Chapter 19

Coastal Systems

Coordinating Lead Authors: Tundi Agardy, Jacqueline Alder

Lead Authors: Paul Dayton, Sara Curran, Adrian Kitchingman, Matthew Wilson, Alessandro Catenazzi, Juan Restrepo, Charles Birkeland, Steven Blaber, Syed Saifullah, George Branch, Dee Boersma, Scott Nixon, Patrick Dugan, Nicolas Davidson, Charles Vörösmarty

Review Editors: Joseph Baker, Patricia Moreno Casasola, Ariel Lugo, Avelino Suárez Rodríguez, Lingzis Dan Ling Tang

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BOXES

FIGURES

TABLES

*This appears in Appendix A at the end of this volume.

Main Messages

Coastal ecosystems—coastal lands, areas where fresh water and salt water mix, and nearshore marine areas—are among the most productive yet highly threatened systems in the world. These ecosystems produce disproportionately more services relating to human well-being than most other systems, even those covering larger total areas. At the same time, these ecosystems are experiencing some of the most rapid environmental change: approximately 35% of mangrove area has been lost or converted (in those countries for which sufficient data exist, which encompass about half of the area of mangroves) and approximately 20% of coral reefs have been destroyed globally in the last few decades, with more than a further 20% being degraded. Coastal wetland loss in some places has reached 20% annually (*high certainty*).

Coastal systems are experiencing growing population and exploitation pressures; nearly 40% of the people in the world live within 100 kilometers of the coast. Demographic trends suggest coastal populations are increasing rapidly, mostly through migration, increased fertility, and tourist visitation to these areas (*high certainty*). Population densities on the coasts are nearly three times that of inland areas. Communities and industries increasingly exploit fisheries, timber, fuelwood, construction materials, oil, natural gas, sand and strategic minerals, and genetic resources. In addition, demand on coastal areas for shipping, waste disposal, military and security uses, recreation, aquaculture, and even habitation are increasing.

Coastal communities aggregate near the types of coastal systems that provide the most ecosystem services; these coastal subtypes are also the most vulnerable. Within the coastal population, 71% live within 50 kilometers of estuaries; in tropical regions, settlements are concentrated near mangroves and coral reefs. These habitats provide protein to a large proportion of the human coastal populations in some countries; coastal capture fisheries yields are estimated to be worth a minimum of $34 billion annually. However, many of these habitats are unprotected or marginally protected; as a result, ecosystems services in many areas are at risk (*medium certainty*).

Human pressures on coastal resources are compromising many of the ecosystem services crucial to the well-being of coastal economies and peoples. Coastal fisheries have depleted stocks of finfish, crustaceans, and mollusks in all regions (*high certainty*). Illegal and destructive fisheries often cause habitat damage as well as overexploitation. Large-scale coastal fisheries deprive coastal communities of subsistence and are causing increasing conflicts, especially in Asia and Africa. Demands for coastal aquaculture have been on the rise, partly in response to declining capture fisheries, but the doubling of aquaculture production in the last 10 years has also driven habitat loss, overexploitation of fisheries for fishmeal and fish oil, and pollution. Overexploitation of other resources such as mangroves for fuelwood, sand for construction material, seaweeds for consumption, and so on also often undermine the ecological functioning of these systems.

The greatest threat to coastal systems is development-related loss of habitats and services. Many areas of the coast are degraded or altered, such that humans are facing increasing coastal erosion and flooding, declining water quality, and increasing health risks. Port development, urbanization, resort development, aquaculture, and industrialization often involve destruction of coastal forests, wetlands, coral reefs, and other habitats. Historic settlement patterns have resulted in centers of urbanization near ecologically important coastal habitats: 58% of the world's major reefs occur within 50 kilometers of major urban centers of 100,000 people or more, while 64% of all mangrove forests and 62% of all major estuaries occur near such centers. Dredging, reclamation, engineering works (beach armoring, causeways, bridges, and so on) and some fishing practices also account for widespread, usually irreversible, destruction of coastal habitats (*medium certainty*).

Degradation is also a severe problem, because pressures within coastal zones are growing and because such zones are the downstream recipients of negative impacts of land use. Worldwide, human activities have increased sediment flows in rivers by about 20%, but reservoirs and water diversions prevent about 30% of sediments from reaching the oceans, resulting in a net reduction of sediment delivery to coasts of roughly 10% (*high certainty*). The global average for nitrogen loading has doubled within the last century, making coastal areas the most highly chemically altered ecosystems in the world, with resulting eutrophication that drives coral reef regime shifts and other irreversible changes to coastal ecosystems. Nearly half the people living along coasts have no access to sanitation and thus face decreasing ecosystem services and increasing risks of disease. Mining and other industries cause heavy metal and other toxic pollution. Harmful algal blooms and other pathogens, which affect the health of both humans and marine organisms, are on the rise, in part because of decreased water quality. Invasions of alien species have already altered marine and coastal ecosystems, threatening ecosystem services.

The health of coastal systems and their ability to provide highly valued services is intimately linked to that of adjacent marine, freshwater, and terrestrial systems, and vice versa. Land-based sources of pollutants are delivered by rivers, from runoff, and through atmospheric deposition, and these indirect sources account for the large majority (77%) of pollutants (*high certainty*). In some areas, especially drylands, pollution in coastal zones contaminates groundwater. Another linkage occurs between expanding desertification and pollution of coral reef ecosystems caused by airborne dust. Destruction of coastal wetlands has similarly been implicated in crop failures due to decreased coastal buffering leading to freezing in inland areas (*medium certainty*).

Sub-national sociological data suggest that people living in coastal areas experience higher well-being than those living in inland areas, but the acute vulnerability of coastal ecosystems to degradation puts coastal inhabitants at greater relative risk. The world's wealthiest populations occur primarily in coastal areas (per capita income being four times higher in coastal areas than inland), and life expectancy is thought to be higher in coastal regions, while infant mortality is thought to be lower (*medium certainty*). However, many coastal communities are politically and economically marginalized and do not derive the economic benefits from coastal areas. Wealth disparity has denied many coastal communities access to resources. Access issues have in turn led to increased conflict, such as between small-scale artisanal fishers and large-scale commercial fishing enterprises. Regime shifts and habitat loss have led to irreversible changes in many coastal ecosystems and losses in some ecosystem services. Finally, given the fact that many degraded coastal systems are near thresholds for healthy functioning (*medium certainty*), and that coastal systems are simultaneously vulnerable to major impacts from sea level rise, erosion, and storm events, coastal populations are at risk of having their relatively high levels of human well-being severely compromised.

Trade-offs occur not only within coastal ecosystems, but also between the different uses of coastal systems and inland areas. In general, the choice to exploit coastal resources results in a reduction of other services; in some cases, overexploitation leads to loss of most other services (*medium certainty*). Within the coastal system, choices that result in irreversible changes, such as conversion of coastal habitat for industrial use, urbanization, or other coastal development, often bring short-term economic benefits but exact longer-term costs, as regulating and provisioning services are permanently lost. Choices made outside coastal areas, such as the decision to divert water for agriculture and thus reduce the flow of fresh water to estuaries, are cause for particular concern because virtually none of the benefits accrue to the coastal sector. Estuaries and coral reefs are the most threatened of all coastal ecosystems, precisely because impacts are both direct (originating from activity within the ecosystem), and indirect (originating in watersheds and inland areas).

Management of coastal systems to maximize the supply of services has been inadequate, but some negative trends are slowing and degradation can be halted with policy reform and by scaling up small successes to broader-scale initiatives. Effective coastal area management requires the integration of management across many sectors that have traditionally been separated. Because coastal systems are strongly affected by activities both in and outside of coastal regions, watershed management is a necessary element of effective coastal management. Integrated coastal management, marine protected area networks that effectively protect the most ecologically important habitats, and comprehensive ocean zoning all hold great promise. Restoration of some coastal habitats such as marshlands and mangrove is being undertaken. Other success stories do exist, but such successes have generally been small-scale, and scaling up has proved difficult. Business as usual will not avert continued degradation, associated loss of services, and declining human well-being in certain portions of society, such as coastal communities in developing countries and much of the low- to middle-income populace of industrial countries (*high certainty*).

19.1 Introduction

Coastal and marine ecosystems are among the most productive, yet threatened, ecosystems in the world; included in this category are terrestrial ecosystems, areas where fresh water and salt water mix, and nearshore coastal areas and open ocean marine areas. For the purpose of this assessment, the ocean and coastal realm has been divided into two major sets of systems: ''coastal systems'' inshore and ''marine fisheries systems.''

Coastal systems are places where people live and where a spate of human activity affects the delivery of ecosystem services derived from marine habitats; marine fisheries systems are places that humans relate to and affect mainly through fisheries extraction. Continental shelf areas or large marine ecosystems span both coastal and marine systems and provide many key ecosystem services: shelves account for at least 25% of global primary productivity, 90–95% of the world's marine fish catch, 80% of global carbonate production, 50% of global denitrification, and 90% of global sedimentary mineralization (UNEP 1992).

These shelf areas contain many different types of coastal systems, including freshwater and brackish water wetlands, mangrove forests, estuaries, marshes, lagoons and salt ponds, rocky or muddy intertidal areas, beaches and dunes, coral reef systems, seagrass meadows, kelp forests, nearshore islands, semi-enclosed seas, and nearshore coastal waters of the continental shelves. Many of these coastal systems are highly productive; Table 19.1 illustrates the relative productivity of some of these coastal ecosystems compared with selected terrestrial ecosystems.

Table 19.1. Relative Productivity Estimates for Select Coastal and Terrestrial Ecosystems (based on Odum and Barrett in press)

Ecosystem Type	Mean Net Primary Productivity	Mean Biomass per Unit Area
	(kilograms per sq. meter per year)	(kilograms per sq. meter)
Swamp and marsh	2.0	15
Continental shelf	0.36	0.01
Coral reefs and kelp	2.5	2
Estuaries	1.5	1
Tropical rain forest	2.2	45

In this assessment, the inland extent of coastal ecosystems is defined as the line where land-based influences dominate up to a maximum of 100 kilometers from the coastline or 50-meter elevation (whichever is closer to the sea, as per Small and Nicholls 2003) and with the outward extent as the 50-meter depth contour. Marine ecosystems begin at the low water mark and encompass the high seas and deepwater habitats. (See Figure 19.1.)

The resulting definition of coastal systems is geographically constrained and departs from many earlier assessments. The narrower band of coastal zone is a terrestrial area dominated by ocean influences of tides and marine aerosols, and a marine area where light penetrates throughout. This narrow definition was chosen for two reasons, relating to inshore and offshore boundaries: first, it focuses on areas that truly rely on and affect coastal ecosystems and it omits areas that may be near the coast but have little connection to those ecosystems (such as areas in valleys behind coastal mountain ranges); second, the ''watery'' portion of the coastal zone to 50 meters depth captures shallow water ecosystem like coral reefs but avoids deeper portions of the continental shelves in which fisheries impacts are paramount above all others (which are treated extensively in Chapter 18).

The heterogeneous ecosystems embodied in these coastal systems are dynamic, and in many cases are now undergoing more rapid change than at any time in their history, despite the fact that nearshore marine areas have been transformed throughout the last few centuries (Vitousek et al. 1997). These transformations have been physical, as in the dredging of waterways, infilling of wetlands, and construction of ports, resorts, and housing developments, and they have been biological, as has occurred with declines in abundances of marine organisms such as sea turtles, marine mammals, seabirds, fish, and marine invertebrates (Jackson et al. 2001; Myers and Worm 2003). The dynamics of sediment transport and erosion deposition have been altered by land and freshwater use in watersheds; the resulting changes in hydrology have greatly altered coastal dynamics. These impacts, together with chronic degradation resulting from land-based and marine pollution, have caused significant ecological changes and an overall decline in many ecosystem services. (Known rates of change and degradation in coastal subtypes are described later in this chapter.)

Dependence on coastal zones is increasing around the world, even as costs of rehabilitation and restoration of degraded coastal ecosystems is on the rise. In part, this is because population growth overall is coupled with increased degradation of terrestrial areas (fallow agricultural lands, reduced availability of fresh water, desertification, and armed conflict all contributing to decreased suitability of inland areas for human use). Resident populations of humans in coastal areas are rising, but so are immigrant and tourist populations (Burke et al. 2001). At the same time, wealth inequities that result in part from the tourism industry decrease access to coastal regions and resources for a growing number of people (Creel 2003). Nonetheless, local communities and industries continue to exploit coastal resources of all kinds, including fisheries resources; timber, fuelwood, and construction materials; oil, natural gas, strategic minerals, sand, and other nonliving natural resources; and genetic resources. In addition, people increasingly

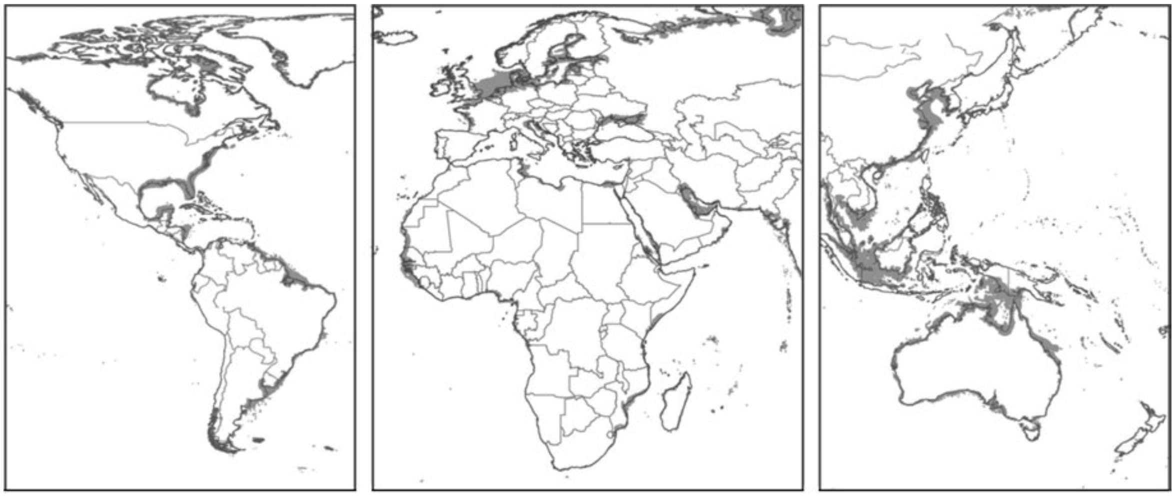


Figure 19.1. Coastal and Marine Systems Delimitation

use ocean areas for shipping, security zones, recreation, aquaculture, and even habitation. Coastal zones provide far-reaching and diverse job opportunities, and income generation and human well-being are currently higher on the coasts than inland.

Despite their value to humans, coastal systems and the services they provide are becoming increasingly vulnerable (*high certainty*). Coastal systems are experiencing growing population and exploitation pressures in most parts of the world. Though the thin strip of coastal land at the continental margins and within islands accounts for less than 5% of Earth's land area, 17% of the global population lives within the coastal systems as defined in this chapter, and 39% of global population lives within the full land area that is within 100 kilometers of a coast (CIESIN 2000). Population density in coastal areas is close to 100 people per square kilometer compared with inland densities of 38 people per square kilometer in 2000. Though many earlier estimates of coastal populations have presented higher figures (in some cases, near 70% of the world population was cited as living within the coastal zone), previous estimates used much more generous geographic definitions of the coastal area and may be misleading (Cohen 1995; Tibbetts 2002). That we have used a narrower definition and refined the coastal population numbers downwards in no way implies that coastal systems have lesser importance to humans—on the contrary, this assessment underlines the central extent to which human well-being is linked to the health and productivity of coastal systems.

Human pressures on coastal resources compromise the delivery of many ecosystem services crucial to the well-being of coastal peoples and national economies. Coastal fisheries, like many more offshore fisheries, have severely depleted stocks. (See Chapter 18.) These depletions not only cause scarcity in resource availability, they also change the viability of coastal and marine food webs, affecting the delivery of other services such as coastal protection (Dayton et al. 1995, 2002).

Biological transformations are also coupled to physical transformations of the coastal zone. Habitat alteration is pervasive in the coastal zone, and degradation of habitats both inside and outside these systems contributes to impaired functioning. Similarly, human activities far inland, such as agriculture and forestry, affect coastal ecosystems when fresh water is diverted from estuaries or when land-based pollutants enter coastal waters (nearly 80% of the pollutant load reaching the oceans comes from terrestrial sources). These chemical transformations affect the functioning of coastal systems and their ability to deliver services. Thus, changes to ecosystems and services occur as a function of land use, freshwater use, and activities at sea, even though these land-freshwater-marine linkages are often overlooked.

Larger forces are also at play. Coastal areas are physically vulnerable: many areas are now experiencing increasing flooding, accelerated erosion, and seawater intrusion into fresh water; these changes are expected to be exacerbated by climate change in the future (IPCC 2003). Such vulnerabilities are currently acute in low-lying mid-latitude areas, but both low-latitude areas and polar coastlines are increasingly vulnerable to climate change impacts. Coral reefs and atolls, salt marshes, mangrove forests, and seagrasses will continue to be affected by future sea level rise, warming oceans, and changes in storm frequency and intensity (*high certainty*) (IPCC 2003). The ecosystems at greatest risk also support large numbers of people; thus human well-being is at risk from degradation of coastal systems.

In general, management of coastal resources and human impacts on these areas is insufficient or ineffective, leading to conflict, decreases in services, and decreased resilience of natural systems to changing environmental conditions. Inadequate fisheries management persists, often because decision-makers are unaware of marine resource management being ineffective, while coastal zone management rarely addresses problems of land-based sources of pollution and degradation (Agardy 1999; Kay and Alder in press). Funds are rarely available to support management interventions over the long term.

At the same time, the incidence of disease and emergence of new pathogens is on the rise, and in many cases coastal degradation has human health consequences as well (NRC 2000; Rose et al. 2001). Episodes of harmful algal blooms are increasing in frequency and intensity, affecting both the resource base and people living in coastal areas more directly (Burke et al. 2001; Epstein and Jenkinson 1993).

Effective measures to address declines in the condition of coastal systems remain few and far between and are often too little, too late. Restoration of coastal habitats, although practiced, is generally so expensive that it remains a possibility only on the small scale or in the most industrialized countries. Education about these issues is lacking. The assessment in this chapter aims to contribute to a better understanding of the condition of coastal ecosystems and the consequence of changes in them, and thereby to help decision-makers develop more appropriate responses for the coastal environment.

19.2 Coastal Systems and Subtypes, Marine Wildlife, and Interlinkages

Total global coastlines exceed 1.6 million kilometers and coastal ecosystems occur in 123 countries around the world (Burke et al. 2001). The MA coastal system includes almost 5% of the terrestrial surface area of Earth. Coastal systems are a complex patchwork of habitats—aquatic and terrestrial. Figure 19.2 illustrates the heterogeneity of the habitats, human communities, and interconnected systems commonly referred to as the coastal zone. The diversity of habitat types and biological communities is significant, and the linkages between habitats are extremely strong (IOC 1993).

Scaling is a very important consideration in deciding how to treat the varied set of habitats in coastal systems, since investigations at fine scales will not reveal the global situation, and investigations at coarse scales will inevitably exclude important detail (O'Neill 1988; Woodmansee 1988). Thus, for the purposes of this discussion, the coastal system is divided into eight subtypes, relying in part on former classification systems (e.g., Allee et al. 2000) and in part on the model set forth in other chapters of the MA. Each subtype is described separately, including discussions of the services each provides, and is then assessed in terms of current condition and trends in the short-term future. In subsequent sections in which we discuss drivers of change, trade-offs, management interventions, and implications for human well-being, the coastal system is treated as a single unit.

19.2.1 Coastal Subtypes: Condition and Trends, Services and Value

19.2.1.1 Estuaries, Marshes, Salt Ponds, and Lagoons

Estuaries—areas where the fresh water of rivers meets the salt water of oceans—are highly productive, dynamic, ecologically critical to other marine systems, and valuable to people. Worldwide, some 1,200 major estuaries have been identified and mapped, yielding a total digitized area of approximately 500,000 square kilometers. (See Figure 19.3.)

