Environmental Conservation 29 (1): 62–77 © 2002 Foundation for Environmental Conservation DOI:10.1017/S037689290200005X

Sandy shore ecosystems and the threats facing them: some predictions for the year 2025

A.C. BROWN[1]* AND A. McLACHLAN[2]

[1]*Zoology Department, University of Cape Town, South Africa 7701 and* [2]*College of Science, Sultan Qaboos University, Oman*

Date submitted: 25 April 2001 Date accepted: 28 November 2001

SUMMARY

Pollution, mining, disruption of sand transport and tourism development widely affect sandy shores, and these systems may be subject to increased erosion in future, yet there have been few attempts to review them. The present review focuses largely on ocean sandy beaches, providing an introduction to much of the relevant literature, and predicting possible states of the system by 2025. Sandy shores are dynamic harsh environments, the action of waves and tides largely determining species diversity, biomass and community structure. There is an interchange of sand, biological matter and other materials between dunes, intertidal beaches and surf zones. Storms and associated erosion present the most substantial universal hazard to the fauna. Human-related perturbations vary from beach to beach; however, structures or activities that impede natural sand transport or alter the sand budget commonly lead to severe erosion, often of a permanent nature. Many beaches also suffer intermittent or chronic pollution, and direct human interference includes off-road vehicles, mining, trampling, bait collecting, beach cleaning and ecotourism. These interferences typically have a negative impact on the system. Identified long-term trends include chronic beach erosion, often largely due to natural causes, as well as increased ultraviolet (UV) radiation and changes related to global warming. It is not expected that predicted temperature changes will have dramatic effects on the world's beaches by 2025, but the expected rise in sea level, if coupled with an increase in the frequency and/or intensity of storms, as predicted for some regions, is likely to lead to escalating erosion and consequent loss of habitat. It is suggested that increased UV radiation is unlikely to have significant effects. Increases in coastal human populations and tourism, thus increasing pressure on the shore, while serious, may be largely offset in developed and developing countries by better management resulting from greater understanding of the factors governing sandy-shore systems and better communication with beach managers and developers. Beach nourishment is likely to become more widely practised. However, the continuing hardening of surfaces in and above the dunes is bound to be damaging. Human pressures in many underdeveloped countries show no signs of being mitigated by conservation measures; it is likely that their sandy shores will continue to deteriorate during the first quarter of this century. A long-term trend that cannot be ignored is the excessive amount of nitrogen entering the sea, particularly affecting beaches in estuaries and sheltered lagoons. The data presently available and the uncertainty of a number of predictions do not permit of quantitative assessment or modelling of the state of the world's sandy shores by the year 2025, but some tentative, qualitative predictions are offered.

Keywords: sandy shores, ecology, climate change, human interference

INTRODUCTION

Sand or mixed sand and rock make up some 75% of the world's ice-free coastlines (Brown 2001). An exposed sandy shore consists of coupled surf zone, beach and dune systems (Short & Hesp 1982), which together constitute a littoral active zone of sand transport. On open coasts subject to oceanic swell, the depth of sediment transport may be 20 m and extend well beyond the surf zone, while aeolian transport of sand extends landwards to the fully vegetated dunes. The sandy shore, from the perspective of sand transport and coupled morphodynamic systems, includes marine and terrestrial components, with the intertidal beach in between. High energy beaches, receiving strong winds and waves, usually have wide surf zones and, because of considerable aeolian sand transport off the subaerial beach, are often backed by large dune systems, such as transgressive dune sheets. Under sheltered conditions, by contrast, the littoral active zone is narrower, with a smaller surf zone and, because of the narrower beach and limited sand transport, small foredunes (Short & Hesp 1982). It is beyond the scope of this paper to give full treatment to all three of the components making up the system; this review therefore focuses on the subaerial beach but also touches on surf and dune systems where relevant. Indeed, as foredunes are in many respects the most sensitive part of the littoral active zone, threats to the dune/beach interface deserve particular attention.

* Correspondence: Professor Alexander Brown e-mail: acbrown@botzoo.uct.ac.za

The present state of the world's sandy shores is extremely variable. Some, in remote areas, are virtually pristine, with low human population levels and yet to be discovered by tourists. Others, in industrial or overpopulated urban areas, are seriously degraded due to chronic pollution and/or the hardening of surfaces, destruction of dunes and the construction of sea walls. Between these extremes is a whole range of sandy shores suffering impacts from a wide variety of causes.

This review attempts to address the chief threats to sandy coastlines and their faunas around the world, and to exposed beaches in particular, in the light of global climate change and increasing human pressures. It considers, as far as feasible, a time frame of some 25 years. At a time when global change is recognized by most authorities and when the human population, concentrated on the coast, exceeds 6 billion, it is timely to take stock of the status of these important and sensitive ecosystems and to assess how they may respond to these threats within the next generation.

Features of sandy shores

Sandy shores are dynamic environments with unstable substrata, presenting hostile conditions to the biota. They display a considerable range of physical conditions, community structures and ecosystem functioning. They consist of accumulations of particles deposited by waves, the particles having diameters of 50–2000 μm (0.05–2 mm). The particles originate chiefly from inland erosion and are transported to sea via rivers; erosion of cliffs and rocky shores may add to the sediment available (Bird 1985). The particles generally consist of either quartz or silica, but may also include heavy minerals, volcanic basalt and feldspar. In addition, beaches commonly receive particles from marine biogenic sources, including shell fragments, pieces of skeleton and sponge spicules (Brown & McLachlan 1990).

The physical features of beaches reflect the interaction of wave height, wavelength and direction with the tidal regime and the sediment that is available (Short 1993*a*,*b*). The resulting physical state of the beach, including slope, particle size distribution and swash climate, in turn determines community structure, zonation and ecosystem functioning. Water movements and their interaction with the sediment thus constitute the overriding factors to which virtually all sandy-beach phenomena are related.

Obvious features of ocean sandy beaches include the absence of attached macrophytes intertidally and the apparent paucity of the fauna. Over 20 species of macrofauna may actually be resident, often in large numbers, but they are mainly cryptic and typically emerge from the sand only at night, if at all (Brown 1983). As the tide rises, other macrofaunal species commonly invade the intertidal beach from the surf zone. However, the majority of intertidal sandy-beach animals are tiny and live between the sand grains; in contrast to the macrofauna, this meiofaunal component may comprise over 600 species (Brown 2001). Virtually all animal phyla are represented. Bacteria and Protista live between the grains often in large numbers, but have for the most part been poorly quantified.

Intertidal sandy substrata range from sheltered sand flats, and sand in estuaries and sheltered lagoons to ocean beaches, which may face waves several metres in height even in calm weather. The interaction of waves and tides with the available sediment results in a series of morphological beach types. For wave-dominated beaches the extremes are represented by the dissipative condition (where the wave energy is largely dissipated in a broad surf zone before reaching the intertidal sand, resulting in a gentle beach slope and non-turbulent swash) and reflective beaches (where there is no true surf zone and waves break on the beach face, much of their energy being reflected back towards the sea) (Short 1993*a*,*b*). Reflective beaches have a more pronounced slope and larger particles than dissipative beaches and the swash tends to be turbulent. Paradoxically, high-energy beaches (i.e. those facing high breakers) tend to be flat and dissipative, while low-energy beaches are typically steep and reflective (Brown & McLachlan 1990).

Wave-dominated beaches are found where waves are high relative to tide range. This relationship may be formulated by the relative tide range (RTR) (Masselink & Short 1993):

$$RTR = TR\,/\,Hb \tag{1}$$

where TR = the range of spring tides and Hb = average breaker height. If the value of RTR is less than 3, the beach is wave-dominated, if greater than 15 it is tide-dominated. If RTR is between 3 and 15, the beach is said to be tide-modified. Tide-dominated sands all display low breaker height (< 1 m) and are morphologically intermediate between ultra-dissipative beaches and sand flats (Short 1996). If the tide range is small (2.0 m or less), tidal effects on beach morphology are minimized, but as tidal range increases, so the location of the shoreline displays increasing mobility with tidal rise and fall. As a result, a given level of the intertidal beach may be exposed to shoaling, surf and swash at different states of the tide.

