SCOPE 64

SUSTAINING BIODIVERSITY AND ECOSYSTEM SERVICES IN SOILS AND SEDIMENTS

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The Scientific Committee on Problems of the Environment (SCOPE)

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Sustaining Biodiversity and Ecosystem Services in Soils and Sediments

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A project of SCOPE, the Scientific Committee on
Problems of the Environment, of the
International Council for Science

ISLAND PRESS

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Vulnerability of Marine Sedimentary Ecosystem Services to Human Activities

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Marine sedimentary ecosystems encompass more of the Earth's surface than any other habitat, but many people consider the sea floor to be a vast, monotonous environment that is remote from human disturbance. Biodiversity is often thought to be of little consequence to the resources we extract from the ocean, to the health of the marine environment, and to quality of human life. Nonetheless, marine sediments provide important extractable goods such as fisheries. They also play regulatory roles in global transfer and cycling of materials and energy (see Weslawski et al., Chapter 4). Many of the ecosystem processes (*sensu* Chapin et al. 2002) that occur in marine sediments also have important consequences for the sustainability of ecosystem services valued by human society (e.g., shoreline stabilization, waste recycling, etc.). Marine sediments from the highly visible coastline (Figure 7.1) to the remote and lesser known deep sea vary in exposure to threats and the probability of being harmed by threats if exposed; both issues contribute to vulnerability, defined here as the propensity of ecological systems to suffer harm from exposure to external stresses and shocks (Wall et al. 2001; Folke et al. 2002). The goal of this chapter is to examine potential threats to biodiversity in marine sedimentary ecosystems. We ask whether changes in biodiversity will increase the vulnerability of systems to loss of processes and services, and we examine their potential to recover from impacts. In most examples, loss of services provided by marine sediments has not yet been addressed by scientists; the discussion, therefore, focuses on processes with the underlying implication that these affect services (see Weslawski et al., Chapter

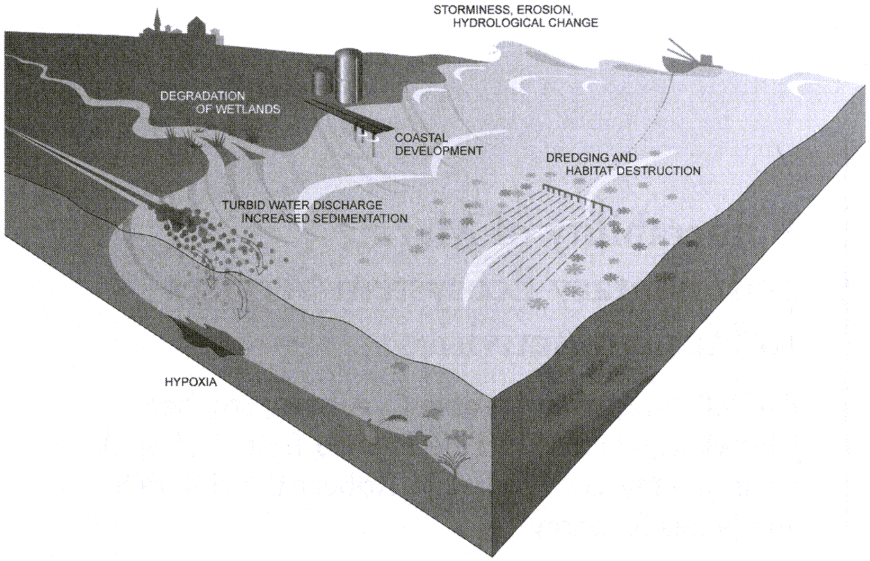

Figure 7.1. Schematic summary of the major threats to ecosystem goods and services in estuarine and coastal ecosystems.

Table 7.1. Summary of major threats to marine sedimentary systems and the scales at which they are manifested.

Scale	*Issue*	*Ecosystems Most Affected*
Small Scale (individual embayments)	invasive species	estuaries, wetlands
	disease	estuaries, wetlands
	coastal development/ habitat alteration	wetlands, estuaries
Mid Scale (regional scale)	hydrologic alteration	wetlands, estuaries, intertidal
	overfishing/habitat destruction	shelf, slope, estuaries, wetlands
	eutrophication/pollution	estuaries, shelf
Large Scale (basin scale)	climate change, including:	
	sea-level change	wetlands, intertidal, estuaries
	rainfall patterns	wetlands, intertidal
	temperature	shelf, intertidal
	wind & circulation	all
	salinity	estuaries, wetlands, intertidal
	ultraviolet radiation	all

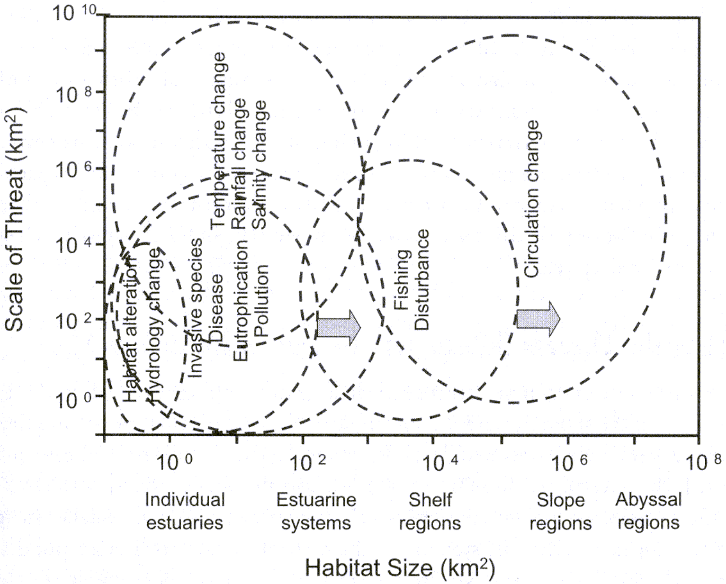

Figure 7.2. Scales of threats to marine sedimentary habitats. Circles denote ranges of affected area and habitats. Arrows for invasive species/disease and fishing disturbance indicate potentially larger scales of threat with increased human disturbance.

