Muddy waters: elevating sediment input to coastal and estuarine habitats

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Changes in land use and the development of coastal regions around the world have markedly increased rates of sediment input into estuarine and coastal habitats. Field studies looking at the consequences of terrestrial sediment deposition, water-borne sediment, and long-term changes in habitats indicate that increasing rates of sediment loading adversely affect the biodiversity and ecological value of estuarine and coastal ecosystems. Managing this threat requires means with which to convey the magnitude of the problem, forecast long-term trends, and assess the risks associated with changes in land use. Here we focus on approaches for assessing the risks of changes in land use, which include combining biological effect studies with catchment and hydrodynamic modeling, using statistical models that forecast the distribution and abundance of species relative to changes in habitat type, and using sensitive species that play important ecological roles as indicators of change.

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Sandy and muddy sediments dominate estuarine and coastal habitats, and the bivalves, snails, worms, echinoderms, crustaceans, and other organisms that live in the sediments are involved in many important ecological and geochemical processes that influence ecosystem function. Understanding these processes is important for developing environmental management strategies that recognize the essential value of these ecosystems. Aesthetic and recreational values, as well as the provision of food resources, are clear examples of the importance of estuaries, but no less significant are influences on the transport and transformation of nutrients, sediments, and pollutants, and on primary and secondary productivity (Herman *et al*. 1999; Levin *et al*. 2001; Austen *et al*. 2002). Often, it is the loss of these values that raises awareness of the degradative changes in estuarine and coastal ecosystems. The key to understanding and managing the biodiversity of estuarine and coastal environments is an appreciation of the contributory functions of different organisms, communities, and habitats.

In a nutshell:

- Estuarine and coastal ecosystems have high intrinsic and resource values
- They are subjected to a multitude of stresses as human populations and levels of exploitation increase
- This situation requires thoughtful and integrative management and open decision-making processes
- Human use of coastal regions increases the input of sediments to many estuarine and coastal regions of the world
- Increased sediment inputs can profoundly alter the structure and function of estuarine ecosystems and reduce their values
- Science-based tools that inform planning decisions and help integrated governance are important in maintaining and restoring ecological values

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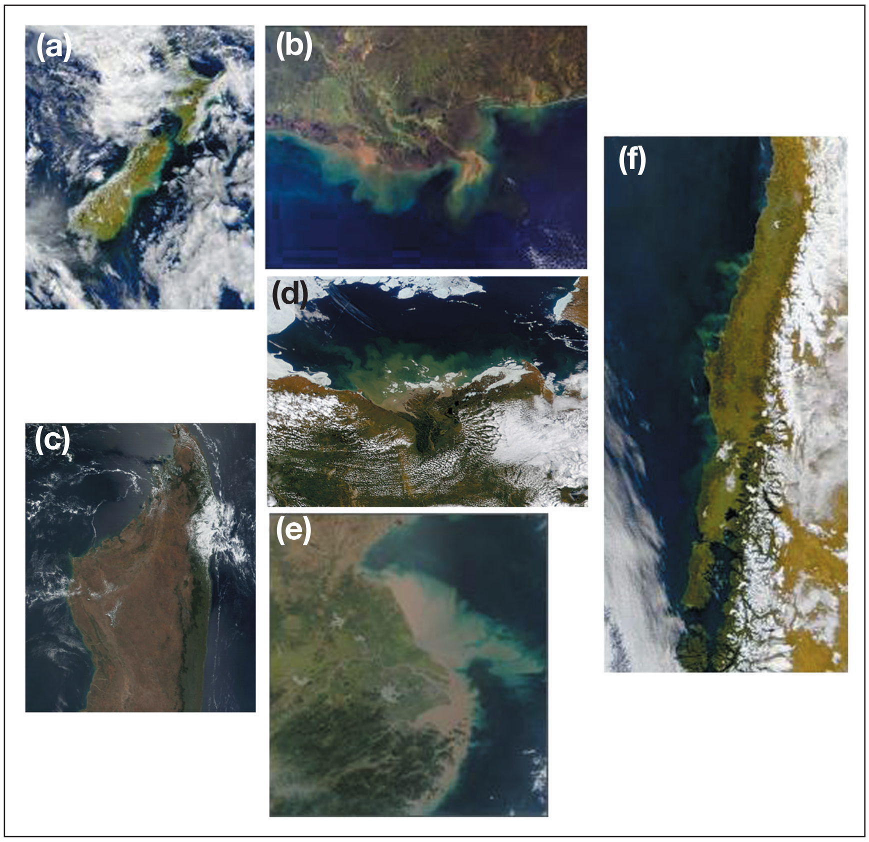
A dynamic balance often exists between the import and export of sediments in coastal systems. While we discuss the consequences of increased sediment loading, it is worth noting that sediment starvation due to damming and diversion can also have profound effects on coastal ecology. The loading of terrestrial sediment to aquatic environments, however, is increasingly recognized as a threat to coastal and estuarine ecosystems. The extent of the problem is illustrated by satellite images from around the world (Figure1). Considering sediment as a contaminant seems contradictory at first; the export of terrestrial material into the sea is a natural process that has occurred over millennia and some estuaries, such as those associated with glaciers, can have naturally high levels of sediment input (Carney *et al*. 1999; Wlodarska-Kowalczuk and Weslawski 2001). Nevertheless, what has clearly changed in modern times is the regime of terrestrial sediment delivery to the sea. A recent study in the highlands of Sri Lanka has shown that the conversion of forest to agricultural land has increased the rate of sediment runoff by two orders of magnitude, from 13–30 metric tons per km^2 per year up to 7000 metric tons per km^2 per year (Hewawasam *et al*. 2003). Average sedimentation rates in the Chesapeake Bay have increased by an order of magnitude since 1760, when land clearing activities were first initiated (Cooper and Brush 1993). Hydraulic mining and extensive forestry during California's gold rush resulted in massive sediment inputs into San Francisco Bay, substantially changing the distribution and nature of habitats (Nichols *et al*. 1986; Holliday 1999). This magnitude of



