The Estuary and Marsh: Habitat Impacts and Environmental Protection

CHAPTER

4

This chapter covers the biology and conservation of ecosystems in estuaries and associated marshes. An **estuary** is a partially enclosed coastal water body where freshwater river input combines with the salt waters of the sea (**Figure 4-1**). Around the edges of the estuary, large rooted emergent vascular plants (macrophytes), partially exposed grasses (**marsh grasses**) in temperate regions, and woody plants (**mangroves**) in tropical regions, grow in the muddy or flooded marsh sediments. The marshes are characterized by such plants that are capable of tolerating the salinity and environmental conditions of the estuaries. A few species of either marsh grasses or mangroves are visibly dominant in the marshes but support a diversity of other organisms, many of which reside as adults in the open waters of the estuary or near-shore ocean. Estuaries and their associated marshes are among the most productive ecosystems on Earth. There are many conservation issues to discuss because estuaries are a valuable source of exploitable resources and they are adjacent to some of the most populated regions on our planet.

4.1 The Estuary

Estuary Types

By definition, estuaries only occur in places where there is a significant input of fresh water to the sea. The morphology and geologic history of an area, however, help determine the nature and prevalence of estuaries in a given region. The most extensive and most prevalent types of estuaries were formed as sea levels rose at the end of the last ice age, about 10,000 years ago. These **coastal-plain estuaries** are prevalent along gradually sloping coastal margins such as the east coast of the United States; they include Chesapeake Bay and the mouth of the Hudson River (**Figure 4-2a**). **Lagoon estuaries** are formed where sandbars are built up parallel to the coastline, creating peninsulas and barrier islands, behind which lagoons accumulate freshwater runoff that mixes with seawater. These estuaries are common along northwest Europe, parts of Australia, and the southeast U.S. Atlantic and Gulf of Mexico coasts (Figure 4-2b). **Tectonic estuaries** form where the land subsides due to geologic activity along the coastline, allowing seawater to invade. These occur along the California coast; San Francisco Bay is one example (Figure 4-2c). The **fjord** estuary forms as the ocean moves into valleys formed by glacial processes. These are often very deep, but partially cut off from the ocean by a **sill**, a rise deposited at the mouth by the previous glacier. These occur along glaciated coastline, such as Alaska, Chile, New Zealand, and Scandinavian countries (Figure 4-2d).

Physical Characteristics

Most aquatic organisms are adapted to live in either ocean waters, with a fairly constant but elevated salinity, or

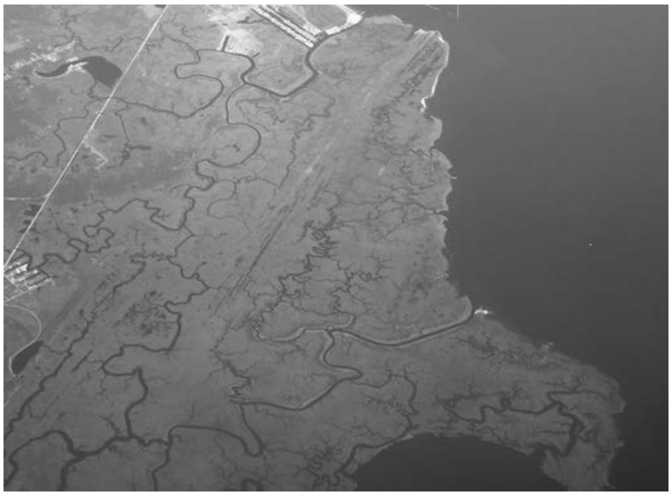


Figure 4-1 Coastal rivers and estuaries on the Gulf of Mexico coast of Texas.

freshwater, with continuously low levels of salts. Estuaries are regions of mixing for the two types of water and the salinity is highly variable on a daily and seasonal basis due to changes in the relative influence of freshwater (e.g., with floods or droughts that affect river input), or the ocean (e.g., due to changes in tidal currents). In general, salinity ranges from fresh at the upper reaches to full-strength seawater (about 35 ppt) at the mouth but can vary considerably within the estuary depending on climate, seasons, tidal cycles, and the geology. In estuaries with substantial freshwater input, a **salt wedge** typically forms at the bottom as the lighter freshwater rides over the incoming sea water (**Figure 4-3**). These are **stratified estuaries**, where a salinity gradient forms from the surface to the bottom as well as from the sea landward. Where there is little freshwater input, estuaries are marine dominated and more **well-mixed** or homogeneous.

The substrate of estuaries also varies depending primarily on the geology and the sediment input. In fjord estuaries, formed at high latitudes by receding glaciers that scrape away sediments, the substrate tends to be rockier; however, accumulating sediments may cover the substrate. Coastal plain estuaries tend to be dominated by thick layer of sediment on the bottom. These sediments are the accumulation of silts and organic matters brought in by the rivers or ocean waters. Silts settle out with decreasing flow as the rivers enter the estuary basin, and are important for the formation of marshes. Other particles suspended in the river waters **flocculate** and sink to the bottom due to chemical processes as the fresh and salt water mix. These flocculants can be an important source of nutrients and organic matter to organism living in the estuary.

Estuaries are physically dynamic and always changing. Not only salinity but also temperature tend to vary more than in surrounding coastal waters. Shallow estuaries can heat up or cool down more rapidly, especially with little tidal flow or river input, and freshwaters entering estuaries have more variable seasonal temperatures than coastal waters. Narrow estuary mouths and the coast adjacent to estuaries tend to dissipate waves coming from the ocean; therefore, wave activity is minimal compared to other coastal regions. Currents in estuaries resulting from river flow or tidal action can be substantial, however, especially in narrow channels. Currents can be important to organisms moving into, out of, or within the estuary. Larval and juvenile fishes, with limited motility that use estuaries as nursery areas, are especially dependent on tidal currents. They coordinate the timing of their migration and depth in the water column with the tidal flow. Turbidity in estuaries tends to be high, resulting from sediments and organic matter in the waters. This is one reason why the majority of the primary production originates from the grasses and woody plants in marshes found along the edges of estuaries, rather than from phytoplankton in the water. Oxygen levels vary greatly in estuaries, depending on water flow and biological activity. In areas with little flow and mixing, oxygen can be rapidly depleted and bottom waters can become extremely **hypoxic**, limiting the organisms that can survive and thrive there. The oxygenated layer in muddy sediments may be very shallow, typically about one centimeter thick, due to low mixing of water and oxygen depletion by organisms in the sediments.

Biological Importance

Estuaries are considered one of the most productive ecosystems on Earth and harbor a rich diversity of organisms. The materials that settle out in the estuary, carried in from the ocean and rivers, are the primary source of nutrients and organic matter supporting this high productivity. The organically rich substrate that is deposited, especially in regions of the estuary sheltered from waves and currents, provides productive sediments where plants can root and animals can burrow and feed. Ecosystems associated with the plants, primarily marsh grasses and mangroves, are discussed below. Most organisms that reside permanently in the estuary are associated with the ecosystems characterized by these plants. The deeper flowing waters of the estuary are an important corridor for diadromous fishes on breeding migrations into freshwaters from the ocean (anadromous species such as the salmons), or from freshwaters to the ocean (catadromous species such as American eels; see Chapter 2).

The majority of fish and swimming invertebrate species living in the estuaries (e.g., crabs and shrimp) are those that migrate from the ocean during some portion

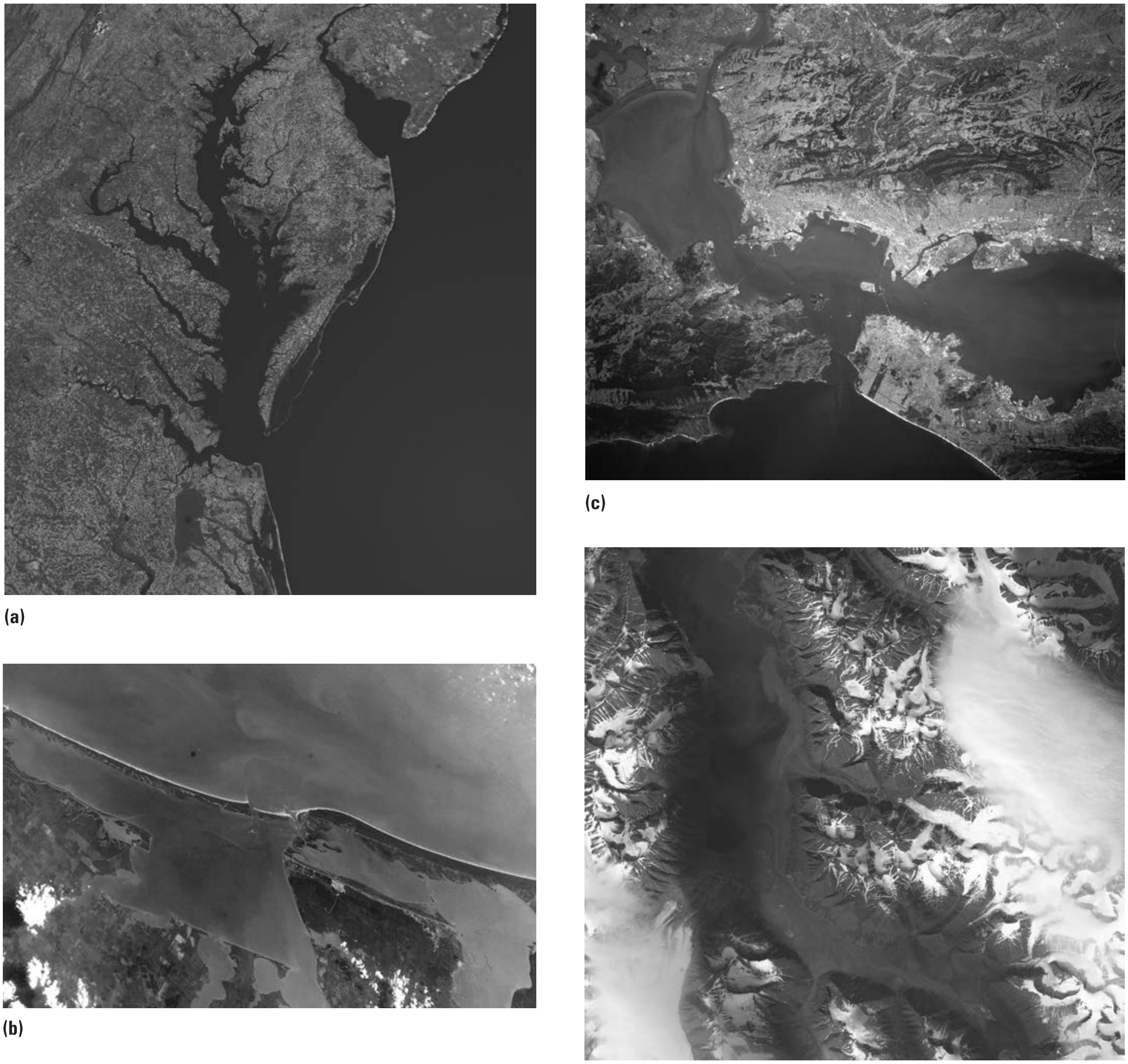


Figure 4-2 Examples of estuary types: **(a)** a coastal-plain estuary, Chesapeake Bay and other U.S. east coast estuaries; **(b)** a lagoon estuary, Matagorda Bay, Texas; **(c)** a tectonic estuary, San Francisco Bay, California; **(d)** a fjord estuary, Boknafjorden fjord in Norway.

of their life history (typically as larvae or juveniles) to use the estuarine habitats for feeding and shelter. In fact, in many regions the majority (about 75% in U.S. waters) of harvested coastal marine species utilizes the estuary, and are thus considered **estuarine dependent**. The use of the estuaries by marine species is highly seasonal and during any time of the year the estuary may be dominated by one or several species. For example, in estuaries of the southeast U.S. there is a progression of larval fishes that move into the estuary from spawning areas offshore, then feed in the estuary until they near maturity, and migrate out of the estuary to offshore feeding and breeding grounds. These species support some of the most valuable coastal fisheries or are important prey species; they include drums and croakers (family Sciaenidae), anchovies (*Anchoa*); mullets (*Mugil*); and menhaden (*Brevoortia*) (**Figure 4-4**).

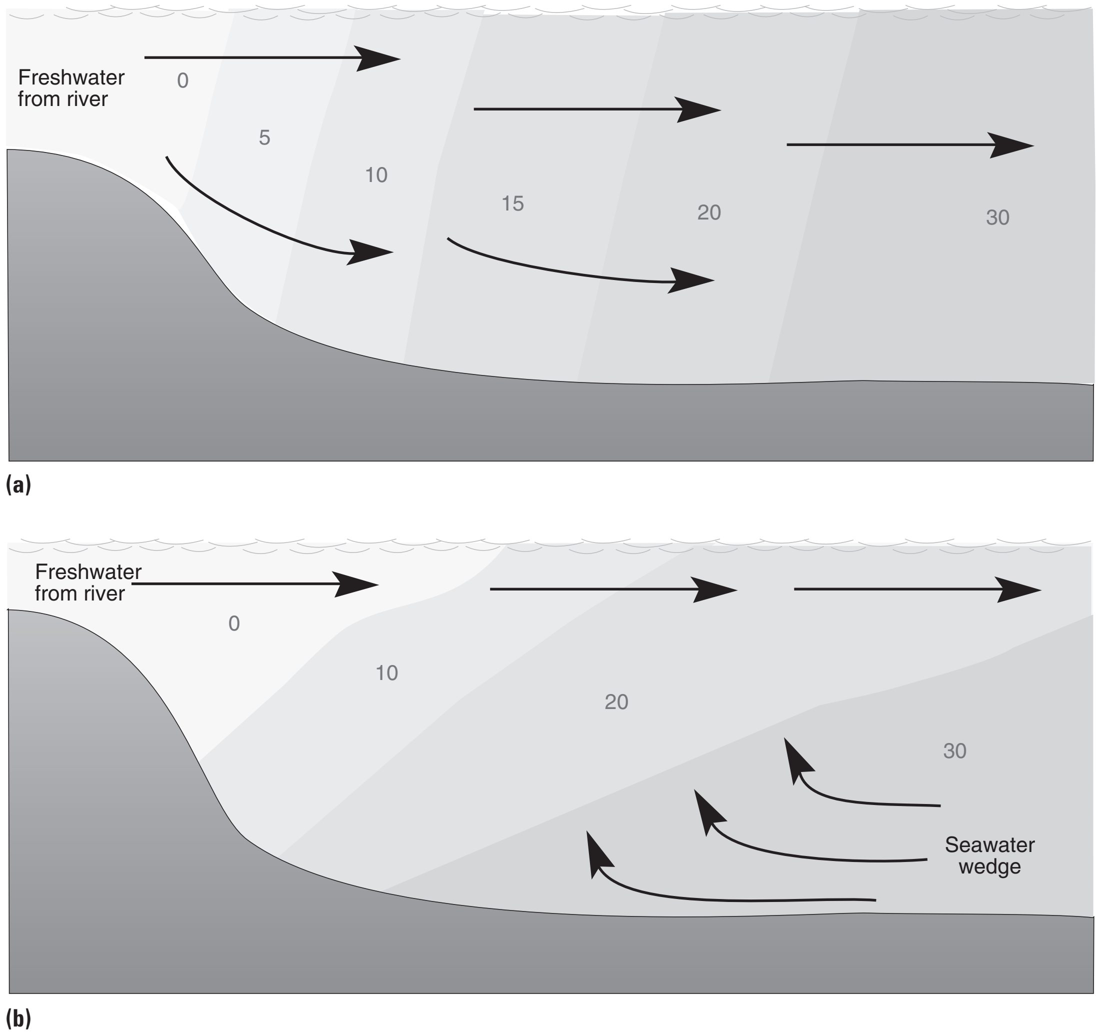
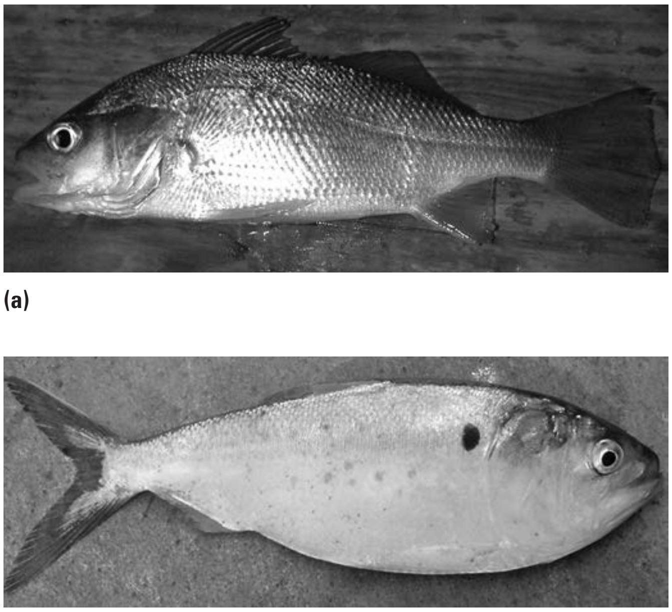


Figure 4-3 Cross sections of **(a)** well-mixed and **(b)** stratified estuaries. Numbers indicate salinities in parts-per-thousand (ppt).

Environmental Impacts

Because of the high biological productivity and presence near mouths of rivers and ports important to humans, estuaries commonly have been exposed to harmful anthropogenic impacts. Important estuarine habitats have been covered for building cities and industrial developments; river runoff can bring in toxic materials and excess nutrients from fertilizers and sewage; and there may be unpredicted effects from factors related to global climate change and human population increases in coastal regions. Around the globe, a proportionately large fraction of the human population lives in the vicinity of estuaries. For example, approximately two thirds of the U.S. coastal population currently lives in counties associated with major estuaries, although these areas comprise less than 6% of the land area along the coast; 70% of the population of southeastern Asia live in coastal or estuarine areas.

Ship traffic through estuaries can be a source of pollution; however, possibly of greater concern is the introduction of foreign aquatic organisms from large ships. Barnacles and bivalves may be introduced when "hitchhikers" come into the estuary attached to boat hulls (see Chapter 3). Many more organisms can be introduced into estuaries from the **ballast** water of tanker ships. When a large tanker ship offloads, it typically takes on water for stabilization during the return voyage to its home port. Small organisms or planktonic larval stages can be taken in with the ballast water. Upon returning to port, the ballast waters are released into estuarine or nearshore waters, along with the exotic organisms they contain. Although most do not survive, only a few individuals may be needed to reproduce and colonize coastal areas, with the potential for long-term negative impacts. One of the most well-documented of such **invasive species** is the European green crab



(a)

(b)

Figure 4-4 The estuarine dependent **(a)** Atlantic croaker, *Micropogonias undulatus* and **(b)** Gulf menhaden *Brevoortia patronus*. Larvae move into estuaries as nursery areas.

Carcinus maenas, a ballast-introduced invasive species that showed up on both the east coast of the United States and the southeast coast of Australia by the early 1800s (**Figure 4-5**). Individuals were documented along the South African and California coastlines in the 1980s, causing declines in native *Hemigrapsus* shore crabs and *Nutricola* clams, and indirectly resulted in increases in polychaete worms. The European green crab has since expanded its range into the Pacific coast of Canada and has showed up in small numbers on coastlines in several areas throughout the Pacific. It is problematic in estuaries as it can tolerate salinities from 4 to over 50 ppt and temperatures from 0° to over 30°C. New restrictions on the exchange of ballast water may limit future introductions; however, even if this is true, problems controlling the effects of past exotic introductions will likely continue.

Over the past several decades many coastal nations have made progress in establishing monitoring and protection programs targeted toward estuaries. In the United States, the largest such program is the National Estuary Program (NEP), initiated in 1987 through the U.S. Clean Water Act. This program was established to encourage collaboration among agencies and stakeholders to protect the estuary ecosystems; 28 areas have been designated as NEP estuaries. Evaluations carried out through this program have categorized U.S. estuaries overall as in "fair" condition, with northeast coast estuaries in "poor" condition, southeast coast estuaries in "good" to "fair" condition, and Gulf coast and west coast estuaries in "fair" condition (**Figure 4-6**). Impacts identified include poor water quality, commonly indicated by high nutrient levels and low dissolved oxygen; poor sediment quality, including contaminants and toxicity; benthic impacts, such as low community diversity and abundance of pollution-tolerant species; and fish tissue contamination by harmful chemicals. Regions with the highest population densities tend to have estuaries of poorer condition. The most commonly identified environmental concern was habitat loss and alteration, followed in order by declines in fish and other wildlife populations, excess nutrients, contamination by toxic chemicals, presence of pathogens, alteration of freshwater flows, and the introduction of invasive species. A focus of programs such as the

(a)

(b)

Figure 4-5 **(a)** The European green crab *Carcinus maenas.* **(b)** Distribution map indicating the native range (tiny white dots off the east and west coasts) and the invasive range (dark gray).

