F. Barnes. 1985. *Forages: The Science of Grassland Agriculture,* 4th ed. The Iowa State Press, Ames, IA.

Heatherly, L.G. 1975. Root and shoot development of grain sorghum (*Sorghum bicolor* (L.) Moench) under field conditions. Ph.D. Diss. University of Missouri, Columbia (Diss. Abstr. 76-7500).

Hegde, R.S., and D.A. Miller. 1992. Concentration dependency and stage of crop growth in alfalfa autotoxicity. *Agron. J.* **84**(6):940–946.

Heichel, G.H., and C.P. Vance. 1979. Nitrate-N and *Rhizobium* strain roles in alfalfa seedling nodulation and growth. *Crop Sci.* **19**(4):512–518.

Heichel, G.H., D. K. Barnes, and C.P. Vance. 1981. Nitrogen fixation of alfalfa in the seeding year. *Crop Sci.* **21**(2):330–335.

Heichel, G.H. 1983. Alfalfa. pp. 127–155. *In* I.D. Teare and M.M. Peet (eds.). *Crop–Water Relations.* John Wiley & Sons, New York.

Heichel, G.H., D.K. Barnes, C.P. Vance, and K.I. Henjum. 1984. N_2 fixation, and N and dry matter partitioning during a 4-year alfalfa stand. *Crop. Sci.* **24**(4):811-815.

Heinrichs, D.H. 1968. Alfalfa in Canada. Canada Dep. of Agric. Pub. 1377.

Helyar, K.R., and A.J. Anderson. (1971) Effects of lime on the growth of five species on aluminum toxicity and on phosphorus availability. *Aust. J. Agric. Res.* **22**(5):707–721.

Henning, J.C. 1990. Urea for preservation of moist hay. *Anim. Feed Sci. Tech.* **31**(3–4):193–204.

Henry, C. 1990. Hay exporters seek new customers. *Hay For. Grow.* **5**(3):46–47.

Hester, W. 1978. Take a hard look at the big S. *Fert. Prog.* **9**(4):20–22, 24, 108.

Hicks, P.M., P.L. Mitchell, E.P. Dunigan, L.D. Newsom, and P.K. Bollich. 1984. Effect of three-cornered alfalfa hopper (Homoptera: Membracidae) feeding on translocation and nitrogen fixation in soybeans. *J. Econ. Entomol.* **77**(5):1275–1277.

Hidiroglou, M., P. Dermine, H.A. Hamilton, and J.E. Troelsen. 1966. Chemical composition and *in vitro* digestibility of forage as affected by season in northern Ontario. *Can. J. Plant Sci.* **46**(2):101–109.

Higley, L.G., L.L. Karr, and L.P. Pedigo. 1989. *Manual of Entomology and Pest Management,* pp. 128–138. MacMillan Publ. Co., New York, NY.

Hill, D.S. 1987. *Agricultural Insect Pests of Temperate Regions and Their Control.* Cambridge University Press, Cambridge.

Hill, R.R., Jr. and R.R. Kalton. 1976. Current philosophies in breeding for yield. p. 51. *In* D.K. Barnes (sec.) Rep. 25th Alfalfa Improve. Conf., 13–15 July, Ithaca, NY. USDA–SEA, Peoria, IL.

Hill, R.R., Jr., J.S. Schenk, and R.F. Barnes. 1988. Breeding for yield and quality. pp. 809–825. *In* A.A. Hanson, D.K. Barnes, and R.R. Hill, Jr. (eds.). *Alfalfa and Alfalfa Improvement.* Agron. Monogr. 29, ASA, CSSA, SSSA, Madison, WI.

Hinojosa, R.D., III, H.E. Kiesling, and G.P. Lofgreen. 1985. Digestibility of diets and performance of growing feedlot steers fed alfalfa and kochia roughages. *J. Anim. Sci.* (Suppl.) **63**(648):427.

Hoeft, R.G., and L.M. Walsh. 1970. Alfalfa and corn response to sulfur. *Better Crops Plant Food* **54**(2):28–31.

Hoffman, E.J., and M.A. Bradshaw. 1937. Losses of organic substance in spontaneous heating of alfalfa hay. *J. Agr. Res.* **54**(3):159–184.

Hoffman, G.D., D.B. Hogg, and G.M. Boush. 1991. Potato leafhopper (Homoptera: Cicadellidae) life history traits on water-stressed alfalfa in the early regrowth and bud stage. *Environment. Entomol.* **20**(4):1058-1066.

Hofstra, G., and J.D. Hesketh. 1969. Effects of temperature on the gas exchange of leaves. *Planta* **85**(3):228–237.

Hofstra, G., and C.D. Nelson. 1969. A comparative study of translocation of assimilated ^{14}C from leaves of different species. *Planta (Berl.)* **88**(1):103–112.

Hoglund, C.R. 1964. Comparative losses and feeding value of alfalfa and corn silage crops when harvested at different moisture levels and stored in gas tight and conventional tower silos: An appraisal of research results. Mich. State Univ. Agr. Econ. Publ. 947. *Silo News,* pp. 1–7, Summer 1964. National Silo Association 8725 Rosehill, Suite 210, Lenexa, KS.

Hojjati, S.M., W.C. Templeton, Jr., and T.H. Taylor. 1978. Nitrogen fertilization in establishing forage legumes. *Agron. J.* **70**(3):429–433.

Holland, C., W. Kezar, and Z. Quade (eds.). 1990. Pioneer forage manual—A nutritional guide. Pioneer Hi-Bred Internat., Des Moines, IA. 55 pp.

Hollingsworth, E.B. 1958. Competition by broadleaved and grassy weeds in the establishment of legumes. *Proc. North Central Weed Control Conf.* **15**:19–20.

Holt, D.A., and A.R. Hilst. 1969. Daily variation in carbohydrate content of selected forage crops. *Agron. J.* **61**(2):239–242.

Honig, H. 1979. Mechanical and respiratory losses during pre-wilting of grass. *Proc. Occas. Sym.,* 11th, pp. 201–204. European Grassl. Fed., Brighton.

Horn, D.J. 1988. Ecological approach to pest management. Guilford Press, Div. of Guilford Publications, Inc. New York.

Horn, G.W. and W.M. Beeson. 1969. Effects of corn distillers dried grains with solubles and dehydrated alfalfa meal on the utilization of urea nitrogen in beef cattle. *J. Anim. Sci.* **28**(3):412–417.

Hornby, J.A., D.R. Alverson, and D. Parler. 1987. Laboratory and field susceptibility of alfalfa weevil, *Hypera postica* (Gyllenhal), to *thuringiensis. J. Agric. Entomol.* **4**(3):255–261.

Horrocks, R.D. and J.B. Washko. 1968. Influence of harvesting forages at three stages of maturity on yield, quality, and stand persistence. Penn. Agric. Exp. Stn., Bul. 753.

Horrocks, R.D., and M. Zaifnejad. 1997. Fall management of alfalfa in the Intermountain West. *J. Prod. Agric.* **10**(1):17–18, 96–101.

Horrocks, R.D., T.A. Kerby, and D.R. Buxton. 1978. Carbon source for developing bolls in normal and superokra leaf cotton. *New Phytol.* **80**(2):335–340.

Horton, G.M.J., and G.M. Steacy. 1979. Effect of anhydrous ammonia treatment on the intake and digestibility of cereal straws by steers. *J. Anim. Sci.* **48**(5):1239–1249.

Hoveland, C.S., E.L. Carden, G.A. Buchanan, E.M. Evans, W.B. Anthony, E.L. Mayton, and H.E. Burgess. 1969. Yuchi arrowleaf clover. Auburn., Alabama Agr. Exp. Stn. Bull. 396.

Hoveland, C.S., G.A. Buchanan, and M.C. Harris. 1976. Response of weeds to soil phosphorus and potassium. *Weed Sci.* **24**(2):194–201.

Hoveland, C.S., R.G. Durham, M.D. Richardson, and T.H. Terrill. 1990. Cutting management of endophyte-free tall fescue. *For. Grassl. Conf.* 1990:125–128.

Hower, A.A., and P.W. Flinn. 1986. Effects of feeding by potato leafhopper nymphs (Homoptera: Cicadellidae) on growth and quality of established stand alfalfa. *J. Econ. Entomol.* **79**(3):779–784.

Hsiao, T.C. 1973. Plant responses to water stress. *Ann. Rev. Plant Physiol.* **24**:519–570.

Huffaker, R.C., and A. Wallace. 1959. Effect of Na and K levels on Na distribution in some plant species. *Soil Sci.* **88**(1):80–82.

Huhnke, R.L., G.H. Brusewitz, and E.M. Barnes. 1992. Large round alfalfa hay bales covered with Nutri-Shield. *Appl. Eng. Agric.* **8**(2):171–174.

Hull, J.L., J.H. Meyer, and R. Kromann. 1961. Influence of stocking rate on animal and forage production from irrigated pasture. *J. Anim. Sci.* **20**(1):46–52.

Hunter, Elmer C. 1963. Forage programs and cattle systems, Colorado mountain–meadow cattle ranches. USDA ERS-100. 18 pp.

Hutchins, S.H., D.R. Buxton, and L.P. Pedigo. 1989. Forage quality of alfalfa as affected by potato leafhopper feeding. *Crop Sci.* **29**(6):1541–1545.

Hutchins, S.H., and L.P. Pedigo. 1989. Potato leafhopper-induced injury on growth and development of alfalfa. *Crop Sci.* **29**(4):1005–1011.

Hutton, C.M. 1970. Tropical pastures. *Adv. Agron.* **22**:1–73.

Hyde, Robert M., and C. Owensby. 1975. Bluestem haying. Kan. Agric. Ext. Serv. Leaflet 281. 6 pp.

Idso, S.B. 1990a. The carbon dioxide/trace gas greenhouse effect: Greatly overestimated. pp. 19–26. *In* B.A. Kimball, N.J. Rosenberg, and L.H. Allen, Jr. (eds.) *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture.* ASA Special Pub. No. 53. American Society of Agronomy, Madison, WI.

Idso, S.B. 1990b. Interactive effects of carbon dioxide and climate variables on plant growth. pp. 61–69. *In* B.A. Kimball, N.J. Rosenberg, and L.H. Allen, Jr. (eds.) *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture.* ASA Special Pub. No. 53. American Society of Agronomy, Madison, WI.

Idso, S.B., R.J. Reginato, D.C. Reicosky, and J.L. Hatfield. 1981. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. *Agron. J.* **73**(5):826–830.

IFDC. 1979. Sulfur in the tropics. Tech. Bull IFDC-T-12. The Sulphur Institute and the International Fertilizer Development Center, Muscle Shoals, AL.

Ishler, V.A., A.J. Heinrichs, D.R. Buckmaster, R.S. Adams, and R.E. Graves. 1991. Harvesting and utilizing silage. Ext. Circ., Penna. State Univ., Agric. Ext. Serv. (396), 34 pp. University Park, PA.

Jackson, R.D., S.B. Idso, R.J. Reginato, and P.J. Pinter, Jr. 1981. Canopy temperature as a crop water stress indicator. *Water Res. Res.* **17**(4):1133–1138.

Jackson, R.D. 1982 Canopy temperature and crop water stress. pp. 43–85. *In* D. Hillel (ed.). *Advances in Irrigation,* Vol. 1. Academic Press, New York.

Jackson, W.A. 1967. Physiological effects of soil acidity. pp. 43–124. *In* R.W. Pearson and F. Adams (eds.) *Soil Acidity and Liming.* Agron. Mono. 12, ASA, CSSA, SSSA. Madison, WI.

Jacobs, J.A., T.R.Peck, and M.W. Walker. 1970. Efficiency of fertilizer topdressings on alfalfa. Univ. of Illinois Bull. 738.

Jacobs, J.J. 1983. Economics of renovating mountain hay meadows. Proc. Intern. Grassland Cong. pp. 836–838. *In* J.A. Smith and V.W. Hays (eds.) *Proc. Int. Grassl. Cong.* 14th 15–24 June, 1981. Lexington, KY. Westview Press, Boulder, CO.

Jaindl, R.G., and S.H. Sharrow. 1987. Winter grazing effects on a ryegrass–white clover pasture. *Soc. Range Mgt.,* Abst. Papers **40**:187.

James, D.W., and A.I. Dow. 1972. Source and degree of soil variation in the field: The problem of sampling for soil tests and estimating soil fertility status. Washington Agric. Exp. Stn. Bull. 749.

James, D.W., P.V. Fonnesbeck, R.C. Lamb, and D.H. Clark. 1985. Factors affecting the quality of alfalfa hay. *Utah Sci.* **46**(2):52–53.

James, D.W., and K.L. Wells. 1990. Soil sample collection and handling: techniques based on source and degree of field variability. pp. 25–44. *In* R.L. Westerman (ed.). *Soil Testing and Plant Analysis.* 3rd ed. Soil Science Society of America Book Series Number 3. Soil Science Society of America, Inc. Madison, WI.

James, D.W., S.S. Dhurmal, M.D.Rumbaugh, and T.A. Tindall. 1995. Inheritance of potassium–sodium nutritional traits in alfalfa. *Agron. J.* **87**(4):681–686.

James, L.F., R.F. Keeler, A.E. Johnson, M.C. Williams, E.H. Cronin, and J.D. Olsen. 1980. Plants poisonous to livestock in the western States. USDA Agric. Info. Bul. 415. 90 pp.

James, W.C., P.S. Teng, and F.W. Nutter. 1991. Estimated losses of crops from plant pathogens. pp. 15–50. *In* D. Pimentel (ed.). *Handbook of Pest Management in Agriculture,* 2nd ed. Vol. 1. CRC Press, Boca Raton, FL.

Janghorbani, M., S. Roberts, and T.L. Jackson. 1975. Relationship of exchangeable acidity to yield and chemical composition of alfalfa. *Agron. J.* **67**(3):350–354.

Janis, C. 1976. The evolutionary strategy of the *Equidae* and the origins of rumen and cecal digestion. *Evolution* (Lawrence, Kans.) **30**(4):757–774.

Jaster, E.H., C.M. Fisher, and D.A. Miller. 1985. Nutritive value of oatlage, barley/pea, pea, oat/pea, pearl millet, and sorghum as silage grown under a double cropping forage system for dairy heifers. *J. Dairy Sci.* **68**(11):2914-2921.

Jean, F.C., and J.E. Weaver. 1924. Root behavior and crop yield under irrigation. Pub. 357. Carnegie Institute, Washington, DC.

Jenny, H. 1980. State factor parent material. pp. 246–275. *In* W.D. Billings, F.Golley, O.L.-Lange, J.S. Olson, and K. Remmert (eds.). *The Soil Resource: Origin and Behavior.* Ecological Studies, Vol. 37. Springer-Verlag, New York.

Jensen, E.H., M.A. Massengale and D.O. Chilcote. 1967. Environmental effects on growth and quality of *alfalfa.* Nev. Agric. Expo. Stn. Western Regional Res. Pub. T9.

Jensen, E.H., R.R. Skivington, and V.R. Bohman. 1981. Dormant season grazing of alfalfa. Nev. Agric. Expt. Sta. R-141. 4 pp.

Jensen, E.H., R.O. Gifford, G.C. McGourty, and R.R. Skivington. 1982. The effect of harvest traffic on alfalfa yield. Max C. Fleischmann College of Agriculture, University of Nevada, R-150.

Jensen, M.E. (ed.) 1973. Consumptive use of water and irrigation requirements. *Irrig. Drain. Div.,* Amer. Soc. Civ. Eng., New York, NY.

Jensen, M.E. (ed.) 1974. Consumptive use of water and irrigation requirements. *Irrig. Drain. Div.,* Amer. Soc. Civ. Eng., New York, NY.

Jensen, R.G., and J.T. Bahr. 1977. Ribulose-1,5-bisphosphate carboxylase oxygenase. *Ann. Rev. Plant Physiol.* **28**:379–400.

Johnson, D.G., D.E. Otterby, R.G. Lundquist, J.A. True, F.A. Benson, R.E. Smith, L.K. Lindor, and R.C. Stommes. 1984. Yield and quality of alfalfa as affected by harvesting and storage methods. *J. Dairy Sci.* **67**(10):2475-2480.