Courtesy of NASA (see http://visibleearth.nasa.gov/)

Figure 1. *Turbid estuarine and coastal waters are seen as brown and turquoise in these satellite images of coastal regions. Sediments transport nutrients fuelling productivity, but close to shore other ecological changes dominate. (a) New Zealand; (b) Mississippi Delta; (c) Madagascar; (d) Mackenzie River, Canadian Arctic; (e) Yangtze delta; (f) Chile.*

disturbance and the large number of ships using the bay during the gold rush may well have set the bay on its trajectory to today's dominance by invasive species (Cohen and Carlton 1998).

On rocky coasts, studies of ecological problems caused by sedimentation have a long history, and a recent review by Airoldi (2003) identifies sedimentation as a widespread and increasing global problem. Sediment loading is also an important issue for coral reefs, although complex and indirect effects often hinder simple predictions (Rogers 1990; Fabricius and De'ath 2001). Conversely, in soft sediment systems, despite some early studies showing the potential for substantial impacts associated with smothering by terrestrial sediment deposits (McKnight 1969; Peterson 1985), there has been little effort by ecologists to understand the magnitude of the effects, document trends, or help in the development of management tools that avoid or mitigate adverse effects. The problem is perhaps one of sliding baselines and changing expectations, as in many cases sediment loading increased early on in the history of human exploitation of the landscape and scientists have thus tended to study systems that are only distantly related to pristine states (Dayton *et al.* 1998).

Understanding the major threats to estuarine and coastal ecosystems and how these interact with environmental change helps to prioritize management actions. Recent studies describe the ecological consequences of elevating rates of sediment loading in estuaries, which smothers benthic communities and elevates turbidity. Such changes can alter the functioning of these ecosystems and lead to degradative change. To advance resource management, various scientific tools can be employed to help determine the magnitude of the problem, assess risk, and forecast trends.

■ Catastrophic dumps

Terrestrial sediment is washed into the aquatic environment as a result of runoff from the land, river and stream channel erosion, and landslides. Small rivers draining small and steep catchments make disproportionally large contributions of sediment (Milliman and Syvitski 1992), and most sediment enters the estuary during storm events. In estuaries, this can result in sediment loads that, for short periods of time, are orders of magnitude higher than average (Hicks *et al.* 2000). The sediment is mostly in the form of fine silts and clays – highly charged particles which flocculate on contact with seawater and are rapidly deposited. When sediment concentrations in the water are very high, however, high-density turbidity currents that flow along the bed of the estuary can be created. Regardless, the net result is the smothering of estuarine and marine sediments (Figure 2). The smothering is easy to detect as the chemical nature of terrestrial sediments, particularly the presence of iron-rich minerals, gives them a distinctive yellow–orange color, clearly distinguishing them from adjacent marine sediments (Figures 2 and 3).