Wright and Short (1984) employed the dimensionless fall velocity (Gourlay 1968; Gibbs *et al.* 1971), commonly known as Dean's Parameter, Ω, to characterize wave-dominated beaches:

$$\Omega = \frac{Hb}{Ws.T} \tag{2}$$

where Hb = average breaker height (m), Ws = sediment fall velocity (m s^{-1}) and T = wave period (s). This formula has been used extensively to quantify beach types ranging from fully dissipative through intermediate conditions to fully reflective. There are strong correlations between Dean's Parameter and macrofaunal species richness and abundance (Fig. 1*a*: No. spp. = $2.1\Omega - 0.6$, $r^2 = 0.89$; Fig. 1*b*: Log $(n + 1) = 0.5\Omega - 0.69$, $r^2 = 0.83$). Beach morphology is not static and may change towards dissipative or reflective according to conditions, often seasonally.

Sand movements are most apparent during storms, when large quantities of sand may be eroded from the upper shore and deposited in the surf zone, to return slowly when conditions are calmer. Storms are thus of great importance in shaping and defining the ecosystem. This is as true of sheltered sands as of exposed shores (Hegge *et al.* 1996). Long-shore sand transport is also typically in evidence and is critical to the maintenance of the sand budget (Clark 1983). There is also a flow of biological materials through the system, essential for nutritional input to an intertidal community largely lacking primary production. Stranded wrack or kelp provides food for semi-terrestrial crustaceans and insects, washed up carrion is important for aquatic crustaceans and scavenging gastropods, while filter feeders such as the clam *Donax* rely on suspended particles, including surf-zone diatoms (Brown & McLachlan 1990). Surf-zone predators invade the intertidal beach as the tide rises, birds during the day and terrestrial animals may invade it at night. Bacteria and meiofauna work over organic material in the sand, returning mineralized nutrients to sea (Griffiths *et al.* 1983).

Dissipative beaches, with their gentle slopes and swash, present less hostile conditions to the fauna than do reflective beaches and display higher diversity and biomass. Reflective beaches are inhabited chiefly by a semi-terrestrial fauna dependent on wrack or kelp, while increasingly dissipative conditions lead to greater food-chain complexity. The surf zone plays an increasingly important role in the bionomics of the system as conditions become more dissipative, especially where circulating cells of water support surf diatoms such as *Anaulus*, which then drive much of the food web (Fig. 2). A semi-closed ecosystem results (McLachlan 1980). Reflective beaches are, in general, net importers of material from the sea, while dissipative systems are exporters (Brown *et al.* 2000).

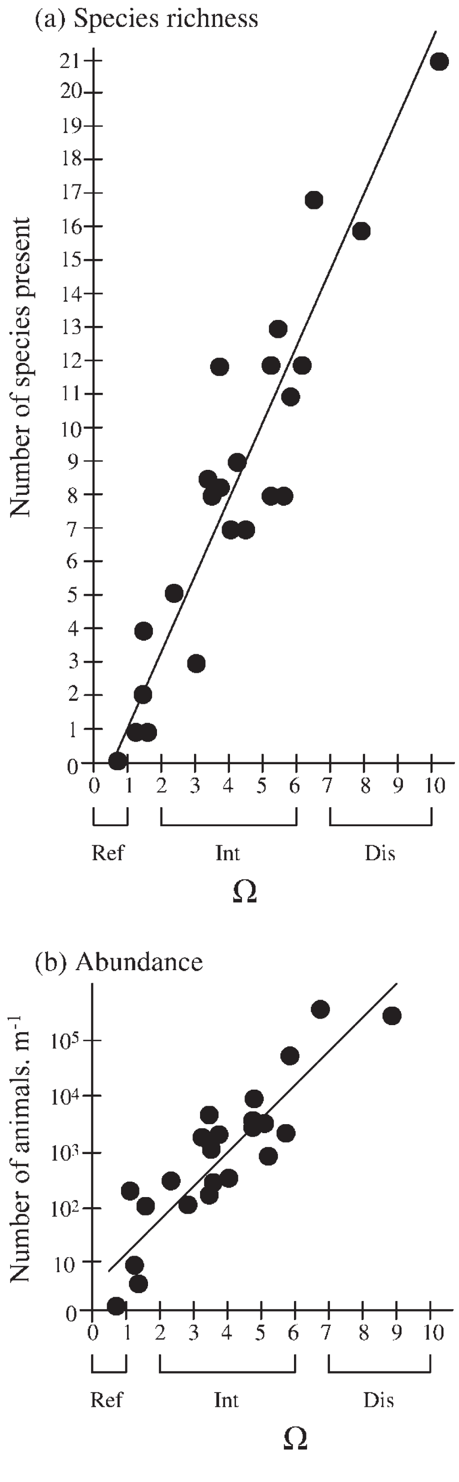

Figure 1 Relationship between beach morphodynamic state (Ω Dean's parameter) and (*a*) species richess and (*b*) macrobenthic abundance for 23 beaches in Australia, South Africa and the USA. Ref = reflective, Int = intermediate, Dis = dissipative (after McLachlan 1990).

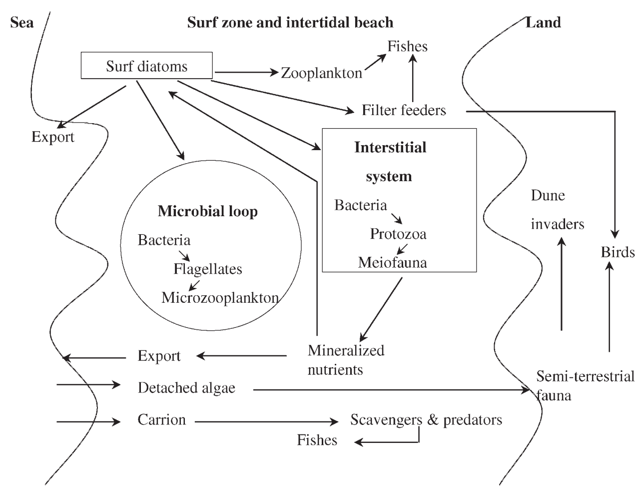

Figure 2 Simplified food web in a dissipative beach and surf zone, with primary production dominated by surf-zone diatoms.

FACTORS CURRENTLY IMPACTING SANDY-SHORE ECOSYSTEMS

Table 1 provides a summary of impacts affecting sandy shores. We will now discuss these in more detail.

Storms

Although storms are an important part of a natural cycle moulding the morphodynamics of the system, they represent the greatest natural hazard faced by sandy-shore animals. Sand and animals are washed out to sea, while others are stranded upshore, where they die of exposure. Such events often result in greater mortality than does predation (Brown & McLachlan 1990). Some animals (e.g. the whelk *Bullia*, aquatic isopods and mysids) can regain the shore if not carried too far out to sea, while others (e.g. clams of the genus *Donax*) cannot. The ability to survive storms by behavioural means is a key feature of sandy-shore animals (Brown 1996), but these mechanisms do not always give adequate protection, especially if significant sand erosion occurs. In compensation, as few macrofaunal species can tolerate the conditions, interspecific competition is minimized (Little 2000).

In extreme cases, so much sand may be eroded from the beach that rocks below the sand become exposed. This disrupts the laminar flow of the swash, making colonization by swash-riding species (e.g. *Bullia* and *Donax*) impossible (Brown *et al.* 1991*b*). Some beaches only occur seasonally, sand deposited during relatively calm periods being totally removed during the months when storms are prevalent. In such cases, there may be some colonization by bacteria and meiofauna as sand is deposited but macrofauna has no time to establish itself. More common are beaches which are simply too inhospitable to macrofauna for much of the year. Some species (e.g. the whelk *Bullia*) remain offshore until storms have flattened the beach and then colonize it during calmer weather (Brown 1996). Juvenile *Donax* may also colonize it briefly but cannot attain adult size before being washed away by the next series of storms.

Disruption of sand transport

Any structures or activities which disrupt the transport of sand either long-shore or vertically on/off shore, may lead to serious erosion. This has resulted most obviously from the construction of harbours, breakwaters, jetties and groins, which deprive down-drift beaches of sand while updrift sand accumulates and advances seawards. The most famous case is probably that of Madras harbour (Komar 1983*a*), and some 700 km of the Florida shore are threatened by severe erosion, jetties being estimated to account for 85% of the problem (Finkl 1996). This has led to ongoing artificial beach replenishment, which is costly and under financial threat. Sometimes it is not apparent why a structure has induced erosion or deposition, but in most cases the effects could have been predicted with some accuracy if an adequate prior impact study had been undertaken. Sometimes such structures have been found to benefit certain categories of fauna, although these have seldom been planned. For example, Botton *et al.* (1994) found that in Delaware Bay shorebirds (red knots, sanderling and ruddy turnstones) aggregated near shoreline discontinuities, including jetties that provided concentrating mechanisms for drifting *Limulus* eggs.

