calibration. Some efforts have, however, been made to model the errors incurred in some specific instruments, with a view to the prediction of performance at sea from dynamic simulation data acquired in the laboratory test tank.

Laboratory tests in controlled conditions thus provide a necessary, though insufficient basis for judging performance, and when a new instrument, or technique, is first used at sea considerable effort is put into intercomparisons with other, longer established instruments or techniques. Not surprisingly, most of the impetus for testing and intercomparison has come from the scientific community; the costs of providing anything other than basic performance data in controlled flow conditions is, with some justification, considered prohibitive by manufacturers. Extensive information on the performance at sea of instruments of many types is, therefore, to be found in the scientific literature, although cheaper instruments are generally less well represented.

Evolutionary Trends

As a result of the advances in electronics and battery technology in recent years, and the painstaking evaluation work accompanying the introduction of new instrument types, sufficient is now known about current measurement that it can in this sense at least be regarded as a relatively mature technology. Yet clear evolutionary trends are in evidence, driven by an increasing operational need for data in support of large-scale monitoring programmes. A further factor is the growing commercial involvement in data gathering. The tendency is towards cheaper, lighter instruments which are more easily handled at sea, and which can be deployed in larger numbers. An example of changes in size, recording capacity and weight that have taken place over the past 25 years is shown by comparing the Vector Averaging Current Meter from the 1970s with a modern acoustic or electromagnetic current meter of similar performance (**Figure 1** and **Table 1**).

Another trend brought about by the growth of processing capability *in situ* is towards the incorporation of current measurement within a complete measurement system embracing a range of physical, chemical, and biological parameters (**Figure 3**). Operational requirements for current data may also in time result in the routine deployment of telemetering systems. At present, satellite telemetry of surface and near-surface measurements is well established, but telemetry of midwater measurements is not yet common practice.

See also

Ocean Circulation. Moorings. Profiling Current Meters. Sonar Systems. Three-dimensional (3D) Turbulence. Turbulence Sensors.

Further Reading

Appell GF and Curtin TB (eds) (1991) Special issue on current measurement. *IEEE Journal of Oceanic Engineering* 16(4): 305–414.

Collar PG, Carson RM and Griffiths G (1983) Measurement of near-surface current from a moored wave-slope follower. *Deep-Sea Research* 30A(1): 63–75.

Dobson F, Hasse L and Davis R (eds) (1980) *Air–Sea Interaction: Instruments and Methods*. New York: Plenum Press.

Hine A (1968) *Magnetic Compasses and Magnetometers*. London: Adam Hilger.

Howarth MJ (1989) *Current Meter Data Quality. Co-operative Research Report* No. 165, Copenhagen: International Council for the Exploration of the Sea.

Myers JJ, Holm CH and McAllister RF (1969) *Handbook of Ocean and Underwater Engineering*. New York: McGraw-Hill.

Pinkel R and Smith JA (1999) *Into the Third Dimension: Development of Phased Array Doppler Sonar*. Proceedings of the IEEE Sixth Working Conference on Current Measurement. San Diego, March 1999.

Shercliff JA (1962) *The Theory of Electromagnetic Flow Measurement*. Cambridge: Cambridge University Press.

SIRENIANS

T. J. O'Shea, Midcontinent Ecological Science Center, Fort Collins, Colorado, USA
J. A. Powell, Florida Marine Research Institute, St Petersburg, FL, USA

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Introduction

The Sirenia are a small and distinctive Order of mammals. They evolved from ancient terrestrial plant feeders to become the only fully aquatic, large mammalian herbivores. This distinctive mode of life is accompanied by a suite of adaptations that make the Sirenia unique among marine mammals in anatomical and physiological features, distribution, ecology, and behavior. Although the Sirenia have a long history of interaction with humans, some of their biological attributes now render them vulnerable to extinction in the face of growing human populations throughout their coastal and riverine habitats.

Evolution and Classification

Fossil History

The order Sirenia arose in the Paleocene from the Tethytheria, a group of hoofed mammals that also gave rise to modern elephants (Order Proboscidea). The beginnings of the Sirenia were probably in the ancient Tethys Sea, near what is now the area joining Africa and Asia. By the early Eocene, sirenians had reached the New World, as evidenced by fossils from the primitive family Prorastomidae from Jamaica. The prorastomids and the sirenian family Protosirenidae were restricted to the Eocene. Protosirenids and prorastomids were amphibious and could walk on land, but probably spent most of the time in water. The fully aquatic Dugongidae also arose around the Eocene, and persisted to the Recent, as represented by the modern dugong (subfamily Dugonginae) and Steller's sea cow. The dugongines were the most diverse lineage, particularly in the Miocene, with greatest radiation in the western Atlantic and Caribbean but also spreading back into the Old World. Two other subfamilies of dugongids also differentiated but became extinct: the Halitherinae, which disappeared around the late Pliocene, and the Hydrodamalinae, which was lost with the extinction of Steller's sea cow in 1768. The hydrodamalines are noteworthy for escaping the typically tropical habitats of sirenians and occupying colder climates of the North Pacific. The family Trichechidae (manatees) arose from dugongids around the Eocene–Oligocene boundary. Two subfamilies of trichechids have been delineated: the Miosireninae, which became extinct in the Miocene, and the Trichechinae, which persists in the three living species of manatees. Early trichechids arose in estuaries and rivers of an isolated South America in the Miocene, where building of the Andes Mountains provided conditions favorable to the flourishing of aquatic vegetation, particularly the true grasses. The abrasiveness of these plants resulted in natural selection for the indeterminate tooth replacement pattern unique to trichechids. When trichechids returned to the sea about a million years ago, this persistent dentition may have allowed them to be more efficient at feeding on seagrasses and outcompete the dugongids that had remained in the Atlantic. Thus dugongids disappeared from the Atlantic, while forms of manatees probably very similar to the modern West Indian manatee spread throughout the tropical western Atlantic and Caribbean, and since the late Pliocene had also dispersed by transoceanic currents to reach West Africa. Beginning in the late Miocene, Amazonian manatees evolved in isolation in what was then a closed interior basin of South America.