Johnson, J.J, Shanahan, J.F., F.C. Schweissing, H.M. Golus, C.H. Pearson, J.P. Hain, C.L. Johnson, and M.A. Weimer. 1993. *Making Better Decisions.* 1997 Colorado corn hybrid performance trials. Tech. Rpt. 97-12, Agric. Exp. Stn. Colorado State University, Ft. Collins, CO.

Johnson, K.D., J. B. Santini, and D.C. Petritz. 1990. Development of a computer-based hay locator program. *For. Grassl. Conf.* 1990:231–235.

Johnson, K.J.R., E.L. Sorensen, and E.K. Horber. 1980a. Resistance in glandular-haired annual *Medicago* species to feeding by adult alfalfa weevils (*Hypera postica). Environ. Entomol.* **9**(1):133–136.

Johnson, K.J.R., E.L. Sorensen, and E.K. Horber. 1980b. Resistance of glandular-haired *Medicago* species to oviposition by alfalfa weevils (*Hypera postica*). *Environ. Entomol.* **9**(2):241–244.

Johnson, K.J.R., E.L. Sorensen, and E.K. Horber. 1981. Behavior of adult alfalfa weevils (*Hypera postica*) on resistant and susceptible *Medicago* species in free-choice preference tests. *Environ. Entomol.* **10**(5):580–585.

Johnson, T.R., J.W. Thoms, K.R. Ahrens, Z.R. Helsel, and C.M. Hansen. 1981. Ammonia treatment of wet hay. *J. Anim. Sci.* **53**(suppl. 1)275(abst).

Jones, D.G., and S.J. Morley. 1981. The effect of pH on host plant "preference" for strains of *Rhizobium trifolii* using fluorescent ELISA for strain identification. *Ann. Appl. Biol.* **97**(2):183–190.

Jones, G.D., and W.M. Moschler. 1966. Alfalfa response to molybdenum on Tatum soil. Virginia Poly. Inst. Res. Rept. 115.

Jones, H.G. 1979. Visual estimation of plant water status in cereals. *J. Agric. Sci.* **92**(1):83–89.

Jones, J.B., Jr., B. Wolf, and H.A. Mills. 1991. *Plant Analysis Handbook.* Micro-Macro Publishing, Inc. 183 Paradise Blvd, Suite 108, Athens, GA 30607.

Jones, L. 1990. The effect of formic acid on the rate of water loss from cut grass and lucerne. *Grass For. Sci.* **45**(1):83–90.

Jones, L. 1991. Laboratory studies on the effect of potassium carbonate solution on the drying of cut forage. *Grass For. Sci.* **46**(2):153–158.

Jordan, T.N. 1989. *Weeds Affecting Alfalfa Quality.* Cert. Alf. Seed Coun., Inc., P.O. Box 2023, Woodland, CA 95695.

Jorgensen, N.A., and J.W. Crowley. 1972. Corn silage for Wisconsin cattle. Wisconsin Coop. Ext. Prog. Bull. A1178.

Jung, G.A., R.L. Reid, and J.A. Balasko. 1969. Studies on yield, management, persistence, and nutritive value of alfalfa in West Virginia. West Va. Agric. Exp. Stn. Bull. 581T.

Jung, G.A., and B.S. Baker. 1985. Orchardgrass. pp. 224–232. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.) *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Press, Ames, IA.

Justin, J.R., and M.A. Jackson. 1985. Sunflowers in New Jersey. Coop. Ext. Serv., Cook Coll. New Brunswick, NJ.

Kalu, B.A., and G.W. Fick. 1981. Quantifying morphological development of alfalfa for studies of herbage quality. *Crop Sci.* **21**(2):267–271.

Kalu, B.A., and G.W. Fick. 1983. Morphological stage of development as a predictor of alfalfa herbage quality. *Crop Sci.* **23**(6):1167–1172.

Kalu, B.A., S.C. Mueller, L.M. Richter, and G.W. Fick. 1987. The stages of alfalfa development for determining mean stage. *Agron. Mimeo.* 87-6, Dept. of Agron., Cornell Univ., Ithaca, NY.

Kane, E.A., and L.A. Moore. 1959. Digestibility of Beltsville first-cut forage as affected by date of harvest. *J. Dairy Sci.* **42**(5):936(Abst.)

Kanemasu, E.T., M.L. Wesely, B.B. Hicks, and J.L. Heilman. 1979. Techniques for calculating energy and mass fluxes. pp. 156–182. *In* B.J. Barfield and J.F. Gerber (eds.) Modification of the aerial environment of plants. Monogr. 2. Amer. Soc. Agr. Eng., St. Joseph, MI.

Karachi, M., H.E. Kiesling, R.D. Pieper, G.M. Southward, and R.E. Kirksey. 1988. Nutritive and toxic properties of *Kochia scoparia* (L.) Schrad. herbage under varied agronomic and grazing systems. N. Mex. Agric. Expt. Sta. Bul. 731. 52 pp.

Kellems, R.O., K.L. Powell, R. Jones, D. Andrus, and M.V. Wallentine. 1990. Comparing sunflower/corn silage to corn silage as a feed for replacement dairy heifers. *J. Dairy Sci.* **73**(Suppl. no. 1):P.123.

Kemper, W.D., and M. Amemiya. 1957. Alfalfa growth as affected by aeration and soil moisture stress under flood irrigation. *Soil Sci. Soc. Am. Proc.* **21**(6):657–660.

Kephart, K.D., L.G. Higley, D.R. Buxton, and L.P. Pedigo. 1990. Cicer milkvetch forage yield, quality, and acceptability to insects. *Agron. J.* **82**(3):477–483.

Kephart, K.D., E.K. Twidwell, R. Bortnem, and A. Boe. 1992. Alfalfa yield component responses to seeding rate several years after establishment. *Agron. J.* **84**(5):827–831.

Kerr, T.W., Jr. and I.H. Stuckey. 1956. Insects attacking red clover in Rhode Island and their control. *J. Econ. Entomol.* **49**(3):371–375.

Kersbergen, R.J., and B.A. Barton. 1986. High moisture hay–stability during storage as influenced by chemical treatment. pp. 177–181. *In* Proc. For. Grassl. Coun., 15–17 Apr. 1986. Athens, GA. Amer. For. Grassl. Coun., Lexington, KY.

Keim, F.D., A.L. Frolik, and G.W. Beadle. 1932. Studies of prairie hay in north central Nebraska. Neb. Agric. Expt. Sta. Res. Bul. 60. 54 p.

Kiesling, H.E., R.E. Kirksey, D.M. Hallford, M.E. Grigsby, and J.P. Thilsted. 1984. Nutritive value and toxicity problems of *Kochia* for yearling steers. N. Mex. Agric. Expt. Sta. Res. Rep. 546. 8 pp.

Kiesselbach, T.A., J.C. Russell, and A. Anderson. 1929. The significance of subsoil moisture in alfalfa production. *J. Amer. Soc. Agron.* **21**(3):241–268.

Kilmer, V.J. 1974. Nutrient losses from grasslands through leaching and runoff. pp. 341–362. *In* D.A. Mays (ed.). *Forage Fertilization.* ASA, CSSA, and SSSA, Madison, WI.

King, K.M., and D.H. Greer. 1986. Effects of carbon dioxide enrichment and soil water on maize. *Agron. J.* **78**(3):515–521.

Kirby, J.M. 1989. Shear damage beneath agricultural tyres: A theoretical study. *J. Agric. Eng. Res.* **44**(3):217–230.

Kitchen, N.R., D.D. Buchholz, and C.J. Nelson. 1990. Potassium fertilizer and potato leafhopper effects on alfalfa growth. *Agron. J.* **82**(6):1069–1074.

Klebesadel, L.J. 1965. Response of native bluejoint grass (*Calamagrostis canadensis*) in subartic Alaska to harvest schedules and fertilizers. *Proc. Internat. Grassland Cong.* **9:**1309–1314.

Klingebiel, A.A., and P.H. Montgomery. 1964. *Land Capability Classification.* USDA Agric. Handbook 210. 21 pp.

Klinner, W.E. 1975. Design and performance characteristics of an experimental crop conditioning system for difficult climates. *J. Agric. Engr. Res.* **20**(2):149–165.

Klinner, W.E., and C.M. Wood. 1981. An experimental field rig for collecting forage crops and separating out stones and metal objects. Dep. Note 1954, Natl. Inst. Agric. Eng., Silsoe.

Knapp, W.R., D.A. Holt, and V.L. Lechtenberg. 1975. Hay preservation and quality improvement by anhydrous ammonia treatment. *Agron. J.* **67**(6):766–769.

Knutson, H., S.G.F. Smith, and M.H. Blust. 1983. Grasshoppers: Identifying species of economic importance. Bull. S-21. Coop. Ext. Serv., Kansas State Univ.

Koegel, R.G., R.J. Straub, and K.J. Shinners. 1985a. Ammonia treatment of large and small hay packages. *Trans. ASE* **28**(3):726–730.

Koegel, R.G., R.J. Straub,, and R.P. Walgenbach. 1985b. Quantification of mechanical losses in forage harvesting. *Trans. ASAE* **28**(4):1047–1051.

Kommedahl, T., J.B. Kotheimer, and J.V. Bernardini. 1959. The effects of quackgrass on germination and seedling development of certain crop plants. *Weeds* **7**(1):1–12.

Kreitlow, K.W. 1953. The northern forage grasses. pp. 262–267. *In* A. Stefferud (ed.). *Plant Diseases.* USDA Yearbook Agric., Washington, DC.

Kresge, C.B. and S.E. Younts. 1962. Effect of various rates and frequencies of potassium application on yield and chemical composition of alfalfa and alfalfa–orchardgrass. *Agron. J.* **54**(4):313–316.

Kronberg, S.L., K.M. Havstad, E.L. Ayers, and D.E. Doornbos. 1986. Influence of breed on forage intake of range beef cows. *J. Range Mgt.* **39**(5):421–423.

Kroth, E.M., and R. Mattas. 1976. Soil test values of several soils under forage crops. *Commun. Soil Sci. Plant Anal.* **7**(8):713–725.

Krotkov, G., V.C. Runeckles, and K.V. Thimann. 1958. Effect of light on the CO_2 absorption and evolution by Kalanchoe, wheat and pea leaves. *Plant Physiol.* **33**(4):289–292.

Kunelius, H.T. 1974. Effects of weed control and N fertilization at establishment on the growth and nodulation of alfalfa. *Agron. J.* **66**(6):806–809.

Kung, L., Jr., D.B. Grieve, J.W. Thomas, and J.T. Huber. 1984. Added ammonia or microbial inocula for fermentation and nitrogenous compounds of alfalfa ensiled at various percents of dry matter. *J. Dairy Sci.* **67**(2):299–306.

Kust, C.A., and D. Smith. 1961. Influence of harvest management on level of carbohydrate reserves, longevity of stands, and yields of hay and protein from Vernal alfalfa. *Crop Sci.* **1**(4):267–269.

Lacefield, G.D. 1988. Alfalfa hay quality makes the difference. Univ. of Kentucky, Coll. Of Agric., Coop. Ext. Ser., GR-137.

Lacey, J., and K.A. Lord. 1977. Methods for testing chemical additives to prevent moulding of hay. *Ann. Appl. Biol.* **87**(3):327–325.

Lamp, W.O., K.V. Yeargan, R.F. Norris, C.G. Summers, and D.G. Gilchrist. 1985. Multiple pest interactions in alfalfa. pp. 345–364. *In* R.E. Frisbie and P.L. Adkisson (eds.). *IPM on Major Agricultural Systems—A Symposium.* Texas Agric. Exp. Stn. Publ. MP-1616.

Lamp, W.O., G.R. Nielsen, and G.P. Dively. 1991. Insect pest–induced losses in alfalfa: Pattern in Maryland and implications for management. *J. Econ. Entomol.* **84**(2):610–618.

Langer, R.H.M., and T.D. Steinke. 1965. Growth of lucerne in response to height and frequency of defoliation. *J. Agric. Sci.* **64**(3):291–294.

Langston, C.W., *et al.* 1958. Microbiology and chemistry of grass silage. USDA Tech. Bul. 1187. US Govt. Printing Office, Washington, DC.

Lanini, W.T., S.B. Orloff, R.N. Vargas, J.P. Orr, V.L. Marble, ans S.R. Grattan. 1991. Oat companion crop seeding rate effect on alfalfa establishment, yield, and weed control. *Agron. J.* **83**(2):330–333.

Lanyon, L.E., J.E. Baylor, and W.K. Waters. 1983. Understanding alfalfa nutrient uptake. *Better Crops Plant Food* **67**(spring):12-13.

Lanyon, L.E., and W.K. Griffith. 1988. Nutrition and fertilizer use. pp. 333–372. *In* A.A. Hanson, D.K. Barnes, and R.R. Hill, Jr. (eds.) *Alfalfa and Alfalfa Improvement.* Agron. Monogr. 29, ASA, CSSA, SSSA. Madison, WI.

Larsen, H.J., and R.F. Johannes. 1965. Summer forage: Stored feeding, green feeding, and strip grazing. Wisc. Agric. Expt. Sta. Res. Bul. 257. 32 pp.

Latheef, M.A., R.C. Berberet, J.F. Stritzke, J.L. Caddel, and R.W. McNew. 1992. Productivity and persistence of declining alfalfa stands as influenced by alfalfa weevil, weeds, and early first harvest in Oklahoma. *Can. Entomol.* **124**(1):135–144.

Laude, H.M. 1956. The seedling emergence of grasses as affected by low temperature. *Agron. J.* **48**(12):558–560.

Laughlin, W.M., G.R. Smith, and M.A. Peters. 1981. Sulfur, manganese, molybdenum, and magnesium influences on bromegrass forage yield and composition in southcentral Alaska. *Commun. Soil Sci. Plant Anal.* **12**(4):299–317.

Lawrence, T., and M.R. Kilcher. 1962. The effect of fourteen root extracts upon germination and seedling length of fifteen plant species. *Can. J. Plant Sci.* **42**(2):308–312.

Lawton, K., M.B. Tesar, and B. Kawin. 1954. Effect of rate and placement of superphosphate on the yield and phosphorus absorption of legume hay. *Soil Sci. Soc. Amer. Proc.* **18**(4):428–432.

Leath, K.T. 1990. Crown and root rot complexes. pp. 43–44. *In* D.L. Stuteville and D.C. Erwin (eds.) *A Compendium of Alfalfa Diseases.* American Phytopathological Society, St. Paul, MN.

Leath, K.T., and R.A. Byers. 1977. Interaction of *Fusarium* root rot with pea aphid and potato leafhopper feeding on forage legumes. *Phytopathology* **67**(2):226–229.

Leath, K.T., and O.W. Barnett. 1981. Viruses infecting red clover in Pennsylvania. *Plant Dis.* **65**(12):1016–1017.

Lechtenberg, V.L., D.A. Holt, and H.W. Youngberg. 1971. Diurnal variation in nonstructural carbohydrates, *in vitro* digestibility, and leaf to stem ratio of alfalfa. *Agron. J.* **63**(5):719–724.

Lechtenberg, V.L., and D.C. Petritz. 1982. Can you afford to store large bales inside? *Hoard's Dairyman* **127**(11):796, 841.

LeClerc, J.A. 1939. Losses in making hay and silage. pp. 992–1016. *In* G. Hambidge (ed.). *Food and Life.* USDA Yearbook, 1939. U.S. Govt. Printing Office, Washington, DC.

LeClerg, E.L. 1979. Nature and extent of damages caused by plant pests. pp. 1–38. *In* W.B. Ennis Jr. (ed.). *Introduction to Crop Protection.* Amer. Soc. Agron. and Crop Sci. Soc. Amer., Madison, WI.

LeClerg, E.L., W.H. Leonard, and A.G. Clark. 1962. *Field Plot Technique,* 2nd ed. Burgess Publ. Co., Minneapolis, MN.

LeCroix, R.L. 1969. Cold tolerance of alfalfa as influenced by source of potassium. M.S. Thesis, Univ. of Wisconsin, Madison.

Lee, C., and D. Smith. 1972. Influence of nitrogen fertilizer on stands, yields of herbage, and protein and nitrogenous fractions of field-grown alfalfa. *Agron. J.* **64**(4):527–530.

Lee, J.W., P.D. Colyer, and S.S. Quisenberry. 1990. The effect of insect defoliation on the presence and severity of *Fusarium* crown-rot in alfalfa. *J. Entomol. Sci.* **25**(2):253–260.