Groins are constructed with the intention of trapping sand to build up a beach or prevent further erosion. Most often, their purpose has been to protect landward property from the effects of storms. However, bad planning or failure to implement the design has frequently led to damage in the very areas they were meant to protect. Even well-designed groins may prove inadequate to protect or restore beach systems, as has been demonstrated by the history of the beachfront at Long Island, New York, USA (Clark 1983), and the groins in Maputo Bay, Mozambique (A.C. Brown, personal observation 1997).

Artificial stabilization of dunes by plants or fences can also have severe effects on sand transport. Some dunefields receive wind-blown sand from updrift beaches and pass it overland to downdrift beaches; stabilization may have severely detrimental effects on the latter (Tinley 1985; Swart & Reyneke 1988). The hardening of surfaces, sea walls and

Table 1 Summary of factors currently impacting sandy shores.

Factors	*Extent*	*Type of beach most affected*	*Importance / severity (max. = 10)*
Storms	Widespread	Exposed	7
Disruption of sand transport	Near structures	Exposed	6
Pollution	Localized/widespread	Sheltered	6
Trampling	Localized	Vegetated dunes	5
Recreation/tourism	Localized (increasing)	Resorts	4
Litter	Localized (increasing)	Resorts	4
Beach cleaning	Localized	Urban/resort	4
Mining	Localized	Various	3
Groundwater changes	Widespread	Arid areas	3
Bait collecting	Widespread	Beaches with rich fauna	3
Fishing	Widespread	Beaches with rich fauna	3

other such structures may also alter sand transport (Kraus & McDougal 1996). Studies of the effects of sea walls on sediment transport have led to apparently contradictory results (Miles *et al.* 2001), which may partly reflect a lack of understanding of the processes involved. Miles *et al.* (2001) used sophisticated methods to study sediment dynamics in front of a sea wall in south Devon, UK, and to make comparisons with an adjacent, natural beach. Sediment suspension and transport were both altered significantly by the wall, suspended sediment concentrations being up to three times higher and onshore sediment transport reduced; longshore transport was an order of magnitude higher in front of the wall than on the natural beach (Miles *et al.* 2001).

Extensive or regular mining of sand from the shore may have equally severe consequences. Komar (1983*b*) studied the effects of removing 12 000 m^3 of sand annually from the beach at Schoolhouse Creek, Oregon, USA. Prior to this operation, gains and losses of sand approximately balanced, but the sand mining tipped the balance, resulting in long-term erosion. Sand mining of the dunes at Hermanus, near Cape Town, South Africa, has totally altered the nature of the shore (A.C. Brown, personal observation 2000). In principle, any kind of excavation on any part of a sandy shore must be presumed to be damaging to the system (Clark 1983).

Beach nourishment and bulldozing

Beach nourishment by importing sand and bulldozing to restore dunes, by transferring sand from low to high levels, have become common practices in some parts of the world, such as North Carolina, USA, which face ongoing beach erosion from man-made structures or from natural causes (Leonard *et al.* 1990; Peterson *et al.* 2000). At Bogue Banks, North Carolina, USA, the imported sand was substantially finer than that of the natural beach and had more shelly material, while bulldozing to augment the primary dune deposited coarser, more shelly sand than that already present and reduced the width of the intertidal beach (Peterson *et al.* 2000). These changes impacted the fauna, the mole crab *Emerita* and the clam *Donax* displaying an 86 to 99% decrease after some weeks; both animals had failed to recover after three months (Peterson *et al.* 2000). Beach and profile nourishment at Perdido Key, Florida, USA, led to negative impacts on the macrobenthos that were still apparent two years after the event (Rakocinski *et al.* 1996). Nevertheless, beach nourishment has often proved to be an effective way of combating erosion (Peterson *et al.* 2000). It may also be used to enhance the habitat of selected species of biota.

Pollution

As with other types of shore, sandy beaches suffer pollution from a large number of sources. The most spectacular pollution events have been due to oil tanker accidents. Accidents to non-tanker vessels are far more common and these typically result in oil pollution, though to a lesser degree (Brown 1985). In addition, oil slicks result from accidental spillages and from the cleaning out of tanks at sea. Spillages from oil terminals and rigs are common and often result in chronic pollution which may be more damaging to the biota than a single severe oil-pollution event (Dicks & Hartley 1982). The beaches of the Congo Republic, West Africa, are permanently covered in oil and tar due to terminals and offshore drilling, while beaches in and around the Arabian Gulf suffer chronic pollution due to heavy tanker traffic. Run-off and natural seepages of petroleum hydrocarbons may also lead to chronic pollution and land-based pollution may be the most important source of these substances for the oceans as a whole (Camp 1989).

Crude oil has a number of effects on sandy-beach biota (Brown 1985). It has a toxic component, consisting mainly of short-chain and polycyclic aromatic hydrocarbons. Secondly, the oil has physical effects, clogging delicate filter-feeding mechanisms and appendages. Thirdly, oil may act as a barrier, reducing oxygen tensions in the sand below it and reducing water flow through the beach (McLachlan & Harty 1981*a*). Recovery from an oil spill takes place in stages. The meiofauna may recover within a year (McLachlan & Harty 1981*b*) and presumably bacterial populations return even sooner. Most macrofaunal species take longer to re-establish themselves and, in the meantime, opportunistic polychaete worms of the families Capitellidae and Cirratulidae may increase in numbers or invade the beach if not previously present, and temporarily dominate the system (Southward 1982). The macrofauna of fine sediments takes longer to recover than that of coarser beaches and oil trapped in the sand may influence the system for six years or more (Thomas 1978).

In the past, oil dispersants have often been sprayed too near the coast or even on the shore itself, with disastrous effects on the biota. Fortunately, this practice is no longer common. All mixtures of oil and dispersant are more toxic than is the oil itself (Norton & Franklin 1980).

Organic enrichment may result from the discharge of raw or partially treated sewage to sea. The tendency in recent decades to increase the length of discharge pipes in an attempt to keep the sewage away from the shore has not always been completely effective; however, the current trend to forbid the discharge of raw sewage may prove beneficial. Although sewage generally contains few toxic substances, organic enrichment leads to a lowering of oxygen tensions within the sand and a consequent upward encroachment of anoxic 'black layers'. This in turn results in impoverishment of the fauna. A worldwide problem is the glut of phosphorus and particularly nitrogen, resulting largely from the increased use of fertilizers (World Resources Institute 1998). These elements reach the sea through sewage, rivers, run-off and stormwater drains. Consequent eutrophication, distorting nutrient cycles and leading to algal blooms and oxygen deprivation, is a major threat to beaches in sheltered lagoons and estuaries (Gowen *et al.* 2000). Observed increases in toxic algal blooms are considered to be related to this increased nitrogen input (World Resources Institute 1998).

Factory effluents vary greatly in their impact on sandy shores, those that cause the greatest public concern due to their colour or smell being not always the most damaging. Factories have tended to be built on estuaries or shallow sheltered bays, so that sandy or muddy beaches incur much pollution from these sources. In many countries, small factories discharge effluent into sewers or stormwater drains, the latter frequently opening onto the beach above high-water mark (Brown *et al.* 1991*a*). Such drains also often present a health hazard, with high concentrations of faecal *E. coli*.

Thermal pollution is a factor on some beaches. Factories frequently discharge effluent at a higher temperature than the sea water, thereby adding thermal pollution to chemical effects. Such pollution is generally insignificant, however, and it is only with the advent of large power stations, and particularly nuclear power stations, that serious study of the effects has been undertaken. Markowski (1959) concluded that no detrimental effects could be observed from power station cooling water effluent, but later studies (Naylor 1965; Nauman & Cory 1969; Hill 1977) concentrated on more subtle effects than Markowski had considered and doubted his conclusions. At Hunterston, Scotland, no major changes to the beach fauna were noted after the power station began operating, but within ten years, the population density of the bivalve *Tellina tenuis* showed a considerable decline, although the animals grew faster. At the same site, the amphipod *Urothöe* started breeding earlier than before and juveniles grew for longer, reaching a 28% greater size (Barnett & Hardy 1969; Barnett 1971). Siegel and Wenner (1984) reported abnormal reproduction in *Emerita* near a nuclear station in Southern California, USA.