Classification, Distribution, and Status of Modern Sirenians

There are four living and one recently extinct species of modern Sirenia. They are classified in two families, the Dugongidae (Steller's sea cow and the dugong) and the Trichechidae (three species of manatees). All four extant species are designated as vulnerable (facing a high risk of extinction in the wild in the medium-term future) by the International Union for the Conservation of Nature and Natural Resources–World Conservation Union.

Steller's sea cow Steller's sea cow, *Hydrodamalis gigas* (**Figure 1**), is placed in the subfamily Hydrodamalinae of the family Dugongidae. These largest of sirenians were found in shallow waters of the Bering Sea around Bering and Copper Islands in the

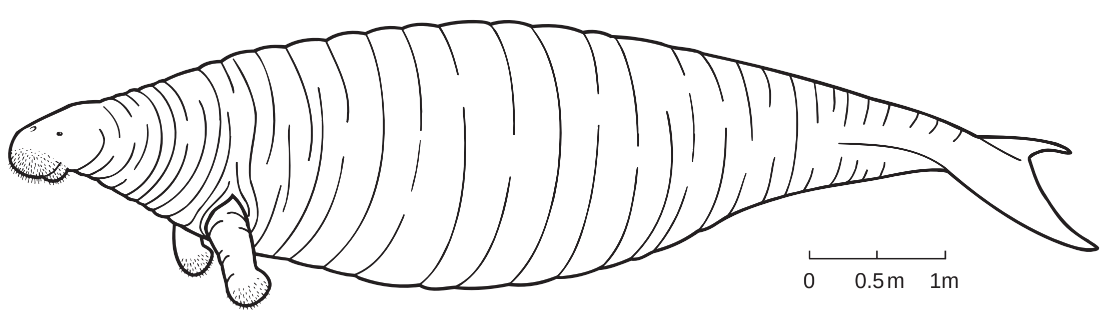

Figure 1 Steller's sea cow (*Hydrodamalis gigas*).

Commander Islands. The first scientist to discover these sea cows was Georg Steller, who first observed them in 1741 during expeditions into the North Pacific led by Vitus Bering. They were hunted to extinction for meat to provision fur hunters about 27 years after their discovery.

Dugongs The dugong (*Dugong dugon*) (**Figure 2**) is the only living member of the family Dugongidae, and is placed in the subfamily Dugonginae. There are no recognized subspecies. Dugongs occur in coastal waters in limited areas of the Indian and western Pacific Oceans. They are currently known from the island of Malagasy and off the east coast of Africa from Mozambique northward to the Red Sea and Persian Gulf; along the Indian subcontinent; off south-east Asia through southern China north to the island of Okinawa in Japan; and through the Phillipines, Malaysia, Indonesia, New Guinea, and most of northern Australia from Shark Bay in Western Australia to Moreton Bay in southern Queensland. Dugongs also occur in very low numbers around the Micronesian islands of Palau. Dugong populations are disjunct and in most areas depleted. Australia provides the major exception, and harbors most of the world's remaining dugongs. One conservative estimate suggests that 85 000 dugongs occur in Australian waters. Dugongs are classified as endangered under the US Endangered Species Act.

West Indian manatees There are two subspecies of West Indian manatees (**Figure 3**): the Florida manatee (*T. manatus latirostris*) (**Figure 4**) of the south-eastern USA, and the Antillean manatee (*T. manatus manatus*) of the Caribbean, Central and South America. West Indian manatees are classified as endangered under the US Endangered Species Act. The Florida subspecies is found year-round in nearshore waters, bays, estuaries, and large rivers of Florida, with summer movements into other states bordering the Gulf of Mexico and Atlantic Ocean. Excursions as far north as Rhode Island have been documented. Winter stragglers occur outside of Florida, sometimes dying from cold exposure. It has not been possible to obtain rigorous population estimates, but it has been estimated that there are between 2500 and 3000 manatees in Florida.

Antillean manatee populations are found in coastal areas and large rivers around the Greater Antilles (Hispaniola, Cuba, Jamaica, and Puerto Rico), the east coast of Mexico, and coastal central America through the Lake Maracaibo region in western Venezuela. There do not appear to be resident manatees along the steep, high-energy

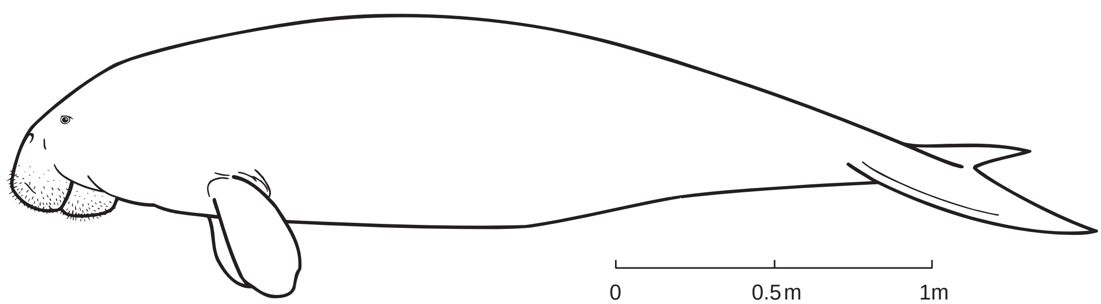

Figure 2 Dugong (*Dugong dugon*).