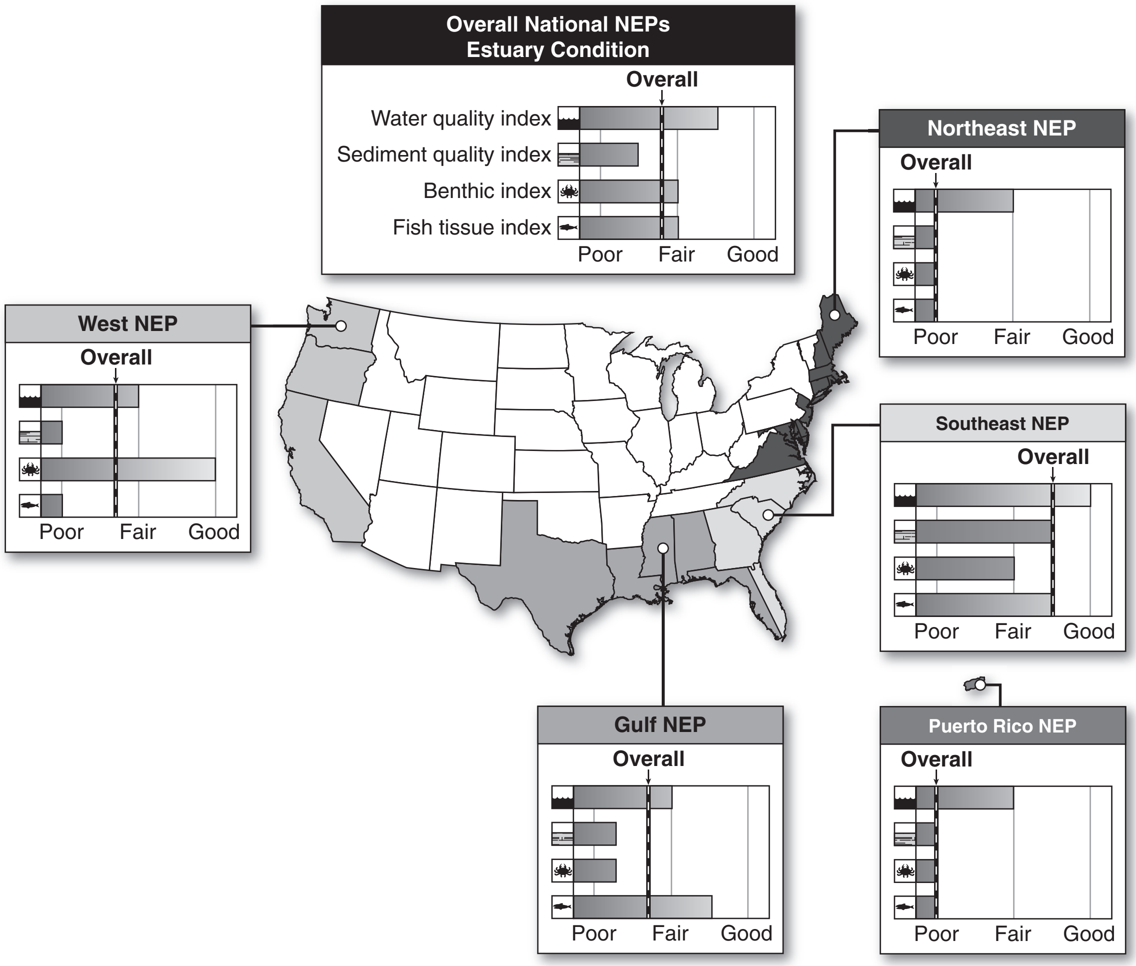


Figure 4-6 Condition ratings assigned by the U.S. Environmental Protection Agency for estuaries in the National Estuary Program (NEP).

NEP is to promote and encourage the protection of estuaries from such impacts. Because the source of these effects can extend all the way from the source of the watershed in the interior of the continents (e.g., agriculture-based pollution) to coastal oceans, simply setting aside estuaries for protection will only partially solve the problems. Some examples of impacts and conservation efforts for estuaries as they relate to the specific ecosystems are discussed below.

Fisheries Conservation

The accessibility of estuaries and coastal waters to humans makes estuarine-dependent species especially vulnerable to fishery harvest impacts. Many organisms are not harvested until they mature and move to offshore waters (offshore harvest issues are discussed for some of these, such as menhadens, in Chapter 6). Fisheries harvest in the estuaries is limited because these species are often present only during larval and juvenile stages, when they are either of little fisheries value or are protected from harvest. For example, the harvest season for shrimp (*Penaeus*) in Louisiana waters is typically closed until the young shrimp in the estuaries reach an average size that is considered adequate to support a profitable fishery without excessive harm to the shrimp populations. In tropical developing countries subsistence fishers are more likely to harvest smaller fishes from mangrove-dominated estuaries. (Fisheries issues in mangrove ecosystems are addressed later in this chapter.) Some species found in temperate estuaries, such as the American and European eels, are valuable enough on the international market at small sizes that young life stages can be overexploited by harvest (**Box 4-1. Current Issue: Eels from the Estuary**). Where commercial fisheries are allowed in estuaries there is typically a limit on the harvest methods; for example, gill nets (see Chapter 11) are so efficient at blocking channels and harvesting a large percentage of the fish that they have been outlawed in most U.S. estuaries. There are many popular recreational hook-and-line fisheries for estuarine-dependent fishes. These include the American shad and striped bass in the northeastern United States, and red drum and spotted seatrout in southeastern U.S. estuaries.

Although anadromous fishes have been harvested from European and North American estuaries for centuries,

Box 4-1 Current Issue: Eels from the Estuary

There are two species of eels in the genus *Anguilla* that have an unusual life history. They are hatched in the deep waters of the mid-Atlantic Ocean, float to the surface, drift toward the coast over a one to three year period, migrate through estuaries up rivers feeding for 3 to 20 years, and finally return to the deep Atlantic where they reproduce and die. These catadromous eels are the American eel (*Anguilla rostrata*), which migrates to North American waters, and the European eel (*Anguilla anguilla*), which migrates to waters of western Europe. During their migration the eels undergo several transformations in body shape. The larvae drifting in the ocean are a leaf-like **leptocephalus**. As they near the coast and reach lengths of about 60 millimeters, they metamorphose into a small, translucent eel-shaped glass eel. As they move into the estuary they transform into an **elver**. Some of the eels (mostly females) enter freshwater rivers and others (mostly males) remain in the estuary. As they feed and grow they develop into an adult form called yellow eels. When the yellow eels reach a size of about 60 centimeters for males or 120 centimeters for females, they begin to mature sexually and transform into a form called silver eels (silvery colored with larger eyes and fins), and stop feeding before they migrate back to spawning grounds (**Figure B4-1**).

Eels are particularly vulnerable to anthropogenic impacts because their survival requires protection all the way from the deep Atlantic into upper reaches of inland rivers. They are vulnerable to harvest from the time they enter the estuary through their freshwater residence until they return through the estuary to the sea.

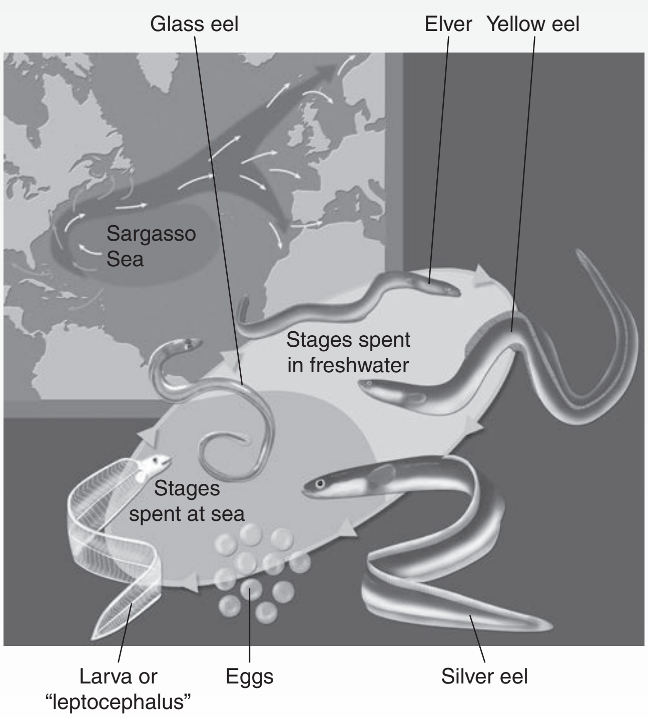


Figure B4-1 Stages of development of the American eel.

A popular commercial fishery harvest for elvers using basket traps has been in existence in Europe, including Italy, France, and England, at least since the 1700s. Eels caught in the Thames River and other estuaries were popular, prepared as "jellied eels," until after World War II, when pollution began eliminating the eels from many European estuaries. As these rivers were cleaned up beginning in the 1960s, however, the eel populations began to return. Then from the 1970s to the 2000s the eels underwent another dramatic decline—of about 90%—for unknown reasons. Studies by I. A. Naismith found low recruitment into the population, with recolonization of the upper ends of the estuary to be especially slow. The possible causes of the poor recovery include overfishing, parasite infections, damming of rivers to block migrations, and pollution; some scientists proposed that natural changes in ocean circulation may be contributing to the decline. One pollutant that has been implicated is polychlorinated biphenyl (PCB; see Chapter 7), which may inhibit reproduction and, when transferred to the eggs, result in death of larval eels. Whatever has caused the decline, European eel populations are considered to be facing possible extinction and are now classified as Critically Endangered by the IUCN.

The fishery for American eels in the United States, primarily for export to European and Asian countries, expanded to levels around 500 to 1,000 metric tons per year in the 1950s. The eels were historically harvested at all stages by traps in the estuaries along the northeast U.S. coast. The harvest of glass eels increased dramatically during the 1970s as their value increased on the Asian market. The young stages are vulnerable to high harvest levels because their migration is seasonal and predictable; nets can be placed across narrow channels as the eels move upstream so a large percentage of the migrating population can be caught. Commercial harvest levels hovered around 1,500 metric tons from 1974 to 1981, before declining to under 500 metric tons annually by the late 1990s through the early 2000s. As concern over the species' long-term survival began to be questioned by conservationists, state restrictions were passed by states. Eventually, all U.S. Atlantic states, except Maine and Florida, passed size restrictions that resulted in the stoppage of the glass-eel fishery. In 2004 the American eel was considered for listing as an endangered species in the United States, citing overfishing, blocking of upstream and downstream migrations by dams and other water control projects, and water pollution as possible factors affecting the eels. In 2007, however, the U.S. Fish and Wildlife Service ruled that an endangered listing was not necessary, stating that, although populations had declined in some regions, the overall species was not endangered with extinction.

This is an example of how new, profitable, and practically unlimited markets develop for fisheries that are easily exploited. For the American eel fishery, virtually every individual could be harvested with available methods if restrictions were not implemented. By the time the urgency of the issue is realized and actions are taken by government enforcement agencies and lawmakers to restrict fishing methods, sizes of fish harvested, and limits on amount harvested, it is often too late to continue a sustainable fishery, at least without a protracted recovery period.

currently commercial harvest is tightly regulated because of the ease of catching fish as they pass through narrow channels. Nets placed across these channels during migrations could catch virtually every fish moving into coastal rivers. The use of such nets and fish wheels, devices powered by the water flow that scoop up the fish as they swim upstream, have been outlawed in most estuaries and coastal rivers, except for limited use by some indigenous groups.

Invertebrates that spend much, or all, of their adult life in estuaries have historically supported valuable local fisheries. These can include numerous species of crustaceans and mollusks around the world. Two groups that can be of considerable commercial value are crabs, such as the blue crab in U.S. Atlantic and Gulf of Mexico estuaries, and bivalves, such as clams and oysters.

Blue Crabs

Many crab species are harvested from estuaries around the world. One of the most abundant, well studied, and commercially profitable is the blue crab *Callinectes sapidus* (**Figure 4-7**), an estuarine and nearshore resident of waters of the West Atlantic extending from Nova Scotia, Canada to Argentina. The genus *Callinectes* is somewhat unique in that, even as an adult, they are capable of swimming using oar-like rear legs (*Callinectes* means "beautiful swimmer"), and are thus more mobile than most other crabs. Blue crabs live, feed, and mate in estuaries, but females undergo a seasonal migration into higher salinity waters for egg laying; however, this migration does not typically extend beyond the mouth of estuaries or far into coastal waters. For example, in Chesapeake Bay, the crabs release eggs near the mouth of the bay where the larvae float and swim for several weeks as they mature, undergoing transitions through several stages of development before becoming juveniles. The juvenile crabs (about 2.5 millimeters wide) move toward fresher waters of the estuary, where they settle to the bottom and begin feeding. In order to continue growing, the blue crabs must molt, or shed their shell (exoskeleton), and form a new one (if harvested just after this molting they are sold as "soft-shell crabs" and bring a higher value). Juvenile crabs undergo about 20 molts before maturing when they are 1½ to 2 years old. After mating, females store the sperm for future fertilization of eggs, and move into higher salinity waters where they release their eggs and remain; they reside most commonly in waters with salinities from about 15 to 30 ppt (**Figure 4-8**). After mating, males typically stay in the upper reaches of the estuary, most common in salinities from about 3 to 15 ppt. During winter they often bury themselves in the muddy bottom. Because of the complex mobile life cycle for many estuarine invertebrates, there is a need for conservation efforts throughout the estuary, rather than focusing exclusively on the adult stages.

Figure 4-7 The blue crab *Callinectes sapidus*, commonly harvested from estuaries of the west Atlantic.

In many estuaries along eastern U.S. and Gulf of Mexico coastlines, blue crabs support valuable local fisheries. Typically they are caught in baited wire-meshed traps called **crab pots**. Historically one of the most important of the blue crab fisheries has been in Chesapeake Bay. This is the largest estuary on the U.S. east coast and the blue crab is its most valuable commercial fishery. Through the 1980s and early 1990s, commercial harvest hovered near 45 million kilograms per year, but then began declining, and fluctuated around 23 million kilograms from 2000 to 2008. Population estimates followed this same trend, showing a decline over this time period. (**Figure 4-9**). Reasons for the population decline are not certain but are believed to include nutrient pollution resulting in eutrophication and hypoxic conditions, the loss of seagrasses that serve as shelter for the young crabs, and excess fishing pressure.

As the fishery declined, management agencies were pressured to reduce levels of harvest; however, many crab fishers resisted, complaining that the problems were the result of pollution and the EPA had failed to limit nutrient input into the watershed from fertilizers and sewage. Efforts in 2001 to reduce harvest, including setting minimum size limits, were not adequate and the crab populations did not recover. This prompted the U.S. Secretary of Commerce to declare the Chesapeake Bay blue crab fishery a "commercial fishery failure" in 2008, releasing financial resources for crab fishers and for the development of recovery and management plans in the region. Management goals included protecting about 50% of the population from harvest and reducing harvest of females by over 30%. In Virginia waters, the number of traps each fisher could use was limited and the practice of dredging up crabs burrowed in the sediment during winter was stopped. In Maryland waters the number of licenses were limited, daily limits were placed

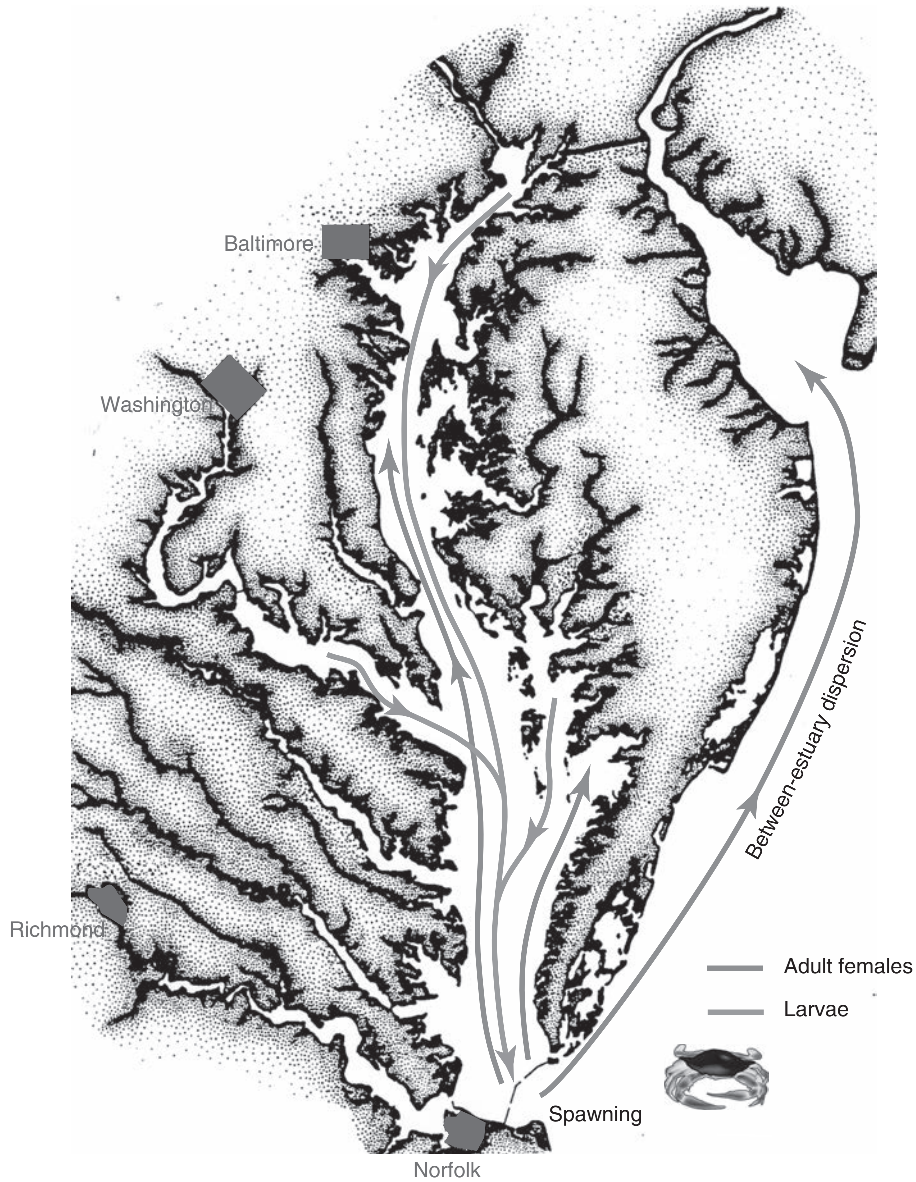


Figure 4-8 Map of Chesapeake Bay, indicating routes taken by adult female blue crabs during spawning migrations and the return routes of the larvae out of the Bay.

on harvest, and the fishery was closed during the peak of female migration in the fall. Some of the fishers were hired to recover lost "ghost traps" that continued to catch crabs. By the spring of 2009 the population of female crabs had increased by about 70%, and by 2010 numbers had more than doubled from the 2008 population size.

This example shows how complicated solutions to estuarine conservation issues can be. When it is difficult to determine exactly why the ecosystem is changing, the tendency is to lay blame on someone else and to resist change. From a social, economic, and political perspective, it is difficult to implement changes even if the cause of the problem appears to be obvious to scientists. When meaningful change is implemented, however, success can be achieved.

Oysters

Various types of bivalves are harvested from estuaries around the world, with oysters supporting some of the most valuable bivalve fisheries. Oysters can be a good indication of the health of estuary waters, because they feed by filtering organisms from the water and are thus susceptible to waterborne diseases and toxicants. These become a human health issue when transferred by consumption of oysters, especially when eaten raw. Oysters can benefit water quality by removing sediments, nutrients, and algae

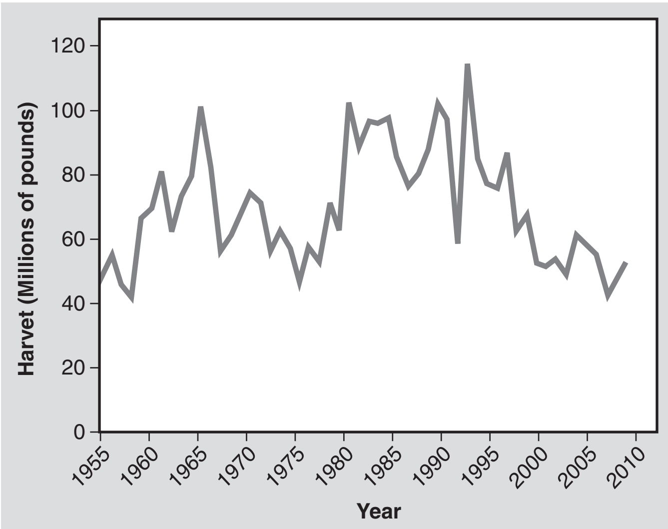


Figure 4-9 Chesapeake Bay blue crab harvest from 1956 to 2009. (Note that the Maryland reporting system changed in 1981, which increased harvest estimates.) Source: NMFS Fisheries Statistics of the United States.

from the water. They provide important bottom habitat in estuaries, providing a hard substrate within the muddy sediments. Many animals live on and among the oysters, including barnacles, anemones, fishes, and crustaceans, and other animals feed on these organisms or the oysters themselves. Some drums (Sciaenidae), such as the black drum, can pulverize the oyster and consume it shell and all.

In estuaries of the eastern United States, the oyster *Crassostrea virginica* typically matures at one year of age and produces sperm that it spews into the water for broadcast spawning. As the oyster grows larger during the following year, it switches to producing eggs (protandry). The fertilized eggs develop into floating, swimming larvae that must find a suitable substrate on which to settle; in estuaries this substrate is typically old oyster shells (in some regions fishers return the shells to encourage settlement of the next generation of oysters). These settled spat, about 25-mm long, accrete a shell and develop into an adult oyster.

