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The continental shelf benthic ecosystem: current status, agents for change and future prospects

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SUMMARY

Continental shelf benthic ecosystems play an important role in the economy of many coastal states through the provision of food, non-living resources and through control of climate. Changes in the status of these ecosystems, through either natural or human-induced environmental drivers can be expected to have important economic and social consequences. Agents that could induce change include climate and oceanography, hydrology (river discharge), land-use and waste disposal practices, fishing, aquaculture and extraction of non-living resources. Trends in all of these drivers, particularly those under human influence, suggest that shelf systems will come under increasing pressure. Attempts to predict the future state of any ecological system are fraught with difficulty, particularly over decadal time-frames. This is, perhaps, especially true for continental shelf ecosystems where data on current status are poor and our understanding of many of the drivers of change somewhat rudimentary. What can be said for certain, however, is that change will occur and, in the short term, many of the signs point towards deterioration in the ecological condition of many shelf systems, but particularly those of developing countries. Trends in land-use practices, with consequences for nutrient, sediment and freshwater input to coastal seas appear to be particularly worrying, but the poor state of many demersal fisheries systems must also be acknowledged. In contrast to the developing world, although challenges undoubtedly remain, particularly with respect to atmospheric inputs resulting from energy production, current trends in environmental management suggest that pressures imposed by land use, waste disposal and fishing will probably decline over the coming decades on the shelves of many developed countries. At the global scale, therefore, the key driver for sustainable use of our continental shelf ecosystems would appear to be intimately linked to the social and economic well-being of poorer nations.

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INTRODUCTION

In the first 20 years of the 21st century, even the most conservative estimates suggest an increase of approximately one billion people from the current level of about 6 billion (United Nations 1998). The increases in the demand for natural resources that will accompany this population rise will place all natural environments under increasing pressure. While terrestrial systems can be expected to face the bulk of the assault, marine systems will certainly not escape; approximately 20% of the world's population lived within 25 km of the coast in 1995 (Cohen *et al.* 1997) and 19% of all lands within 100 km of the coast have been classified as altered by humankind (Burke *et al.* 2001). From a marine perspective, increases in population, land clearing and coastal development seem set to impose their most severe effects on intertidal environments, wetlands and estuarine systems, owing to the especially intimate association between these systems and the land. In addition, however, we can expect man's footprint to also press more firmly onto the world's continental shelves and effects on these systems must also be evaluated to ensure that we fully appreciate the consequences of change and manage the associated risks appropriately.

The purpose of this review is to look forward and consider the future of continental shelf benthic ecosystems to the time horizon of the year 2025. Although less charismatic than coral reefs, and less familiar than wetlands or mangroves, continental shelf benthic systems support a major component of global fisheries production, exert important controls on marine productivity and contain rich and varied marine communities. For anyone concerned about human welfare, or the conservation of our marine natural heritage, the future of these ecosystems deserves careful consideration.

The first part of this review describes the general nature of continental shelf benthic ecosystems. I then go on to consider the natural and human-induced agents for change in the benthic invertebrate and demersal fish communities that our continental shelves support, along with what is known of the long-term trends in these groups. This part of the review is intended to provide a broad perspective on the various factors that control the state of continental shelf systems.

Table 1 The mean area of the inner continental shelf (i.e. depth <65 m) covered by each sediment type and the trends in distribution with latitude. Constructed from data in Eisma (1998) and Hayes (1967).

Sediment type	*Mean area*	*Trends with latitude*
Mud	37%	Most common (up to 50%) in the humid tropics, often due to the influence of large rivers, declining to <10% in cold climates. Occasional areas with high mud coverage off some arid coasts, probably due to formation of calcareous muds, and polar coasts due to deposition of glacial muds and loess (wind) deposits
Sand	47%	Forming >30% of deposits at all latitudes, but increasing to a maximum of 60% at 20–30° latitudes with moderate temperature and rainfall
Rock/gravel	3%/3%	Most common in areas of low temperature, <10% at 30° latitude, rising to 50% at 70°
Coral	6%	Confined to warmer seas below 30° latitude, where temperatures do not fall below 13–14°C
Shell deposits	4%	Uniformly distributed with respect to latitude

Having considered what is known of long-term trends and the suite of mechanisms responsible, and mindful of the fact that past trends will not necessarily continue into the future, I then offer a personal view of how things might develop over the next 25 years. A 25-year time frame has been chosen as being sufficiently far into the future for us to expect key drivers to effect observable change (for example, fishery catches, climate, sea level), but not so far ahead that they go beyond currently available projections for those drivers.

Continental shelf benthic ecosystems

The continental shelves of the world occupy 7.5% of the total area of the oceans, and are usually defined as extending from low-water mark to the shelf break where the slope of the seabed steepens markedly. This steepening usually occurs at between 100 m and 200 m depth (average 132 m). The average width of the shelf is 78 km, but ranges from 0 to 1500 km (Eisma 1998). The continental shelf also includes a number of broad, largely enclosed, shelf seas (for example, the North Sea, Yellow Sea and Java Sea), some of which contain deeps and troughs. In the Barents Sea, for example, most of the seafloor is between 200 and 400 m, yet it is usually still classed as being on the continental shelf. Although this is the conventional definition, for convenience some authors have also defined the continental shelf as waters shallower than 200 m.

On an areal basis, the continental shelves of south-east Asia, the Bering Sea region and the Patagonian shelf are dominant (Fig. 1); the projection exaggerates the area of shelf in northern Russia. Figure 1 also shows the relative distributions of estimated demersal fisheries catch potential and current oil and gas production among shelf regions. These two resources are by far the most important in monetary value of those extracted from continental shelves.

The geological structure of shelf regions can be broadly divided into two classes, namely those areas where the surface of the seafloor comprises igneous or metamorphic rocks and those where it consists of sedimentary deposits. Most shelves are a mixture of both types, with sediment predominating and some exposed rock, although the converse can apply in some areas. Because most present day shelves are covered primarily with sediments, they can be conveniently classified on the basis of their grain size and origin. Table 1 provides one such classification and describes the trends in coverage with latitude for the inner continental shelf (i.e. ≤ 65 m water depth). Broadly speaking, the kind of sediment that covers a shelf region is determined by its tectonic setting, the size of the sediment load from rivers emptying onto it, and the wave energy that affects it (Eisma 1998).

As noted above, the outer boundary of the world's continental shelves can be straightforwardly defined as the area shoreward of the shelf break. However, given the treatment that estuaries, seagrass beds and intertidal shores have received elsewhere (Duarte 2002; Kennish 2002; Thompson *et al.* 2002), we must give some consideration to what is to be included or excluded from the term as we approach the shore. As with most other ecological boundaries, those between the different zones of the coastal ocean are blurred, in this instance by the oceanography of a particular region (Alongi 1998). In particular, the zone of freshwater influence varies, making the distinction between an estuarine and coastal system somewhat arbitrary. This area of influence depends on local patterns of factors including water circulation, topography, river discharge and climate. In the extreme case of the wet tropics, in proximity to large rivers such as the Amazon, freshwater influence can extend beyond the shelf edge (Alongi 1998). As a result, where mixing of fresh water and salt water occurs across the shelf, there is inevitably some overlap between consideration of estuaries proper and the coastal ocean. As far as possible, this review is restricted to the area between the recognizable mouth of a river and the shelf break. While this minimizes the degree of overlap with analyses of estuarine systems (Kennish 2002), some duplication is inevitable.

Formal study of continental shelf biota can be traced back at least to Aristotle (384–322 BC), who described a number of benthic species and fish from the Aegean Sea. It was not until the 1800s, however, when scientists such as G.O. Sars deployed dredges and grabs from ships, that we obtained any real appreciation of the diversity, distribution and abundance of benthic taxa on the shelf. Because most of the shelf is covered by sediments and is below the photic zone it is benthic infaunal invertebrates and the fish species they support that dominate the biota. In areas where currents have

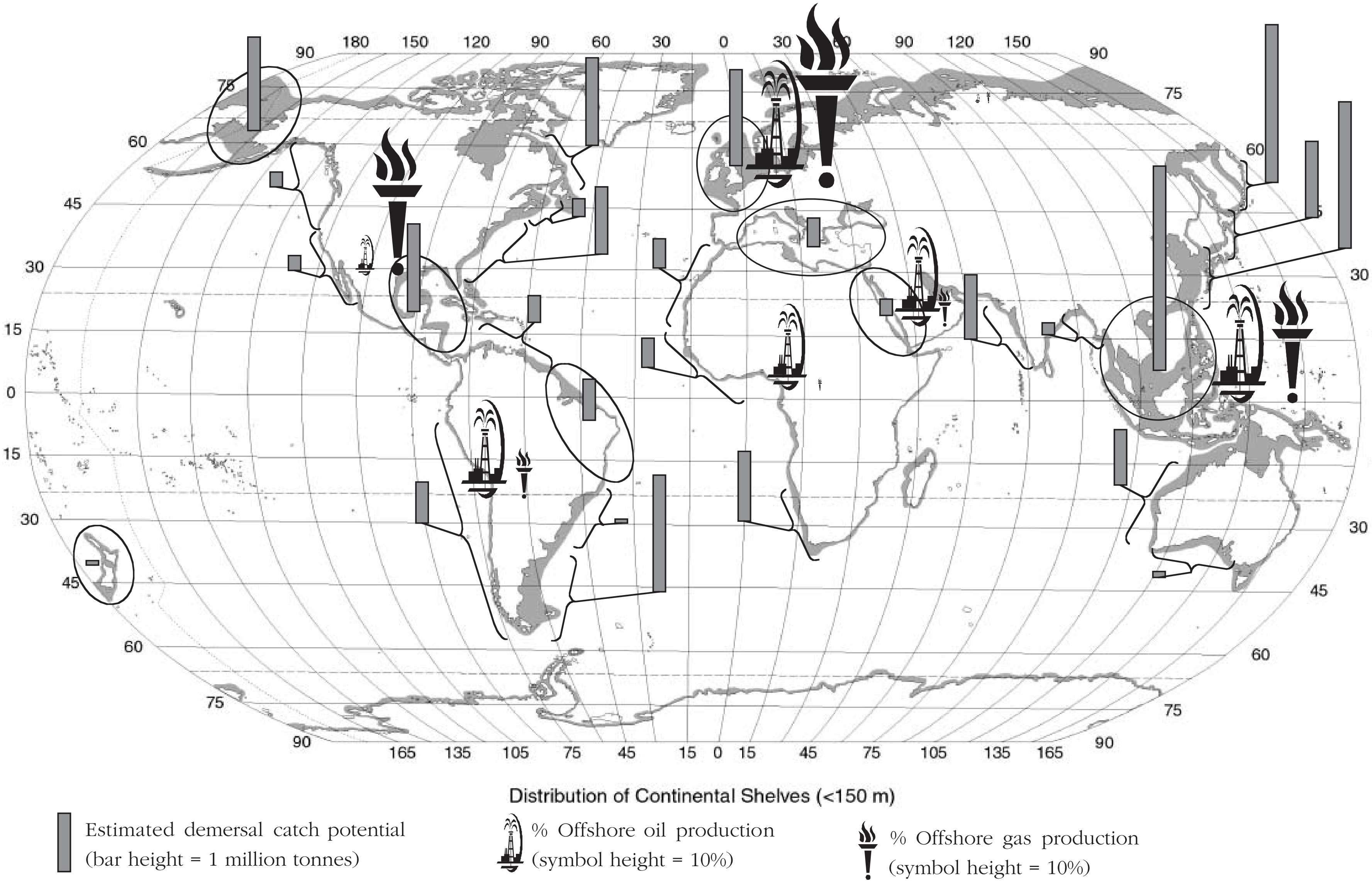

Figure 1 The distribution of the world's continental shelves, showing the relative distribution of estimated demersal fish catch potential (tonnes), and percentage of global offshore oil and gas production (1995) for each region. Sources: estimated demersal catch potential (tonnes) obtained from Sharp (1998); oil and gas production (%) from Pickering (2000).

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exposed the underlying rock, however, surface dwelling epifaunal species can also be found in high abundance.