4). As in Chapter 4 of this volume, marine systems here are grouped into estuarine, continental shelf, and deep-sea sediments. *Estuaries* encompass sedimentary habitat at the land-sea interface where seawater is measurably diluted by freshwater input, the *continental shelf* refers to the sea floor between continents and the top of the continental slope (~130 m deep), and *deep-sea habitat* encompasses the comparatively steep (~4°) continental slope that extends from the edge of the continental shelf to the continental rise (~ 4,000 m) that grades into the vast abyssal plains (4,000–6,000 m) that cover much of the deep ocean floor. *Seamounts* are submerged mountains on abyssal plains that extend thousands of meters above the sea floor.

Threats and Scales of Vulnerability

Sedimentary ecosystems are exposed to multiple threats stemming from human activity (Table 7.1) with the potential to exert significant impacts on species composition and ecosystem processes across local (a bay or semi-enclosed coastal area), regional (hundreds of kilometers) and basin-wide scales (Hixon et al. 2001). Like other ecosystems, marine environments have a capacity to withstand and recover from human-induced disturbances. For example, sustainable fisheries are possible because populations of organisms have an innate capacity to increase their numbers, and individuals removed by fishing are replaced by the offspring of those that escaped the fishery. Likewise, many marine systems can accommodate some sewage input without loss of biodiversity or generation of anoxia. The problem is that disturbances often exceed the capacity of the system to recover, resulting in loss of species and, in some instances, loss of the capacity to produce goods and services. The size of a system and its proximity to human populations may influence vulnerability at different scales, and we therefore examine vulnerability to threats by scale of impact (Figure 7.2) from the land-sea interface to the deep sea.

Local-Scale Threats (kilometers to tens of kilometers)

Estuaries are more likely than continental shelf (gently sloping regions from 0–130 m depth between the shoreline and the upper edge of the continental slope) and deep sea (regions beyond the continental shelf, including the continental slope [~130–3,000 m], continental rise [~3,000–4,000 m], and the abyssal plains [~4,000–6,000 m]) systems to experience severe local-scale effects because they are smaller in spatial extent, less open to adjacent systems, and physically closer to human populations (Levin et al. 2001). However, we also recognize that intense local effects (e.g., many individual trawls) can spread and become regional (e.g., broad-scale fishing impacts). Below we outline local-scale threats.

Alien Taxa

Alien species are often introduced from point sources (e.g., ship ballast water and hull fouling, mariculture [marine aquaculture] activities; see Carlton & Geller 1993), though in instances where species are highly invasive, they can quickly create problems at a regional scale through rapid dispersal of propagules (Wehrmann et al. 2000). Invasive species may also exhibit population lags over many generations before becoming a problem (Crooks & Soulé 1999). Within estuarine habitats, biotic invasions rank second only to habitat alteration among potential threats to biodiversity (Vitousek et al. 1997; Carlton 2001), and invasion rates to coastal marine systems have accelerated over the past 200 years (Ruiz et al. 2000; Carlton 2001). Most benthic faunal invaders have been crustaceans and mollusks (Ruiz et al. 2000), but polychaetes (Roehner et al. 1996), plants, and disease organisms also have altered benthic diversity (Carlton 2001). Introduced plants can alter communities and ecosystem processes because of their trophic importance in estuarine food webs and effects on physical habitat structure (e.g., architecture, sedimentation). For example, *Phragmites australis* reduces plant species diversity where it invades (Lenssen et al. 2000), lowering soil salinity and water levels, reducing microtopographic features, and changing sediment oxidation (Windham & Lathrop 1999), but it is not known to reduce benthic faunal diversity in freshwater wetlands (Ailstock et al. 2001). Invasions can reduce density, elevate species richness, and change infaunal composition in tidal wetlands (Talley & Levin 2001) with unknown functional consequences. Hybridization with local species can also alter or reduce genetic diversity (Ayres et al. 1999).

Disease

Diseases represent a natural threat to all living organisms. Humans can exacerbate that threat by increasing susceptibility to disease through physiological stress, by accelerating the spread of disease, or by introducing contaminants into the marine environment in an attempt to control disease. Effects may include loss of goods and services or alteration of processes. For example, chemical contamination can cause chronic lesions in (Moore et al. 1997) and increased effects of parasitism (Khan 1987) on benthic fishes, reducing the commercial value and potentially compromising the sustainability of fisheries. Transport of toxic dinoflagellate cysts in ballast water can contaminate new areas (Hallegraeff & Bolch 1992), resulting in losses to mariculture and wild shellfish yields. Antibiotic use in mariculture appears to be a localized threat, but drugs used to control parasites may have toxic effects on benthic invertebrates that extend well beyond mariculture locales (Goldburg et al. 2001). Many mariculture programs also use nonendemic species or stocks, and introductions or escapes of pathogens have contributed to invasive species problems in estuaries (Carlton 2001). However, there is little evidence linking this emerging industry to large-scale disease impacts on benthic communities (Rothschild et al. 1994; Naylor et al. 2000).