Experimental application of terrestrial sediments onto intertidal flats (Figure 3) have helped to define critical thresholds in the depth of deposits that create adverse ecological effects and to understand how these factors vary with environmental conditions (Norkko *et al.* 2002; Cummings *et al.* 2003; Hewitt *et al.* 2003; Thrush *et al.* 2003a). These small-scale mimics of natural catastrophic events revealed that once the estuarine sediment is smothered by +2 centimeters of terrestrial sediment, it quickly becomes anaerobic, resulting in the death of the resident fauna. Although a deposit that is 2 cm thick may represent many times the long-term average annual sedimentation rate, events of greater magnitude do occur.

To understand the ecological importance of such events, it is necessary to consider the rate of recovery following such a disturbance. After all, if the resident community recovers quickly, then increased sediment loading is unlikely to lead to long-term change. Measures of macrobenthic recovery have emphasized the importance of regional variations in physical and biological processes (eg wave disturbance, flow velocity and elevation, and sediment mixing by animals) in speed of recovery (Thrush *et al.* 2003a). Furthermore, the lack of complete recovery over the duration of field experiments that lasted 212–603 days indicates the potential for broad-scale degradation of estuarine communities. As catastrophic events can be of sufficient extent to smother large expanses of estuaries, or may occur at frequencies that exceed the rate of recovery of the infaunal community, a mosaic of disturbed and recovering patches are created. The net result is that undisturbed areas that aid recovery by supplying a diverse range of colonists will become increasingly rare with increased sediment loading.

Figure 2. *Orange-colored terrestrial sediment deposited after heavy rainfall smothers estuarine seagrass and shellfish beds.*

It is reasonable to expect that extreme sedimentation events that deposit thick layers of terrestrial sediment are likely to be less frequent than events that deposit thinner (1 mm or less) layers, because many natural phenomena show this type of inverse relationship between the size and frequency of events. Deposition of thinner layers of terrestrial sediment, although potentially more extensive and frequent, may not result in direct mortality of residents, but in chronic effects on physiological condition and behavior of macrofauna, together with changes in biogeochemical gradients in the sediment and the growth of benthic microalgae. We have shown that as little as 3 mm of terrestrial sediment is sufficient to alter macrobenthic community structure (Lohrer *et al.* in press). Ten days after the application of 7mm of terrestrial sediment, experimental plots had lost about 50% of their individuals and species; these effects were reasonably consistent for individual experiments conducted in different habitats and seasons. In these experiments, the depletion of sediment Chlorophyll *a*, (an indicator of microalgal standing stock) varied, probably due to seasonal differences in the timing of experiments and spatial variation in the responses of different benthic microalgae. Another study of thin silt deposits found that active migration by diatoms (a type of microalgae) was a key mechanism for restoring oxygenation of the sediment surface, indicating that these plants affect biogeochemical gradients (Wulff *et al.* 1997). Benthic microalgae are also a primary food resource for many sediment-dwelling organisms that would probably avoid or move away from areas of low food quality and quantity (Nilsson *et al.* 2000; Stocks and Grassle 2001; Cummings *et al.* 2003).

Effects of elevated suspended sediment concentration

Terrestrial sediment is not only deposited on the seabed, but also contributes to increased suspended sediment

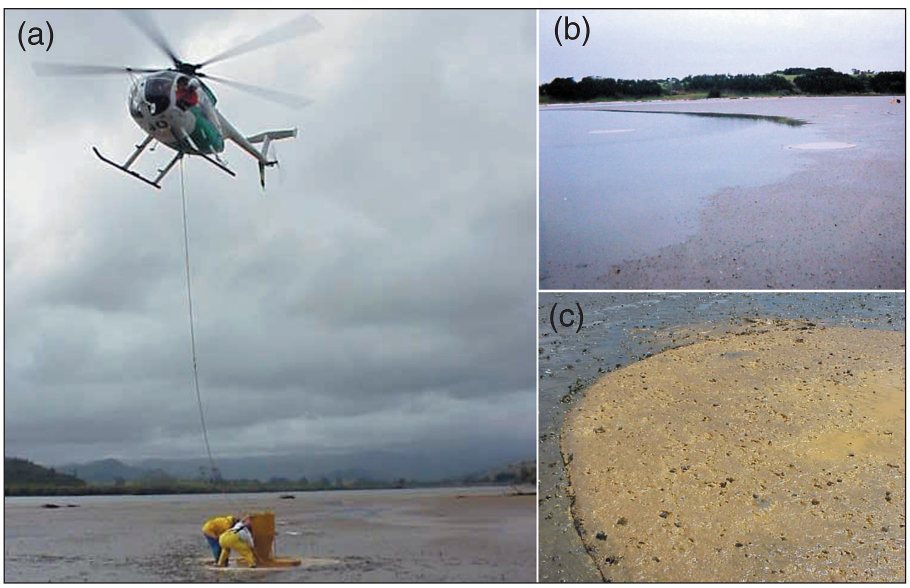


Figure 3. *Experimental mimics of sediment deposition events provide insight into the impact and recovery process; (a) sediment slurries are flown to experimental plots; (b) plots are arrayed across the sandflat to assess the effect of different depths of deposition; (c) plots remain distinct from surrounding sediments for long periods.*