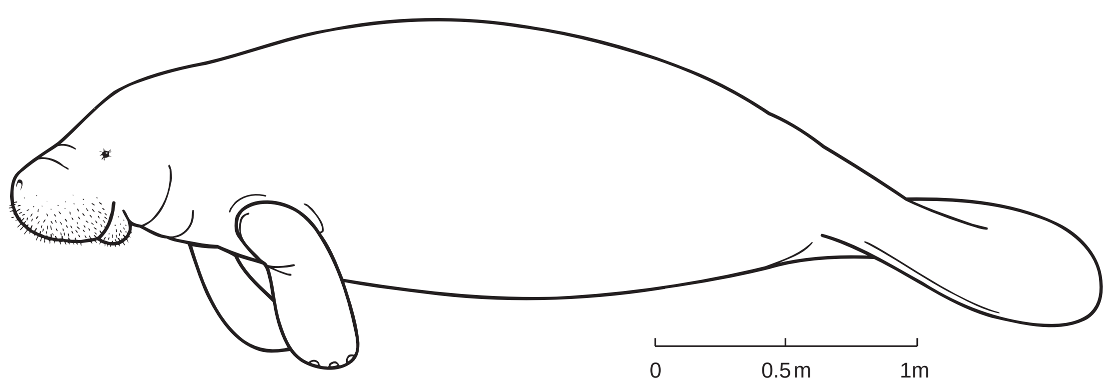

Figure 3 West Indian manatee (*Trichechus manatus*).

Figure 4 Florida manatee (*Trichechus manatus latirostris*).

Caribbean coastline of Venezuela, but populations are found along the Atlantic coast and far inland in large rivers from eastern Venezuela southward to below the mouth of the Amazon near Recife in Brazil. They have not been documented in the lower Amazon. Estimates of Antillean manatee population sizes are unavailable, but they are thought to have declined throughout their range.

West African manatees West African manatees (*Trichechus senegalensis*) (**Figure 5**) are found in Atlantic coastal waters of Africa from Angola in the south to Senegal and Mauritania in the north. They extend far inland in large rivers such as the Senegal, Gambia and Niger, into landlocked and desert countries such as Mali and Chad. There are no recognized subspecies. There are no rigorous data on populations, but they have probably suffered widespread declines due to hunting. West African manatees are classified as threatened under the US Endangered Species Act.

Amazonian manatees There are no recognized subspecies of Amazonian manatees (*Trichechus inunguis*) (**Figure 6**). This species is found in the Amazon River system of Brazil, as far inland as upper tributaries in Peru, Ecuador, and Colombia. Areas occupied include seasonally inundated forests. They apparently do not overlap with West Indian manatees near the mouth of the Amazon, and do not occur outside of fresh water. Amazonian manatee populations have declined this century, but there are

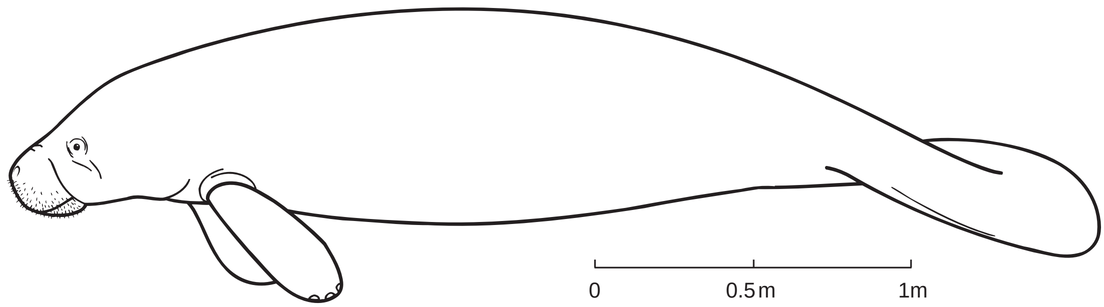

Figure 5 West African manatee (*Trichechus senegalensis*).

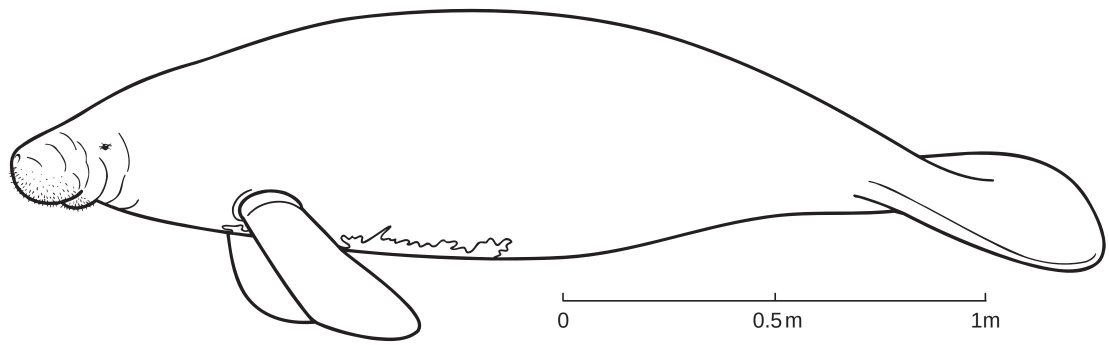

Figure 6 Amazonian manatee (*Trichechus inunguis*).

no firm estimates of numbers. They are classified as endangered under the US Endangered Species Act.