Coastal Development and Habitat Alteration

Human activities alter the physical structure of coastal habitats across a range of spatial and temporal scales. Lerberg et al. (2000) related the amount and type of shoreline development to changes in species richness and populations of key functional groups. Perhaps the most direct negative impacts on infaunal (organisms living in sediments) communities are associated with sediment disturbance during dredging of waterways for navigation (Newell et al. 1998), and the more chronic effects of heavy gear (e.g., fish trawls, scallop dredges) frequently used to harvest estuarine and coastal species (Hall-Spencer & Moore 2000; Thrush & Dayton 2002). Even relatively localized sediment disturbances (e.g., pipeline installation, increased land erosion runoff of sediments) can affect macrofaunal biodiversity (Lewis et al. 2002). These disturbances often damage or eliminate larger, sessile, and long-lived benthic filter-feeding invertebrates (e.g., corals, sponges, bivalves), as well as seagrass, mangrove, and marsh vegetation. This reduces structural complexity and habitat diversity as well as the system's capacity to trap sediments (Morris et al. 2002), improve water quality (Coen et al. 1999), and mitigate effects of stressors such as hypoxia (depleted oxygen concentrations) (Lenihan & Peterson 1998). In finfish pen mariculture, hypoxia beneath pens reduces benthic diversity (Weston 1990). Disturbances in natural habitats including estuaries often create conditions that favor different species than those that occur in undisturbed areas, with potential consequences for ecosystem processes and their associated benefits to humans.

Channel alteration—construction of impoundments, docks, roads, and shoreline armoring (to protect nearshore property from erosion)—may affect the functioning of coastal habitats (Kneib 2000). Shoreline armoring, where protective physical structures such as concrete breakwaters are built to protect coastal property, prevents natural inland migration of wetlands with sea-level rise (Pethick 2001), posing a serious long-term threat to both diversity and ecosystem processes (Morris et al. 2002). Armored shorelines support hard substrate faunas (i.e., organisms that are found on exposed bedrock and other nonsedimentary habitat) in environments that previously supported sedimentary ecosystems (Davis et al. 2002). Key trophic links and ecosystem processes (e.g., energy flows) also depend on maintaining physical corridors between estuaries and habitats for movement of materials and organisms (Micheli & Peterson 1999; Kneib 2000).

Estuaries function as nurseries for mobile species that are harvested elsewhere (e.g., nearshore shelf waters) and are sometimes spared the direct impacts of commercial (though not recreational) fisheries. Yet there are many examples of overexploitation of resources in estuaries and bays including reductions or extinctions of benthic filter-feeders, a key functional group that strongly influences bentho-pelagic coupling (linkages between the bottom [benthic] and water column [pelagic] environment) and water quality (Jackson et al. 2001; Dayton et al. 2002).

Regional-Scale Threats (hundreds to thousands of kilometers)

Hydrological Alteration

Hydrological alteration occurs when rivers are diverted or outflow is substantially reduced for other purposes (e.g., hydroelectric projects, irrigation). Effects often are local (such as single estuaries) but significant diversions can affect an entire coastal region. Increased extraction and consumption of water lowers the water table and reduces freshwater input, increasing marine influences on estuaries with potentially serious consequences for benthic biodiversity and ecosystem processes. Changes in the amount or timing of freshwater flow disrupt the balance between the influence of land and sea on the estuarine environments (Sklar & Browder 1998), and affect the life cycles of species dependent upon seasonal cycles of freshwater inputs to estuaries. Regional rainfall correlates with the areal extent of intertidal marshes and mangrove forests within temperate and tropical estuaries and coastal embayments (Deegan et al. 1986), and species diversity in estuaries is related to changes in salinity (Kalke & Montagna 1991; Jassby et al. 1995). Pulsed flooding events can change sediment and nutrient inputs to favor deposit-feeders (high sediment loads) and suspension-feeders (low sediment loads) in different seasons (Salen-Picard & Arlhac 2002). Likewise, reduced ocean exchange can create hyper- or hyposalinity and hypoxia (Teske & Wooldridge 2001).

Mariculture

Studies of broad-scale impacts of aquaculture on biodiversity of benthic communities are rare, but environmental impacts of mariculture operation are linked to all of the threats to biodiversity listed above, but especially to habitat destruction. In many developing countries, intertidal mangrove forest and other wetlands have been replaced by shrimp mariculture ponds. In Thailand, 54 percent of the estuarine mangrove forests present in 1961 were converted to other uses by 1993, primarily for the construction of shrimp ponds (Macintosh et al. 2002). The high biodiversity of benthic communities and high production of wild shrimp and other fisheries' species in natural mangrove forest systems may be permanently lost (Naylor et al. 2000) because attempts to restore these damaged habitats rarely produce the biodiversity of crustacean and molluscan species found in undisturbed mature mangrove habitats (Macintosh et al. 2002).

Overfishing and Habitat Alteration

Shallow coastal and shelf systems are often fished heavily for target species with considerable collateral damage through bycatch. Excessive fishing mortality of target species and/or bycatch can alter food webs substantially (Pauly et al. 1998). Bottom trawl fisheries can also be destructive by homogenizing large areas of sea floor that provide habitats for benthic and near-bottom species (Dayton et al. 1995). Although overfishing is concentrated in estuarine and shelf areas (Auster et al. 1996), it has spread to seamounts and continental slopes.

Fishing impacts are the threat of greatest concern on shelf systems (National Research Council 1995). In estuarine coastal and shelf systems, overfishing reduces stock levels and alters trophic support processes and food web dynamics between the pelagic and benthic zones and also within the benthos (Pauly & MacLean 2003). Commercially harvested fishes are often top predators, and their overexploitation has cascading effects through to lower parts of the food chain (Myers & Worm 2003; Worm & Myers 2004). Similarly, harvesting of large filter-feeder bivalves eliminates populations that perform key processes in benthic systems (Pauly et al. 1998; Jackson et al. 2001). Food web disruption through overfishing, eutrophication, and invasive species act in concert to further reduce availability of fish and shellfish as food (Lancelot et al. 2002).