concentrations. These effects on water turbidity can influence the structure and function of estuarine ecosystems. Highly turbid water can restrict light transmission, thereby influencing the relative importance of primary production by phytoplankton versus large plants attached to the seafloor. Seaweeds and seagrasses typically require more sunlight for photosynthesis than phytoplankton; this, combined with the constraint of being attached to the seabed, makes them particularly susceptible to elevated concentrations of suspended sediments (Duarte 1991; Markager and Sand-Jensen 1992). Global ecological forecasts for seagrass habitats recognize that changes in the sediment regime are an important issue, especially in Southeast Asia (Duarte 2002).

Inorganic silts and clays directly affect suspension-feeding animals by clogging feeding structures, interfering with particle selection, and requiring the use of energy to clear away unwanted particles. For example, suspended sediment concentrations as low as 80 mg per L, which are commonly recorded during storms, can depress the feeding rate of the horse mussel (*Atrina zelandica;* Figure 4). Combined laboratory and field experiments and surveys on *Atrina* have demonstrated the strong negative effect on its physiological condition, resulting in a natural distribution limit controlled by suspended sediment load (Ellis *et al.* 2002). Suspension-feeding bivalves modify the coupling between seafloor and water column processes, influencing phytoplankton population dynamics and nutrient cycling (Dame 1993), and such effects can transfer through to the rest of the ecosystem. In the case of *Atrina*, the species also adds three-dimensional structure to soft-sediment habitats by modifying flow conditions, providing refuge from predation for small fish and invertebrates and hard surfaces for the settlement of encrusting fauna (Green *et al.* 1998; Cummings *et al.* 2001). Interestingly, the strength of *Atrina's* ecological role varies with location, and the animals have a weaker influence on community structure as background sedimentation increases (Norkko *et al.* 2001).

Long-term degradative change

As stated above, terrestrial sediment can influence estuarine and coastal ecology and changes in the magnitude of effects may vary, depending on the scale of disturbance; in addition, increased suspended sediment concentrations can influence primary production and the benthic animals that feed by filtering seawater. These effects can flow through the communities and ecosystem along a variety of pathways (Figure 5). The more challenging aspects of research in this area are the more pervasive and subtle effects that are difficult to document and forecast. The danger is that as the estuaries become muddier, habitat diversity decreases, with a concomitant loss of ecosystem values.

Changes in the estuarine sediment-loading regime will favor some species and habitats over others and thus influence estuarine biodiversity. Elevated suspended sediment concentrations and the frequency, extent, and magnitude of deposition events influence the recovery response of the benthic community by affecting habitat suitability and the scope for unimpacted refuge sites to provide colonists to disturbed areas (Figure 6). Understanding the potential for a resulting depletion of sensitive species, particularly those that play positive roles in influencing habitat structure and ecosystem function, is key to understanding the risk of long-term degradative change. Yet the potential for ecosystems undergoing radical shifts in structure and function is not fully understood, and there could be critical thresholds beyond which recovery to some previous valued state is unlikely. Ecological systems have been observed tipping into alternative states as a result of the loss of ecosystem functions, and it is important to be able to assess the consequent loss of diversity and ecological value (Huston 1994; Scheffer *et al.* 2001).