Despite the early start, progress in mapping the distribution and abundance of the benthos of continental shelves over the intervening century has been relatively poor, a fact that can probably be attributed to the high costs of ship time and the lack of an efficient way to obtain, sort and identify large numbers of soft-sediment benthic samples (Hall *et al.* 1994). Despite the rapid recent advances in acoustic and video seabed mapping tools our capacity for synoptic surveys of even structural epibenthic community remains extremely limited and our data holdings on the benthic communities of our continental shelves commensurately poor. This relative paucity of data makes even general statements on the global diversity, distribution and current status of benthic fauna difficult to make and statements about temporal trends almost impossible. For example, although it seems certain that the highest overall benthic diversity occurs in the tropical Indo-Western Pacific, which includes the waters off the coasts of Asia, East Africa, northern Australia, and the Pacific Islands, separate assessment for soft-sediment communities are lacking because current estimates include the fishes and invertebrates of coral reefs (Clarke & Crame 1997).

Although, in general, data on the distribution and abundance of species on continental shelves is rather limited, a few areas have been studied reasonably comprehensively and efforts have been generally enhanced by seabed survey work in the last 20 years in support of oil and gas exploration (see, for example, Heyward *et al*. 1997). Notable among the better studied areas is the North Sea and the east coast of the USA (see Thorson 1957; Sanders 1968; Johnson 1970, 1973; Young & Rhoads 1971; Glemarec 1973; McCall 1977; Whitlatch 1977; Creutzberg 1985; Basford & Eleftheriou 1988; Eleftheriou & Basford 1989; Thouzeau *et al*. 1991; Heip *et al*. 1992; Sherman *et al*. 1998; Zilstra 1998). These studies show clear correlations between fauna, sediment characteristics, water depth and hydrographic features. These influences on community structure appear to be general features of most continental shelf systems studied to date and are considered further in the following section.

With respect to our knowledge of energy transfer and production processes, Alongi (1998) recently reviewed what is known of along and cross-shelf gradients on continental shelves and showed how their differing characteristics around the world lead to marked differences in the patterns of energy and nutrient flow through benthic food webs. These differences appear to be driven largely by differences in rates of carbon fixation, which are ultimately determined by local and ocean scale patterns of water circulation, chemistry and shelf geomorphology (Alongi 1998).

In general, carbon fixation in the water column is positively correlated with the supply of food to the benthos and hence benthic biomass. This correlation is supported by a positive feedback whereby high benthic production leads to high rates of nutrient remineralization to support pelagic production (McLusky & McIntyre 1998). (As we will see later, however, when water column productivity is very high this pattern can break down owing to anoxia in bottom waters.) These fundamental relationships are believed to explain the generally higher secondary productivity by marine benthos at temperate latitudes compared to the tropics (McLusky & McIntyre 1998). It should be noted, however, that although production is generally lower for tropical benthic taxa, production:biomass ratios are generally higher, implying a higher turnover rate (McLusky & McIntyre 1998).

In general, the relationship between high water-column productivity and benthic biomass has been shown to break down for polar systems, owing to high consumption rates and recycling within the water column (Grebmeier & Barry 1991). However, for some nearshore shelf systems (i.e. the Bering and Chukchi Seas, and parts of the Barents Sea and Canadian Archipelago) a tight correlation between water column productivity and benthic biomass is observed (Grebmeier & Barry 1991).

In general, fisheries productivity and biomass on the shelf is largely a reflection of nutrient supply (FAO [Food and Agricultural Organization of the United Nations] 1997). Although this relationship seems to be most evident with respect to pelagic resources, this pattern suggests that, as with benthos, a correlation between demersal fish biomass and carbon fixation in the water column is likely to exist.

AGENTS OF CHANGE AND LONG-TERM TRENDS

Climate and regional scale oceanography

Hydrographic processes play a key role in determining the structure of continental shelf systems largely through their influence on the distribution of sediments and the supply of organic matter from the water column to the seabed. Relationships have been observed, therefore, with various oceanographic features including current patterns, convective mixing, river run-off and fronts. For example, a long-term study of a transect in the North Sea from a tidally-mixed area to a summer-stratified one showed a transition from sandy to muddy sediments at the tidal front, with a concomitant change in community structure (Creutzberg 1985). This study also showed that there was an area of enriched organic matter and higher benthic biomass in a 15 km band north of the boundary, leading Creutzberg to conclude that tidal currents determined the position of this feature through advection and deposition of organic matter. This example illustrates how advection of organic material along the seabed, driven by tidal currents, must be included as a process explaining distribution patterns for benthic community structure, along with the impact of material deposited from the water column above (see also Escobar-Briones & Soto 1997).

El Niño and other larger scale hydrographic events have also been shown to affect benthic communities. For example,

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Table 2 A generalized model of benthic faunal responses to tidal river discharge. Adapted from Rhoads et al. (1985).

Location	*River mouth* ⟶			*Open sea*
Pelagic characteristics	Dominated by river effluent	Light limited due to high sediment burden, low primary productivity, high nutrients, some algal blooms	Eutrophic, high primary productivity, high rates of nutrient release to the water column from benthic activity	Oligotrophic, low primary productivity
Sediment characteristics	Sediments undergo periods of deposition and erosion, distinct layering of sediments visible	Moderate sedimentation rates	High levels of phytodetritus settle to the benthos, high levels of bioturbation	Sediment accumulation minimal
Faunal characteristics	Seabed too unstable to support macrofauna, dominance by bacteria	Increasing distance from the river mouth and deepening water gradually increases suitability for benthic organisms	Dominance by surface deposit feeders and microbial decomposers, which release high levels of nutrients back into the water column	Low benthic biomass

in a study off Chile, meiofaunal taxa at mid-shelf locations were more abundant and occurred deeper in the sediment during an El Niño period as a result of increased penetration of oxygen and mitigation of the anoxic conditions that often occurred during non-El Niño periods (Neira *et al.* 2001).

An illustration of the effects of currents on adult fish distributions is provided by Magnusson *et al.* (1981), who studied responses to short term dynamics of the Gulf Stream front in the shelf area north of Cape Hatteras. When the front was present more fish species were found, and comparisons between the different sides of the front showed that predatory species were generally more abundant on the northern side. This phenomenon may have been related to short-term turbidity due to a storm or to or more general patterns related to the Gulf Stream (Magnuson *et al.* 1981), but it illustrates how changing oceanographic conditions can affect fish species distributions.

Hydrography also plays an important role in fish recruitment processes. For North Sea cod, for example, salinity anomalies, prevalence of westerly or northerly winds, wind stress and winter cooling have all been implicated in recruitment processes to some degree (see, for example, Hall 1999, p. 160). For other demersal fisheries systems there are also clear indications of effects on larval and adult distributions and recruitment success resulting from changes in hydrographic conditions and circulation patterns. Cushing (1982) provided a thorough treatment of monthly to millennial influences of climate on fisheries, and more recent work continues to add to our understanding (for example, Bakun 1990; Glantz 1992; Ware 1995; O'Brien *et al.* 2000).

As with circulation patterns, the influence of storms and other natural disturbances, such as iceberg scour, exercise important control (Hall 1994). In general, currents set up by large winter storms, monsoons, hurricanes, and typhoons rework the bottom by winnowing out the fine-grained materials and carrying them either back into the estuaries or beyond the shelf break, where they are lost from the shelf system.

River discharge and other land inputs

For many shelf systems river discharge is a prime source of nutrient and fresh water to the sea and a major conduit for the input of pollutants to the ocean. A major exception, however, is for shelves in arid climates near western boundary currents where nutrient supply from the upwelling of deeper water predominates. An increasing recognition of the importance of atmospheric inputs of nutrients and contaminants is dealt with later in this section.

The world's rivers drain nearly 60% of the Earth's land area ($1.5 \times 10^8\,km^2$), annually discharging nearly $38 \times 10^3\,km^2$ of fresh water to the sea and roughly 70% of the total sediment input (Milliman 1991). It is reasonable to conclude, therefore, that the quantity and quality of river discharge is a critical determinant of the status of continental shelf ecosystems. Since accurately predicting the impacts of any change in fluvial processes requires knowledge of input rates to the sea and the fate of those inputs, it is worrying to note the limited amount of data that are available on these issues.

With respect to the geographic distribution of sediment and water inputs from rivers, the shelf sea ecosystems of Asia, South America and Oceania are particularly dominated by river dynamics, whereas Africa, Europe and the Eurasian Arctic are much less so (Fig. 2). Another difference in dynamics is revealed by the ratio of sediment to water discharge in the different regions (Alongi 1998, p. 240), which is indicative of the fact that the Asia and Oceanian tropics are generally characterized by many small rivers, draining smaller basins, compared to few large rivers that drain much larger basin areas; smaller drainage basins have less area to store sediments, which results in up to a seven-fold increase in sediment discharge for every 10-fold decrease in basin area (Milliman 1991). This explains, for example, the

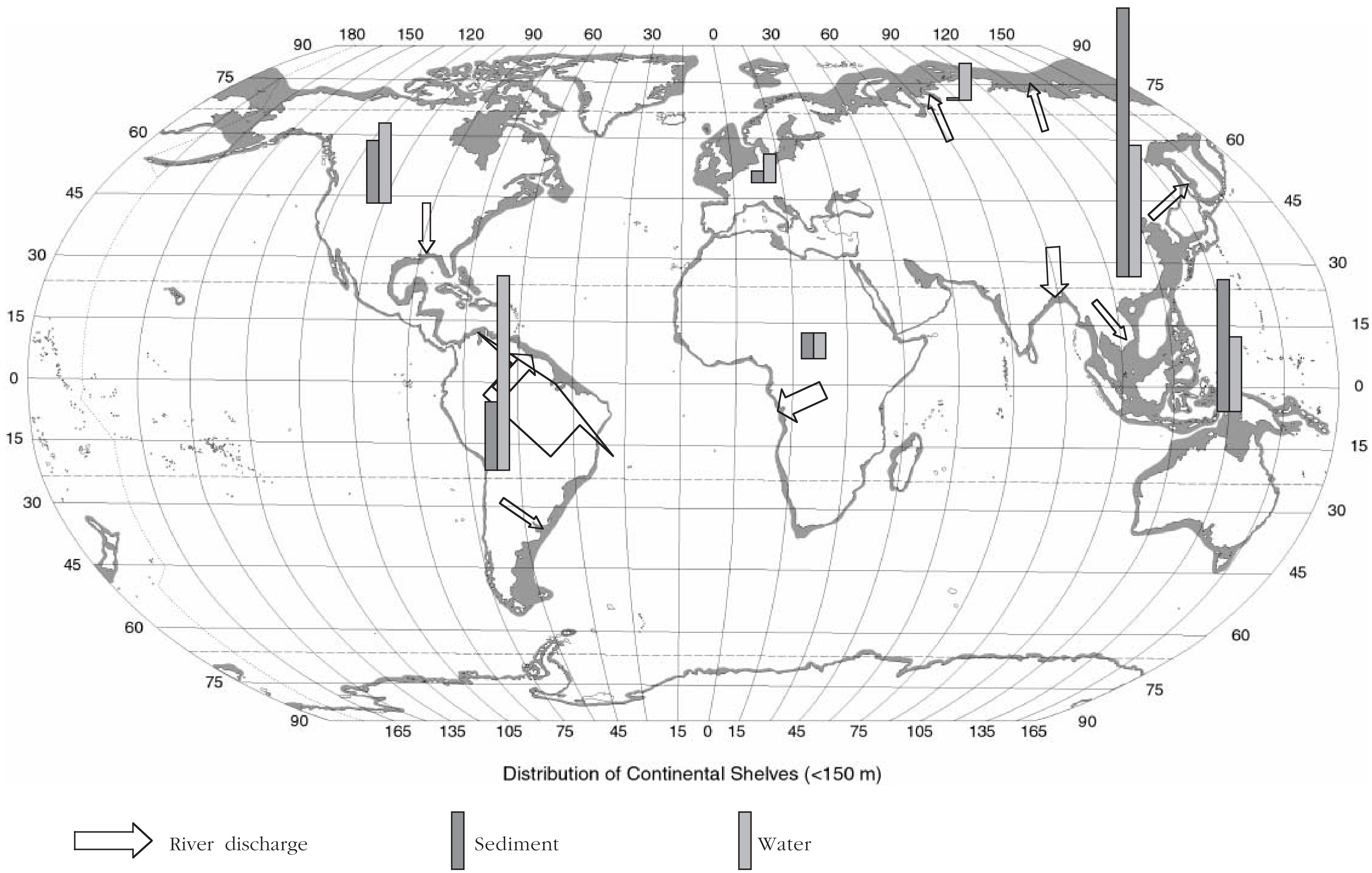

Figure 2 Proportional distribution of sediment and water discharge for various shelf regions and the river discharge from the world's ten largest rivers. Adapted from data in Milliman (1991).

very high sediment discharges from the small rivers of Taiwan and New Zealand, which, in combination, transport more sediment to the ocean than the Mississippi (Milliman 1991), despite draining a much smaller total area. The aggregate result of this pattern is that rivers draining only 10% of the land area carry 60% of the total sediment discharged to the ocean.