Although recreational fisheries can cause substantial mortality in top-level predators (Dayton et al. 2002), the effect on benthic biodiversity is less studied and findings are mixed. There is evidence from manipulative mesocosm experiments (Kneib

1991; Duffy & Hay 2000) that indicates trophic interactions involving top predators can have cascading effects on the composition (hence biodiversity) of benthic assemblages, but it is uncertain whether mesocosm results can be scaled up to any large, open system. It is nearly impossible to investigate this issue in many regions because of public and political resistance to establishing fully protected marine reserves that prohibit fisheries exploitation. For example, less than 1 percent of marine environments in the United States are more than nominally protected; most of these are coral habitats (Palumbi 2002).

At larger scales offshore and inshore, habitat alteration is caused by dragging fishing gear through sediments, which disrupts established chemical and biotic gradients. Globally, trawling impacts many thousands of square kilometers of continental shelf seabed, although effects depend on sediment type, fishing gear, and trawling frequency (Collie et al. 2000). The larger macrofauna and epifauna living within and on the sediment are most vulnerable to trawling mortality (Kaiser et al. 2000), injury from fishing gear (Ramsay et al. 1998), and exposure to predators. Mollusks such as whelks are physically rolled over and exposed by fishing gears and are, therefore, more vulnerable to predation (Ramsay & Kaiser 1998). Scavengers increase food intake in fished areas (Kaiser & Spencer 1994), and sharks and rays associate trawlers with food (Stevens et al. 2000). Larger infauna and epifauna create local, small-scale habitat patchiness through altering water flow or creating biogenic structures such as burrows and tubes, or by moving sediment and feeding. By reducing these populations, trawling homogenizes the sediment and landscape interconnection via habitat patches and refugia (Auster et al. 1995; Thrush et al. 2002). Organisms that create small-scale heterogeneity and habitat structure also stabilize sediment through accretion and alteration of water flow at the sediment-water interface.

The great depth of the abyssal plains, their remoteness, and the low abundance of harvestable species concentrates most deep-sea fisheries activities in upper to mid continental slope depths. Deep-sea organisms often grow slowly, mature at a later age than shallow water species, and produce comparatively few offspring (Merritt & Haedrich 1997). Declines in catch rate and stock size have been observed for commercially exploited fish species (Clark 1995), deep-sea crab, and shrimp (Orensanz et al. 1998). Bycatch has also caused drastic reductions in abundances of deep-sea fishes that are not targeted by fisherman in the North Atlantic (Baker & Haedrich 2003). As in other systems, fishing removes top predators that are hypothesized to play a regulatory cropping role in deep-sea diversity maintenance (Dayton & Hessler 1972; Myers & Worm 2003) and patch creation (Grassle & Sanders 1973). Fishing gear can have significant impacts on deep-sea bottom habitat akin to that seen in shelf environments (Koslow et al. 2000). Seamounts and deep-sea coral (*Lophelia*) reefs are an extreme example of this problem, where destructive trawl gear damages epifauna that are unique to specific seamount or reef regions and that may provide key habitat for fishes and other organisms (Koslow et al. 2001; Hall-Spencer et al. 2002).

In more homogeneous deep-sea settings, the impacts of habitat destruction and predator removal are mitigated by the vast extent of the environment. Effects of fisheries on deep-sea diversity (aside from seamounts with high levels of endemism) are difficult to know, given that estimates of the total species present varies by an order of magnitude (Grassle & Maciolek 1992; Lambshead & Boucher 2003) and distribution maps do not exist for most deep-sea species.

Removal of pelagic top consumers (e.g., whales, tuna) and the fishing down of food webs may also have cascading effects on deep-water food chains (Butman et al. 1995). Inputs of large organic matter falling to the deep-sea floor may decrease, affecting food supply for many scavenger species that contribute to diets of other deep-water fishes.

The deep sea holds extensive mineral and hydrocarbon deposits. Manganese nodules (rock-like, golf ball–sized structures that are rich in manganese and other minerals and are found in dense concentrations in some areas of the abyssal plains) and crusts, polymetalic sulfides (chimney-like deposits that form at deep-sea hydrothermal vents), and phosphorites all contain valuable cobalt, nickel, copper, and manganese but their extraction is not yet economically viable (Glover & Smith 2003). Potential effects on benthos depend in part on whether mining waste (mostly sediments) is discharged at the seabed. Any scenario includes damage and crushing from mining gear, but seabed discharge could also smother organisms. Some effects included initial reduction followed by increases in megafaunal abundance driven primarily by scavenging species (Bluhm et al. 1995) and no change or decreases in macrofaunal abundance and diversity (Borowski 2001). Although benthic populations can recover from simulated disturbance within three years, diversity effects may remain after seven years. Experiments show relatively localized, noncatastrophic effects, though the small scale of these experiments suggests caution in extrapolating to commercial impacts (Ozturgut et al. 1981). There is, nonetheless, a specialized manganese nodule fauna that could be reduced or lost in intense mining scenarios (Thiel et al. 1993).

Oil and gas drilling beyond the shelf break has gone from only a possibility, a half century ago, to a reality in recent decades. For example, the Brazilian company PetroBos has some production activity at depths greater than 1,800 m off western Africa (Glover & Smith 2003), and exploration by other companies is occurring at depths greater than 3,000 m in the Gulf of Mexico (Minerals Management Service 2004). If drilling is done carefully, effects on diversity and biomass may be very localized (kilometer scale), with the exception of greater effects in connection with major spills (Thiel 2003) or drilling over long temporal scales. In contrast, the mining of methane hydrates, though not yet technically possible, could destabilize slope areas and cause mass slumping events with broad-scale mortality (Thiel 2003). Methane hydrate is a gas that freezes at depths greater than 300 m, and may someday be the most important deep-sea resource because it is thought that oceans hold over twice as much carbon in methane hydrate as all other sources of fossil fuel (USGS Survey Fact sheet: http://marine.usgs.gov/fact-sheets/gas-hydrates/title.html).