There are a few examples where trends in sediment loading are matched to broad-scale changes in ecology. A study of Tasmanian estuaries indicated that silt loading has had a widespread and detrimental effect on estuarine communities (Edgar and Barrett 2000). Across a number of estuaries, these authors observed a switch in the dominance of the ben-

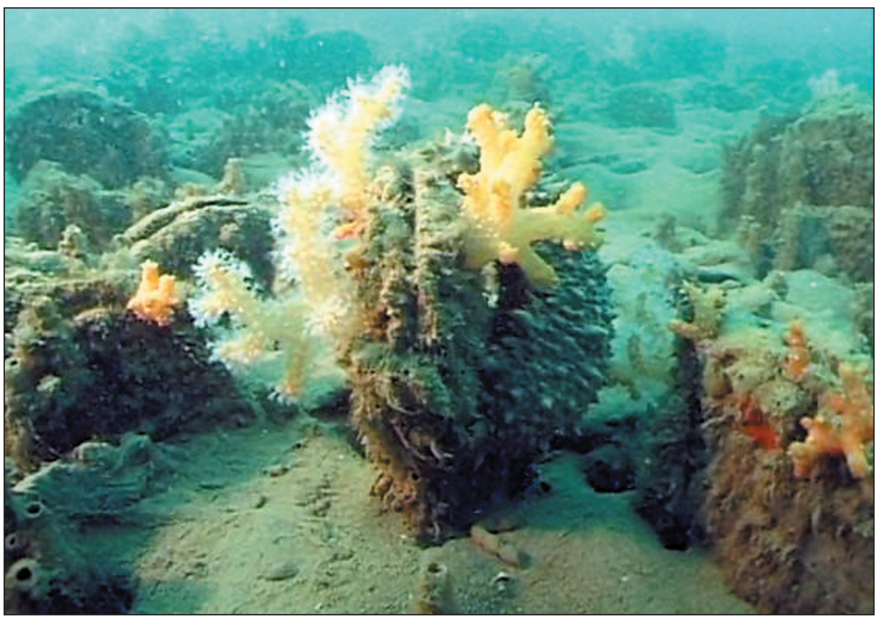


***Figure 4.** Suspension feeding bivalves, such as the horse mussel (*Atrina zelandica*), create structure, provide habitat, and affect food supply on the seafloor. The bivalves are adversely affected by elevated suspended sediment concentrations, thus causing greater changes in the structure and function of benthic communities.*