What do we know of the effects of river water and sediment discharge on the dynamics of continental shelf benthic communities? For tropical regions, studies of the Amazon and Papuan shelves indicate that freshwater inflow, sediment deposition and topography are the factors that control the sedimentary conditions of the benthic system, which in turn closely affect the benthic food chains and microbial decomposition processes that operate (Alongi & Robertson 1995). Examination of faunal abundance patterns for a number of river-dominated shelf systems led Rhoads *et al*. (1985) to propose a generalized model of their ecology in which the interplay of sediment and water column processes combine to determine benthic faunal structure (Table 2).

More recent data generally confirm this early work. Off the Amazon, for example, strong seasonal and spatial patterns in benthic community structure have been shown to covary with shelf-wide physical processes (Aller & Stupakoff 1996). During the period rising to peak riverine discharge and maximum trade-wind stress, shelf-wide minima occur in the sizes, numbers and vertical distributions of benthos, reflecting the peak instability of the seabed. In contrast, during periods of falling and low riverine discharge and minimum wind stress, the seabed appears to be most stable, resulting in successful benthic recolonization. During this latter period there are large influxes of burrowing infauna, meiofauna become abundant (particularly juvenile macrofauna) and bacterial numbers increase up to two orders of magnitude relative to other periods (Aller & Stupakoff 1996).

It appears that physical disturbance is the primary determinant of the distribution, abundance and structure of river-dominated tropical and sub-tropical benthic assemblages on the shelf (Alongi & Robertson 1995). A number of lines of evidence support this conclusion. First, X-ray radiographs on the Amazon, East China Sea and Indonesian shelves, reveal a large number of primary physical structures (for example, erosional or burial discontinuities in subsurface sediments) and disrupted biogenic structures, suggesting periodic benthic colonization and elimination. Second, radiochemical profiles indicate deep scouring and depositional episodes; off the Amazon for example, sediment mobilization to a depth of one metre has been recorded (Aller & Stupakoff 1996) and laminated sediment deposits are common in all these river dominated areas (Alongi & Robertson 1995). Further analysis of seasonal and spatial patterns in invertebrate death assemblages in subsurface deposits off the Amazon suggest cycles of surface exposure and burial out to a depth of 40 m, implying very large-scale seabed disturbance (Aller 1995).

Land-use effects on sediment and nutrient inputs

The very high sediment loads of Asian rivers reflect the considerable influence of human activity (Milliman 1990). Most notable of these are poor agricultural practices that lead to excessive soil erosion; it is estimated, for example, that the Yellow River now discharges 10 times more sediment than it did prior to the widespread cultivation of the land in northern China. The global sediment discharge to the oceans is estimated now to be 3.7 times greater than it was 2500 years ago, before humans began deforestation and farming (Milliman 1990). This, despite the fact that the river now ceases to discharge to the sea during dry periods owing to excessive water abstraction (de Villiers 1999).

Between 1990 and 1995 there was a net loss of 56.3 million ha of forest, but with a marked disparity between developed and developing countries; a loss of 65.1 million ha in developing countries was partly compensated for by an increase in forest area of 8.8 million ha during the same period for developed nations (FAO 2000*a*). The main causes of forest loss in developing nations are the expansion of subsistence agriculture in Asia and Africa and resettlement, agriculture and infrastructure initiatives in Latin America. Although there has been no assessment of the likely impact of these continuing changes in land use on the supply of sediment and nutrient to the oceans, it seems likely that they will continue to rise in the next 5–10 years.

One notable influence of river inputs on the ecology of shelf seas concerns the generation of anoxic conditions in near bottom waters. These conditions arise due to large inputs of phytodetritus (usually primarily of diatom origin) that fuel rapid rates of community respiration, thereby consuming the oxygen at the sediment-water boundary. Many areas experience such conditions periodically, usually in summer when water-column stratification intensifies (Biddanda *et al*. 1994; Diaz & Rosenberg 1995). Notable locations for large- scale anoxic events include the Baltic (Diaz & Rosenberg 1995), the Adriatic (UNEP [United Nations Environment Programme] 1996) and the Gulf of Mexico (Turner & Rabalais 1994; Fig. 3), often, varying from year-to-year in response to regional wind fields, currents and river discharge (Alongi 1998).

Anoxic events are a natural feature of benthic communities of some river-dominated continental shelves, but have their extent, frequency and intensity increased due to man's activities? The answer would appear to be 'yes'. For the Mississippi, for example, where nitrogen loading has doubled from the turn of the century to 1980, Turner and Rabalais (1994) linked increasing severity of anoxic events to eutrophication. The conclusion that coastal eutrophication has increased in the region is also supported by studies of the sedimentary record from the inner Louisiana shelf (Eadie *et al*. 1994), where stable isotopes and other organic tracers in sediment cores show changes consistent with increased nutrients, that began in the mid-1950s, accelerated in the mid-1960s and levelled off in the mid-1980s.

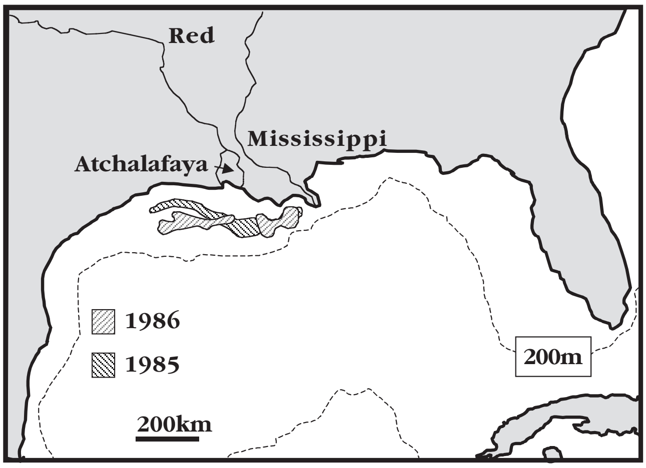

Figure 3 Approximate distribution of hypoxic bottom waters in July 1985 and 1986 in the Gulf of Mexico in the area adjacent to the Mississippi delta, USA. Adapted from Alongi (1990).

Importantly, however, it is not only riverine inputs that have contributed to this increase. There is now increasing recognition of the importance of atmospheric inputs of nitrogen species and contaminants in rain and aerosols (GESAMP [Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection] 2001). For those systems that have been examined, between 10 and >70% of fixed nitrogen has been estimated to be delivered to coastal waters from atmospheric sources. Burning of fossil fuels is a principle source of this input and atmospheric contributions seem to be most important in highly-populated, heavily-industrialized areas, or where highly-managed agriculture occurs. It has been estimated that, for Europe and North America, atmospheric inputs of nitrogen have increased by between 50 and 200% in the last 50 years (Paerl 1995).

An interesting analysis of trends has recently become available for the Gulf of Mexico, which has been subject to an integrated scientific assessment conducted under the auspices of the US National Science and Technology Council (CENR [Committee on Environmental and Natural Resources] 2000). Among other things, this report concluded that eutrophication and hypoxia have increased during the latter half of the 20th century during a period when the flux of nitrate-nitrogen almost tripled, concomitant with a rapid increase in the use of chemical fertilizers. CENR (2000) further concluded that about 90 % of the nitrate load comes from diffuse sources, particularly from agricultural land along the Mississippi and Ohio rivers nearly 1000 miles upstream from the river mouth. This extreme separation between the cause and effect can make it especially difficult to impose mitigation measures, particularly when, as the report concludes, the economic effects of the hypoxia on the Gulf ecosystems and fisheries are difficult to quantify (CENR 2000).

A recent comprehensive assessment for the entire USA provides a wider regional perspective on nutrient inputs to coastal seas (Boesch *et al*. 2000), indicating that, while the discharge of organic wastes from municipal and industrial sources has declined in the last 30 years as a result of improved treatment, eutrophication in many areas has become more extensive due to increased inputs of mineral nutrients, particularly nitrogen and phosphorus. Inputs from rivers on the Atlantic and Gulf coasts of the USA, for example, are estimated to have increased four- to eight-fold from the time of European colonization, primarily in the last half of the 20th century (Howarth *et al.* 1996). Not surprisingly, systems with low inflow, poor flushing, or strong stratification are particularly susceptible to eutrophication, but coastal seas and larger bays do not escape entirely.

Similar increases in eutrophication and anoxia have been suggested elsewhere. In the Po Delta, for example, summer stratification and high nutrient loads combine to create hypoxic conditions in the bottom waters of the northern Adriatic, which causes mass mortality of benthic communities and declines in fish yields (Justic 1991). Evidence suggests that these anoxic events are becoming more frequent and that benthic communities have been in a state of decline (in both densities and number of species) since the first large-scale hypoxia was detected in 1969 (Justic 1991). Such a pattern of change appears to be a common feature of benthic communities that experience an increasing frequency of anoxic events (Diaz & Rosenberg 1995).

Other contaminants inputs to the sea are of course also of concern, in addition to nutrients. These contaminants are most often from industrial sources and comprise heavy metals, specific organic compounds and radionuclides. GESAMP (2001) provides an excellent review of current knowledge and illustrates how impacts of industrial effluents, albeit often fairly local, have been documented for almost all marine regions (GESAMP 2001). Examples of extreme metal contamination are particularly notable, especially in the Russian Arctic in the vicinity of smelter operations and in Greenland where mine wastes have been dumped (GESAMP 2001).

Water abstraction

While current trends in deforestation, land development and agriculture generally lead to increases in nutrient and sediment loads transported to the sea by rivers, dams and subsequent diversions for industrial and agricultural purposes lead to declines. The balance of these countervailing effects varies depending on the local situation. In the Adriatic, for example, discharge from the Po and small rivers has declined by about 12% in the last few years, resulting in less nutrient input and lower primary productivity in the Adriatic (Alongi 1998). Similarly, reduction in sediment supply from dam construction can have profound impacts on the coastal systems, particularly coastal deltas. With the construction of the barrage on the Nile in 1868, for example, the slow accretion of the delta was reversed. When the Aswan High Dam and others were also constructed, the sediment load reaching the Nile delta was reduced further, leading to coastal erosion rates of up to 5–8 m per year, and in some areas in excess of 240 m per year (World Commission on Dams 2000). Such effects are not, however, restricted to deltas. It has been estimated, for example, that the cessation of sediment supply to the sea, caused by the construction of the Akosombo dam on the Volta River in Ghana, has led to erosion rates of 10–15 m per year for the coastlines of Togo and Benin (World Commission on Dams 2000). These reductions in supply are also likely to have important consequences for the subtidal benthic communities in the region.

Decline in fresh water and hence nutrient supplies to coastal waters also has consequences, once again illustrated by the case of the Aswan High Dam on the coastal waters of the Mediterranean, where production at all trophic levels around the Nile Delta declined through a reduction in nutrient supply rates when the dam was constructed from 1965–1967 (Caddy 2000). This change led to a marked decline in catches of sardines (Caddy 2000). Similarly in the Zambezi delta, flow modification has led to a reduction of $US 10 million per year in the value of the local shrimp fishery (World Commission on Dams 2000). A subsequent increase in fishery production around the Nile delta from about 1978 appears to be associated with increased inputs from large cities and other sources of nutrients draining from the delta into the Mediterranean. For the Nile, the decline in sardine catch was reflected in a change in the ratio of landings of pelagic to demersal fish (P:D ratio) during and following dam construction (Fig. 4). This trend led Caddy to suggest that the P:D ratio may be a robust indicator of nutrient availability (Caddy 2000).