Eutrophication and Pollutants

Estuaries and semi-enclosed bays often support dense human populations and industry, with associated high inputs of pollutants (e.g., heavy metals, hydrocarbons) and nutrients, which can cause phytoplankton blooms that subsequently decay and create bottom hypoxia. Estuaries and bays with limited exchange with the open ocean are particularly vulnerable; however, larger-scale hypoxic events are becoming increasingly frequent over shelf areas adjacent to inputs from nutrient-enriched estuaries or large river systems (Diaz & Rosenberg 1995). Although many estuarine and shelf ecosystems have a significant capacity to recycle organic matter and nutrients without inducing hypoxia, a balanced community of microbes and bioturbators is needed to provide this ecosystem service.

Pollutant inputs to estuaries and coasts from point and non-point sources are an increasing global problem (Boesch et al. 2001). Many estuaries are exposed to a broad spectrum of contaminants, including oil spills that induce complex changes in benthic invertebrate assemblages (Long 2000; Peterson 2000; Peterson et al. 2003). Excessive nutrient inputs to estuaries have cascading effects that reduce benthic biodiversity (Howarth et al. 2000), and increase frequency of harmful algal blooms and hypoxia or anoxia (Boesch et al. 2001). Reductions in rooted vegetation (Howarth et al. 2000) and simplification of community structure result from increased frequency and persistence of hypoxic events (Diaz & Rosenberg 1995).

Effluents from mariculture may contribute to eutrophication and local changes in sedimentation, all of which affect benthic biodiversity and the functional role of benthos in semi-enclosed ecosystems such as estuaries, bays, and fjords (Naylor et al. 2000). Few and limited effects of mariculture effluents have been measured in the water column (McKinnon et al. 2002), and most impacts have been seen in sediments (Ervik et al. 1997). Sedimentation of excess food particles and fecal material in the vicinity of mariculture facilities has contributed to local hypoxia/anoxia and reductions in benthic biodiversity. As long as an impacted area is not already over-enriched from other sources, the additional nutrient loading is not expected to have substantial large-scale impacts on benthic biodiversity. Rearing filter-feeding organisms in mariculture may even improve water quality and offset negative effects of eutrophication on benthic biodiversity. Modestly sized mariculture operations designed to minimize habitat destruction and, with a focus on production of native species low in the food web (bivalves and herbivorous fishes), may pose little threat to benthic biodiversity (Naylor et al. 2000).

On the continental shelves and through the interface between estuarine and shelf waters, threats include direct and indirect inputs of pollutants (Clark 1997). Some pollutants are discharged directly onto the shelf via pipelines or dumping from ships. Indirect inputs occur through discharge into rivers and estuaries, and through airborne contamination of rainwater. Hypoxia can stress and increase mortality in meio- and macrofauna (Gray et al. 2002), and in larger organisms such as fishes (Diaz & Rosenberg 1995). The resulting disruption of microbial communities and production affects oxygenation processes and detoxification of contaminants within the sediments. Dumping of waste in deeper waters of the shelf and spillage from oil installations and ships also result in pollution farther from the coastal margins. Shipwrecks and collisions cause large-scale pollution (Peterson 2000; Peterson et al. 2003) with effects that can persist for many years (e.g., more than 10 years in Dauvin 1998), though the spatial scales of spills in the open ocean tend to be small relative to the habitat area, and cumulative effects are unknown.

Dumping dredged material causes habitat alteration through smothering and toxicity (Somerfield et al. 1995). Alteration of water flow into rivers and dredging of river channels changes shelf hydrology, salinity, and sediment deposition (de Jonge & de Jonge 2002). Effects may be even more severe than in estuaries because shelf organisms seem less physiologically tolerant to these types of disturbance.

Materials dumped in the deep sea have included conventional munitions and chemical weapons (Schriever et al. 1997), low- and intermediate-level radioactive wastes (Thiel 2003), sewage sludge (Bothner et al. 1994), dredge spoil containing contaminants (Tyler 2003), and various vessels and structures associated with the military, shipping, and oil and gas exploitation (Schriever et al. 1997). Modern deep-sea research has revealed that this ecosystem is more dynamic and reactive than previously believed (Tyler 2003) and for the most part, western countries have ceased deep-ocean dumping. The deep sea is now being considered as a repository for excess carbon dioxide (Herzog et al. 2000), which is liquid at high pressures and low temperatures (Glover & Smith 2003). Deep-sea carbon dioxide disposal could mitigate atmospheric CO_2 increases and decrease surface ocean pH, but concurrently reduce deep-ocean pH (Caldeira & Duffy 2000) to lethal levels in the CO_2 plumes (Glover & Smith 2003).

Continental slopes exhibit the highest carbon deposition, the greatest animal productivity, and perhaps the highest biodiversity in the deep sea (Rex 1983). Because they are also the most accessible deep-sea setting, human activities can have greater impacts on biodiversity and key slope sediment processes such as carbon burial or production. There are few studies that address these issues for the deep sea.

Enrichment experiments in the deep sea (Snelgrove et al. 1992) suggest that organic input selects for shorter-lived, surface-dwelling, opportunistic species, and similar effects may occur with disposal of sewage sludge and dredged materials in the deep sea. Enrichment can also alter diets and locally enhance epibenthic species (Grassle 1991; Van Dover et al. 1992). Physical disturbance from bottom trawling also generates opportunistic, low-diversity assemblages. Replacement of larger, deeper-dwelling species by small opportunists reduces bioturbation, limits oxygenation of the sediment, and slows carbon degradation and burial rates. Slope macrofauna typically consume and bury (to 10 cm or more) fresh organic matter within days of its arrival on the seabed (Graf 1989; Levin et al. 1997), so that most labile carbon is respired or buried rapidly. At abyssal depths, human-induced suppression of bioturbation and carbon burial may occur from CO_2 sequestration or nodule mining activities, with effects akin to natural mass slumping (Masson et al. 1994).