There are various definitions of an estuary. One commonly accepted one is "a partially enclosed coastal body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of sea water with freshwater derived from land drainage" (Hobbie 2000). Other definitions accommodate the fact that the

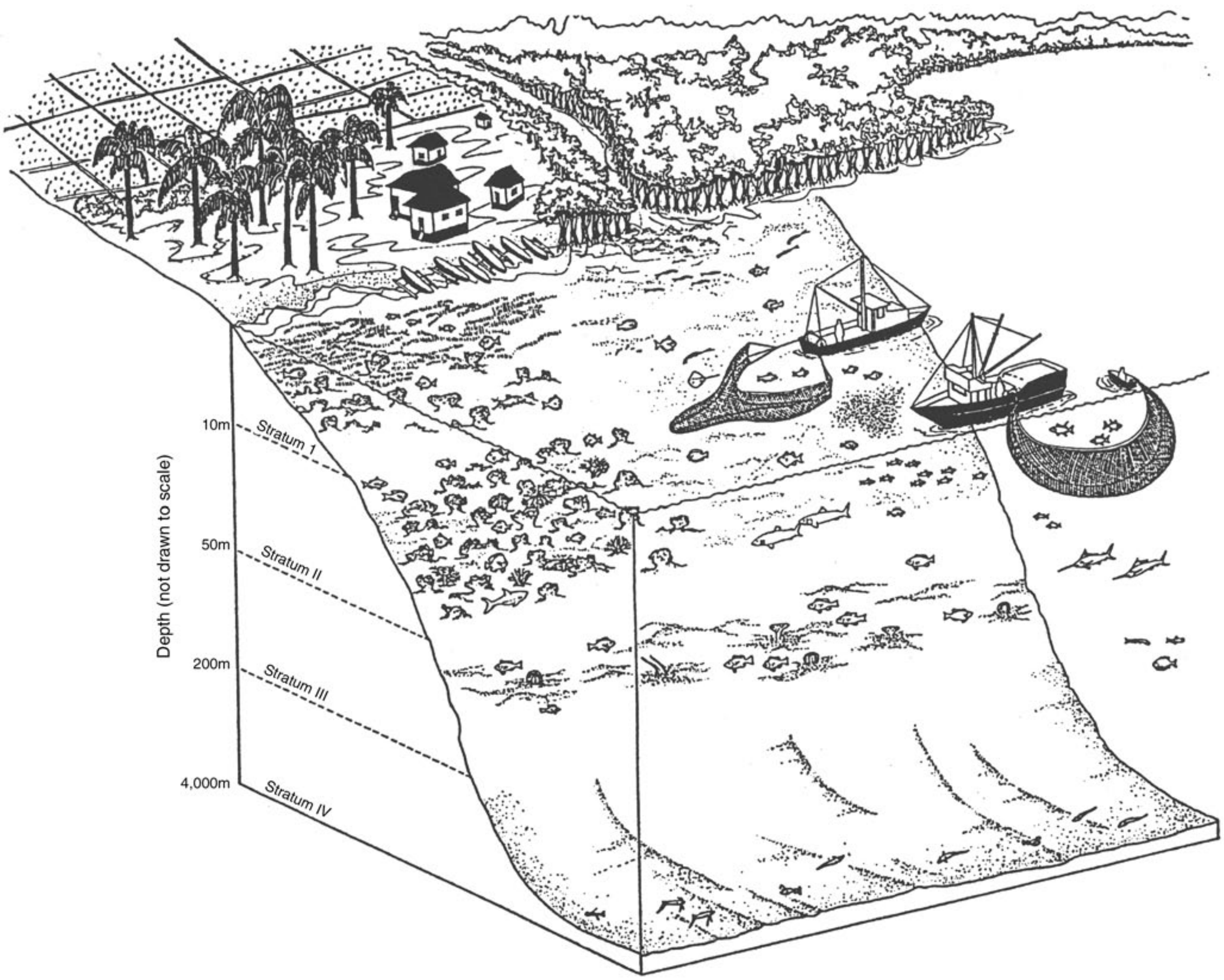


Figure 19.2. Schematic of Coastal System (Pauly et al. 1998)

Figure 19.3. Distribution of World's Major Estuaries (UNEP-WCMC 2003b)

range of estuarine organisms is often larger than suggested by a "biophysical" definition. Coastal marshes and lagoons are essentially extensions of true estuaries and are included in estuarine analysis and assessment. Mangroves are also often found in estuaries, but their importance to coastal communities warrants a separate detailed discussion, which is given in the next section.

Regardless of location or latitude, estuaries, marshes, and lagoons play a key role in maintaining hydrological balance, filtering water of pollutants, and providing habitat for birds, fish, mollusks, crustaceans, and other kinds of ecologically and commercially important organisms (*high certainty*) (Beck et al. 2001; Levin et al. 2001). The 1,200 largest estuaries, including lagoons and fiords, account for approximately 80% of the world's freshwater discharge (Alder 2003).

Of all coastal subtypes, estuaries and marshes support the widest range of services and may be the most important areas for ecosystems services. One of the most important processes is the mixing of nutrients from upstream as well as from tidal sources, making estuaries one of the most fertile coastal environments (Simenstad et al. 2000). There are many more estuarine-dependent species than estuarine-resident species, and estuaries provide a range of habitats to sustain diverse flora and fauna (Dayton 2003). Estuaries are particularly important as nursery areas for fisheries and other species, and form one of the strongest linkages between coastal, marine, and freshwater systems and the ecosystem services they provide (Beck et al. 2001).

Freshwater wetlands close to the coast form a salinity gradient and play a key role in maintaining freshwater flows. These areas are also under pressure for conversion to other uses, as well as for fish production. Many of these freshwater wetlands have been lost, and those that remain are under threat from coastal development, with pollution exacerbating threats. The European Union Habitats Directive has declared the conservation of coastal freshwater wetlands a priority (Ledoux et al. 2003).

An array of anthropogenic impacts has degraded, altered, or eliminated these ecosystems in many areas. The main threats include the loss or destruction of large areas of an estuary's watershed; eutrophication; effects of non-nutrient pollutants such as pesticides, herbicides, and bacteria; overfishing; invasions of exotic species; and, most important, habitat conversion within estuaries themselves. There has been a substantial loss of estuaries and associated wetlands globally (Levin et al. 2001). In California, for example, less than 10% of natural coastal wetlands remain, while in the United States more generally, over half of original estuarine and wetland areas have been substantially altered (Dayton 2003). In Australia, 50% of estuaries remain undamaged, although these are away from current population centers (Dayton 2003). Of the world's major estuaries, 62% occur within 25 kilometers of urban centers having 100,000 or more people.

Estuaries, especially those in proximity to urban centers, are often subjected directly and indirectly to trade-offs between development and conservation. Alterations such as infilling, dredging, channeling, installation of harbor works including seawalls and groins affect estuaries directly. Altering soft bottom habitat to hard bottom in the process often affects estuaries indirectly by creating conditions for new assemblages of species, and facilitating range expansions of invasive species (Ruiz and Crooks 2001). The resulting ecosystems may have losses in some ecosystem services and biodiversity. In New Zealand, invasive species have displaced commercially important mussel beds, causing significant economic losses for many mussel farmers (NOAA News Online 2003).

Figure 19.4 shows the interplay among urbanization, port development, and estuary loss worldwide. (See also Box 19.1.) Changes to freshwater flows through river impoundment and diversion are indirect trade-offs—worldwide, human activities have increased sediment flows in rivers by about 20% but reservoirs and water diversions prevent about 30% of sediments from reaching the oceans, resulting in a net reduction of sediment delivery to coasts of roughly 10% (*high certainty*) (Syvitski et al. 2005; Vörösmarty et al. 2003). Delivery of ecologically important nutrients is also impeded by freshwater diversion in watersheds, affecting not only coastal ecology but also marine fisheries yields. In the Nile Delta region of the Mediterranean, fish yields dropped significantly following the construction of the Aswan Dam (Nixon 2003). Although biomass levels rebounded from increasing nutrient input through human sewage, species composition was altered, and fish caught from the polluted waters of the Nile estuary continue to have human health impacts.

Poor management of watersheds often leads to degradation of estuaries. Agricultural and grazing practices that destroy natural riparian habitats have resulted in floods and burial of the natural estuarine habitats under silt and enriched sediment (Teal and Teal 1969). Urbanization of watersheds interrupts natural flows of both fresh water and nutrients, and it increases pollution. Agricultural inputs often result in excessive nutrient loading, which in turn causes large coastal areas to become eutrophied, hypoxic, or even anoxic (Boesch et al. 2001; D'Avanzo et al. 1996). An extreme example is the massive dead zone (up to 15,000 square kilometers) in the Gulf of Mexico (Turner and Rabalais 1994). Eutrophication is pervasive close to most of the world's large estuaries and all centers of human population, and the resulting ecosystem

Figure 19.4. Distribution of Major Ports and Estuaries (UNEP-WCMC 2003b; GDAIS 2004)

BOX 19.1

Case Study of the Paracas National Reserve

The Paracas National Reserve (335,000 hectares) is located along the Peruvian Pacific Coast, 250 kilometers south of the capital city, Lima. The reserve represents the best example of Pacific sub-tropical coastal desert on the South American continent (Rodriguez 1996). It includes relicts of the coastal desert plant communities (*lomas*). Paracas is one of the most biologically productive marine areas in the world, serving as a home for nearly 300 fish species, over 200 migratory bird species (60 of which migrate between Peru and the United States), and marine mammals and reptiles. The reserve also provides food for human populations in local communities and numerous coastal cities, providing about 60% of the seafood consumed by the people of Lima, which is home to 8 million people.

Historically, the arid coasts near Paracas gave rise to numerous pre-Colombian cultures, including the Paracas culture, and their villages built up "a life of unexpected richness in the arid dunes" (Stone-Miller 1995). The allochthonous subsidies from the sea may explain the apparent contrast between the aridity of the habitat (Paracas is a Quechuan word meaning "sand falling like rain") and the richness of the Paracas culture. Today the industrial effluents from fish meal and fish oil factories reaching the Paracas Bay cause massive deaths of fish and marine invertebrates. Overfishing and overcollecting of invertebrates has reduced the food source of numerous seabirds and marine mammals, whose populations have been declining continuously since the middle of the last century. Currently, a fractionation plant to process natural gas is being built in the buffer zone of the protected area within the Paracas Bay, adding another source of environmental risk to an already vulnerable and degraded marine ecosystem.

The Paracas National Reserve is an important source of income for local fishers. Overfishing and overcollecting might have serious social and economic consequences in the town bordering the reserve, where most of the economy is centered on sea products. An economic valuation of Independencia Bay (Cuadros Dulanto 2001), a 25-by-9 kilometer bay in the southern part of the reserve, calculated its direct use value as \$17.42 million. Fish and seafood accounted for 98% of this, whereas guano accounted for 1.4% and algae 0.4%. The value of indirect use, calculated through a model accounting for carbon sequestration by phytoplankton, was of \$181,124 per year. Potential, existence, and biodiversity values were estimated to be \$9.5 million, \$2.7 million, and \$29.8 million, respectively.

changes are difficult (though perhaps not impossible) to reverse once algae take over benthic habitats or cause shifts in trophic structure.

Estuarine systems are among the most invaded ecosystems in the world, with exotic introduced species causing major ecological changes (Carlton 1989 and 1996). Often introduced organisms change the structure of coastal habitat by physically displacing native vegetation (Grosholz 2002; Harris and Tyrrell 2001; Murray et al. 2004). For example, San Francisco Bay in California has over 210 invasive species, with one new species established every 14 weeks between 1961 and 1995 (Cohen and Carlton 1995, 1998). Most of these bioinvaders were bought in by ballast water of large ships or occur as a result of fishing activities (Carlton 2001). The ecological consequences of the invasions include habitat loss and alteration, altered water flow and food webs, the creation of novel and unnatural habitats subsequently colonized by other exotic species, abnormally effective filtration of the water column, hybridization with native species, highly destructive predators, and introductions of pathogens and disease (Bax et al. 2003; Ruiz et al. 1997).

Salt ponds and salinas are formed when evaporation causes constrained marine waters to become hypersaline. Some are naturally formed and others are artificial, such as salt pans and shrimp ponds. In effect, these subtypes are the biophysical opposites of estuaries, yet these coastal features provide key feeding areas for coastal birds and have their own unique biological communities. In the Red Sea region, these salt flats contribute nitrogen to adjacent mangroves (Potts 1980; Saifullah 1997b). Many of these features are seasonal or ephemeral and provide certain services only during certain times of year. Salt ponds and salt flats are often converted for other uses.

Salt marshes and coastal peat swamps (see Chapter 20) have also undergone massive change and destruction, whether they are within estuarine systems or along the coast. Salt marsh subsidence has occurred in part due to restricted sediment delivery from watersheds. Peat swamps in Southeast Asia have declined from 46–100% in countries monitoring changes (MacKinnon 1997). Coastal birds using estuaries and salt marshes both are indicators of ecosystem condition and provide many of the aesthetic ecological services of coastal systems (Benoit and Askins 2002); shorebird diversity and abundance has declined dramatically in the last few decades (International Wader Study Group 2003). Changes in relative sea level have affected and continue to affect salt marsh productivity and functioning, especially the ability of marshes to accumulate and retain sediments (Adam 2002). Relative sea level is a function of absolute sea level, changes in land level due to plate tectonics, and sediment delivery levels. Since sea level is rising due to climate change and land subsidence, and since freshwater diversion impedes delivery of sediments to estuarine systems (Vörösmarty and Meyback 1999), salt marshes will continue to be degraded and lost (Cahoon et al. 1999). The greatest threat may be to salt marshes in the tropics, which are relatively poorly studied (Adam 2002).

In many parts of the world, freshwater wetlands occur inland along the gradient of coastal ecosystems that begins offshore and moves inland through estuaries and salt marshes. Such coastal freshwater wetlands include herbaceous wetlands (marshes) and arboreal wetlands (swamps). Freshwater wetlands are discussed in detail elsewhere in this volume (Chapters 7 and 20), but it should be noted that the provision of ecosystem services by coastal systems can be highly dependent on the condition of these freshwater wetlands, and many have been and continue to be degraded by coastal development, changes to hydrology, and pollution.

19.2.1.2 Mangroves

Mangroves are trees and shrubs found in intertidal zones and estuarine margins that have adapted to living in saline water, either continually or during high tides (Duke 1992). Mangrove forests are found in both tropical and sub-tropical areas (see Figure 19.5 in Appendix A), and global mangrove forest cover currently is estimated as between 16 million and 18 million hectares (Valiela et al. 2001; Spalding et al. 1997). The majority of mangroves are found in Asia.

Mangroves grow under a wide amplitude of salinities, from almost fresh water to 2.5 times seawater strength; they may be classified into three major zones (Ewel et al. 1998) based on dominant physical processes and geomorphological characters: tide-dominated fringing mangroves, river-dominated riverine mangroves, and interior basin mangroves. The importance and quality of the various goods and services provided by mangroves varies among these zones (Ewel et al. 1998). Fringe forests provide protection from typhoons, flooding, and soil erosion; organic matter export; animal habitat; and a nursery function. Riverine mangroves also provide protection from flooding and erosion, as well as sediment trapping, a nursery function, animal habitat, and the harvest of plant products (due to highest productivity). Basin forests provide a nutrient sink, improve water quality, and allow the harvest of plant products (due to accessibility).

These forests thus provide many ecosystem services, playing a key role in stabilizing land in the face of changing sea level by trapping sediments, cycling nutrients, processing pollutants, supporting nursery habitats for marine organisms, and providing fuelwood, timber, fisheries resources. They also buffer land from storms and provide safe havens for humans in the 118 coastal countries in which they occur (Spalding et al. 1997). Mangroves have a great capacity to absorb and adsorb heavy metals and other toxic substances in effluents (Lacerda and Abrao 1984). They can also exhibit high species diversity. Those in Southeast Asia, South Asia, and Africa are particularly species-rich, and those in association with coral reefs provide food and temporary living space to a large number of reef species. In some places mangroves provide not only nursery areas for reef organisms but also a necessary nursery ground linking seagrass beds with associated coral reefs (Mumby et al. 2004). Removal of mangrove can thus interrupt these linkages and cause biodiversity loss and lower productivity in reef and seagrass biomes.

Mangroves are highly valued by coastal communities, which use them for shelter, securing food and fuelwood, and even as sites for agricultural production, especially rice production. Due to their function as nurseries for many species, fisheries in waters adjacent to mangroves tend to have high yields; annual net values of $600 per hectare per year for this fishery benefit have been suggested (Giesen et al. 1991). In addition, an annual net benefit of $15 per hectare was calculated for medicinal plants coming from mangrove forests, and up to $61 per hectare for medicinal values (Bann 1997). Similarly large economic benefits are calculated for shoreline stabilization and erosion control functions of mangroves (Ruitenbeek 1992).

Many mangrove areas have become degraded worldwide, and habitat conversion of mangrove is widespread (Farnsworth and Ellison 1997). Much of the coastal population of the tropics and sub-tropics resides near mangroves; 64% of all the world's mangroves are currently within 25 kilometers of major urban centers having 100,000 people or more. Mangroves have been converted to allow for aquaculture and for agriculture, including grazing and stall feeding of cattle and camels (which in Pakistan, for instance, is the second most serious threat to mangrove ecosystems (Saifullah 1997a)). Mangrove forests are also affected by removal of trees for fuelwood and construction material, removal of invertebrates for use as bait, changes to hydrology in both catchment basins or nearshore coastal areas, excessive pollution, and rising relative sea levels (Semesi 1992, 1998).

Along with conversion to agriculture, salt pans, and urban and industrial development, an important cause of loss is the aquaculture industry, typically through conversion of mangrove wetlands to shrimp or prawn farms. This destruction is particularly wasteful and costly in the long term, since shrimp ponds created out of mangrove forest lose their productivity over time and tend to become fallow in 2–10 years (Stevenson 1997). Historically, abandoned shrimp ponds are rarely restored, but new policy directives and a shift in the aquaculture industry is helping to make aquaculture less destructive and more prone to supporting restoration or regrowth in some parts of the world.

Estimates of the loss of mangroves from countries with available multiyear data (representing 54% of total mangrove area at present) show that 35% of mangrove forests have disappeared in the last two decades—at the rate of 2.1%, or 2,834 square kilometers, per year (Valiela et al. 2001). In some countries, more than 80% of original mangrove cover has been lost due to deforestation (Spalding et al. 1997). In summary, the current extent of mangroves has been dramatically reduced from the original extent in nearly every country in which data on mangrove distribution have been compiled (Burke et al. 2001). The leading human activities that contribute to mangrove loss are 52% aquaculture (38% shrimp plus 14% fish), 26% forest use, and 11% freshwater diversion (Valiela et al. 2001). Restoration has been successfully attempted in some places, but this has not kept pace with wholesale destruction in most areas.

19.2.1.3 Intertidal Habitats, Deltas, Beaches, and Dunes

Rocky intertidal, nearshore mudflats, deltas, beaches, and dunes also provide ecosystem services such as food, shoreline stabilization, maintenance of biodiversity (especially for migratory birds), and recreation.

Rocky intertidal habitats display interesting patterns of biological regulation and have been the location of much of the research that provided the foundation for our knowledge of predator-prey interactions, keystone species, and other biological regulation (Foster et al. 1988; Paine 2002; Sebens 1986). (See Chapter 11 for more on biological regulation in coastal systems.) The rocky intertidal habitats of temperate areas are highly productive and, in some cases, an important source of food for humans (Murray et al. 1999b). Food and bait collection (including mollusks and seaweeds) and human trampling have substantially depleted many of the organisms in these habitats. In the United States, the rocky intertidal zone has undergone major transformation in the last few decades: the California mussel *Mytelus californianus* has become very rare, the seastar *Pisaster* sp. is now almost never seen, and the once abundant black abalone (*Haliotis cracherodii*) can no longer be found in southern California (Dayton 2003). In addition, dozens of formally abundant nudibranch species are now rare (Tegner and Dayton 2000). Similar trends have been observed elsewhere in the world (Dayton 2003). Along the Yellow Sea coast, China has lost around 37% of habitat in intertidal areas since 1950, and South Korea has lost ~43% since 1918 (Birdlife International 2004a).