Fishing

Marine finfish species yielded a catch of 45 million tonnes in 1999, 16 of which came from demersal (primarily shelf) species (FAO 2000*b*). A further 10 million tonnes of unidentified and miscellaneous marine fish are reported in the FAO statistical database and may contribute further to the shelf total. Estimated demersal catch potential (tonnes) is distributed unevenly, with south-east Asia and the Bering Sea being especially important (Fig. 1). As we might expect, not only does the catch potential differ between regions, but also the importance of the fish catch for human welfare. It is developing countries in particular that are dependent on this source of animal protein: of the 30 countries most dependent on fish, all but four are from the developing world (Burke *et al.* 2001).

In 1996, 77 countries reported a trawl or dredge catch of at least 500 tonnes per year from their continental shelf and the size of the reported catch ranged from 500 tonnes per year for Madagascar to over 2 million tonnes per year each for the USA and Russian Federation (I. Poiner, F. Pantus & S. Hall, unpublished analyses of FAO statistics 2000). Fifteen countries account for about 75% of the catch and around 80% of the 129 937 trawlers reported to the FAO for the 1989 to 1995 period. A large proportion of the catch (67%) is reported from the cold-north region.

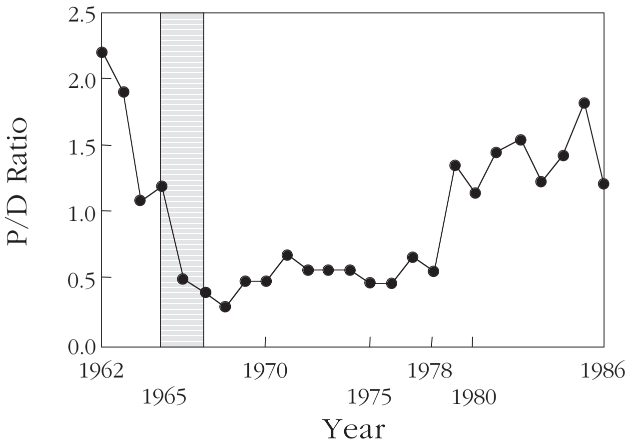

Figure 4 Trends in the ratio of pelagic to demersal fish biomass from the Nile Delta from the period surrounding the construction of the Aswan Dam (shown by vertical lines). Adapted from Caddy (2000).

Demersal catches have continued to rise since the 1950s (Fig. 5), but the general consensus is that any further increases in fishing effort will not lead to increased catches (Pauly 1996). FAO data suggest that total annual demersal catch has been relatively stable since the mid-1970s at 14–16 million tonnes, with most countries showing relatively constant landings. Notable exceptions to this pattern, however, include the USA where catches increased over the 1980s, and Japan and the Russian Federation where they decreased. There have also been some notable changes in the catch of individual species with some marked increases (for example, *Theragra chalcogramma*) and decreases (for example, *Gadus morhua*) over past 20 years. A note of caution is warranted, however, when using FAO data to infer trends owing to the incompleteness and inaccuracy in reporting by some fishing nations. For example, the Chinese catch has been exaggerated in recent years (Watson & Pauly 2001).

In general, fisheries productivity and biomass on the shelf are largely a reflection of nutrient supply (FAO 1997). Although this relationship seems to be most evident with respect to pelagic resources, this pattern suggests that, as with benthos, a correlation between demersal fish biomass and carbon fixation in the water column is likely to exist. The most recent assessment of the status of fishery resources by the FAO (2000*b*), notes that globally, between 1974 and 1999, the proportion of stocks classified as 'exploited beyond the maximum sustainable yield limit' (i.e. overfished, depleted or slowly recovering), appears to have increased; the North Atlantic and North Pacific showed a continuous worsening of the situation until the 1980s or early 1990s, although there was a possible stabilization thereafter, particularly in the North Atlantic (FAO 2000*b*). In contrast, the tropical and southern regions of these oceans seem still to be deteriorating, with the possible exception of the tropical Atlantic, which may now have stabilized (FAO 2000*b*). Clearly, a full review of trends in demersal fish communities is beyond the

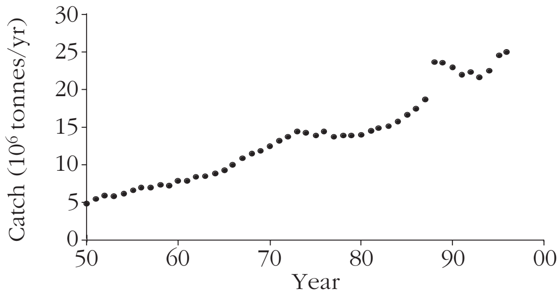

Figure 5 Trends in worldwide demersal fish catch from 1950–1996. Extracted from FAO (1998).

scope of this paper and there are many texts that deal with this issue. It should be recognized, however, that the biomass removals associated with fishing have been substantial (see Overholtz & Tyler 1985; Bax 1991) and that shelf ecosystems that have traditionally supported demersal fisheries have been altered considerably.

In view of these large-scale changes it is, perhaps, informative to ask how continental fishery systems might be classified with respect to notions of ecosystem overfishing. Although there is no consensus on criteria for defining such a condition, Murawski (2000) has proposed a set of criteria by which a candidate ecosystem overfishing definition might be assessed. Drawing on Hall (1999), Murawski (2000) summarized the current status of three well-studied demersal fishery systems with respect to these criteria (Table 3). Although the utility of using a definition in the absence of clear objective upon which a management regime could act is questionable, this table indicates that all of these systems could arguably be described as being ecosystem overfished.

It is also important to recognize that many fish species do not recognize the arbitrary boundaries that are defined for the marine environment; the juveniles of many species develop in inshore areas (see McNeill *et al.* 1992) and adults will often range off the shelf into deeper water (Mahon *et al*. 1998). Thus, discussion of continental shelf systems and the dynamics of fish populations that occupy them is necessarily incomplete without reference to other domains.

Effects of trawling and dredging on benthos

As noted earlier, at a global scale, calculations, based on fleet sizes, catch data and preliminary maritime boundaries show trawling to occur on the continental shelves of almost all countries. As we would expect, however, there are marked differences in the level of effort between regions. In the USA jurisdiction, for example, the largest regional contrast is between the high levels of fishing effort in the Gulf of Mexico, which appear to be the largest in the country (albeit with the lightest type of trawl gear) and the relatively low levels in Alaska, where a number of large closed areas have restricted the distribution of trawling and only a small portion of the total shelf and upper slope is actually fished (US National Research Council 2002). For example in the 1999–2000 period only 14% of the 702 898 km^2 making up the Bering Sea shelf and upper slope was fished (US National Research Council 2002).

Using data from 24 countries for which there was sufficient information, Watling and Norse (1998) estimated that trawling grounds covered 8.8 million km^2 (57%) of the continental shelf. The utility of such a startling statistic bears examination, however. The two fundamental pieces of information needed to scale the potential effects of such trawling and dredging activity to the ecosystem level are: (1) the type and magnitude of the effect of the specific gear on communities in different habitats and (2) the spatial and temporal extent of fishing activity. With respect to (1), we have a reasonable understanding of the immediate and chronic effects of trawling on a given community when trawling occurs (see Collie *et al.* 2000). What is usually missing, however, is appropriate information on the distribution of trawling in a habitat that would allow us to predict at least the short-term and chronic effects at the habitat scale. Unfortunately, most fishing effort data are reported at rather coarse scales, with reporting units covering tens to thousands of square kilometres. These data are of limited use because, to estimate the ecological effects of bottom fishing, we need to know whether, and how often, a trawl is dragged over a particular square metre. Using fishing effort data that are not reported on a spatial scale relevant to the scale of the impact (m^2), could lead to either an overestimate or underestimate the actual effects of mobile fishing gear for continental shelf ecosystems (US National Research Council 2002).

Where data at appropriate scales have been collected it has been found that the fine-scale distribution of fishing effort is very patchy, determined by factors such as seabed topography, the distribution of the target species, the behaviour of fisherfolk and legislation (Poiner *et al.* 1998; Rijnsdorp *et al.* 1998; Pitcher *et al.* 1999). These findings suggest that a comprehensive global assessment of fishing impact on the seabed will require fine-scale data for all regions of interest. All we can really say at this stage is that, while some areas have been chronically impacted for many generations, others are hardly ever fished, if at all.

The likely consequences of including better spatially-resolved information to obtain a global estimate of trawl impact can be illustrated with data from Australia, which has a continental shelf area of 1 962 900 km^2. Over 20% of Australia's total marine fisheries production is from continental shelf trawl and dredge fisheries according to the Australian Bureau of Agricultural and Resource Economics (1998). However, by simply taking account of the extent of the known fishing grounds for each of the fisheries the estimated area exposed to trawling decreases from 100% to 62%. More significantly, using spatial effort data resolved to 6×6 nautical mile grids, which cover 88% of the fished area, calculations based on the 1996 effort data, reduce the estimates of the trawled area to about 18% of Australia's continental shelf (I. Poiner & F. Pantus, unpublished analysis 2000). The message from this analysis is clear: when data with greater spatial resolution are available, estimates of the

Table 3 Candidate criteria for a definition of ecosystem overfishing and the status of three demersal fishery systems. Adapted from Murawski (2000). (✓ = criterion supported by available data; ✗ = criterion not supported by available data; ? = unclear pattern)

Criterion	*Study*		
	Gulf of Thailand	*North-east USA*	*North Sea*
Biomass of one or more important species fall below minimum biologically acceptable limits	✓ Important demersal fish species abundance one-tenth of their levels in 1960s	✓ Exploitation rates on principal groundfishes reduced recently, but harvest rates on other components increased to non-sustainable levels	✓ No signs of persistent recruitment overfishing, biomasses of important resource stocks are below minimum acceptable levels
Biological diversity declines significantly	✓ Decline in diversity, owing to loss of important components, but continuing high total yields	✓ Dominance of species groups changed as a direct result of excessive fishing and sequential depletion	✗ Diversity of the system has fluctuated without trend
Harvesting leads to increased year-to-year variation in populations/catches	✗ No increase in interannual variation in aggregate landings	✓ Greater interannual fluctuations in landings owing to increased dominance of species with more variable recruitment characteristics	✗ No apparent increase
Significant decrease in resilience or resistance of the ecosystem to perturbations	✗ No apparent trend	? No data available	? No data available
Lower cumulative net economic or social benefits than might be obtained with less intense fishing	✓ Net benefits from the fish community would be higher with less fishing effort, but increased shrimp landings provide substantial alternative benefits	✓ Rebuilding of depleted resources and their efficient management would result in very large additional benefits	? No data available
Fishing impairs long-term viability of ecologically important non-resource species	? Unclear, almost all species are used	✓ Small pelagic prey species remain abundant and underexploited. By-catch of turtles and marine mammals are of significant concern	✓ Concern about viability of some elasmobranch species

areal extent of impact of trawling on the global seabed declines substantially, suggesting that estimates such as that provided by Watling and Norse (1998) may be grossly misleading.

Notwithstanding the comments above, there is no doubt that, where trawling does occur, impacts on benthic communities can be expected. The effects observed in many studies, confirm a priori expectations from ecological disturbance theory by showing a shift from communities dominated by relatively high biomass species towards dominance by high abundances of small-sized organisms (Collie *et al*. 2000). It seems likely that this is a general consequence of fishing by mobile gears and one that is to be expected wherever fishing is intense. Intensively fished areas are likely to be maintained in a permanently altered state, inhabited by fauna adapted to frequent physical disturbance (Hall 1999). In habitats that experience relatively little disturbance these differences will be profound (Collie *et al*. 1997), while in those areas where natural disturbance is common they will be subtle (Tuck *et al*. 1998).