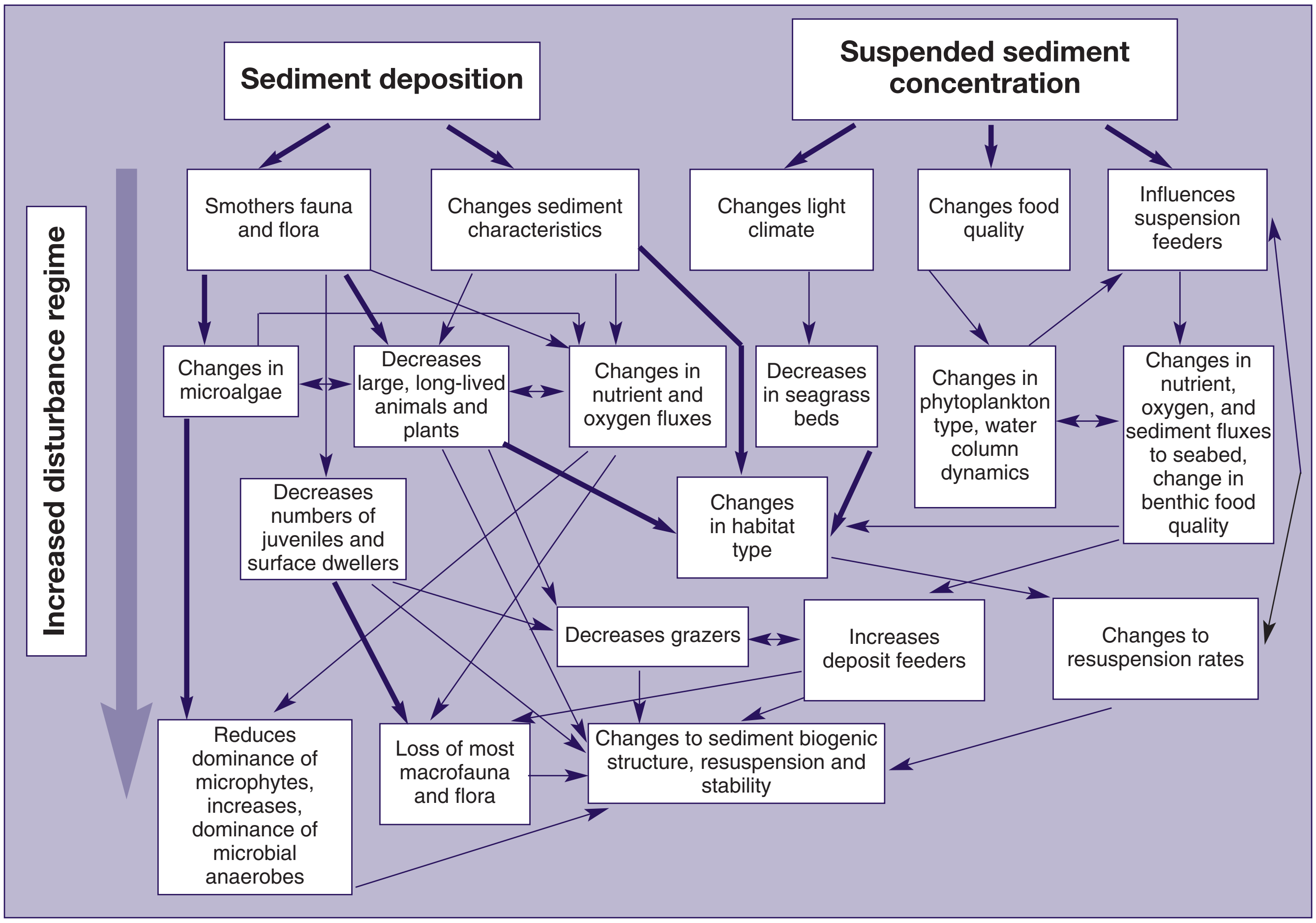


Figure 5. *The various ways that either deposited or suspended terrestrial sediment can trigger changes in estuarine soft-sediment communities. As the disturbance regime increases, more effects are triggered; thick lines mark strong effects determined by field studies.*

thic community and sediment type that coincided with changes in the density of humans in the catchment from 1 to 10 individuals per km^2. Major changes to the seafloor community of Kane'ohe Bay (Hawaii) have also been linked to high rates of sedimentation associated with changes in land use (Smith and Kukert 1996). While the previous history of sediment inputs may limit the ecological sensitivity of the receiving environment, it is important to identify how natural features and human activity combine to elevate the threat of continued degradation.

Elevated sedimentation regimes tend to reduce the overall ecological heterogeneity. The modification of available habitats due to elevated sedimentation has been shown to lower diversity and abundance, and to cause functional differences, including reductions in the abundance of suspension feeders (Ellis *et al.* 2004). As yet,

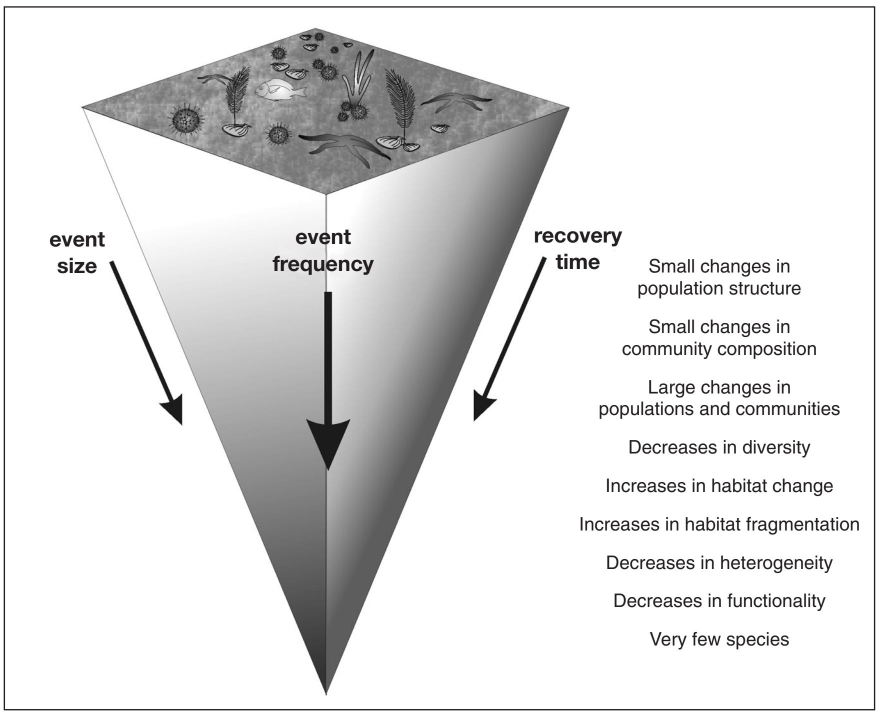


Figure 6. *Changes in the magnitude and frequency of disturbance, along with changes in benthic community recovery rates, can lead to broad-scale changes as biodiversity becomes increasingly homogenized and slow-growing and colonizing species are excluded.*

there is insufficient information to assess the relative importance of different processes in contributing to long-term change in estuarine ecosystems. Nevertheless, more generally, the loss of large macrofauna could have important implications (Levin *et al.* 2001; Thrush and Dayton 2002). In estuaries, multiple habitat types, such as saltmarsh, mangrove, seagrass, unvegetated intertidal flats, tidal channels, and subtidal habitats, promote diversity by enhancing recruitment and maintaining species with requirements for multiple resources.