Radioactive pollution affects few beaches, but has been a source of concern near nuclear power stations and especially close to nuclear reprocessing plants (McKay *et al.* 1986). Plutonium has understandably been the chief focus of attention. Plutonium from such sources is generally finely particulate or in solution and tends to bind strongly onto sediment particles, especially fine particles, affecting marine life (Brown 1994).

While pollution of intertidal beaches most commonly arises from seaborne materials, pollution of the dunes is more likely from land-based sources. Fertilizer residues from agricultural land behind the dunes have been found to effect changes in dune plant communities (Ranwell 1972) and pesticides may be a problem. Airborne pollution can be an important factor, in addition to run-off. Polluted groundwater is likely to seep seawards, thus affecting the intertidal beach and even the surf zone. More attention needs to be devoted to movements of groundwater with regard to both pollution and nutrient transport (Uchiyama *et al.* 2000).

Off-road vehicles

A variety of vehicles, connected with recreation or industry, may invade a sandy shore, causing different types and degrees of negative impact. Some recreational vehicles, such as motorcycles, 4 × 4 vehicles and vehicles of the 'beach-buggy' type, with large, wide tyres, driven up and down dunes, often at considerable speed, cause displacement of sand and destroy dune vegetation. This can be extremely damaging in view of the fragile nature of the dune ecosystem. In addition, shorebirds are disturbed and their nests, eggs and young may be destroyed. Both these and more conventional vehicles may be driven along the beach itself. This often causes little impact along the wet foreshore, although this is not true of all beaches. On some New Zealand beaches, vast numbers of sand dollars (*Echinodiscus*) dominate the foreshore and are crushed by vehicles (S.C. Webb, personal communication 2000). Higher up the slope, vehicles are liable to crush semi-terrestrial invertebrates, such as isopods, talitrid amphipods and ocypodid crabs on the surface or in their burrows. Wolcott and Wolcott (1984) considered the negative effects of off-road vehicles on populations of the crab *Ocypode*, while Van der Merwe (1988) reviewed the literature on the impacts of traffic on coastal ecosystems. Van der Merwe and Van der Merwe (1991) investigated the damaging effects of off-road vehicles on the fauna of a beach, including the crushing of *Tylos* (Fig. 3: $Y = 0.75X - 4.6$, $r^2 = 0.99$, $p = 0.008$) and Brown (2000) identified off-road vehicles as a major cause of decline in populations of *Tylos granulatus* on the South African west coast. Hosier *et al.* (1981) noted that vehicle tracks in the sand presented barriers to the seaward progress of turtle hatchlings.

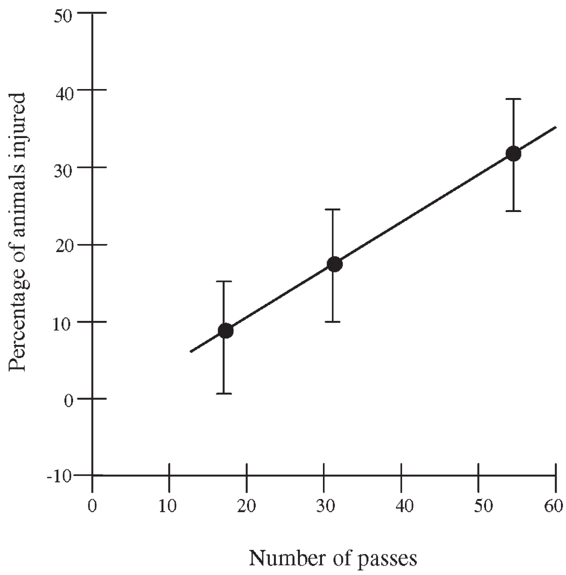

Figure 3 Regression of percentage injury to the semi-terrestrial oniscid isopod *Tylos capensis* against off-road vehicle passes. 95% confidence limits are shown (after Van der Merwe & Van der Merwe 1991).

Mining

Mining activities can have very severe effects on the ecosystem. In addition to removal of sand itself, mining may take place for precious stones, such as diamonds, or for various minerals. It may be undertaken on the beach itself or in the surf zone or beyond; in all cases heavy vehicles and machinery are involved on the beach. Strip mining of the intertidal beach effectively destroys the ecosystem. Many animals, including the meiofauna, eventually return as the beach re-establishes its former characteristics, but some semi-terrestrial Crustacea may fail to do so (Brown 2000). Offshore mining can be equally disruptive, as the material is usually pumped ashore and the 'tailings' left on the beach, altering the beach profile and its particle-size structure. At Elizabeth Bay, in Namibia, the dumping of coarse tailings resulted in the beach becoming more reflective, with a consequent loss of fauna (McLachlan 1996). Mining in the dunes and behind them destroys the vegetation and may disrupt sand transport, in addition to adversely affecting shorebirds. Tailings or topsoil run-off from mining behind the dunes may pollute the beach.

Trampling

Trampling associated with recreational activities may have extreme negative effects on dune systems (Fig. 4). These include not only direct damage to vegetation and the fauna, but also physical impact on the substratum, notably compaction, which influences soil moisture, run-off, erosion, vegetation and micro-organisms (Liddle & Moore 1974). The most obvious effects occur at low levels of trampling, further impact decreasing thereafter. Trampling on the intertidal slope typically has much less impact than in the dunes, although it is measurable and, even in the lower intertidal, may injure delicate crustaceans and juvenile bivalves (Moffet *et al.* 1998).

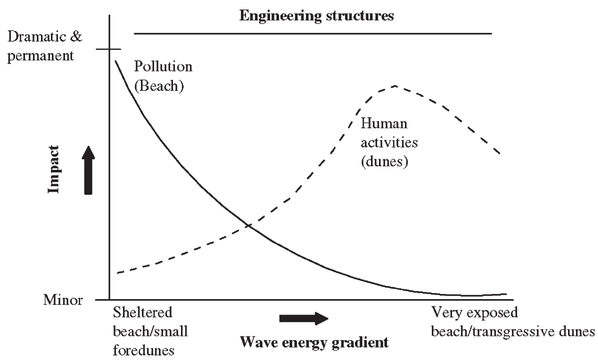

Figure 4 Relative importance of three kinds of human impact on sandy shores along an exposed gradient. Pollution chiefly affects the subaerial beach, trampling and off-road vehicles mainly impact the dunes, while coastal engineering structures permanently alter sand budgets for the entire littoral active zone (after Brown & McLachlan 1990).

Beach cleaning

Many beaches are regularly cleaned during the holiday season and in some cases throughout the year. Cleaning commonly takes the form of clearing the beach not only of debris left behind by visitors, but also of kelp, wrack and other dead or stranded biota. This deprives the ecosystem of valuable nutritional input, semi-terrestrial forms such as talitrid amphipods, oniscid isopods and ocypodid crabs being the most deprived. Mobile beach-cleaning machines are employed on some beaches. These suck up and filter the sand, capturing not only debris, but also any small animals, such as talitrids, near the surface. Talitrid populations can be effectively eliminated by this process and the mobile machines can crush more deeply buried invertebrates in their burrows. Some of these effects have been studied by Llewellyn and Shackley (1996).

Groundwater level changes

In addition to pollution of groundwater, human activities commonly result in a lowering of the water table. One such activity is the drawing off of water for domestic or agricultural purposes. This may be intensified by the hardening of surfaces, so that surface water from rain is diverted to stormwater drains instead of sinking into the soil. Lowering of the dune water table can have serious adverse effects on the dune ecosystem, which in turn may affect the intertidal beach (Brown & McLachlan 1990). Flooding, on the other hand, raises the water table and hastens erosion.

Bait and food collecting

The collection of invertebrates for use as bait is common on beaches that are stable enough to support the burrows of prawns such as *Callianassa* or of the lug worm, *Arenicola*. Beach clams are also harvested, for both food and bait, in some regions attaining the status of commercial enterprise. Indeed, 15 species of beach clam are harvested extensively around the world and in several cases overexploitation has led to the collapse of the fishery (McLachlan *et al.* 1996). Nevertheless, while populations are often drastically reduced by these activities, they are seldom if ever eliminated, as they reach a level at which the effort of collecting fails to justify the reward. Recovery thus begins as soon as collecting ceases. The exploited clam *Mesodesma* in Uruguay recovered rapidly after the beach was closed to the fishery for 32 months, and recruitment displayed over-compensation (Defeo 1996). In northern KwaZulu-Natal, South Africa, ghost crabs (*Ocypode*) and mole crabs (*Hippa* and *Emerita*) are harvested in a subsistence fishery; this appears to be sustainable (Kyle *et al.* 1997). In addition to the removal of beach animals, collecting typically involves digging or the use of prawn pumps, as well as trampling. The results of these physical disturbances may be more deleterious to the ecosystem than the actual removal of target animals (Wynberg & Branch 1997).