Lema, F., N.A. Jorgensen, J.M. Scholl, H.W. Ream, and E.L. Jensen. 1977. *In vivo* and *in vitro* measures as predictors of the nutrition value of alfalfa and bromegrass hays. Wis. Agric. Exp. Stn. Res. Bull. R2903.

Lenssen, A.W., E.L. Sorensen, G.L. Posler, and L.H. Harbers. 1989. Sheep preference for perennial glandular-haired and eglandular *Medicago* populations. *Crop Sci.* **29**(1):65–68.

Le Tourneau, D., and H.G. Heggeness. 1957. Germination and growth inhibitors in leafy spurge foliage and quackgrass rhizomes. *Weed Sci.* **5**(1):12–19.

Lewis, Rulon D. 1960. Mountain meadow improvement in Wyoming. Wyo. Agric. Expt. Sta. Bul. 350R. 19 p.

Libbin, J.D., B.E. Mayberry, and L.B. Catlett. 1988. Market value of alfalfa quality characteristics. *J. Amer. Soc. Farm. Mge. Rural Appr.* **52**(2):94–97.

Liebl, R.A., and A.D. Worsham. 1983. Inhibition of pitted morning glory (*Ipomoea lacunosa* L.) and certain weed species by phytotoxic components of wheat straw. *J. Chem Ecol.* **9**(8)1027–1043.

Lippke, H. 1990. Intake and digestibility of berseem clover and ryegrass silages. Texas Agric. Exp. Stn., Mar. 1990 (4690–4729), pp. 210–212. College Station, TX.

Lipps, R.C., and R.L. Fox. 1956. Subirrigation and plant nutrition. II. Utilization of phosphorus by alfalfa from the soil surface to the water table. *Soil Sci. Soc. Amer. Proc.* **20**(1):28–32.

Lofgreen, G.P., and W.N. Garrett. 1968. A system for expressing net energy requirements and feed values for growing and finishing beef cattle. *J. Anim. Sci.* **27**(3):793–806.

Lolas, P.C., and H.D. Coble. 1982. Noncompetitive effects of johnsongrass (*Sorghum halepense*) on soybeans (*Glycine max*). *Weed Sci.* **30**(6):589–593.

Lucus, R.E., and B.D. Knezek. 1972. Climatic and soil conditions promoting micronutrient deficiencies in plants. pp. 265–288. *In* J.J. Mortvedt, P.M. Giardana, and W.L. Lindsay (eds.). *Micronutrients in Agriculture.* Soil Sci. Soc. Amer. Madison, WI.

Mader, T.L., J. Dahlquist, and C. Shapiro. 1990. Long-term storage effects on alfalfa losses and quality. Nebraska Beef Cattle Rep. MP-55.

Mahler, R.L. 1983. Influence of pH on yield and N and P nutrition of alfalfa grown on an andic mission silt loam. *Agron. J.* **75**(5):731–735.

Mahler, R.L., J.E. Hammel, and R.W. Harder. 1985. The influence of crop rotation and tillage methods on the distribution of extractable boron in northern Idaho soils. *Soil Sci.* **139**(1):67–73.

Main, C.E., and S.V. Byrne (ed.) 1986. Estimates of crop losses in North Carolina due to plant diseases and nematodes. Dept. Plant Path. Spec. Publ. No. 6, N.C. State Univ., Raleigh, NC.

Manglitz, G.R. 1985. Insects and related pests. pp. 269–294. *In* N.L. Taylor (ed.). *Clover Science and Technology.* Agron. Monogr. 25. ASA, CSSA, ASSA, Madison, WI.

Marble, V.L. 1974. Optimizing alfalfa production in desert areas of the southwestern United States. pp. 75–91. *In* Proc. California/Arizona Low Desert Alfalfa Symp. El Centro, CA. 16–17 January. Univ. of California Coop. Ext. Ser., Davis.

Marble, V.L., and W.C. Templeton. 1985. Development of a national alfalfa quality assessment procedure in the United States. *Proc. Intern. Grassland Cong.* **15**:963–964.

Marks, S., and B.R. Strain. 1989. Effects of drought and CO_2 enrichment on competition between two old-field perennials. *New Phytol.* **111**(2):181–186.

Markus, D.K., and W.R. Battle. 1965. Soil and plant responses to long-term fertilization of alfalfa (*Medicago sativa* L.). *Agron. J.* **57**(6):613–616.

Marten, G.C. 1970. Temperature as a determinant of quality of alfalfa harvested by bloom or age criteria. pp. 506–509. *In* M. J. T. Norman (ed.). Proc. Int. Grassl. Congr., 11th. Surfers Paradise, Queensland, Australia. 13–23 April. University of Queensland Press, St. Lucia, Australia.

Marten, G.C. 1978. The animal–plant complex in forage palatability phenomena. *J. Anim. Sci.* **46**(5):1470–1477.

Marten, G.C. 1984. Analysis of alfalfa hay by near infrared reflectance spectroscopy. pp. 27–30. *In* V.L. Marble (ed.). Proc. Natl. Alfalfa Hay Quality Testing Workshop, Chicago. 22–23 March 1984. Agronomy Ext., Univ. Calif., Davis.

Marten, G.C. 1985. Reed canarygrass. pp. 207-216. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Press, Ames. IA.

Marten, G.C., and R.N. Andersen. 1975. Forage nutritive value and palatability of 12 common annual weeds. *Crop Sci.* **15**(6):821–827.

Marten, G.C., and N.P. Martin. 1986. The future of forage quality evaluation. *For. Grassl. Conf.* 1986:7–19.

Marten, G.C., C.C. Sheaffer, and D.L. Wyse. 1987. Forage nutritive value and palatability of perennial weeds. *Agron. J.* **79**(6):980–986.

Martin, J.H., W.H. Leonard, and D.L. Stamp. 1976. *Principles of Crop Production,* 3rd ed. Macmillan, New York.

Martin, W.E., and J.E. Matocha. 1973. Plant analysis as an aid in the fertilization of forage crops. pp. 393–426. *In* L.M. Walsh and J.D. Beaton (eds.) *Soil Testing and Plant Analysis.* Soil Sci. Soc. Amer., Madison, WI.

Matches, A.G., and J.C. Burns. 1985. Systems of grazing management, 1985. pp. 537–547. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Univ. Press, Ames, IA.

Mayland, H.F. 1986. Factors affecting yield and nutritional quality of crested wheatgrass. *In* K.L. Johnson (ed.). *Crested Wheatgrass: Its Values, Problems, and Myths:* Symposium Proceedings, Logan, Utah, October 3–7, 1983. Utah State Univ., Logan, pp. 215–266.

Mayne, C.S., and F.J. Gordon. 1986. The effect of harvesting system on nutrient losses during silage making. 1. Field losses. *Grass For. Sci.* **41**(1):17–26.

Mays, D.A., and E.M. Evans. 1973. Autumn cutting effects on alfalfa yield and persistence in Alabama. *Agron. J.* **65**(2):290–292.

McAllan, A.B., and R.H. Phipps. 1977. The effect of sample date and plant density on the carbohydrate content of forage maize and changes that occur on ensiling. *J. Agric. Sci.* **89**(3):589–597.

McBratney, J.M. 1984. Productivity of red clover grown alone and with companion grasses: Further studies. *Grass For. Sci.* **39**(2):165–175.

McCallon, S.E.A., and F.R. Weedon. 1940. Toxicity of ammonia, chlorine, hydrogen cyanide, hydrogen sulfide, and sulfur dioxide gasses. II. Fungi and bacteria. *Contrib. Boyce Thompson Inst.* **11**:331–342.

McCalmont, J.R. 1939. Silo types and construction. USDA Farmers Bul. 1820. US Govt. Printing Office. Washington, DC.

McCalmont, J.R. 1960. *Farm Silos.* USDA Misc. Publ. 810. US Govt Printing Office. Washington, DC.

McClaugherty, F.S., and R.C. Carter. 1960. Small grain vs. corn silage for wintering beef calves. Virginia Polytechnic Institute. Virginia Agricultural Experiment Station, 7 pp. Blacksburg, VA.

McCullough, M.E. 1970. Silage research at the Georgia Station. GA Agr. Exp. Sta. Res. Rpt. 75.

McCullough, M.E. 1978. Silage—some general considerations. pp. 1–26. *In* M.E. McCullough (ed.). *Fermentation of Silage—A Review.* Nat'l Feed Ingred. Assoc. West Des Moines, IA.

McDonald, P. 1981. *The Biochemistry of Silage.* John Wiley & Sons. Inc. New York. 226 pp.

McGechan, M.B. 1988. Susceptibility to losses during mechanical silage and haymaking operations in relation to grass dry matter content. *Grass For. Sci.* **43**(4):387–393.

McGechan, M.B. A review of losses arising during the conservation of grass forage: Part 1. Field losses. *J. Agric. Eng. Res.* **44**(1):1–21.

McGill, S. 1991. Baling versus silage-making. *Furrow* **96**(4):22–23.

McGlohon, N.E, J.N. Sasser, and R.T. Sherwood. 1961. Investigations of plant-parasitic nematodes associated with forage crops in North Carolina. North Carolina Agric. Exp. Stn. Tech. Bull. 148.

McHan, F., D. Burdick, and R. Wilson. 1984. Change in organic acids and digestibility of coastal bermudagrass silage treated with monensin. *J. Dairy Sci.* **67**(2):294–298.

McHan, F., R. Spencer, J. Evans, and D. Burdick. 1979. Composition of high and low moisture coastal bermudagrass ensiled under laboratory conditions. *J. Dairy Sci.* **62**(10):1606-1610.

McKee, G.W. 1962. Effects of shading and plant competition on seedling growth and nodulation in birdsfoot trefoil. Pennsylvania Agric. Exp. Stn. Bul. 689. University Park, PA.

McKee, G.W., and A.R. Langille. 1967. Effect of soil pH, drainage, and fertility on growth, survival, and element content of crownvetch, *Coronilla varia* L. *Agron. J.* **59**(6):533–536.

McNaught, K.J. 1958. Potassium deficiency in pastures. I. Potassium content of legumes and grasses. *New Zeal. J. Agr. Res.* **1**(2):148–181.

Medlar, J.T. 1941. The nature of injury to alfalfa caused by *Empoasca fabae* (Harris). *Ann. Entomol. Soc. Amer.* **34**(2):439–450.

Meek, B.D., T.J. Donovan, and L.E. Graham. 1980. Summertime flooding effects on alfalfa mortality, soil oxygen concentrations, and matric potential in silty clay loam soil. *Soil Sci. Soc. Am. J.* **44**(2):433–435.

Meek, B.D., E.A. Rechel, L.M. Carter, and W.R. DeTar. 1988. Soil compaction and its effect on alfalfa in zone production systems. *Soil Sci. Soc. Amer. J.* **52**(1):233–236.

Meek, B.D., E.A. Rechel, L.M. Carter, and W.R. DeTar. 1989. Changes in infiltration under alfalfa as influenced by time and wheel traffic. *Soil Sci. Soc. Amer. J.* **53**(1):238–241.

Meidner, H., and D.W. Sheriff. 1976. *Water and Plants.* John Wiley & Sons, New York.

Meinzer, O.E. 1927. Water supply. Paper A77. U.S. Government Printing Office, Washington, DC.

Meister. 1998. *Weed Control Manual, 1994.* Meister Publishing Co., 37733 Euclid Ave., Willoughby, OH.

Meister. 1999a. *Farm Chemical Handbook, 1994.* Meister Publishing Co., 37733 Euclid Ave., Willoughby, OH.

Meister. 1999b. *Insect Control Guide, 1994.* Meister Publishing Co., 37733 Euclid Ave., Willoughby, OH.

Mellin, T. N., B. R. Poulton, and M. J. Anderson. 1962. Nutritive value of timothy hay as affected by date of harvest. *J. Anim. Sci.* **21**(1):123–126.

Melton, B., J.B. Moutray, and J.H. Bouton. 1988. Geographic adaptation and cultivar selection. pp. 595–620. *In* A.A. Hanson (ed.). *Alfalfa and Alfalfa Improvement.* Monograph 29, ASA, CSSA, SSSA, Madison, WI.

Mengel, K., and E.A. Kirkby. 1980. Potassium in crop production. *Advan. Agron.* **33**:59–110. Academic Press, New York and London.

Mengel, K., and E.A. Kirkby. 1982. *Principles of Plant Nutrition,* 3rd ed. International Potash Institute, P.O. Box, CH-3048 Worblaufen–Bern/Switzerland.

Mertens, D.R. 1979. Biological effects of mycotoxins upon rumen function and lactating dairy cows. pp. 118–136. *In Interactions of Mycotoxins in Animal Production.* Natl. Acad. Sci., Washington, DC.

Meyer, R.D., R. Benton, and D.B. Marcum. 1984. Alfalfa response to nitrogen, phosphorus, potassium and other treatments. pp. 51–55. *In* Proc. Ann. California Fertilizer Conf., 31st, Anaheim, CA. 24–25 February. California Fertilizer Association, Sacramento, CA.

Midgley, A.R. 1931. The movement and fixation of phosphates in relation to permanent pasture fertilization. *J. Amer. Soc. Agron.* **23**(10):788–799.

Miller, D., and B. Melton. 1983. Description of alfalfa cultivars and germplasm sources. N. Mex. Agric. Exp. Stn. Spec. Rep. 53.

Miller, D.A. 1983. Allelopathic effects of alfalfa. *J. Chem. Ecol.* **9**(8):1059–1072.

Miller, D.A. 1992. Allelopathy in alfalfa and other forage crops in the United States. pp. 169–177. *In* S.J.H. Rizvi and V. Rizvi (eds.). *Allelopathy: Basic and Applied Aspects.* Chapman and Hall, London.

Miller, H.F., Jr. 1960. Power in the harvest. pp. 164–183. *In* A. Stefferud (ed.). *Power to Produce.* USDA Yearbook of agriculture. U.S. Government Printing Office, Washington, DC.

Mills, H.A., and J.B. Jones, Jr. 1996. *Plant Analysis Handbook, II.* MicroMacro Publishing, Inc., 183 Paradise Blvd., Ste. 104, Athens, GA.

Minson, D.J. 1990. *Forage in Ruminant Nutrition.* Academic Press, San Diego, CA. 483 pp.

Mir, Z., S. Bittman, and L. Townley-Smith. 1991. Nutritive value of kochia (*Kochia scoparia*) hay or silage grown in a black soil zone in northeastern Saskatchewan for sheep. *Can. J. Anim. Sci.* **71**(1):107–114.

Mislevy, P., J.B. Washko, and J.D. Harrington. 1978. Plant maturity and cutting frequency effect on total nonstructural carbohydrate percentages in the stubble and crowns of timothy and orchardgrass. *Agron. J.* **70**(6):907–912.

Moellenbeck, D.J., and S.S. Quisenberry. 1991. Effects of three-cornered alfalfa hopper (Homoptera: Membracidae) on 'Florida 77' alfalfa plants. *J. Econ. Entomol.* **84**(6):1889–1893.

Moellenbeck, D.J., S.S. Quisenberry, and P.D. Colyer. 1992. *Fusarium* crown-rot development in alfalfa stressed by three-cornered alfalfa hopper (Homoptera: Membracidae) feeding. *J. Econ. Entomol.* **85**(4):1442–1449.

Moen, A.N. 1984. Ecological efficiencies and forage intake of free-ranging animals. pp. 215–273. *In* Natl. Res. Council/Natl. Acad. Sci. *Developing Strategies for Rangeland Management.* Westview Press, Boulder, Colorado.

Moline, W.J., and L.R. Robison. 1971. Effects of herbicides and seeding rates on the production of alfalfa. *Agron. J.* **63**(4):614–616.

Monson, W.G., and G.W. Burton. 1982. Harvest frequency and fertilizer effects on yield, quality, and persistence of eight bermudagrasses. *Agron. J.* **74**(2):371–374.

Monteith, J.L. 1981. Evaporation and surface temperature. *J.R. Meteorol. Soc.* **107**:1–17.

Moon, N.J., L.O. Ely, and E.M. Sudweeks. 1981. Fermentation of wheat, corn, and alfalfa silages inoculated with *Lactobacillus acidophilus* and *Candida* sp. at ensiling. *J. Dairy Sci.* **64**(5):807–813.