Broad-Scale Threats (Basin Scale): Climate Change

Climate change will alter salinity, temperature, and wind patterns, which will affect local, regional, and broad-scale hydrography (Manabe et al. 1994), but this may occur slowly. Sea-level rise, for example, will have few direct effects on shelf or deep-sea systems, but it will have substantial effects on coastal environments (Smith et al. 2000). Similarly, rising sea levels cause a loss of open tidal flats and landward migration of marshes (Donnelly & Bertness 2001), but shoreline armoring constrains this movement, resulting in intertidal estuarine habitat loss (Pethick 2001). Because rooted vegetation is a key part of habitat structure and primary production in estuarine wetlands, broad-scale losses associated with sea-level rise (Barras et al. 2003) pose serious threats to biodiversity and ecosystem processes and services (Morris et al. 2002).

At larger spatial scales, impacts will probably result from changes in the frequency of basin-wide meteorological phenomena such as ENSO (El Niño-Southern Ocean) and NAO (North Atlantic Oscillation) events and in the strength of boundary currents.

Climate changes that alter seasonal patterns of rainfall or temperature have little effect on deep-sea systems. However, in coastal regions, climate change may cause local extinctions of endemic benthic invertebrates adapted to historical patterns of environmental variation, and at the same time promote expansion of the range of some invasive species. Although many invasive species in estuaries are euryhaline (able to tolerate a wide range of salinities), more invasions occur in high than low salinities (Ruiz et al. 2000). Reduced freshwater flow allows marine waters to penetrate farther into estuaries, and successful introductions, including those of disease organisms (e.g., the parasitic dinoflagellate, *Hematodinium* spp.), are more frequent during droughts or reduced freshwater flows into the system (Carlton et al. 1990; Messick et al. 1999). There is apparently wide variation in the resistance of estuarine benthic communities to invasion (Ruiz et al. 2000), and evidence from hard substrate communities suggests that diversity helps resist invasion (Stachowicz et al. 2002). With climatic change, it is therefore reasonable to expect shifts in invasion resistance and the abundance of invaders.

Climate change is increasing the frequency and scale of extreme weather, and strong winds increase wave action, which results in physical disturbance to the sea bed along coastlines and in shallower shelf waters (Hall 1994). The effects are similar to those of widespread fishing disturbance. In shallow regions, wind-induced wave action may actually increase nutrient cycling due to physical disturbance of the sediment, enhancing pollutant detoxification through increased oxygenation of sediments. Under normal conditions, shelf benthic organisms in the Peru-Chile upwelling zone are often oxygen stressed, with low biodiversity, low biomass, and little bioturbation activity. El Niño upwelling replaces normally hypoxic shelf waters with well-oxygenated water masses, promoting greater benthic biodiversity, productivity, nutrient cycling, and food production. This type of climate event may enhance most marine goods and services (Tarazona et al. 1988; Gutierrez et al. 2000).

Additional rainfall during winter and reduced rainfall during summer in temperate zones will change coastal hydrologic characteristics and could affect sediment loading and the effectiveness of flood and erosion control by reef-forming and sediment-stabilizing organisms. Accelerated glacial meltdown, wide-scale reductions in salinity (some of which will be offset by increased damming of rivers), and increased temperatures will change benthic community structure and diversity (Smith et al. 2000; Austen et al. 2002). Increases in temperature may enhance productivity where nutrients are not limiting, resulting in positive effects on some of the goods and services provided by marine benthos.

Little is known about potential effects of increased ultraviolet radiation in marine sedimentary benthos, but work on pelagic eggs of near-bottom fishes (Kouwenberg et al. 1999) suggest that effects on planktonic larval stages are possible.

Comparison Among Systems

We have summarized the vulnerability to different threats for each of the three ecosystem groupings (Tables 7.A1–7.A3 in the appendix on page 184), as they relate to provisioning of goods (e.g., food, fiber) and services (e.g., water filtration, flood control, waste recycling), as well as their supporting ecosystem processes (e.g., carbon sequestration, nutrient cycling, decomposition), habitat maintenance services, and aesthetic services (spiritual enrichment, recreation, scientific inquiry). Because many of the available data on vulnerability are either anecdotal or collected and interpreted in very different frameworks for different threats, an objective, quantitative comparison across systems is not possible. We have used our collective experiences and available studies on ecosystem processes and services to develop a qualitative ranking scheme to address the relative vulnerability of different systems to loss of services or processes (Tables 7.A1–7.A3 in the appendix on page 184). In some instances a given threat may actually enhance some service or process, and thus a negative score is possible. For example, an introduced species may create ecological havoc but, if it is edible and abundant, it may increase provisioning of food.

We interpret from this exercise that estuarine systems are currently the most vulnerable of our three broadly categorized marine systems, in part because of the wide range of services that are carried out in the environments and in part because of the intensity and number of threats. Remote deep-sea systems are the least vulnerable marine systems under current patterns of exploitation because of their large area of interconnected habitat and their relatively low exposure to human activity. Because of its size, large- to mid-scale effects (e.g., climate change) are of greatest concern. Nonetheless, seamounts represent an area of extreme concern, and continental slopes are vulnerable to human exploitation where localized effects are increasing.

Recovery, Restoration, and Rehabilitation of Marine Ecosystems

Marine restoration has lagged behind that of terrestrial and freshwater ecosystems, in part because oceans are massive in scale and common in ownership, which hinders intervention. In recent years, however, a framework for recovery, restoration, and rehabilitation (see Frid & Clark 1999 and Hawkins et al. 1999 for definitions) of marine ecosystems has developed, particularly on coastal systems dominated by habitat-providing biota such as seagrass beds, mangroves, and salt marshes (Ewel et al. 2001).