In general, epifaunal organisms are less prevalent in areas subjected to intensive bottom fishing owing to the impacts of the gear (Sainsbury 1987; Collie *et al*. 1997). An important consequence of this effect is the reduction in habitat complexity (architecture) that accompanies the removal of sessile epifauna. For example, there is compelling evidence that loss of structural epibenthos can have important effects on the resident fish community in a tropical system, leading to a shift from a high-value community dominated by Lethrinids and Lutjanids to a lower value one dominated by Saurids and Nemipterids (Sainsbury 1987). Similar arguments have also been made for temperate systems where structurally-rich habitats may support a greater diversity and productivity of fish species. Importantly, such effects may not be restricted to the large biotic or abiotic structure provided by large sponges or coral reefs. We could quite imagine, for example, that juveniles of demersal fish on continental shelves might benefit from a high abundance of relatively small physical features such as sponges, empty shells and small rocks, but that over time trawling will gradually lower the physical relief of the habitat with deleterious consequences for some fish species. While it is certainly true that juvenile fish species do aggregate near seabed structures, our current understanding of the functional role of many of the larger-bodied long-lived benthic species (for example, as habitat features, bioturbators, etc.) is limited and should be addressed to predict or explain the outcome of permitting chronic fishing disturbance in areas where these animals occur.

While much attention has been paid to the effects of mobile gears on the benthic biota, relatively little has been paid to the effects on the underlying structure of the substrate. For sands or hard rock of course, this effect will be minimal, but for areas where softer rock outcrops can be found gear damage is much more serious; epifauna can regrow if left alone for long enough, a limestone pavement that has been broken up and reduced to sandy rubble cannot. In south-east Australia, fishers have targeted very specific habitats on the shelf; they now believe that low-relief limestone reefs that traditionally yielded good catches of high-value fishes are being eroded and removed (Bax *et al*. 1999). In particular, when low-relief reefs are distributed in patches, they are especially vulnerable to being 'opened-up' by fishers, who with ever more powerful vessels and accurate positioning equipment, can avoid the unmovable obstacles and remove the remainder. Estimates of the extent of such environmental damage are currently unavailable.

Aquaculture

Starting from an insignificant total production, inland and marine aquaculture production grew by about 5% per year between 1950 and 1969 and by about 8% per year during the 1970s and 1980s; it has increased further to 10% per year since 1990 (FAO 2000*b*). This has resulted in an overall production increase of 20 million tonnes over the last decade. Most of the mariculture component is coastal, however, so little of the current production could legitimately be argued to be supported by the continental shelf *per se*. Nevertheless at the shoreward margin, local impacts on seabed communities caused by inputs from shore-based aquaculture facilities (for example, ponds) or sea cages have been clearly documented (see Findlay *et al*. 1995).

Coastal aquaculture may have a wider indirect influence on continental shelf systems, however, through the changing patterns in demand for wild caught resources. In the USA, for example, declines in wild stocks have made the market entry of new farmed species such as catfish and tilapia much easier, and in Europe salmon seems to be replacing groundfish. Such changes in markets may alter the incentives in the wild harvest sector in future and alter future patterns of species exploitation. It should also be recognized that there is a significant demand for wild caught fish for the manufacture of aquaculture feeds. As aquaculture production grows this demand is likely to increase with concomitant impacts on shelf fisheries.

Petroleum exploration and production

By far the largest mineral resources to be exploited from continental margins are oil and natural gas (Fig. 1). Although onshore oil reserves dominate, in the last two decades offshore reserves have become an increasingly important source of supply, with an approximate doubling of the contribution of offshore reserves to crude oil production (from 16 to 30%) between 1975 and 1995 (Pickering 2000). In contrast, offshore gas reserves have accounted for a relatively stable proportion (approximately 20%) of global natural gas production over the same period (Pickering 2000).

Considerable effort has been expended documenting the impacts of oil production on seabed communities (see Kingston 1992; Olsgard & Gray 1995). Suffice to say that the drill mud cuttings, production water and other impacts on the seabed are sufficient to lead to marked changes in benthic community structure (for example, a decrease in species diversity), with a progressive return to background with increasing distance from the rig (see Gray *et al*. 1990; Warwick & Clarke 1995). After a period of 6–9 years using oil-based drilling muds on the Norwegian shelf, contamination and community impacts extended to a distance of up to 6 km from rigs (Olsgard & Gray 1995). It should be noted, however, that results from oil fields where only water-based muds are used indicate a reduction in environmental contamination and biological impact (Olsgard & Gray 1995) and that in other regions effects have been very localized, for example, extending only 100 m from gas platforms in the Gulf of Mexico (Montagna & Harper 1996).

In addition to nearfield effects, we must also consider more pervasive impacts from oil production. For example, regional surveys of monooxygenase enzymes (EROD and cECOD) measured in the livers of North Sea flatfish have suggested that detoxification of hydrocarbon pollution is widespread (Stagg *et al*. 1995).

FUTURE PROSPECTS

In this section we look forward to examine the likely effects that each of the agents for change considered above might impose on continental shelf ecosystems. Before doing so, however, the issue of how we attribute change to particular causative agents needs to be considered. Determining the relative importance of these various agents is a continuing difficulty, particularly given the contemporaneous nature of their time-series trends. Because world population, industrial production of fertilizers, marine landings and fishing fleet size have all increased in parallel since the 1960s, it is usually very difficult to ascribe observed changes to any particular causative agent. For example, the increased biological productivity in semi-enclosed seas caused by eutrophication (Howarth *et al*. 1996) complicates the analysis of the direct effects of fishing considerably. In moderation this increase could be viewed as beneficial and it has been suggested that fishery production of some formerly oligotrophic seas has increased in recent decades with moderate enrichment from land (Caddy 1993). Such enrichment effects also complicate interpretation of observed changes in food web structure at both regional (for example, the North Sea; Daan 1989) and global scales (Pauly *et al.* 1998). The decline in the mean trophic level at which fish harvests are obtained has been widely reported and is usually explained by the sequential removal of predators at higher trophic levels and the consequent shift in emphasis of fleets towards to lower trophic levels (Pauly *et al.* 1998). Simple arguments based on ecological efficiency would predict that higher yields would be obtained by fishing at lower trophic levels, but prior removal of predators and the consequent relaxation of predation pressure on lower levels should also increase yields. For semi-enclosed seas, however, bottom-up effects resulting from run-off may be equally important (Caddy 2000), explaining observed increases in small pelagic fish at the expense of demersal species in eutrophic systems as a consequence of enhanced primary productivity and degraded benthic conditions, for example, through increases in anoxic episodes (Fig. 6). In essence, eutrophication has been argued to lead to a shift towards systems more akin to upwelling areas, with a predominance of smaller pelagic fish, rather than the more characteristic demersal fish community of the shelf.

These difficulties in partitioning causality between agents must be clearly borne in mind when speculating on future trends. To complicate matters further, we are becoming increasingly aware of the importance of decadal scale shifts in system state, the so-called regime shifts, which are driven by changing climatic and hydrographic conditions (Ware 1995; Steele 1996).

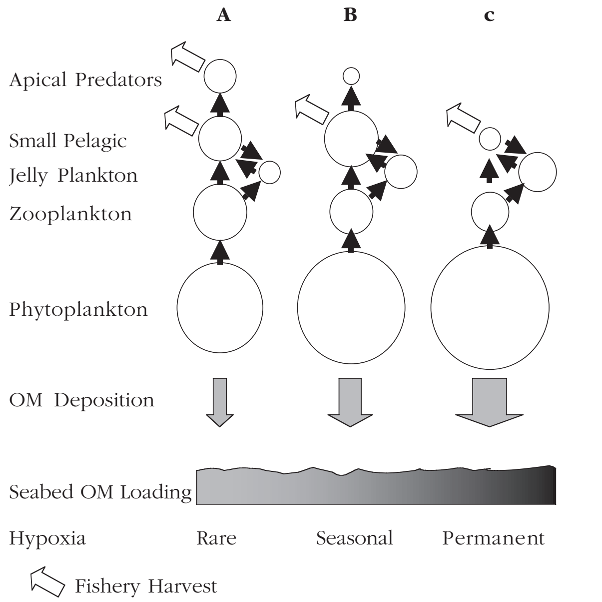

Figure 6 Three states of the food web along a continuum, resulting from the synergistic effects of nutrient enrichment and fishing in a semi-enclosed marine ecosystem, as proposed by Caddy (2000). A = original state; B = overexplotation of apex predators and moderate nutrient enrichment; C = eutrophic. The size of the circles for each ecosystem component provide a rough index of log biomass. (Adapted from Caddy 2000.)

Natural disturbance and the effects of climate change

Climate change and shelf communities

One of the major concerns over coming decades is of course global climate change, the impacts of which may be extremely pervasive for marine systems (see Maul 1993; Mooney *et al.* 1993; Peterson & Estes 2001). Kennedy (1990) identified five environmental factors that might be modified as the climate warms into the 21st century: sea-level rise, water-column warming, precipitation, wind and water-column circulation. To this must be added the potential for an enhanced frequency and intensity of storms (Muller-Karger 1993). More recent assessments continue to consider these possibilities (IPCC [Intergovernmental Panel on Climate Change] 2000).

For two of the above changes there is general agreement about the direction of change in different regions: sea-level rise is expected to increase at an accelerating pace everywhere (mainly through thermal expansion of water and the melting of ice sheets) and warming is expected to be greater towards the poles than the tropics (IPCC 2000). The direction of change in different regions for precipitation, wind and water circulation, and storm frequency and intensity is less certain but also needs to be considered. Since sea-level rise will only affect the coastal margin, it will not be dealt with here.

Temperature effects. Current assessments suggest that global warming is likely to have a marked effect on biological processes and biodiversity in the oceans. In general it would appear that we will see, in addition to an overall rise in temperature, a reduction in the equator to poleward temperature gradient (IPCC 2000). We are also predicted to see more El Niño like conditions in the tropical Pacific, with the eastern tropical Pacific warming more than the western (IPCC 2000).

To examine the possible importance of temperature effects, many have examined the distribution patterns of organisms for clues (see references in Kennedy 1990; Ware 1995; Lehody *et al.* 1997; Peterson & Estes 2001). In conjunction with hydrographic conditions, temperature plays a significant role in determining the biogeographic distribution of species and we can undoubtedly expect to see distribution changes as the climate changes (Hayden & Dolan 1976). For example, Kennedy (1990) drawing on earlier work by Bousfield and Thomas (1975), hypothesized that a northward extension of warmer conditions may lead to merging of the currently disjunct distribution of warm temperate species such as the commercially-important hard-clam *Mercenaria mercenaria* and the eastern oyster *Crassostrea virginica*. At present the northern limit of the main distribution of these species is Cape Cod, but there is a second concentration found in the warmer waters of the Gulf of St Lawrence.

Observations on a reef off North Carolina also provide evidence of likely warming effects for fish communities (Parker & Dixon 1998). Two surveys separated by 15 years, revealed a marked shift in community composition, coincident with a marked warming trend. Mean monthly bottom water temperatures in winter were 1–6ºC higher in the later survey, when two new families and 29 new species of tropical fishes were recorded in the area. An increase in fish-cleaning symbiosis was also especially noticeable (Parker & Dixon 1998). While it seems plausible to expect similar changes to those already observed with any future increase in temperature, Kennedy (1990) highlights the cautionary notes of Bakun (1990) who stresses that, if the causal mechanisms for warming are different, other associated influences are also likely to differ.