Moon, N.J. and L.O. Ely. 1983. Addition of *Lactobacillus* sp. to aid fermentation of alfalfa, corn, sorghum, and wheat forages. pp. 634–636. *In* J.A. Smith and V.W. Hays (eds.). Proc. Int. Grassl. Congr. 14th. 15–24 June 1981. Lexington, KY. Westview Press, Boulder, CO.

Moore, K.J., L.E. Moser, K.P. Vogel, S.S. Waller, B.E. Johnson, and J.F. Pedersen. 1991. Describing and quantifying growth stages of perennial forage grasses. *Agron. J.* **83**(6):1073–1077.

Moore, L.A., H.M. Irvin, and J.C. Shaw. 1953. Relationship between TDN [total digestible nutrient content] and energy values of feeds. *J. Dairy Sci.* **36**(1):93–97.

Moore, R.P. 1943. Seedling emergence of small-seeded legumes and grasses. *J. Amer. Soc. Agron.* **35**(5):370–381.

Morley, F.H.W. 1961. Subterranean clover. *Advan. Agron.* **13**:57–123. Academic Press, New York and London.

Morris, D.R., D.B. Nelson, D.L. Friesner, and B.W. Barber. 1988. Performance of mungbean, cowpea, and soybean cut for greenchop, silage, and hay and effects of seed inoculation on forage yield and quality. pp. 43–47. *In* Annu. Prog. Rep. Southeast Res. Stn., Louisiana Agric. Exp. Stn. Baton Rouge, LA.

Mortensen, L.M., and R. Moe. 1983. Growth responses of some greenhouse plants to environment. V. Effect of CO_2, O_2 and light on net photosynthetic rate in *Crysanthemum morifolium* Ramat. *Sci. Hortic.* **19**(1):133–140.

Mortensen, L.M., and R. Ulsaker. 1985. Effect of CO_2 concentration and light levels on growth, flowering and photosynthesis of *Begonia* x *hiemalis* Fotsch. *Sci. Hortic.* **27**(1):133–141.

Mortvedt, J.J. 1981. Nitrogen and molybdenum uptake and dry matter relationships of soybeans and forage legumes in response to applied molybdenum on acid soil. *J. Plant Nutr.* **3**:245–256.

Moschler, W.W., G.D. Jones, and G.W. Thomas. 1960. Lime and soil acidity effects in alfalfa grown on a red–yellow podzolic soil. *Soil Sci. Soc. Am. Proc.* **24**(6):507–509.

Mouat, C.H., and T.W. Walker. 1959. Competition for nutrients between grasses and white clover. I. Effect of grass species and nitrogen supply. *North Cent. Weed Cont. Conf. Proc.* **17**:26–27.

Mowat, D.N., R.S. Fulkerson, and E.E. Gamble. 1967. Relationship between stem diameter and *in vitro* digestibility of forages. *Can. J. Plant Sci.* **47**(4):423–426.

Mueller, J.P., J.T. Green, Jr., D.S. Chamblee, and J.S. Bailey. 1984. Alfalfa production in North Carolina. N.C. Agric. Coop. Ext. Serv. AG-344.

Mulder, E.G. 1948. Importance of molybdenum in the nitrogen metabolism of microorganisms and higher plants. *Plant Soil* **1**(1):94–119.

Mulder, E.G., and W.L. Van Veen. 1960. Effect of pH and organic compounds on nitrogen fixation by red clover. *Plant Soil* **13**(2):91–113.

Mullahey, J.J., and J.P. Mueller, and J.T. Green. 1988. Enhancement of field hay curing with potassium carbonate. *Agron. J.* **80**(2):186–192.

Munns, D.N. 1965. Soil acidity and growth of a legume. I. Interactions of lime with nitrogen and phosphate on growth of *Medicago sativa* L. and *Trifolium subterraneum* L. *Aust. J. Agr. Res.* **16**(5):733–741.

Munns, D.N. 1968a. Nodulation of *Medicago sativa* in solution culture. I. Acid-sensitive steps. *Plant Soil* **28**(1):129–146.

Munns, D.N. 1968b. Nodulation of *Medicago sativa* III. Effects of nitrate on root hairs and infection. *Plant Soil* **29**(1):33–47

Munns, D.N. 1970. Nodulation of *Medicago sativa* in solution culture. V. Calcium and pH requirements during infection. *Plant Soil* **32**(1):90–102.

Munns, D.N. 1977. Mineral nutrition and the legume symbiosis. pp. 353–391. *In* R.W. Hardy and A.H. Gibson (eds.). *A Treatise on Dinitrogen Fixation. Section IV. Agronomy and Ecology.* John Wiley & Sons, New York.

Munns, D.N., R.L. Fox, and B.L. Koch. 1977. Influence of lime on nitrogen fixation by tropical and temperate legumes. *Plant Soil* **46**(3):591–601.

Murata, Y., J. Iyama, and T. Honma. 1966. Studies on the photosynthesis of forage crops. The influence of slil moisture content on the photosynthesis and respiration of seedlings in various forage crops. *Proc. Crop Sci. Soc. Japan* **34**(3):385–390.

Murdoch, J.C. 1964. Some factors affecting the efficient utilization of conserved grass. *J. Brit. Grassl. Soc.* **19**(1):130–138.

Murdoch, J.C., and D.I. Bare. 1963. The effect of conditioning on the rate of drying and loss of nutrients in hay. *J. Brit. Grassl. Soc.* **18**(4):334–338.

Murphy, R.P., and A.C. Arny. 1939. The emergence of grass and legume seedlings planted at different depths in five soil types. *J. Amer. Soc. Agron.* **31**(1):17–28.

Murphy, W.M., J.G. Welch, R.H. Palmer, B.E. Gilman, C.W. Albers, and D.T. Dugdale. 1984. Digestibilities of silages made from corn interplanted with soybean or fababean. *J. Dairy Sci.* **67**(7):1532–1534.

Musselman, E.V. 1978. Nitrogen fixation and photosynthate transport in soybeans: The effects of nitrate on. M.S. Thesis, Brigham Young University, Provo, UT.

Nagy, J.G., G. Vidacs, and G.M. Ward. 1967. Previous diet of deer, cattle, and sheep and ability to digest alfalfa hay. *J. Wildl. Mgt.* **31**(3):443–447.

Nakayama, F.S., and R.J. Reginato. 1982. Simplifying neutron moisture meter calibration. *Soil Sci.* **133**(1):48–52.

Narasimhalu, P., R.P. White, and K.B. McRae. 1986. The effect of harvesting before and after frost on corn silage composition, and its intake and digestibility in sheep. *Can. J. Plant Sci.* **66**(3):579–584.

National Research Council. 1962. Glossary of energy terms. Natl. Acad. Sci.–Natl. Res. Council, Washington, DC. 11 pp.

National Research Council. 1981a. Effect of environment on nutrient requirements of domestic animals. Natl. Acad. Press. Washington, DC. 152 pp.

National Research Council. 1981b. Nutrient requirements of domestic animals. Number 15. Nutrient requirements of goats: Angora, dairy, and meat goats in temperate and tropical countries. Natl. Acad. Press, Washington, DC. 91 pp.

National Research Council. 1985. Nutrient requirements of domestic animals. Number 5. Nutrient requirements of sheep, 6th rev. ed. Natl. Acad. Sci., Washington, DC. 99 pp.

National Research Council. 1987. Predicting feed intake of food-producing animals. Natl. Academy Press, Washington, DC. 85 pp.

National Research Council. 1988. Nutrient requirements of domestic animals. Number 3. Nutrient requirements of dairy cattle, 6th ed. Natl. Acad. Sci., Washington, DC. 157 pp.

National Research Council. 1989. Nutrient requirements of domestic animals. Number 6. Nutrient requirements of horses, 5th ed. Natl. Acad. Sci., Washington, DC. 100 pp.

National Research Council. 1996. Nutrient requirements of domestic animals. Number 4. Nutrient requirements of beef cattle, 7th rev. ed. Natl. Acad. Press, Washington, DC. 258 pp.

Nehrir, H., W.L. Kjelgaard, P.M. Anderson, T.A. Long, L.D. Hoffman, J.B. Washko, L.L. Wilson, and J.P. Mueller. 1978. Chemical additives and hay attributes. *Trans. ASAE* **21**(2):217–221,226.

Neidig, R.E. 1914. Chemical changes during silage fermentation. Iowa Agr. Exp. Sta. Res. Bul. 16.

Nelson, A.B., C.H. Herbel, and H.M. Jackson. 1970. Chemical composition of forage species grazed by cattle on arid New Mexico range. New Mexico Agric. Stn. Bull. 561.

Nelson, W.L., and S.A. Barber. 1964. Nutrient deficiencies in legumes for grain and forage. pp. 143–179. *In* H.B. Sprague (ed.). *Hunger Signs in Crops.* David McKay Co., New York.

Nevens, W.B. 1933. Types and varieties of corn for silage. Ill. Agr. Exp. Sta. Bul. 391.

Nevens, W.B., K.E. Harshbarger, and K.A. Kendall. 1946. Grass and legume silages for dairy cattle. Univ. of Illinois, College of Agric., Ext. Serv., 19 pp. Urbana, IL.

Nevens, W.B., and K.A. Kendall. 1954. Sorghum and soybeans as silage crops for milk production. Univ. of Illinois, Agric. Exp. Stn. 62 pp. Urbana, IL.

Nicholson, J.W.G., G. Belanger, and P.L. Burgess. 1986. Comparison of silages from densely seeded and conventionally seeded corn for beef steers. 1986. *Can. J. Anim. Sci.* **66**(2):431–439.

Nielsen, D.C., K.L. Clawson, and B.L. Blad. 1984. Effect of solar azimuth and infrared thermometer view direction on measured soybean canopy temperature. *Agron. J.* **76**(4):607–610.

Niemczyk, H.D., and G.E. Guyer. 1963. The distribution, abundance and economic importance of insects affecting red and Mammoth clover in Michigan. Michigan Agric. Exp. Stn. Tech. Bull. 293.

Noble, A.D., M.V. Fey, and M.E. Sumner. 1988. Calcium–aluminum balance and the growth of soybean roots in nutrient solutions. *Soil Sci. Soc. Am. Proc.* **52**(6):1651–1656.

Nocek, J.E., J.B. Fallon, and M. R. Fessenden. 1986. Drying rate and ruminal nutrient digestion of chemically treated alfalfa hay. *Crop Sci.* **26**(4):813–818.

Nocek, J.E., and J.B. Russell, and J. B. Fallon. 1988. Influence of chemical drying agent and surfactant on drying time and ruminal nutrient digestion of first-cutting alfalfa hay. *Agron. J.* **80**(3):525–532.

Noller, C.H. 1973. Grass–legume silage. pp. 558–568. *In* M.E. Heath, D.S. Metcalfe, and R.F. Barnes (eds.). *Forages: The Science of Grassland Agriculture,* 3rd ed. Iowa State University Press, Ames, IA.

Norris, D.O. 1958. Lime in relation to the nodulation of tropical legumes. pp. 164–180. *In* E.G. Hallsworth (ed.). *Nutrition of the Legumes.* Butterworths, London.

Norris, D.O. 1970. Nodulation of pasture legumes. pp. 339–348. *In* R.M. Moore (ed.). *Australian Grasslands.* Aust. Nat. Univ. Press, Canberra.

Norris, K.H., R.F. Barnes, J.E. Moore, and J.S. Shenk. 1976. Predicting forage quality by infrared reflectance spectroscopy. *J. Anim. Sci.* **43**(4):889–897.

Nuttall, W.F. 1980. Effect of nitrogen and phosphorus fertilizer on a bromegrass and alfalfa mixture grown under two systems of pasture management. II. Nitrogen and phosphorus uptake and concentration in herbage. *Agron. J.* **72**(2):295–298.

Nuttall, W.F. 1985a. Effect of N, P, and S fertilizers on alfalfa grown on three soil types in northeastern Saskatchewan. I. Yield and soil tests. *Agron. J.* **77**(1):41–46.

Nuttall, W.F. 1985b. Effect of N, P, and S fertilizers on alfalfa grown on three soil types in northeastern Saskatchewan. II. Nitrogen, P, and S uptake and concentration in herbage. *Agron. J.* **77**(2):224–228.

Nuttall, W.F., D.A. Cooke, J. Waddington, and J.A. Robertson. 1980. Effect of nitrogen and phosphorus fertilizer on a bromegrass and alfalfa mixture grown under two systems of pasture management. I. Yield percentage legume in sward and soil tests. *Agron. J.* **72**(2):289–294.

Ocumpaugh, W.R., and A.G. Matches. 1977. Autumn–winter yield and quality of tall fescue. *Agron. J.* **69**(4):639–643.

Oellermann, S.O., M.J. Arambel, and J.L. Walters. 1989. Effect of chemical drying agents on alfalfa hay and milk production response when fed to dairy cows in early lactation. *J. Dairy Sci.* **72**(2):501–504.

Ohio State University. 1972. Agronomy guide. Bull. 472.

Ohman, J.H., and T. Kommedahl. 1960. Relative toxicity of extracts from vegetative organs of quackgrass to alfalfa. *Weeds* **8**(4):666–670.

Oldfield, J.E. (Task Force Chm.). 1986. Forages: Resources for the future. CAST Rep. 108. 50 pp.

Oleszek, W., M. Jurzysta, and P.M. Gorski. 1992. Alfalfa saponins — The allelopathic agents. pp. 151–167. In S.J.H. Rizvi and V. Rizvi (eds.). *Allelopathy: Basic and Applied Aspects.* Chapman and Hall, London.

Oloumi-Sedeghi, H., L.R. Zavaleta, S.J. Roberts, E.J. Armbrust, and G. Kapusta. 1988. Changes in morphological stage of development, canopy structure, and root nonstructural carbohydrate reserves of alfalfa following control of potato leafhopper (Homoptera: Cicadellidae) and weed populations. *J. Econ. Entomol.* **81**(1):368–375.

Onstad, D.W., C.A. Shoemaker, and B.C. Hansen. 1984. Management of potato leafhopper, *Empoasca fabae* (Homoptera: Cicadellidae), on alfalfa with the aid of systems analysis. *Environ. Entomol.* **13**(4):1046–1058.

Orloff, S.B., H.L. Carlson, and B.R. Hanson. 1995. Irrigation. *In* S.B. Orloff and H.L. Carlson (eds.). *Intermountain Alfalfa Management.* Publication 3366, University of California, Div. Agric. Natural Res., Oakland, CA.

O'Toole, J.C., and J.L. Hatfield. 1983. Effect of wind on the crop stress index derived by infrared thermometry. *Agron. J.* **75**(5):811–817.

O'Toole, J.C., and J. Real. 1984. Canopy target dimensions for infrared thermometry. *Agron. J.* **76**(5):863–865.

Overdahl, C.J. 1972. Fertilizer experiments with alfalfa on a Brainard sandy loam. Univ. Minnesota Misc. Rep. 107.

Owens, F.N., and A.L. Goetsch. 1988. Ruminal fermentation. pp. 145–171. *In* D.C. Church (ed.). *The Ruminant Animal: Digestive Physiology and Nutrition.* Prentice-Hall, Englewood Cliffs, New Jersey.

Ozanne, P.G., and A. Petch. 1978. Effects of species and cultivation on the responses to phosphate of annual pastures and crops. *Aust. J. Agric. Res.* **29**(2):225–233.

Ozanne, P.G., and K.M.W. Howes. 1970. Calcium and subterranean clover persistence. pp. 366–369. *In* M.J.T. Norman (ed.). Proc. Int. Grassl. Cong., 11th, 13–23 Apr. 1970. Surfers Paradise, Queensland, Australia.

Page, M.S., F.A. Gray, W.G. Kearl, and R.L. Hossfeld. 1990. Impact of verticillium wilt on Wyoming alfalfa hay production. Bul. 935, Wyo. Agric. Exp. Stn, University of Wyoming, Laramie, WY.

Papadopoulos, Y.A., B.R. Christie, and G.J. Boland. 1989. Determining alfalfa resistance and yield losses associated with verticillium wilt infestations. *Crop Sci.* **29**(6):1513–1518.

Park, W.L., and M.V. Wallentine. 1986. Economic comparison of bagged haylage vs. baled hay systems for dairy cattle. *J. Soc. Farm Mang. Rur. App.* **50**(1):6–15.