Morphology and Physiology

Adult dugongs range to 3.4 m in length and 420 kg in mass. Florida manatees are larger, ranging to 3.9 m and up to 1655 kg. Morphometric data on West African manatees and Antillean manatees are limited, but they are similar or slightly smaller in size than Florida manatees. Amazonian manatees are the smallest trichechids, ranging up to 2.8 m in length and 480 kg in mass. Steller's sea cow was the largest of all known sirenians, reaching a length of about 9–10 m, and a body mass estimated as high as 10 metric tonnes. The earliest sirenians were about the size of pigs, and had legs, narrow snouts, and the bulky (pachyostotic), dense (osteosclerotic) bones lacking marrow cavities also typical of dugongs and manatees. The heavy skeleton serves as ballast to keep the animals submerged in shallow water. Adaptations for an existence as fully aquatic herbivores also led to rapid loss of hind limbs and development of a broadened down-turned snout. The forelimbs became paddle-like flippers that were positioned relatively close to the head through shortening of the neck, allowing great leverage for steering. Forelimbs are also used to grasp and manipulate objects, including food plants, and to 'walk' along the bottom. The flippers of West African and West Indian manatees have nails at their distal ends, but nails are not present in Amazonian manatees or dugongs. Forward propulsion is attained by vertical strokes of the horizontal tail, which is spatulate in manatees, but deeply notched like the flukes of whales in dugongs and Steller's sea cow. Horizontal orientation is important for feeding on plants, and is facilitated by the long, horizontally oriented, and unilobular lungs. The lungs are separated from the other internal organs by a horizontal diaphragm.

Manatees lack notable sexual dimorphism, although female Florida manatees attain larger sizes than males and the vestigial pelvic bones differ in size and shape. Mammary glands of manatees and dugongs consist of a single teat located in each axilla. Incisors erupt in male dugongs (and occasionally in old females) and take the form of small tusks used in mating-related behavior. The dorsal surfaces of dugongs often bear parallel scar marks left from wounds inflicted by tusks of males. The Amazonian manatee has a very dark gray-black appearance and many have white ventral patches. West Indian and West African manatees and