Fishing

Dissipative surf zones are important nursery areas for fish (McLachlan 1983; Brown & McLachlan 1990) and are home to a number of adult species. Both rod-and-line recreational fishing and commercial seining have significantly depleted populations of the latter in many areas, thus impacting the surf-zone system and reducing predation in the intertidal zone as the tide rises. Recreational fishing commonly involves off-road vehicles, while seining often results in a bycatch of sand crabs and other animals of non-commercial value, which may be dispatched on the spot or left on the beach to die.

Recreational activities

The recreational value of sandy beaches can hardly be overemphasized. Recreational activities such as swimming, wading, surfing, running, dog walking, picnicking, ball games, horseback riding, sand sailing, wave kites, cooking and building sand castles, must all have some impact, although this has never been quantified. In general, recreational pressures decrease sand stability and increase its mobility (Carter 1975; Artukhin 1990). However, observations suggest that impact on the intertidal beach is usually slight and that surf-zone invertebrates are little affected. The experiment of Jaramillo *et al.* (1996), in which a fenced-off strip of beach was compared with an adjacent area open to the public, indicated no significant effect of recreation on the crustacean infauna of a Chilean beach, probably because sand movements due to changes in wave climate overshadowed physical effects of human disturbance. However, fish, including elasmobranchs, may be frightened into deeper water (A.C. Brown, personal observation 1975), while shorebirds such as sanderlings are reluctant to come onto the beach to feed, possibly resulting in nutritional stress or causing them to migrate to less populated beaches. On the Florida coast, increasing human presence within 100 m of sanderlings was found to lead to decreased foraging times of the birds during the day and increased nocturnal foraging (Burger & Gochfeld 1991).

Ecotourism and bird watching

Ecotourism, especially in developed areas with dense human populations, although it encourages appreciation of coastal environments, may have a severe impact on coastal bird populations. On the coast of New Jersey, USA, rare birds attract more attention than common species, adding to their vulnerability, but bird colonies are more vulnerable to disturbance than are isolated individuals (Burger *et al.* 1995). Least terns have been severely impacted by coastal development and ecotourism and piping plovers are widely threatened in the USA. Piping plovers in areas less disturbed by people spent more time foraging and less time being vigilant than birds at other sites; the presence of people was stressful for breeding adults and chicks, possibly accounting for decreased reproductive success (Burger 1991). Ecotourism affects bird behaviour, reproductive success and population levels of both breeding and migratory birds in New Jersey, USA, in various ways (Burger *et al.* 1995), and frequent human intrusion leads to avian habituation and learning. The exclusion of people from some habitats has had beneficial effects for some species.

Litter

Litter left behind on the beach and in the dunes by human visitors has become an escalating problem. Teagle (1966, cited in Ranwell 1972) quantified litter deposited in Studland Dunes, Dorset, during a two-year period and observed some impact on the fauna. Since this work, non-biodegradable plastic materials have become the chief items of litter, affecting surf-zone animals as well as those higher up the slope. Moore *et al.* (2001) have recently studied the composition and distribution of beach debris in Orange County, California. In some regions of the world, litter is simply allowed to accumulate, or be washed out to sea. In others, it is collected but then buried above high-water mark or among the dunes, where it tends to resurface. Only in countries with a commitment to environmental conservation is the litter removed to landfill or incinerators. An important negative feature of litter is its detraction from the aesthetic value of the beach.

LONG-TERM TRENDS

Accretion and erosion

Short-term changes in beach morphology, in response to fluctuating wave regimes or weather conditions, are well known (Brown & McLachlan 1990; Short 1996). Superimposed on these are slow, long-term trends in accretion or erosion, often only apparent over periods of decades or even centuries. On some beaches, retention of newly-available sand leads to accretion and the coastline slowly advances seawards. The beach at Hastings, southern England, presents a good example of this process. Parts of Scandinavia have displayed land uplift of about 1 m per century (Aubrey & Emery 1993), pushing beaches seawards. Apparently far more common worldwide is long-term beach erosion, with a loss of sediment, diminishing beach volumes and consequent retreat of the coastline; a number of factors, some mentioned above, may be involved in such chronic erosion (Bird 1985). In addition, the damming of rivers deprives estuaries and the oceans of the natural fluvial input of sediment. In 1950 there were 5270 large dams in the world; there are currently in excess of 36 500 (World Resources Institute 1998). Reduction of cliff erosion, either by man-made structures or due to natural causes, also reduces the available sediment (Bird 1985). Long-term reduction in the transport of sand from the sea floor may also be an important factor. Interception of longshore drift by human constructs (see above) or natural causes inevitably leads to down-drift beach degradation, while strong onshore winds may effectively remove sand from the system by blowing it far enough inland to prevent its return to the beach. Sand may also be reduced in volume due to weathering, brought about by repeated grinding of the grains by wave action and/or by leaching; finer grains are more easily removed from the system by waves, currents and wind. Excessive precipitation and flooding behind the beach also favour erosion, as the escape of this water to sea carries sand with it and causes a rise in groundwater. Past sea-level changes must have had marked effects on accretion and erosion. Coastal emergence leads to coastline advance, while a rise in sea level, as in many areas in recent decades (IPCC [Intergovernmental Panel for Climate Change] 1996*a*) results in recession and loss of beach sand to the sea floor. Long-term climatic changes, including changes in rainfall patterns and especially increases in the frequency and/or intensity of storms, have significant effects on beach dynamics. Sand is characteristically transported to sea during storms, returning slowly in calmer weather; increasing storminess will change this balance and lead to continuing erosion.

Global warming

Global warming, due to the release of greenhouse gases, and in particular carbon dioxide, together with the destruction of forests, has been under way for at least the last 150 years, but has only attracted serious attention in the past two decades or so. There is now general agreement that the greenhouse effect poses real and substantial problems for the environment, including sandy shores (IPCC 2001*a,b, c*). In addition to temperature change, sea level rise is implicated as polar ice and glaciers melt, though whether the rise in sea level already recorded from many parts of the world (IPCC 1996*a*, 2001*b*) is a direct result of global warming is somewhat uncertain. However, open water now appears at the North Pole and the Northwest Passage is open to shipping. Rising sea levels promote increased erosion of sandy shores. In addition, global warming may be expected to incur increased storminess, at least in some regions, as well as changes in rainfall patterns; again, whether the floods and storms of 2000/2001, which were particularly severe, were largely due to global warming is debatable. Increased storminess results in erosion, retreat of beaches, dune scarping and dune vegetation loss.

Pressure of human activities

Since 1995 the global human population has increased at a rate of 1.33% a year, representing an addition of roughly 79 million people each year (United Nations 1998). This is lower than the peak rate of over 2% per year recorded for 1965–1970, largely because in 61 developed countries the fertility rate (2.1 children or less per woman) approximately balanced the death rate. The fertility rate in some developing (or 'emerging') countries is also dropping and could reach about 2.1 children per woman by the year 2050 (Potts 2000). No such trend is documented for many Third World countries; for example, Niger currently has 5.7 children per woman, as against 2.6 in South Africa (South African Bureau of Statistics, personal communication 2001).

The effect of population growth on sandy-shore ecosystems is intensified by the tendency of people to move to within a few kilometres of the coast (Roberts & Hawkins 1999). In First World countries, this is linked largely to affluence, aesthetic considerations and recreation. In Third World countries, for example in much of Africa, the migration is frequently an attempt to avoid conflicts or population pressures inland or is linked to the perception that there is more easily-acquired food at the coast. Both factors may operate at the same time, as has been seen in Mozambique (A.C. Brown, personal observation 1997).