Parks, W.L., and L.M. Safley. 1961. Alfalfa fertilization on a Dickson soil. Bull. 330. Univ. of Tennessee.

Parrish, D.J., and A.C. Leopold. 1977. Transient changes during soybean imbibition. *Plant Physiol.* **59**(6):1111–1115.

Passioura, J.B. 1980. The meaning of matric potential. *J. Exp. Bot.* **31**(123):1161–1169.

Patterson, D.T., and E.P. Flint. 1980. Potential effects of global atmospheric CO_2 enrichment on the growth and competitiveness of C_3 and C_4 weed and crop plants. *Weed Sci.* **28**(1):71–75.

Pauli, A.W., V.L. Lectenberg, and W.F. Wedin. 1988. Equipment for harvesting, transporting, storing, and feeding. pp. 567–594. *In* A.A. Hanson (ed.). *Alfalfa and Alfalfa Improvement.* ASA, CSSA, SSSA. Mono. 29. Madison, WI.

Peake, R.W., and H. Chester. 1943. Hay making with crested wheatgrass in the dry areas of Alberta. Can. Dept. Agric. Pub. 753. 10p.

Pearce, R.B., R.H. Brown, and R.E. Blaser. 1968. Photosynthesis of alfalfa leaves as influenced by age and environment. *Crop Sci.* **8**(6):677–680.

Pearson, R.W., and C.S. Hoveland. 1974. Lime needs of forage crops. pp. 301–322. *In* D.A. Mays (ed.). *Forage Fertilization.* ASA, CSSA, SSSA. Madison, WI.

Peck, N.H., D.J. Lathwell, M.T. Vittum, and G.E. MacDonald. 1969. Plant response to concentrated superphosphate and potassium chloride fertilizers. II. Alfalfa. New York Agric. Exp. Stn., Bull. 829. Geneva, NY.

Pedersen, J.F., and D.A. Sleper. 1988. Considerations in breeding endophyte-free tall fescue forage cultivars. *J. Prod. Agric.* **1**(2):127–132.

Penman, H.L. 1948. Natural evaporation from open water, bare soil, and grass. *Proc. R. Soc. London* **193**(2):120–146.

Penman, H.L. 1953. The physical bases of irrigation control. Rep. 13th Int. Hortic. Congr. 1952 **2**:913–924.

Penman, H.L., and R.K. Schofield. 1951. Some physical aspects of assimilation and transpiration. *Symp. Soc. Exp. Biol.* **5**:115–129.

Pennypacker, B.W., K.T. Leath, and R.R. Hill, Jr. 1988. Growth and flowering of resistant alfalfa infected by *Verticillium albo-atrum. Plant Dis.* **72**(5):397–400.

Perry, L.J., Jr., and K.L. Larson. 1974. Influence of drought on tillering and internode number and length in alfalfa. *Crop Sci.* **14**(5):693–696.

Perry, T.W., D.M. Caldwell, J.R. Reedal, and C.B. Knodt. 1968. Stage of maturity of corn at time of harvest for silage and yield of digestible nutrients. *J. Dairy Sci.* **51**(5):799–802.

Perry, T.W., and D.M. Caldwell. 1969. Comparative nutritive value of silages from high-sugar male sterile hybrid corn and regular starchy corn. *J. Dairy Sci.* **52**(7):1119–1121.

Peters, E.J. 1973. Control of pasture weeds by increasing competition from forages. *Weed Sci. Soc. Amer.* Abstr. 59.

Peters, E.J., and S.A. Lowance. 1969. Gains in timothy forage from goldenrod control with 2,4-D and 2,4-DB and picloram. *Weed Sci.* **17**(4):473–474.

Peters, E.J., and S.A. Lowance. 1971. Establishment of crownvetch with herbicides. *Agron. J.* **63**(2):230–232.

Peters, R.A. 1961. Legume establishment as related to the presence or absence of an oat companion crop. *Agron. J.* **53**(3):195–198.

Petritz, D. 1989. Confusing hay terms don't make the grade. *Hay For. Grow.* **4**(3):38.

Petritz, D. 1990. Southeastern buyers reveal hay preferences. *Hay For. Grow.* **5**(3):17.

Petritz, D. 1991. Auction hay buying: prepare before bidding. *Hay For. Grow.* **6**(1):14.

Peverill, K.I., and G.P. Briner. 1974. The sulfur status of victorian grasslands. pp. 410–420. *In* V.G. Iglovikov and A.P. Mousisyants (eds.). Proc. Int. Grassl. Cong., 12th, Vol. II, 11–20 June 1974. Moscow, USSR.

Phillips, R.E. 1981. Farm buildings: From planning to completion. Doane-Western, Inc., 8900 Manchester Roads, St. Louis, MO 63114.

Pizarro, E.A., and D.B. James. 1972. Estimates of respiratory rates and losses in cut swards of *Lolium perenne* (S321) under simulated haymaking conditions. *J. Brit. Grassl. Soc.* **27**(1):17–21.

Pond, K.R., W.C. Ellis, and D.E. Akin. 1984. Ingestive mastication and fragmentation of forages. *J. Anim. Sci.* **58**(6):1567–1574.

Pond, K.R., W.C. Ellis, C.E. Lascano, D.E. Akin, and Richard B. Russell. 1987. Fragmentation and flow of grazed coastal bermudagrass through the digestive tract of cattle. *J. Anim. Sci.* **65**(2):609–618.

Postgate, J.1985. Nitrogenase. *Biologist* **32**(1):43–48.

Pruitt, W.O. 1966. Empirical method of estimating evapotranspiration using primarily evaporation pan. pp. 57–61. *In* Conf. Evapotranspiration and its role in water resources management, Chicago, 5–6 December. Amer. Soc. Agric. Eng., St. Joseph, MI.

Pruitt, W.O., and J. Doorenbos. 1977. Empirical calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data. Int. Round Table Conf. on Evapotranspiration, Budapest, Hungary. 26–28 May. International Committee on Irrigation and Drainage, New Dehli, India.

Puckridge, D.W. 1968. Photosynthesis of wheat under field conditions. I. The interaction of photosynthetic organs. *Aust. J. Agric. Res.* **19**(5):711–719.

Pumphrey, F.V., and D.P. Moore. 1965a. Sulfur and nitrogen content of alfalfa herbage during growth. *Agron. J.* **57**(3):237–239.

Pumphrey, F.V., and D.P. Moore. 1965b. Diagnosing sulfur deficiency of alfalfa (*Medicago sativa* L.) from plant analysis. *Agron. J.* **57**(4):364–366.

Radler, F. 1965. Reduction of loss of moisture by the cuticle wax components of grapes. *Nature (Lond.)* **207**(5000):1002–1003.

Raguse, C.A., and D. Smith. 1966. Some nonstructural carbohydrates in forage legume herbage. *J. Agric. Food Chem.* **14**(4):423–426.

Raleigh, R.J., C.B. Rumburg, and J.D. Wallace. 1964. Digestibility of native flood meadow hay at different growth stages. *J. Anim. Sci.* **23**(2):603.

Rand, R.E., D.R. Keeney, and L.M. Walsh. 1969. Availability of and crop response to sulfur in Wisconsin. Wisc. Agr. Exp. Stn. Res. Rep. 52.

Raschke, K. 1986. The influence of the CO_2 content of the ambient air on stomatal conductance and the CO_2 concentration in leaves. pp. 87–102. *In* H. Z. Enoch and B.A. Kimball (eds.). *Carbon dioxide Enrichment of Greenhouse Crops. Vol. II. Physiology, Yield, and Economics.* CRC Press, Boca Raton, FL.

Ratcliffe, R.H., and J.H. Elgin, Jr. 1987. A seedling test to select for alfalfa weevil (Coleoptera: Curculionidae) resistance in alfalfa. *J. Econ. Entomol.* **80**(4):975–978.

Ratcliffe, R.H., and J.H. Elgin, Jr. 1990. Turkish alfalfa cultivars screened for alfalfa weevil resistance. *Crop Sci.* **30**(5):994–996.

Raymond, F., G. Shepperson, and R. Waltham. 1986. *Forage Conservation and Feeding,* 4th ed. Farming Press, Ltd., Wharfedale Road, Ipswich, Suffolk, England.

Raymond, F., P. Redman, and R. Waltham. 1986a. Principles of forage conservation. pp. 8–26. *Forage Conservation and Feeding,* 4th ed. Farming Press Ltd., Wharfedale Road, Ipswich, Suffolk, England.

Raymond, F., P. Redman, and R. Waltham. 1986b. The feeding value of conserved forages. pp. 27–45. *Forage Conservation and Feeding,* 4th ed. Farming Press Ltd., Wharfedale Road, Ipswich, Suffolk, England.

Read, J.C., R.M. Jones. 1986. Small grain for silage or hay variety test. R Tex. Agric. Exp. Stn. College Station, Tex. (4347) pp. 27–28.

Reber, R.J. 1987. The ruminant and human nutrition. *For. Grassl. Conf.* 1987:3–8.

Rechel, E.A., B.D. Meek, W.R. DeTar, and L.M. Carter. 1990. Fine root development of alfalfa as affected by wheel traffic. *Agron. J.* **82**(3):618–622.

Rechel, E.A., B.D. Meek, W.R. DeTar, and L.M. Carter. 1991. Alfalfa yield as affected by harvest traffic and soil compaction in a sandy loam soil. *J. Prod. Agric.* **4**(2):241–246.

Redeva, V., and A. Topchieva. 1979. Effect of periodic soil moisture tension on dry matter accumulation, seed yield and some physiological characters of lucerne. Commonweath Agric. Bur. Record 1192037. Rasteniev'dni Nauki 16(1):13–25. (In Bulgarian, English summary.)

Reeves, D.L., and H.S. Sraon. 1976. How an oat plant develops. Agric. Exp. Stn. Bul. 645. South Dakota State Univ., Brookings, SD.

Reid, J.L., R.C. Berberet, and J.L. Caddel. 1989. Effects of alfalfa dormancy on egg and larval population levels of the alfalfa weevil (Coleoptera: Curculionidae). *J. Econ. Entomol.* **82**(1):264–269.

Reid, J.T., W.K. Kennedy, K.L. Turk, S.T. Slack, G.W. Trimberger, and R.P. Murphy. 1959. Effect of growth stage, chemical composition, and physical properties upon the nutritive value of forages. *J. Dairy Sci.* **42**(3):567–571.

Reid, R.L., A.J. Post, and G.A. Jung. 1970. Mineral composition of forages. West Virginia Univ. Bull. 589 T.

Reid, R.L., and L.F. James. 1985. Forage–animal disorders. pp. 430–444. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Univ. Press. Ames, IA.

Rench, W.E. and R.H. Shaw. 1971. Black layer development in corn. *Agron. J.* **63**(2):303–305.

Rendig, V.V., and D.L. Grunes (eds.). 1979. *Grass Tetany.* Amer. Soc. Agron. Spec. Pub. 35. 175 pp.

Reuss, J.O., P.N. Soltanpour, A.E. Ludwick. 1977. Sampling distribution of nitrates in irrigated fields. *Agron. J.* **69**(4):588–592.

Reynolds, J.H. 1971. Carbohydrate trends in alfalfa (*Medicago sativa* L.) roots under several forage harvest schedules. *Crop Sci.* **11**(1):103–106.

Reynolds, J.H., C.R. Lewis, and K.F. Laaker. 1971. Chemical composition and yield of orchardgrass forage growth under high rates of nitrogen fertilization and several cutting managements. Tenn. Agric. Exp. Stn. Bull. 479.

Rhykerd, C.L., K.L. Washburn, Jr., and C.H. Noller. 1970. Should N be applied to alfalfa. Agronomy guide, Purdue Univ. AY–184.

Rhykerd, C.L., and C.J. Overdahl. 1972. Nutrition and fertilizer use. pp. 437–468. *In* C.H. Hanson (ed.). *Alfalfa Science and Technology.* Agron. Monogr. 15, ASA, CSSA, SSSA, Madison, WI.

Rice, E.L. 1974. *Allelopathy.* Academic Press, New York.

Rice, E.L. 1979. Allelopathy—an update. *Bot. Rev.* **45**(1):15–109.

Rice, W.A. 1975. Effect of $CaCO_3$ and inoculum level on nodulation and growth of alfalfa in an acid soil. *Can. J. Soil Sci.* **55**(3):245–250.

Richard, C., R. Michaud, A. Freve, and C. Gagnon. 1980. Selection for root and crown rot resistance in alfalfa. *Crop Sci.* **20**(6):691–695.

Richard, J.L., and R.J. Cole (eds.). 1989. Mycotoxins: Economic and health risks. Council for Agric. Sci. Tech. (CAST) Rep. 116. 8 pp.

Richards, C.R., G.F.W. Haenlein, M.C. Calhoun, J.D. Connolly, and H.G. Weaver. 1962. Date of cut vs. the combination of crude fiber and crude protein as estimators of forage quality. *J. Anim. Sci.* **21**(4):844–847.

Rider, A.R. 1985. What's ahead in hay and forage production, storage, and handling systems. pp. 322–334. *In* F.H. Baker and M.E. Miller (eds.) *Emerging Technology and Management for Ruminants.* Winrock International, Westview Press, 5500 Central Avenue, Boulder, CO 80301.

Rider, A.R., S.D. Barr, and A.W. Pauli. 1993. *Hay and Forage Harvesting. Fundamentals of Machine Operation.* Deere and Company, John Deere Road, Moline, IL 61265.

Rings, R.W. 1977. An illustrated field key to common cutworm, armyworm, and looper moths in the north central states. Res. Circ. 227. Ohio Res. Dev. Center, Wooster, OH.

Rings, R.W., and G.J. Musick. 1976. A pictorial field key to the armyworms and cutworms attacking corn in the north central states. Res. Circ. 221. Ohio Res. Dev. Center, Wooster, OH.

Ritchie, S.W., and J.J. Hanway. 1982. How a corn plant develops. Spec. Rpt. No. 48 (rev.). Iowa State University, Coop. Ext. Ser., Ames, IA.

Roberts, C.A., K.J. Moore, and J.O. Fritz. 1987. Chemical regulation of tall fescue growth and quality. *For. Grass. Conf.* 1987:162–165.

Robertshaw, D. 1987. Heat stress. pp. 31–35. *In* Proc. Grazing livestock nutrition Conf. 23–24 July 1987, Jackson, WY. University of Wyoming, Laramie, WY.

Roepnack, A.N. 1980. U.S. Patent 4,185,549. U.S. Patent Office.

Roethe, H.E. 1937. Spontaneous heating and ignition of hay. *Agric. Eng.* **18**(12):547–550,554.

Rogers, H.H., G.E. Bingham, J.D. Cure, J.M. Smith, and K.A. Surano. 1983. Responses of selected plant species to elevated carbon dioxide in the field. *J. Environ. Qual.* **12**(4):569–574.

Rohweder, D.A., R.F. Barnes, and N. Jorgensen. 1978. Proposed hay grading standards based on laboratory analyses for evaluating quality. *J. Anim. Sci.* **47**(3):747–759.

Rohweder, D.A., and M. Collins. 1980. Harvesting and storing high quality silage. For. Grass. *Conf.* 1980:193–215.

Rohweder, D.A., N. Jorgensen, and R.F. Barnes. 1983. Proposed hay-grading standards based on laboratory analyses for evaluating quality. pp. 534–548. *In* J.A. Smith and V.W. Hays (eds.). Proc. Int. Grassl. Cong. 14th 15–24 June, 1981. Lexington, KY. Westview Press, Boulder, CO.

Rominger, R.S., D. Smith, and L.A. Peterson. 1975. Yields and elemental composition of alfalfa plant parts at late bud under two fertility levels. *Can. J. Plant Sci.* **55**(1):69–75.

Rominger, R.S., D. Smith, and L.A. Peterson. 1976. Yield and chemical composition of alfalfa as influenced by high rates of K topdressed as KCl and K_2SO_4. *Agron. J.* **68**(4):573–577.

Rook, J.A., L.D. Muller, and D.B. Shank. 1977. Intake and digestibility of brown-midrib corn silage by lactating dairy cows. *J. Dairy Sci.* **60**(12):1894–1904.

Rorison, H.I. 1958. The effect of aluminum on legume nutrition. pp. 43–61. *In* E.G. Hallsworth (ed.). *Nutrition of Legumes.* Butterworths, London.