Oysters have been harvested from estuaries for millennia. This is evidenced by oyster middens found around the world. For example, spectacular middens located on Dauphin Island, Alabama, a barrier island in the northern Gulf of Mexico, are protected as Indian Mound Park. There are six oyster shell middens, the largest of which is 50 meters across and up to 7 meters high, that were created by Native Americans from 1100 to 1550 AD. The oysters were probably taken during low tide from oyster banks, steamed and eaten, with the shells discarded to form the mounds. There is no indication of overharvest, and the oysters probably provided a reliable source of food throughout this time period.

Oysters continue to be harvested today—but not always sustainably—and are popular seafood items in many coastal areas, eaten either raw or in various preparations. Environmental impacts and overharvest have affected the edibility and the availability of oysters. The list of local problems that have affected oysters are numerous. They include viruses (e.g., herpes) resulting from inadequate sewage treatment, bacterial infestations that cause human illnesses and result in closing oyster beds to harvest, excess nutrients from fertilizers affecting water quality, accumulation of toxins from harmful algae blooms, and contamination by oil or chemical spills. In U.S. waters, there are valuable oyster fisheries throughout the Gulf of Mexico and the Atlantic coast (**Box 4-2. Learning from History: Oysters from Chesapeake Bay**). Over 55% of the U.S. oyster harvest is from Gulf of Mexico waters, about 10 million kilograms (approximately 550,000 bushels) annually.

4.2 Salt Marsh Ecosystems

Salt Marsh Development

Estuaries in temperate regions are characterized by tidal creeks, shallow pools, and mudflats, and are typically bordered by salt marshes (**Figure 4-10**). A salt marsh develops in areas sheltered enough for the accumulation of muddy sediments. Salt tolerant grasses colonize the sediments and spread by developing leaves and roots from extensive horizontal stems (rhizomes) that spread out underground. These plants enhance sediment accumulation, thus promoting further marsh development. Areas with a more extensive tidal range typically have broader salt marshes, especially those on gradually sloping coasts. These conditions are typified on the mid-Atlantic and Gulf of Mexico coasts of the United States, regions with gradually sloping coasts, broad estuaries, and shallow bays that are ideal for the development of salt marshes (**Figure 4-11**). Because the Pacific coast is steeper and rockier, it does not support the development of large salt marshes.

Salt Marsh Ecology

Grasses of the salt marsh typically extend from the edge of tidal flats to the height of the highest tide. The degree of exposure of the marsh varies daily with the tides; however, the grasses are tall enough that even at high tide their tops are typically not covered by water. The extreme and variable physical conditions limit salt marsh ecosystems to a low diversity of plants; typically a few species of grasses dominate in a given geographic region. These extremes include low oxygen levels in waterlogged soils, due to water filling of air spaces around the soils and roots while bacteria consume the remaining oxygen. Waterlogged low-oxygen sediments are not tolerated by most plants because the roots must

Box 4-2 Learning from History: Oysters from Chesapeake Bay

Based on estimates of pre-1600 pristine populations in Chesapeake Bay, Roger Mann and colleagues calculated that oysters could have filtered the entire bay's waters in three to four days; at current population levels it would take almost a year. Oysters populations were heavily harvested by European settlers in the United States far earlier than were many other coastal fishery populations because motor-driven boats and modern technology are not needed. Oysters are simply scraped from the bottom using various types of rakes and dredge devices (see Chapter 11), and at low tide many oyster banks are exposed above the water. The work was hard but profitable.

Oysters were already overharvested in the northeastern United States by the late 1800s. The "watermen" who harvested the oysters then moved south to Chesapeake Bay to continue their business. In Maryland waters, the annual harvest from 1871 to 1878 was ten to fifteen million bushels (the exact definition of a bushel varies from place to place, but the U.S. standard is about 2,750 cubic inches, about 45,000 cubic centimeters; a New Jersey study found that, on average, there were about 270 oysters in a bushel). Annual harvest declined by over 10% in three years as the oysters began disappearing. During this time period, there were no limits on harvest, but it stabilized at about two to three million bushels from the 1930s through the 1950s, and then declined to just over one million bushel by the mid 1960s. The decline of oysters in Chesapeake Bay was apparently due to one cause: excessive harvest (**Figure B4-2**).

By 1960, as it became apparent that oysters would not recover on their own especially as harvest continued, some proactive measures were taken. Oysters need hard bottom for settling of the spat, but removing oyster shells over the past century had destroyed critical habitat from the bay. The state of Maryland began repletion programs whereby oyster shells were dredged from areas where they were abundant and placed into waters where the oysters shell habitat was gone. This was supplemented by developing oyster "seed bars" where young

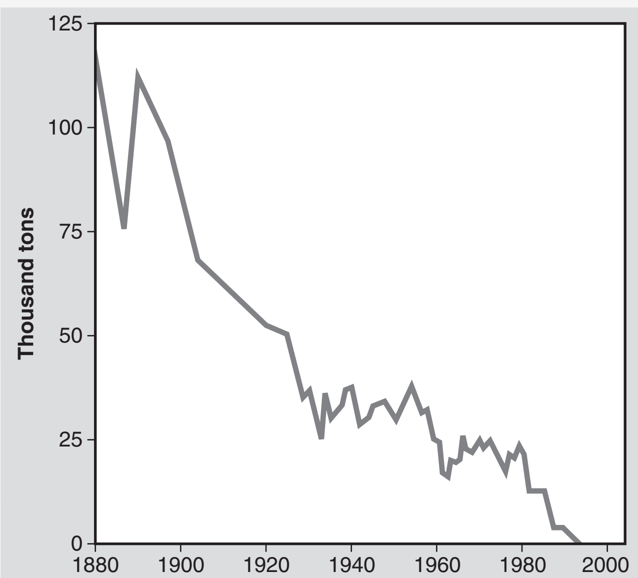


Figure B4-2 Oyster landings in Chesapeake Bay, 1880–2000.

oysters were allowed to grow until being transplanted into the new habitat. These programs appeared to be successful, because oyster harvests increased to two to three million bushels annually from 1970 through the mid 1980s.

Just when it appeared that management efforts were going to at least stabilize the populations, if not totally recover them, another impact hit Chesapeake Bay. Diseases and parasite infections that killed the oysters began to appear with a greater frequency, probably as a result of more polluted waters. Some infections were documented as early as the 1960s but in the late 1980s and early 1990s three major diseases associated with parasitic infections resulted in oyster death rates as high as 90% in some areas of the Bay. Annual harvest declined to levels under 100 thousand bushels in 1994 and stayed under 500 thousand bushels annually through 2006.

This historical account might suggest that conservation of oyster populations in Chesapeake Bay will continue to be a losing battle. But beginning in the late 1980s, Maryland began restoration programs not only to restore the oysters for harvest, but to enhance their ecological roles, including filtering and providing habitat and food. Sanctuaries were established, some of over 5,000 acres, where oysters have been planted and no harvest is allowed. Other areas are set up as reserves, where oysters are planted and protected for five years before managed harvest can begin. Still, commercially harvested oyster populations remain low and new restrictions continue to be applied to limit harvest.

It remains to be seen whether restoration efforts will be able to restore the oyster populations in Chesapeake Bay to anything near pristine levels of the mid-1800s, especially if disease outbreaks continue and pollution in the Bay cannot be managed. Many entities have come together to work on the oyster problem as well as other issues in the Bay, and educate and encourage the cooperation of the public. These include Federal government agencies, state agencies, nongovernmental organizations (NGOs), and community groups.

One way to provide commercial oysters while avoiding the problems of overharvest is to move toward aquaculture. The aquaculture industry for oysters (as well as many other marine species, see Chapter 11) has grown dramatically. For example, Virginia has continued a multi-million dollar clam and oyster industry by leasing beds to individuals where they plant spat to be harvested later. This has become commonplace in other regions. In Louisiana it has been common practice since the mid-1800s to lease bottoms to oystermen who plant the "seed oysters" for later harvest.

The limited success of oyster restoration efforts through 2011 has led to more creative ideas for oyster restoration in Chesapeake Bay. One proposal, suggested in the early 1990s, was to use the non-native Asian oyster *Crassostrea ariakensis*, commonly called Suminoe oysters, to assist with recovery of the oyster fishery. This recommendation is based on the Suminoe oyster's excellent growth in estuaries and resistance to the diseases that are harming native *C. virginica* populations. Those who support the introduction, including the harvesters and the seafood industry, hope that it would rapidly populate and reduce plankton blooms resulting from eutrophication of the Bay. Oppositions to introduction of the Suminoe oyster are based on fears that it could displace or cross-breed with native oysters (possibly producing sterile offspring), damage the ecosystem and fisheries, bring new exotic species or diseases into the Bay, or end up in other waters outside of Chesapeake Bay. Scientific studies were carried out and numerous meetings of state agencies and public hearings were held to assess these alternatives for oyster recovery. State and U.S. federal agencies, including the U.S. Fish and Wildlife Service, NOAA, and the EPA, eventually came out in opposition to any use of the non-native *C. ariakensis.* The State of Maryland Department of Natural Resources (DNR) concluded that only native oysters (*C. virginica*) should be used in ecological restoration and revitalization of the oyster industry. Management alternatives should include restoration of native oysters, implementing further restrictions on harvest, rehabilitating habitat and creating sanctuaries, and expanding aquaculture with native triploid oysters and those bred for disease resistances. The reasons for the stand taken by the Maryland DNR include observations that methods used to sterilize native Asian oysters are not 100% successful. History with other sterilization programs for aquatic species (e.g., carp in U.S. freshwaters) has taught us that despite precautions, it is likely that eventually there will be an introduction of fertile individuals into the wild.

The battle to recover oysters and the ecosystem of Chesapeake Bay undoubtedly will continue into the foreseeable future, involving science, conservation, politics, and economic considerations. Not everyone will be satisfied with all of the decisions but, hopefully, lessons from past mistakes will be considered and guide decision-makers in the direction that is in the interest of long-term health of the ecosystem.

take in oxygen for respiration. Marsh grasses tolerate these conditions with special adaptations. Anaerobic respiration is possibly for many of these plants; however, this results in lower growth rates and possible death due to the accumulation of toxic chemicals. Marsh grasses can enhance aerobic respiration by conveying oxygen taken in by the leaves through air spaces (**aerenchyma**) to the roots. Succulent plants such as *Salicornia* take in oxygen through above-ground shoots that is transferred to the roots. Although salt marsh plants are tolerant of tidal submersion, their reliance on atmospheric oxygen means that constant submersion is stressful and can be lethal. Another source of stress is highly variable salinities. Marsh grasses are **halophytes** (salt-tolerant plants) that tolerate high salinities by excreting salts through specialized salt glands. Succulent salt marsh plants (e.g., *Salicornia*) avoid excessive salt concentrations in their tissues by minimizing salt uptake and transport to the growing shoots of the plant.

Figure 4-10 A Mississippi salt marsh.

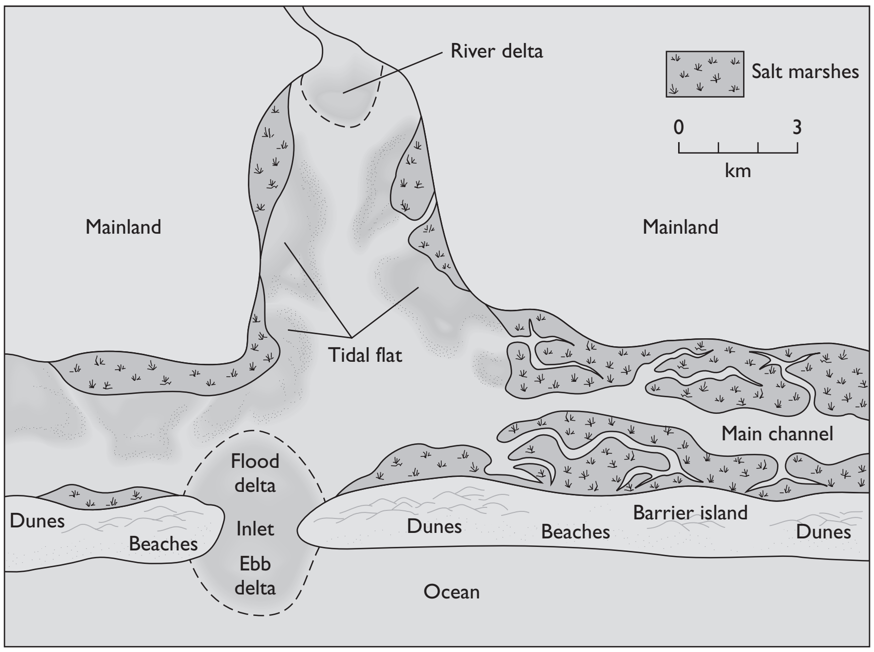
The variability among plant species in the mechanisms for dealing with the physiological stresses of living in the salt marsh environment results in a well-defined distribution along gradients of salinity and exposure. Along the seaward edge of salt marshes the grasses are mostly in the genus ***Spartina***. *Spartina* grasses occur worldwide; in salt marshes of the eastern United States, two species of *Spartina* dominate: the cordgrass *Spartina alterniflora* along the shore, and marsh hay *Spartina patens* in the higher marsh. In the highest portions of the marsh another grass, black rush (*Juncus roemerianus*) dominates. Other salt marsh grasses include the saltgrass *Distichlis spicata*, native to the Americas but introduced onto other continents. Glassworts

Figure 4-11 NASA satellite image of the eastern United States showing numerous bays and estuaries along the coast.

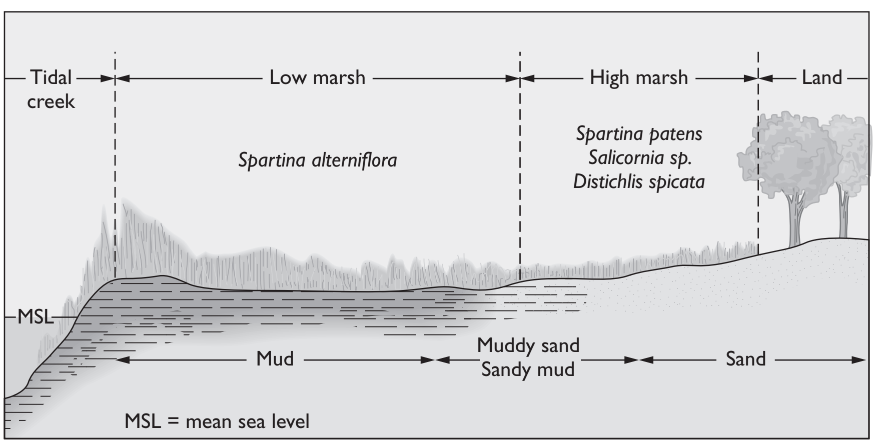
in the genus *Salicornia* are succulent, halophytic plants that can be found in salt marshes as well as in beach and mangrove habitats. At the inland edge of the marsh there may be other succulent plants and a line of woody shrubs (**Figure 4-12**).

The salt marsh is one of the most productive ecosystems on Earth. The primary productivity is provided mostly by the grasses, and the muddy bottom is covered with bacteria, diatoms, and algae. Bacteria play an important role by decomposing the dead grass leaves. This is a substantial amount of organic matter because much of the leaf biomass dies during the winters. Because many animals cannot digest the grasses directly, decomposition makes the nutrients available for the rest of the salt marsh food web. The bacteria themselves also provide a significant amount of nutrition to organisms that consume detritus.

Burrowing **macroinvertebrates** are common in the soft muddy bottoms of the salt marsh. The most obvious are the polychaete worms and bivalves (**Figure 4-13**). Other invertebrates live among the marsh detritus, including **meiofauna**, organisms barely visible to the naked eye, such as copepods and amphipods. Crabs are common salt marsh inhabitants. One of the most conspicuous is the fiddler crab *Uca,* which builds burrows along the edge of the mudflat and feeds on detritus in the mud. Male fiddler crabs attract females to their burrows by waving their enlarged left claw in the air. It is common to see hundreds of these fiddler crabs desperately waving their claws on the exposed

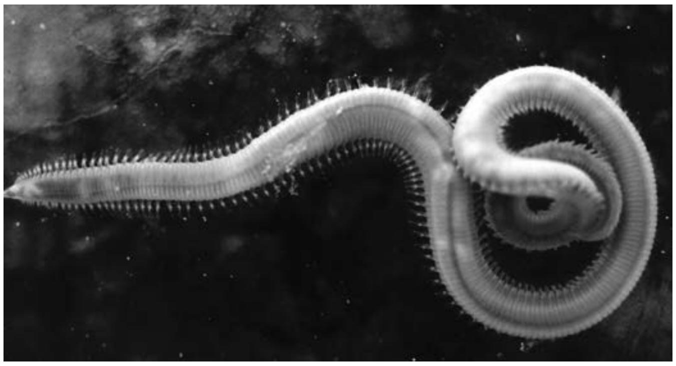


(a) SALT MARSHES AND OTHER COASTAL ENVIRONMENTS

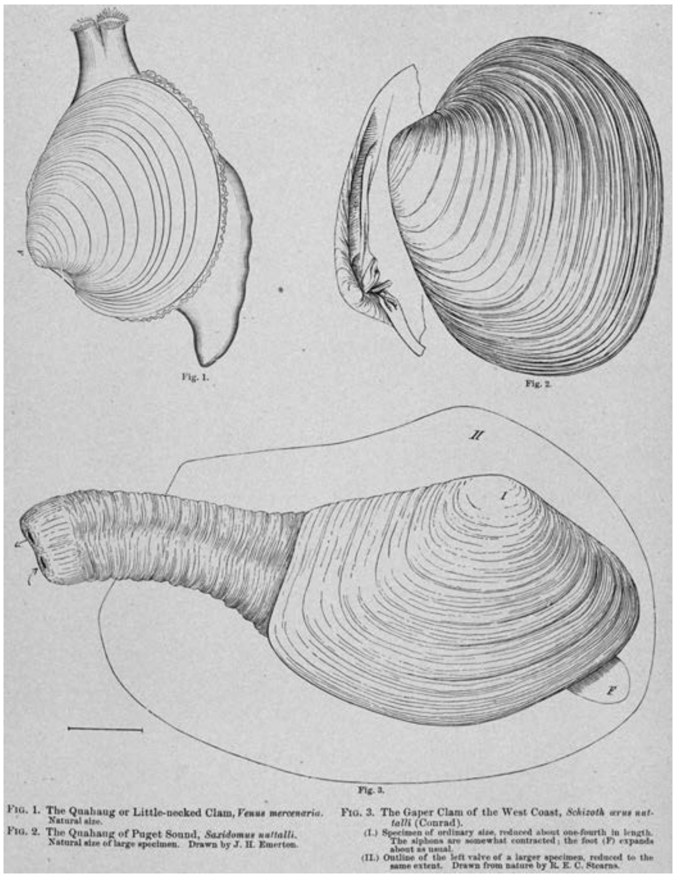


(b) SALT-MARSH PROFILE

Figure 4-12 **(a)** Locations of salt marshes and associated habitats within a coastal estuary. **(b)** Profile of a U.S. east coast salt marsh, indicating dominant vegetation and substrate type along a low to high marsh gradient.



(a)



(b)

Figure 4-13 Salt-marsh macroinvertebrates: **(a)** a polychaete worm *Glycer* from a South Carolina salt marsh, and **(b)** quahog and gaper clams common in coastal marshes.

mudflats at low tide. Another conspicuous invertebrate in the salt marsh is the periwinkle *Littorina,* a snail that can live and breathe out of the water, and is commonly found slowly climbing up the plants as the tide moves in. *Littorina* feed on organisms attached to marsh grasses and can have a significant impact on the salt marsh under certain conditions (**Box 4-3. Geese and Snails, Top-Down Killers of the Marsh**).

Salt marshes support relatively few subtidal attached organisms, such as sponges, barnacles, or tunicates, compared to mangroves; this is probably due to the lack of hard substrate (with the exception of oyster beds) and the extreme temperatures in temperate shallow waters. Some fish species can tolerate the extremities of the marsh throughout their lives. These include **resident** species such as killifishes (Fundulidae) and silversides (Atherinidae), that feed and reproduce in the marsh. Juveniles of many **transient** fishes and crustaceans use the productive marshes as **nursery areas**, using the tidal creeks and pools at low tide and moving into the marsh grasses at high tide to escape predators that move into the estuary with the tide. Many of these organisms are important fisheries species as adults in coastal waters. Predators include larger fishes, such as the seatrouts (*Cynoscion*) and drums (family Sciaenidae) (**Figure 4-14**). These predators support recreational fisheries in the marshes and estuaries. Many birds such as rails (**Figure 4-15**) also feed and nest in the salt marsh, and small mammals such as raccoons may visit the marsh to feed.

The large amounts of organic matter and nutrients that are produced in the marsh benefit not only the marsh and estuary but adjacent marine habitats as well. It is difficult to make precise measurements of production export from the salt marsh and it varies from marsh to marsh. Generally there is a net export of production through a process called **outwelling** (the outflow of nutrients from an estuary). Some of this transport is through organisms that migrate from the salt marsh into adjacent coastal habitats, and this is considered important in supporting coastal marine fisheries. There is also an outwelling of nutrients and organic matter in the form of detritus and dissolved organic matter. The outwelling from salt-marsh estuaries occurs in pulses dependent on rainfall and tidal flow, and the degree of outwelling depends on the amount of production, the geomorphology of the estuary, and tidal amplitude. The importance of outwelling provides a strong argument for the conservation of salt-marsh ecosystems.