In some developing countries, population growth and movement towards the coast have been partially mitigated by an increasing awareness of environmental issues and practical steps to conserve the ecosystem, including legislation. The South African situation is a good example of this healthy trend. In the mid-1950s, when one of us (A.C. Brown) began work on sandy shores, the only restrictions on visitors to the beach were limits on the number of bait animals (e.g. the clam *Donax*) that could be removed per person per day, and these limits were seldom enforced. There was no attempt to protect the ecosystem in other ways, conservation had not entered the vocabulary of politicians and there was no portfolio concerned with the environment. Only in the late 1960s did the Minister of Planning become Minister of Planning and the Environment, and only much later was the latter function separated to provide a Ministry of Environmental Affairs (later a Ministry of Environmental Affairs and Tourism). Public awareness of conservation issues increased concurrently and brought pressure to bear on government bodies to promote conservation in all its aspects. Marine reserves were established, often offering total protection to the biota, and a number of these included sandy shores. In the past decade, or so, tourism has been given a high priority, and linked to it a need to step up protection of the environment. On popular beaches, virtually throughout the country, access is along wooden walkways through the dunes, thus protecting the dune ecosystem from trampling. Off-road vehicles are restricted and conservation laws more strictly enforced. Commercial initiatives, such as mining, have to undergo rigorous environmental impact assessment and be exposed to public participation in planning; the organizations involved are committed to restoring beaches or dunes affected during the operation. Projects such as the Cape Peninsula National Park, which will give added protection to the marine biota, are now popular with the public and taken seriously by government. There is general awareness of the need to protect endangered or threatened shore species, such as the African black oystercatcher and turtles. The Department of Environmental Affairs and Tourism in South Africa has for some years had a Coastal Management Office that issues attractive coloured brochures, written in simple language, for the benefit of the public and local authorities, on the subject of coastal conservation. At the time of writing, there is legislation before Parliament to ban all off-road vehicles from beaches and dunes. Regrettably, however, communication between scientists, legislators and beach managers still leaves much to be desired and the latter generally have a poor understanding of management issues and how to address them (Brown *et al*. 2000).

Ozone depletion and enhanced ultraviolet radiation

Seasonal variations in the thickness of the ozone layer and resulting increases in ultraviolet (UV) radiation (Friedrich & Reis 2000) present a potential hazard to organisms through a variety of effects; shallow-water species are not immune to these effects, as UV radiation has been shown to penetrate water to greater depths than previously supposed (Booth & Morrow 1997). Reduced productivity of marine ecosystems may thus result (Hader 1997; Browman *et al*. 2000). Impacts of increased UV radiation on surf-zone biota, including phytoplankton, bacteria, crustaceans and their larvae and fish (Browman *et al*. 2000; Gustavson *et al*. 2000; Wubben 2000) are more likely to be apparent than on the beach fauna. Most intertidal species are cryptic, living within the sand, and are thus protected from changes in solar radiation; most of those that emerge from the sand do so only at night (Brown 1983).

TOWARDS THE YEAR 2025

In attempting to predict changes in the state of sandy-shore ecosystems by the year 2025, the chief trends to be taken into account are (1) the effects and implications of global warming, (2) increasing human pressures, bearing in mind possible mitigation, and (3) ozone depletion and its effects on UV radiation.

Global warming

Changes in sea temperature can have severe effects on marine populations, as witnessed during events such as El Niño. The impacts of El Niño on some South American beaches give an indication of changes that might be expected from rapid global warming. On Peruvian beaches, the abundance of many species plummeted during El Niño events, but this was followed by rapid recovery when conditions returned to normal (Arntz *et al*. 1988; Tarazona & Parendes 1992). Subtidal areas that had been anoxic saw an increase in abundance and diversity, and extension of vertical distribution in many species during El Niño events (Tarazona *et al*. 1985, 1988). These changes are largely related to changes in productivity, indicating that effects of elevated temperature on beach biota may be indirect.

In comparison with El Niño events, sea temperature changes between now and the year 2025 due to global warming are predicted to be gradual (IPCC 2001*b*), allowing marine populations some time to adjust and acclimate. Moreover, predicted temperature increases, though significant, are not such as would be likely to totally disrupt sandy-shore ecosystems. These predictions have been revised from time to time (IPCC 1990, 1992, 1996*a*, *b*, 2001*b*), present predictions indicating an atmospheric temperature rise of between 1 and 5ºC by the year 2100 (IPCC 2001*b*). Temperature rise for the oceans as a whole is likely to be only about half this value, although semi-enclosed marine lagoons and shallow bays may in some regions mirror the atmospheric temperature rise. In such situations, the worst scenario for the year 2025 would appear to be a water temperature increase of between 1 and 1.25ºC. This is a small change compared with that experienced by some beaches close to cooling water discharges from nuclear power stations (P.A. Cook, personal communication 2001) or those subject to El Niño. Moreover, aquatic sandy-shore animals are in many regions used to quite rapid changes in temperature and in areas of upwelling these can be extreme, the temperature changing by up to 10ºC in an hour or so (Brown & McLachlan 1990).

Sandy-shore animals seldom experience temperatures close to their upper tolerance levels, an exception being some ocypodid crabs (Fishelson 1983). All sandy-beach animals are capable of burrowing and of escaping below the sand if conditions at the surface become hostile. However, if the temperature rise were to be added to natural warm-water events, such as El Niño, in some regions, this combination could have severe negative impact.

Possible effects of increased temperatures on fish, including effects on proteins, muscle function, cardiovascular performance, reproduction, development and growth, metabolism and increased sensitivity to pollution have been reviewed (Wood & McDonald 1997). Many of the findings must apply in principle to invertebrates as well. In most cases, however, experimental temperatures far exceeded those anticipated by the year 2025 and the rise involved was far more acute.

Effects of temperature rise due to global warming up to 2025 are in general likely to be subtle rather than dramatic. Some redistribution of species may be apparent, animals from the tropics and subtropics tending to invade higher latitudes; the distribution of the clam *Donax* may change, as it appears to be limited by the 5ºC sea-surface isotherm (Brown & McLachlan 1990). However, some distributional contraction may occur, as some regions, such as Western Europe, may become cooler due to the disruption of currents such as the Gulf Stream (IPCC 2001*b*). Changes in temperature regimes may affect the growth rates and breeding seasons of some sandy-shore species. Among the more subtle effects of temperature change are alterations in the speed of burrowing into the sand by invertebrates (McLachlan & Young 1982). However, given the time scale and the relatively small changes in ambient temperature envisaged, we predict compensatory metabolic adaptations to temperature change are likely for most species.

More serious are predicted rises in sea level, due to the melting of polar ice and glaciers. Average sea level rise is predicted to be between 15 and 95 cm by the year 2100 (IPCC 2001*b*), or under 30 cm by 2025. As with temperature changes, this rise will be extremely slow. The mobile, highly adaptable sandy-shore biota will not be at direct risk from it. The most significant threat to them is loss of habitat, especially if sea level rise is accompanied by increased storminess. The observed tendency to beach erosion, which is more common than long-term accretion (see above), will inevitably be enhanced, while beaches on which the sand budget is at present balanced will also suffer erosion and a retreat of the shoreline. Beaches showing long-term accretion (such as Hastings) may well suffer a reversal of this tendency.

We consider it likely that some narrow beaches will disappear completely, while others lacking dune systems will become severely restricted. Sandy-shore ecosystems that currently incorporate extensive dune systems should suffer the least, the habitat remaining essentially unchanged though moving landwards. Erosion may be mitigated by beach nourishment and it is probable that this practice will become more widespread.

Changes in current patterns and the implications of such changes are difficult to determine with accuracy (IPCC 2001*a,b*), but it seems certain that altered patterns will emerge, inevitably changing sand transport and budgets. While most beaches will suffer shoreline retreat, new beaches might form in some areas. Another, related, uncertainty is the effect of global warming on upwelling; at present opinions differ as to whether upwelling will increase, decrease or remain relatively unaffected (J.G. Field, personal communication 2001).

Among the less publicized features of enhanced CO_2 is the prediction that it could lead to increased primary production through its effect on photosynthesis (Melillo *et al.* 1993). Surf-zone diatoms might therefore increase in density and result in enhanced nutritional input to the intertidal beach.

There have recently been significant advances in the development of mitigating scenarios for greenhouse gas emissions, including the costs of mitigation (IPCC 2001*c*). However, even if global greenhouse gas emissions become stabilized, global warming and all its consequences will continue to increase during the present century because of the lag in climate response (Wigley 1995).

Predicted global patterns of change resulting from global warming suffer from a considerable measure of uncertainty. This is especially true for secondary effects such as increased storminess and changes in current patterns, including upwelling (IPCC 2001*b*). At local or regional levels, there is even greater uncertainty and any quantitative projections with regard to specific sandy shores must have a very low level of confidence, to the extent that they could be completely misleading.