In open marine ecosystems, barriers to larval dispersal are few and there is good potential for natural recovery by recolonization from unimpacted populations. Whereas natural recovery can be rapid, active restoration in open ocean systems is difficult except where biological structure creates and maintains habitat. For example, biologically generated structure such as seagrasses, saltmarsh halophytes, and mangroves may not disperse well (Orth et al. 1994), but active planting can accelerate habitat restoration and associated ecosystem processes and services.

Enclosed waters such as estuaries, bays, and lagoons can be amenable to restoration by the manipulation of water quality and ocean flushing. For example, macrophytes can sequester nutrients in semi-enclosed areas that might otherwise become eutrophic. Phytoplankton standing crop may also be influenced by filter feeders (Officer et al. 1982; Davies et al. 1989; Hily 1991). The openness of most marine systems means that water quality can be improved by regional reductions of harmful inputs and activities. Where flushing by ocean tides is restricted, for example, by road construction or episodic inlet closure through sedimentation, habitat may be restored by active dredging, manipulating flow, and constructing permanently open inlets.

Many nearshore and shelf areas are heavily impacted by disturbances where effects can be mitigated only by leaving large areas undisturbed. Marine protected areas are proposed worldwide as pragmatic precautionary fisheries management tools with broader marine conservation benefits (US Commission on Ocean Policy 2004). These can have various levels of protection (see Jennings & Kaiser 1998 and Hall 1999 for excellent overviews) from absolute exclusion ("no take zones") to less strict regions where gear types are limited or fishing is excluded in some seasons.

Most coastal restoration work has focused on particular habitats, biotopes, assemblages, or species, but coastal ecosystems are strongly interconnected and coordinated efforts are sometimes needed. Thus, seagrass restoration may aid saltmarsh recovery or restoration. Active restoration has the strongest cascading effects where "ecosystem engineers " (Lawton 1994) are involved. Oyster reefs, mussel beds, seagrass beds, saltmarsh, and mangroves are all examples where a strong structural element is conferred

by the dominant biota. Rooted macrophytes (e.g., seagrasses) can be planted to form the nuclei of new beds (Fonseca et al. 2002). Conversely, oyster reef restoration is less successful near salt marsh and seagrass beds, which provide corridors for large mobile predators (Micheli & Peterson 1999).

Conclusion

Our discussion focused on many processes and services in marine sediments that in some instances are only now being recognized. The importance of critical habitats, such as those utilized by juvenile fishes, has become a major focus for fisheries organizations only in the last decade or so. Are there future services and processes that are deteriorating but are receiving no attention because they are not yet recognized? It is the unknown future value of marine sedimentary systems that places a particular urgency on preserving the remaining systems that are still relatively pristine; the potential losses in service and process that we have summarized here may represent only part of the story. Ultimately, biodiversity has value in and of itself that goes beyond goods and services provided to humans and the processes that biodiversity may help to support. But even for those who fail to recognize a beauty in the diversity of living things and our ethical obligation to preserve this diversity, the potential for loss of desirable goods and services supported by marine sedimentary fauna should at least provide pause (and provide food) for thought, and an impetus to protect these living resources.

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Appendix Table 7.A1. Vulnerability of continental shelf ecosystem services and processes to perturbations.

We summed the columns to determine which threats ranked highly among multiple services and processes, and thus contributed most to the vulnerability of each system. In cases where a range of scores was entered, the median score for that range was used in the row sums. Where information was insufficient to allow assignment of a rank value, a question mark was entered in the table and a value of zero was used in sums. Although the sums are numerically irrelevant, the relative rankings provide a yardstick of vulnerability among ecosystems and identify habitats of greatest concern.

	Large Scale (ocean basin)				*Mid Scale (e.g., regional coast)*							*Small Scale (e.g., bays)*			
Service	*Sea level*	*Salinity*	*Temperature*	*Wind*	*UV radiation*	*Over exploitation*	*Habitat loss*	*Persistent pollutants*	*Eutrophication*	*Hydrology change*	*Disease*	*Alien taxa*	*Development*	*Habitat loss*	*Row Sums*
Provisioning services															
Plants as food	0	1	2	2	1	1	0	1	2	1	1	2	1	1	16
Animals as food	1	1	−2 to 2	1	1	3	3	2	3	2	3	1	2	3	26
Other biological products	1	1	2	2	1	2	2	2	3	2	3	1	2	3	27
Biochemical/ medicines/models	1	1	1	1	1	1	3	1	1	1	1	?	?	3	16
Fuels/energy	0	0	0	0	0	1	?	0	0	0	0	0	0	0	1
Fiber	0	0	0	0	0	3	3	0	0	0	1	0	0	3	10
Nonliving materials (geological effects)	0	1	2	0	0	3	3	0	0	2	0	0	0	3	14
Clean seawater	0	1	1	1	−1 to 1	0	2	3	3	2	0	0	0	1	14
Regulation services															
Sediment formation: biodeposition	0	1	1	2	?	2	3	1	1	3	1	0	2	2	19
Nutrient cycling	0	1	−2 to 2	−2 to 2	1	2	3	1	3	2	0	?	1	2	16
Biological control & resistance	0	1	1	0	?	2	2	1	1	1	?	1	2	1	13
Detoxification, waste disposal	0	1	−2 to 2	−2 to 2	?	0	3	1	2	1	1	0	1	2	12
C sequestration	0	1	1	0	0	1	1	1	1	1	0	0	1	1	9
Food web support processes	0	2	−2 to 2	1	1	3	3	2	2	2	2	1	1	3	23
Atmosphere composition	0	1	−1 to 1	1	1	0	2	1	1	2	1	0	0	2	12
Flood & erosion control	0	0	−1 to 1	1	1	0	2	1	1	3	0	0	−1 to 0	3	11.5
Redox processes	0	1	−1 to 1	1	1	0	2	1	2	2	0	0	1	2	13
Habitat maintenance services															
Landscape connection & structure	0	1	1	1	0	2	3	1	1	2	1	1	−1 to +1	3	17
Aesthetic services															
Spiritual	0	0	3	2	0	3	3	1	1	2	3	0	−1	0	17
Aesthetic	0	0	0	0	0	1	1	1	1	1	1	0	1	0	7
Recreation	0	0	0	0	0	2	2	1	1	1	1	0	0	1	9
Scientific understanding	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−13
Column sums	3	15	14	15	8	31	45	22	29	32	19	6	12.5	38	289.5

Appendix Table 7.A2. Vulnerability of deep-sea ecosystem services and processes to various perturbations. See Table 7.A1 for detailed explanation.