Salt marshes serve other important ecological functions, such as filters to remove sediments and a limited amount of nutrients and pollutants from the water. Marshes act as physical buffers for the mainland by absorbing much of the impact of storm surges and reducing erosion of the coastline. Salt marshes typically recover from the impact of storms and hurricanes by accumulating sediment and regrowing where they have been destroyed.

Salt-Marsh Destruction

As modern human settlements were established along temperate coastlines around the world, many of the salt marshes were destroyed or covered over. Most of the salt marsh habitats in Europe were lost hundreds or thousands

Box 4-3 Research Brief: Geese and Snails, Top–Down Killers of the Marsh

Most of the research on salt marsh impacts has focused on bottom–up effects, that is, how inputs of nutrients, changes in soil chemistry, or physical factors affect the growth of marsh grasses. Research indicated that biomass of the marsh grasses entered the food web only as dead plant material that was turned into detritus and decomposed. It was even debated whether the bacteria that consumed the dead grass were as important as a source of nutrition as the grass itself. The common paradigm was that top–down effects from predation of marsh grasses were not important. Recent studies of two marsh ecosystems have begun to change this paradigm, however.

The first of these is in the marshes of the New England region of the northeast United States. Snow geese (*Chen caerulescens*) and Canada geese (*Branta canadensis*) populations feed and breed in these marshes during the summer months. At historic population densities the geese actually benefitted the salt marshes through their activities. Snow geese would return from overwintering in southern marshes and migrate to breed in the New England marshes. Although the geese fed on the marsh grasses, they also defecated in the marshes, putting nutrients back into the ecosystem. Once they left, the marshes recovered. Over the past 30 years, however, Canada geese and snow geese populations have grown rapidly, in part due to decreased use of harmful pesticides but also due to increased access to farm crops. From winter to spring the snow geese migrate from croplands in the southern United States to salt marshes in the northeast by the millions, where they begin feeding on the roots and rhizomes of the marsh grasses. They can denude millions of square meters of marsh in an hour. Once the grasses are gone, evaporation can increase the salinity in the marshes and eventually dry out the soils, conditions under which the marsh grasses cannot recolonize. Once the soil qualities change in the exposed mudflats, it could take decades for the grasses to return, even if the grazing pressure from the geese is removed.

Another series of studies was carried out in salt marshes along the southeastern United States and Gulf of Mexico coasts by Brian Silliman and colleagues. Die-offs of *Spartina* marsh cordgrasses totaled more than 250,000 acres over a six-year period following severe drought years in 1999–2001. These die-offs were initially attributed solely to the drought's effect on salinity and factors related to soil moisture. Evidence indicated, however, that other interactions were involved. The marsh periwinkle snail *Littoraria irrorata* feed on fungi that grow on the *Spartina.* During feeding, the snails damage the *Spartina* and facilitate additional fungal infection. At high snail densities, feeding on these infected areas stresses and can kill the *Spartina* plant. Through field observations, experiments, and modeling, Silliman and colleagues found that the drought and snail predation were working together to cause the marsh diebacks. The intense droughts resulted in stressful soil conditions that, either alone or in combination with snail grassing, caused die-offs of the *Spartina* in some areas. The snail populations increased dramatically in the stressed areas. As the stressed area was denuded, the snails concentrated at the border of healthy marshes adjacent to the die-off area. These snail "consumer fronts" then moved into healthy marshes, destroying grasses as the fronts progressed. Eventually the fronts subsided as the snails dispersed; however, the snail fronts persisted in some marshes for as much as one year after the impact of the drought subsided. By 2003 much of the marsh affected by the drought had begun recovering as *Spartina* recolonized the mudflats; however, many areas affected by the snail fronts still had not recovered by 2005. There is a concern that with climate change severe droughts may become more severe and these events may become more frequent. To add to this concern, blue crabs, which are potential snail predators, have recently declined by as much as 40% to 80% in southeastern U.S. salt marshes. There appears to be a natural **trophic cascade**, whereby the crabs prey on the snails that prey on the marsh grasses. Loss of the crabs releases the snail populations that can destroy the marsh grasses.

These studies have shown that ecological interactions in the marsh are complex and factors initiated far from the marsh or even on a global scale may have unexpected effects. These all must be considered in protecting the remaining salt marshes. Scientists are striving to develop a better predictive understanding of the salt marsh ecosystem so that environmental groups and government officials will have the knowledge needed to protect what remains of one of the most productive ecosystems on earth.

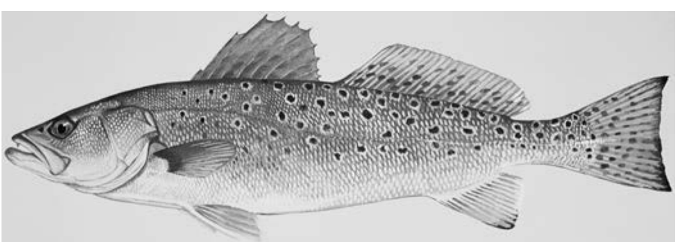


Figure 4-14 Spotted seatrout *Cynoscion nebulosus,* common predatory fish in salt marshes of the southeastern United States.

of years ago. These marshes were modified to support settlements, livestock grazing, and farming, and many are still maintained for agriculture. Early European settlers to North America used the salt marshes for livestock grazing and often modified the marsh with canals and dikes to enhance hay production. More than 50% of the marshes were gone in southern New England before large permanent European colonies were established. Most of these salt marshes were never restored to their original function, and many were eventually filled for development. The greatest effect of urban sprawl on salt marshes has been in the heavily populated areas; for example, around large cities

Figure 4-15 A clapper rail *Rallus longirostris,* which feeds and nests in temperate and tropical coastal salt marshes throughout much of the Americas. Populations have declined in some regions due to marsh loss.

most of the marshes were destroyed by dredging, channel deepening, and port construction.

Through the 1900s, marshes were filled and canals were dug for control of mosquitoes, based on the perception that they harbored diseases and not realizing their importance to coastal fisheries. The most recent major effect on salt marshes was total destruction to create areas for residences, industry, and agriculture, primarily from the 1950s to mid 1970s. In some areas marshes were filled to create tourist accommodations and beaches. Typically the beach is maintained with sands dredged from offshore, a process referred to as **beach nourishment** (see Chapter 3; **Figure 4-16**).

Figure 4-16 A view of the Mississippi Gulf of Mexico coast where salt marshes have been covered to maintain beaches and accommodations.

Even without filling, the marshes can be affected by development or changes in the tidal flow. Too much fresh water can flow into the marsh when woody vegetation is removed from along the landward edge of the salt marsh. Salt water tidal flow into the marsh can be restricted by sea walls or embankments. Without the seawater influence, freshwater vegetation such as cattails (*Typha*) or reeds of the genus *Phragmites* will outcompete the cordgrass. Roadways and railroads affect the flow of water in the marsh, causing much of the marsh to be drained and other areas to be overrun with freshwater. The intrusion of seawater into freshwater marshes can destroy vegetation that is intolerant of salt water, including trees such as cypress.

Along the U.S. Atlantic and Gulf of Mexico coasts, the importance of the salt marsh is now generally appreciated and the remaining marshes are mostly protected from destruction by state and federal laws. Indirect effects of flow modification for flood control or canals built for boat access, however, still affect the salt marshes. For example, the dredging of the Intracoastal Waterway in northeast Florida resulted in the loss of over 35% of the marshes in regions around the canal. Some salt marshes have been designated as Marine Protected Areas and function more like parks, receiving near total protection from direct harm.

Impoundments

During the settlement of the United States, salt marshes were generally considered useless to humans and they were often filled, drained, or impounded. Vast tracts of salt marshes along the U.S. east coast were diked and drained for rice or other forms of agriculture, or impounded for waterfowl. After the Civil War, the abandoned rice field often continued to be maintained for attracting waterfowl (**Figure 4-17**).

Impoundments are constructed by building earthen dikes around an area of marsh to control the tidal flow.

Figure 4-17 A coastal marsh impoundment south of Charleston, South Carolina.

Although some water flow may be allowed, this affects the natural ecosystem by limiting the tidal flow. These impoundments have a more constant salinity, sometimes near zero percent. In summer the oxygen level in impoundments can be severely depleted due to the stagnation of the water, lack of tidal exchange, and decomposition of organic matter. This kills many of the marsh residents that use impoundments. Impoundments managed for waterfowl are controlled at low salinity, because plants preferred by waterfowl will not tolerate higher salinities. Water levels are regulated and the impoundment bed may be cultivated, reducing or eliminating salt marsh species.

In the late 1900s the modification of the salt marshes and the right of private ownership of impoundments became controversial. Many believed that the marshes should be returned to their natural function of supporting coastal ecosystems and fisheries and protected as a common resource. Conservationists argue that the value of the marsh should be in supporting natural ecosystems and fishery species as nursery areas, and that natural salt marsh habitat should be considered a public resource. Laws have been passed in most states to eliminate the impounding of salt marshes and some impoundments have been returned to natural marshes. Still, many impounded areas remain; for example, in South Carolina approximately 15% of the coastal marshes are still impounded to some degree. These impounded areas are managed in a variety of ways. Some are maintained as freshwater wetlands, others retain their estuarine function through openings to coastal inlets, and some are still managed for primarily for migrating or wintering waterfowl.

Pollution

Even away from large cities or impounded areas the cumulative impact on salt marshes can be substantial. Pollution can accumulate in marshes that receive water from various sources. **Point-source pollutants** (those from a single source like an industrial factory) are typically regulated by permits. **Non-point source pollutants** (those not from a defined point, such as street or agricultural runoff), however, can be a significant problem because of the difficulty in monitoring and regulating their input. Excess nutrients from agriculture and other sources entering the marsh through river input or local runoff can result in eutrophication. Even at more moderate levels, an increase in nutrients can modify the species makeup of the marsh. For example, in northeastern United States, nutrient pollution from agriculture runoff has resulted in lower plant diversity in some salt marshes, making marshes less useful as a nursery area for fishes and invertebrates. Salt marshes can be vulnerable to accumulation of heavy metals or pesticides that are deposited into the marsh along with sediments and organic matter that originate inland. Herbicides can affect salt marsh plants. Studies by Chris Mason and colleagues found that, even at sublethal concentrations, herbicides in England's marshes have been shown to lower growth and production of grasses and diatoms, and play a role in increased erosion of the marshes.

Impacts of River Channelization

Large coastal rivers, such as the Mississippi River flowing into the Gulf of Mexico, provide an important source of sediments to coastal salt marshes. When the rivers flood onto the coastal plains, accumulated sediments support marsh development. But after the marsh lands are formed they gradually compact, causing the level of the marsh to sink or **subside**. Therefore, without a source of sediment to replenish the marsh it will eventually convert to open water. This is exactly what is happening in much of coastal Louisiana.

Over about the past century there have been extreme efforts to keep the lower Mississippi River in its current channel within its banks by building levees and channelizing the river to enhance boat traffic and protect cities such as New Orleans (**Figure 4-18**). (Even New Orleans has subsided below sea level but is normally kept dry by a massive assemblage of pumps.) The completion of river modification projects from the 1920s through the 1960s resulted in a 67% decrease in the sediments delivered to the Louisiana coast. The only times the river and estuary overflow the banks are in times of severe flooding or when hurricanes, such as Katrina in 2005, move up the Mississippi River. Damming of the rivers in the Mississippi River watershed also has reduced the sediment load by over 50%,

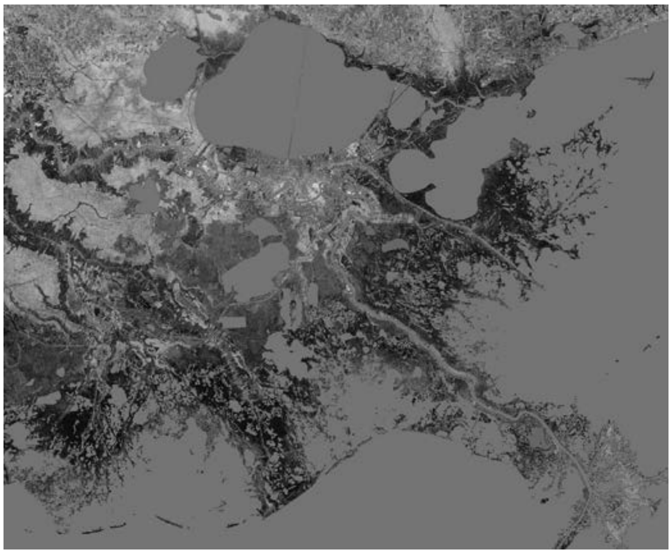


Figure 4-18 The lower Mississippi River and Delta. (See Color Plate 4-18.)

reducing the amount of sediment transported down the river. Most of those sediments are being transported out onto the continental shelf in the Gulf of Mexico.

Not only are the marshes in the vicinity of the Delta hurting, but marshes to the west are also gradually disappearing. These marshes also depend in the long term on sediments from the Mississippi River. After the Delta builds over several millennia, the river eventually switches its location along the coastline and thus provides sediments to a new area. Over several tens-of-thousands of years the Mississippi River has changed its course several times. The current tendency is for more water to flow down **distributaries** (streams that branch off and flow away from the main river channel) to the west of the current river channel, which would produce a new delta and replenish the marsh sediments in that region. Allowing the Mississippi to switch courses, however, would dramatically affect shipping traffic on the Mississippi and the economy of New Orleans and other areas along the lower Mississippi.

As a result of these effects, much of the marshlands of coastal Louisiana have literally sunk into the sea, becoming open water where salt marshes used to be. To add to the impact, canals have been dug through the marshes themselves. During oil exploration this is one of the easiest ways to gain access to the marsh. With erosion, the channels expand into areas of open water in the marshes.

In total, Louisiana has lost almost 5,000 square kilometers of coastal marshes and wetlands in the 20th century (**Figure 4-19**). An increase in tropical storms and hurricanes could increase the rate of marsh loss. The numerous hurricanes that hit the Louisiana coast in the first decade of the 21st century resulted in the loss of over 500 square kilometers of wetlands, and without the sediments to replenish them they will be unable to return on their own. It is predicted that over 1,600 additional square kilometers could be lost in the next 50 years if adequate preventive measures are not taken. If that occurs, one-third of coastal Louisiana will have been lost.

In some marsh systems, hurricanes can enhance the marsh by moving sediments from coastal beaches and dunes into the marsh. For example, this has been documented in coastal areas of Texas. Building over the dunes, however, has inhibited this natural erosion and movement of sediments to the marshes.

What effect does marsh loss have on coastal ecosystems? As described above, salt marshes are an important nursery area for many coastal fish species, and loss of the marshes removes critical habitat. Another effect of this land loss is the loss of habitable land along the coast. Towns can be literally disappearing into the sea. Without the marsh as a buffer, coastal areas are more vulnerable to flooding and erosion from storms. To further exaggerate the problems, freshwater marshes are being destroyed by **saltwater intrusion** as ocean water moves further inland and kills vegetation intolerant to high salinities.

Salt Marsh Restoration Methods

With the realization of the important functions of salt marshes have come increases in efforts to protect the healthy salt marshes that remain. A hands-off approach can be best in some situations. But when the marsh has been destroyed or severely impacted more active restoration efforts may be necessary. Of course, each situation must be approached independently; however, research has established a set of standard methods that can be adapted to a given situation.

In the simplest situation, restoration involves simply removing the fill that covers a former marsh and allowing the marsh grasses to recolonize the area. Changing the drainage and tidal exchange (for example, by adding

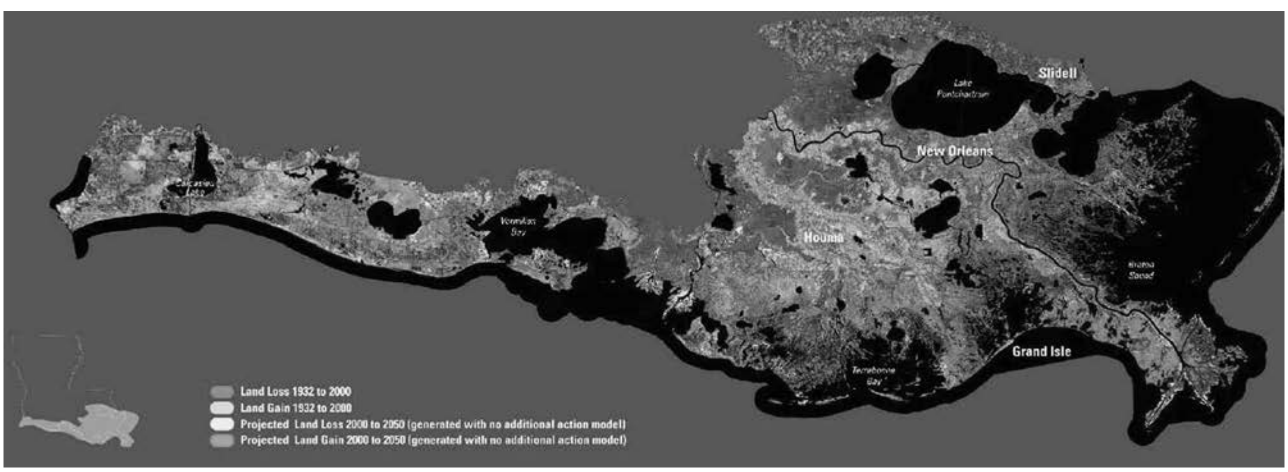


Figure 4-19 Historic and predicted land loss in coastal Louisiana. (See Color Plate 4-19.)

culverts in the proper location during road construction) may enhance the recovery. At times salt marshes are created or restored unintentionally. If land use changes cause changes in river flow and drainage that result in the creation of a new mudflat, this mudflat may be colonized naturally by marsh grasses and eventually develop into a healthy salt marsh. Manmade dikes or levees may naturally erode, resulting in the building of a new mudflat that eventually establishes marsh grasses and develops into a salt marsh.

A natural recovery may be a long, uncertain process as the sediments need to accumulate and marsh plants become reestablished. For severely damaged marshes, more active efforts are needed. In some areas along the U.S. Atlantic coast, recovery methods include pumping dredge spoils onto the marsh and replanting marsh grasses. The removal of invasive plants from marshes may be necessary before replacement by native *Spartina* in some marshes. One such invasive is a European strain of the common reed *Phragmites australis,* introduced into U.S. marshes in the late 1800s. This grass has a low tolerance for high salinity waters, and invades marshes when the salinity regime has been altered by changes in tidal water flow. It outcompetes *Spartina,* forming dense colonies that are barriers to the movement of marsh animals, including shorebirds and wading birds. Eventually open water areas of the marsh begin filling in, raising the marsh elevation. If *Phragmites* is removed (with herbicides and mowing) and salt water tidal flows restored, *Spartina* may eventually return on its own. Because *Phragmites* is intolerant of salinities over 18 ppt, the restoration of tidal flow alone may result in *Spartina* recovery. Because natural replacement can take 10 to 20 years, however, replanting may be desirable. In China the opposite situation exists, where *Spartina* is the invasive species, taking over marsh habitat once dominated by *Phragmites. Spartina* was intentionally introduced into estuaries in China to enhance land accretion and enhance biological production; however, as Shuqing An and colleagues report, this has resulted in a loss of native biodiversity in regions where it has been introduced, including a loss of insect species that depend on *Phragmites* and bird species that depend on the natural marsh habitats.

Some of the most active research on salt marsh restoration is in coastal Louisiana. Because of the large area involved restoration will require massive efforts. There are currently over 100 separate restoration projects in Louisiana, sponsored by various federal, state, and NGOs. These include the National Marine Fisheries Service of NOAA, the U.S. Fish and Wildlife Service (USFWS), the U.S. Environmental Protection Agency (EPA), and the Louisiana Department of Natural Resources. Many collaborative efforts have been initiated; for example, the Barataria-Terrebonne National Estuary Program, established by an agreement between the State of Louisiana and the EPA.

Some of the methods used to restore salt marshes in coastal Louisiana include spreading dredge materials across the subsidized area until the level is high enough for marsh development, constructing terraces to protect areas from further erosion, placing breakwaters offshore to minimize wave impact, and replanting grasses in areas being reestablished. Even placing discarded Christmas trees into open waters can assist in the accumulation of sediment and reestablishment of the marsh. One of the most ambitious plans is to harvest sediments from the bottom of the Mississippi River and deliver them as a slurry through pipelines to be deposited into the marshes. It is estimated that this would build up the marshes around the Mississippi River Delta region of Louisiana to their 1956 conditions in 50 years. The price tag, in the hundreds-of-millions of dollars per year, however, will make this project difficult to implement.

One of the most productive long-term solutions would be to allow the Mississippi River to run its natural course and perform its normal function in restoring marsh sediments. Removing levees along the river would allow natural flooding of the marshes and changes in flow would result in redistribution of sediments to other areas along the coast. Allowing this natural progression is not considered acceptable due to our dependence on the river for barge and boat traffic, and flood control is necessary for protection of agriculture lands and cities, including New Orleans. A compromise has been reached to allow some flow into distributaries to the west of the current channel.Thirty percent of the Mississippi River flow is now allowed into the Atchafalaya River using control structures at the junction of the two rivers. This has resulted in a substantial increase in marshlands and delta sediments in this basin. Allowing the diversion of river flow is also controversial because of effects the freshwaters may have on the salt marshes (such as harming oyster beds).