Intertidal mudflats and other soft-bottom coastal habitats play pivotal roles in ocean ecology, even though research and public interest have not historically focused on these habitats. Soft-bottom coastal habitats are highly productive and can be extraordinarily diverse (Levin et al. 2001), with a species diversity that may rival that of tropical forests (Gray 1997). Mudflats are critical habitat for migrating shorebirds and many marine organisms, including commercially important species like the horseshoe crab (*Limulus polyphemus)* and a variety of clam species. Unfortunately, mudflats are commonly destroyed during port development or maintenance dredging (Rogers et al. 1998), and coastal muds in many areas are highly contaminated by heavy metals, PCBs, and other persistent organic pollutants, leading to mortality and morbidity in marine species and to human health impacts.

Coastal deltas are extremely important microcosms where many dynamic processes and human activity converge. The IPCC has identified "deltas, estuaries, and small islands" as the coastal systems most vulnerable to climate change and sea level rise (IPCC 2003). Deltas are high population and human land use areas and are dynamic and highly vulnerable. They are also experiencing significant global changes as a class in themselves, aside from their overlap with the categories of mangrove, marshes, and wetlands (discussions of which do not capture all the dynamic influences in deltas).

Beaches and sandy shores also provide ecological services and are being altered worldwide. Sandy shores have undergone massive alteration due to coastal development, pollution, erosion, storms, alteration to freshwater hydrology, sand mining, groundwater use, and harvesting of organisms (Brown and McLachlan 2002). Disruptions to the sand balance in many locations is causing the total disappearance of beaches and with it the loss of ecological services, such as the provision of food to migratory birds, provision of nesting habitat, delivery of land-based nutrients to the nearshore coastal system, and provision of both food and recreational space to humans. Removal of beach wrack (seaweeds cast up on beaches) near urban centers and tourism resorts also alters habitat and services.

Dune systems occur inland of the intertidal zone but are commonly found in conjunction with beaches and sandy shores. These habitats are often highly dynamic and mobile, changing their form in both the short and long term. Although dune systems are not as productive exporters of nutrients as many other coastal systems, they act as sediment reserves, stabilize coastlines, provide areas for recreation, and provide breeding and feeding sites for seabirds and other coastal species. Dunes support high species diversity in certain taxonomic groups, including endangered bird, plant, and invertebrate species. Encroachment in dune areas often results in shoreline destabilization, resulting in expensive and ongoing public works projects such as the building of breakwaters or seawalls and sand renourishment. In the United States alone, coastal erosion of dunes and beaches costs $500 million in property losses annually (The Heinz Center 2000). Not only are such projects costly, they also have cascading impacts throughout the coast and nearshore areas.

19.2.1.4 Coral Reefs and Atolls

Coral reefs exhibit high species diversity and endemism and are valued for their provisioning, regulating, and cultural services (McKinney 1998). Reef-building corals occur in tropical coastal areas with suitable light conditions and high salinity and are particularly abundant where sediment loading and freshwater input is minimal. The distribution of the world's major coral reef ecosystems is shown in Figure 19.6 (in Appendix A). Reef formations occur as barrier reefs, atolls, fringing reefs, or patch reefs, and many islands in the Pacific Ocean, Indian Ocean, and Caribbean Sea have extensive reef systems occurring in a combination of these types. Coral reefs occur mainly in relatively nutrient-poor waters of the tropics, yet because nutrient cycling is very efficient on reefs and complex predator-prey interactions maintain diversity, productivity is high. However, with a high number of trophic levels the amount of primary productivity converted to higher levels is relatively low, and reef organisms are prone to overexploitation.

Reefs provide many of the services that other coastal ecosystems do, as well as additional services: they are a major source of fisheries products for coastal residents, tourists, and export markets; they support high diversity that in turn supports a thriving and valuable dive tourism industry; they contribute to the formation of beaches; they buffer land from waves and storms and prevent beach erosion; they provide pharmaceutical compounds and opportunities for bioprospecting; they provide curios and ornamentals for the aquarium trade; and they provide coastal communities with materials for construction and so on (Ahmed et al. 2004).

The fine-tuned, complex nature of reefs makes them highly vulnerable to negative impacts from overuse and habitat degradation—when particular elements of this interconnected ecosystem are removed, negative feedbacks and cascading effects occur (Nystrom et al. 2000). Birkeland (2004) describes ecological ratcheting effects through which coral reefs are transformed from productive, diverse biological communities into depauperate ones, along with similar cascading effects caused by technological, economic, and cultural phenomena. Coral reefs are one of the few marine environments displaying disturbance-induced phase shifts: a phenomenon in which diverse reef ecosystems dominated by stony corals dramatically turn into biologically impoverished wastelands overgrown with algae (Bellwood et al. 2004).

Most tropical reefs occur in developing countries, and this is where the most intensive degradation is occurring (Burke et al. 2002). Of all the world's known tropical reef systems, 58% occur within 25 kilometers of major urban centers having populations of 100,000 or more. Coral reefs are at high risk from many kinds of human activity, including coastal construction that causes loss of habitat as well as changes in coastal processes that maintain reef life; coastal constructions that change physical processes; destructive fishing and collecting for the marine ornamental trade; overfishing for both local consumption and export (Chapter 18); inadequate sanitation and poor control of run-off leading to eutrophication; dumping of debris and toxic waste; land use practices leading to siltation; oil spills; and degradation of linked habitats such as seagrass, mangrove, and other coastal ecosystems (Wilkinson 2000, 2002). In 1999, it was estimated that approximately 27% of the world's known reefs had been badly degraded or destroyed in the last few decades (Wilkinson 2000), although the latest estimates are of 20% of reefs destroyed (Wilkinson 2004) and more than a further 20% badly degraded or under imminent risk of collapse.

Of all the world's ecosystems, coral reefs may be the most vulnerable to the effects of climate change (Hughes et al. 2003). Although the mechanisms are not clear, warming seawater triggers coral bleaching, which sometimes causes coral mortality. Corals bleach when the symbiotic zooxanthellae that live in the tissue of the coral polyps and catalyze the reactions that lead to calcium carbonate deposition are changed or expelled. Bleaching does not automatically kill corals, but successive bleaching events in close proximity, or prolonged bleaching events, often do lead to mass mortality (Pandolfi et al. 2003). However, it has been estimated that approximately 40% of the reefs that were seriously damaged in the 1998 coral bleaching events are either recovering well or have fully recovered (Wilkinson 2004).

Climate change also has other detrimental impacts on coral. For example, rising carbon dioxide levels change the pH of water, reducing calcium carbonate deposition (reef-building) by corals. Climate change also facilitates the spread of pathogens leading to the spread of coral diseases. It has been suggested that climate change will reduce the world's major coral reefs in exceedingly short time frames—one estimate suggests that all current coral reefs will disappear by 2040 due to warming sea temperatures (Hughes et al. 2003), and it is not known whether the reefs that take their place will be able to provide the same level of services to humans and the biosphere.

Coral reefs are highly degraded throughout the world, and there are likely to be no pristine reefs remaining (Hughes et al. 2003; Pandolfi et al. 2003; Gardner et al. 2003). Historical analysis of conditions suggests that reef degradation, involving the decline of large animals, then smaller animals and reef-building species, precedes the emergence of bleaching and disease (Pandolfi et al. 2003). This suggests that overfishing, combined with pollution from land-based sources, predisposes reefs to be less resilient to disease and the effects of climate change. Such pollution includes increases in turbidity resulting from sediments washing into nearshore waters or from release during dredging, which results in significantly lower light levels reach corals, disrupting photosynthesis in algal symbionts and reducing calcification rates (Yentsch 2002). The coral reefs of the Caribbean Sea and portions of Southeast Asia have suffered the greatest rates of degradation and are expected to continue to be the most threatened (Gardner et al. 2003).

19.2.1.5 Seagrass Beds or Meadows

Seagrass is a generic term for the flowering plants that usually colonize soft-bottom areas of the oceans from the tropics to the temperate zones (some seagrass can be found on hard-bottom areas but the ones occupied are usually small). In estuarine and other nearshore areas of the higher latitudes, eelgrass (*Zostera* spp.) forms dense meadows (Deegan et al. 2001). Further toward the tropics, manatee and turtle grass (*Thalassia testudinum* and *Syringodium filiforme*) cover wide areas. Along with mangroves, seagrass is thought to be a particularly important in providing nursery areas in the tropics, where it provides crucial habitat for coral reef fishes and invertebrates (Gray et al. 1996; Heck et al. 1997). Seagrass is highly productive and an important source of food for many species of coastal and marine organisms in both tropical and temperate regions (Gray et al. 1996). It also plays a notable role in trapping sediments and stabilizing shorelines.

Seagrass continues to play an important ecological role even once the blades of grass are cut and carried by the water column. Drift beds, composed of mats of seagrass floating at or near the surface, provide important food and shelter for young fishes (Kulczycki et al. 1981), and the deposit of seagrass castings and macroalgae remnants on beaches is thought to be a key pathway for nutrient provisioning to many coastal invertebrates, shorebirds, and other organisms. For instance, nearly 20% of the annual production of nearby seagrass (over 6 million kilograms dry weight of beach cast) is deposited each year on the 9.5-kilometer beach of Mombasa Marine Park in Kenya, supporting a wide variety of infauna and shorebirds (Ochieng and Erftemeijer 2003).

Tropical seagrass beds or meadows occur both in association with coral reefs and removed from them, particularly in shallow, protected coastal areas such as Florida Bay in the United States, Shark Bay and the Gulf of Carpentaria in Australia, and other geomorphologically similar locations. Seagrass is also pervasive (and ecologically important) in temperate coastal areas such as the Baltic Seas (Fonseca et al. 1992; Green and Short 2003; Isakkson et al. 1994). The distribution of these major seagrass beds is shown in Figure 19.7 (in Appendix A).

Human impacts, including dredging and anchoring in seagrass meadows, coastal development, eutrophication, hypersalinization resulting from changes to inflows, siltation, habitat conversion for the purposes of algae farming, and climate change, are all causing widespread damage to seagrasses globally (Duarte 2002). Increased nutrient inflows into shallow water coastal areas with limited flushing (prime areas for seagrass growth) can cause algal and epifaunal encrustation of seagrass blades (Duarte 1995), limiting their ability to photosynthesize and in extreme cases smothering the meadows altogether (Deegan et al. 2001; Short and Wyllie-Echeverria 1996). Major losses of seagrass habitat have been reported from the Mediterranean, Florida Bay, and Australia (Duarte 2002). Present losses are expected to accelerate, especially in Southeast Asia and the Caribbean (Burke et al. 2001; Duarte 2002), as eutrophication increases, algal grazers are overfished, and coastal development increases.

19.2.1.6 Kelp Forests

The productivity of kelp forests rivals that of the most productive land systems (Dayton 2003). These temperate ecosystems have a complex biological structure organized around large brown algae, supporting a high diversity of species and species interactions. Kelp support fisheries of a variety of invertebrate and finfish, and the kelp itself is harvested for food and additives. Kelp forests are remarkably resilient to natural disturbances such as wave impacts, storm surges, and other extreme oceanographic events (Dayton 2003).

Kelp forests and other macroalgae provide specialized nursery habitats for some species. For instance, the upper layers of kelp provide nursery habitat for young rockfish and other organisms. Kelp communities consist of several distinct canopy types supporting many herbivores. Most important among these are sea urchins, which are capable of destroying nearly all fleshy algae in most kelp systems, and the spines of the red sea urchin (*Strongylocentrotus franciscanus*) provide crucial nursery habitat for other sea urchin species (Tegner and Dayton 1977). Factors affecting the abundance of sea urchins are thus important to the integrity of kelp ecosystems (Dayton 2003).

Unfortunately, the biological communities of many kelp forests have been so destabilized by fishing that they retain only a fraction of their former diversity (Tegner and Dayton 2000). It is likely that no kelp systems exist in their natural condition (Dayton

2003), and there have been enormous system responses to human impact. Fishing impacts (see Chapter 18) can cause cascading effects, reducing diverse kelp forests to much simplified sea urchin–dominated barren grounds. Such ''urchin barrens'' are exactly as the name implies: devoid of many normal forms of life and dominated by urchins. Urchin barrens are or were prevalent in the northwest Atlantic (Labrador to Massachusetts), the Aleutian Islands, southern California, the Chilean coast, Japan, New Zealand, and Australia.

Removal of predators plays a key role in these regime shifts, some of which regularly oscillate between states, while others remain in the barren state for long periods of time. For example, in the Atlantic Ocean large fish such as halibut (*Hippoglossus hippoglossus*), wolfish (*Anarichus latifrons*), and cod (*Gadus spp.*), which are the key predators of sea urchins, have been largely removed from the system, causing sea urchin populations to explode (Tegner and Dayton 1977; Dayton et al. 1998). Following this, directed exploitation and disease led to a collapse of the urchin populations, but kelp forests have not fully recovered and continue to be vulnerable to waves of exotic species (Dayton 2003).

In other places, kelp communities are tied to sea otter populations. When sea otters were decimated in the Aleutian Islands through hunting, kelp forests were destroyed by booming populations of sea urchins. Following protection of sea otters, the kelp forests temporarily recovered, but the barrens returned in the 1990s when the otters began declining again (Estes et al. 1998). The health of kelp forests is thus strongly related to the health of the predator populations.

19.2.1.7 Other Benthic Communities: Rock and Shell Reefs, Mud Flats, Coastal Seamounts, and Rises

Although public interest in coastal biodiversity has tended to focus on coral reefs, many other coastal systems harbor vast amounts of species (Gray 1997; Gray et al. 1997). Within estuaries, for instance, oyster reefs are considered important nursery areas, not just for oysters but also for a wide range of fish species, other mollusks, crabs, and other fauna. Rock reefs, for example, provide rich nursery habitat for fisheries, such as those that occur in the extensive banks inshore from the upwelling areas of the northern Gulf of Guinea in West Africa (Binet and Marchal 1993), as well as in temperate areas such as in the Mediterranean Sea. Mud flats in the intertidal area and on banks are also productive habitats that exhibit surprising species diversity.

Hard-bottom habitats below the photic zone tend to be dominated by sponges, corals, bryozoans, and compound ascidians. Most of these temperate, non-reef-building corals are found in deeper waters beyond the coastal limit, although their ecosystem dynamics and the threats facing them are similar to many coastal systems. Human-induced disturbances can cause major ecological damage and compromise biodiversity, regardless of whether these communities occur more inshore or offshore. Bottom trawling and other fishing methods that rake the benthos have destroyed many of these communities already (Dayton 2003; Jennings and Kaiser 1998). These impacts on biodiversity sometimes result in permanent losses when endemic or restricted species are wiped out. (See the section on biodiversity in Chapter 18.)

About 70% of Earth's seafloor, including that located within the MA coastal system, is composed of soft sediment (Dayton 2003). Although soft-sediment habitats do not always appear as highly structured as some terrestrial or marine reef habitats, they are characterized by extremely high species diversity. There is now strong evidence of fishing effects on seafloor communities that have important ramifications for ecosystem function and resilience (Dayton 2003; Rogers et al. 1998). Given the magnitude of disturbance by trawling and dredging and the extension of fishing effort into more vulnerable benthic communities (Chapter 18), this type of human disturbance is one of the most significant threats to marine biodiversity (Dayton 2003). Sponge gardens in soft substrates face particular threat from bottom trawling, since the soft substrate is easily raked by heavy trawling gear.

In places, the ocean floor's soft sediment is interrupted by highly structured seamounts with highly diverse communities of organisms (Dayton 1994). These underwater mountains or volcanoes are usually found far offshore and are thought to be crucial for many pelagic fish species, not just as sites for breeding and spawning, but also as safe havens for juvenile fishes seeking refuge from open ocean predators (Johannes et al. 1999). Since the vast majority of large seamounts occur in deeper marine waters, they are discussed in detail in Chapter 18. However, smaller seamounts occur in conjunction with coral reefs and elsewhere in the coastal zone, and they contribute significantly to coastal fisheries production and biodiversity maintenance. Because their high species diversity is concentrated into a relatively small, localized area, and because of their occasionally high endemism, seamounts are extremely vulnerable to fishing impacts. (See Chapter 18.)

Other benthic habitats that might be expected to fall into this subtype are not discussed in this assessment, such as the fjords of Norway and non-kelp-dominated rocky slopes and banks. Cold water corals of the temperate deeper waters are discussed in Chapter 18. Some of these habitats provide ecosystem services important to humankind, and some are also being degraded, but these habitats are either so specialized as to make generalizations impossible, or assessment information is lacking at the global scale.

19.2.1.8 Semi-enclosed Seas

A semi-enclosed sea is legally defined as ''a gulf, basin or sea surrounded by two or more States and connected to another sea or the ocean by a narrow outlet or consisting entirely or primarily of the territorial seas and exclusive economic zones of two or more coastal States'' (Convention on Law of the Sea, Article 122). Although this is a geopolitical, not an ecological, definition, and despite the fact that large portions of semi-enclosed seas thus defined fall outside the MA category of ''coastal,'' these areas are described here as another coastal subtype. (Chapter 18 mentions these systems in regard to fisheries as well.)

Notable examples of semi-enclosed seas include the Mediterranean, Black, Baltic, and Red Seas and the Gulf of Aden. Semi-enclosed seas can be intercontinental (such as the Mediterranean Sea), intracontinental (such as the Black and Baltic Seas), or marginal (such as the North and Bering Seas). Gulfs with restricted openings such as the Gulf of California in Mexico and the Gulf of Thailand could also be considered ''semi-enclosed.'' These systems all share similar attributes: they tend to be highly productive (primarily due to exogenous inputs from lands nearby), often have high species diversity and endemism, are heavily used by the countries and communities that border them, and are often at high risk from pollution.

Perhaps more than open ocean systems, semi-enclosed seas are directly linked to human well-being. Many of the world's great civilizations sprung up along the shorelines of semi-enclosed seas, which have historically provided food, trade routes, and waste processing services to burgeoning human populations. Today most semi-enclosed seas of the world are highly valued as tourism and recreational venues, adding to their value in continuing to provide food and other services (Sheppard 2000). Yet they are becoming highly degraded due to demands placed on them and their physical configuration.

Freshwater inflows to semi-enclosed seas have been severely curtailed in most areas, robbing them of recharging waters and nutrients. A particularly acute case of this degradation has occurred in the Gulf of California, which now receives only a trickle of water through the now dry, but once very fertile, delta of the Colorado River (GIWA 2003). At the same time, water reaching these basins is often of poor water quality due to land-based sources of pollution such as agricultural and industrial waste (GESAMP 2001). Such degradation is highly prevalent in semi-enclosed seas with major river drainages, such as the Black Sea (Bakan and Büyükgüngör 2000), Baltic Sea (Falandysz et al. 2000; Kautsky and Kautsky 2000), and even large parts of the Mediterranean Sea (Cognetti et al. 2000). The limited flushing and long recharge times in semi-enclosed seas means that pollutants are not as quickly diluted as in the open sea, and eutrophication and toxics loading are often the result.

Virtually all semi-enclosed seas have undergone dramatic transformation as the consequence of coastal development, ever-increasing fishing pressures, declines in freshwater input, and pollutant loading. The pollution that enters semi-enclosed seas from drainage basins is a significant source of degradation in these physically constrained coastal areas, especially in regions with major river basins and high rainfalls (for instance, see Cognetti et al. 2000 on the Adriatic Sea and Bakan and Büyükgüngör 2000 on the Black Sea). In the Bosporus region of Turkey, sewage pollution has been implicated in the decline of many fish species. However, land-based sources of pollution can also be a problem in arid and semiarid regions, as evidenced by the extensive local degradation of coral reefs in the Red Sea caused by seepage and runoff of untreated sewage into nearshore waters (Sheppard 2000).

Negative synergies often act together to bring about cataclysmic change in ecosystem condition in relatively short amounts of time. The Black Sea, which once supplied much of Europe with fisheries products, has undergone a slow but chronic environmental degradation in the last century as industrial pollution from major rivers, including the Danube, Dniester, and Dnieper, as well as more coastally based pollution, contaminated the waters. Overfishing and wetlands destruction occurred during roughly the same period, but intensified even as the health of the sea began to falter. When an Atlantic ctenophore, *Mnemiopsis leidyi,* was introduced through ship ballast water sometime in the 1980s, the voracious predator eagerly preyed on the struggling biota, causing the loss of over two dozen major fisheries (Zaitsev and Mamaev 1997). In recent years, the anoxic layer of this basin has expanded and moved upwards, making restoration of the sea to its once-vibrant state difficult.