Putting the information to work for resource management

Documenting real effects on ecosystems and assessing how changes are likely to influence biodiversity and ecosystem values are key elements of ecology, but it is also important that scientists provide information to help managers minimize the risk and reduce threats, once the magnitude and scope of a particular problem has been identified. Estuaries are often areas of intensive and diverse human use, where high quality information and open decision making are particularly needed to facilitate effective environmental management. Important applications of ecological knowledge include defining threshold effects, prioritizing actions, and forecasting ecological responses.

An example of information use to assess threats to an estuary as a result of changes in land use comes from a study in the Okura estuary catchment, located on the outskirts of Auckland, New Zealand. As the city spreads, farmland is subdivided, posing the threat of increased sediment loading to the estuary, while roads are constructed and building sites are cleared of vegetation. There are a number of best management practices for sediment control that help to restrict sediment runoff (ARC 2003), but sediment loads can still increase during this phase of development. Considering limits to the minimum size of subdivisions and the number of dwellings, influencing the configuration of roads, or restricting development in sensitive parts of the landscape and intensifying development in low risk areas are therefore important management considerations. But how do we determine what trade-offs are appropriate between risks associated with development and the maintenance or improvement of ecological values for the estuary?

During the development phase, the major threat to the estuary is likely to be catastrophic sediment deposition due to runoff from exposed soils and road cutting. Experiments on terrestrial sediment deposits have enabled identification of critical deposition thresholds. Combined with models of sediment runoff from the catchment and particle dispersal models that predict the threat of deposition to different parts of the estuary, this information can be used to assess the relative ecological risk to different estuarine habitats under different development scenarios. These risk assessments allow managers to compare the threats posed by various scenarios of land development and thereby improve decision making.

Another approach is the use of statistical models designed to forecast the responses of species to increased muddiness or changes in the relative proportion of habitats by relating ecological variables to environmental factors (Figure 7; Thrush *et al.* 2003b). This approach assumes that the relationships apparent in the observed spatial patterns match those that will later occur over time. Such models take a top-down view of ecological systems and seek to identify general patterns and reveal species with different sensitivities to habitat change. These types of models are therefore also useful in identifying species or groups of organisms that can act as indicators of change.

There is also the potential to develop models that relate changes in suspended sediment concentrations to more sensitive ecological responses, such as an animal's physiological condition and growth. Initially, relatively simple "scope-for-growth" models where only absorbtion, respiration, and excretion are considered were derived (eg Bayne and Widdows 1978), but these simple models are problematic (Jorgensen 1996) and more complicated eco-physiological models are being developed (Ren *et al.* 2000). However, such complicated models require a great deal of information, and are currently restricted to aquaculture species. At present, they are unable to include event-driven variations in food quality and the duration of elevated levels of suspended sediments, or site-specific differences caused by environmental history, food preferences, or algal composition of the water.

These applications of scientific information help resource managers and society make informed decisions about threats and define desired outcomes for estuarine and coastal ecosystems. They help convey the magnitude of the problem, assess the risks associated with changes in land use, and forecast trends. These latter points are important because like any diffuse-source catchment-derived problem, solutions are often complex and need to be well targeted. For example, controls on land use and deforestation and implementing best management practices to restrict soil loss are important, but maintaining or restoring wetlands, mangroves, and other habitats may also help limit sediment entering and being redistributed around an estuary. The problem with the latter is that flash floods that deliver large quantities of sediment down small rivers are not likely to be affected by small wetland–flood plain regions. Thus, careful land management should emphasize reducing the frequency of these events. Furthermore, activities in the estuary and along the adjacent coastline that modify flushing and sediment transport regimes (eg dredging, construction, and shoreline modification) are also needed as part of the solution.

Conclusions

Estuaries are transitory features in geological time, but over ecological time and at scales generally relevant to humanity they provide a variety of important benefits.