	Large Scale (ocean basin)				*Mid Scale (e.g., regional coast)*							*Small Scale (e.g., bays)*			
Service	*Sea level*	*Salinity*	*Temperature*	*Wind*	*UV radiation*	*Over exploitation*	*Habitat loss*	*Persistent pollutants*	*Eutrophication*	*Hydrology change*	*Disease*	*Alien taxa*	*Development*	*Habitat loss*	*Row Sums*
Provisioning services															
Plants as food	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Animals as food	0	0	1	1	1	3	3	1	0	1	0	?	0	2	13
Other biological products	0	0	0	0	0	1	0	0	0	0	0	0	0	1	2
Biochemical/ medicines/models	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuels/energy	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3
Fiber	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3
Nonliving materials (geological effects)	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3
Clean seawater	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Regulation services															
Sediment formation: biodeposition	0	0	1	1	0	1	1	0	0	0	0	0	0	0	4
Nutrient cycling	0	0	1	1	0	1	0	0	0	0	0	0	0	0	3
Biological control & resistance	?	?	?	?	?	?	?	?	?	?	?	?	?	?	0
Detoxification, waste disposal	0	0	1	1	0	0	1	1	0	0	0	?	0	0	4
C sequestration	0	0	3	3	0	0	1	0	0	0	0	?	0	0	7
Food web support processes	0	0	3	3	0	2	3	0	0	0	0	?	0	0	11
Atmosphere composition	0	0	1	1	0	0	0	0	0	0	0	?	0	0	2
Flood & erosion control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Redox processes	0	0	2	2	0	1	2	0	0	0	0	?	0	0	7
Habitat maintenance services															
Landscape connection & structure	0	0	0	0	0	1	2	0	0	0	0	?	0	0	3
Aesthetic services															
Spiritual	0	0	0	0	0	0	1	1	0	0	0	?	0	0	2
Aesthetic	0	0	0	0	0	0	0	0	0	0	0	?	0	0	0
Recreation	0	0	0	0	0	0	0	0	0	0	0	?	0	0	0
Scientific understanding	0	0	−1	−1	0	−2	−2	−1	0	0	0	?	0	0	−7
Column sums	0	0	12	12	1	14	15	2	0	1	0	0	0	3	60

Appendix Table 7.A3. Vulnerability of estuarine ecosystems to various perturbations. See Table 7.A1 for detailed explanation.

	Large Scale (ocean basin)				*Mid Scale (e.g., regional coast)*							*Small Scale (e.g., bays)*			
Service	*Sea level*	*Salinity*	*Temperature*	*Wind*	*UV radiation*	*Over exploitation*	*Habitat loss*	*Persistent pollutants*	*Eutrophication*	*Hydrology change*	*Disease*	*Alien taxa*	*Development*	*Habitat loss*	*Row Sums*
Provisioning services															
Plants as food	3	3	3	2	3	1	3	3	3	3	1	?	3	3	34
Animals as food	3	3	3	2	2	3	3	3	3	3	3	−3	2	3	33
Other biological products	3	2	2	1	0	3	3	1	2	2	1	−3	2	3	22
Biochemical/ medicines/models	1	2	1	1	1	2	3	3	1	1	?	?	2	3	21
Fuels/energy	2	0	0	0	0	2	?	0	0	0	0	0	2	2	8
Fiber	2	2	2	2	?	2	3	1	1	3	?	?	3	3	24
Nonliving materials (geological effects)	0	0	2	0	0	2	3	1	0	2	0	0	2	3	15
Clean seawater	3	3	2	3	−1	3	3	3	3	2	0	−1	2	2	27
Regulation services															
Sediment formation: biodeposition	3	2	1	3	?	2	3	1	1	3	2	−1 to 1	3	3	27
Nutrient cycling	1	1	2	1	1	2	2	1	3	2	0	?	2	2	20
Biological control & resistance	1	2	3	1	?	2	2	1	2	2	?	2	2	1	21
Detoxification, Waste disposal	3	2	3	2	?	?	2	1	3	2	1	1	2	2	24
C sequestration	1	1	1	0	0	1	1	1	2	1	0	0	2	2	13
Food web support processes	3	3	3	1	1	3	3	1	3	3	1	2	2	3	32
Atmosphere composition	3	2	3	2	1	1	2	1	2	2	1	2	2	3	27
Flood & erosion control	3	2	2	2	1	1	2	1	2	3	1	−3	3	3	23
Redox processes	1	1	2	1	1	1	2	1	3	3	0	2	1	2	21
Habitat maintenance services															
Landscape connection & structure	3	−2 to 2	2	2	1	2	3	1	2	3	2	−3 to 3	3	3	27
Aesthetic services															
Spiritual	?	0	3	0	0	3	3	3	3	2	3	2	3	3	28
Aesthetic	3	1	−1 to 1	0	0	1	2	1	3	2	3	−2 to 2	3	3	22
Recreation	3	1	−1 to 1	0	0	3	3	3	3	2	3	−1 to 1	−1 to 2	3	24.5
Scientific understanding	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	−1 to 1	0
Column sums	45	33	40	26	12	40	51	32	45	46	22	0	46.5	55	493.5