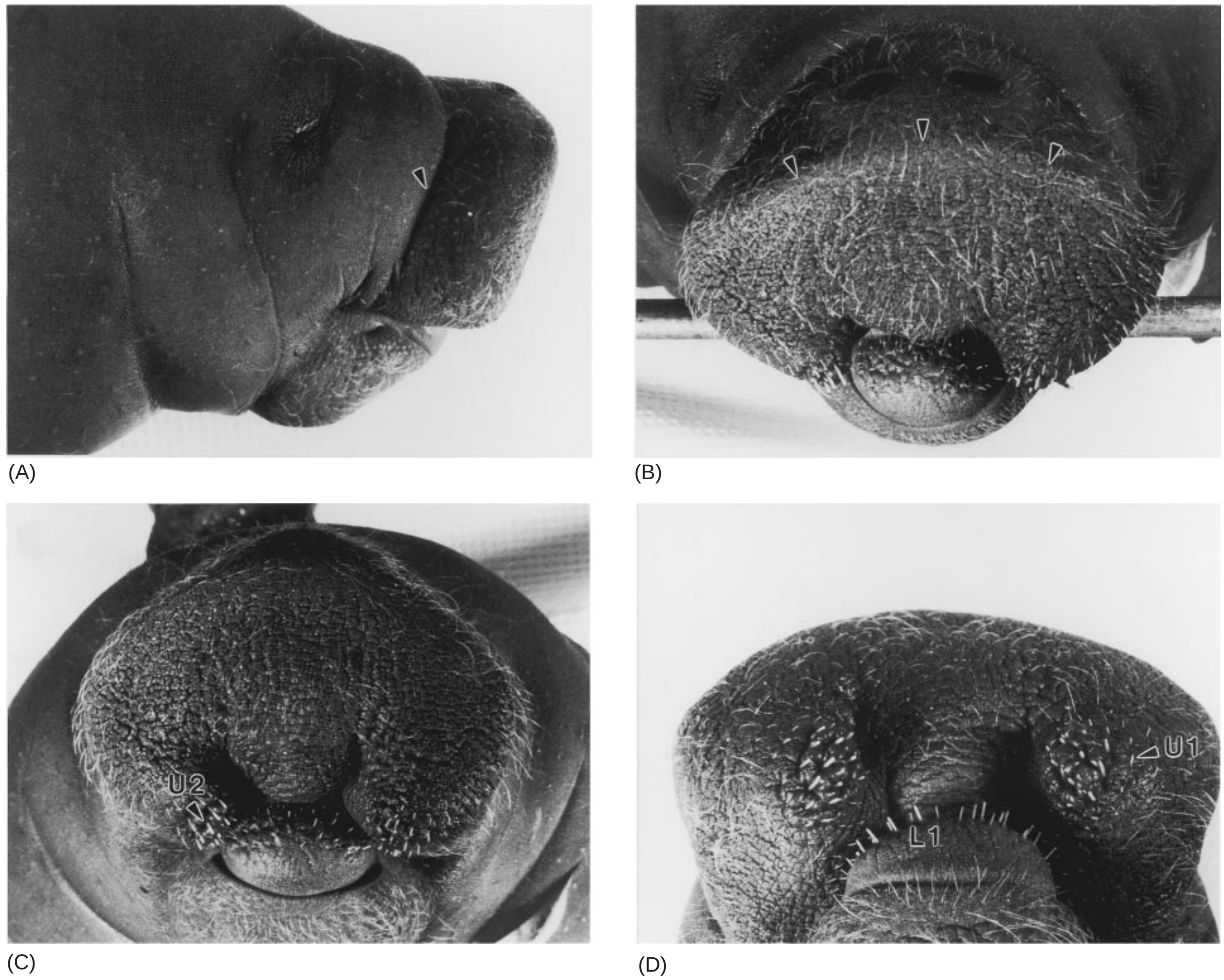

Figure 7 Facial vibrissae, bristles, and muzzle region of a Florida manatee (*Trichechus manatus latirostris*). Facial muscles of the oral disk and bristles combine to form the only prehensile bristles in mammals. (A) Arrow shows postnasal crease which bounds the supradisk of the prehensile muzzle-bristle apparatus. (B) Arrows show the orofacial ridge of the oral disk. (C) The oral disk is seen face forward, with U2 denoting one of the grasping bristle groups. (D) Bristles are everted at U1 and U2 and on the lower lip pad (L1). (Photographs reproduced with permission of *Marine Mammal Science* and Dr Roger Reep.)

dugongs are gray in color, but may also appear brown. Ventral patches are rare and there is little counter-shading in these three species. Hairs are sparsely distributed along the sides and dorsum, and are especially dense and sensitive on the muzzle. These serve a tactile function, which may be particularly important in turbid water and at night. Hairs inside the upper muzzle and lower lip pad are modified into stiff bristles that together with unique facial muscle arrangements form the only prehensile vibrissae known in mammals (**Figure** 7). Steller's sea cow had a small head in relation to the body, and the skin was described as bark-like, dark brown, and in some instances flecked or streaked with white. The forelimbs were reduced to stumps for locomotion along rocky shorelines. They had no teeth and instead relied on horny plates in the mouth to crush kelp. Dugongs have a strongly downwardly deflected snout and are obligate bottom feeders. Dugongs produce a total of six cheek (molariform) teeth in each quadrant of the jaw but also have tough, horny plates in the roof of the mouth. These plates play a significant role in mastication. Dugong teeth are resorbed anteriorly and fall out as they wear, except that the last two molars in each quadrant have persistent pulps and continue to grow throughout life. Manatee cheek teeth, in contrast, continually erupt at the rear of the jaw and move forward as they wear through resorption and reworking of bone. There are no fixed numbers of teeth in manatees, and they erupt throughout life.

Compared with most terrestrial and marine mammals of the same body size, sirenians have unusually low metabolic rates. Metabolic rates of Amazonian manatees are approximately one-third those expected based on measurements of other mammals of similar size. Florida manatee metabolic rates are 15–22% of rates predicted for mammals of their size. They are also poorly insulated, and cannot maintain positive energy balance in cool water, restricting distribution to tropical and subtropical areas. The large size of the Steller's sea cow was in part an adaptation to maintain thermal inertia in the cool North Pacific. Low metabolic rates in the Sirenia can be viewed as adaptations to a diet of aquatic vegetation, which is low in nutritional quality compared with the foods of other marine mammals (such as fish, krill, or squid). Sirenians are hind-gut digesters that may consume up to 10% of body weight per day. The stomach includes a specialized 'cardiac' gland in which special secretory cells are concentrated to avoid abrasion from coarse vegetation. The large intestine is up to 25 m long in dugongs, and passage time of ingesta may take 5–7 days.

Amazonian manatees have an unusual capacity to persist for long periods without food. When food is readily available during the flood season large quantities of fat are deposited, and when individuals are left in isolated pools with receding waters of the dry season they subsist by drawing on this stored energy. Fat deposits coupled with a low metabolic rate may allow Amazonian manatees to go without feeding for up to 7 months. Brains of adult sirenians are very small for mammals of their body size. This may be due to a combination of factors, including low metabolic rates and natural selection for lengthy postnatal growth in body size. Brains also lack marked cerebral convolutions. However, other aspects of neuroanatomy (elaboration of cortical centers and cerebral cytoarchitecture) suggest that sirenians are fully suited for complex behavior. Manatees in captivity can learn a variety of conditioned tasks.

Behavior and Social Organization

Manatees lack strong circadian (24 h) rhythms in activity, although in the more temperate climate of Florida, winter activity can depend on diel changes in water temperature. This lack of circadian activity correlates with the absence of a pineal gland. Seasonal migrations occur within Florida to avoid cool water in winter. Some of these are local movements to constant temperature artesian springs, whereas others span one-way distances of 500 km or more along a north–south gradient. Florida manatees can travel at rates of 50 km per day. Their seasonal destinations can consist of core areas used annually. The methods by which sirenians orient and navigate accurately and directly between destinations through murky waters is unknown. They have small eyes, no external ear, and minute ear openings.

Mating behavior in Florida manatees consists of groups of up to about 20 males actively pursuing females in estrus. The pursuits can last up to 2 weeks, cover distances up to 160 km, and involve vigorous jostling and chasing. Copulations with more than one male have been observed. Dugongs show greater variability in mating systems, and during violent encounters males will inflict cuts with their tusks. In eastern Australia dugongs may exhibit mating behavior similar to that of Florida manatees. In western Australia, however, dugongs also form leks in which single males set up small territories that are visited by individual females. Males advertise their presence on these leks with complex audible underwater vocalizations. Florida manatees also produce audible underwater sounds, but these vocalizations function more as contact calls, may signal simple motivational states, and can serve in individual recognition. Vocal communication is most pronounced between females and calves. West African and Amazonian manatees also produce underwater communication sounds, but these have been less well studied. No stable social organization has been observed in sirenians, other than the long bond between females and calves during lactation. Manatees appear to be primarily solitary but form small transient groups of about 1–20. They may also aggregate in larger numbers around concentrated resources such as freshwater seeps and winter thermal refugia in Florida. Dugongs can aggregate in herds of a few hundred. Herding behavior may have advantages in cultivation grazing, in which feeding activities keep seagrass beds in stages of succession that favor certain food plants.