19.2.2 Marine Wildlife

The world's oceans and coasts are home to many hundreds of species of marine mammals, turtles, crocodiles, and seabirds—some common, others rare; some with global distributions, others with narrow coastal distributions. Those with wide-ranging distributions demonstrate the connectivity of ecosystems and the need for holistic approaches to management of coastal and marine systems. Several species are threatened, either because they have not recovered from earlier exploitation (such as the Northern right whale, *Eubalaena glacialis*) or because they continue to suffer excessive mortality, mainly through incidental catches or as bycatch of fishing (such as the vaquita, *Phocoena sinus,* a dolphin endemic to the northern Gulf of California (D'Agrosa et al. 2000) and albatrosses (Stehn et al. 2001)).

Other human activities also threaten marine wildlife. Recent studies have found strong correlations between mass strandings of some marine mammals, such as beaked whales (family Ziphiidae), and military low frequency sonar exercises (Piantadosi and Thalmann 2004). More widespread is the threat of incidental catch in fisheries. Bycatch is currently recognized as a significant threat to conservation of small cetaceans (Dawson et al. 1998) and seabirds (Tasker et al. 2000).

19.2.2.1 Turtles and Crocodiles

None of the 23 known crocodile species have gone extinct despite local extirpations and multiple threats to their habitats as well as interactions with humans (Webb 1999). Although some species of crocodile are still threatened with extinction, others have increased in number and through appropriate management plans are being harvested sustainably (Ross 1998).

Marine turtles, along with marine mammals and seabirds, are key indicator species for problems and changes in the marine environment. The overall situation of the seven marine turtle species found worldwide is no better than that of most marine mammals. Human-related impacts—particularly habitat destruction, direct harvest of adults and eggs, international trade, bycatch, and pollution—are seriously threatening the survival of marine turtles. All seven species of turtles are listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora Appendix I, thereby restricting international trade in turtles or turtle-derived products between parties to the convention. According to the *IUCN Red List,* three of the seven species are critically endangered with extinction, three are endangered, and the status of the Australian flatback (*Chelonia depressa*) remains unknown due to insufficient information.

Although survival of marine turtles is threatened on a global scale, at the regional scale different turtle subpopulations show different growth trajectories. However, this may be a reflection of data availability. For example, information about turtle populations in Africa has been lacking until recently (Fretey 2001) and is still largely incomplete.

Green turtle (*C. mydas*) populations are particularly at risk in the Indo-Pacific, primarily due to high levels of directed take of adults, juveniles, and eggs. Leatherback turtle populations (*Dermochelys coriacea*) are especially at risk in the Eastern Pacific. It has been estimated that the number of leatherback turtles in that region has decreased from just under 100,000 adult females in 1980 to fewer than 3,000 adult females in 2000 (Spotila et al. 2000). Conservative estimates are that longline and gill-net fisheries were responsible for the mortality of at least 1,500 female leatherbacks per year in the Pacific during the 1990s (Spotila et al. 1996).

Similarly, leatherbacks and loggerhead turtles (*Caretta caretta*) at sea suffer from high rates of mortality due to unsustainable levels of bycatch in various fisheries (notably longline fisheries). Should these levels be sustained, Eastern Pacific leatherback turtles are anticipated to become extinct in the next few decades (Crowder 2000). In many parts of the world, however, direct harvest (as occurs for the hawksbill, *Eretmochelys imbricata*) and incidental capture of marine turtles in inshore fisheries represent a greater source of mortality than bycatch in longline fisheries (Seminoff 2002; Kaplan 2001).

In addition to mortalities experienced at sea, habitat loss and destruction of nesting beaches and important foraging grounds have contributed to marine turtle population declines (WWF 2003). Turtle products, such as jewelry made from hawksbill shells, also threaten marine turtles. Thousands of turtles die from eating or becoming entangled in nondegradable debris each year. Trash, particularly plastic bags, causes mortality for species like the leatherback, which cannot distinguish between floating bags and jellyfish prey. Pollution has also been linked to increased incidence of fibropapilloma disease, which kills hundreds of turtles annually (Herbst et al. 2004). However, the greatest recent historical losses in turtle populations occurred as a result of early European colonization of the Americas, when trade in turtle products helped finance further exploration and settlement, as occurred in the Caribbean (Carr 1979; Jackson et al. 2001).

19.2.2.2 Marine Mammals

Marine mammals are affected and frequently threatened by fisheries and other human activities (Northridge 2002). In the past, the main threats were large-scale whaling and sealing operations focused initially on the waters of northern Europe and Asia. Operations soon extended to Antarctica and reduced populations to small fractions of their former abundances (Perry et al. 1999) or extirpated them completely, as with the now extinct Atlantic grey whale (Mitchell and Mead 1977) or the Caribbean monk seal (Kenyon 1977; Gilmartin and Forcada 2002). While many of the pinniped (seals, sea lions, and walrus) species appear to have recovered quite successfully from former exploitation levels, recovery of some of the heavily depleted whale species has been slow, making them more susceptible to other emerging threats, such as bycatch in commercial fisheries or climate change (Clapham et al. 1999).

In recent decades, incidental entanglement in fishing gear, chemical and acoustical pollution, habitat degradation, climate change, and ship strikes are regarded as the most serious human-related threats for marine mammals, although impacts of these are highly variable for different species.

Small cetaceans such as dolphins are probably most threatened by bycatch (Northridge 2002; Kaschner 2003)—in some cases, to the verge of extinction, such as the vaquita (D'Agrosa et al. 2000). And worldwide estimated mortalities across all species add up to several hundred thousands every year (Read et al. 2003). Although entanglement in fishing gear is generally not fatal for the larger baleen whales, it may seriously affect the ability of an animal to feed and may potentially result in starvation (Clapham et al. 1999).

Increasing levels of chemical pollution and marine debris in the marine environment are likely having impacts on most marine mammal species through ingestion of pollution and floating plastic debris or entanglement (Merrick et al. 1987). Various health problems in marine mammals have been associated with high levels of accumulated pollutants that have been found in many species of predatory marine mammals (Aguilar and Borrell 1994).

Pinniped species combined represent the most abundant group of marine mammals in terms of population size. However, a high proportion of pinniped species are restricted to polar waters, and this group is most likely to be negatively affected by climate change (Harwood 2001). Currently, almost a quarter of all pinniped species are listed as endangered or vulnerable in the *IUCN Red List*.

19.2.2.3 Waterbirds

Many waterbirds are dependent on coastal systems (see Chapter 20 for a more detailed assessment of waterbird status and trends), and waterbirds themselves are important in the delivery of a number of coastal ecosystem services, including nutrient cycling, recreation, food provisioning, and cultural values. Coastal systems are vital for both shorebirds and seabirds, which use coastal areas for breeding, foraging and resting. There are 336 species of seabirds (Schreiber and Burger 2002). Some species, notably gulls, have increased because of widespread discarding of bycatch. Others have strongly declined in recent decades, both due to the reduction of their food base by fisheries and because they are caught as bycatch of pelagic fisheries.

Shorebirds are declining worldwide: of populations with a known trend, 48% are declining in contrast to just 16% increasing (International Wader Study Group 2003). For shorebirds in Africa and Western Eurasia, three times as many populations are decreasing as are increasing, although the trend status of the majority of populations seems not to have changed significantly over the last 10–20 years. Overall, 45 (34%) of African-Eurasian migratory shorebird populations are regarded as of conservation concern due to their decreasing or small populations (Stroud et al. 2004). Similarly, 54% of shorebird populations occurring in North America are in a significant or persistent decline, with only 3% increasing significantly and as many as 80% of populations in this region showing evidence of declines (Morrison et al. 2001). However, shorebird trend status in other regions is poorly known and has not been reassessed since the 1980s.

Information on trends in shorebirds and seabirds is highly variable geographically. For shorebird (wader) flyways in Africa-Eurasia, trend information is available for 93% of populations using the coastal East Atlantic flyway and 76% using the Black Sea/Mediterranean flyway. Only 35% of populations on the West Asia/East Africa flyway have good trend information, and the status of resident African populations is particularly poorly known (only 30%) (Stroud et al. 2004). While fewer seabirds than inland waters species have become extinct, a much larger proportion (41.8%) of extant seabirds are globally threatened. (See Chapter 20.) The decline in seabirds is occurring in all parts of the world and across major habitat types. The most threatened families are albatrosses (90.5% of species globally threatened), penguins (58.8%), petrels and shearwaters (42.9%), and frigate birds (40%).

Land use change and habitat loss and degradation seem to continue to be drivers of shorebird declines. For example, the decline of certain long-distance East Atlantic flyway populations (while other populations on the same flyway are stable or increasing) has been attributed to their high dependency on deteriorating critically important spring staging areas, notably the international Wadden Sea, that are being affected by commercial shellfisheries. Similar situations are reported from other flyways and key spring staging areas such as Delaware Bay in the United States and the Yellow Sea coast. Maintaining the ecological character of such staging areas is increasingly recognized as vital for the survival of Arctic-breeding species, yet many remain under threat (Baker et al. 2004; Davidson 2003).

For seabirds, direct drivers of declines are likely to be different from those of coastal and freshwater waterbirds. For example, for albatrosses—the seabirds showing the most dramatic current population declines—it is highly certain that the main driver is adult mortality caused by pelagic (longline) fisheries in southern oceans (BirdLife International 2004b).

For sea- and shorebirds, climate change is considered to be additional to the drivers of land use change and habitat loss and degradation. For example, changes in the non-breeding distribution of coastal wintering shorebirds in western Europe have been attributed to rising mid-winter temperatures (Austin et al. 2000), and seabird breeding failures in the North Sea in 2004 have been linked to a northward shift in plankton distribution driven by rising sea temperatures (Edwards and Richardson 2004).

Any effects of climate change on waterbirds are generally considered to be additive to the impacts of direct drivers such as habitat degradation. However, it is predicted that reduction in areas of Arctic tundra breeding habitat will contribute to population declines in high-Arctic breeding species (*medium certainty*). Similar shifts in distribution in several other parts of the world are well known and occur in relation to El Niño events (*medium certainty*).

19.2.3 Summary and Linkages with Other Systems

Coastal ecosystems are diverse, highly productive, ecologically important on the global scale, and highly valuable for the services they supply. (See Table 19.2.) Dividing the coastal system into separate subtypes and discussing each one independently obscures the fact that these habitats and the ecological processes within them are highly linked, with water mediating many of these linkages. While it is true that all habitats are ultimately connected in the marine environment, some habitats are more intimately connected than others.

Coral reefs provide a good example of this interconnectedness (Hatcher et al. 1989). The internal interconnectedness of coral reefs has historically been emphasized, giving the impression of self-contained entities: very productive ecosystems with nutrients essentially locked up in the complex biological community of the reef itself. Many of the most ecologically crucial habitats for reef organisms are actually not on the coral reef itself, however, but rather in seagrass beds, mangrove forests, and seamounts sometimes far from the reef (Birkeland and Frielander 2002; Mumby et al. 2004). Thus the coral reef ecosystem depends on these essential linked habitats as well. Currents and the mobile organisms themselves provide the linkages among the reefs, nursery habitats, and places where organisms move to feed or breed.

One of the strongest links between coastal subsystems is that between areas that act as nursery grounds for fish species. The majority of the world's marine fishery species are caught or reared in continental shelf waters, and many of these species spend at least some part of their life histories in the nearshore coastal habitats (Sherman 1993, cited in Burke et al. 2001). When nursery areas are lost due to habitat conversion, freshwater diversion from estuaries, or degradation, fisheries even outside the nursery area can be significantly affected (Deegan and Buchsbaum 2001; Lenanton and Potter 1987). Loss of nursery areas has been implicated in the collapse of some fisheries in North America, North Africa, and elsewhere (Chambers 1992; Deegan 1993).

Nursery areas and other habitats crucial for fisheries production can also be ecologically "lost" when degraded by seemingly natural (or, in any case, biotic) events. Harmful algal blooms, for instance, can be devastating to eggs and larvae of fish and can thus cause loss of nursery services. Often the population growth of such harmful algae is spurred by eutrophic conditions—the result of agricultural, sewage, aquacultural, or fish processing wastes overcoming the assimilative capacity of the coastal environment.

The ocean and coastal habitats are not only connected to each other, they are also inextricably linked to land. (See Table 19.3.) Fresh water is one specific mediator here: rivers and streams bring nutrients as well as pollutants to the ocean, groundwater flows to coastal systems, and the ocean gives some of these materials back to land via the atmosphere, tides and seiches, and other pathways, such as the deposition of anadromous fish (salmon carcasses, for instance) after spawning. The salinization of aquifers from marine intrusion, usually due to excessive freshwater extraction) is another factor. Seawater to freshwater linkages also occur; in experimental settings, polluted coastal water has been shown to contaminate freshwater aquifers (Jones 2003). But the atmosphere also provides a linkage, and land-sea-air interactions sometimes create complex feedback mechanisms between impacts on one habitat type and consequent impacts on another. For example, in

Table 19.2. Summary of Ecosystem Services and Their Relative Magnitude Provided by Different Coastal System Subtypes. The larger circles represent higher relative magnitude.

Direct and Indirect Services	Estuaries and Marshes	Mangroves	Lagoons and Salt Ponds	Intertidal	Kelp	Rock and Shell Reefs	Seagrass	Coral Reefs
Food	●	●	•	●	•	●	•	●
Fiber, timber, fuel	●	⬤	●					
Medicines, other	•	•	•		●			•
Biodiversity	●	●	●	⬤	●	⬤	●	⬤
Biological regulation	●	⬤	●	•		•		●
Freshwater storage and retention	•		•					
Biochemical	•	•			•			•
Nutrient cycling and fertility	●	●	●	•	•	•		●
Hydrological	•		•					
Atmospheric and climate regulation	●	●	●	•		•	•	●
Human disease control	●	●	●	●		•	•	•
Waste processing	⬤	⬤	●			•	●	•
Flood/storm protection	●	●	•	•	•	●	●	⬤
Erosion control	●	⬤	•				•	•
Cultural and amenity	⬤	•	●	⬤	•	●	●	⬤
Recreational	⬤	•	•	⬤	•			⬤
Aesthetics	●	•	●	●				⬤

Table 19.3. Fluxes from Land to Sea and from Sea to Land, Differentiating between Natural and Anthropogenic Factors (Modified from Kjerfve et al. 2002)

Factor	Land to Sea	Sea to Land
Natural	river discharge groundwater sediment nutrients and minerals humics and organics storm debris earthquake debris volcanic debris	energy and debris from hurricanes cold water and nutrients from upwelling wave action salt and salt aerosols sand nutrients through carcasses, guano
Anthropogenic	sediment (increase from land use and decrease from dams) nutrients and organic matter from agriculture and sewage coliform bacteria herbicides and pesticides heavy metals oil and chemicals	oil and chemical spills chronic input of oil and chemicals sewage from ships ballast water with exotic organisms debris from ships brackish infiltrations of groundwater reservoirs by water extraction pharmaceuticals

Florida in the United States, the loss of coastal wetlands and their buffering capability may have caused severe freezes affecting inland agricultural lands in recent winters, costing millions of dollars in failed crops (Marshall et al. 2003).

Coastal systems serve as a major sink for sediments and are major sites of nutrient-sediment biogeochemical processes. Water quality in river systems plays a crucial role in the sustainability of coastal aquatic habitats, food webs, and commercial fisheries that serve as a major protein source for humans (Burke et al. 2001). The transport of sediment and biotically active materials (nutrients and toxic substances) to the coastal zone through long-distance river transport ultimately links the continental landmass to the oceans (Vörösmarty and Meybeck 1999). (See Box 19.2.) Thus coastal issues need to be addressed from a system perspective involving the whole catchment scale and the coupling of human and natural systems.

The cross-habitat movement of nutrients, detritus, prey, and consumers exerts major effects on populations and food webs in practically all habitats and can sustain communities of abundant consumers even in places with little or no primary productivity (Polis et al. 1997). This relationship is particularly strong in the coastal system, especially where highly productive oceanic waters meet relatively unproductive, dryland habitats (Polis and Hurd 1996).

The Pacific coast of Peru is one of the best examples of this, where high- and low-productivity systems are juxtaposed: highly productive marine waters associated with upwelling of the Humboldt current are next to one of the world's most arid areas, the Atacama desert. The system of the Humboldt current has a primary productivity rate that makes it one the world's richest marine areas (Arntz and Fahrbach 1996), whereas the desert it faces receives less than 5 millimeters of rainfall a year. Other examples are the Namib Desert facing the Benguela upwelling system, the Banc d'Arguin region of Mauritania, and the coasts and islands of the Gulf of California in Mexico.

The movement of nutrients from the ocean to land can occur in two different pathways. The first is the guano pathway, which includes the accumulation of seabird excrement. This pathway is likely to be significant only for islands and rocky shores where sea birds congregate in large numbers. The second is the detritus/scavenger pathway, with a significant amount of biomass entering the terrestrial system through algal or seagrass mats and through animal carcasses washing ashore. Fish or mammals may also become vectors of marine-derived energy and nutrients by migrating over large distances. River otters and sea lions have been shown to enrich terrestrial vegetation with marine-derived nitrogen in coastal environments.

Perhaps the best-known example is anadromous Pacific salmon (*Oncorhynchus kisutch, O tshawytscha, O. nerka*), the carcasses of which fertilize forests (Helfield and Naiman 2003) and provide a valuable source of nutrients for scavengers in the sites where they congregate to spawn (Ben-David et al. 1998b). In regions these salmon carcasses seem to be a keystone nutrient resource for scavengers, populations of such scavengers are greatly affected by reductions in anadromous fish stocks (Willson and Halupka 1995).

The idea that marine resources are also a key resource to human populations is verified archeologically. Moseley (1975) proposed a "marine hypothesis" to demonstrate that the paradigm of agricultural economy as being the foundation of civilizations does not hold for ancient populations in coastal Peru. He proposed instead that the enormous productivity of the upwelling system caused the rise of Andean civilizations. Numerous archeologists have challenged this hypothesis, noting that other sources of food had to be available for populations exposed to high variability in marine productivity. However, there is no doubt that marine productivity accounted for a large part of the diet in several major coastal civilizations.

In the Atlantic, for example, cod was said to fuel the immigration and growth of New England and Canadian maritime population centers, and in Europe herring is thought to have underpinned the mercantile expansion. The declining availability of marine resources has affected large portions of these populations even today. More recently, it has been surmised that declining availability of coastal and freshwater fish for subsistence fishers in West Africa has driven the increase in the illegal bush meat trade. This trade, in turn, has imperiled many endangered species in the region and is thought to contribute to outbreaks of primate-borne and other viruses in human populations (Brashares et al. 2004).

Ocean climate in one region may affect land and coastal systems in another, and in complex ways. For instance, it is now surmised that the warming of the Indian Ocean has caused the recent droughts of the Sahel, directly affecting millions of people through increased crop failure and decreased health (Giannini 2003), while the increased desertification of the Sahel region may have caused mortality of corals half a world away through the transport and subsequent deposition of Saharan dust. (See MA Caribbean Sub-global Assessment.)

Thus, negative impacts on coastal ecosystems, whether on land, in areas of fresh or brackish water, or in the sea itself, have enormous ramifications for the health and productivity of other terrestrial and marine systems, in addition to affecting coastal systems and their provisioning of ecosystem services. As human population pressures continue to grow, these declines in coastal ecosystem services will increase the strain on coastal communities and have negative impacts on human well-being in coastal systems.