Rosenberg, N.J., and S.B. Verma. 1978. Extreme evapotranspiration by irrigated alfalfa: A consequence of the 1976 midwestern drought. *J. Appl. Meteorol.* **17**(7):934–941.

Roth, R.L., B.R. Gardner, G.K. Tritz, and E.A. Lakotos. 1983. Alfalfa response to water and nitrogen variables. pp. 83–88. *In* Proc., 13th California Alfalfa Symp., Holtvill, CA. 7–8 December. Univ. Calif. Coop. Ext., Davis, CA.

Roth, G., and D. Undersander (eds.). 1995. *Corn Silage Production, Management, and Feeding.* ASA, CSSA, SSSA, 677 S. Segoe Road, Madison, WI.

Rotz, C.A., S.M. Abrams, and R.J. Davis. 1987. Alfalfa drying loss, and quality as influenced by mechanical and chemical conditioning. *Trans. ASAE* **30**(3):630–635.

Rotz, C.A., and R.J. Davis. 1985. Sprayer design for chemical conditioning of alfalfa. Paper 84–1527, Am. Soc. Agric. Eng., St. Joseph, MI.

Rotz, C.A., and R.J. Davis. 1986. Drying and field losses of alfalfa as influenced by mechanical and chemical conditioning. pp. 157–161. *In* Proc. 1986 Forage and Grassl. Conf. 15–17 April. American Forage and Grassland Council, Athens, GA.

Rotz, C. A., D. J. Sprott, and J. W. Thomas. 1984. Interaction of mechanical and chemical conditioning of alfalfa. *Trans. ASAE* **27**(4):1009–1014.

Rotz, C.A., and J.W. Thomas. 1983. Chemical conditioning to speed alfalfa drying. pp. 163–169. *In* Proc. Forage Grassl. Conf., Eau Claire, WI. 23–26 Jan. 1983. Am. For. Grassl. Counc, Madison, WI.

Rotz, C.A., J.W. Thomas, T.R. Johnson, and D.A. Herrington. 1982. Mechanical and chemical conditioning to speed alfalfa drying. Am. Soc. Agric. Engr. Paper 82–1036. Am. Soc. Agric. Engr. St. Joseph, MI.

Rumbaugh, M.D. 1982. Origins of alfalfa cultivars used for dryland grazing. pp. 15–19. *In* A.C. Wilton (ed.). *Alfalfa for Dryland Grazing.* USDA/ARS, SEA. Agric. Info. Bull. 444.

Rumburg, C.B. 1963. Production of regrowth forage on native flood meadows. *Agron. J.* **55**(3): 245–247.

Rumburg, C.B. (Ed.). 1975. Alternative meadow and livestock management systems. Colo. Agric. Expt. Sta. Bul. 565S. 28 pp.

Ryle, G.J.A. 1970. Partition of assimilates in an annual and a perennial grass. *J. Appl. Ecol.* **7**(2):217–227.

Ryle, G.J.A., C.E. Powell, and A.J. Gordon. 1981a. Patterns of ^{14}C-labelled assimilate partitioning in red and white clover during vegetative growth. *Ann. Bot.* **47**(4):505–514.

Ryle, G.J.A., C.E. Powell, and A.J. Gordon. 1981b. Assimilate partitioning in red and white clover either dependent on N2 fixation in root nodules or utilizing nitrate nitrogen. *Ann. Bot.* **47**(4):515–523.

Saeki, T. 1960. Interrelationships between leaf amount, light distribution, and total photosynthesis in a plant community. *Bot. Mag. (Tokyo)* **73**(2):55–63.

Salisbury, F.B., and C.W. Ross. 1992. *Plant physiology.* 4th ed. Wadsworth Pub. Co., Belmont, CA.

Sammis, T.W. 1981. Yield of alfalfa and cotton as influenced by irrigation. *Agron. J.* **73**(2):323–328.

Sampson, K., and J.H. Western. 1954. *Diseases of British Grasses and Herbage Legumes,* 2nd ed. Cambridge University Press, Cambridge.

Sanchez, P.A., and J.G. Salina. 1981. Low-input technology for managing oxisols and ultisols in tropical America. *Adv. Agron.* **34**:279–406.

Sanderson, M.A., D. Meyer, and H. Casper. 1984. Prevention of dicoumarol formation in sweetclover hay. *For. Grassl. Conf.* 1984:157–161.

Sanford, J.O., D.L. Myhre, B.L. Arnold, and R.E. Coats. 1968. Crop response to lime on loess soils. Mississippi Agr. Exp. Stn. Bull. 764.

Satter, L.D., T.R. Dhiman, C. Cadorniga, and M.A. Faldet. 1989. Are we overvaluing the protein of alfalfa? pp. 1–9. *In* Proc. 1989 For. Grassl. Conf., 22–25 May 1989. University of Guelph, Guelph, Ontario, Canada. Amer. For. Grassl. Coun., R.D. 1, Box 129, Belleville, PA.

Savoie, P. 1988. Hay tedding losses. *Can. Agric. Eng.* **3**(1):39–42.

Schaber, B.D., and T. Entz. 1991. Effect of annual and/or biennial burning of seed alfalfa stubble on populations of alfalfa weevil and pea aphid. *Ann. Appl. Biol.* **119**(3):425–431.

Schmid, A.R., and R. Behrens. 1972. Herbicides vs. oat companion crops for alfalfa establishment. *Agron. J.* **64**(2):157–159.

Scholl, J.M., and D.W. Staniforth. 1957. Establishment of birdsfoot trefoil as influenced by competition from weeds and companion crops. *Agron. J.* **49**(8):432–435.

Schollenberger, C.J., and R.M. Salter. 1943. A chart for evaluating agricultural limestone. *J. Amer. Soc. Agron.* **35**(11):955–966.

Schreiber, M.M., and L.R. Oliver. 1969. Microenvironment of weed competition in alfalfa establishment. *Weed Sci. Soc. Amer.* Abstr. No. 156

Schreiber, M.M., and L.R. Oliver. 1971. Microenvironment of weed competition on birdsfoot trefoil establishment. *Weed Sci. Soc. Amer.* Abstr. No. 116.

Schulte, E.E., J.B. Peters, C.R. Simson, and K.A. Kelling. 1982. Influence of soil pH on the establishment, persistence and yield of forage legumes. p. 81. *In* Proc. 1982 Forage Grassl. Conf., 21–24 Feb. 1982. Rochester, MN.

Seamands, W.J. 1966. Increase production from Wyoming mountain meadows. Wyo. Agric. Exp. Sta. Bul. 441. 5 pp.

Seaney, R.R., and P.R. Henson, 1970. Birdsfoot trefoil. *Advan. Agron.* **22**:119–157. Academic Press, New York and London.

Seim, E.C., A.C. Caldwell, and G.W. Rehm. 1969. Sulfur response by alfalfa (*Medicago sativa* L.) on a sulfur-deficient soil. *Agron. J.* **61**(3):368–371.

Siemer, E.G., and R.H. Delany (eds.). 1984. Proceedings of the Second Intermountain Meadow Symposium, Gunnison, Colorado, July 11–13, 1984. Colo. Agric. Expt. Sta. Spec. Rep. 34. 155 pp.

Shade, R.E., T.E. Thompson, and W.R. Campbell. 1975. An alfalfa weevil larval resistance mechanism detected in *Medicago. J. Econ. Entomol.* **68**(3):399–404.

Shaner, G. 1991. Genetic resistance for control of plant disease. pp. 495–540. *In* D. Pimentel (ed.). *Handbook of Pest Management in Agriculture,* 2nd ed. Vol. 1. CRC Press, Boca Raton, FL.

Shantz, H.L., and L.N. Piemeisel. 1927. The water requirements of plants at Akron, Colo. *J. Agric. Res.* **34**(12):1093-1190.

Sheaffer, C.C., and N.A. Clark. 1975. Effects of organic preservatives on the quality of aerobically stored high moisture baled hay. *Agron. J.* **67**(5):660–662.

Sheaffer, C.C., G.D. Lacefield, and V.L. Marble. 1988. Cutting schedules and stands. pp. 411–437. *In* A.A. Hanson *et al.* (eds.). *Alfalfa and Alfalfa Improvement.* Agron. Monogr. 29. ASA, CSSA, and SSSA, Madison, WI.

Sheaffer, C.C., J.V. Wiersma, D.D. Warnes, D.L. Rabas, W.E. Lueschen, and J.H. Ford. 1986. Fall harvesting and alfalfa yield, persistence and quality. *Can. J. Plant Sci.* **66**(2):329–338.

Sheaffer, C.C., G.C. Marten, R.M. Jordan, and E.A. Ristau. 1992. Forage potential of kura clover and birdsfoot trefoil when grazed by sheep. *Agron. J.* **84**(2):176–180.

Sheesley, R., D.W. Grimes, W.D. McClellan, C.G. Summers, and V. Marble. 1974. Influence of wheel traffic on yield and stand longevity of alfalfa. *Calif. Agric.* **28**(10):6–8.

Shepherd, J.B. 1959. Effects of a chemical desiccant on the speed of curing of hay. *J. Aust. Inst. Agric. Sci.* **25**(3):218–221.

Shepherd, J.B., C.H. Gordon, and L.F. Campbell. 1953. Development and problems in making grass silage. USDA Bur. Dairy Ind. Info. Bull. 149.

Shepherd, J. B., H. G. Wiseman, R. E. Ely, C. G. Melin, W. J. Sweetman, C. M. Gordon, L. G. Schoenleber, R.E. Wagner, L.E. Campbell, G.D. Roane, and W.H. Hosterman. 1954. Experiments in harvesting and preserving alfalfa for dairy cattle feed. USDA Tech. Bull. 1079:1–47.

Shepperson, G., J. K. Grundey, and R. Wickens. 1962. Crop conditioning experiments: Part I—Drying rates and yields. *Exp. Husb.* 8:65–84.

Shitao, Y.L., and R.M. Reisenauer. 1968. Zinc nutrition of alfalfa. *Agron. J.* **60**(5):464–466.

Shockey, W.L., and H.R. Conrad. 1984. Effects of propionic acid added to supplemental corn on utilization of complete ensiled diets by lactating dairy cows. *J. Dairy Sci.* **67**(5):969–977.

Shockey, W.L., B.A. Dehority, and H.R. Conrad. 1985. Effects of microbial inoculant on fermentation of alfalfa and corn. *J. Dairy Sci.* **68**(11):3076–3080.

Shockey, W.L., and A.L. Barta. 1987. Relationship between alkaline mineral concentration and rate of pH decline in ensiled greenhouse-grown alfalfa. *Agron. J.* **79**(2):307–310

Sholar, J.R., J.L. Caddel, J.F. Stritzke, and R.C. Berberet. 1983. Fall harvest management of alfalfa in the southern Plains. *Agron. J.* **75**(4):619–622.

Simpson, J.R., and T.H. Stobbs. 1981. Nitrogen supply and animal production from pastures. pp. 261–287. *In* F.H.W. Morley (ed.). *Grazing Animals.* Elsevier, Amsterdam,

Singh, S.P., U.R. Pal, and K. Luka. 1989. Allelopathic effect of three serious weeds of Nigerian savanna on germination and seedling vigour of soybean and maize. *J. Agron. Crop Sci.* **162**(4):236–240.

Slade, J.J., and J.H. Reynolds. 1985. Plant growth regulator effects on forage quality of tall fescue and Bermudagrass. *Tenn. Farm Home Sci.* **134**:19–23.

Smith, D. 1962. Carbohydrate root reserves in alfalfa, red clover, and birdsfoot trefoil under several management schedules. *Crop Sci.* **2**(1):75–78.

Smith, D. 1969. Influence of temperature on the yield and chemical composition of 'Vernal' alfalfa at first flower. *Agron. J.* **61**(3):470–472.

Smith, D. 1970a. Yield and chemical composition of leaves and stems of alfalfa at intervals up the shoots. *J. Agr. Food Chem.* **18**(4):652–656.

Smith, D. 1970b. Influence of temperature on the yield and chemical composition of five forage legume species. *Agron. J.* **62**(4):520–523.

Smith, D. 1970c. Influence of cool and warm temperatures and temperature reversal at inflorescence emergence on yield and chemical composition of timothy and brome grass at anthesis. pp. 510–514. *In* M.J.T. Norman (ed.). Proc. Int. Grassl. Congr., 11th, 13–23 April 1970. Surfers Paradise, Queensland, Australia, Univ. of Queensland Press, St. Lucia, Queensland, Australia.

Smith, D. 1971. Levels and sources of potassium for alfalfa as influenced by temperature. *Agron. J.* **63**(3):497–500.

Smith, D. 1981. *Forage Management in the North,* 4th ed. Kendall/Hunt Publishing Co., Dubuque, IA.

Smith, D., R.J. Bula, and R.P. Walgenbach. 1986. *Forage Management.* 5th ed. Kendall/Hunt Publishing Company, Dubuque, IA.

Smith, D., H.J. Lowe, A.M. Strommen, and G.N. Brooks. 1954. Establishment of legumes as influenced by the rate of sowing and oat companion crop. *Agron. J.* **46**(10):449–451.

Smith, D., G. C. Marten, A. G. Matches, and W. F. Wedin. 1968. Dry matter yields of Vernal and DuPuits alfalfa harvested by calendar date and plant maturity schedules in Missouri, Iowa, Wisconsin, and Minnesota. Wis. Agric. Exp. Stn. Res. Rep. 37.

Smith, D., and L.A. Peterson. 1975. Chlorine concentrations in alfalfa herbage and soil with KCl topdressing of a low fertility silt loam soil. *Commun. Soil Sci. Plant Anal.* **6**(5):521–533.

Smith, D., and B. E. Struckmeyer. 1974. Gross morphology and starch accumulation in leaves of alfalfa plants grown at high and low temperatures. *Crop Sci.* **14**(3):433–436.

Smith, R.R., N.L. Taylor, and S.R. Bowley. 1985. Red clover. pp. 457–470. *In* N.L. Taylor (ed.). *Clover Science and Technology.* Monograph 25. AS, CSSA, SSSA, Inc. Madison, WI.

Snaydon, R. W. 1972. The effect of total water supply, and of frequency of application, upon lucerne. II. Chemical composition. *Aust. J. Agric. Res.* **23**(2):253–256.

Sollenberger, L.E., W.C. Templeton, Jr., and R.R. Hill, Jr. 1984. Orchardgrass and perennial ryegrass with applied nitrogen and in mixtures with legumes. 1. Total dry matter and nitrogen yields. *Grass For. Sci.* **39**(3):255–262.

Sorensen, E.L., E.K. Horber, and D.L. Stuteville. 1986. Registration of KS94GH6 glandular-haired alfalfa germplasm with multiple pest resistance. *Crop Sci.* **26**(5):1088.

Sorenson, J.W. Jr., and N.K. Person, Jr. 1967. Harvesting and drying selected forage crops. Texas A&M Univ. Bul. 1071.

Sorenson, R.C., E.J. Penas, and U.U. Alexander. 1968. Sulfure content and yield of alfalfa in relation to plant nitrogen and sulfur fertilization. *Agron. J.* **60**(1):20–23.

Stachon, W.J., and R.L. Zimdhal. 1980. Allelopathic activity of Canada thistle (*Circium arvense*) in Colorado. *Weed Sci.* **28**(1):83–86.

Stanhill, G. 1962. The control of field irrigation practice from measurements of evaporation. *Israel J. Agric. Res.* **12**(1):51–62.

Stegman, E.C., A. Bauer, J.C. Zubriski, and J. Bauder. 1977. Crop curves for water balance irrigation scheduling in S.E. North Dakota. N. Dak. Agric. Exp. Stn. Res. Rep. 66.

Stephenson, G.R., and A. Veigel. 1987. Recovery of compacted soil on pastures used for winter cattle feeding. *J. Range Mgt.* **40**(1):46–48.

Stern, W.R., and C.M. Donald. 1962. Light relationships on grass–clover swards. *Aust. J. Agric. Sci.* **13**(4):599–614.

Stevenson, F.J., and H.A. Jones. 1953. Some sources of resistance in crop plants. pp. 192–216. *In* A. Stefferud (ed.). *Plant Diseases,* USDA Yearbook of Agric. Washington, DC.