The paleontological record can also provide clues. For example, rapid warming associated with the inflow of the warm Tsushima Current during the transition from Pleistocene glacial to interglacial stages has been shown to be associated with major changes in the benthic molluscan fauna of the Sea of Japan continental shelf (Kitamura *et al*. 2000). The fossil record suggests that there were two stages of faunal change. The first occurred when warm-water species migrated into the Sea of Japan and coexisted with cold-water species, which coincided with a northward shift in species ranges. The second stage involved the further range expansion of warm-water molluscs shortly after the local extinction of cold-water species. During this phase, it is speculated that benthic molluscan communities with very low diversity and density existed temporarily and locally at inner shelf depths (<100 m). Such a community has no modern analogue, but may have resulted from a marine climate with a higher seasonality than occurs today (Kitamura *et al*. 2000). These findings suggest that another period of rapid warming might have severe impacts on offshore benthic communities and lead to community patterns that are not represented by modern faunal distributions. Importantly, range expansions may not be as rapid as range contractions because the former requires the conjunction of numerous factors for successful invasion (transport, absence of predators and pathogens, etc.). We can expect, therefore, to see new mixes of species arising, perhaps leading to shifts in the patterns of biological control (i.e. competition and predation) in these communities.

Temperature effects on fisheries are of particular concern since water temperature has a dominant effect, not only on fish distributions (Lehody *et al*. 1997), but also on spawning and survival of larvae and fish growth (Heath 1992). It seems likely that important changes in fish distributions could occur, but current assessments suggest that overall productivity will be unaffected (Wood & McDonald 1997; IPCC 2000). To make specific predictions at regional scales, however, decadal scale shifts in hydrographic conditions must also be taken into account; improvements in general circulation models will be required to achieve this (IPCC 2000).

In general, the effects of temperature change are likely to be more profound at higher latitudes, especially when the effects on ice sheets are taken into account. Sea ice covers approximately 11% of the ocean, depending on season, and it is predicted that both the extent, thickness and duration will all decline (IPCC 2000). We have already seen a 10 to 15% decline in ice cover in the northern hemisphere since the 1950s, and some areas that were closed to navigation in the past are now permanently open (IPCC 2000). This change in access may lead to changes in patterns of ocean resource use and the geographical location of production zones (Peterson & Estes 2001). It also seems likely that further declines in ice cover or later freezing may lead to changes in nearshore ice dynamics, seabed scouring and sediment transport. In particular, the storms occurring on shoreline sediments that are no longer bound together by ice are likely to lead to much greater sediment inputs into the nearshore (IPCC 2000).

Another area of particular concern with respect to warming in semi-enclosed water bodies is the potential for increased incidences of anoxia owing to the lower oxygen carrying capacity of water at higher temperatures and the increased oxygen demand of the biota. Coupled with the increased likelihood of such events due to eutrophication, this may become increasingly important for coastal fisheries. In the coastal waters of the USA, for example, a reduction in the availability of oxygen-rich cooler water may have consequences for striped bass (Coutant 1990) and for the commercially important blue crab (*Callinectes sapidus*; Stickle *et al.* 1989).

One aspect of global warming that might be positive is the possibility that growing seasons and growth rates for aquaculture species may be extended, an effect that may be especially marked in the northern hemisphere (IPCC 2000).

Changes in rainfall. Given the dominating influence of river and land run-off on coastal systems (see above), effects of climate change on rainfall, particularly monsoon rains in the tropics, are also likely to be important. Figure 7 shows the inter-model consistency in rainfall predictions for the globe (IPCC 2000), which suggests little change in South-east Asia and South America, where riverine influences are especially important, but potentially small increases (5–20%) for the Indian sub-continent, East Asia, Canada and Northern Europe, and potentially large increases (>20%) for Northern Asia and the Sahara. Even if rainfall estimates are correct, however, determining influences on continental shelves is fraught with difficulty, owing to the confounding effects of land clearing and water abstraction. It seems likely, however, that recruitment in tropical Asian fisheries (Pauly & Navaluna 1983) and for penaeid shrimps (Garcia & Le Reste 1981) may be markedly affected. Changes in rainfall will also have an effect on buoyancy driven water currents, although the likely consequences of this have yet to be assessed.

Changes in water circulation. Of the effects of climate change that may already be taking place, perhaps the most notable is

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the recorded increased upwelling intensity which results from intensified longshore wind stress on the ocean surface (Bakun 1990). Since the intensity of upwelling is critical for many of the most productive fisheries in the world, the potential for climate change to affect fisheries seems, therefore, to be profound, although speculation to date has focused primarily on pelagic resources. Apart from the possibility of upwelling intensification owing to increase in wind stress, which is likely to affect pelagic fisheries most (Bakun 1990), other effects resulting from wind and circulation changes are also possible. For example, there are many cases in the literature of the possible importance of wind-induced currents for larval transport (see Heath 1992). Without clearer predictions of how circulation patterns might change, however, speculation on the effects on fisheries is moot.

Changes in storm frequency. A change in climate is likely to affect wind and current regimes in a region, and in tropical regions this may be manifest as an increase in the heat content of the ocean with a consequent increase in wind activity and the frequency of storms (Muller-Karger 1993). In this respect, Gray (1993) notes a relationship between increased sea-surface temperature and both the frequency and intensity of hurricanes, implying that tropical coastal seas may expect greater hurricane activity in future. Unfortunately, however, current models used to predict climate change are incapable of simulating or predicting the generation of hurricanes so quantifying the magnitude of the likely increase is not possible (Muller-Karger 1993).

If storm intensity does increase we can certainly expect impacts on benthic communties. One study that examines this issue is that of Rothlisberg *et al*. (1990) who considered the effects on Penaeid prawn species, one of Australia's most valuable fishery resources. The conclusion was that increased banana prawn populations are to be expected if global warming leads to an increase in sea level, rainfall and cyclone activity (Rothlisberg *et al*. 1990). This would occur due to the inundation of tidal flats. In contrast, a decrease in tiger prawn populations would be expected because seagrass beds would be destroyed by cyclones. Destruction of 20% of the seagrass beds in the Gulf of Carpentaria (some 183 km^2) in 1986 led to a 30% reduction in tiger prawn catch for the area, because the beds form the nursery grounds for the species (Rothlisberg *et al*. 1990). Increases in the frequency of such effects of habitat

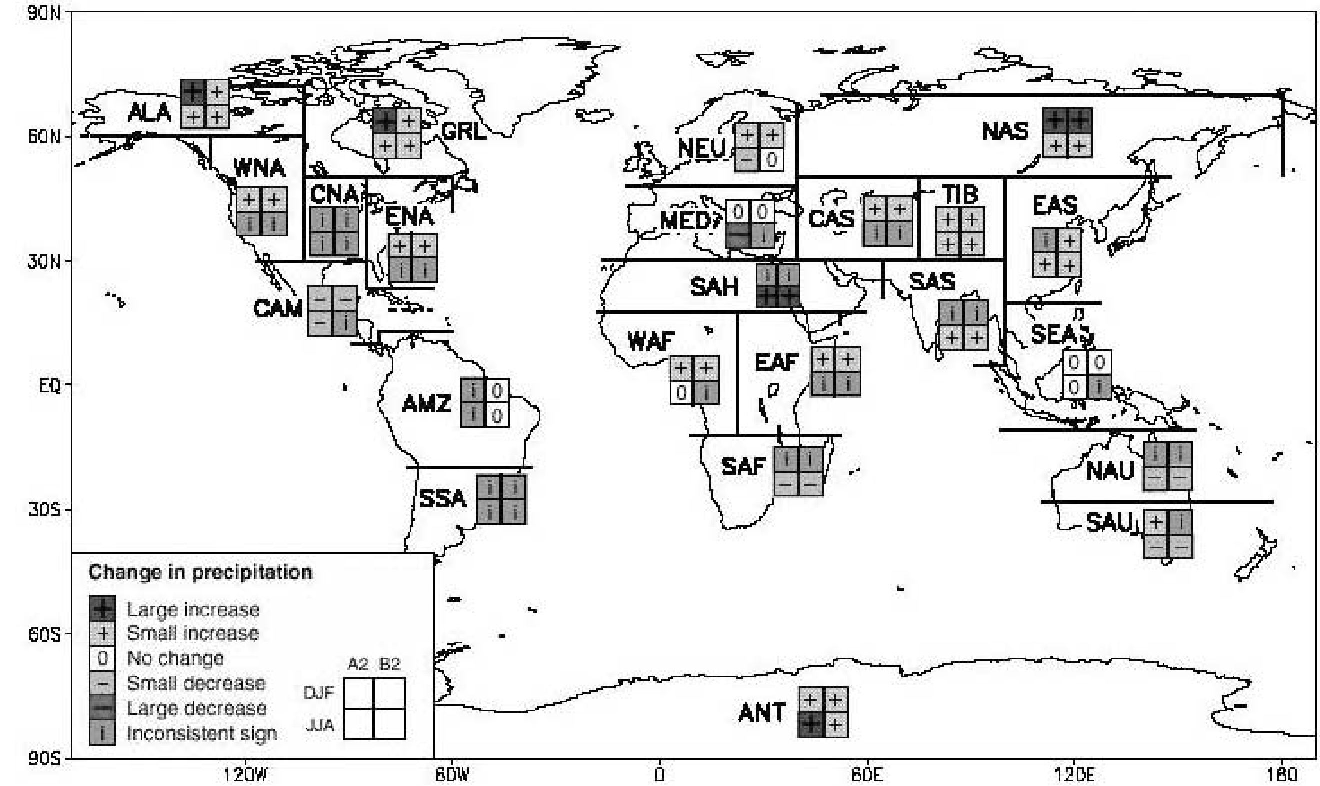

Figure 7 Analysis of inter-model consistency in regional precipitation change. Regions are classified as showing either agreement on increase, with an average change greater than 20% ('Large increase'), agreement on increase with an average change between 5 and 20% ('Small increase'), agreement on a change between −5 and +5% or agreement with an average change between −5 and 5% ('No change'), agreement on decrease with an average change between −5 and −20% ('Small decrease'), agreement on decrease with an average annual change of less than −20% ('Large decrease'), or disagreement ('Inconsistent sign'). A consistent result from at least seven of the nine models used was deemed necessary for agreement. Reproduced with permission (IPCC 2000).

destruction are to be expected both here and elsewhere in the tropics. Given the immense value of shrimp fisheries to the economies of some countries, such effects could be profound.

Lessons from ENSO?

Although prediction is difficult, one approach that has been adopted by a number of authors is to speculate by analogy, using the observed responses of systems to ENSO events. For the most part, however, such observations and speculation with respect to nearshore systems have focused on intertidal and shallow subtidal hard substrate communities and coral reefs (see Glynn 1988). Unfortunately, the dynamics of such systems, where species interactions, often mediated through competition for space, have been shown to have important controlling influences, may be quite different from soft-sediment benthos, where such competitive interactions are probably less important. Nevertheless, Castilla *et al*. (1993) provide one good example of positive correlations between El Niño intensity and both scallop and mussel landings in Chile. These observations strongly implicated large-scale oceanographic changes as the causative factor and are indicative of the types of changes we might expect.

A number of caveats must be borne in mind, however, when using this comparative approach (Lubchenco *et al*. 1993). First, the rate of change in physical and chemical environmental parameters is far greater with an ENSO event, thereby precluding the possibility that the biota could adapt or acclimate. Second, the duration of the change is much shorter. Thirdly, ENSO events have occurred in the past evolutionary history of the species involved.

Another important question to address, of course, is whether ENSO events themselves will increase as a result of global warming but, as with hurricanes, climate models that have been used to examine the influence of increased greenhouse gases can only simulate the rudiments of ENSO-like events, and they are not yet realistic enough to address this question with any confidence (Trenberth 1993).

Resource exploitation

Fishing

Most fisheries are close to or at full exploitation and it will only be in deeper water that any new fisheries are likely to develop. What then does the future hold for continental shelf fisheries? Can we expect to see ecosystem overfishing of the kind described by Murawski (2000) as the norm on the shelf? I suspect that, in the longer term, the answer is probably 'no', but the rate of improvement may be slow and further degradation can be expected in the interim in certain locations. The reason for my guarded optimism is that current emerging trends in fishery management seem to me to be likely to lead to steady improvement in the health of fisheries resources in the longer term. This optimism is shared by Garcia and Grainger (1996) who identify the necessary changes (Table 4) and argue that fisheries management should improve rapidly in the next decade, noting the following reasons for such an expectation:

- Official recognition of the poor state of fisheries.
- Increasing concern over the environment and people's participation and empowerment.
- Consensus that it is institutional (and political) failure that is the primary reason for the current state.
- A readiness for change at the highest levels of governance.
- International agreements are in place, which lay down the path to sustainability (and responsibility).