Ecology and Population Biology

Sirenians are usually found in shallow waters, as aquatic plants do not grow at significant depth where light is restricted. Dugongs feed exclusively on marine angiosperms, the seagrasses of the families Potamogetonaceae and Hydrocharitaceae. The historic distribution of dugongs coincides with the distribution of these food plants. Around tropical Australia, dugongs can be found wherever adequate seagrass beds occur, including distances as far as 60 km offshore and waters to 37 m deep. More delicate, sparsely dispersed deep-water species of seagrasses are fed upon under the latter conditions.

Manatees feed on a much wider variety of plants than dugongs, including seagrasses, overhanging mangrove leaves, true grasses along banks and in floating mats, and various rooted, submerged, and floating plants. Predation on sirenians has only rarely been observed. There are uncommon reports of sharks preying on manatees and of the presence of shark bite marks on surviving manatees, but manatees do not typically occur in regions occupied by large sharks. Uncommon reports also exist of predation or possible predation by jaguars on Amazonian manatees, and by sharks, killer whales, and crocodiles on dugongs.

Florida manatees and dugongs have life history characteristics that allow only modest population growth rates, and these characteristics are probably similar in Amazonian and West African manatees. Florida manatees can live 60 years. Litter size is one (with twin births occurring in $<2\%$ of pregnancies) after an imprecisely known gestation estimated at about 1 year or slightly longer. Age at first reproduction for females is 3–5 years. Calves suckle for variable periods of 1–2 years, and adult females give birth at about 2.5 year intervals. Survival rates for Florida manatee calves and subadults are not well known. Adult survival, however, has the greatest impact on manatee population growth rates. If adult annual survival is 96%, manatee populations with the healthiest observed reproductive rates can increase at about 7% per year. Growth rates decline by about 1% for every 1% decrease in adult survival. Even when reproductive output is at its maximum, populations cannot remain stable with less than about 90 % adult survival. Dugongs have even slower growth rates than manatees. The oldest age attained by adult female dugongs from Australia was 73 years, litter size is one (twins have not been reliably documented) after a gestation period that is probably similar to that of the Florida manatee, and age at first reproduction for females may be 9–10 years or older. The period of lactation is at least 1.5 years, and adult females give birth on a schedule of 3–7 years. Data to support calculations of dugong survival rates are not available, but modeling of life history traits suggest that under best observed reproduction, populations cannot grow by more than about 5–6% annually.

Conservation and Interactions with Humans

Low population growth rates make sirenians vulnerable to modern agents of mortality. Intensifying human activities in coastal areas produce additional sources of death, injury, and habitat change (**Figure 8**). Throughout their recent history, humans have hunted sirenians for meat and fat. People in many indigenous tropical cultures use oil and powders from bones as folk remedies for numerous ailments. Hides have been used for leather, whips, shields for warfare, and even as machine belting during shortages of other materials in World War II. Numerous cultures ascribe magical powers to manatee and dugong bones and body parts. Jewelry and intricate carvings are also made from the dense bones. Ingenious means were employed to hunt sirenians, including the use of box traps in parts of West Africa (**Figure 9**). In most indigenous tropical cultures through the mid-1900s, however, sirenians were hunted principally by hand with harpoons and spear points, and were recognized to be elusive and difficult quarry. Human populations were more sparse, and typically only a few people in any region acquired skills needed to hunt sirenians. Mortality under such conditions may have been sustainable. With the advent of firearms, motors for boats and canoes, and burgeoning numbers of people, overexploitation has occurred. Sirenians have been hunted as a source of bush meat at frontier markets as well as commercially. In Brazil manatee meat was legally sold in processed form, and during peak exploitation in the 1950s as many as 7000 per year were killed for market. In addition, growth in artesanal fisheries has introduced many inexpensive synthetic gill-nets throughout areas used by sirenians. Death due to incidental entanglement has become an additional and significant mortality factor globally. Gill-net commercial fisheries have been excluded from several areas in Australia that are important for dugongs, but few efforts to manage gill-netting for sirenian protection have been instituted elsewhere. Nets deployed to protect bathers from sharks on the coast of Queensland resulted in the deaths of hundreds of dugongs from the 1960s to 1996. Many of these nets have since been replaced with drum lines and deaths have dropped. The vulnerability of sirenians to overexploitation was most markedly illustrated in the case of the Steller's sea cow. Unable to submerge, they were easy quarry as provisions of meat for fur traders on their long voyages into the North Pacific. This caused extirpation of this sea cow within 27 years of discovery by western science. Today sirenians are legally protected in nearly every country in which they occur, as well as by international treaties and agreements. However, few nations provide active law enforcement or enduring conservation programs for manatees.

Overexploitation of manatees by hunting is no longer an issue in Florida. Instead, extensive coastal development accompanied by technological

Figure 8 A Florida manatee showing massive wounds inflicted by a boat propeller. Wounds occur on the dorsum. The nostrils are in the lower center of the photograph, breaking the surface slightly as the animal rises to breathe. (Photograph courtesy of Sara Shapiro, Staff Biologist, Florida Fish and Wildlife Conservation Commission.)

advances in boating and water diversions have created major new sources of mortality. Overall human-related mortality accounts for about 30% of manatee deaths in Florida each year. Collisions with watercraft account for about 24% of all manatee mortality and have increased more rapidly than overall mortality in recent years (**Figure 10**). About 4% of known manatee deaths are caused by crushing or drowning in flood control structures and canal locks. Other human-related causes of manatee mortality such as entanglement in fishing gear represent approximately 3% of the total.