Stewart, B.A., and L.K. Porter. 1969. Nitrogen-sulfur relationships in wheat (*Triticum aestivum* L.), corn (*Zea mays*), and beans (*Phaseolus vulgaris*). *Agron. J.* **61**(2):267–271.

Stewart, G., and I. Clark. 1944. Effect of prolonged spring grazing on the yield and quality of forage from wild-hay meadows. *J. Amer. Soc. Agron.* **36**(3):238–248.

Stewart, T.A., and I.I. McCullough. 1985. A comparison of silages made from red clover/grass, white clover/grass and high nitrogen grass swards for beef production. *Anim. Prod.* **40**(2):267–277.

Stitt, M. 1986. Regulation of photosynthetic sucrose synthesis: integration, adaptation, and limits. pp. 331–347. *In* J. Cronshaw, W.J. Lucas, and R.T. Giaquinta (eds.). *Phloem Transport.* Alan R. Liss, New York.

Stoneberg, E.G., F.W. Schaller, D.O. Hull, V.M. Meyer, N.J. Wardle, N. Gay, and D.E. Voelker. 1968. Silage production and use. Iowa State Univ. Pam. 417.

Stout, P.R., W.R. Meagher, G.A. Pearson, and C.M. Johnson. 1951. Molybdenum nutrition of crop plants. I. The influence of phosphate and sulfate on the absorption of molybdenum from soils and solution culture. *Plant Soil* **3**(1):51–87.

St. Pierre, N.R., R. Bouchard, G. St. Laurent, G.L. Roy, and C. Vinet. 1987. Performance of lactating dairy cows fed silage from corn of varying maturities. *J. Dairy Sci.* **70**(1):108–115.

Streeter, C.L., D.F. Burzlaff, D.C. Clanton, and L.R. Rittenhosue. 1966. Effect on stage of maturity, method of storage, and storage time on nutritive value of Sandhills upland hay. *J. Range Mgt.* **19**(2):55–59.

Stuedemann, J.A., and C.S. Hoveland. 1988. Fescue endophyte: History and impact on animal agriculture. *J. Prod. Agric.* **1**(1):39–44.

Sullivan, J. T. 1969. Chemical composition of forages with respect to the needs of the grazing animal. USDA-ARS Bull 34–107.

Sullivan, J.T. 1973. Drying and storing herbage as hay. pp. 1–31. *In* G.W. Butler and R. W. Bailey (eds.). *Chemistry and Biochemistry of Herbage,* Vol. 3. Academic Press, London.

Summers, C.G., and D.G. Gilchrist. 1991. Temporal changes in forage alfalfa associated with insect and disease stress. *J. Econ. Entomol.* **84**(4):1353–1363.

Sund, J.M., G.P. Barrington, and J.M. Scholl. 1966. Methods and depths of sowing forage grasses and legumes. pp. 319–323. *In* A.G.G. Hill (ed.). Proc. Int. Grassl. Congr., 10th, 7–16 July 1966, Univ. of Helsinki, Helsinki, Finland.

Swanson, C.O. *et al.* 1919. Losses of organic matter in making brown and black alfalfa. *J. Agr. Res.* **18**(6):299–304.

Takano, N., Y. Masaoka, and T. Manda. 1983. Effect of delayed sealing during ensiling on fermentation and dry-matter loss. pp. 629–631. *In* J.A. Smith and V.W. Hays (eds.). Proc. Int. Grassl. Congr., 14th, 15–24 June 1981, Lexington, KY. Westview Press, Boulder, CO.

Takeda, T. 1961. Studies on the photosynthesis and production of dry matter in the community of rice plants. *Japan. J. Bot.* **17**(3):403–437.

Tanner, C.B. 1963. Plant temperatures. *Agron. J.* **55**(2):210–211.

Tanner, C.B. 1967. Measurement of evapotranspiration. Irrigation of agricultural lands. *Agronomy* **11**:534–574.

Tanner, C.B., and C.P. Mamaril. 1959. Pasture soil compaction by animal traffic. *Agron J.* **51**(6):329–331.

Taylor, K.E., and M.C. MacCracken. 1990. Projected effects of increasing concentrations of carbon dioxide and trace gases on climate. pp. 1–17. *In* B.A. Kimball, N.J. Rosenberg, and L.H. Allen, Jr. (eds.). *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture.* ASA Special Pub. No. 53. Am. Soc. Agron., Madison, WI.

Taylor, S.A. 1952. Use of mean soil moisture tension to evaluate the effect of soil moisture on crop yields. *Soil Sci.* **74**(3):217–226.

Taylor, T.H., and W.C. Templeton, Jr. 1976. Stockpiling Kentucky Bluegrass and tall fescue forage for winter pasturage. *Agron. J.* **68**(2):235–239.

Temme, D.G., R.G. Harvey, R.S. Fawcett, and A.W. Young. 1979. Effects of annual weed control on alfalfa forage quality. *Agron. J.* **71**(1)51–54.

Templeton, W. C., Jr. 1984. Background and recommendations of the National Alfalfa Hay Quality Committee for expressing nutritive value of alfalfa hay. pp. 3–7. *In* V. L. Marble (ed.). Proc. Natl. Alfalfa Hay Quality Testing Workshop, Chicago. 22–23 March Agronomy Extension, Univ. of California, Davis.

Tenhunen, J.D., O.L. Lange, J. Gebel, W. Beyschlag, and J.A. Weber. 1984. Changes in photosynthetic capacity, carboxylation efficiency and CO_2 compensation point associated with midday stomatal closure and midday depression of net CO_2 exchange of leaves of *Quercus suber*. *Planta* **162**(3):193–203.

Terashima, I., S-C Wong, C.B. Osmond, and G.D. Farquhar. 1988. Characterisation of nonuniform photosynthesis induced by abscisic acid in leaves having different mesophyll anatomies. *Plant Cell Physiol.* **29**(3):385–394.

Terman, G.L., E.C. Doll, and J.A. Lutz, Jr. 1960. Rate, source, time, and method of applying phosphates for alfalfa and legume–grass hay and pasture. *Agron. J.* **52**(5):261–264.

Tesar, M.B. 1984. Good stands for top alfalfa production. Mich. Coop. Ext. Serv. Bull. E-1017.

Tesar, M.B. 1993. Delayed seeding of alfalfa avoids autotoxicity after plowing or glyphosate treatment of established stands. *Agron. J.* **85**(2):256–263.

Tesar, M.B., K. Lawton, and B. Kawin. 1954. Comparison of band seeding and other methods of seeding legumes. *Agron. J.* **46**(5):189–194.

Tesar, M.B., and V.L. Marble. 1988. Alfalfa establishment. pp. 303–332. *In* A.A. Hanson, D.K. Barnes, and R.R. Hill Jr. (eds.). *Alfalfa and Alfalfa Improvement.* Monogr. 29, ASA, CSSA, SSSA, Madison, WI.

Tesar, M.B., and G. V. Triplett. 1960. Improvements in methods of establishing alfalfa. pp. 348–352. *In* C.L. Skidmore (ed.). Proc. Int. Grassl. Congr., 8th, 11–21 July 1960, Univ. of Reading, Reading, England, UK.

Tesar, M.B., and J.L. Yager. 1985. Fall cutting of alfalfa in the North Central USA. *Agron. J.* **77**(5):774–778.

Thomas, C., K. Aston, and S.R. Daley. 1985. Milk production from silage. 3. A comparison of red clover with grass silage. *Anim. Prod.* **41**(1):23–31.

Thomas, C., and P.C. Thomas. 1988. Factors affecting the nutritive value of grass silages. pp. 274–307. *In* W. Haresign and D.J.A. Cole (eds.). *Recent Developments in Ruminant Nutrition* 2. Butterworths, London.

Thomas, G.W. 1989. The soil bank account and the farmer's bank account. *J. Prod. Agric.* **2**(2):122–124.

Thomas, M.D., and G.R. Hill. 1937. The continuous measurements of photosynthesis, respiration and transpiration of alfalfa, and wheat growing under field conditions. *Plant Physiol.* **12**(2):285–307.

Thomas, M.D., and G.R. Hill. 1949. Photosynthesis under field conditions. pp. 19–52. *In* J. Franck and W.E. Loomis (eds.). *Photosynthesis in Plants.* Iowa State College Press, Ames, IA.

Thompson, T.E., R.E. Shade, and J.D. Axtell. 1978. Alfalfa weevil resistance mechanism characterized by larval convulsions. *Crop Sci.* **18**(2):208–209.

Thompson, T.E., and G.W. Fick. 1981. Growth response of alfalfa to duration of soil flooding and to temperature. *Agron. J.* **73**(2):329–332.

Thorlacius, S.O., and J.A. Robertson. 1984. Effectiveness of anhydrous ammonia as a preservative for high-moisture hay. *Can. J. Anim. Sci.* **64**(4):867–880.

Thornley, J.H.M. 1976. *Mathematical Models in Plant Physiology.* Academic Press, NY.

Thrasher, F.P., C.S. Cooper, and J.M. Hodgson. 1963. Competition of forage species with Canada thistle, as affected by irrigation and nitrogen levels. *Weeds* **11**(2):136–138.

Tietz, N. 1990. World's largest hay market. *Hay For. Grow.* **5**(7):6–7.

Tietz, N. 1991. No-hassle Hay Marketing. *Hay For. Grow.* **6:**(4):12.

Tisdale, S.L. 1977. Sulphur in forage quality and ruminant nutrition. Sulphur Inst. Tech. Bull. 22. The Sulphur Institute, 1725 K Street, N.W., Washington, D.C. 20006.

Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil Fertility and Fertilizers. 5th ed. Macmillan Pub. Co., New York.

Tollenaar, M. 1989. Genetic improvement of grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988. *Crop Sci.* **29**(6):1365–1371.

Tomlin, D. C., R. R. Johnson, and B. A. Dehority. 1965. Relationship of lignification to *in vitro* cellulose digestibility of grasses and legumes. *J. Anim. Sci.* **24**(1):161–165.

Towne, Gene, andPaul D. Ohlenbusch. 1992. Native hay meadow management. Kan. Agric. Ext. MF-1042. 2 pp.

Tracy, W.F., and J.G. Coors. 1990. Agronomic performance of sugary-brawn2 maize: A potential additive for high-protein silage production. *Agron. J.* **82**(1):1–4.

Triplett, G.B., and M.B. Tesar. 1960. Effects of compaction, depth of planting, and soil moisture tension on seedling emergence of alfalfa. *Agron. J.* **52**(12):681–684.

Troelsen, J. E., and J. B. Campbell. 1969. The effect of maturity and leafiness on the intake and digestibility of alfalfa and grasses fed to sheep. *J. Agric. Sci.* **73**(1):145–154.

Truog, E. 1938. Putting soil science to work. *J. Am. Soc. Agron.* **30**(12):973–985.

Truog, E., and R.J. Jones. 1938. Fate of soluble potash applied to soils. *Ind. Eng. Chem.* **30**(7):882–885.

Tullberg, J. N., and D. E. Angus. 1978. The effect of potassium carbonate solution on the drying of lucerne. 1. Laboratory studies. *J. Agric. Sci.* **91**(3):551–556.

Tullberg, J. N., and D. J. Minson. 1978. The effect of potassium carbonate solution on the drying of lucerne. 2. Field studies. *J. Agric. Sci.* **91**(3):557–561.

Turner, N.C., and J.E. Begg. 1978. Responses of pasture plants to water deficits. pp. 50–66. *In* J.R. Wilson (ed.). *Plant Relations in Pastures.* CSIRO, Melbourne, Australia.

Turner, N.C., and M.M. Jones. 1980. Turgor maintenance by osmotic adjustment: A review and evaluation. pp. 87–103. *In* N.C. Turner and P.J. Kramer (eds.). Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York.

Upchurch, R.P., and R.L. Lovvorn. 1951. Gross morphological root habits of alfalfa in North Carolina. *Agron. J.* **43**(10):493–498.

Urness, P.J. 1980. Supplemental feeding of big game in Utah. Utah Div. Wildl. Resources Pub.. 80–88. 12 pp.

USDA. 1965. Losses in agriculture. U.S. Dep. Agric. Handbook No. 291. 120 p. U.S. Govt. Printing Office, Washington, DC.

USDA. Forest Service. 1981. An assessment of the forest and range land situation in the United States. USDA For. Res. Rep. 22. 352 pp.

Valdez, F.R.; J.H. Harrison, D.A. Deetz, and S.C. Fransen. 1988a. *In vivo* digestibility of corn and sunflower intercropped as a silage crop. *J. Dairy Sci.* **71**(7):1860–1867.

Valdez, F.R., J.H. Harrison, and S.C. Fransen. 1988b. Effect of feeding corn-sunflower silage on milk production, milk composition, and rumen fermentation of lactating dairy cows. *J. Dairy Sci.* **71**(9):2462–2469.

Valdez, F.R., J.H. Harrison, and S.C. Fransen. 1989. Effect of feeding silage of early and late maturing corn planted at two population densities to lactating dairy cows. *J. Dairy Sci.* **72**(8):2081–2086.

Valentine, S.C., M.J. Cochrane, and R. B. Wickes. 1983. Effect of potassium carbonate solution on the rate of drying and nutritive value of lucerne, grass/clover and oat crops cut for hay. *J. Aust. Inst. Agric. Sci.* **49**(4):224–226.

Vallentine, J.F. 1989. *Range Development and Improvements,* 3rd ed. Academic Press, San Diego, Calif. 524 pp.

Vallentine, J.F. 1990. *Grazing Management.* Academic Press, San Diego, Calif. 533 pp.

Van Bavel, C.H.M. 1967. Changes in canopy resistance to water loss from alfalfa induced by soil water depletion. *Agric. Meteorol.* **4**(3):165–176.

Van Horn, H.H., O.C. Ruelke, R.P. Cromwell, M. Ryninks, and K. Oskam. 1988. Effects of chemical drying agents and preservatives on composition and digestibility of alfalfa hay. *J. Dairy Sci.* **71**(8):2256–2263.

Van Keuren, R.S., A.D. Pratt, H.R. Conrad, and R.R. Davis. 1966. Utilization of alfalfa–bromegrass as soilage, strip-grazing, and rotational grazing for dairy cattle. Ohio Agric. Expt. Sta. Res. Bul. 989. 20 pp.

Van Keuren, R.W. 1980. Managing established pastures. pp. 165–175. *In* Proc. 1980 For. Grassl. Conf., 11–13 Feb. 1980. Louisville, KY.

Van Keuren, R.W., W.W. Heinemann. 1959. Irrigated sudangrass and millet for forage and seed in central Washington. State College of Washington, Agricultural Experiment Station, Bull. 605. 9 pp. Pullman, WA.

Van Reen, R., and W.R. Singleton. 1952. Sucrose content in the stalks of maize inbreds. *Agron. J.* **44**(12):610–614.

Van Riper, G.E., and D. Smith. 1959. Changes in the chemical composition of the herbage of alfalfa, medium red clover, ladino clover, and bromegrass with advances in maturity. Wisc. Agr. Exp. Stn. Res. Rep. No. 4.

Van Soest, P.J. 1964. Symposium on nutrition and forage and pastures: New chemical procedures for evaluating forages. *J. Anim. Sci.* **23**(3):838–845.

Van Soest, P.J. 1967. Development of a comprehensive system of feed analyses and its application to forage. *J. Anim. Sci.* **26**(1):119–128.

Van Soest, P.J. 1982. *Nutritional Ecology of the Ruminant: Ruminant Metabolism, Nutritional Strategies, the Cellulolytic Fementation, and the Chemistry of Forages and Plant Fibers.* O&B Books, Corvallis, OR. 373 pp.

Van Soest, P. J. and J. B. Robertson. 1980. Systems of analysis for evaluating fibrous feeds. pp. 49–60. *In* W. J. Pigden *et al.* (eds.). *Standardization Anal. Method. Feeds.* Proc. Int. Workshop, Ottawa, ON, Canada. 12–14 Mar. 1979. International Development Research Centre, Ottawa, ON.

Vanderlip, R.L., and H.E. Reeves. 1972. Growth stages of sorghum [*Sorghum bicolor,* (L.) Moench.]. *Agron. J.* **64**(1):13–16.

Vanderlip, R.L. 1979. How a sorghum plant develops. Coop. Ext. Ser., Kansas State Univ., Manhattan, KS.