BOX 19.2

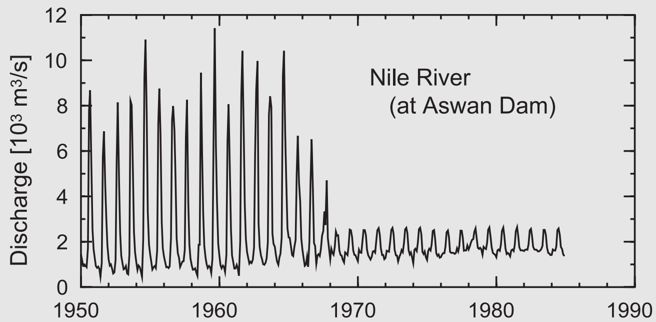
Trends in Sediment Loads into Coastal Zones

Fluvial systems evolve along with the landscape, and the sediment load observed today is influenced by the geologic history of these paleo-systems. Therefore it remains difficult to determine the sediment flux of unaffected rivers, given the natural variability within fluvial systems. While there is no accepted estimation for the paleo-flux of sediment to the coastal zones (Syvitski 2001, 2003), Milliman and Syvitski (1992) argued that the modern 20 gigatons a year global flux value may have been 50% smaller about 2,000 years ago, before human impact was great.

A recent study of the annual sediment load records for the world's rivers shows many examples of nonstationary behavior (Walling and Fang 2003). Simple trend analysis of this database indicates that about 50% of the sediment load records showed evidence of statistically significant upward or downward trends, with the majority evidencing declining loads. In about 50% of rivers, the sediment load records showed no evidence of significant trends. In some rivers, loads are declining as a result of dam construction and the implementation of soil and water conservation and sediment control programs. In other systems, loads are increasing due to land clearance and land use change and intensification, along with other forms of catchment disturbance and increased runoff as a result of increased precipitation and runoff. The results suggest that the dominant trends in sediment flux to the global coastal zone are either stability or a decrease. This analysis has not included rivers from other areas of the world, such as Africa, Southeast Asia, and South America.

Under this picture of the world's decreasing sediment load, less river sediment discharge alters the sedimentation-erosion equilibrium within the coastal zone. Coarse-grained bed load is normally taken to represent 10% or less of the total sediment discharge delivered to the coast. Hence, it has been assumed that a decrease of approximately 5% of the total sediment flux represents the critical threshold, beyond which the coastal system is likely to show evidence of significant deterioration (such as coastal erosion). This level of change results in mangrove siltation and severe erosion of coastal ecosystems and beaches (Lacerda et al. 2002). Thus river sediment flux plays an important role in the sediment budget of the coast.

Dramatic and virtually instantaneous changes are recorded in water fluxes measured at river discharge monitoring stations before and after impoundment. The Nile River has experienced, as many river systems worldwide, reduced flows and distortion of runoff due to water use for irrigation (Nixon 2003). (See Figure.)



Compared with the past five decades, both river discharge and sediment load will probably decrease for some large fluvial systems 30–40% in the next 50 years (Vörösmarty et al. 1997; Vörösmarty and Meybeck 1999) and decrease to 50% in the next 100 years as a result of human activities and dam construction (Yang et al. 1998). Thus general erosion in the coastal zone, including estuaries, deltas, and associated beach systems, seems to be inevitable.

The future discharge of sediment to the coastal oceans will continue to be controlled by humans and climate change. Determining the balance between increasing sediment loads (from land use, engineering, climate change, and climate variability) and decreasing sediment loads from reservoirs, engineering, climate change, and climate variability is of utmost importance for sound coastal zone and resource management (Syvitski 2003).

19.3 Coastal Systems and Human Communities

19.3.1 Humans in the Coastal System: Demographics and Use of Services

Humans are a natural element within coastal systems and have been so for thousands of years. However, the balance of nature in these systems has become altered. While human dependence on coastal systems has greatly increased in the last centuries, the impacts on the ecology of these habitats have become so severe that their productivity and functioning have been altered, mostly in the last few decades. It is increasingly difficult for coastal systems to accommodate the increased collective demands of growing populations and markets.

Coastal populations are not spread evenly throughout the coastal zone. Using night light analysis, Small and Nicholls (2003) graphically demonstrated the concentration of habitation on the world's coasts. Quantitative analysis of newer population data has shown that there has been a decrease in the rate at which interior populations are increasing relative to coastal populations. Coastal population densities are nearly three times that of inland areas: in 2000, population density in coastal areas was 99.6 people per square kilometer, while in inland areas density was 37.9 people per square kilometer (Kay and Alder in press). At the turn of the millennium, half of the world's major cities (those with more than 500,000 people) were found within 50 kilometers of a coast. Growth in these cities since 1960 was significantly higher than in inland cities of the same size (Kjerfve et al. 2002).

Not only are population pressures high relative to those in many other ecosystems worldwide, but the bulk of those pressures stress many of the most ecologically important and valuable ecosystems within coastal zones. Some 71% of the world's coastal people live within 50 kilometers of an estuary, 31% live within 50 kilometers of a coral reef system, 45% live within 50 kilometers of mangrove wetlands, and 49% live within 50 kilometers of seagrass ecosystems (See Table 19.4.) This is not accidental, of course—these habitats and the ecosystem services they provide present many of the "pull" factors that resulted in initial settlement along a coast as well as subsequent migration to it. Historically, settlements first inhabited the sheltered areas near estuarine bays (many with associated mangrove and seagrass) and reef-protected coasts and only later expanded to other coastal areas.

Conversely, 58% of the world's major coral reef systems occur within 25 kilometers of urban centers with more than 100,000 people; 62% of major estuaries occur near such urban centers, and 64% of major mangrove forests are found near major centers. This

Table 19.4. Share of World and Coastal Populations Living within 50 Kilometers of Estuaries, Coral Reefs, Mangroves, and Seagrass. Based on spatially referenced population data; due to overlap of some habitat types, figures do not add up to 100 percent. (CIESN 1995)

Subtypes	Population	Share of World Population	Share of Coastal Population
	(million)	*(percent)*	
Estuaries	1,599	27	71
Coral Reefs	711	12	31
Mangroves	1,030	18	45
Seagrass	1,146	19	49
Total	**5,596**		

means that pressures from urbanization, including habitat conversion as cities and their areas of influence grow, are affecting the majority of these key coastal habitats. In fact, analysis of areas of recent rapid land cover change shows that all but three of the world's cities showing greatest rates of change and highest population occur in coastal areas, in both the tropics as well as higher latitudes. (See Chapter 28 for more on this work.)

By all commonly used measures, the human well-being of coastal inhabitants is on average much higher than that of people in inland communities. Of the world's total GNP of approximately $44 trillion, 61% comes from coastal areas within 100 kilometers of a coastline. Whereas per capita GNP in 1999 averaged only $4,018 across all inland areas, in the 100-kilometer coastal area it was nearly four times as much—at $16,035. Figure 19.8 shows that the concentration of global wealth as measured by GNP occurs primarily in coastal regions, although concentrations of wealth also occur in some inland areas (especially in the United States and Europe). Infant mortality and life expectancy indices are also thought to be relatively better in coastal areas. This situation partly explains why rates of population increase are highest in coastal areas.

Nonetheless, many coastal communities are at risk. There are considerable physical risks associated with living in some coastal areas; low-lying atolls, for example, are at risk of catastrophic events such as hurricanes, cyclones, tsunamis, and storm surge flooding, as well as losses incurred from both sudden and chronic shoreline erosion. Figure 19.9 illustrates potential global vulnerability to erosion by highlighting areas where soil types and slope make shorelines prone to erosion and inundation from storm events. Many of these risks are increasing with climate change–driven changes to meteorology. And some countries, such as the United Kingdom, are developing contingency plans to cope with such changes (see www.foresight.gov.uk/fed.html). Some areas are prone to flooding because of relative changes in sea level—the average global sea level rise is projected at 1–2 millimeters per year over the next century (Church et al. 2001). This is an especially acute problem in small island nations, atoll communities, and low-lying flood-prone areas like much of Bangladesh.

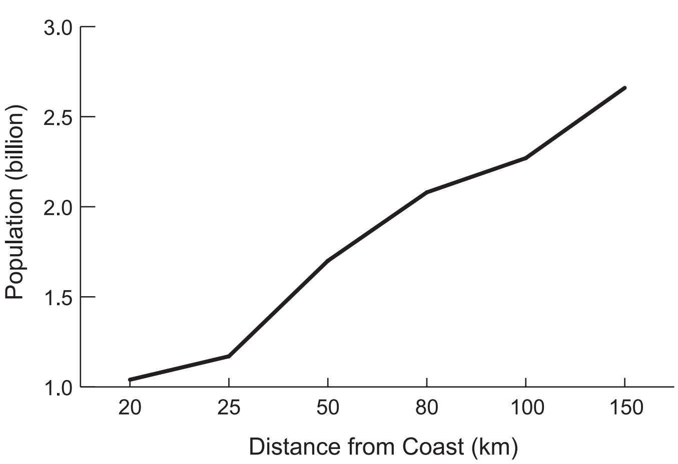


Figure 19.8. Population Density by Distance from Coast (CIESIN 2003)

Coastal communities are also at risk because the coastal ecosystems they exploit and rely on are stressed—and many are nearing ecological breaking point or thresholds (Birkeland 2004; Dayton 2003). Technological advances that allow greater access to resources, including boat design, navigation, fishing gear, and oil exploration methods and equipment, have pushed the use of many coastal resources beyond sustainable limits. Such advances have also increased the conflicts between large-scale industries and small-scale local users, such as subsistence fishers (Curran and Agardy 2002). Poorly planned or executed development has already compromised the ability of many coastal ecosystems to provide regulating services such as maintenance of hydrological balance, nutrient fluxes, and shoreline stabilization (Kay and Alder in press). Thus the relatively high levels of human well-being experienced by many coastal communities are at risk of declining as ecosystems continue to be degraded, lost, or rendered unproductive.

Human communities are also at risk from the health implications of these degraded ecosystems. Cholera and other waterborne diseases are on the rise in coastal countries (Anderson et al. 2001) and may be related to eutrophication-driven algal blooms (Colwell and Spira 1992; Islam et al. 1990). Cholera affects human well-being directly by increasing human morbidity and mortality rates, but it also has severe economic impacts in coastal countries (Rose et al. 2001). For instance, tuna coming from countries having incidences of cholera must be quarantined; this restriction affects many of the major tuna-producing and -exporting countries.

Algal blooms (including red tides) have caused neurological damage and death in humans through consumption of affected seafood (Rose et al. 2001). There are significant health impacts from swimming and bathing in water contaminated by fecal coliform and other pathogens; approximately half the people living in coastal areas have no access to sanitation, and even where sewage treatment exists it is often inadequate, with the result that coastal areas become polluted (UNEP 2002). In a particularly severe outbreak in Italy in 1989, harmful algal blooms cost the coastal aquaculture industry $10 million and the Italian tourism industry $11.4 million (UNEP 1992). Ciguatera, a tropical fish disease causing severe illness and sometimes mortality in humans who consume affected fish, is on the rise, both in terms of the number of cases and number of affected areas.

Human health effects are also caused by pollution of nearshore waters, whereby humans eat fish or other marine products that contain heavy metals, PCBs, and other toxins that have bioaccumulated in the food chain (Verlaan 1997). UNEP and the Water Supply and Sanitation Council estimate the global economic costs related to pollution of coastal waters is $16 billion annually (www.wsscc.org), much of which is due to human health impacts.

Changes in coastal systems also affect the well-being of those living there and elsewhere in more subtle ways. The destruction

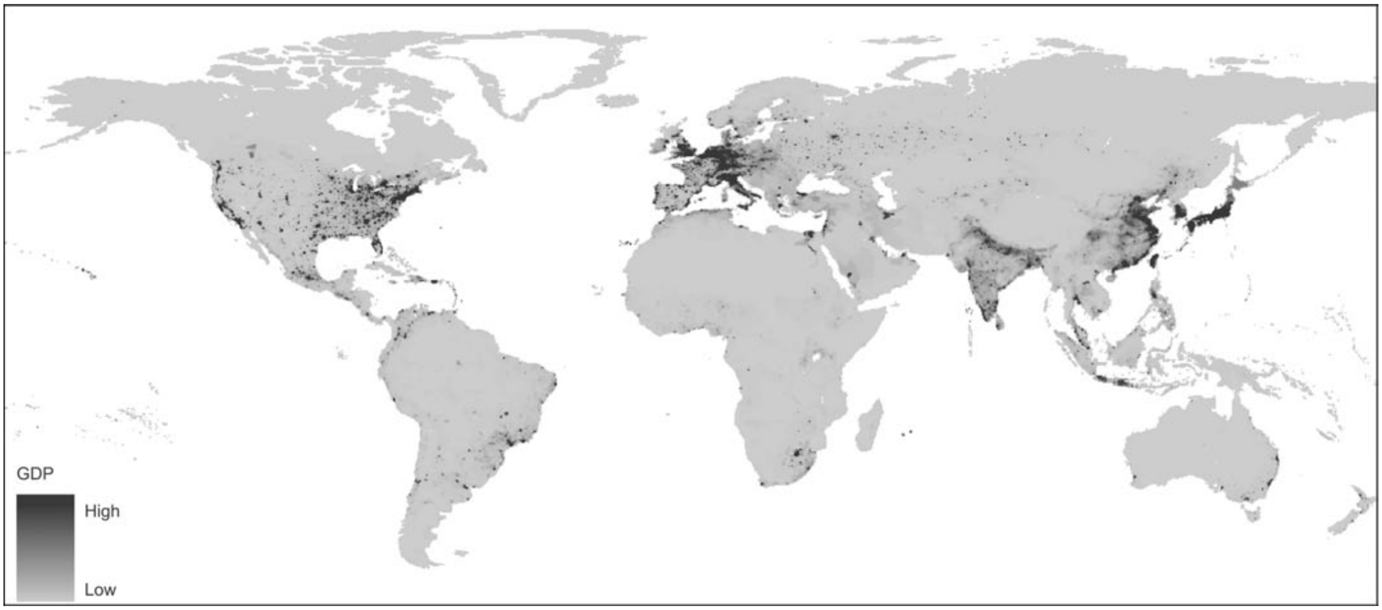


Figure 19.9. Relative Levels of GDP (CIESIN 2003; World Bank 2004)

of places that create opportunities for recreation, that are spiritually or culturally important, or that could potentially increase our knowledge and respect for the natural world entail costs that are more difficult to quantify. Surveys everywhere show that humans maintain strong spiritual connections to the sea and care about its condition, even if they live far inland with no direct reliance on coastal areas for obtaining food or employment, for example.

19.3.2 The Value of Coastal System Services

Coastal ecosystems provide a wide range of services to human beings (Wilson et al. 2004). These include regulation and supporting services such as shoreline stabilization, nutrient regulation, carbon sequestration, detoxification of polluted waters, and waste disposal; provisioning services such as supply of food, fuelwood, energy resources, and natural products; and amenity services such as tourism and recreation. These services are of high value not only to local communities living in a coastal zone (especially in developing countries), but also to national economies and global trade (Peterson and Lubchenco 1997).

In addition to the production of marketable goods and services, such as commercial fisheries and tourism, coastal systems provide services such as nutrient recycling, support for terrestrial and estuarine ecosystems, habitat for plant and animal life, and the satisfaction people derive from simply knowing that a beach or coral reef exists (Wilson et al. 2004). While estimating exchange-based values of marketed services in this case is relatively straightforward, as observable trades exist from which to measure value (Freeman 1993), estimating the economic value of coastal services not traded in the marketplace is more difficult (Freeman 1993; Bingham et al. 1995). However, such analysis often reveals social costs or benefits associated with coastal ecosystem services that otherwise would remain hidden or unappreciated. Market values and nonmarket values are discussed separately in this section.

Studies of specific regions and biomes give us some idea of the enormous economic value of coastal habitats (Balmford et al. 2002). The Wadden Sea in northern Europe, for instance, has provided up to one quarter of the North Sea catch of plaice, sole, shrimp, dab, and herring (De Groot 1992). Coral reef–based fisheries are also valuable: those in Southeast Asia generate $2.4 billion per year (Burke et al. 2001). Although it is widely cited that coral reefs contribute about one quarter of the annual total fish catch in developing countries, providing food to about 1 billion people in Asia alone, the empirical evidence to support such statements is not strong. However, the value of reef fisheries in this region is undeniably significant: Cesar et al. (2003) estimated net benefit streams of reef-dependent fisheries in Asia at over $2 billion.

In principle, a global picture of the potential economic value associated with the coastal zone can be built up via the aggregation of a number of existing valuation studies. For example, in a preliminary estimate of the total economic value of ecosystem services provided by global systems, Costanza et al. (1997) showed that while the coastal zone covers only 8% of the world's surface, the goods and services provided by it are responsible for approximately 43% of the estimated total value of global ecosystem services: $12.6 trillion (in 1997 dollars). While controversial (Pimm 1997; Pearce 1998), this preliminary study made it abundantly clear that coastal ecosystem services do make significant contributions to human well-being at a global scale. Furthermore, it demonstrated the need for additional research and indicated that coastal areas are among the ecosystems most in need of additional study (Costanza 2000).

19.3.2.1 Market Coastal Values

Coastal ecosystems are among the most productive in the world today, rivaling even tropical rainforests in terms of their overall productivity of raw materials and goods used by humans (Primavera 1991; Spurgeon 1992; Barbier 1993). As the following examples show, many coastal regions are valued through market activities that directly support humans—such as fishing, hunting, fuelwood and woodchip extraction, harvesting ornamental materials, and the extraction of medical resources.

Coastal systems generate a variety of seafood products such as fish, mussels, crustaceans, sea cucumbers, and seaweeds (Moberg and Folke 1999; Ronnback 1999). Many commercially important marine species, like salmon, shad, grouper, snapper, bluefish, striped bass, and invertebrates (such as shrimp, lobster, crabs, oysters, clams, mussels), use coastal nursery habitats. Capture fisheries in coastal waters alone account for $34 billion in yields annually. (See Chapter 18.) Given this level of economic productivity, it is perhaps not surprising that overfishing and intensive aquaculture have caused serious ecological and social problems in coastal regions throughout the world (Primavera 1991; Primavera 1997; Jackson et al. 2001).

Valuation studies of food directly or indirectly supplied by coastal systems have predominantly focused on the economic value of fishery products (Batie and Wilson 1978; Lynne et al. 1981; Farber and Costanza 1987; Buerger and Kahn 1989; Rivas and Cendrero 1991; Bennett and Reynolds 1993; Ruitenbeek 1994; Kaoru et al. 1995; Deb 1998; Gilbert and Janssen 1998; Ronnback 1999; Barbier 2000; Sathirathai and Barbier 2001). Most often, the market price of seafood products is used as a proxy when calculating the value of ecosystem goods provided by coastal systems. For example, the annual market value of seafood supported by mangroves has been calculated to range from $750 to $16,750 (in 1999 dollars) per hectare (Ronnback 1999). High-value species are harvested from coral reefs to meet live fish demand in restaurants, mainly in Asia. (See Chapter 18.)

Coastal areas also provide the foundation for the mariculture (marine aquaculture) industry, which uses coastal space or relies on wild stock to produce valuable fisheries products, from tiger prawns to bluefin tuna. Human reliance on farmed fish and shellfish is significant and growing. Global annual per capita consumption of seafood averages 16 kilograms, and one third of that supply currently comes from aquaculture (Lubchenco 2003). Globally, aquaculture is the fastest-growing food-producing sector, with production rates doubling in weight and value from 1989 to 1998 (Goldburg et al. 2001). Much of that growth has occurred in the shrimp and salmon farming industries.

Besides food and raw materials, at least three other types of marketable goods are provided by coastal systems: genetic, medical, and ornamental resources. For example, coral reefs have been shown to be an exceptional reservoir of natural bioactive products, many of which exhibit structural features not found in terrestrial natural products (Carte 1996). The pharmaceutical industry has discovered several potentially useful substances among the seaweeds, sponges, mollusks, corals, sea cucumbers, and sea anemones of reefs (Carte 1996; Moberg and Folke 1999). (See Chapter 10 for more on bioprospecting in coastal systems.) Furthermore, many coastal products are collected not only as food but also to sell as jewelry and souvenirs. Mother-of-pearl shells, giant clams, and red coral are collected and distributed as part of a worldwide curio trade (Craik et al. 1990). The marine aquarium market is now a multimillion-dollar industry trading in live reef-dwelling fishes that are collected and shipped live from coral reef communities (Moberg and Folke 1999; Wabnitz et al. 2003).