Many of the current and historical impacts on salt marshes reflect a misunderstanding of their function and importance to coastal marine ecosystems, the production of commercially valuable fishery resources, and protection of human settlements in coastal regions. Education, therefore, can be a key to salt marsh protection. With education, the perception of salt marshes as wastelands is slowly being replaced with the understanding that these are critical components of ecosystems, both aesthetically and economically. Programs are in place around the North American coast to educate children, fishers, developers, political leaders, and other citizens while studying, protecting, and preserving salt marshes and other components of estuarine ecosystems. These programs include the National Estuary Program established by the U.S. EPA. NOAA's National

Estuarine Research Reserve System protects 27 areas in different biogeographic regions of the United States and supports long-term research, monitoring of water quality, and education. One of the goals of this program is to work with local communities and regional groups to establish management policies, restore habitat, and address pollution and invasive species issues.

In establishing restoration programs, care must be taken to consider the landscape surrounding the marsh. For example, research by Melissa Partyka and Mark Peterson found that the simple presence of salt marsh habitat within an altered landscape was not adequate to ensure a healthy ecosystem. Marshes located within a natural landscape exhibited healthy conditions, demonstrating the importance of habitat protection along the entire gradient from terrestrial through freshwater ecosystems, through estuaries to the sea.

4.3 Mangrove Ecosystems

Mangrove ecosystems replace salt marshes in comparable environments of tropical regions; the most pronounced difference is the woody vegetation that replaces marsh grasses as the dominant emergent vegetation. Mangroves are the most prevalent of the woody plants that can tolerate exposure to a broad range of salinities and sediments with low oxygen levels. This tolerance allows them to take advantage of the productive silty habitats in tropical coastal areas associated with estuaries. Mangroves are not limited to estuaries, however, and tend to dominate along any tropical coastline that is sheltered and shallow enough to accumulate sediments to support emergent plant growth. They are excellent colonizers of small oceanic islands, where they grow on shallow banks or in lagoons. The roots are exposed to full-strength seawater but can tolerate an extreme range of salinities, influenced by heavy rainfall at one extreme and evaporation at the other. Variations in the hydrology and the topography where mangroves can colonize lead to variations in the animal species that utilize them; this results in a diverse assemblage of organism in mangrove communities. As with other estuarine and coastal ecosystems, increasing human populations and the associated impacts result in many mangrove-associated conservation issues and conflicts.

Mangrove Distribution

The term **mangrove** is not a formal taxonomic term but is used to refer to woody plants, in the form of shrubs or trees, that have a set of physiological adaptation that allow them to thrive in coastal areas exposed to seawater. The ecosystem associated with the mangroves (**Figure 4-20**) is often termed a **mangal;** however, in this chapter "mangrove" will typically

Figure 4-20 Underwater view of mangrove roots and their associated ecosystem.

refer to either the plants or the ecosystem. About 60% to 70% of the Earth's tropical coastlines are lined with mangroves, typically in sheltered areas away from the ocean's wave action. Mangroves follow a similar broad distribution to coral reef ecosystems, and the two are often associated with each other; however, mangroves occur in some regions not tolerated by corals because of excess sediment input (e.g., the west coast of Africa or Amazon coastal region of South America), or cool areas of upwelling (e.g., off the west coast of South America and Africa; **Figure 4-21**). Mangroves are missing from some isolated coral islands in the central Pacific, presumably because the mangrove seeds cannot disperse the distances necessary to colonize these islands. There has been much debate as to why mangroves are limited to tropical regions. One primary reason is that they cannot tolerate freezing well. The full physiological explanation is still uncertain; however, studies by Stephanie Stuart and colleagues indicated that the physical characteristics of salt water result in excess tension in the mangrove xylem during freezing, limiting the mangrove's ability to supply water to the leaves. In temperate areas, typically above about 25 degrees north and south latitude, mangroves are replaced by salt marshes. The mangroves' range is extended farther in some regions due to movement of warm currents along the coast (see Chapter 1), for example, off the east coast of South America, Africa, and Australia, and in the Gulf of Mexico. In the continental United States, mangrove marshes are limited primarily to southern Florida and the southern tip of Texas. The limits on mangrove distributions result in a remarkable contrast, with woody vegetation dominating most of tropical coastlines but almost totally absent from temperate coastlines.

The largest areas of mangroves are in estuaries associated with deltas of large rivers, such as the Indus Delta of Pakistan and the Amazon Delta of South America. Sediments deposited in these areas provide new habitat for mangrove

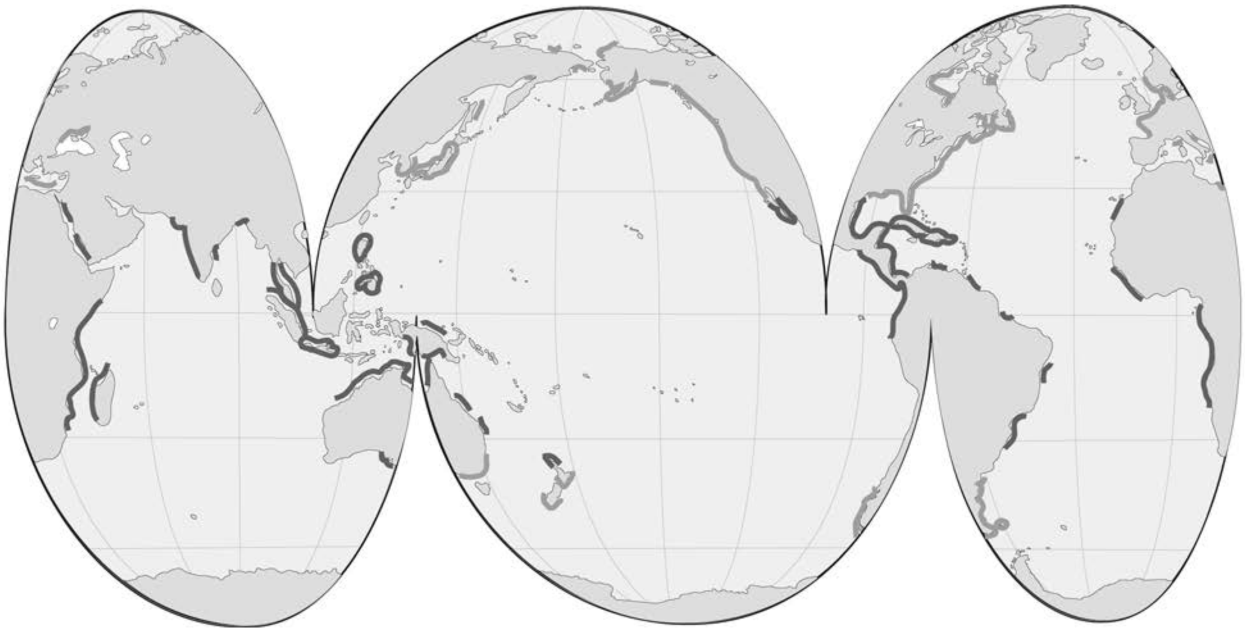


Figure 4-21 The global distribution of mangroves (dark gray), compared to that of salt marshes (light gray).

settlement (**Figure 4-22**). Damming thus can affect these ecosystems by removing a source of sediments in a manner similar to that discussed above for salt marshes. Mangroves are able to trap sediments and can increase sedimentation rate and slow down erosion. Apparently they do not actually create new land by accumulating sediments, however. It is more likely that they take advantage of the accumulation of new sediments, or disappear as shores erode. A primary ecological function of mangroves in estuaries thus is to turn what would be a uniform mud flat into a complex productive environment supporting a rich and diverse ecosystem.

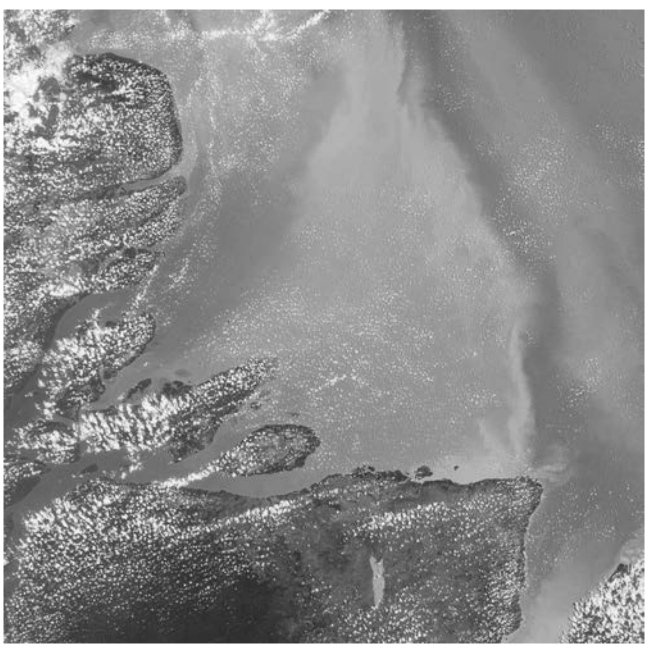


Figure 4-22 The Amazon River mouth. Mangrove habitat extends along the seaward edge of the river's mouth. Note the sediment plume extending into the ocean. (See Color Plate 4-22.)

Less extensive mangroves are found fringing some coastlines away from river influence, especially where tidal currents transport enough sediment to support the mangrove roots. If lagoons form behind this fringe, mangroves may form. **Overwash mangroves** form away from the coast in some areas of the Caribbean. Here they grow with no substantial source of sediments, but are supported by peat accumulation on small islands (**Box 4-4. Conservation Focus: the Belizean Reef Mangroves**).

Because mangrove habitats are in soils either covered by water or inundated periodically by the tides, the soils are continuously waterlogged. Waterlogged soils are typically low in oxygen for two primary reasons. For one, water that fills the spaces in the soil does not supply nearly as much oxygen as air, and, in addition, the oxygen that is present is rapidly used by bacteria in the soil. Because the roots of plants require oxygen for respiration, waterlogged sediments are not readily tolerated by many plants. Some mangroves species, such as the black mangrove *Avicennia germinans,* tolerate these hypoxic sediments by using porous upward extensions of shallow roots (**pneumatophores**) adapted to exchange gases for respiration (**Figure 4-23**). Other species, such as the red mangrove *Rhizophora mangle,* have long, thin prop roots extending from above the ground or aerial roots extending from branches (**Figure 4-24**). Mangroves also use roots for obtaining nutrients, primarily nitrogen

Box 4-4 Conservation Focus: Belizean Reef Mangroves

Most mangroves are components of estuarine ecosystems; however, mangroves can grow in areas far from significant freshwater input, even on small islands limited almost entirely to exposure to full-strength seawater. One of the most prominent of such ecosystems is associated with coral islands off the coast of Belize, Central America. The coral reefs here receive much attention as the longest continuous barrier reef in the Western Hemisphere. The Belizean Reef Mangrove Ecoregion, covering or fringing most of the undeveloped cayes (islands), also houses a large, diverse, and productive ecosystem. Many of these islands are completely covered with mangroves, mostly red mangroves, which can better tolerate continuous exposure to water than other species (**Figure B4-3**). These offshore mangroves are unique in that they are supported by the largest mangrove peat deposits in the world. There are mangroves over 12 kilometers offshore that have peat deposits as thick as 8 meters. Peat cores taken by Matthew Wooller and colleagues document that these deposits accumulated as sea levels rose over the past 8,000 years.

Many birds are associated with the mangroves, including important breeding and nesting populations of various egrets, herons, ibis, and the magnificent frigate bird *Fregata magnificens.* These birds contribute to the productivity of the mangrove ecosystem by depositing nutrient-rich guano. The underwater portion of the mangrove ecosystem is rich in organisms typical of Caribbean mangrove ecosystems. Much of this mangrove ecosystem is included in the Belize Barrier Reef Reserve; however, limited monitoring and enforcement have led to some conservation problems. These problems include illegal hunting of birds or egg collection during nesting season, disturbance of nesting colonies by tourists, and introductions of rats to some islands.

Tourism development on the islands off Belize has resulted in conflicts between developers and conservationists. Because mangroves naturally cover or fringe these islands, the sandy beaches that many tourists expect are uncommon; therefore, some developers remove mangroves to establish resorts and beaches. One of the most popular tourist destinations and one of the larger cayes in Belize is Ambergris Caye, where past development has resulted in much mangrove removal. The Belizian government, however, has tried to put a halt to future mangrove removal with recent moratoriums and laws requiring permits for any mangrove removal. Much of the southern tip of Ambergris Caye is still covered with mangroves, but there are proposals for development of a portion of this area into a resort.

Figure B4-3 Man-O-War Caye, mangrove island off Belize.

If approved, this project would require the removal of large areas of mangroves on the southern tip of the island and could also affect the reefs offshore that are included in the Hol Chan Reef Reserve. This situation will be a test for the conservation movement in Belize and could counter complaints by NGOs that politically-motivated environmentally-harmful decisions have been common in the past.

On the island just south of Ambergris Caye lies one of the better protected island mangrove habitats, the 100 acre Caye Caulker Forest Reserve. Despite protection of the mangroves there are still problems with rats, feral dogs, and cats. Man-O-War Caye is a much smaller island protected in the South Water Caye Marine Reserve. This island has one of the 10 largest magnificent frigate bird colonies in the Caribbean and the only nesting site in Belize for the brown booby *Sula leucogaster*. This caye is well protected from direct harm but has been damaged as a result of nearby tourist development. Sand dredging from underwater near the island to build up the foundation and beach around tourist resorts resulted in erosion and undercutting of the mangroves as sand slumped away from the island to fill in the depression left by the excavation (**Figure B4-4**).

Much effort is being put into developing a conservation ethic that will encourage the protection of Belize's mangrove ecosystems by its citizens and leaders. Progress is being made through education. For example, in 1998, a Coastal Zone Management Plan was established to develop policies and strategies for managing Belize's coastal resources for conservation, involving government and NGOs. The Coastal Zone Management Authority and Institute of Belize has recently promoted education by establishing workshops on sustainable mangrove management. It remains to be seen whether compromises can be reached that allow development for tourism along with long-term conservation of the mangrove ecosystems.

Figure B4-4 Evidence of erosion on Man-O-War Caye, Belize, an important breeding site for brown-footed boobies and magnificent frigatebirds.

Figure 4-23 Pneumatophores of black mangroves.

and phosphorous, which tend to be low in mangrove soils. Mangroves recycle nutrients using two strategies: the roots penetrate decaying parts of dead mangroves, and the trees resorb most of the nutrients from dead leaves.

Mangroves are not physiologically limited to saltwater habitats. Most species grow well in freshwater but are typically outcompeted in areas that are exposed only to freshwater. In estuary and coastal habitats, mangroves dominate because of their ability to tolerate exposure to brackish water and saltwater. The mechanisms of salt tolerance vary among mangrove species but are limited to several possibilities. First, mangroves tend to be more tolerant than other plants of salt in the tissues, but salt may still need to be eliminated. The main mechanisms mangroves use to deal with this issue are exclusion of the salt by the roots, extrusion of salt from the leaves through glands (if you look closely you may see salt crystals on the mangrove leaves), or deposition of salt into bark or leaves that are subsequently dropped. Mangrove roots also appear to be capable of selectively using freshwater sources that are accessible, such as at the surface after a rainfall. Mangroves conserve water with succulent leaves covered by a waxy cuticle on the upper surface and a dense layer of hairs on the underside that minimize evaporation losses.

Figure 4-24 The prop root system of red mangroves.

Although there are about 55 species worldwide that are considered true mangroves; about 35 species in four families are most prevalent. One to several species typically dominate the plant community in a given region; for example, four species are common throughout the Caribbean. Mangroves function in the ecosystem not only as a source of energy at the base of the food web, but also as a filter for terrestrial runoff, a sediment trap, structure and shelter for a diversity of animals, and a nursery areas for young fish and crustaceans.

Mangrove Reproduction and Growth

Mangroves reproduce by forming flowers and seeds. Pollination is by wind, insects, birds, or bats depending on the region and mangrove species. All mangroves disperse their **propagules** by water. In red mangrove, the seeds are unusual compared to other plants in that they germinate and sprout while still on the plant; the seedling remains on the plant for several months, and can grow as a spindle-shaped structure 25 cm or longer before dropping onto the ground or into the water (**Figure 4-25**). Those that land in the water can remain alive floating for up to one year, and may even

Figure 4-25 Propagules on a red mangrove.

sprout roots and leaves while floating. Absorption of water at the tip makes the mangrove propagule float point-down. Those that contact the bottom begin to form roots in about ten days. After taking root in the sediments the mangrove can grow rapidly. Growth varies by species and depends on environmental factors; however, intertidal species such as the red mangrove may grow to one meter in one year, into a maze of prop roots in three years, into a small forest in five years, and eventually may reach heights of ten meters or more. Mangroves in areas with low nutrient input (e.g., on small islands) typically exhibit extremely slow growth rates; small stunted trees can be decades old. The reproductive characteristics of mangroves provide an excellent dispersal mechanism and are critical factors for recolonizing areas where mangroves are lost due to severe storms, including hurricanes, or human activities.

The Mangrove Ecosystem

In a given geographic region, the level of the land relative to the water is the primary determinant of which species of mangrove will dominate. The reasons for this are complex, but at least in part it is determined by tolerance to salt water or exposure. A gradient thus is formed from the seawater's edge inland. For example, in the Caribbean, as you move landward away from the water, mangrove stands change from red mangroves (*Rhizophora mangle*) at the water's edge, to black mangroves (*Avicennia germinans*), and then white mangroves (*Laguncularia racemosa*) growing in the shallow intertidal waters and mudflats. Red mangroves are adapted to live in the shallow waters along the coast by elevating themselves with stilt-like prop roots. Black mangroves are most tolerant to high salinities that may occur in the upper tidal regions, while white mangroves are less tolerant of tidal flooding and high salinities and are restricted to higher ground. In river estuaries there may be a gradient of mangrove species up the river, and in some regions there is no clear pattern of zonation, for example, in much of Australia's mangroves.

Although few animals eat the mangrove plant or its leaves directly, the nutrients in the mangrove support a highly productive ecosystem. Although the mangroves do not drop their leaves seasonally, they can produce tons of leaf litter per hectare each year. For example, in Australia, branch and leaf-fall averages about ten tons per hectare per year. The dropped leaves are decomposed by fungi, bacteria, and other organisms, making the nutrients available to other organisms, such as mangrove crabs or small shrimp, which in some regions consumes the majority of the **detritus.** These organisms are an important source of food for larger animals and support a complex food web. Detritus also can be flushed out of the mangrove marshes to support other coastal ecosystems. For example, on average over 3,000 kilograms of particulate organic matter is transported from each hectare of Australian mangrove habitats into marine waters each year. In areas with a substantial tidal range, the mud flats around mangroves can be exposed at low tide and become accessible to wading birds, such as ibis, that feed on worms, mollusks, and crustaceans living in the sediments.

Mangrove Community Diversity

The Mangal Habitat

The importance of mangroves is not limited to the estuarine and marine organisms they support (**Figure 4-26**). Mangroves are used by migratory or roosting birds. For example, the mangroves in many regions serve as breeding and nesting sites for egrets, herons, cormorants, ibis, boobies, frigate birds, and eagles. Surveys by Gaetan Lefebvre and colleagues found that numerous other bird species use mangroves as shelter or for roosting, feeding, or nesting. The mangroves are important habitats for these species because they may be the only woody vegetation along the coastline. Mangroves not only play an important role in the health of these bird populations, but the birds can also contribute to the productivity of the mangrove ecosystem through nutrient input via guano. Wading birds such as herons and egrets also can be important predators on invertebrates and fishes living among the mangroves.

A large diversity of insects and other invertebrates live on and in the exposed portion of the mangal. They are not typically active or apparent during the daytime, probably due to stress from the lack of freshwater and hot sun; many of the insects feed at night or remain inside the

Figure 4-26 Brown boobies (l) and magnificent frigatebirds (r) are dependent of mangroves as roosting habitat in the Caribbean, here on an island off Belize.

plant. Consumption of the leaves by insects is typically low, averaging around 5% of leaf production, possibly due to toxic chemicals or salts in the leaves. Wood borers such as moths and beetles can attack the propagules and branches. They create hollow tubes within the mangrove branches that can be inhabited by scorpions, spiders, moths, termites, ants, and other insects. Some of these insects, for example, the root boring beetle *Coccotrypes rhizophorae,* may be an important consumer of mangrove propagules and young roots. Other invertebrates damage the mangroves by burrowing into the roots. These include shipworms (actually a teredinid bivalve) and isopod crustaceans. Wood borers can be very harmful to the mangroves; extreme infestations can destroy the roots and result in death of the mangroves.