Vattikonda, M.R., and R.B. Hunter. 1983. Comparison of grain yield and whole-plant silage production of recommended corn hybrids. *Can. J. Plant Sci.* **63**(3):601–609.

Vincent, J.F.V. 1983. The influence of water content on the stiffness and fracture properties of grass leaves. *Grass For. Sci.* **38**(2):107–114.

Virtanen, A.I. 1928). Ueber die Einwirkung der Bodenaziditat auf das Wachstum und die Zusammensetzun der Leguminosenpflanzen. *Biochem. Z.* **193**(4):300–312.

Volenec, J.J., J.H. Cherney, and K.D. Johnson. 1987. Yield components, plant morphology, and forage quality of alfalfa as influenced by plant population. *Crop Sci.* **27**(2):321–326.

Vough, L. R. 1983. Hay preservatives and chemical driers: Do they work? *Dairy Herd Manage.* **20**(8):16,18,43.

Vough, L.R., and G.C. Marten. 1971. Influence of soil moisture and ambient temperature on yield and quality of alfalfa forage. *Agron. J.* **63**(1):40–42.

Waddington, J., and S. Bittman. 1984. Establishment and subsequent productivity of bromegrass and alfalfa seeded with an Argentine rapeseed companion crop in northeastern Saskatchewan. *Can. J. Plant Sci.* **64**(2):303–308.

Wahab, H.A., and D.S. Chamblee. 1972. Influence of irrigation on the yield and persistence of forage legumes. *Agron. J.* **64**(6):713–716.

Waldo, D. R. 1985. Regulation of forage intake in ruminants. pp. 233–237. *In* R. F. Barnes *et al.* (eds.). Proc. (Trilateral Workshop) Forage Legumes for Energy-Efficient Animal Production, Palmerston North, New Zealand, 30 April–4 May 1984. USDA–ARS, Washington, DC.

Waldo, D. R., and N.A. Jorgensen. 1981. Forages for high animal production: nutritional factors and effects of conservation. *J. Dairy Sci.* **64**(6):1207–1229.

Waldo, D. R., D. J. Thompson, H. K. Goering, and H. F. Tyrrell. 1982. The voluntary intake, growth rate, and tissue retention of cattle fed grass or legume silage. *Proc. Nutr. Soc.* **41**:24A.

Walgenbach, R.P., G.C. Marten, and G.R. Blake. 1981. Release of soluble protein and nitrogen in alfalfa. I. Influence of growth temperature and soil moisture. *Crop Sci.* **21**(6):843–849.

Walgenbach, R. P, and L.J. Massingill. 1986. Research techniques and performance evaluations of hay preserving agents. pp. 172–175. *In* Proc. For. Grassl. Coun., 15–17 Apr. 1986. Athens, GA. Amer. For. Grassl. Coun., Lexington, KY.

Walker, G.K., and J.L. Hatfield. 1983. Stress management using foliage temperatures. *Agron. J.* **75**(4):623–629.

Walker, T.W., and A.F.R. Adams. 1958. Competition for sulphur in a grass clover association. *Plant Soil* **9**(4):353–366.

Wallace, A., E. Frolich, and O.R. Lunt. 1966. Calcium requirements of higher plants. *Nature* **209**(5023):634.

Wallace, J.D. 1984. Some comments and questions on animal preferences, ecological efficiencies, and forage intake. pp. 275–287. *In* Nat'l Res. Council/Natl. Acad. Sci. *Developing Strategies for Rangeland Management.* Westview Press, Boulder, CO.

Wallentine, M.V. 1986. Baled, bagged alfalfa silage compared for dairy cows. *Feedstuffs* **58**(38):14–15, 18.

Waller, S.S., P.E. Reece, L.E. Moser, and G.A. Gates. 1985. *Understanding Grass Growth: The Key to Profitable Livestock Production.* Trabon Print. So., Kansas City, MO 20 pp.

Walton, P. D. 1983. *Production and Management of Cultivated Forages.* Reston Publishing Company, Inc., Reston, VA 336 pp.

Ward, C.Y., and R.E. Blaser. 1961. Effect of nitrogen fertilizer on emergence and seedling growth of forage plants and subsequent production. *Agron. J.* **53**(2):115–120.

Ward, G.M. 1959. Effect of soil fertility upon the yield and nutritive value of forages. A review. *J. Dairy Sci.* **42**(2):277–297.

Wardlaw, I.F., and L. Eckhardt. 1987. Assimilate movement in *Lolium* and *Sorghum* leaves. IV. Photosynthetic responses to reduced translocation and leaf storage. *Aust. J. Plant Physiol.* **14**(5):573–591.

Warrick, A.W. 1990. Nature and dynamics of soil water. pp. 69–92. *In* B.A. Stewart, and D.R. Nielsen (eds.). *Irrigation of Agricultural Crops.* Agron. Monogr. 30, ASA, CSSA, SSSA, Madison, WI.

Watson, D.J. 1947. Comparative physiological studies on the growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Ann. Bot.* (N.S.) **11**(1):41–76.

Watson, J. S., and M. Nash. 1960. *The Conservation of Grass and Fodder Crops.* Oliver and Boyd. Edinburgh

Wear, J.I., and R.M. Patterson. 1962. Effect of soil pH and texture on the availability of water-soluble boron in the soil. *Soil Sci. Soc. Amer. Proc.* **26**(4):344–346.

Weaver, J.E. 1926. *Root Development of Field Crops.* McGraw-Hill Book Co., New York, NY.

Weaver, J.E. 1968. *Prairie Plants and Their Environment. A Fifty-Year study in the Midwest.* Univ. of Nebraska Press, Lincoln

Wedin, W.F. 1976. Integration of forage resources for beef cattle production in the western cornbelt. pp. 4–19. *In* Proceedings for Symposium on Integration of Resources for Beef Cattle Production, February 16–20, 1976. Omaha, Neb. Society for Range Management, Denver, CO.

Wedin, W.F., and T.J. Klopfenstein. 1985. Cropland pastures and crop residues. pp. 496–506. *In* M.E. Heath, R.F. Barnes, and D.S. Metcalf (eds.). *Forages: The Science of Grassland Agriculture,* 4th ed. Iowa State Univ. Press, Ames, IA.

Weeks, M.E., and D.J. Lathwell. 1967. *Crop Response to Time in the Northeastern United States.* Agron. Monogr. 12:233–263.

Weiss, W.P., V.F. Colenbrander, and V.L. Lechtenberg. 1982. Feeding dairy cows high moisture alfalfa hay preserved with anhydrous ammonia. *J. Dairy Sci.* **65**(7):1212–1218.

Weller, R.F., R.H. Phipps, and A. Cooper. 1985. The effect of the brown midrib-3 gene on the maturity and yield of forage maize. *Grass For. Sci.* **40**(3):335–339.

Wells, G.J. 1969. Skeleton weed (*Chrondrilla juncea*) in the Victorian Mallee. I. Competition with legumes. *Aust. J. Expt. Agric. Anim. Husb.* **9**(40):521–527.

Welty, L.E., R.L. Ditterline, and L.S. Prestbye. 1988. Fall management of alfalfa. *Montana Agric. Res.* **5**(2):16–19.

West, C.P. (ed.). 1989. Proceedings of the Arkansas Fescue Toxicosis Conference, 1989. Ark. Agric. Expt. Sta. Spec. Rep. 140. 58 pp.

Westermann, D.T. 1975. Indexes of sulfur deficiency in alfalfa. II. Plant analyses. *Agron. J.* **67**(2):265–268.

Whitehead, D.C. 1964. Soil and plant-nutrition aspects of the sulphur cycle. *Soil Fertil.* **27**(1):1–8.

Whitesides, R.E. 1990. Feeds and forages: variety performance trials in Utah—1990. Coop. Ext. Ser., Utah State Univ., Logan, UT.

Whitlow, L.W. 1987. Stage of maturity affects yield and feeding value of small grain silage. North Carolina Dairy Ext. Newsl. North Carolina Agric. Ext. Ser. Apr 1987. p. 2. Raleigh, N.C.

Whitney, L.F. 1966. Hay losses from baler and chopper components. *Trans. ASAE* **9**(2):277–278.

Whyte, R.O., G. Wilsson-Leissner, and H.C. Trumble. 1953. Legumes in agriculture. FAO Agric. Series No. 21. Food Agr. Organ. U.N., Rome, Italy.

Widstrom, N.W., M.E. Carr, M.O. Bagby, and L.T. Black. 1988. Distribution of sugar and soluble solids in the maize stalk. *Crop Sci.* **28**(5):861–863.

Wieghart, M. 1979. Acceleration of forage drying by chemical application at cutting. M.S. Thesis. Michigan State Univ., East Lansing, MI.

Wieghart, M., J.W. Thomas, and M.B. Tesar. 1980. Hastening drying rate of cut alfalfa with chemical treatment. *J. Anim. Sci.* **51**(1):1–9.

Wieghart, M., J. W. Thomas, M. B. Tesar, and C. M. Hansen. 1983. Acceleration of alfalfa drying in the field by chemical application at cutting. *Crop Sci.* **23**(2):225–229.

Wiggins, R.G. 1937. The influence of stage of growth of corn on the composition of silage. *J. Am. Soc. Agron.* **29**(6):456–467.

Wilde, S.A., and G.K. Voigt. 1952. The determination of color of plant tissues by the use of standard charts. *Agron. J.* **44**(9):499–500.

Wilkins, R.J., and E.A. Garwood. 1986. Effects of treading, poaching, and fouling on grassland production and utilization. pp. 19–31. *In* J. Frame (ed.). *Grazing.* Bri. Grassland Soc., Hurley, Berkshire, England.

Wilkinson, J.M. 1981. Losses in the conservation and utilisation of grass and forage crops. *Ann. Appl. Biol.* **98**(2):365–375.

Wilkinson, J.M., P.F. Chapman, R.J. Wilkins, and R.F. Wilson. 1983. Interrelationships between pattern of fermentation during ensilage and initial crop composition. pp. 631–634. *In* J.A. Smith and V.W. Hays (ed.). Proc. Int. Grassl. Congr., 14th, 15–24 June 1981, Lexington, KY. Westview Press, Boulder, CO.

Wilkinson, R.H., and C.W. Hall. 1966. Respiration heat of harvested forage. *Trans. ASAE* **9**(3):424–427.

Wilkinson, S.R., and D.A. Mays. 1979. Mineral nutrition. pp. 41–73. *In* R.C. Buckner and L.P. Lush (eds.). *Tall Fescue.* Agron. Monogr. 20, ASA, CSSA, SSSA. Madison, WI.

Willett, G.S. 1983. How to analyze a hay shed investment. Coop. Ext. Ser., Wash. State Univ., EB 1210, 12p.

Willhite, F.M., R.D. Lewis, and H.K. Rouse. 1962. Improving mountain meadow production in the west. USDA Agric. Info. Bul. 268. 22 pp.

Williams, R.J., and D.G. Stout. 1981. Evapotranspiration and leaf water status of alfalfa growing under advective conditions. *Can. J. Plant Sci.* **61**(3):601–607.

Williams, W.A. 1956. Evaluation of the emergence force exerted by seedlings of small seeded legumes using probit analysis. *Agron. J.* **48**(6):273–274.

Willis, J.A. 1973. *A Dictionary of the Flowering Plants and Ferns,* 8th ed. Revised by H. K. Airy Shaw. Cambridge Univ. Press, London.

Wilson, H.K., and S.S. Quisenberry. 1987. Impact of feeding by three-cornered alfalfa hopper (Homoptera: Membracidae): greenhouse and field study. *J. Econ. Entomol.* **80**(1):185–189.

Wilson, J. R. 1983. Effects of water stress on in vitro dry matter digestibility and chemical composition of herbage of tropical pasture species. *Aust. J. Agric. Res.* **34**(4):377–390.

Wilson, J. R., and T. T. Ng. 1975. Influence of water stress on parameters associated with herbage quality of *Panicum maximum* var *trichoglume. Aust. J. Agric. Res.* **26**(1):127–136.

Wilson, M.C. 1982. Improving alfalfa forage quality: How to detect an manage the potato leafhopper problem. Cert. Alf. Seed Coun., Inc. P.O. Box 2023, Woodland, CA 95695.

Wilson, M.C. 1984. Manage the alfalfa weevil to improve alfalfa yield and quality. Cert. Alf. Seed Coun., Inc. P.O. Box 2023, Woodland, CA 95695.

Wilson, M.C., J.K. Stewart, and H.D. Vail. 1979. Full season impact of the alfalfa weevil, meadow spittlebug, and potato leafhopper in an alfalfa field. *J. Econ. Entomol.* **72**(6):830–834.

Wilson, M.C., F.C. Chen, and M.C. Shaw. 1984. Susceptibility of the alfalfa weevil to a *Bacillus thuringiensis* exotoxin [*Hypera postica,* biological control]. *J. Ga. Entomol. Soc.* **19**(3):366–371.

Wilson, R.C., and L.C. Hardle. 1978. The allelopathic activity of Canada thistle (*Circium arvense*) residue on crop growth. pp. 57–58. Abstracts 1978, Meeting of Weed Sci. Soc. Amer., Champaign, IL.

Winch, J. E., R. W. Sheard, and D. N. Mowat. 1970. Determining cutting schedules for maximum yield and quality of brome grass, timothy, lucerne, and lucerne/grass mixtures. *J. Br. Grassl. Soc.* **25**(1):44–52.

Wolf, D.D., and R.E. Blaser. 1971. Photosynthesis of plant parts of alfalfa canopies. *Crop Sci.* **11**(1):55–58.

Wolf, D.D., and E.W. Carson. 1973. Respiration during drying of alfalfa herbage. *Crop Sci.* **13**(6):660–662.

Wolf, D.D., and R.E. Blaser. 1981. Flexible alfalfa management: Early spring utilization. *Crop Sci.* **21**(1):90–93.

Wolfe, E.C., and A. Lazenby. 1973. Grass–white clover relationships during pasture development. I. Effect of superphosphate. *Aust. J. Exp. Agric. Anim. Husb.* **13**(64):367–574.

Womack, C.L. 1984. Reduction in photosynthetic and transpiration rates of alfalfa caused by potato leafhopper (Homoptera: Cicadillidae) infestations. *J. Econ. Entomol.* **77**(2):508–513.

Wong, S.-C., I.R. Cowan, and G.D. Farquhar. 1985. Leaf conductance in relation to rate of CO_2 assimilation. III. Influence of water stress and photoinhibition. *Plant Physiol.* **78**(4):830–834.

Wood, J.G.M., and J. Parker. 1971. Respiration during the drying of hay. *J. Agric. Eng. Res.* **16**(3):179–191.

Wood, J.I. 1953. Three billion dollars a year. pp. 1–15. *In* A. Stefferud (ed.). *Plant diseases.* USDA Yearbook Agric., Washington, DC.

Woodhouse, W.W., Jr. 1964. Forages need lime, phosphate, and potash. *Better Crops Plant Food* **48**(2):12–19.

Woodward, T.E., W.H. Hosterman, P.V. Cardon, and E.W. McComas. 1939. The nutritive value of harvested forages. pp. 956–991. *In* G. Hambidge (ed.). *Food and life.* USDA Yearbook. US Govt Printing Office, Washington, DC.

Woolford, J.A. 1987. Influence of additives on fermentation of high moisture alfalfa silage and its utilization by dairy animals. Ph. D. Diss. Univ. of Wisconsin, Madison (Diss. Abstr. 87–27262).

Woolford, M.K. and M.K. Sawczyc. 1984a. An investigation into the effects of cultures of lactic acid bacteria on fermentation in silage. 1. Strain selection. *Grass For. Sci.* **39**(2):139–148.

Woolford, M.K., and M.K. Sawczyc. 1984b. An investigation into the effects of cultures of lactic acid bacteria on fermentation in silage. 2. Use of selected strains in laboratory-scale silages. *Grass For. Sci.* **39**(2):149–158.

Wright, J.L. 1982. New evapotranspiration crop coefficients. *J. Irrig. Drain. Div., Am. Soc. Civ. Eng.* **108**(1):57–74.

Zelitch, I. 1971. *Photosynthesis, Photorespiration, and Plant Productivity.* Academic Press, New York.

Zink, F.J. 1936. Moisture content at which alfalfa leaves shatter. *Agric. Eng.* **17**(8):329–330.

INDEX