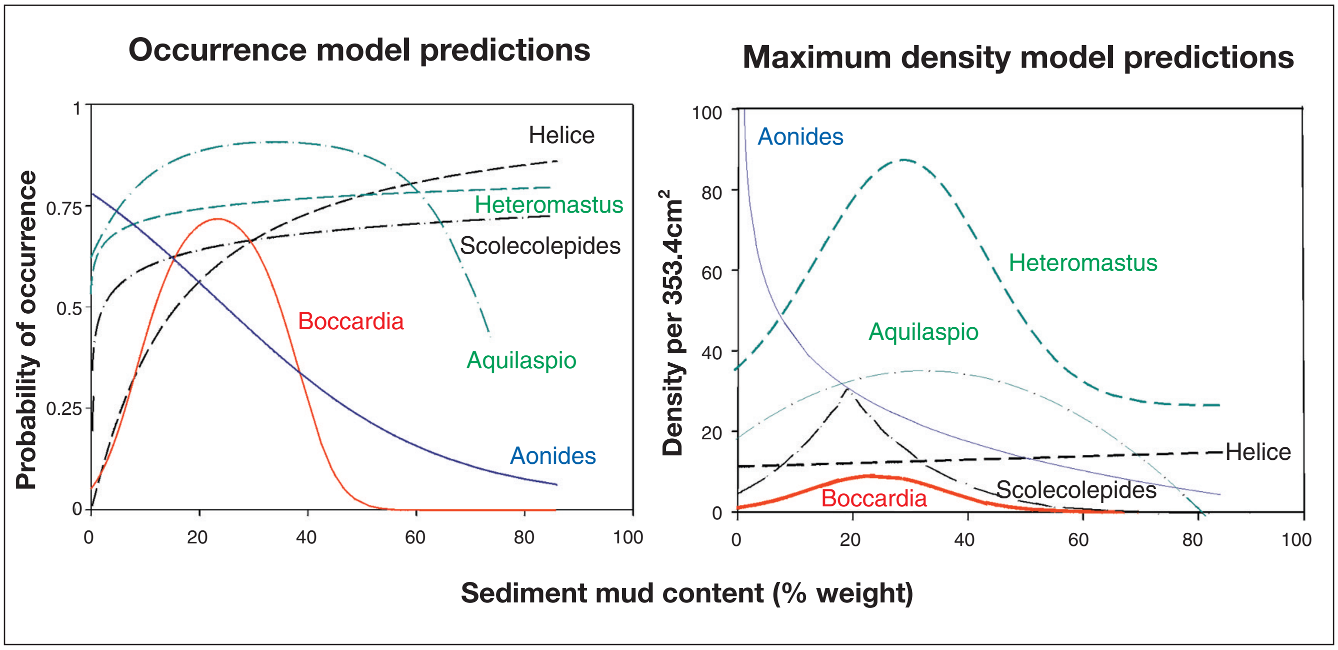


Figure 7. *Statistical models that forecast the probability of occurrence or the maximum density provide a way of showing how species distribution and abundance patterns can change with habitat type (from Thrush* et al. *2003b).*

Within estuaries, sedimentation is natural and provides a number of important functions: supplying nutrients, burying contaminated sediments, and buffering coastal erosion. However, environmental problems occur when the rate at which sediment is being transferred to and deposited within estuarine and coastal regions is increased. This has the potential to profoundly alter the structure and function of estuarine ecosystems. Here we have focused on the direct effects of sediment as a function of the magnitude of material entering the estuarine environment, but, depending on geology and land use, sediments may also contribute contaminants such as hydrocarbons, heavy metals, and nutrients. Due to the ever-increasing pressure on land, sediment runoff and rapid sedimentation events may become more common in many parts of the world (Cicin-Sain *et al.* 2002). Moreover, climate projections for many regions indicate that sea levels will rise, rainfall will be more intense, and the frequency of storms will increase, further compounding the problem (Inman and Jenkins 1999; Burkett *et al.* 2001).

Inevitably, estuarine and coastal ecosystems are subject to multiple stressors, complicating both assessment of specific effects and the prioritization of management actions. The pressures imposed on these ecosystems result both from individual events and longer-term, broader-scale degradation. Broad-scale, degradative ecological changes are usually triggered by the loss of organisms that contribute considerably to the functional diversity of estuarine and coastal ecosystems. Better information on processes, rates, and connectivity in seafloor ecosystems is critically needed to help demonstrate the ecological value of coastal and estuarine ecosystems and to underpin management decisions. This concept is encapsulated in a quote from Miller *et al.* (2002): "The value of a habitat is far more than its species list, yet it is difficult to place a value on organisms that are unfamiliar or have no commercial value".

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