19.3.2.2 Nonmarket Coastal Values

In addition to marketable goods and products, landscape features and ecological processes within the coastal zone also provide critical natural services that contribute to human well-being and have significant economic value (Farber and Costanza 1987). As the data just cited suggest, much of what people value in the coastal zone—natural amenities (open spaces, attractive views), good beaches for recreation, high levels of water quality, protection from storm surges, and waste assimilation/nutrient cycling—is provided by key habitats within coastal systems. In Thailand, the conversion of mangroves to shrimp aquaculture ponds reduced the total economic value of the intact mangroves by 70% in less than a decade (Balmford et al. 2002).

Open space, proximity to clean water, and scenic vistas are often cited as a primary attractor of residents who own property and live within the coastal fringe (Beach 2002). Hedonic pricing techniques have been used to show that the price of coastal housing units varies with respect to characteristics such as ambient environmental quality (proximity to shoreline, for example, or water quality) (Johnston et al. 2001). For example, Leggett and Bockstael (2000) use hedonic techniques to show that water quality has a significant effect on property values along the Chesapeake Bay in the United States. They use a measure of water quality—fecal coliform bacteria counts—that has serious human health implications and for which detailed, spatially explicit information from monitoring is available. The data used in this analysis consist of sales of waterfront property on the western shore of the Chesapeake Bay between 1993 and 1997 (Leggett and Bockstael 2000). The authors consider the effect of a hypothetical localized improvement in observed fecal coliform counts on a set of 41 properties. The projected increase in property values due to the hypothetical reduction in coliform bacteria totaled approximately $230,000. Extending the analysis to calculate an upper limit benefit for 494 properties, it is estimated that the benefits of improving water quality at all sites would be around $12.145 million (Leggett and Bockstael 2000).

Stretches of beach, rocky cliffs, estuarine and coastal marine waterways, and coral reefs provide numerous recreational and scenic opportunities. Boating, fishing, swimming, walking, beachcombing, scuba diving, and sunbathing are among the leisure activities that people enjoy worldwide and thus represent significant economic value (Farber 1988; King 1995; Kawabe and Oka 1996; Ofiara and Brown 1999; Morgan and Owens 2001). Both travel cost and contingent valuation methods are commonly used to estimate this value. (See Chapter 2 for more on these valuation techniques.) For example, the Chesapeake Bay estuary has also been the focus of considerable research on nonmarket recreational values associated with coastal systems. When attempting to estimate the monetary worth of water quality improvements in Chesapeake Bay, Bockstael et al. (1989) focused on recreational benefits because it was assumed that most of the increase in well-being associated with such improvements would accrue to recreational users. The authors estimated the average increases in economic value for beach use, boating, swimming, and fishing with a 20% reduction in total nitrogen and phosphorus being introduced into the estuary. Using a combination of the two valuation methods, the annual aggregate willingness to pay for a moderate improvement in the Chesapeake Bay's water quality was estimated to be in the range of $10–100 million (in 1984 dollars) (Bockstael et al. 1989).

Global tourism has been deemed the world's most profitable industry, and coastal tourism is one of its fastest-growing sectors. Much of this tourism centers on aesthetically pleasing landscapes and seascapes, intact healthy coastal ecosystems with good air and water quality, opportunities to see diverse wildlife, and so on. For instance, much of the economic values of coral reefs—with net benefits estimated at nearly $30 billion each year—is generated from nature-based and dive tourism (Cesar et al. 2003). The demand for biologically rich sites to visit increases the value of intrinsically linked habitats such as mangroves and seagrass beds. Temperate bays and estuaries can similarly generate tourism revenues of similar orders of magnitude.

The link between tourist visits and the revenues from and condition of the coastal system has not been analyzed at the global level, but local case studies point to a strong correlation between value and condition. In the United States alone, reef ecosystems with their nursery habitats support millions of jobs and billions of dollars in tourism each year. For example, reef-based tourism generated over $1.2 billion in the Florida Keys alone, while in Hawaii, reefs generate some $360 million per year, with annual gross revenues generated from just one half-square-mile coral reef reserve exceeding $8.6 million (Birkeland 2004).

As these reefs decline in biodiversity and ecosystem health, these nature-based tourism industries stand at risk (Cesar and Chong 2004). In Jamaica and Barbados, for instance, destruction of coral reefs resulted in dramatic declines in visitation; loss of revenue streams subsequently led to social unrest and even further tourism declines (MA Sub-global Assessment on Caribbean Sea). Similarly, ''willingness to pay'' studies in the Indian Ocean suggest that the health of coral reefs is an important factor for tourists: they were willing to pay, on average, $59–98 extra per holiday to experience high-quality reefs (Linden et al. 2002). And in Florida, reef degradation is rapidly changing the structure of the tourism market, from high-value, low-volume tourism toward larger numbers of budget travelers (Agardy 2004).

Recreational fishing is also a major industry in many parts of the world, and it primarily targets marine or anadromous fishes in coastal ecosystems. The estimated revenue generated by coral reef–based recreational fisheries reaches several hundred million dollars annually (Cesar et al. 2003). The coastal zone also supplies nonmarket values associated with both recreational and commercial fisheries by providing some of the most productive habitat refugia in the world (Gosselink et al. 1974; Turner et al. 1996). Eelgrass, salt marsh, and intertidal mud flats all provide a variety of services associated with their nursery functions (Gosselink et al. 1974; Turner et al. 1996).

As already noted, improvements in the condition of these habitats may ultimately lead to measurable increases in the production of market goods such as fish, birds, and wood products. In other cases, however, ecological productivity itself can represent a unique class of values not captured by traditional market-based valuation methods. (See Box 19.3.) Instead, these values represent an increase in the production of higher trophic levels brought about by the increased availability of habitat, though analysis must be careful not to risk double counting some aspects of value or measuring the same benefits in different ways.

The seas and coasts are also of great spiritual importance to many people around the world, and such values are difficult to quantify. While the depth and breadth of these values are as diverse as the cultures that are found worldwide, there is the common theme of a cultural or spiritual connection. For example, the Baju peoples of Indonesia (Sather 1997) and the aboriginal people of the Torres Strait in Australia have a culture intimately connected to oceans, while many of the native peoples of North America have similar strong ties to coastal systems. Even systems on which we place low economic value today may be of importance and value tomorrow because they support species that may turn out to have pharmaceutical value or because they support species or habitat types that may become rare and endangered in the future. This gives them high option value associated with an individual's willingness to pay to safeguard the option to use a natural resource in the future, when such use is not currently planned. Non-use values are representative of the value that humans bestow upon an environmental resource, despite the fact they may never use or even see it.

In summary, ecosystem services are critical to the functioning of coastal systems and also contribute significantly to human well-being, representing a significant portion of the total economic value of the coastal environment. The best available market and nonmarket data suggest that substantial positive economic values can be attached to many of the marketed and nonmarketed services provided by coastal systems.

BOX 19.3

Examples of Productivity Analyses

In an example of coastal wetland productivity analysis, Johnston et al. (2002) used a simulation model based on biological functions that contribute to the overall productivity of the food web in the Peconic Estuary System in Suffolk County, New York, in the United States. Based on habitat values for fin and shellfish, birds, and waterfowl, an average annual abundance per unit area of wetland habitat in the estuary system was estimated by summing all relevant food web values and habitat values for a year (Johnston et al. 2002). The value of fish and shellfish was based on commercial harvest values. The marginal value of bird species usage of the habitat was based on the benefits human receive from viewing or hunting waterfowl. Using these values as input data, the simulation model resulted in annual marginal asset values for three wetland types: eelgrass ($1,065 per acre per year); salt marsh ($338 per acre per year); and intertidal mud flat ($67 per acre per year).

Farber and Costanza (1987) estimated the marginal productivity of a coastal system in Terrebonne Parrish, Louisiana, in the United States by attributing commercial values for several species to the net biomass, habitat, and waste treatment of the wetland ecosystem. Arguing that the annual harvest from an ecosystem is a function of the level of environmental quality, the authors chose to focus on the commercial harvest data for five different native species—shrimp, blue crab, oyster, menhaden, and muskrat—to estimate the marginal productivity of wetlands. The annual economic value (marginal product) of each species was estimated (in 1983 dollars) as shrimp, $10.86 per acre; blue crab, $0.67 per acre; oyster, $8.04 per acre; menhaden, $5.80 per acre; and muskrat pelts, $12.09 per acre. Taken together, the total value of marginal productivity of wetlands in Terrebonne Parrish was estimated at $37.46 per acre.

19.4 Projections of Trends, Areas of Rapid Change, and Drivers of Change

19.4.1 Projections of Trends and Areas of Rapid Change

Coastal habitat loss is likely to continue and possibly accelerate as increasing and sometimes conflicting demands for coastal space and resources rise (*high certainty*). Coastal systems and the habitats within them are rapidly becoming degraded around the globe; many have been lost altogether. Sometimes the changes are natural (such as hurricanes and naturally occurring climate variation), but more often than not the impacts are human-induced. These anthropogenic impacts are direct, such as the filling in of wetlands, or indirect, such as the diversion of fresh water from estuaries or land-based sources of pollution. Habitat is lost, usually permanently, when coastal development and marine resource use is destructive or unsustainable.

The greatest factor leading to loss of coastal habitats is conversion of wetlands, including marshes, seagrass beds, mangrove forests, beaches, and even mudflats to make way for coastal development. In the Philippines, for instance, 210,500 hectares of mangrove—40% of the country's total mangrove cover—were lost to aquaculture from 1918 to 1988 (UNESCO 1993). By

1993, only 123,000 hectares of mangroves were left—equivalent to a loss of 70% in roughly 70 years (Nickerson 1999; Primavera 2000). Transportation infrastructure claims much coastal land and will continue to do so as roads are widened, ports and airports are expanded, and so on. Climate change–induced sea level rise will likely exacerbate rates of habitat loss due to development, especially in vulnerable areas such as atolls, deltas, and floodplains (Nicholls 2004). Habitat conversion and loss is thus expected to continue, at least until all available natural habitat is used up or until policy reform stems the tide of habitat loss.

Exploitation beyond sustainable levels is likely to continue and even increase in rate for many resources (*high certainty*). Coastal ecosystems will likely continue to be used for both commercial and artisanal fisheries, and if current trends continue many of these stocks will be depleted to commercial and ecological extinction. The drivers behind coastal resource overexploitation may be direct, such as consumption, or they may be indirect, such as marginalization, perverse subsidization, political corruption, and socioeconomic condition (Myers and Kent 2001). (See Chapter 18.)

Some members of the biological community in coastal habitats have special roles to play in maintaining ecological interactions; the removal of keystone species, for example, can cause large-scale ecological havoc (Kaufman and Dayton 1997). The removal of fish and invertebrates that graze algae living on seagrasses can destroy seagrass beds when heavy algal mats subsume the seagrass meadows. Human activities also affect coastal ecology indirectly by causing the alteration and degradation of distant habitat and by causing mortality of species within the habitat (Keough and Quinn 1998). This threat is often unseen, noticed only once the cumulative effects of degradation has altered or destroyed these ecosystems.

One of the most severe anthropogenic impacts on coastal areas in the near future will likely be through continued interference with hydrology and water flows to the coast (Pringle 2000) (*medium certainty*). Diversion of fresh water from estuaries and riparian-zone conversion of land for agriculture, human use, and hydroelectric generation causes the hypersalinization of estuarine areas and renders them unable to fulfill these important ecological functions and services (Diop et al. 1985; Weinstein and Kreeger 2000). Reduced water delivery to coasts also lowers sediment delivery and greatly accelerates rates of deltaic loss and coastal erosion. For instance, the damming of the Nile caused severe erosion and exacted high costs due to the need for shoreline protection, as well as loss of fertility of agricultural lands in the floodplain. Fisheries in the Nile Delta region of the Mediterranean have also been altered and yields decreased, at least in part due to silicate depletion and changes in phytoplankton communities away from diatoms.

Although there are many specific, often quantified benefits derived from the use and diversion of water in river basins, such hydrological changes are expected to cause rapid change to many estuaries, deltas, and semi-enclosed seas worldwide in coming years, with largely unknown consequences. (See Box 19.4.)

The next few decades will see large increases in rates of eutrophication and prevalence of hypoxic or dead zones as levels of nutrient inputs and wastes rise and as ocean waters warm (*high certainty*). Some 77% of the pollutant load reaching the coastal ecosystems currently originates on land, and 44% of this comes from improperly treated wastes and runoff (Cicin-Sain et al. 2002). These figures are expected to rise if population growth continues to outpace proper sanitation and if agricultural and other runoff remains unregulated. The result will be increased rates of eutrophication through the addition of large quantities of fertilizers, sewage, and other non-natural nutrients, which will change the processes occurring in these ecosystems (NRC 2000). Eutrophied conditions are evident in virtually all coastal waters near areas of human habitation, being especially acute in areas where coastal wetlands and their filtering function have been destroyed. High nutrient concentrations are expected to have particularly large impacts on the ecology of semi-enclosed and other seas in arid areas (Beman et al 2005).

Since nutrient production through agricultural waste and human sewage are expected to increase in the future, and since wetland loss will likely occur at current or higher rates, eutrophication will undoubtedly increase worldwide (*medium certainty*). Numerous river basin and coastal zone studies (in the Baltic region, for instance, the Mississippi River and Gulf of Mexico, the North Sea, the Northern Adriatic, and the Black Sea) have shown that elevated levels of nutrients, coastal eutrophication, toxic phytoplankton blooms, and bottom-water hypoxia are a consequence of human settlement and industrialization. It has been estimated that fluvial fluxes of inorganic N and P to the world oceans have increased severalfold over the last 150–200 years. In certain regions, such as in Western Europe, N and P levels are ten- to twentyfold over pre-industrial levels (Meybeck and Ragu 1997; Vörösmarty and Meybeck 1999).

With *high certainty,* pollutant levels are expected to increase in the near future, despite effective controls on some substances in some areas. River loadings of biotically active elements, metals, hormones, antibiotics, and pesticides are known to have increased severalfold since the beginning of the industrial era, and levels of these toxins are expected to continue to increase. Pollutants not only affect water quality, and with it many provisioning and amenity services, but are also implicated in large-scale failures of fish farming operations. These failures are extremely costly (white spot syndrome in shrimp cost India $200 million over three years, and it nearly caused the collapse of the shrimp farming industry in Ecuador in 1999), and they can affect both ecosystem health at the farming site and human health where the product is consumed. Human health effects from all forms of pollutants have not been comprehensively quantified, but coastal pollutant–related human mortality and morbidity are undoubtedly on the rise (Verlaan 1997).

The geographically largest impacts to coastal systems will be caused by global climate change, and since rates of warming are generally expected to increase in the near future, projected climate change–related impacts are also expected to rise (IPCC 2003). Warming of the world's seas degrades coastal ecosystems and affects species in many ways: by changing relative sea level faster than most biomes can adapt; by stressing temperature-sensitive organisms such as corals and causing their death or morbidity (in corals, this is most often evidenced by coral bleaching); by changing current patterns and thus interfering with important physiobiotic processes; and by causing increased incidence of pathogen transmission. Coral reefs may be the most vulnerable, having already evidenced rapid change, and some projections predict the loss of all reef ecosystems during this century (Hughes et al. 2003). Climate change also alters the temperature and salinity of estuary and nearshore habitats, making them inhospitable to species with narrow temperature tolerances. Warming can also exacerbate the problem of eutrophication, leading to algal overgrowth, fish kills, and dead zones (WRI 2000). (See Figure 19.10 for the location of major hypoxic areas in coastal systems.) Finally, warming is expected to further increase the transmission rates of pathogens and hasten the spread of many forms of human and nonhuman disease.

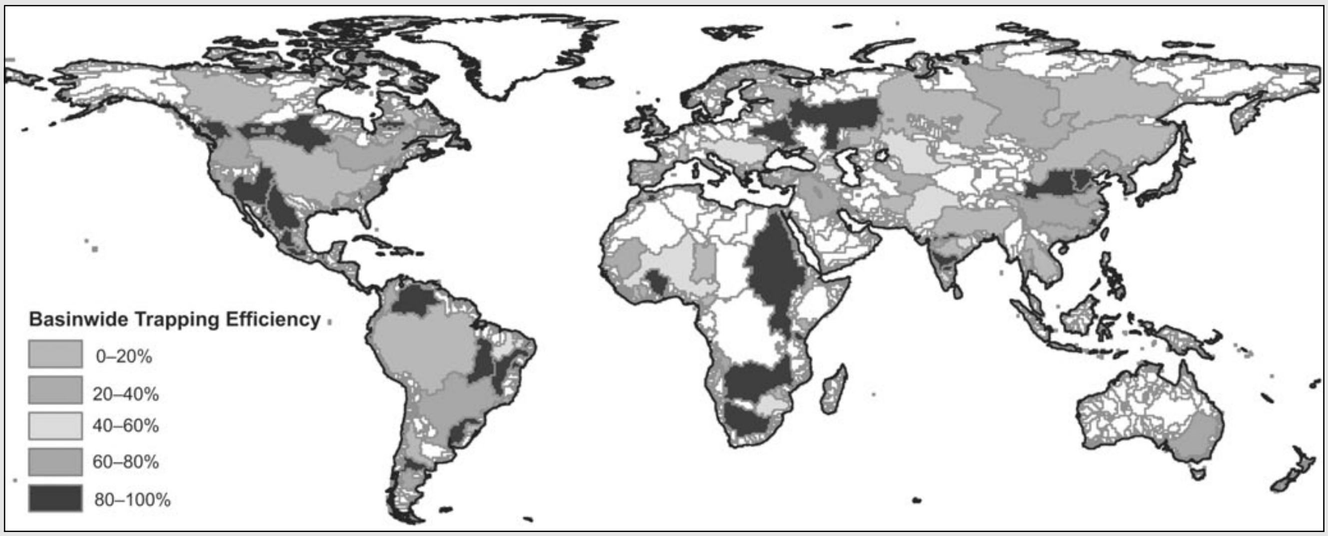
BOX 19.4

Water Diversion in Watersheds versus Water and Sediment Delivery to Coasts

The degree to which river water and sediment reach the coastal zone depends on other human activities, such as the construction of structures for water diversion, flood control, power generation, and recreation. Reservoirs and irrigation channels can retain a large proportion of the fluvial sediment discharge (Farnsworth and Milliman 2003). According to Vörösmarty et al. (1997, 2003), the 663 dams with large reservoirs (greater than 0.5 cubic kilometers maximum storage capacity) globally store about 5,000 cubic kilometers of water (approximately 15% of the global river water discharge). Also, global large reservoirs intercept more than 40% of global water discharge, and approximately 70% of this discharge maintains a sediment trapping efficiency of more than 50%.

Further analysis of the recent history of anthropogenic sediment retention by large dams (Vörösmarty et al. 2003) indicates that between 1950 and 1968, there was an increase from 5% to 15% in global sediment trapping, another increasing trend to 30% by 1985, and stabilization thereafter. As much as 25% of the current sediment load from the land to the coastal zones is trapped behind reservoirs. The trapping effect of fresh water discharge and suspended sediment by 45,000 dams analyzed in this study has dramatic impacts on water and sediment destined for the global coastal zone and inland seas. (See Figure.) Assuming that the global natural sediment discharge is between 18 and 20 gigatons per year, then the combined impact of all large dams will be on the order of 4–5 gigatons per year. Therefore, modern dam construction reduces the global sediment flux to the world's coastal zones by 25–30%.

According to Syvitski (2003), by decreasing sediment loads to the river through damming, coastal erosion is increased, and coastal marine ecosystems frequently deteriorate. Many dramatic examples of river control and utilization and their impacts on coastal systems have been recognized. After the Aswan Dam was completed in 1964, for example, the productive fishery collapsed and was reduced by 95%, and the delta subsided rapidly. The fishery remained unproductive for 15 years. It began a dramatic recovery during the 1980s, coincident with increasing fertilizer use and thus a flux of nutrients, expanded agricultural drainage, and increasing human population and sewage collection systems (see Nixon 2003). Similarly, after the Colorado River in the United States was dammed, sediment and nutrient discharge decreased dramatically and the shrimp catch in Baja California collapsed. After completion of the Kotri Barrage on the Indus River in Pakistan in 1956, fish catch decreased by a factor of three. And in China's Sea of Bohai, when the sediment discharge of the Yellow River was reduced the shrimp fishery decreased by 85% and the percentage of high-quality fish dropped by an order of magnitude.