None of the above, however, should be taken to suggest that there will not problems in coming years. While more developed nations may progressively reduce levels of fishing mortality to sustainable levels, improving fisheries management in poorer countries is likely to take much longer. We will probably also see further single species collapses, such as that of the Canadian cod (Hutchings & Myers 1994). Moreover, the widely held belief that the biology of fish species made them relatively resilient, and able to recover from over-fishing fairly quickly, appears to be flawed (Hutchings 2000, 2001). Meta-analysis has shown that recovery of a collapsed stock is usually very slow, with biomass often remaining low 15 years after a collapse (Hutchings 2000), and that the rate of recovery is largely independent of the level to which fishing mortality is reduced following a collapse (Hutchings 2001). The rather paradoxical implication of these results is that, while stock recovery will depend on reducing fishing mortality, the rate of recovery will be independent of the rate of reduction (Hutchings 2001). Notwithstanding these cautionary notes, however, there is a realistic expectation that the FAO Code of Conduct for Responsible Fisheries (FAO 1995) will be increasingly applied and that, on balance, things seem set to improve in the longer term.

Of course, even if continental shelf fisheries are all managed optimally, with concomitant reductions in the area subject to intensive fishing, trawling on the seabed will still occur and some areas will be markedly affected. A question remains, therefore, concerning the impact of such disturbance and the extent to which it is locally sustainable. Experimental data on rates of recovery after cessation of trawling are very patchy. However, analyses by Collie *et al*. (2000) permit us to speculate about the level of physical disturbance that is sustainable in some types of habitat. For example, mobile sandy sediment communities may be able to withstand 2–3 incidents of physical disturbance per year without changing markedly in character (Collie *et al*. 2000). It is important to bear in mind, however, that while available data allow us to predict the recovery rate for small-bodied taxa such as polychaetes, which dominate available data sets, sandy sediment communities often contain one or two long-lived and therefore vulnerable species. It is also important to recognize that in physically more stable environments,

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Table 4 Changes in objectives and the policies required to achieve them for future fisheries management. From Garcia and Grainger (1996)

Present		***Future***
Objectives		
Sustaining stocks	⇒	Sustaining assemblages and ecosystems
Maximizing annual catches	⇒	Maximizing long-term welfare
Maximizing employment	⇒	Providing sustainable employment
Ensuring full resource use	⇒	Ensuring efficient resource use (minimizing waste)
Tending to short-term interests	⇒	Addressing both short and long-term interests
Addressing local considerations	⇒	Addressing both local and global considerations
Policies		
Open and free access	⇒	Limited entry, user rights, and user fees
Sectoral fishery policy	⇒	Coastal zone inter sectoral policy
Command and control instruments	⇒	Command and control and macro economic instruments
Top-down and risk-prone approaches	⇒	Participative and precautionary approaches

particularly those characterized by structural epibenthic communities, recovery after trawling will take much longer. Clearly habitats that take extended periods to recover will be strong candidates for protection from fishing activities and much better data on effects for these physically more stable habitats is required. We also need better maps of the distribution of these habitats to ensure that they are adequately protected.

Improving the basis upon which fisheries are managed remains a challenge, and management agencies continue to struggle with the problem of how to define in operational terms, let alone implement, an ecosystem-based framework for managing fisheries. There are clearly no simple solutions for achieving this objective, but a number of approaches are being explored. Prominent among these is the notion that an ecosystem-based approach will be well served by the establishment of areas where the influence of human activities are restricted through establishing marine protected areas (MPAs).

The literature concerning the establishment of MPAs and their potential utility is growing rapidly. No purpose would be served by attempting to review it here (Coleman *et al*. 2000 and Hall 2002 provide a starting point for the interested reader; US National Research Council 2002). A number of points should, however, be made. First, an indication of the value and importance of the MPA as a conservation measure is provided by the fact that the IUCN [World Conservation Union] and others have called upon national and intergovernmental agencies to adopt a series of goals centred upon them (Agardy 1997). Specifically, they have argued for a global system of representative MPAs in accordance with a set of guiding principles and for national governments to also set up their own systems of MPAs. A number of nations have already taken such steps, including Australia, Canada and the USA, with other nations likely to follow suit in the future. Such initiatives are certainly encouraging, and an increasing proportion of the world's continental shelves is coming under some form of formal protection; rising from approximately 2750 MPAs with some marine element in 1990 to 3250 in 1999 (Burke *et al*. 2001). The recent establishment of an area in the Great Australian Bight, which occupies 19 769 km^2 and contains a 20 nautical mile wide strip extending 200 nautical miles offshore as a benthic protection area is a notable recent example (Environment Australia 2000). Considerable concern remains, however, regarding (1) the establishment of areas in legislation, but with no means of enforcement (so-called paper MPAs) and (2) calls for MPAs in the absence of clearly articulated objectives concerning the purpose they are to serve.

While MPAs certainly have their place in the environmental manager's toolkit, Bax *et al*. (1999) propose an interesting alternative to simply closing particular habitats, suggesting that we might limit their use through economic means. For example, a fisher might be given the right to harvest a certain fraction of a year class subject to the perceived ecological damage associated with harvesting. In other words, the proportion of the stock caught would be weighted by the damage to the environment from catching it. Enforcement through satellite monitoring of fishing vessels could then be based on the distribution of fishing effort in relation to habitat (Bax *et al*. 1999). For example, if fishing was undertaken in an area where smaller fish reside, leading, therefore, to higher expected discarding and thus greater environmental harm, then landed catch would count more against stock rights than a similar catch from less vulnerable habitat. Similarly, a tonne of fish caught from fishing in sensitive areas or with gear that damages benthic habitat would attract a higher proportion of that year's stock rights than one caught elsewhere. Such ideas, if adopted, hold great prospect for a more ecologically responsible fishery system. Quoting Bax (1999), 'Transferable ecological stock rights would provide managers with an instrument more clearly linked with the goals of ecosystem management and ESD [Ecologically Sustainable Development] than ITQs [Individual Transferable Quotas] are and would treat the problem, not the symptoms'.

Aquaculture

If badly managed, aquaculture will undoubtedly put increasing pressure on local coastal and inshore environments. In particular, effects on benthic communities in the vicinity of sea cages or effluent outfalls from land-based production facilities are likely to affect benthic communities. The spatial extent of impact around an installation is usually limited, however, with impacts around sea cages often restricted to less that 100 m from a cage (see Findlay *et al.* 1995). On an areal basis impacts on the continental shelf are likely to the relatively small and largely avoidable through sound management practices (GESAMP 2001). Moreover, it seems likely that aquaculture will be increasingly used in developing countries to reduce the impact of anthropogenic pollution through integrated systems that exploit high nutrient wastes for food production. For example, Mara *et al.* (1993) described a situation in Calcutta where pond culture was being used to treat 55 000 m^3 of untreated wastewater to produce 13 000 tonnes of fish for the urban poor, while simultaneously and substantially reducing nutrient, biochemical oxygen demand (BOD) and bacterial loadings to the coastal zone.

Having acknowledged that inshore areas will probably remain the focus for mariculture, we can nevertheless expect an increase in offshore cage culture as technology improves. Indeed, speculating on future food production needs, Ausubel (2000) argues that we can expect serious consideration to be given in the coming decades to fertilization of nutrient-poor coastal seas and large-scale offshore mariculture that does not rely on wild capture fisheries to produce feeds.

Mineral and petroleum exploration and production

Global energy demand is expected to increase by 65% between 1995 and 2020, with fossil fuels still supplying 92% of total needs at the end of this period (Pickering 2000). In contrast to the past 20 years, it is expected that there will be an increasing dependence on oil supplies from the Middle East, with sources from non-OPEC countries reaching maturity and becoming more marginal. Non-OPEC countries will still remain important, however, and most of the new oil supply from these countries is expected to come from offshore sources (Pickering 2000). For the most part, however, this expansion will be from deeper waters off the continental shelf (for example, from within the Timor Sea and off Brazil), with the major oil-producing areas on the continental shelf expected to decline in production and importance. The production from the North Sea, for example, is expected to peak around 2004; a decline in production from the continental shelf of the USA will also occur. As in other areas, it is deeper water reserves that are offsetting these declines (Pickering 2000).

The picture for gas is somewhat different from that for oil. There is likely to be a growing shift towards natural gas to supply the energy demands of many nations, with concomitant increases in energy efficiency. Offshore gas reserves are expected, therefore, to play an increasingly important role, with future reserve discoveries expected to be substantial for many areas. Pickering (2000), for example, notes that there will be substantial growth in natural gas production in the US federal waters of the Gulf of Mexico and that current reserves are now thought to exceed 1997 estimates of total recoverable gas resources for the entire USA. Areas such as the Nile Delta and the Timor Gap are also expected to increase in importance as gas provinces (Pickering 2000).

The importance of these developments for the shelf largely centres upon the expansion of infrastructure that will be needed to satisfy growing market demand. In particular, pipeline-laying activity can be expected to increase. Although on a total area basis this impact may be trivial it is conceivable that local issues associated with such development will emerge. In contrast, fixed rig installations for drilling or production are a largely a thing of the past, having been superseded by mobile and reusable platforms for deeper water operation (Pickering 2000).

One issue that does remain is the decommissioning or abandonment of existing installations as they come to the end of their useful life. The likely fate of the remaining rigs is difficult to predict, but for the 450 rigs in the North Sea, the UK target date for decommissioning smaller satellite structures is between 2006 and 2011 with the larger structures to be dealt with between 2011 and 2016. Considerable research has been undertaken to evaluate various decommissioning and disposal solutions and assess likely environmental impacts. Among these the recognition that the hard substrate provided by oil installations leads to growth of rich epifaunal communities, and that they also attract fish species has led to consideration of decommissioned structures as artificial reefs as one option.

Not surprisingly, the issue of decommissioning has proved to be highly contentious. Recently, however, the OSPAR [Oslo and Paris] Convention for the North East Atlantic has placed substantial restrictions on the dumping of all oil and gas platforms by member states, with strict criteria for derogations from complete removal (OSPAR Decision 98/3).

Land and freshwater use

The prospect for continental shelves is intimately bound to the practices of humans on land. Among these, agricultural and forest land use are almost certainly the most important. No predictions can be made, therefore, without consideration of these issues.

With respect to land use, the key question for this review is: will present trends continue? In the short term, the answer is almost certainly 'yes'. Contaminant inputs are a function of industrial and agricultural practices. For developing countries in particular, trends in these drivers are likely to lead to increased inputs to the sea from the atmosphere, rivers and land run-off. For example, while population increased in developing countries, the percentage of the population supplied with sewage treatment declined from 35% to 26% between 1975 and 1980 (World Resources Institute 1998). Similarly, it is predicted that reactive nitrogen from fertilizers and NO_x inputs to the atmosphere from energy use will continue to increase, notably in Asia, South and Central America, and North and South Africa (Table 5). With respect to absolute increases, it is estimated that the developed world will increase fertilizer use from 60 million nutrient tonnes in 1989–1990 to 170 million tonnes in 2020, whereas the increase in the developed world will be from 85–95 million tonnes (GESAMP 2001).

With respect to the contaminants (metals, hydrocarbons, etc.), we can expect to see continued reductions in the levels of inputs in developed countries as increasingly strict regulations are put into place. In contrast, for developing countries it seems likely that inputs will continue to increase as industrial activity increases in the absence of environmental legislation to regulate activities. With respect to persistent organic pollutants (POPs), for example, it is predicted that inputs will decline in the developed world whereas in the developing world, where regulations are absent and stockpiles are high, serious problems will continue to occur (GESAMP 2001).

Another issue of concern that is being increasingly recognized is the impact of marine environmental conditions on human health. The most notable aspect of this problem is with respect to poisoning from shellfish contaminated by algal toxins. It is estimated, for example, that toxic algal blooms cause 1000–2000 serious cases of poisoning from seafood consumption globally each year (Shuval 1986). Although there is speculation that toxic blooms are increasing in frequency as a result of human activities this hypothesis remains controversial (Smayda 1990). Predictions about future trends in frequency would, therefore, appear to be moot. Nevertheless, with the likely rise in cultured shellfish consumption health issues will remain prominent.