Relatively few amphibians and reptiles reside permanently within the mangrove habitat. A few species of frogs can tolerate the brackish water, including the crab-eating frog *Rana cancrivora,* which may be locally abundant enough to be harvested and eaten. Lizards and snakes of terrestrial origin come into the mangroves to feed. Some crocodiles tolerate brackish or salt water sufficiently to be an important predator in some mangrove ecosystems; these include the American crocodile *Crocodylus acutus* in Central America, the Nile crocodile *Crocodylus niloticus* in western Africa, and the estuarine crocodile *Crocodylus porosus* in tropical southeastern Asia and Australia.

Few terrestrial mammals depend solely on the mangroves, although they may visit the mangroves to feed. These include mongooses, raccoons, deer, rodents, otters, monkeys, rhinoceros, water buffalos, and bats. In Bangladesh, the mangroves are considered critical habitat for the endangered Bengal tiger, although their preference for this habitat is largely due to the loss of critical habitat elsewhere. Grazing domestic camels and buffalo have harmed mangroves in Arabia and Pakistan.

The intertidal area, including the mangrove roots and the mudflats, is often inhabited by a species assemblage similar to that of temperature salt marshes. This includes crustaceans, gastropods, bivalves, and polychaete worms. The species assemblage in a given area is affected largely by the tidal exposure or freshwater influence. The most numerous animals are meiofauna in numerous phylogenetic groups, including copepods, amphipods, nematodes, oligochaetes, and flatworms. These typically live in the upper layers of sediment, feeding on algae, bacteria, and detritus. They are apparently not a major food source for many of the larger organisms but are important to some fishes and crustaceans that feed in the muds.

Crustacean representatives include a diversity of crabs that can be seen feeding at low tide on the mangroves or mudflats (**Figure 4-27**). Many of these are grapsid crabs that forage at low tide and return to their burrows as the

Figure 4-27 Fiddler crabs (*Uca*) in a Jamaican mangrove marsh.

mudflats are covered by high tides. On some mangrove mudflats there may be over fifty crabs per square meter. The grapsid crabs tend to be generalist feeders. For example, the mangrove tree crab *Aratus pisonii* is common in Caribbean mangroves, living on the red mangrove roots above the waterline and feeding primarily on mangrove leaves and seeds as well as insects. Many of the grapsid crabs are primarily herbivorous. Some scrape algae or diatoms from the mud or the plants, but most prefer decaying fallen mangrove leaves that are easier to digest, and they often will store leaves in their burrows before consuming them. Ocypodid mangrove crabs of the genus *Ucides* feed on mangrove leaves and other plant material, detritus, and algae. Research by Inga Nordhaus and Matthias Wolff documented that *Ucides cordatus* serve an important role in mangrove ecosystems of northern Brazil, because their feces makes organic matter from mangrove detritus available to other species. Crabs can affect mangroves' propagule survival. For example, in Malaysia and Australia, most (sometimes over 95%) of the propagules produced are destroyed within days of falling from the trees, but in Florida only about 5% of propagules are taken by crabs.

Uca fiddler crabs can be commonly seen out of burrows on intertidal mudflats around the mangroves feeding on detritus particles and associated diatoms and bacteria (Figure 4-27). Populations of fiddler crabs can be very dense, as many as 70 per square meter are common on mudflats associated with southeastern Asia mangroves. Burrowing by these and other crabs benefits the mangrove ecosystem by aerating the muds and allowing deeper oxygen penetration. Without this mixing, bacterial action results in hypoxia even at shallow depths below the sediment surface. Hermit crabs, mostly *Clibanarius* species, also can move onto the mudflats or into trees to forage.

Many crustaceans live in the muds of the mangroves, and barnacles are often found attached to the intertidal portion of the mangrove roots. These and other **encrusting** organisms are filter feeders that depend on the organisms present in the water at high tide. They can harm the mangroves if present in large numbers by inhibiting gas exchange through the aerial roots and pneumatophores.

Mollusks in the intertidal zone include gastropod snails and bivalves, such as oysters, attached to roots. Snails are conspicuous foragers on the mangroves and mudflats. These include many species that feed by scraping organic particles, diatoms, or algae from the surface of muds, roots, stems, or leaves; few feed directly on the mangrove leaves. The most abundant of these are congeneric with the *Littoraria* periwinkles so important in the salt marshes.

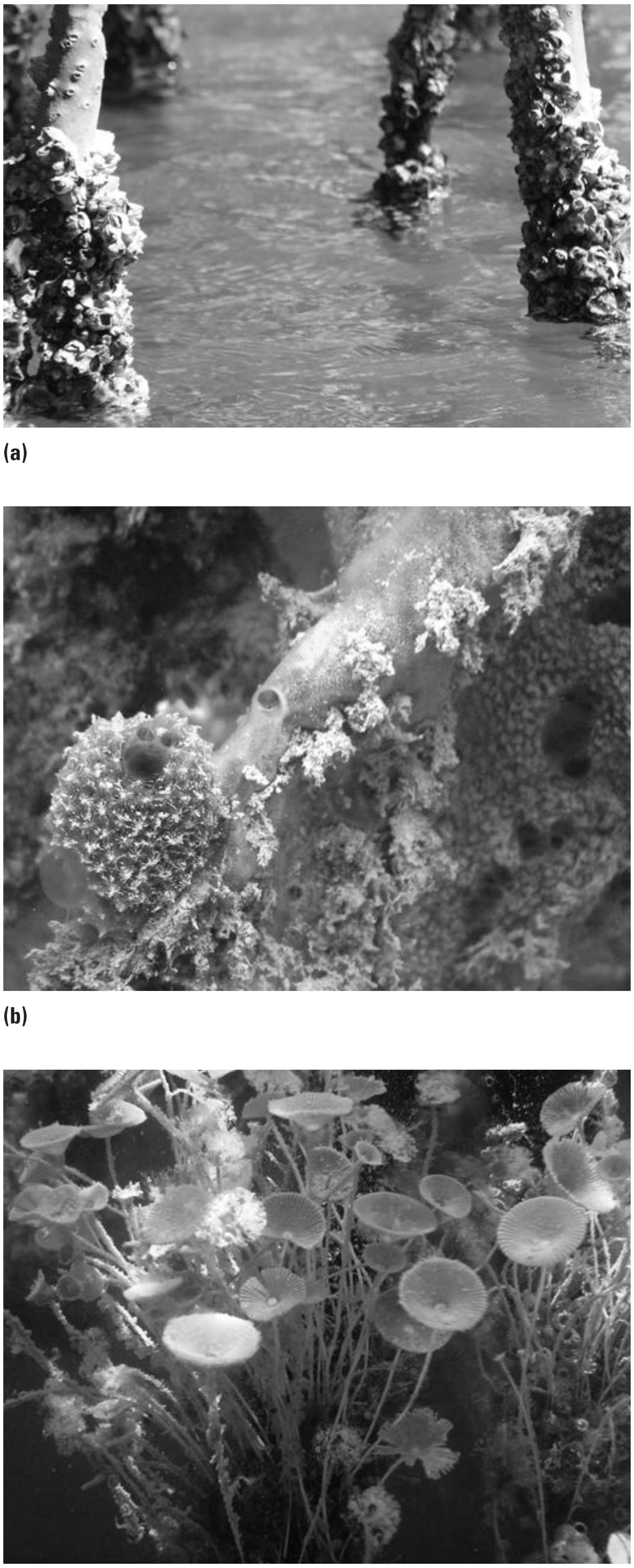
A few fish species can come out of the waters onto the mudflats to feed. The mudskipper, a type of goby, is associated with mangrove ecosystems, primarily in tropical southeastern Asia; it can crawl out of the water and pull itself across the muds, spending most of its time at low tide feeding on organisms living on the mangroves or surrounding mudflats. It retreats into burrows when the mudflats are covered at high tide. The mangrove rivulus, *Rivulus marmoratus,* found in some Caribbean mangrove ecosystems, can tolerate long-term isolation in pools, and has even been observed in standing water on decaying mangrove trunks. This is one of the few species of fishes that are **simultaneous hermaphrodites**, capable of producing both eggs and sperm and self-fertilizing, an adaptation to the likelihood of becoming isolated in pools without access to potential mates.

Subtidal Mangrove Ecosystem

Animals living in the subtidal habitat associated with the mangroves are diverse and abundant due to: the high biological productivity of the mangrove ecosystem, the availability of shelter in the submerged root system, and the nearness of other productive marine ecosystems such as coral reefs and seagrasses. For example, experiments by Pia Laegdsgaard and Craig Johnson found that juvenile fish are attracted to mangroves primarily to take advantage of food availability and shelter from predation. Larger fishes are more likely to move out of the mangroves onto adjacent mudflats to feed.

The region around the subtidal roots exhibits the highest diversity and abundance of organisms associated with the mangroves. A diversity of attached organisms (**epibionts**) cover the roots, including algae, barnacles, sponges, and tunicates (**Figure 4-28**). These organisms typically do not harm the mangroves; in fact, they can benefit the roots by protecting them from root-boring animals.

Some of the most visible animals attached to the mangroves are the sponges. Sponges are mostly limited to the subtidal portion of the mangrove roots; however, some species, for example, as documented in Belize by Klaus Rutzler,



(a) (b) (c)

Figure 4-28 Marine organisms living attached to mangrove roots (epibionts): **(a)** barnacles, **(b)** sponges, and **(c)** *Acetabularia,* a single-celled green algae called the "mermaid's wineglass."

can tolerate several hours' exposure during very low tides. Colorful sponges can cover a large fraction of the surface of the mangrove roots. For example, in Key Largo, Florida almost 75% of the available root space is covered by sponges, a total of ten different species. Sponges have a mutualistic relationship with mangroves in the Caribbean, where the mangroves gain protection from root-boring isopods and a source of nitrogen from the sponges, while the sponges obtain carbon from the submerged roots. Sponges can grow up to ten times faster on mangrove roots than other surfaces, and mangroves produce small roots that penetrate through the sponge. Studies by Sebastian Engel and Joseph Pawlik found that there is a competition for space on the roots among the sponge species, with some sponges capable of overgrowing others, and some able to produce **allelochemicals** to resist overgrowth by other sponges. Some of the sponges found on mangroves are restricted to mangrove habitats, but others are the same species as present on nearby coral reefs. Sponges on the mangroves may grow to larger sizes because sponge predators are uncommon around the mangroves. Abiotic factors can be an important determinant of sponge diversity. Such factors as sedimentation, temperature extremes, hypoxia, currents, storms, and anthropogenic factors affect the diversity and distribution of sponges on the mangroves.

Tunicates are another group of conspicuous animals sometimes attached to mangrove roots. Mangrove tunicates have been used for bioprospecting in a search for potential pharmaceutical chemicals, as have coral reef organisms (see Chapter 5). For example, the mangrove tunicate *Ecteinascidia turbinata* has shown potential in reducing tumor growth in cancer research.

The bottom sediments around and near the mangroves are typically partially covered with seagrasses, algae, and other organisms. Crustaceans, bivalves, and polychaete worms also live in the subtidal area around the mangrove roots or burrowed into the sediments (**Figure 4-29**). The upside-down jellyfish *Cassiopea xamachana* is a conspicuous animal around some mangrove ecosystems in the Caribbean, named for its behavior of resting on the bottom with its tentacles reaching upward. Symbiotic **zooxanthellae** reside in the tissues of the jellyfish (a relationship similar to the one found in many corals; see Chapter 5) and provide much of its nutrition; therefore, they are typically found in shallow sunlit waters. The jellyfish can also take dissolved nutrient from the water or use the stinging nematocysts on its tentacles for feeding and protection.

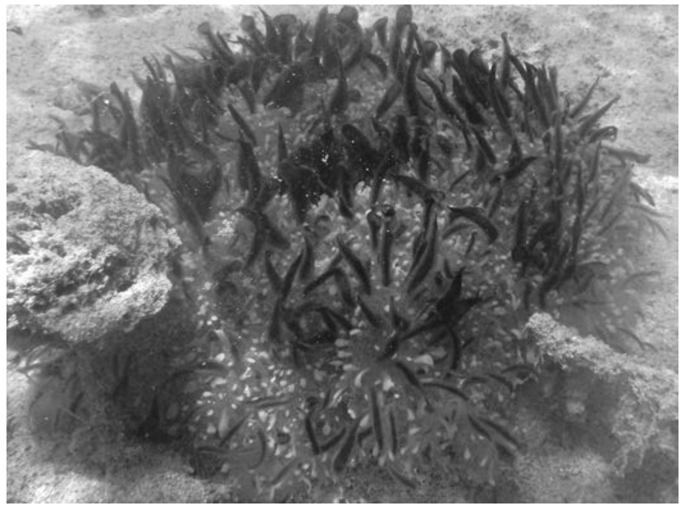


Figure 4-29 Upside-down jellyfish *Cassiopea* in a mangrove ecosystem in Belize.

Mangroves as a Nursery

Many tropical shrimp and fish species inhabit the mangrove ecosystem at some stage in their life. Some species remain in the mangrove marshes as adults (e.g., centropomid snooks); however, few spawn there and many depend on the mangroves primarily when they are larvae and juveniles. The planktonic larvae of many invertebrates and fish are moved into mangrove habitats by currents and are retained there by the structures, channels, and inlets that reduce the water flow. Up to nine different shrimp species utilize mangrove habitats, especially those associated with estuaries, as nursery areas. The most commercially valuable are the penaeid shrimps and *Macrobrachium,* commonly marketed as freshwater prawns. Strong correlations have been documented between coastal shrimp production and the extent of mangrove habitat. It is estimated that, on average, over 150 kilograms of shrimp are produced for each hectare of healthy mangrove habitat. These shrimp are of high commercial value, but have been displaced in many regions by removal of mangroves for shrimp farms, discussed below.

Crabs are of important local value for fisheries harvest in many regions. The mangrove mud crab *Scylla serrata,* a portunid crab related to the blue crab found in temperate estuaries, is harvested in the Indo-West Pacific region. The ocypodid crabs can be important for local harvest along Atlantic and Pacific coasts of South America. Various species of bivalves (e.g., oysters, mussels, and cockles) and gastropods (e.g., conch) are harvested from and near mangrove ecosystems around the world.

A large number of tropical marine fish species also use the mangrove ecosystem, many as a nursery during juvenile life stages (**Figure 4-30**). For example, mangrove-dominated estuaries in India and Australia are used by almost 200 species of fish. There are two important benefits of the mangroves for these juvenile fish. One is the availability of structure and shallow waters as a refuge for

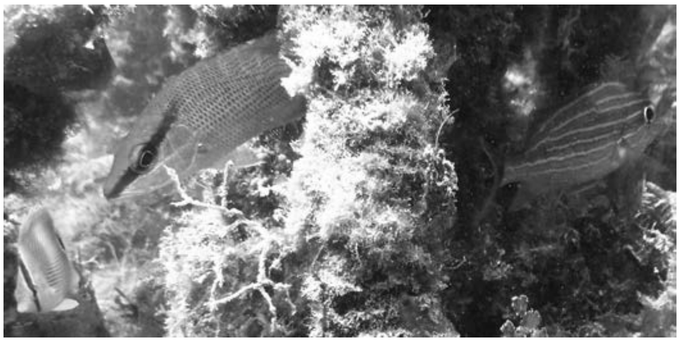


Figure 4-30 A diversity of fishes use the mangroves for shelter and as a foraging location; here a foureye butterflyfish *Chaetodon capistratus,* a young mangrove snapper *Lutjanus griseus,* and a bluestriped grunt *Haemulon sciurus.*

protection from predation, a major source of mortality for small fish and shrimp. Many juvenile fish and shrimp move substantial distances to gain access to the refuge of the mangrove, especially during high tides. Not only does the structure provide protection, but the abundance of large carnivores is also lower in the mangroves compared to other nearshore habitats. The other benefit of the mangroves as a nursery area is for feeding; mangroves are typically a more productive source of food than adjacent coastal ecosystems. Zooplankton, including crab larvae, are the most valuable food source for larval and juvenile fishes using the mangroves. Small shrimp and mangrove crabs can be the most important food link from the detritus to the larger fish in the mangroves.

The importance of mangroves as a nursery for harvested fishery species has recently been emphasized in encouraging conservation. For example, the proportion of harvested species that use mangrove ecosystems is estimated at over 75% in southern Florida, approximately 60% in Fiji waters, and over 65% off eastern Australia. In some regions (e.g., on some small islands) the harvest supported by mangroves is by subsistence fisheries, which often are not included in harvest statistics. Some of the most common harvested species are detritivores such as mullets (Mugilidae), scavengers such as catfish (Ariidae), and predators such as groupers (Serranidae), snappers (Lutjanidae), tarpons (Megalopidae), snooks (Centropomidae), and sharks and rays. Smaller plankton feeders, such as herrings (Clupeidae) and anchovies (Engraulidae), which are important food for marine fish predators, also use the mangroves as a nursery. The movements of fishes in and out of the mangrove ecosystem tend to integrate the mangroves with other tropical marine ecosystems, including coral reefs, mud flats, and sea grasses. The average biomass of fish within the mangroves, however, is much higher than in adjacent coastal habitats (with the exception of coral reefs). Mangroves have been shown to support from 4 to over 30 times the number of fish compared to adjacent seagrass beds.

Some marine mammals and reptiles also move into the mangroves to feed, including dolphins, manatees, and sea turtles. Observations by Colin and Duncan Limpus indicate that mangrove leaves can comprise a significant portion of the diet of some sea turtles. Green sea turtles feed not only on the mangrove leaves but also on tunicates, invertebrates, seagrass, and algae in mangrove ecosystems, and the mangroves can be an important nursery for young green sea turtles. Hawksbill sea turtles are primarily sponge eaters but can feed on bark, leaves, and fruit of the mangroves.

Mangroves, in a manner similar to salt marshes discussed earlier, can provide a source of organic matter and nutrients to adjacent ecosystems. A portion of this is from animals that feed in the mangroves and migrate to other ecosystems. Other sources of export are detritus, particulate organic matter, and dissolved organic matter and nutrients. Outwelling of organic matter in the form of particulate matter and leaf detritus can be substantial (e.g., as much as 30% of leaf production from an Australian estuary) but varies depending on such factors as production and tidal flow. For example, a tidal mangrove is more likely to be a source of export than a mangrove on higher land.

Mangroves as a Buffer and Filter

Mangroves are an important buffer for marine ecosystems offshore as well as terrestrial ecosystems inland. Mangroves reduce coastal erosion by stabilizing the shoreline and river banks. The retention of fresh waters in the mangroves protects less tolerant marine ecosystems, such as coral reefs, from harmful salinity fluctuations. Mangroves also protect coral reefs by retaining excess sediments and assimilating nutrients that are input along with the fresh waters. Other pollutants may be retained or decomposed in mangrove sediments, keeping them from harming more sensitive ecosystems such as coral reefs. Mangroves also provide a buffer to terrestrial and freshwater ecosystems especially against the effects of storms, including hurricanes or typhoons, or tsunamis, as discussed below.

Natural Impacts on Mangroves

Organisms associated with the mangrove community have evolved and adapted to survive or recover from most natural environmental events. Infrequent extreme natural events may have substantial local impacts on mangroves, however. Cold weather can kill mangroves at the edge of their distribution range, as occurred in southern Florida in January 1997; however, more cold-tolerant species survived the low temperatures. Flood events originating inland may actually increase the area available to mangroves by transporting sediments into the river delta.

The broad, extensive prop roots and aerial roots of mangroves help them absorb the impact of most storms hitting the coast, and in regions frequented by cyclonic storms the mangroves tend to be shorter and more tolerant of high winds and storm surge. The hurricanes in the Caribbean Sea and Gulf of Mexico, and typhoons in the western Pacific, however, can severely damage or destroy mangroves with high winds, storm surges, and heavy rainfall. Caribbean islands and regions of southeastern Asia are particularly vulnerable. For example, Vietnam is hit by eight to ten typhoons per year on average. Tsunamis, though much less frequent, can cause damage similar to hurricanes.

One of the most well-documented hurricane events affecting mangroves was Hurricane Andrew, which struck south Florida in 1992, severely damaging about 150 square kilometers of mangrove habitat with 240 km per hour winds and a 2-m storm surge (**Figure 4-31**). About 60% of the mangroves were uprooted or broken, and many of the surviving trees eventually died. Of those that remained, the red mangroves survived better than other species. Recolonization by seedlings was rapid; however, mortality was high and growth slow, resulting in a slow recovery. The species distribution of the mangroves was also modified, at least initially, due to differential ability to recolonize and grow. Evidence indicates that even after major hurricanes, recovery of the mangrove ecosystem is likely if the area is protected from other impacts.

Human Impacts on Mangrove Ecosystems

The location of mangroves in areas close to human populations has resulted in severe harm to the mangrove ecosystems. Approximately 20% of the world's mangroves were lost due to human actions from 1980 to 2005, and many more have been seriously impaired. The estimated annual rate of loss was about 1% during the 1980s. The greatest losses were in Asia, Central America, and Africa. Although mangroves are still in decline, the loss rate has slowed somewhat, to 0.7% annually from 2000 to 2005. In a few countries, such as Bangladesh, there has been an increase in mangroves due to protection in forest reserves, and the removal of coastal shrimp farms has allowed for the recolonization by mangroves in some countries, such as Ecuador.

Figure 4-31 Mangrove forest in Biscayne National Park, Florida in September 1992, three weeks after being crossed by the eye of Hurricane Andrew.