Direct human pressures

The best estimate of future global human population growth is 7.1 billion people by the year 2020 (United Nations 1998) and it is predicted that up to 75% of these will live within 60 km of the coast (Roberts & Hawkins 1999). These figures take into account mortality due to the AIDS pandemic and other factors. However, to predict future pressures on sandy shores by multiplying present pressures by the ratio of future coastal populations to existing populations would be extremely naive. One reason for this is the increase in ecotourism, which is economically driven rather than population driven. In developed, and especially in some developing, countries, measures to preserve the coast, including sandy shores, advance continually and are increasingly the result of well-informed legislation. Although often linked to tourism, this is only part of the story, the public becoming increasingly aware of the need for environmental and biological conservation and protection.

Simple measures often bring about dramatically improved results, an example being the construction of wooden walkways across the dunes to beaches (Brown & McLachlan 1990). The dune system is at once protected and this protection continues even if the number of users doubles. A ban on off-road vehicles, if enforced, brings immediate benefit to the biota, and proper environmental impact assessment of new, proposed structures can ensure that the sand budget is not significantly affected. The total exclusion of people from areas frequented by rare or endangered species, including birds, brings the species immediate protection. Such measures are increasingly effected and we anticipate that they will continue to be improved in developed and developing countries, counteracting some of the impact of increasing human pressures.

Measures to reduce pollution must obviously also be taken into account in projecting the state of sandy shores in 2025. More and more countries are moving towards the adoption of the London Dumping Convention and the European Union Directives concerning marine pollution (Figueras *et al.* 1997). It is likely that in the near future the discharge of raw sewage to sea will be banned in all countries aspiring to a measure of socio-economic stability.

In marked contrast to the above, in many relatively under-developed countries, especially in Africa, virtually no measures are taken to protect the environment. More than half the countries in Africa have been involved in civil war in the last few decades, and political instability is the norm rather than the exception. In these circumstances, conservation is hardly ever mentioned and what legislation there might be is not enforced. To make matters worse, sandy shores generally come low down on any list of conservation priorities, long behind rocky shores, as used to be the case in more developed countries. While it is feasible that some of these African countries will have attained a measure of stability over the next quarter century and begin to devote time and energy to conservation matters, in most cases this hope is remote. Exploding population growth, poverty, AIDS, unemployment, economic ills and crises of governance are likely to be the order of the day until at least 2025, even if internal conflicts cease, completely overshadowing environmental concerns.

Ozone depletion and increased UV radiation

Increased UV radiation would have rather less effect on sandy shores than on most other ecosystems, only the biota of the surf zone being at real risk. However, the consensus of scientific opinion is that, thanks to reduction in the emission of aerosols which lead to ozone depletion, further depletion is unlikely, the phenomenon having either peaked or being about to do so (Friedrich & Reis 2000).

CONCLUSIONS AND MANAGEMENT

Conclusions

Sandy shores are dynamic environments for which the overriding process is the action of waves and tides on the available sediment. This and aeolian sand transport higher up the slope determine the physical characteristics of the shore, which in turn determine the constitution of the biota. The ecosystem comprises dunes, beach face and surf zone, with exchanges of material among these three entities. The fauna inhabiting these shores is extremely mobile and adaptable to changing conditions. Figure 5 summarizes the factors impacting sandy shores.

The chief long-term threat to these systems, virtually worldwide, is increasing erosion resulting largely from sea level elevation and increased storminess associated with global warming, the damming of rivers, preventing sediment flow to the sea, and sea walls and other structures that alter sand transport. It is predicted that beach nourishment, as a

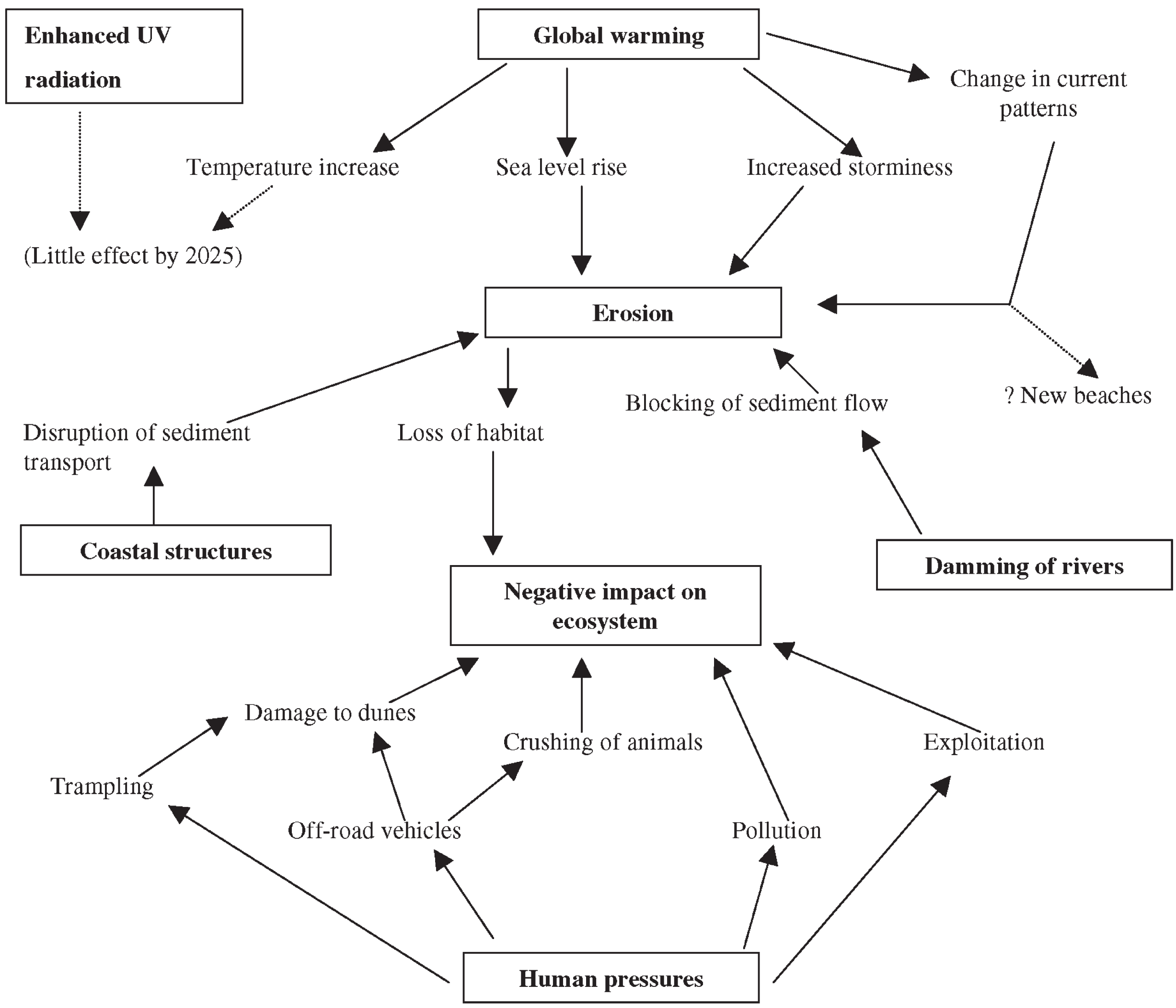

Figure 5 Summary of some factors impacting sandy shores.

means of combating erosion, will be increasingly employed in developed countries, and may significantly influence sandy-shore ecology in the future. Temperature rise by the year 2025 is predicted to have only subtle effects, but projected changes in current patterns may significantly alter sand transport, making erosion more rapid in some instances, but possibly favouring accretion in others.

While human populations near the coast are expected to increase, in some cases dramatically, and ecotourism escalates, increased pressure on sandy shores may well be mitigated by improved legislation and management resulting from a better understanding of sandy-shore processes. Underdeveloped countries, especially in Africa, are expected to lag behind in this regard, with increasing pressures on the ecosystems.

It is not expected that increased UV radiation will have significant effects on the biota.

There is a considerable measure of uncertainty about rates of expected climate change and sea level rise due to global warming (IPCC 2001*b*) and even greater uncertainty with regard to changes in ocean current patterns and increased storminess. Some uncertainty also exists with regard to possible reductions in UV radiation and the effects of increasing human pressure on sandy shores. Added to this is the fact that only for very few beaches are existing parameters quantified satisfactorily. Predictions of impacts by the year 2025 are of necessity both tentative and qualitative.