The east and south-west coasts of Florida have lost between 30 and 60% of former seagrass habitat due to development, dredging, filling, and scarring of seagrass beds caused by motor boats. Some human activities, however, such as dredging of canals and the construction of power-generating plants (that provide warm water for refuge at northern limits of the manatee's winter range), may have opened up previously unavailable habitat. Destruction of quality seagrass habitat through activities that disturb bottoms (*e.g.* dredging and mining) or increase sedimentation and turbidity can also impact

Figure 9 A box trap used to capture manatees in West Africa. Walls are made of poles bound by fibrous leaves, with a door at one end that is propped open. Pieces of cassava tubers are left around and in the box as bait. After a manatee swims inside to feed on the starchy cassava, it will jar loose the stick propping the door, which descends and traps the manatee alive.

dugongs. Loss of seagrasses due to a cyclone and flooding in Hervey Bay, Queensland, was accompanied by numerous dugong deaths, and a reduction in the estimated population in the bay from about 1500–2000 to <100 dugongs. Direct mortality, reduced immune function, or impaired reproduction of sirenians in relation to environmental contaminants have not been observed. Low positions in marine food webs reduce exposure to many of the persistent organic contaminants that build up in tissues of other marine mammals, but sirenians may be more likely to be exposed to toxic elements that accumulate in sediments and are taken up by plants.

Outlook for the Future

In 1999, at least 268 manatees died in Florida and at least 82 (30%) of these were killed by watercraft. The total number of deaths in 1999 was the highest recorded, except for 1996 when a large red tide event increased manatee deaths in south-west Florida. Watercraft-related mortality is increasing more rapidly than overall mortality. However, aerial survey counts and monitoring of identifiable individual manatees indicate that numbers in particular regions of Florida have been slowly increasing. Some argue that there are more manatees now than ever before, so we should expect a higher proportion to die each year as the population grows. Alternatively, population models suggest that the current level of manatee mortality and the low survival of adults, will result or has already resulted in a manatee population decline. Because of inherent variation in counts due to survey conditions, several years of survey data are required to determine conclusively whether a change in population trend has actually occurred. However, the current human population in Florida is about 15 million people, a doubling in the past 25 years. By 2025 the population is expected to reach 20 million. Florida's waterways are a major source of recreation and revenue. Increasing boat traffic and coastal development resulting from Florida's growth will probably accelerate human-related manatee mortality. Other factors that complicate the future of manatees are the loss of warm-water refugia as spring flows decrease from increased ground-water extraction and drought

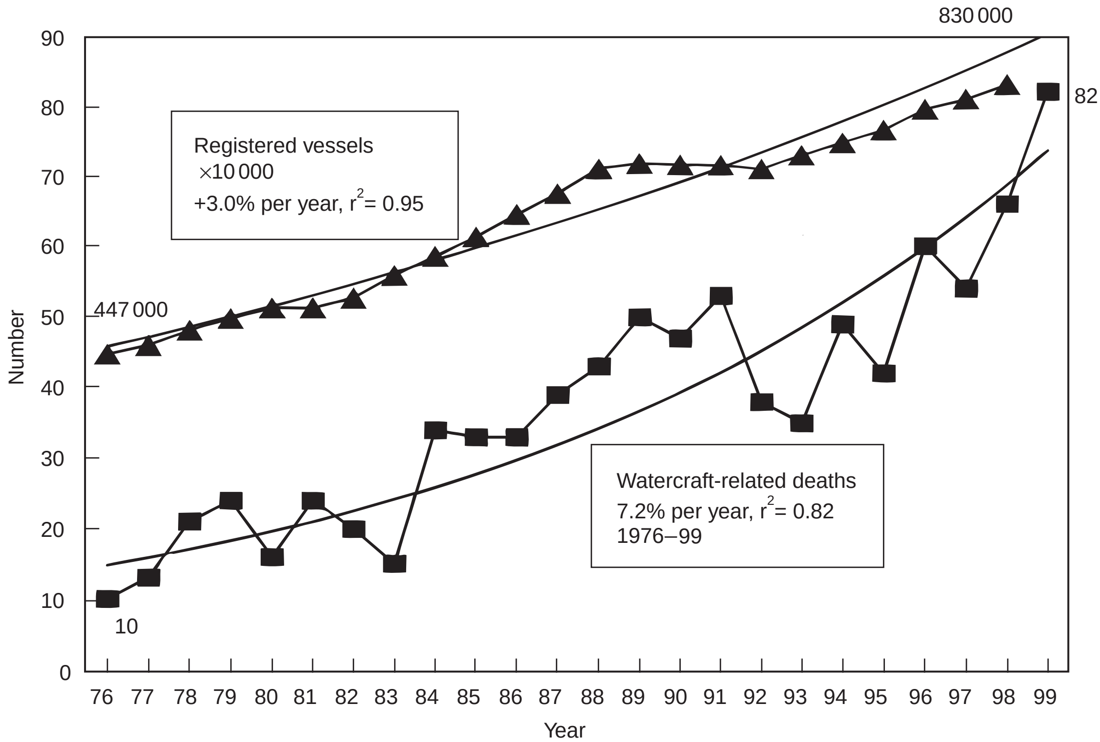

Figure 10 Patterns of increase in the annual numbers of boats registered in Florida and annual totals of boat-killed Florida manatees, 1976–99. Numbers of registered vessels have increased from 447 000 to 830 000. Numbers of boat-killed manatee carcasses recovered have increased from 10 annually to over 80.