There is a long list of human factors impacting mangroves. Mangroves are removed for agriculture, aquaculture, human settlements, and industrial or tourism development. The trees are harvested for many uses in some regions of the world, including for wood products or firewood, leaves to make baskets or mats, propagules for consumption, sap for producing soft drinks or alcoholic beverages, and various parts for medicinal use. Fishes and other organisms can be overharvested from the mangrove ecosystem. Excess siltation due to deforestation and coastal pollution, and changes in freshwater input through damming, channelization, or irrigation all can cause harm to mangroves.

Changes in adjacent marine ecosystems also can affect mangroves. For example, coral reefs serve as a buffer to the mangroves against strong currents or waves; without them the sediments can erode from around the mangrove roots and seedlings can be prevented from taking root.

Changes in Freshwater Input

There is a certain amount of natural variability in the amount of freshwater entering the mangrove ecosystem on an annual, seasonal, and daily basis. This variability is dependent on climate changes, rainfall, seasonal effects, and whether or not the mangrove ecosystem is associated with an estuary. These variables affect the species composition of the mangroves and other associated communities, as discussed above. The ecosystem, however, is tolerant and can adjust to most natural variability in freshwater input or salinity.

Mangroves may not be able to tolerate extreme conditions that result in a rapid decrease or increase in freshwater river input, such as with damming, channelization, or irrigation. Without adequate river input, the morphology and salinity of the estuaries can change dramatically. Estuarine mangrove species cannot tolerate extreme salinities or drying out of the sediments. In areas of southeastern Asia, for example the Indus Delta of Pakistan, irrigation has reduced river flow and caused a reduction in mangroves.

Sediment input is important to maintain stability for the mangrove plants and may increase the area available for mangrove colonization, but a large influx of sediments can result in death of the mangroves. Increased deforestation inland can cause erosion and such extreme increases in sediment input to the mangrove ecosystem that the mangrove roots are smothered, inhibiting their ability to exchange gases through the roots or pneumatophores.

Coastal Pollution

Pollution can enter the mangrove ecosystem locally or from sources far from the coast through river input. Metal pollution affects mangrove ecosystems in areas close to mining operations or those exposed to industrial waste. Although no noticeable effect on the mangrove plants has been documented, heavy metals are highly toxic to crab larvae and can bioaccumulate in predatory organisms. Increases in agriculture along the coast result in excess inputs of chemicals and nutrients. Some degradation of herbicides and pesticides occurs in the anoxic sediments, so mangrove ecosystems may not be as sensitive to these pollutants as ecosystems that lack anoxic sediments. Low levels of nutrient input from sewage effluent may increase productivity of mangroves, and studies have shown that mangroves might be used for waste water treatment. Higher nutrient levels are likely to cause excess algae growth, however, creating anoxic conditions due to bacterial decomposition. Algae can cover aerial roots and pneumatophores, inhibiting gas exchange, or cover seedlings.

Toxicants applied directly to the mangroves can cause extreme damage. For example, during the Vietnam War in the 1960s the United States destroyed over 100,000 hectares of mangrove forests, over one fourth of the estimated mangrove area, through the application of herbicides and defoliants. Many of these mangroves have not recovered, in part due to inadequate protection and a lack of resources for recolonization efforts.

Ongoing chemical pollution problems include oil or chemical spills in regions near oil terminals, refineries (e.g., the Middle East and Central America), industry, or boat traffic (e.g., the Panama Canal region). Mangroves are especially vulnerable to oil and other pollutants released accidentally because they are exposed to chemicals that float on the water's surface. Heavy oils carried into the mangroves by the tides can coat pneumatophores and aerial roots and inhibit gas exchange. Mangroves appear to be able to eventually recover from moderate impacts from oil spills if protected or assisted. The complex structure of the mangroves make the clean-up of oil spills difficult, however, and it may take decades for an area to recover. Mangroves have been severely damaged in the Niger Delta of Nigeria where oil exploration activities have not been well regulated. Oil spills also have affected mangroves in countries of the Middle East and eastern Africa.

One of the most well-studied, oil-damaged mangrove habitats is the Bahia las Minas on the coast of Panama. A spill in 1968 resulted in deaths of about 4% of the mangroves in the bay, but by 1979 mangroves had returned to most of the area. In 1986, a second large oil spill from a ruptured refinery storage tank occurred in the same area. About half of the mangroves in the bay that were initially covered by the oil died within a few months. Eventually other areas were affected as the oil washed into the mangroves with the currents and tides. Mangrove roots were covered and organisms in the intertidal area showed massive mortality; over 40% of the mangrove habitat in the bay was affected. Natural recovery of the mangroves was slow, in part because residual oil remained in the sediments and the spill killed most of the mangrove seedlings. Some areas were converted into open water due to erosion before the mangroves could recover. Replanting efforts were eventually used to assist in the recovery. Five years after the spill, however, oil was still washing out of the sediments and affecting the ecosystem. Bivalves still had high levels of oil in their tissues. Based on studies of this and other spills, it appears that about 20 to 30 years are needed for mangroves to recover from a major oil spill.

Wood Harvest

Mangroves do not typically grow into trees that are valuable as timber, but many other uses have been discovered for the wood and other parts of the mangrove plant. In some areas mangroves have been used locally to build dwellings or boats. Mangrove wood can be a good source of fuel because of its density and hardness. For example, in some African countries a main reason for removing the mangroves is for smoking fish, and in Pakistan the wood has been used in the boilers of trains. Overharvest for charcoal production has affected mangroves in Central America and Indonesia. In Central America and Asia, the wood is used to extract tannins for tanning leather or fish nets. Other products made from mangroves include roof shingles, fish traps, traditional masks, paper pulp, matchsticks, and household utensils. Materials from mangroves are used to produce beverages, local medicines, or foods. Mangroves are farmed in some areas for some of these uses; however, the harvest from natural mangrove stands is still common in many countries. Most of the wood harvest is a local industry; however, in Indonesia and Malaysia extensive areas of mangroves have been cleared for the international wood chip market.

Sustainable harvest of the mangroves for wood is possible if closely regulated. This is rare, but has been successful in some regions, such as the Matang mangroves in Malaysia. If not regulated and monitored, however, these activities can result in a non-renewable use of the mangroves and cause ecosystem degradation or destruction. Still, wood removal is rarely the main impact on mangroves around the world; the major problems are more typically the removal of mangroves for other uses of the habitat.

Fisheries Harvest

As discussed earlier, mangroves are important to many coastal fisheries species, especially as a nursery for larvae and juveniles, not typically harvested in the mangroves. Many regions have a substantial harvest of organisms directly from the mangroves, including shrimp, oysters, clams, and other invertebrates. For example, the large spiral-shaped marine snail *Telescopium* is harvested from mangroves in the Indo-Pacific for consumption, and chemicals have been extracted from it as potential pharmaceutical products and antibiotics. It is difficult to document mangrove fisheries and their effect on mangrove ecosystems because many are subsistence fisheries for which harvests are not routinely reported. One documented fishery is in the Sarawak mangrove of Borneo, where trap fisheries catch more than thirty fish species, ten shrimp species, two jellyfish species, and at least one species of crab.

Coastal Agriculture

Agriculture for livestock or crops in coastal areas can result in the removal of mangroves and the construction of dykes and embankments to protect the farmland from salt water intrusion. For example, mangrove habitats have been converted to sugar cane farms in many regions. Conversion to rice farms in Africa and Asia is sometimes supported by governments to encourage self-sufficiency of food production. In southern China, farmers built levees across the mouths of inlets and converted the area behind the barrier to rice farms or shrimp ponds. These levies were continually destroyed by typhoons until farmers began planting mangroves on the seaward side of the levies to protect the paddies and ponds. In Guinea, on Africa's west coast, farmers cut through the mangroves and build mud dikes to limit the tidal flow into rice paddies; this removes the connection between the mangrove ecosystem and the ocean and eventually kills the mangroves (**Figure 4-32**). In Indonesia, conversion of mangrove habitat to farmland has been one of the major causes of mangrove loss. In some regions mangrove habitat has been converted to grazing lands for livestock. For example, in arid countries in Africa and the Middle East, grazing camels, goats, or cattle have reduced the quality of mangrove habitats.

Coastal Aquaculture

Over the past 30 years, shrimp farming has probably received more attention globally than any other anthropogenic factor impacting mangroves. In southern China, mangrove habitats have been used for farming shrimp for centuries. The ancient methods of farming, however, did not require removing the mangroves; wild shrimp were harvested from impounded mangrove habitats. These methods are inefficient for current commercial enterprises, and recent practices are much more destructive to the mangroves.

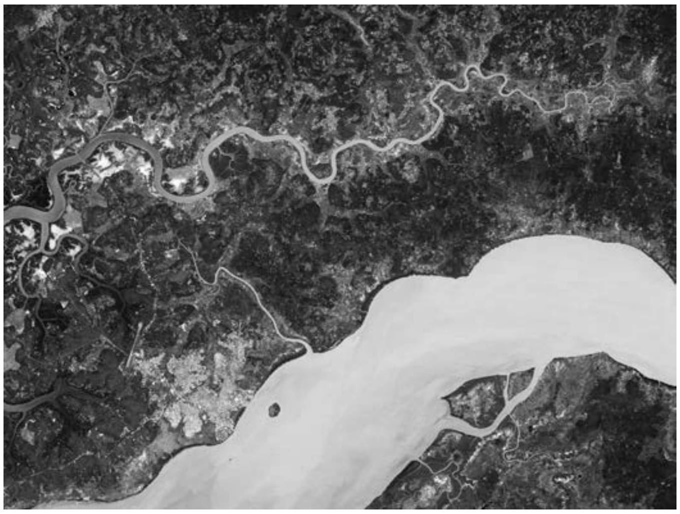


Figure 4-32 Area along the Mansoa River in Guinea-Bissau. Dark gray regions adjacent to the river are mangroves; lighter gray regions are mostly rice paddies. (See Color Plate 4-32.)

Since the 1970s, shrimp aquaculture practices have probably damaged or removed more mangrove ecosystems worldwide than any other activity. Methods involve clearing the mangroves, allowing the tides to flood the area, and then building dikes and levees to turn the area into small ponds. Young shrimp were netted from local waters, placed into the ponds, fed naturally occurring organisms, and raised to harvest size over several months. The ponds were typically used for two to five years, and then abandoned (**Figure 4-33**). The farmers moved to another area and repeated the cycle. As the market grew, pond sizes grew, and entire coastlines were being cleared of mangroves for shrimp farming (**Figure 4-34**). When mangroves are cleared, the entire mangrove-based ecosystem is lost or dramatically harmed. To compound the affect, removal of the mangroves for shrimp farming results in a decline in populations of wild mangrove-dependent shrimp. Even when the farms have been abandoned, the wastes can continue to wash into surrounding ecosystems and the ponds are slow to recover. The recovery of abandoned farms to healthy mangrove ecosystems typically takes about 30 years. Although laws have been passed in many countries prohibiting the removal of mangroves, many former mangrove habitats continue to be used as shrimp farms. It is estimated that about 800,000 hectares of mangrove habitat, mostly in Asia and Latin America, were lost to shrimp aquaculture.

(a)

(b)

Figure 4-33 Mangrove marshes are sometimes converted to aquaculture ponds; here shrimp culture ponds are adjacent to coastal mangroves, north of Belize City, Belize: **(a)** flooded in 2006, **(b)** abandoned in 2009.

Figure 4-34 False-color satellite images of the Gulf of Fonseca region on the Pacific coast of Honduras in 1999. Dark grays indicate areas covered in water. Light grays indicate vegetation including mangroves adjacent to the water. Shrimp ponds appear as rectangles. (See Color Plate 4-34.)

As shrimp farming developed into a global industry in the 1980s and 1990s, methods were refined and modernized to provide a greater production of shrimp. Higher production requires replacing the more traditional **extensive** methods with **intensive** aquaculture. In intensive farming, shrimp are produced in hatcheries and raised at higher densities on artificial feeds in aerated ponds away from the coast, using water pumped from coastal areas (**Figure 4-35**). Effluent from the ponds, containing excess nutrients, antibiotics, pesticides, and shrimp feed (30% of feed may remain uneaten) ends up in the surrounding waters, affecting other coastal ecosystems and inhibiting the recovery of the mangroves. Some nutrients and organic matter from farming can be tolerated by mangroves and adjoining ecosystems; however, the area of habitat needed to process the effluent is 30 to over 100 times that of the area of the intensive shrimp farm.

Because the development of intensive aquaculture methods has focused on a few species, it is often not native shrimp species that are being farmed. The two most common cultured species are the giant tiger prawn *Penaeus monodon* and the Pacific white shrimp *Litopenaeus vannamei.*

Figure 4-35 Hatchery ponds used in intensive shrimp farming in Japan.

Raising non-native species may protect local shrimp populations, but presents other problems, including the potential introduction of a new invasive shrimp species and diseases that may accompany the non-natives. To minimize these problems, laws have been introduced that require the shrimp sold as broodstock to be certified as pathogen-free.

As public pressure to limit the harmful effects of shrimp farming increased in the 1990s, efforts were made to encourage the shrimp farming industry to develop practices that were less harmful to mangrove and coastal ecosystems. One of the first efforts was to encourage consumers to ask stores not to stock shrimp unless they come from sustainable sources. It has been difficult to track and label the source of all shrimp products and to decide what should be considered ecologically sound practices. A more inclusive program was established in 1999 through the World Bank, Food and Agriculture Organization of the United Nations (FAO), World Wide Fund for Nature (WWF), and aquaculture organizations to develop improvements in farming practices and establish educational programs. The international shrimp farming industry has begun adopting many of the recommended practices. In a 2006 meeting organized by the FAO, 50 countries worked out a set of international principles for responsible shrimp farming. In many countries it is now illegal to remove mangroves to build new shrimp farms; instead, new intensive farms are built outside of the mangrove areas. Waste water treatment methods have been developed, and there is some effort by the industry to develop mangrove reforestation projects that use the treated wastes to establish new mangrove stands.

Despite these efforts, most of the mangroves that were cleared for farming still have not recovered, and small farming operations in developing countries still use mangrove habitat to farm shrimp. Many local NGOs continue to discourage the expansion of shrimp farming in mangrove habitats. For example, Friends of Earth Indonesia works to stop the expansion of shrimp farming, and the Network of Aquaculture Centres in Asia-Pacific (NACA) organizes meetings and provides education on sustainable shrimp aquaculture practices.

By 2007, the worldwide annual farmed shrimp production had increased to over 3 million metric tons. Asia was responsible for over 85% of this total, with China being by far the largest producer (1.3 million metric tons), followed by Thailand, Vietnam, and Indonesia. Most of the remaining 15% is from Latin American countries, Ecuador and Mexico being the largest producers. Although farmed shrimp production in the United States comprises only about 0.1% of the world total, over 15% of the production is imported into the United States (European Union nations import comparable amounts). The low price of these imports has driven down the value of wild-caught shrimp in the United States, affecting the profitability of the shrimp trawling industry.

Development and Mangrove Loss

Coastal development is another source of destruction and degradation of mangrove ecosystems. Development can lead to mangrove removal and filling in of the habitat, modification of water flow and circulation, input of toxins, and inadequate treatment of sewage and other wastes. Oil exploration and drilling not only results in removal of the mangroves, but associated canals, roads, pipelines, and other structures can alter the flow and drainage. Urban development has become widespread in tropical coastal areas and often leads to mangrove removal. In some regions, such as south Florida, Central America, and some eastern African and South American countries, urban development has been the primary factor impacting mangroves. The direct loss of mangroves to urban development is relatively permanent; however, control of urban wastes that reach the remaining mangroves can assist in their protection and recovery.

In many regions, development for tourism has been the major cause of recent destruction or harm to mangroves. Mangroves are removed and covered to build hotels, resort areas, marinas, beaches, or golf courses, and the resulting pollution can affect the remaining mangrove ecosystems. Increasing the size of ports to accommodate cruise ships has resulted in the loss of coastal mangrove and reef habitats. Development for tourism can be very attractive to small tropical countries as a quick way to improve the economy by attracting developers, businesses, and tourists. Often times, the long-term impacts of mangrove removal are not adequately considered in rushing to develop. Tourism can be, but often is not, done in a manner that minimizes the environmental effects. Development for tourism is the main factor resulting in recent loss of mangroves in the Caribbean Islands. In Asia and Latin America only shrimp aquaculture has resulted in greater loss of mangroves than tourism.

Social Impacts of Mangrove Loss

Coastal human communities throughout the tropics depend on mangroves both directly and indirectly, especially in subsistence cultures. If the ecological function of the mangrove is compromised, a major source of sustenance and livelihood will be affected. An impacted mangrove ecosystem may not support the fisheries species on which coastal residents rely, and aquaculture or tourist developments can displace coastal residents, especially if they are not employed by these industries.

Even if people remain in coastal settlements near where mangroves have been removed, the indirect impact can be even more severe. Loss of the mangroves removes the buffer against storm-induced waves. There are numerous examples where healthy mangrove forests could have avoided or minimized the effects of tropical storms and cyclones. For example, in Bangladesh, devastation of coastal regions by cyclones has increased dramatically since the removal of the mangrove habitats. Residents of Bangladesh and India realized the importance of the mangroves and resisted their replacement with shrimp farms; at times this even resulted in violent confrontations. It is believed that the four-meter storm surge produced by Cyclone Nargis that destroyed low-lying coastal settlements and killed tens-of-thousands of people in Myanmar (Burma) in May 1982 could have been minimized if coastal mangroves were still in place.

Tsunamis are infrequent and unpredictable but potentially devastating to coastal communities, and areas closest to the source of large tsunamis may not be able to avoid large-scale damage. Even with warning systems in place, there may be inadequate time to move coastal residents to higher ground. Nevertheless, mangroves can provide substantial protection from much of the damage from tsunami waves that move onshore in tropical regions. For example, following the Indian Ocean tsunami that hit regions of southeastern Asia in 2004, an assessment by Finn Danielsen and colleagues indicated fewer human deaths and less property damage in regions that were near healthy mangroves. In one region of India, regions where mangroves had been removed were adjacent to those with healthy mangrove forests still in place. Villages adjacent to the coast without mangrove protection were totally destroyed; those behind the mangroves experienced minimal damages. Models indicate that mangrove stands can reduce the intensity of tsunami waves by at least 90%.

Fishery harvest in the mangroves or of mangrove-dependent species is important in many tropical regions, and these local fisheries provide food security in many African and southeast Asian coastal regions. A decline in fishery harvest has been linked to mangrove loss in various regions, and this is particularly well documented in Jamaica and southern Florida.

Even though coastal shrimp farming results in enormous economic benefits for some individuals, these are often outweighed by the negative economic impacts of mangrove loss and water pollution, especially if the long-term effects are considered. Economic losses resulting from shrimp farming practices can be five times the potential earnings, and in many countries the locals are not the people who benefit from the shrimp farming. For example, in Bangladesh, the shrimp farming industry moved into coastal areas, denied access to the coast by local fishers, and destroyed mangrove ecosystems that were considered common public resources depended on by locals for food and livelihood.

The shrimp farming industry generates about 10 billion dollars annually in export value. Most of the shrimp farmed in Asian countries ends up in the United States, Europe, and Japan, where shrimp consumption tripled over a decade after shrimp farming boomed beginning in the early 1990s. In some cases the profits from shrimp farming end up in the hands of large international conglomerates; however, in other countries, including Thailand, many farms employ and are managed by locals. By the late 1990s some shrimp farming operations were collapsing in Hong Kong, Thailand, China, and other areas due to diseases, overuse of chemicals, and other poor farming practices, leaving the former mangrove habitats in a devastated condition. A large investment or a long time will be needed for these to recover.

In Vietnam the loss of mangroves has resulted in a cascade of effects. Most of the mangroves that were damaged or destroyed during the Vietnam War were converted to shrimp farms before they were able to recover. Now, coastal areas are more vulnerable to storm damage and intrusion of salt water that damages farm crops. Larval shrimp (needed to stock ponds) and edible mud crabs, both of which depend on mangroves, have declined, and an increase in standing pools of water has resulted in an increase in malaria-carrying mosquitoes.

Mangrove Protection Methods

In order to conserve and protect mangrove ecosystems, political leaders, users of the mangroves, and other citizens need to understand the importance and value of the mangroves ecologically, socially, and economically. This has been achieved increasingly over the recent decades, in part as a result of education campaigns involving locals, fishers, government, and NGOs. For example, the NGO Greenpeace has organized peaceful protests in over 15 different countries to demonstrate against harmful practices by the shrimp farming industry.

Education has led to action to protect an increasing percentage of the remaining healthy mangrove habitats. The removal of mangroves for aquaculture is now banned in most countries, and the large-scale removal of mangroves for any purpose often requires an environmental impact statement, though politics and enforcement are often problematic. Many conservation biologists are proposing the increased protection of the remaining mangroves by creating a network of Marine Protected Areas around mangrove ecosystems.