Climate change–related sea level rise will cause continued inundation of low-lying areas, especially where natural buffers have been removed (Church et al. 2001). Sea level rise is due to thermal expansion of ocean waters and melting of land based–ice, and both expansion and ice melts are expected to increase (IPCC 2003). In most if not all cases, global climate change impacts act in negative synergy with other threats to marine organisms and can be the factor sending ecosystems over the threshold levels of stability and productivity. In limited cases, new habitats may be created. Changes in weather patterns modeled in some extreme scenarios of climate change—including increased precipitation in some areas, abrupt warming at the poles, and increased frequency and intensity of storm events—would affect oceanic circulation (perhaps even leading to the collapse of thermohaline circulation) and currents as well as the ability of organisms to live or reproduce.

Different coastal subtypes, habitats, and even taxonomic groups will be affected by these direct and indirect impacts to greater or lesser degrees. Coral reefs may be the most vulnerable of all coastal subtypes (*medium certainty*), since multiple threats affect systems and since tolerances for corals and related reef species are generally of a narrow range. Estuaries are also vulnerable because these systems are directly subject to impacts from land (Gosselink et al. 1974; Turner et al. 1996) and water. Semi-enclosed seas are more vulnerable to degradation than open ocean basins—and because more isolated coastal waters have higher endemism, biodiversity is at greater risk in these areas.

Looking ahead 10–50 years suggests that some geographic areas of the world are expected to show particularly high rates of change and loss of certain ecosystem services. Southeast Asia, with its burgeoning population growth, limited land area, and largely ineffective controls on fisheries, pollution, and coastal development, is expected to continue to be an area of extremely rapid coastal change with losses in food provisioning, biodiversity, nutrient cycling, and storm protection services (*high certainty*). Small islands will continue to suffer dramatic alterations to their coastal

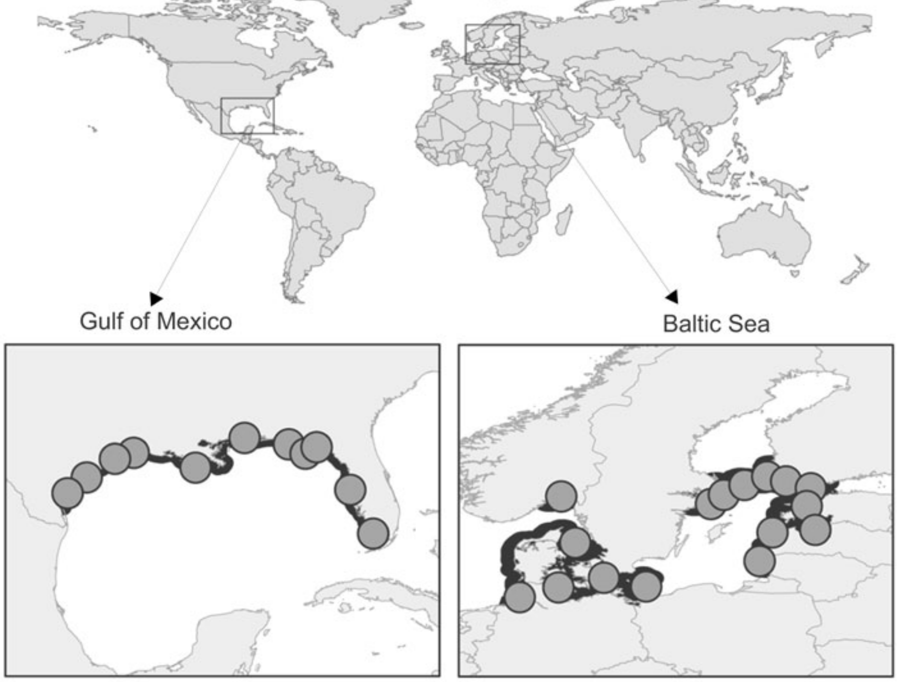


Figure 19.10. Hypoxic Zones in Gulf of Mexico and Baltic Sea (UNEP 2004)

environments, especially in the Pacific Ocean, Indian Ocean, and Caribbean Sea, where archipelagos of small islands support large numbers of residents and tourists but where monitoring and enforcement of regulations is difficult due to the distances between islands and limited resources. The areas of greatest change in land use that are situated in the coastal zone, such as those in the Middle East region, will also suffer rapid coastal change in the coming years.

The continued degradation of coastal ecosystems is paradoxical. Despite the value of coastal areas in supporting the tourism industry, for instance, coastal tourism development often uses habitats such as estuaries, mangroves, marshes, and atoll lagoons for waste disposal, degrading these areas and reducing their capacity to provide ecosystem services such as waste processing and coastal protection. Tourism development also results in conversion of habitat to accommodate infrastructure, resulting in loss of dune systems, wetlands, and even coral reefs. Damming damages estuaries and reduces fisheries yields, even if there are benefits of freshwater diversion for increasing food supply in terrestrial systems.

The costs of such trade-offs are significant, especially since the economic value of coastal developments that are put at risk by loss of protective and regulating services are high. A relatively new and rapidly growing form of coastal development that severely affects coastal ecosystems is uncontrolled building of shrimp ponds and other aquaculture sites (Lubchenco 2003). Dredging of waterways, as well as sand and coral mining, also cause habitat loss. Urbanization has enormous impact on the coasts, both in developing countries where displaced landless people often take up residence in urban shanties and in industrial countries where urban and suburban sprawl threaten natural habitats and ecosystem services. Finally, humans increasingly cause the loss of coastal habitats through destructive fishing practices such as blast fishing (the use of underwater explosives) and trawling (dragging of weighted nets along the sea floor).

For some degraded coastal habitats, such as mangroves, marshes, and areas of seagrass, it may be possible to regain ecosystem services through restoration, but the prohibitively high costs prevent restoration being an effective policy for other habitat types. Some ecosystems under the right conditions may recover or regenerate without intervention, but in most ecosystems active and expensive restoration may be necessary. Toxin loadings, pathogens, and alien species invasions will further stress coastal ecosystems and may impede natural recovery and managed restoration; human well-being will suffer as a consequence unless significant improvements to coastal management are systematically made across wide regions of the globe (*high certainty*).

19.4.2 Drivers of Change in the Coastal System

As noted previously, population growth is highest in coastal countries, and population densities within the coastal system are high. Urban areas are often concentrated on the coast: half of all major cities (with populations above 500,000 inhabitants) are located in coastal systems. Population doubling rates are highest in coastal areas.

However, the link between sheer population number and environmental quality is not clear-cut. Some authors argue that a direct link exists between the number of people and the quality of the environment or loss of diversity, regardless of consumption patterns (McKee et al. 2004). Others argue that the number of households is better correlated to the environmental impact or ecological footprint left by humans (Liu et al. 2003). In the coastal zone, however, neither population numbers nor household numbers tell the full story. Patterns of consumption and other human behaviors greatly influence the ecological footprint left by communities, and migration and its effects often spell the difference between sustainable and unsustainable use (Creel 2003; Curran and Agardy 2002). Local resource use and migration patterns are also affected by local and international markets.

In many industrial countries, urban sprawl is a major driver behind coastal ecosystem impacts and habitat loss. In the United

States, for example, it is the pattern of growth, which includes runaway land consumption, dysfunctional suburban development patterns, and exponential growth in automobile use, rather than population growth itself in the coastal zone that has affected ecosystems and their services (Beach 2002).

National and local economies influence the ability of countries to manage resource use and lessen impacts on ecosystem services. Industrial countries with strong economies have the ability to put resource management programs in place, undertake pollution mitigation and ecological restoration, and support surveillance and enforcement. However, wealthy countries also tend to be proportionately greater consumers, and their large-scale industries often threaten the environment (Creel 2003). Agribusiness and other large-scale industries often have a disproportionately large voice in democratic governments, since they can underwrite extensive lobbying on their behalf (Speth 2004), and subsidization can also steer such industries away from sustainability (Myers and Kent 2001).

Even individual wealth can have a negative impact on the environment. Expensive chemicals are generally available only to industry or the wealthy (such as tributyltin, used to prevent fouling of ship hulls, which has harmed marine species and caused changes in sex in exposed organisms), while in the industrial world, improved access to drugs threatens coastal systems, since antibiotics and hormones (especially ethinyloestradiol, a synthetic estrogen used in birth control pills) find their way into streams and rivers and eventually into coastal systems (Colburn et al. 1996). Since the magnitude of the impact of these chemicals on coastal ecology and on human health is not fully understood, there has been little impetus to implement mitigation measures to prevent pollutants from entering streams, rivers, sewers, and estuaries.

Foreign markets and globalization have been major drivers behind degradation of coastal ecosystems and diminishing services. Globalization causes greater mobilization of fishers and other users, greater flow of information and access to resources, increased fishery or other trade-related pollution and habitat loss, and loss of rights and representation of local peoples, leading to marginalization (Alder and Watson 2004). Access to markets and growing consumer demand (for both legal and illegal goods) increase pressures on resources and can lead to overexploitation and habitat loss.

For instance, conversion of habitat for aquaculture drives much of the loss of habitat and services in coastal South America and Southeast Asia. Although in Latin America, habitat conversion is undertaken primarily by large international corporations, in Thailand and Viet Nam there is a more balanced mixture of small- and large-scale farms. Production is geared completely toward export markets. The growth in this industry has little or nothing to do with population growth or local demands for sources of food. In Ecuador, more than 50,000 hectares of mangrove forest has been cleared to make shrimp ponds since 1969, representing a 27% decline in mangrove cover. During the same period, shrimp ponds have gone from zero to over 175,000 hectares. While there has been some recent reforestation in Ecuador (representing approximately 1% increase in a four-year period), this may be more to do with increasing market competition with Southeast Asian producers.

In Thailand, both primary conversion of mangroves and wetlands and secondary conversion of rice, rubber, and other agricultural crops to shrimp farms has occurred. Ten years of observations of shrimp farm production in Thailand (Lebel et al. 2002) suggests that once shrimp farms are established, the resulting sedimentation, salinization, and changed tidal influences may seriously impede natural or planned regeneration of coastal forests or tidal basin species and may alter animal communities in waterways and wetlands. An analysis of shrimp farm production also demonstrates the multitude of linkages via the vital flow of water between human-based, land-based, coast-based, and marine-based systems. (See Box 19.5.)

The aquaculture-driven conversion of coastal habitat in Asia presents lessons about understanding drivers of ecosystem change in all coastal habitats. While it is necessary to separate threats to ecosystems in order to assess their impact, it is equally important to note that most coastal areas are facing multiple threats simultaneously, and many have experienced chronic impacts over long periods of time. Table 19.5 presents a typology of drivers of change in coastal systems and ecosystem services.

In a set of systems as complex and diverse as coastal systems, however, it is more germane to discuss drivers behind certain classes of impacts separately, rather than speaking of coastal ecosystem degradation more generally. Arguably, the greatest impacts on coastal systems worldwide are caused by the conversion of habitat for the purposes of coastal development (wetlands infilling, dredging of bays and harbors for port development, and so on) and through certain kinds of resource use (mangrove harvest, destructive fishing, and the like). These changes cause major if not total losses in ecosystem services and are largely irreversible.

For this reason, much attention has been paid to population growth in the coastal zone and the ways in which population drives habitat loss. Certainly this is true in poorly developed areas, where mangrove remains an important source of fuelwood and competition for increasingly scarce fisheries forces fishers to use unsustainable techniques. However, population is not the only driver behind habitat loss, and a confluence of chronic negative impacts may eventually lead to as debilitating a loss of ecosystem services as the more visible loss of habitat caused by growing populations.

19.5 Trade-offs, Synergies, and Management Interventions

19.5.1 Trade-offs, Choices, and Synergies

A central concern in coastal management is one of making trade-offs between ecosystem services in allocating increasingly scarce resources among society's members. Decision-makers face questions such as, Should this shoreline be cleared and stabilized to provide new land for development, or should it be maintained in its current state to serve as wildlife habitat? Should that wetland be drained and converted to agriculture, or should more wetland area be created to provide nutrient filtration services? Should this coral reef be mined for building materials and the production of lime, mortar, and cement, or should it be sustained to provide renewable seafood products and recreational opportunities?

To choose from among competing options, it is often necessary to compare the value that various groups in society receive from any improvement in a given coastal ecosystem with the value these groups give up to degrade the same system. Given this, a key question comes down to, What gets counted and how? Unfortunately, there are usually very few (if any) studies that can provide decision-makers with information on the full range of values provided by coastal ecosystem services, which is needed to evaluate specific trade-offs.

The wide variety of habitats, resources, and ecosystem services provided by coastal systems, and the strong interlinkages between these various components and processes suggest that complicated choices and difficult trade-offs exist whenever any form of coastal

BOX 19.5

Four Pathways to Coastal Ecosystem Degradation and Poverty through Shrimp Production in Thailand (Lebel et al. 2002 and references therein)

Shrimp production and sales are one of the fastest-growing food commodity markets in the world. Farmed shrimp production in the world market went from 815,250 tons in 1999 to 1.6 million tons in 2002. The industry has been growing at the rate of 10–20% a year over the last five years. The increase in production results from the spread of shrimp farm production along coastal ecosystems and tidal plains around the world. The area farmed for shrimp is approximately 1.2 million hectares. This number does not include the estimated 250,000 hectares of abandoned shrimp farms around the globe.

In 2000, the vast majority of shrimp farms were located in Pacific rim countries, along the coasts of South, East, and Southeast Asia. Approximately 89% of shrimp farmland is located in Asia. Thailand is the leading exporter of shrimp, with 25% of the world market, and the growth in Thai shrimp farms has been dramatic. In 1995, there were 19,700 farms covering about 65,000 hectares; by 2003 there were 35,000 farms encompassing 80,000 hectares.

Shrimp farm production has garnered attention from environmentalists because the building of shrimp farms is often linked to mangrove forest clearing. But extensive work by Lebel and colleagues in Thailand over the last decade suggests that the relationship between shrimp farm production and coastal ecosystem degradation is much more complex than popular science would predict. Lebel describes four pathways through which shrimp farm production there degrades coastal ecosystems and affects coastal communities' livelihoods. The complex interaction between shrimp farm production for global markets, coastal ecosystems, farmer/fisher livelihoods, and unsustainable and short-lived capacity of individual shrimp ponds spurred both a dramatic deterioration of coastal ecosystems over the last decade and recent, aggressive exploration of inland freshwater systems as a substitute.

The first pathway is sedimentation. Artificial shrimp ponds must be dredged and cleaned regularly. Typically, farmers empty the sludge into nearby coastal creeks or river basins. The resulting sedimentation has several effects. The filling of creeks and river tidal basins deters small fisher navigation through the creeks and tidal basins, disrupts nesting and breeding grounds of coastal dependent marine and shore species, and diminishes coastal fisheries. The buildup of sediment also diminishes the flushing and nutrient cycling role of tidal surges, further depleting the quality of coastal creeks and tidal basins. Sedimentation results from the building of fish ponds, which are usually bulldozed, the regular dredging of the ponds, and the more frequent pumping of pond water into coastal creeks. Although regulations stipulate that all larger farms must operate post-production water treatment ponds, many do not.

Salinization, the second pathway, is the result of three processes. First, the standing water in ponds and the resulting evaporation yields a buildup of salt in the pond water. Second, because tidal surges are minimized, the salt buildup is not naturally flushed out to sea. Third, in some locations saline water is pumped or trucked inland because local water sources are too fresh. The impacts appear to be most serious in areas without immediate access to coastal inlets or the ocean. Here, wastewater effluent from ponds is dumped into canals and waterways previously for irrigation of rice, orchards, and rice-sugar palms systems. Productivity declines and some tree species die, making it hard for non-shrimp farming land uses to persist in an area. These "off-site" or landscape effects have often been a source of sharp conflict between shrimp farmers and other farmers. Over the past couple of years, techniques for rearing shrimp under freshwater conditions have greatly improved and spread.

Although the building of shrimp farms typically takes place on private land, the residual creeks, wetlands, and shoreline are frequently understood to be public lands, so public accessibility can be the third pathway of degradation. Because of the value of shrimp, however, shrimp farm producers limit access to once-public natural resources that are near ponds. Guards actively dissuade local fishers, farmers, and hunters from using these public goods. Those who need access to these public resources are those in most need of the livelihood income generated from gathering freshwater clams, plants and greens, and small fish.

Impoverization is the fourth pathway identified by Lebel et al. The establishment of shrimp farms improves wage-based employment opportunities for many local residents, and the presence of shrimp farms in an area provides opportunities for short-term work in sorting, pond cleaning, equipment maintenance, and reselling of inputs. Where factories are present, there can also be substantial wage-earning opportunities, primarily for young women. As a result, the poorest members of coastal villages, who used to define their livelihoods as coastal fishers, now work as low-wage earners in shrimp farm production. In addition, during the early to middle years of the growth in shrimp production, many small fishers and farmers established their own farms, despite the high cost of entry. Many of these smaller producers quickly lost their ponds, however, as the economies of scale, the high incidence of disease outbreaks, and the fluctuation in prices precluded success for those with few assets in reserve. Currently many owners of coastal land rent their property to large corporate shrimp farm producers. Rental contracts typically include clauses that abrogate a renter's responsibility for payment if the shrimp harvest fails.

In both cases, coastal residents—whether low-wage workers on shrimp farms or owners of land rented to shrimp farm producers—are increasingly vulnerable to global market price fluctuations that affect the profitability of local shrimp ponds, as well as the rapidly deteriorating quality of the coastal ecosystem. The latter not only increases the likelihood of disease outbreaks and shrimp pond abandonment, it also precludes possible alternative coastal-based resource livelihoods once the shrimp farm economy collapses or moves elsewhere. Recently, as a result of the deterioration of coastal sites and limited new sites for expansion along the coast, corporate research and development has focused on shifting shrimp production into freshwater systems.

development or protection takes place. For example, the choice to cut down mangrove forest to build a seaside resort will not only involve opportunity costs in reducing mangrove availability to local people, it will also have an impact on other uses of the coastal zone, such as fishing, and will dramatically reduce ecological services such as storm buffering, maintaining water and sediment balances, water purification, nutrient delivery, biodiversity maintenance, and provisioning of nursery areas for coastal fishery species. Similarly, the decision to protect a key habitat via establishment of a marine protected area will mean that access to resources will be restricted, and it may incur additional costs such as overexploitation of resources outside the protected area, as well as the costs of protected area management. Thus decisions over the management of coastal systems need to consider the various trade-offs inherent in alternative management practices (Brown et al. 2001).