conditions, and the phasing out of coastal power-generating plants because of industry deregulation and competition as more efficient inland plants come on-line. Florida manatees are thus faced with a very uncertain future. Proper planning, good information, and effective management are critical to the long-term survival of this species in Florida, where societal concern, dedicated financial resources, and formal protection for manatees are among the strongest in the world. West Indian manatees elsewhere in the Caribbean and South America probably have an even less optimistic future. This is because of past suppression or local elimination of populations from hunting and net entanglement, as well as habitat loss and ever-increasing pressure on resources from human populations. This is particularly true for manatees around island countries. On the mainland the outlook is more mixed. In some areas hunting pressure has declined, and conservation efforts have been enhanced. West Indian manatees are likely to persist in very remote and undeveloped areas of South America as long as such conditions prevail.

The outlook for dugongs in Australia is more guardedly optimistic, but recovery of populations and indeed the continued existence of dugongs in most of the rest of their range are much less likely. This is due to severe reductions from hunting and fishing activities in the past, and continued degradation of coastal habitat as human populations burgeon in these areas. Although the distribution of Amazonian manatees has remained similar to historical records, populations have been reduced in many areas of former abundance. Illegal capture for commercial sale of meat and incidental take in fishing nets continue, habitat degradation is increasing, and there is concern about heavy metal contamination of aquatic food plants from mining.

In West Africa the manatee's range has not changed appreciably from historical accounts. However, it is believed that numbers have been reduced due to illegal hunting. Several countries are particularly important for manatees, including Senegal, The Gambia, Guinea-Bissau, Sierra Leone, Ivory Coast, Nigeria, Cameroon, Gabon, and Angola. In these countries manatees are not uncommon, probably because there are extensive areas of optimal habitat located in relatively remote areas where hunting pressure is reduced. Hunting is the primary threat to manatees in Africa. For example, in Guinea-Bissau a single fisherman had sternums from over 40 manatees in his hut. Although manatees are protected throughout their range, the lack of enforcement of hunting laws and the need for supplemental protein in many areas contributes to hunting pressure. Damming of rivers poses an emerging threat, both directly and indirectly. Crushing in dam structures has been reported from Senegal, Ghana and Nigeria (and also in Florida). Dams on many rivers in the manatee's range may cut off needed seasonal migrations. Killing of manatees as they aggregate at freshwater overflows of dams has also been reported. In recent years, there has been increasing trade in West African manatees for commercial display facilities. Accelerating habitat destruction and cutting of mangroves for construction and firewood will have negative effects. There is considerable cause for concern for the manatee's future in several regions of Africa unless hunting is reduced. However, there has been increasing interest in West African manatee conservation, and several countries are moving towards increased protection involving coastal sanctuaries and law enforcement. To prevent future loss of manatees from all but a few remote and protected areas of West Africa, law enforcement and protection must become regional in scale, improvements must be made in economic conditions that contribute to hunting, and modifications will be needed on dams and other structures that kill manatees.

See also

Marine Mammal Evolution and Taxonomy. Marine Mammal Overview. Marine Mammals, History of Exploitation.

Further Reading

Bryden M, Marsh H and Shaughnessy P (1998) *Dugongs, Whales, Dolphins and Seals*. St. Leonards, NSW, Australia: Allen & Unwin.

Domning DP (1996) Bibliography and index of the Sirenia and Desmostylia. *Smithsonian Contributions to Paleobiology* 80: 1–611.

Domning DP (1999) Fossils explained 24: sirenians (seacows). *Geology Today* (March–April): 75–79.

Hartman DS (1979) *Ecology and Behavior of the Manatee* (Trichechus manatus) *in Florida*. American Society of Mammalogists Special Publication 5: 1–153.

O'Shea TJ (1994) Manatees. *Scientific American* 271 (1): 66–72.

O'Shea TJ, Ackerman BB and Percival HF (eds) (1995) *Population Biology of the Florida Manatee*. US Department of Interior, National Biological Service Information and Technology Report 1.

Reynolds JE III and Odell DK (1991) *Manatees and Dugongs*. New York: Facts on File, Inc.

Rosas FCW (1994) Biology, conservation and status of the Amazonian manatee, *Trichechus inunguis*. *Mammal Review* 24: 49–59.

SLOPE FRONTS

See **SHELF-SEA AND SLOPE FRONTS**

SMALL PELAGIC SPECIES FISHERIES

R. L. Stephenson, St. Andrews Biological Station, St. Andrews, New Brunswick, Canada
R. K. Smedbol, Dalhousie University, Halifax, Nova Scotia, Canada

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Introduction

The so-called 'pelagic' fish are those that typically occupy the midwater and upper layers of the oceans, relatively independent of the seabed (*see* **Pelagic Fishes**). Small pelagic species include herrings and sprats, pilchards and anchovies, sardines, capelin, sauries, horse mackerel, mackerels, and whiting. Most of these fish have a high oil content and are characterized by a strong tendency to school and to form large shoals. These features have contributed to the development of large fisheries, using specialized techniques, and to a variety of markets for small pelagic species.

Two of the major pelagic species (herring and capelin) are found in polar or boreal waters, but most are found in temperate or subtropical waters. The sardine, anchovy, mackerel, and horse mackerel are each represented by several species around the world, with the largest concentrations being found in the highly productive coastal upwelling areas