If done properly, replanting mangroves can be an excellent way to recover areas that have been lost due to natural causes, such as hurricanes or typhoons, or man-made causes, such as pollution or aquaculture. This is especially true if the habitat is protected but natural recovery is unlikely or deemed too slow (for example, if there are not enough healthy mangroves nearby to provide propagules). Some mangrove species, such as the red mangroves, can be replanted simply by taking propagules from healthy mangals and inserting them in the mud. Jurgenne Primavera and Janalezza Estaban, however, found that rehabilitation programs in the Philippines were generally carried out in areas not normally colonized by mangroves (mudflats, sandflats, and seagrass meadows) because mangrove habitat was occupied by fish ponds; this resulted in low 10% to 20% long-term survival. Mortality can be also be high from predators such as crabs or toppling of the seedlings by other organisms. Many replanting efforts therefore are enhanced by raising the propagules in nurseries for a few months before replanting. A method called **encased replanting** provides a means of protecting the seedling, for example, with a section of PVC pipe, until aerial roots develop to stabilize the plant (about 3 years; **Figure 4-36**). Studies have shown that local involvement can increase the success of replanting programs over more costly government or international programs (in one study in southeast Asia survival increased from as low as 10% to as high as 97% with local involvement). One probable reason for the success is that locals have a vested interest and will spend the time and energy needed to maintain the plants.

Regional Mangrove Status

Summary statistics can give an indication of how mangroves are fairing, on average, globally. The status and protection levels for mangroves vary considerably around the world, however. In order to get a feeling for the variety and extent of mangrove conservation, some specifics for various regions are reviewed below, as reported by the Food and Agriculture Organization of the United Nations (FAO).

Figure 4-36 Mangrove recovery area using encased replanting in southwest Puerto Rico.

Asia has the largest area of mangrove habitat in the world (estimated at over 6 million hectares). Although the extent of mangroves has declined by 1% to 1.5% annually since 1980, there are several large well-protected reserves in the region. The reserve that has possibly seen the greatest long-term protection of any mangrove system is the Sundarbans Forest on the border between Bangladesh and India. Protections of this 542,000 hectare reserve began in 1875, and have remained in place in much the same area ever since. In other parts of India, local residents have donated money to buy mangrove areas to be set aside for protection from destruction for shrimp farming. Mangrove seedlings are collected to be transplanted into areas designated for mangrove replenishment. In these situations education plays a major role in enhancing protection of the mangroves.

The Matang Mangrove Forest Reserve in Malaysia has been managed since 1902 (see below). The Ranong Mangrove Forest in Thailand is a protected mangrove reserve supported by ecotourism and a scientific research center; local fishers are allowed to live in the reserve. Brunei, on the island of Borneo in the western Pacific, has some of the most well-preserved mangroves in southeastern Asia. In Thailand, one of the countries hit hardest by mangrove loss due to shrimp farming, a creative method is being used to protect mangrove habitat. The WWF is working with Thailand's army to develop a nature park in a mangrove forest, including tours and educational programs, with a goal of educating the public of the importance of mangroves. Many countries have established laws to protect mangroves outside of parks and reserves; however, enforcement is often hampered by a lack of resources.

In South America some of the tallest mangrove forests in the world survive as a result of protection in reserves and a lack of accessibility. In areas of northeast Brazil, including the Amazon River Delta, mangrove trees can reach heights of 40 to 50 meters and extend up to 40 kilometers inland.

In the Caribbean, mangroves occur in both estuaries and along exposed coastlines as well as covering small islands that might be covered at high tide (see Box 4-4, Conservation Focus: the Belizean Reef Mangroves). These are particularly vulnerable to destruction for tourism development, so the establishment of protected areas and reserves is important. The Central Mangrove Wetland in Grand Cayman is the largest area of protected inland mangroves in the Caribbean; it includes 4,000 hectares of mangrove habitat protected under the Marine Parks Law (**Figure 4-37**). Protected estuarine mangrove areas, some with mangroves as tall as 30 to 40 meters, are found in Mexico, Costa Rica, Panama, and Belize. In Cuba, mangroves are protected under habitat laws, and major mangrove plantation efforts were begun in 1980 and continue today.

Figure 4-37 A portion of the Central Mangrove Wetland in Grand Cayman (foreground). The city of George Town is visible across North Sound in the background.

The remaining mangroves in south Florida are heavily protected within a system of protected areas. Mangrove recovery is achieved by first assessing and removing the cause of mangrove loss, and then either allowing the mangroves to recolonize on their own or replanting mangrove seedlings. In this region, the mangrove ecosystem will typically replenish itself naturally in 15 to 30 years. In Florida, the Mangrove Trimming and Protection Act prohibits the removal, trimming, or disturbance of mangroves without a permit. In the Bahamas, educational programs have been designed to increase awareness, such as a Coastal Awareness Month, initiated in April 2005. In Central American countries insufficient enforcement of legislation hinders mangrove protection; however, reserves and parks have been established in Costa Rica and Honduras.

In much of Africa, laws are considered inadequate to protect and conserve the remaining mangrove ecosystems; however, legal protections are in place in Congo, Egypt, Kenya, and South Africa. Rehabilitation programs are increasing in some nations, including Mauritius, and in Tanzania all mangroves are legally protected. Even in areas where legal protection is lacking, education programs are increasing to inform locals of the benefits of conserving mangroves, for example, in Guinea, Mauritius, and Sierra Leone. A replanting program was organized by NGOs in Senegal involving thousands of youths from over 100 villages, providing education as well as recovery.

Throughout the world, further legislation and enforcement are needed to protect the remaining mangroves. Education and local citizen actions will serve crucial roles in determining the fate of mangrove ecosystems. Aaron Ellison points out that the mixed results of mangrove recovery efforts calls for increased international cooperation, greater sharing of information among developing countries, and further application of ecological theories to improve the success rate of restoration projects.

Ecotourism has provided an incentive to protect mangroves in some regions, as the income generated both protects the mangroves and employs locals. For example, kayak tours of the mangroves are organized in Florida and Honduras. Wildlife watching attracts tourists in some mangroves. For example, the Kuala Selangor Nature Park in Malaysia has developed paths and walkways, bird-watching blinds, and tours to view the synchronous flashing fireflies. Bird watching attracts ecotourists in mangroves of Trinidad to view the scarlet ibis, and in Belize to visit brown booby roosts. Many ecotourism agencies now include mangrove tours on their agenda, and some snorkeling guides include visits to mangrove habitats. It is idealistic to propose that the majority of mangrove ecosystems around the world be protected as sanctuaries untouched by humans, especially in countries where they are depended upon for subsistence. Managing the mangroves sustainably is better than destroying them for some other use, however. Probably the best example of a middle-ground solution is the Matang mangroves of Malaysia (**Figure 4-38**). This region is comprised of 40,000 hectares; about 5% (2,000 hectares) is protected as a "virgin-jungle reserve" and some smaller areas are protected as bird sanctuaries or for ecotourism and education. The remainder has been managed for over a century for wood production much as a commercial forest. Small areas are clearcut on a 30-year rotation, leaving the adjacent mangroves, including a three-meter strip next to the water, to produce propagules for recolonizing the clearcut area. The harvested wood is used mainly for charcoal production. Replanting is done after one year when necessary, using seedlings from local nurseries. As the mangroves grow, they are thinned, and the mangroves that are removed are used for fishing poles and materials for building village houses. The managed forest differs from that of an untouched mangrove ecosystem; however, there is a diversity of birds and other wildlife in the managed mangroves, and healthy fish populations in the associated marine habitats. The fisheries in the coastal region appear to be managed sustainably, with a harvest of more than 50,000 tons per year. Although this is not an extreme conservation solution to mangrove protection, it is an excellent model to consider when total protection is not a practical alternative.

Mangrove Conservation Prognosis

So, what is the future prognosis for mangrove ecosystems? As discussed above, these ecosystems are vulnerable to numerous impacts around the globe because of their accessibility and location near heavily populated coastal areas. There is no one simple solution to the problems of mangrove degradation and loss because impacts vary with

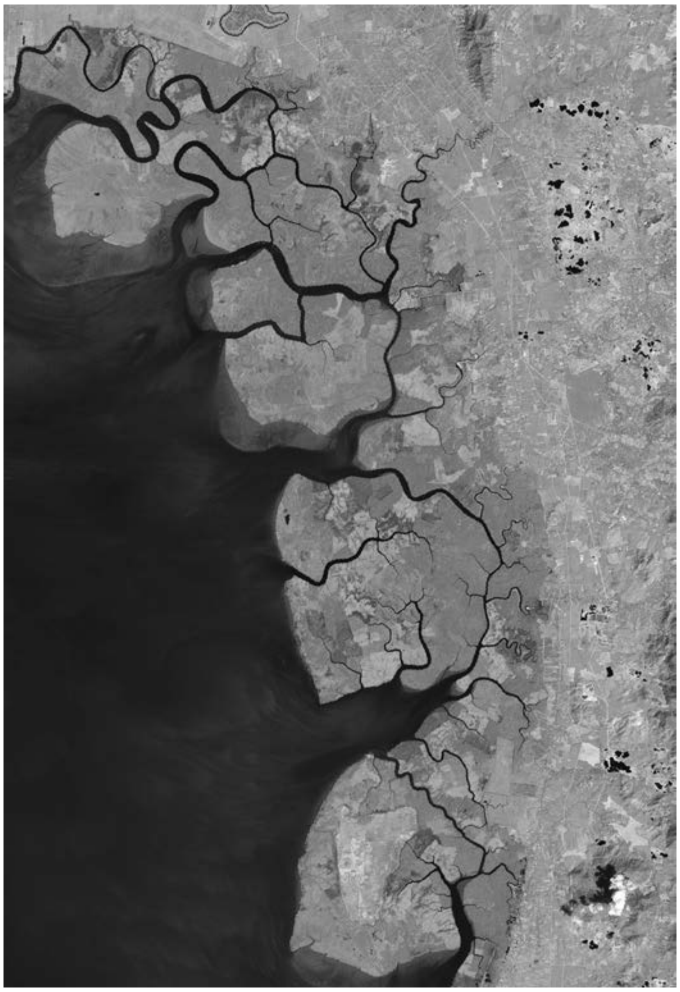


Figure 4-38 False-color satellite photo of the Matang Mangrove Forest, Malaysia. dark grays are mangroves, blacks are rivers flowing through the estuary to the sea, very light grays are cleared areas (including towns and fishing villages within the mangroves), and medium grays are agriculture or other vegetation. (See Color Plate 4-38.)

geography, climate, history, human culture, politics, and economics. The first step is education of the importance of mangroves, tailored to the specific region, and targeted to children and adults, political leaders, businesses and industries, and local residents. Each of these groups must realize that destruction of the mangroves is in no one's long-term interest. Although conservation should not be driven solely by economic value of ecosystems—and these values are difficult to generate—an awareness of the great economic value of mangroves can help to convince political leaders that mangroves are worth protection. For example, an analysis by Patrick Ronnback estimates the market value of fisheries supported by mangroves could be over $10,000 per hectare.

Resources are needed to assist in the recovery of damaged mangrove ecosystems, but involvement by locals can make recovery remarkably inexpensive. More protected areas are needed in parks or reserves to preserve some of the remaining healthy mangroves. Acceptance will be more readily achieved if locals are involved in decision making and can benefit from employment in park management or ecotourism. It is impractical to expect all mangroves to be protected as sanctuaries because many people depend on the mangroves for the natural resources they produce. It is in the interest of these people to develop sustainable management plans, however, which may include harvest of the mangroves for wood or taking mangrove-dependent organisms for food. Larger issues that affect mangroves that involve protecting watersheds and ocean ecosystems or minimizing effects of climate change are not as simple, but need to take the mangrove ecosystems into account. Much scientific progress has been made in recent years in understanding what needs to be done and how to do it. It remains to be seen how seriously people will take this information and apply it to mangrove conservation.

4.4 Global Climate Change and Marsh Ecosystems

Because of the unpredictability of global climate change it is not known when or how much estuary and marsh habitats will be impacted. Changes in temperature, carbon dioxide levels, and rainfall patterns could have effects on salt marsh and mangrove ecosystems that are difficult to predict. Sea level change may have the most predictable impacts. Higher sea levels could result in the inability of salt marsh grasses and mangroves to survive in much of their current habitats. In theory, the marsh ecosystems could "migrate" inland and be re-created in new regions. Many of these areas are currently occupied by human settlements or other developments, however, or blocked by sea walls or levies. If sea levels rise, habitable areas along the coast will be at a premium and it is doubtful they will be abandoned to allow for new salt marshes and mangroves. Coastal communities will be forced to continually replenish the coastline with sediments dredged from offshore or the estuaries.

If sea level rise is within the ranges that many scientists predict (see Chapter 1), many coastal regions will be covered with water within 50 to 100 years or sooner. Other changes that are predicted include: an inundation of brackish waters with sea water, inhibiting the growth of marsh grasses, and greater wave activity and increased erosion due to rising water levels. An analysis by Rusty Feagin and colleagues indicated that salt marshes could be naturally maintained, or even expanded, where there is adequate sediment deposition and accretion of organic material, especially if rates of sea level rise are at the lower bound of current estimates. Urbanized areas, however, could limit the migration or expansion of marshes. At upper bounds of estimates, the rate of accretion may not be adequate in most estuaries to maintain the level needed for the survival of the marshes. Studies by Patty Glick and National Wildlife Federation scientists, for example, estimated that, for Chesapeake Bay, a sea level increase by 0.6 meters would result in the loss of 652 square kilometers of brackish marsh and more than half of the region's salt marshes.

The most obvious way to minimize the impact of sea level rise is to minimize climate change, a global problem discussed in Chapter 1 (see Box 1-1, Conservation Concern: Global Warming and the Ocean). Considering that efforts may not be adequate, there needs to be a consideration of ways to minimize the local effects. For example, in Chesapeake Bay there has been a call for planning by government and NGOs. These plans include: prioritizing sites for protection based on their ecological importance and vulnerability, expanding protected areas to account for migration of the marshes with sea level rise, restoring and protecting other coastal ecosystems, identifying areas that might be enhanced by replenishment of sediments, and expanding monitoring programs. Similar methods are being discussed and applied in other regions; for example, the Mississippi River Delta of Louisiana, as discussed above. Both of these areas are already seeing the effect of sea level rise due to global warming in combination with marsh subsidence. Efforts to replenish the marshes include using dredge spoils to restore islands and marsh lands; however, a continual replenishment as sea levels rise may be cost prohibitive.

Mangroves will be exposed to similar impacts as sea levels rise. If deposition of sediment and detritus is great enough and rates of sea level rise low enough, the ecosystem may be able to maintain itself. This would likely only apply to mangroves associated with some estuaries and river deltas with large sediment inputs, however; those in arid areas and on offshore islands or coastlines away from substantial river input would eventually be exposed to rising water levels. Fossil records from the Caribbean have shown that the mangroves have been able to deposit sediments rapidly enough to keep up with increases in sea level of about 10 centimeters per century. Much higher rates of sea level rise, as have been predicted, would result in the loss of many island mangrove habitats.

As mangrove habitats are covered by rising sea levels, the species zonation pattern discussed above would shift inland. Beyond the current upper extension of the marshes inland, however, the availability of habitat for their migration is low. Many of the coastal regions where mangroves thrive are heavily populated or the habitats are already occupied by rice paddies or shrimp farms. But in Australia, rising sea levels appear to have already resulted in the expansion of mangrove habitat into certain drowned river valleys.

Mangroves are better adapted to tolerate higher temperatures than coral reefs; therefore, a temperature increase would probably not substantially affect their survival or productivity. In fact, increases in temperature may allow mangroves to extend their range into higher latitudes, and habitat is potentially available for expansion along coasts in the Pacific and Atlantic. In the United States, mangroves could replace salt marshes in the northern Gulf of Mexico and northward along the Atlantic coastline beyond the south Florida coast.

The biological community dependent on estuaries, mangroves, and salt marshes will be harmed by the loss of habitat. Many populations—and possibly some species—would be lost. Some species that use the estuaries and marshes as nurseries might survive without them. It is debated whether some species using the estuaries for a portion of their life are truly "estuarine dependent" or whether they might be considered "estuarine opportunist." Although a decline in estuaries may not drive species to extinction, the loss of these optimal habitats could undoubtedly have a dramatic effect on their populations.

The human-caused loss of mangroves and salt marsh ecosystems could be severe in coastal areas, in particular those that depend on these ecosystems for subsistence fisheries or for the protection they provide from violent storms. If global climate change increases the frequency of tropical storms, as some predict, this would further exacerbate the impact of global climate change.

4.5 The Future of Estuary and Marsh Conservation

Solving estuary and marsh conservation problems are complex due to a myriad of reasons. Estuaries and marshes are biologically complex and variable; we may never completely understand the ecological interaction and predict biological responses within these ecosystems. They are also critical, often to an unknown degree, to the survival of other marine and inland ecosystems. They can be affected by impacts originating all the way from headwater streams to the open ocean, due to their position at the intersection of where the freshwaters from rivers meet the tides and currents from the sea. Because they are in regions of the largest human population densities in the world, they are vulnerable to human actions; rising human populations will only exacerbate many of the current conservation problems. Their high productivity will continue to attract exploitation by humans living in coastal regions, continually creating new conservation challenges. Although the habitats themselves are not the most appealing tourist destinations, estuaries and salt marshes are in the vicinity of some of the most popular tourism-dependent regions in the world. Continual work is needed to balance tourism development with conservation. Finally, these ecosystems are managed and regulated by hundreds of governments around the world with different needs and conservation ethics; it is impossible to avoid political and social issues in protecting these ecosystems.

Despite these complexities, much progress has been made in recent years to understand what is needed to protect estuarine and marsh ecosystems. Although there remains much to be learned, we understand the biology of these ecosystems better than ever. Although human actions can be devastating, these ecosystems are more tolerant of moderate impacts than some other marine ecosystems (e.g., coral reefs). Scientists, managers, and conservationists now generally accept that we must consider scientific, social, political, and economic factors if these ecosystems are going to be protected.

Education programs at the local, national, and global levels are being implemented around the world; positive results are allowing the establishment of model programs to be implemented in other regions. Methods are being developed to minimize harm and still exploit resources from these ecosystems for aquaculture and harvest of renewable resources.

It is important that conservation efforts and outcomes continue to be monitored and that lessons are learned from mistakes. More than for most ecosystems, this will continue to require coordination among scientists, political leaders, government organizations, NGOs, and the public as we move forward in a continually changing world.

STUDY GUIDE

Topics for Review

1. Describe how the four types of estuaries differ in size and shape.
2. Why do estuaries tend to be more physically variable than other aquatic ecosystems? Describe the sources of this variability.
3. Why are estuaries and marshes attractive to fishes as nursery areas for young live stages?
4. What are the major impacts from rivers that flow into estuaries?
5. What special considerations are used in U.S. estuaries to protect fisheries species from harmful exploitation?
6. What are the possible reasons for the decline in blue crabs in Chesapeake Bay? What factors have kept these populations from recovering?
7. How do healthy oyster populations benefit estuarine ecosystems?
8. Describe the setbacks that have slowed efforts to recover oyster populations in Chesapeake Bay.
9. List the biological factors that make American and European eels particularly vulnerable to anthropogenic effects.
10. Describe the physical factors that govern the distribution of salt marshes and mangroves.
11. What factors limit the plant diversity in salt marshes and mangroves?
12. How and why do the animal communities of salt marshes and mangroves differ?
13. How does the destruction of salt marshes and mangroves affect inland ecosystems and human settlements?
14. Other than direct destruction, how does coastal development affect the function of salt marshes?
15. How does the function of an impounded salt marsh differ from a healthy salt marsh ecosystem?
16. How have studies of grazing geese and snail consumer fronts changed paradigms about salt marsh ecological functions?
17. How has channelization of the Mississippi River caused the loss of salt marshes in coastal Louisiana?
18. What factors have limited restoration of river flow as an acceptable method of marsh restoration?
19. What reproduction and growth characteristics of mangroves enhance their ability to recolonize after physical impacts such as hurricanes or cyclones?
20. How do the nutrients and organic matter from mangrove leaves reach predatory organisms that feed in mangrove ecosystems?
21. How do mangrove habitats function to protect coral reefs and freshwater marshes?
22. How do mangroves and salt marshes function to protect human settlements?
23. Why are mangroves and salt marshes more tolerant to moderate levels of organic pollution than coral reefs?
24. How would damming of rivers inland potentially affect mangroves?
25. How can wood products be taken from mangrove in a sustainable manner?
26. Describe how extensive aquaculture methods are particularly harmful to mangrove ecosystems as well as coastal fishers.
27. What are the major impacts of coastal tourism on mangrove ecosystems?
28. Why is mangrove replanting sometimes preferable over allowing a natural recovery of destroyed mangals?
29. How is traditional tourism more harmful to mangrove ecosystems than ecotourism?

Conservation Exercises

1. List the methods that you would recommend to most practically and efficiently achieve each of these conservation objectives. Consider biological, social, and economic factors in developing your lists.
   a. Recover oyster populations in Chesapeake Bay, while developing a sustainable harvest.
   b. Protect and recover endangered populations of the European eel.
   c. Develop a strategy for managing coastal impoundments in South Carolina to enhance coastal fisheries.
   d. Protect New England marshes from destruction by snow geese.
   e. Recover coastal Louisiana salt marshes.
   f. Recover mangrove habitats in coastal Vietnam.
   g. Establish protections for mangroves in Africa without destroying the livelihood of coastal communities.
   h. Recover mangroves in Thailand without economically destroying the shrimp aquaculture industry.
   i. Protect reef mangroves in Belize while minimizing the impact on the tourism industry.
   j. Protect mangrove ecosystems in Indonesia without totally eliminating harvest for wood products.

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