Often the trade-offs are related to who has access to resources or who benefits from coastal development (Creel 2003). For ex-

Table 19.5. Drivers of Change in Coastal Ecosystems

Direct Drivers	Indirect Drivers
Habitat Loss or Conversion	
Coastal development (ports, urbanization, tourism-related development, industrial sites)	population growth, poor siting due to undervaluation, poorly developed industrial policy, tourism demand, environmental refugees and internal migration
Destructive fisheries (dynamite, cyanide, bottom trawling)	shift to market economies, demand for aquaria fish and live food fish, increasing competition in light of diminishing resources
Coastal deforestation (especially mangrove deforestation)	lack of alternative materials, increased competition, poor national policies
Mining (coral, sand, minerals, dredging)	lack of alternative materials, global commons perceptions
Civil engineering works	transport and energy demands, poor public policy, lack of knowledge about impacts and their costs
Environmental change brought about by war and conflict	increased competition for scarce resources, political instability, inequality in wealth distribution
Aquaculture-related habitat conversion	international demand for luxury items (including new markets), regional demand for food, demand for fishmeal in aquaculture and agriculture, decline in wild stocks or decreased access to fisheries (or inability to compete with larger-scale fisheries)
Habitat Degradation	
Eutrophication from land-based sources (agricultural waste, sewage, fertilizers)	urbanization, lack of sewage treatment or use of combined storm and sewer systems, unregulated agricultural development, loss of wetlands and other natural controls
Pollution: toxics and pathogens from land-based sources	lack of awareness, increasing pesticide and fertilizer use (especially as soil quality diminishes), unregulated industry
Pollution: dumping and dredge spoils	lack of alternative disposal methods, increased enforcement and stiffer penalties for land disposal, belief in unlimited assimilative capacities, waste as a commodity
Pollution: shipping-related	substandard shipping regulations, no investment in safety, policies promoting flags of convenience, increases in ship-based trade
Salinization of estuaries due to decreased freshwater inflow	demand for electricity and water, territorial disputes
Alien species invasions	lack of regulations on ballast discharge, increased aquaculture-related escapes, lack of international agreements on deliberate introductions
Climate change and sea level rise	insufficient controls on emissions, poorly planned development (vulnerable development), stressed ecosystems less able to cope
Overexploitation	
Directed take of low-value species at high volumes exceeding sustainable levels	population growth, demand for subsistence and market goods (food and medicinal), industrialization of fisheries, improved fish-finding technology, poor regional agreements, lack of enforcement, breakdown of traditional regulation systems, subsidies
Directed take for luxury markets (high value, low volume) exceeding sustainable levels	demand for specialty foods and medicines, aquarium fish, and curios; lack of awareness or concern about impacts; technological advances; commodification
Incidental take or bycatch	subsidies, bycatch has no cost
Directed take at commercial scales decreasing availability of resources for subsistence and artisanal use	marginalization of local peoples, breakdown of traditional social institutions

ample, conflicts frequently occur between large-scale commercial fisheries and small-scale (local) artisanal or subsistence fishing (see Chapter 18), or between tourism resort development and local communities who frequently receive little if any of the derived profits (nor even national economies in some instances). Zoning areas can reduce trade-offs and allow a suite of benefits to be derived from the same ecosystem, whether this occurs through smaller-scale marine protected areas (Brown et al. 2001; Villa et al. 2001) or through other coastal planning efforts such as those being installed throughout the Great Barrier Reef in Australia (Day 2002). Ocean zoning is also slowly becoming accepted as a problem-solving tool in much the same way that land use zoning evolved slowly (and simultaneously) in many regions of the world decades ago. Zoning plans and permitting procedures for development that is potentially environmentally harmful are most effective when taking into account the costs of losing the ecosystem processes and services that these areas provide (U.S. Oceans Commission 2004).

Environmental impact studies that take into account the full value of the most important coastal areas where ecological processes are concentrated help decision-makers understand and quantify the trade-offs to be made when coastal development, environmental degradation through waste discharge, or exploitation of coastal areas occurs (Bocksteal et al. 1989; Brown et al. 2001). However, such studies require the kind of detailed assessment information that is lacking in many coastal areas and countries.

Some choices, when made in concert with others, will have an exponentially larger impact on ecosystem services than merely the additive effect of individual choices (a synergetic effect). For instance, if a management authority authorizes the development of coastal hotels that do not have sewage treatment facilities and at the same time authorizes fisheries on reefs nearby, the combined effect of increased nutrient pollution and decreased abundances of grazing fishes leads to algal overgrowth of the reefs and, in extreme cases, a regime shift from coral reefs to algal reefs (Birkeland 2004; McManus et al. 2000). Recovery from such alternate states is very difficult to achieve—and since the alternate state (algal reef) may not be as attractive to tourists, the resort business may well falter (Moberg and Ronnback 2003). Thus decision-makers who weigh not only the immediate costs and benefits from development but also the longer-term ones make better and often economically more viable choices.

Long time frames are extremely important to keep in mind. Many of the impacts humans have on coastal systems are small-scale, but when these become chronic, the cumulative impact may be quite large. In coastal systems that are downstream of recipients of terrestrial environmental degradation and sites of more immediate and direct degradation, threats to ecosystem health are multiple and especially cumulative. In these cases, decisions about resource and space utilization that are viewed holistically, with the long term in mind, are likely to have better outcomes for society.

19.5.2 Management Interventions

The story of human impacts on coastal ecosystems is a complex one involving not only a large number of diverse drivers acting simultaneously but also cumulative effects over time. Unfortunately, effective responses to such impacts on natural systems have typically only emerged after changes have taken effect, and management of coastal areas remains largely reactive.

Complex problems require comprehensive solutions. Integrated management of watersheds, land use planning, and impact assessment are key to protecting coastal ecosystems (Sorenson 1997). For this reason, tackling the issues of loss and degradation of coastal areas by addressing single threats to these environments has not proved effective in the past. The holistic approach—looking at how human activities affect coastal ecosystems, identification of key threats, and implementation of management that is integrated across all sectors—is a relatively new focus and is likely to produce much more effective decision-making. Effective management of these crucial areas means coordinated pollution controls, development restrictions, fisheries management, and scientific research.

Resource use that is managed in a way that considers the impacts that resource removal has on all linked ecosystems and human well-being has proved to be more effective than sectoral or single-species management (Kay and Alder 2004). Fisheries management agencies and conservationists are promoting ecosystem-based fisheries management—management that looks at multispecies interactions and the entire chain of habitats these linked organisms need in order to survive and reproduce (Agardy 2002). Due to the linkages between marine fisheries production and coastal ecosystem condition, the protection of coastal habitats figures very prominently in ecosystem-based fisheries management (Pauly et al. 2002). However, truly holistic integrated management of coastal areas also requires complementary watershed management and land use planning to ensure that negative impacts do not reach coastal areas from outside the coastal realm.

Significant strides have been made in coastal management in the last few decades, in both the industrial and the developing world. Many of the world's 123 coastal countries have coastal management plans and legislation, and new governance arrangements and regulations are being developed every year (Burke et al. 2001). In 1993, it was estimated that there were 142 coastal management initiatives outside the United States and 20 international initiatives (Sorensen 1993). By 2000, there were a total of 447 initiatives globally, including 41 at the global level (Hildebrand and Sorensen 2001). This dramatic increase in activity was attributed both to initiatives that had started since 1993 and to the improved ability to find information on coastal management initiatives though the use of the Internet (Kay and Alder in press). The latest survey estimates that there are 698 coastal management initiatives operating in 145 nations or semi-sovereign states, including 76 at the international level (Sorensen 2002).

Yet even countries with well-developed coastal zone plans that have been in place for decades struggle with overexploitation of resources, user conflicts, habitat loss, and indirect degradation of ecosystems from activities occurring sometimes hundreds of kilometers away from the coastal zone itself. Management has not kept pace with degradation, as the number of management interventions worldwide has only increased two- or threefold over the last decade, while degradation of many habitats like coral reefs and mangroves has increased significantly more in the same time (Kay and Alder in press).

Some key coastal habitats such as mangrove forests, marshes, and seagrass meadows can be, and are being, restored once degraded. The science of mangrove restoration is relatively advanced, especially in the new world where natural species diversity is low and where replanting a few species can restore the ecosystems and most services quickly (Kaly and Jones 1998). Marshlands are also easily restored, as long as major alterations to hydrology have not taken place. Such restoration initiatives are risky, however, since it has yet to be shown that the full range of ecosystem services can be supported by artificially reconstructed wetlands (Moberg and Ronnback 2003; NRC 1992). Coral reef transplantation, though technologically possible, can only be practiced at a small scale and has had limited success (Moberg and Ronnback 2003). Furthermore, the costs of such restoration can be enormous, as the $7.8-billion price tag for the restoration of the Everglades cord grass system in Florida in the United States attests. In fact, most full-scale restoration (habitat reconstruction) is practiced in highly industrialized countries that are able to finance the high costs over the long time frames needed.

Management interventions to deal with pollution in coastal areas have largely failed. One method of mitigation is to conserve, reconstruct, or construct new wetlands that act as filters of these pollutants before the compounds enter the coastal environment. Another is to encourage land use practices such as buffer strips in agriculture and forestry to prevent the runoff of fertilizers, sediments, and so on. Municipal waste and storm runoff is sometimes controlled to limit hydrocarbons and other toxic inputs, and regulations regarding dredging operations help control the release of pollutants deposited into coastal sediments. However, no country has succeeded in comprehensively limiting pollution of the nearshore environment, despite the large number of initiatives and regulations in place.

One reason for these failures is that neither the status of coastal habitats nor the full values of coastal systems are known in many parts of the world. Effective management of coastal systems and the evaluation of trade-offs and choices requires both information and awareness. Education plays a key role in supplying both, and although education about ecology has generally improved in recent decades, education on marine systems is underfunded and underdeveloped (Kay and Alder in press). Further applied multidisciplinary research on ecosystem function, sustainable yields, and economic valuation of coastal ecosystems is also needed (Lubchenco 1998). Research focused on fundamental questions about ecosystem function, impacts, and efficacy of management measures will aid decision-makers in mitigating loss and degradation of these habitats. Fully protected areas help in this regard because they provide crucial control sites to test management interventions and allow for baseline monitoring. Better economic valuations—particularly quantitative estimates of marginal benefits—are also required to understand fully the importance of coastal systems.

Individual sites are sometimes recognized for their valuable services, and management interventions are put in place to conserve these habitats and the species within them through marine protected areas (NRC 2001). These may be small fisheries reserves in which resource extraction is prohibited, or they may occur in the context of larger multiple-use areas. Increasingly, marine protected areas are being established in networks in order to safeguard key areas of the coastal and marine environment over a geographically large area (Agardy 1999; Murray et al. 1999a; Pauly et al. 2002). A prime example of this is the network of reserves encompassed by the newly rezoned Great Barrier Reef Marine Park in Australia (Day 2002).

In order for marine protected areas to succeed in meeting the objectives of conserving habitats and protecting fisheries and biodiversity, their management seeks to address all the direct threats to marine and coastal areas. In most habitats, these threats are multiple and cumulative over time. Thus protected areas that address only one of these threats will usually fail to conserve the ecosystem or habitats and the services they provide (Agardy 1997).

Marine and coastal protected areas already dot coasts around the world, and the number of protected areas continues to increase. The last official count of coastal and marine protected areas, in 2003, yielded 4,116 (Spalding et al. 2003), a marked increase over the 1,308 listed in 1995 (Kelleher et al. 1995), though this is a significant underestimate because unconventional protected areas that do not fit the IUCN categories for protected areas are typically not counted.

By far the bulk of these protected areas occur in coastal zones, and many include both terrestrial and aquatic components. However, even with the large number of individual sites, coverage accounts for less than 1% of the world's oceans. Many marine protected areas occur in relatively close proximity to human settlements—in fact, nearly 10% of the world lives within 50 kilometers of a marine protected area, and over 25% of the worldwide coastal population lives within 50 kilometers of one. (See Table 19.6.)

Management effectiveness of most marine protected areas remains questionable, and many of these areas have no operational management or enforced legislation at all. It is *well established* that marine protected area tools are not being used to their fullest potential anywhere in the world (Agardy et al. 2003). Nonetheless, there are good examples of effective marine management, such as the Great Barrier Reef Marine Park. And examples such as this highlight how even a protected area that begins with relatively modest protection measures can be strengthened over time (Lawrence et al. 2002).

Table 19.6. Share of World and Coastal Populations Living Close to a Coastal Marine Protected Area

Category	Within 50 Kilometers of MPA	Within 100 Kilometers of MPA	Within 150 Kilometers of MPA
		(percent)	
World population	9	19	26
Coastal population	25	51	70

Tenure of marine areas and some forms of traditional use can also be effective coastal conservation interventions, even when these patterns of sustainable use of marine and coastal resources occur outside of conventional protected areas (Curran and Agardy 2002; Young 2004). Common property and common property management regimes have evolved in many coastal communities and have in some cases been shown to be much more effective than conventional, top-down methods in keeping resource use to sustainable limits (Agardy 1997; Curran and Agardy 2002). Legitimizing such traditional uses remains an issue in many coastal countries, and recently nongovernmental organizations have begun to liaise with governments to help codify use rights for local communities.

An analysis of the efficacy of coastal and marine protected areas, sustainable traditional use regimes, and common property management regimes highlights the fact that all such local action must be supplemented by effective management at much larger scales (Agardy 1999). Indeed, the interlinkages between terrestrial environments, fresh water, coastal systems, and the marine realm prevent local interventions from succeeding unless the larger context is addressed. Coastal zone management at the provincial, state, or national level can help scale up management efforts, as can zoning initiatives (Norse in press). Coastal management is a particularly important facet of national policy-making, as most coastal zones exist wholly within the exclusive economic zones of individual nations (Sorenson 1997).

A relatively recent movement in this direction is the coupling of coastal zone management with catchment basin or watershed management, as has occurred under the European Water Framework Directive and projects undertaken under the LOICZ (Land–Sea Interactions in the Coastal Zone) initiative. Such freshwater–marine system coupling has resulted in lower pollutant loads and improved conditions in estuaries. However, due to the fluid nature of the marine system and the large-scale interconnectivities, even larger-scale integrated management initiatives are required for effective management of coastal and marine systems over the long term.

Several international instruments provide a framework for such larger-scale regional cooperation, including the United Nations Convention on the Law of the Sea (UNCLOS 1982), U.N. Regional Seas Conventions and Action Plans, the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA 1995), the Jakarta Mandate on the Conservation and Sustainable Use of Marine and Coastal Biological Diversity (CBD 1995), the RAMSAR Convention, Chapter 17 of *Agenda 21* (UNCED 1992), and Paragraph 29 of the Implementation Plan of the World Summit on Sustainable Development (WSSD 2002). While some of these international agreements pertain more directly to marine systems (as discussed in Chapter 18), all carry obligations or give guidance to parties on management of coastal areas. Yet while many international agreements and policies promote the idea of ecosystem-based management, the practical application of the concept is still being developed.

Global treaties and multilateral agreements can bridge some of the gaps that occur between small-scale interventions on the ground and large-scale coastal problems, but most of these international instruments have not been effective in reversing environmental degradation (Speth 2004). For shared coastal and marine resources, it may well be that regional agreements will prove more effective, especially when such agreements capitalize on better understandings of costs and benefits accruing from shared responsibilities in conserving the marine environment.

Large marine ecosystems have been put forward as a logical way to frame such agreements (Duda and Sherman 2002; Kimball 2001). Each of the world's 64 LMEs averages 200,000 square kilometers and is characterized by distinct bathymetry, hydrology, productivity, and trophically dependent populations (Sherman 1993). The LME concept was originally applied in the fisheries context under CCAMLR to take into account predator/prey relationships and environmental factors affecting target stocks; thus Antarctica was the site of the first truly ecosystem-based approach to fisheries management (Griffis and Kimball 1996). Several recent international instruments refer to LMEs, and the geographic units serve as the basis for some global assessments, such as GIWA (UNEP's Global International Waters Assessment). In many parts of the world, however, the political constituency for nations to cooperate to conserve large-scale ecosystems is lacking, though this situation may well be improving (Wang 2004).

Coastal ecosystems are crucial elements of the global environment, supporting not only marine food webs but also providing key services for humankind. To stave off the dramatic losses in coastal habitats that are now occurring worldwide, valuing these habitats and communicating their value to the public is crucial. And because in many parts of the world migration dramatically undermines regulation of coastal resource use, migration patterns and the drivers behind them merit investigation to provide the foundation for migration policies. Coastal systems are so complex, and the impacts humans have on them so varied, that coastal ecosystem services will only be successfully protected when the entire spectrum of threats and integrated responses to them are addressed. As human dependence on coastal services grows, management will continue to be challenged to manage the coastal environment more effectively.

19.6 Coastal Systems and Human Well-being

The coastal systems of the world are crucially important to humankind and are under ever-increasing threat from activities within and outside the coastal zone. Provisioning, regulating, supporting and cultural services have all been affected by human use and indirect impacts on coastal habitats, and some habitat types are close to being degraded to the point that important services will be lost altogether. Diminishing services caused by poor choices threaten the well-being of not only coastal communities, but coastal nations and the global community as well.

Many of these impacts affect rural communities in developing nations, especially where livelihoods are closely tied to availability of coastal resources. However, coastal degradation affects people in industrial countries as well, and has an impact on suburban and urban human well-being. For instance, according to a new study by the European Commission, a fifth of the coastline of the newly enlarged European Union is eroding away from human-induced causes, in a few cases as much as 15 meters (49 feet) shoreline erosion inland a year (European Commission 2004). Such erosion threatens homes, roads, and urban infrastructure and the safety of individuals, as well as affecting biodiversity.

Resource overexploitation and coastal degradation undermine subsistence use of coastal ecosystems. Small rural populations are not the only ones to suffer from overexploitation and mismanagement, however—national economies are affected as well. For instance, potential net benefit streams from coral reefs include fisheries, coastal protection, tourism, and biodiversity values are estimated to total $29.8 billion annually (Cesar et al. 2003). Much of these revenues are at risk from ever-accelerating rates of coastal degradation. When the negative impacts from overfishing are coupled with inadequate environmental management that allows increases in pollutant levels and stresses coral reef health, the consequences can be a full-fledged ecosystem collapse or regime shifts to alternate (and less desirable) states (Birkeland 1997).

Many coastal communities, especially in poorer developing countries, are trapped in what has been called "a vicious cycle of poverty, resource depletion and further impoverishment" (Cesar et al. 2003). As in many other coastal and marine ecosystems, marginalization of fishers is largely responsible for "Malthusian" or exponentially increasing rates of overfishing (Pauly 1997). This phenomenon is not unique to coral reefs, of course, but once coral reefs are destroyed, restoration is extremely difficult, and the costs brought about by loss of services such as coastal protection continue to be incurred for long periods thereafter (Moberg and Ronnback 2003).

Pollution puts coastal inhabitants at great risk—directly, by affecting human health, and indirectly, by degrading the resource base on which many of them depend. Poor sanitation affects not only slum dwellers. For instance, South Asian waters are highly polluted throughout the region, partly as a result of 825 million people who live without basic sanitation services (UN System-Wide Earthwatch, cited in Creel 2003). Pathogens are spread more quickly and reach greater numbers of people in coastal ecosystems that have become degraded. Chronic exposure to heavy metals and other bioaccumulating pollutants may not cause death in large numbers of people, but their cumulative effect can lead to reproductive failure and significantly decreased well-being. Food security is also greatly compromised in degraded coastal ecosystems.

Yet even when people are made aware of the importance of coastal ecosystems, they still may not be able to stop the kinds of activities that destroy or degrade these areas unless alternative resources or livelihoods are made available to them. For instance, boat-builders of the coastal and island communities of East Africa have little choice but to harvest mangrove for boat construction from key nursery habitats, which support the very fisheries on which their boat-building industry is based (Agardy 1997). Few alternative materials for boat building exist, except when conservation projects have expressly built in alternatives and training on how to use them. In areas in which resource extraction is moving beyond ecologically sustainable limits or the removal of the resource causes major physical changes to the habitat, the search for alternatives is particularly crucial.

A "business as usual" approach is projected to lead to continued loss of habitats and species, with attendant changes to ecosystem services and negative impacts on many coastal-dependent industries and coastal communities. Degradation will result in future choices of either accepting loss of ecosystem services or investing in costly restoration programs that are not guaranteed to reinstate the full range of services. Connectivity of systems and the large spatial scale of impacts will mean that local-scale or site-specific conservation and management investments will be increasingly at risk as overall coastal and marine conditions deteriorate. Changes in species distribution and abundance in response to climate change, resource use, and pollution may render many protected areas ineffective.

Yet enough is known to change the current approach and begin to systematically develop strategic plans for more effective protection and more sustainable use of coastal ecosystems (Kay and Alder, in press). Coastal areas could be zoned to allow appropriate uses in various areas, reduce user conflicts, and limit the impacts of detrimental trade-offs. Marine protected areas could well serve as starting points for such zoning measures, as well as acting as small-scale models for integrating coastal and marine management across all sectors (Agardy 2002).

In all parts of the world, it will be crucial to find ways to involve local communities in planning management interventions and zoning schemes in order to better safeguard resources, coastal areas, and human well-being. At the same time, ecological linkages between systems must be maintained in order to continue the delivery of services. Effective management for sustainable use of coastal systems will best be achieved by applying an ecosystem-based, whole-catchment approach that addresses land use upstream and the use of marine resources far out to sea. Multilateral, regional initiatives and agreements could help foster an integrated and comprehensive approach and may well lessen the costs of management through economies of scale. Regional cooperation schemes would facilitate a scaling up of management interventions that have to date been on too small a scale, and thereby help abate declines in coastal services and related human well-being.

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