Water abstraction and river modification will continue to be a major issue for coastal systems in the coming years, with demands on fresh water for industrial and agricultural purposes increasing along with the need for flood control. While it would appear that the major era of dam building is at an end, with few places left where dams would be economical (de Villiers 1999; the major exception being the Three Gorges Dam on the Yangtse River in China), there are now few rivers that are entirely free of man-made obstructions. For many areas the flow from rivers seems likely to diminish further, although in some developed countries there is growing pressure to increase environmental flows for environmental purposes.

If we were to predict areas of continental shelf that are most likely to change in the coming years it would be in areas adjacent to rivers in developing countries. It has been argued, for example, that hydraulic modification is the most severe threat to the Arctic marine ecosystem, an issue highlighted by a debate about a storm surge barrier in St Petersburg that is likely to affect both fisheries and human health owing to the discharge of untreated sewage into the harbour (GESAMP 2001).

Table 5 Predicted percentage increases in reactive nitrogen by fertilizer production and energy generation from NO_x for different regions. Adapted from GESAMP (2001).

Region	*% increase in NO_x production from energy generation*	*% increase in fertilizer production*
Asia	40%	87%
Caribbean and South America	18%	5%
Africa	15%	6%
Former Soviet Union	15%	–
North America	10%	2%
Australia	1%	–
Europe	1%	–

A divergence between the developed and developing world

What is apparent from the available data is that we can expect a huge divergence in the trends in human drivers of environmental change that will be observed between the developed and the developing world. The economic well-being of the developed world allows it the luxury of increasingly strict regulatory controls on industrial activity and increasingly efficient agriculture, each of which is likely to lead to a continuing reduction in the stress placed on coastal systems. To this must also be added the declining or stable population of many developing countries. By contrast, in the developing world, with its imperatives to feed an increasing population and rapidly develop an industrial economic base, we can expect to see increased pressure.

While in the short to medium term, the prospects do not look good for the developing world, the trends in the developed world may offer a longer term picture for these regions and, for developed countries themselves, efforts will continue to be made to arrest current problems. With respect to likely improvements, an analysis for the Gulf of Mexico is revealing. For this region, models predict that significant reductions in hypoxia will occur with a 20–30% reduction in nitrogen loading (CENR 2000). Such reductions could be achieved with two approaches: (1) improved agronomic practices to reduce nitrogen losses from farm fields, and (2) trapping nitrogen lost from fields in restored wetlands, vegetated buffers, reconnected flood plains and coastal wetlands. In the case of the Gulf of Mexico, however, owing to the uncertainty of the science, the costs and impacts on food production among mid-western states and agricultural interests, commitments to such target reductions has met with considerable resistance. Nevertheless, a variety of federal, state and tribal government agencies have now jointly set a general goal to reduce the average area experiencing hypoxia to $<5000\,km^2$ from the current maximum of $20\,000\,km^2$. This is expected to require a reduction of nitrogen inputs by 30% (Boesch *et al.* 2000; CENR 2000). More generally, the National Research Council of the USA recently called for a national strategy to reduce the effects of nutrient pollution through a 10% reduction in the number of coastal water bodies demonstrating severe impacts by 2010 and a 25% reduction by 2020 (US National Research Council 2000).

To meet such goals, reducing and controlling diffuse sources of land run-off through large-scale landscape management will almost certainly be required. Such management will need to include restoration of riparian zones and wetlands. In the case of the Gulf of Mexico, for example, it is estimated that approximately 2 million ha of restored wetlands in the Mississippi river basin would reduce nitrogen loading to the Gulf by 20%. If such a measure were combined with feasible controls in agriculture, close to a 40% reduction in nitrogen inputs to the Gulf could be achieved (Boesch *et al*. 2000). In other developed countries, reductions in nutrient loading are occurring. For example, nitrogen inputs from the Rhine to the North Sea declined from 569 000 to 400 000 tonnes per annum from 1983–1987 to 1993–1997. Values for the Elbe declined from 328 500 to 233 800 tonnes per annum between the same periods (Ducrutoy *et al*. 2000).

The idea that we will experience a reversal in the human footprint on the landscape has been put forward by Ausubel (1996, 2000). Ausubel argues that in the middle of the 20th century humans began to reverse the pattern of extending the land area they used to meet their needs for food and materials. With respect to forests, for example, the area under forest in the USA has been relatively stable since 1900 (it has actually risen in the last five years), while the volume of wood in forests has increased by 36% since 1950 (Ausubel 2000). Opportunities for further increasing forest yields on any given hectare will lead to the decoupling of the demand for wood from the demand for land in the USA, suggesting that a modest 1.0% annual improvement in productivity, combined with a falling demand for wood could lead to a 1.5% decline in the area affected by logging annually. The compound effect of this would be to shrink the area affected by logging by 50% by 2050. While the land occupied by cities will rise during this period, the rate of encroachment on new land will be much lower than the rate at which land is being returned to forest (Ausubel 2000). For developing nations this trend is common; as noted earlier, there has been an 8.8 million ha increase in forest area in developed nations between 1990 and 1995 (FAO 2000*a*). The question is whether the same pattern will start to emerge for developing countries and at what rate. One encouraging sign is that the annual estimate of forest loss declined to 13.7 million ha yr^{-1} for 1990–1995, compared to 15.5 million ha yr^{-1} for 1980–1990 (Ausubel 2000). As with many other environmental issues, it seems likely that mitigation of impacts in poorer countries will become more widespread as their economies grow.

Forest loss is a product of two demands. The first of these is for timber products, for which rising productivity of well-managed forests should allow 20% or less of the 3 billion ha of land under forest today to supply most of the world commercial wood demand sustainably by 2050 (Ausubel 2000). The second demand is for land for other purposes, most often agriculture. Here again, the long term prospect may not be as bleak as many would have us believe, a conclusion aptly summed up in the following quotation:

'If the world farmer reaches the average yield of today's US corn grower during the next 70 years, ten billion people eating as people now on average do will need only half of today's cropland' (Ausubel 2000).

This apparently utopian situation (the land spared would exceed Amazonia in size) would be achieved if the 2% annual increase in grain yields per hectare that have been obtained since the 1960s are maintained. While this might seem a tall order, the continued diffusion of current best practice to farmers around the globe will do a lot to achieve it. Even if the rate of increase falls to 1%, an area the size of India would be turned over to natural landscape by 2070. Benefits attendant upon this trend would be a decline in the use of fertilizers and water consumption, through more precise fertilizer application and improved irrigation systems. For example, the amount used per tonne of crop has also declined in the USA with the advent of 'precision agriculture' that carefully manages fertilizer and water application dependent on crop types and soil characteristics (Ausubel 2000). Combining this with other approaches that limit nutrient losses from fields will certainly pay dividends. For example, it is estimated that a 40–90% reduction in soil erosion is achievable in East Asia and that this should lead to a 188% increase in yield (GESAMP 2001). Transfer of these technologies to developing countries will do much to accelerate these trends. Similarly with water use, there are prospects for large increases in efficiency (de Villiers 1999). Farming practices that need to be encouraged in both developed and developing nations are summarized in Table 6.

CONCLUDING COMMENTS

Attempts to predict the future state of any ecological system are fraught with difficulty, particularly over decadal timeframes. This is, perhaps, especially true for continental shelf ecosystems where data on current status are poor and our understanding of many of the drivers of change somewhat rudimentary. What we can say for certain, however, is that change will occur and, in the short term, many of the signs point towards deterioration in the ecological condition of many shelf systems, but particularly those of developing countries. Trends in land-use practices, with consequences for nutrient, sediment and freshwater input to coastal seas appear to be particularly worrying, but the poor state of many demersal fisheries systems must also be acknowledged. With respect to inputs of contaminants, a useful regional perspective on future priorities (Table 7) is provided by GESAMP (2001).

The picture is somewhat more encouraging, however, for developed countries where increasingly strict pollution controls, more precise use of fertilizers and a general increase in environmental awareness and environmentally sound legislation seem likely to lead to progressive improvements to the marine environment over the coming years. With respect to demersal shelf fisheries, while most of stocks are now fully or over-exploited, the prospects for developed countries are good for improved management regimes and stock status over the coming decade, with fishing concentrated on traditionally rich grounds, rather than an ever wider search for a decent catch. It also seems likely that we will see increasing areas of the shelf protected from trawl fishing altogether, with the establishment of networks of MPAs, although uncertainty about rates of habitat recovery is an important issue that awaits further investigation.

Although the short-term prospects may be bleak in some areas of the developing world, in the longer term, we can but hope that many of the improvements that are predicted to occur over the next decade in the developed world will also begin to be seen elsewhere. Perhaps one aspect of change for which less optimism is warranted is water abstraction. The global demand for fresh water is likely to be a major challenge and the political will to maintain environmental flows may be weak (de Villiers 1999). If environmental flows are reduced further this will certainly affect benthic invertebrate and demersal fish communities in shelf regions that are currently under riverine influence.

Table 6 Farming practices that will need to be more widely adopted to reduce nutrient inputs to coastal seas (adapted from Boesch et al. 2000).

Objective	*Approaches*
Reduce soil erosion	Contour ploughing
	Timing of cultivation
	Conservation tillage (little or none)
	Stream-bank protection
	Grazing management
Efficient fertilizer use	Soil testing to precisely match fertilizer applications to crop needs
	Timing fertilizer applications to when they are needed
	Crop rotation
	Planting cover crops in autumn
	Using soil and many area amendments
	Specialised fertilizer application methods
Landscape modification to trap nutrients	Maintaining buffer strips between cultivated fields and streams
	Moderate excessive drainage by ditches and tile lines
	Maintain wooded riparian areas

With respect to the impact of climate change, the extent to which accurate prediction can be made is highly limited, a fact highlighted by recent discussion by Lubchenco *et al*. (1993), who discussed the usefulness of simple predictions with respect to temperature change and sea level rise for predicting the responses of nearshore biota during and after the 1982–1983 ENSO event. Information on biotic responses directly related to temperature and sea-level rise would have been 'grossly insufficient', largely because of: (1) the important role of the frequency and severity of winter storms, and (2) the indirect biotic effects that occur following primary responses. Trends in neither of these drivers can be predicted at present (Lubchenco *et al*. 1993).

While it is tempting in an assessment like this to conclude with a sensationalist doom-laden prognosis, I think the longer-term prospect for continental shelf seabed ecosystems is relatively bright, albeit contingent on economic growth in the developing world. The stress imposed on these systems, their sheer size and the degree to which they are already adapted to the agents for change lead me to conclude that they are much less at risk than estuaries, coastal wetlands, coral reefs or other coastal ecosystems. Such an assessment should in no sense, however, be taken as a case for complacency. Indeed, a systematic global effort to establish a better baseline for the status of communities supported by the soft sediments of continental shelves is long overdue and should form the foundation for monitoring future trends.

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Table 7 Regional priorities for human impacts on coastal systems as identified by GESAMP (2001). 1 = highest priority.

	Priority				
Region	*1*	*2*	*3*	*4*	*5*
Eastern Africa	Sewage	Physical alteration	Nutrients	POPs	Sediments
West and Central Africa	Sewage	Physical alteration	Nutrients	POPs	Oil
East Asia	Sewage	Nutrients	Sediments	Physical alteration	POPs
Persian Gulf/Gulf of Oman	Oil	Physical alteration	Sediments	Sewage	Nutrients
Upper south-west Atlantic	Sewage	POPs	Heavy metals	Nutrients	Sediments
South-east Pacific	Sewage	Nutrients	Heavy metals	POPs	Physical alteration
Red Sea/Gulf of Aden	Physical alteration	Sewage	Nutrients	Sediments	
South Pacific	Sewage	Sediments	Physical alteration	Nutrients	Oil/POPs
Black Sea	Nutrients	Sewage		Oil	Sediments
Arctic	Heavy metals	POPs	Physical alteration	Radionuclides	Oil

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