Management needs

There is a need in many countries for improved legislation with regard to protection of the environment and of the biota. This applies especially to sandy shores, which are often still accorded a low priority or even left out of consideration. In many instances, it is assumed that the only reason for ensuring apparently pristine beaches is to attract tourists and holiday-makers; this attitude must be revised. The protection of rare and endangered species is important in its own right in preserving the integrity of the ecosystem and biodiversity.

Top priority must be given to the avoidance and rejection of structures or activities that may reduce natural sand transport either longshore or up and down the shore. Any impact assessment must clearly take into account projected sea level rise, as well as possibly increased erosion of the shore. The foredunes should be protected as far as possible.

An important counter to erosion is beach nourishment, which is infinitely preferable to the construction of sea walls and other structures. However, in order to protect the biota, beach profiles should be changed as little as possible and every effort should be made to ensure that the new sediment deposited is similar to that occurring naturally.

The construction of groins may be beneficial in some situations, not only to protect the physical beach, but also to provide refuge for certain shorebirds and other threatened species. Such constructs need careful planning and execution and a thorough knowledge of sand transport and budgets in the area is mandatory.

Strict control over routes of access, particularly through the dunes, needs to be enforced universally. Limiting the number of people allowed on the beach may also be beneficial, as may the exclusion of the public from certain areas harbouring threatened species.

Off-road vehicles must be forbidden, except under rare, unavoidable circumstances, such as an attempt to save human life. Beach-cleaning machines should not be employed.

Exploitation of beach animals for food or bait must be strictly controlled, in order to be sustainable, and disallowed in some areas.

Special attention needs to be accorded to threatened species of shorebirds and turtles which come ashore to breed. Total protection of such species needs to be the aim. More reserves need to be created, especially where threatened species are concerned.

Beach managers and would-be developers should always be kept well informed not only about legislation, but also as to why these measures are considered necessary. Such information needs to be provided in simple language and, if possible, in attractive format.

References

Arntz, W.E., Valdivia, E. & Zeballos, J. (1988) Impact of El-Niño 1982-83 on the commercially exploited invertebrates (Mariscos) of the Peruvian shore. *Meeresforshung* **32**: 3–22.

Artukhin, Y.V. (1990) Anthropogenic effects on recreational beaches. In: *Recreational Uses of Coastal Areas*, ed. P. Fabbris, pp. 231–234. Amsterdam, The Netherlands: Kluwer Academic Publications.

Aubrey, D.G. & Emery, K.O. (1993) Recent global sea levels and land levels. In: *Climate and Sea Level Changes: Observations, Projections and Implications*, ed. R.A. Warrick, E.M. Barrow & T.M.L. Wigley, pp. 45–56. Cambridge, UK: Cambridge University Press.

Barnett, P.R.O. (1971) Some changes in intertidal sand communities due to thermal pollution. *Proceedings of the Royal Society of London, Series B* **177**: 353–364.

Barnett, P.R.O. & Hardy, B.L.S. (1969) The effects of temperature on the benthos near the Hunterston generating station, Scotland. *Chesapeake Science* **18**: 255–256.

Bird, E.C.F. (1985) *Coastline Changes: a Global Review*. Chichester, UK: Wiley-Interscience.

Booth, C.R. & Morrow, J.H. (1997) The penetration of UV into natural waters. *Photochemistry and Photobiology* **65**: 254–257.

Botton, M.L., Loveland, R.E. & Jacobsen, T.R. (1994) Site selection by migratory shorebirds in Delaware Bay, and its relationship to beach characteristics and abundance of Horseshoe Crab (*Limulus polyphemus*) eggs. *Auk* **111**: 605–616.

Browman, H.I., Rodriguez, C.A., Beland, F., Cullen, J.J., Davis, R.F., Kouwenberg, J.H.M., Kuhn, P.S., McArthur, B., Runge, J.A., St-Pierre, J.F. & Vetter, R.D. (2000) Impact of ultraviolet radiation on marine crustacean zooplankton and ichthyoplankton: a synthesis of results from the estuary and Gulf of St Lawrence, Canada. *Marine Ecology Progress Series* **199**: 281–311.

Brown, A.C. (1983) The ecophysiology of sandy-beach animals – a partial review. In: *Sandy Beaches as Ecosystems*, ed. A. McLachlan & T. Erasmus, pp. 575–605. The Hague, the Netherlands: W. Junk.

Brown, A.C. (1985) *The Effects Of Crude Oil Pollution On Marine Organisms*. Pretoria, South Africa: South African National Scientific Programmes Report No. 99.

Brown, A.C. (1994) Plutonium and marine life. *Transactions of the Royal Society of South Africa* **49**: 213–224.

Brown, A.C. (1996) Behavioural plasticity as a key factor in the survival and evolution of the macrofauna on exposed sandy beaches. *Revista Chilena de Historia Natural* **69**: 469–474.

Brown, A.C. (2000) Is the sandy-beach isopod *Tylos granulatus* an endangered species? *South African Journal of Science* **96**: 466.

Brown, A.C. (2001) Biology of sandy beaches. In: *Encyclopedia of Ocean Sciences, Volume 5*, ed. J.H. Steele, S.A. Thorpe & K.K. Turekian, pp. 2496–2504. London, UK: Academic Press.

Brown, A.C. & McLachlan, A. (1990) *Ecology of Sandy Shores*. Amsterdam, the Netherlands: Elsevier.

Brown, A.C., Davies, B.R., Day, J.A. & Gardiner, A.J.C. (1991*a*) Chemical pollution loading of False Bay. *Transactions of the Royal Society of South Africa* **47**: 703–716.

Brown, A.C. McLachlan, A., Kerley, G.I.H. & Lubke, R.A. (2000) Functional ecosystems: sandy beaches and dunes. In: *Summary Marine Biodiversity Status Report for South Africa*, ed. B.D. Durham & J.C. Pauw, pp. 4–5. Pretoria, South Africa: National Research Foundation.

Brown, A.C., Wynberg, R.P. & Harris, S.A. (1991*b*) Ecology of shores of mixed rock and sand in False Bay. *Transactions of the Royal Society of South Africa* **47**: 563–573.

Burger, J. (1991) Foraging behaviour and the effects of human disturbance on the Piping Plover (*Charadrius melodus*). *Journal of Coastal Research* **7**: 39–52.

Burger, J. & Gochfeld, M. (1991) Human activity influence and diurnal and nocturnal foraging of Sanderlings (*Calidris alba*). *Condor* **93**: 259–265.

Burger, J., Gochfeld, M. & Niles, L.J. (1995) Ecotourism and birds in coastal New Jersey: contrasting reponses of birds, tourists and managers. *Environmental Conservation* **22**: 56–65.

Camp, C.R. (1989) Oil in the marine environment. In: *Marine Pollution – a 1988 Perspective*, ed. A.G.S. Moldan & J.H. Richter, pp. 63–65. Pretoria, South Africa: CSIR, South African National Scientific Programmes Report No. 161.

Carter, R.W.G. (1975) The effect of human pressures on the coastlines of County Londonderry and County Antrim. *Irish Geography* **5**: 72–85.

Clark, J.R. (1983) *Coastal Ecosystem Management*. Malabar, Florida, USA: R.E. Krieger Publishing Co.: 928 pp.

Defeo, O. (1996) Experimental management of an exploited sandy beach bivalve population. *Revista Chilena de Historia Natural* **69**: 605–614.

Dicks, B. & Hartley, J.P. (1982) The effects of repeated small oil spillages and chronic discharges. *Philosophical Transactions of the Royal Society of London, Series B* **297**: 285–307.

Figueras, M.J., Polo, F., Inza, I. & Guarro, J. (1997) Past, present and future perspectives of the EU bathing water directive. *Marine Pollution Bulletin* **34**: 148–156.

Finkl, C.W. (1996) What might happen to America's shoreline if artificial beach replenishment is curtailed: a prognosis for southeastern Florida and other sandy regions along regressive coasts. *Journal of Coastal Research* **12**: iii–ix.

Fishelson, L. (1983) Population ecology and biology of *Dotilla sulcata* (Crustacea, Ocypodidae) on sandy beaches of the Red Sea. In: *Sandy Beaches as Ecosystems*, ed. A.McLachlan & T. Erasmus, pp. 643–654. The Hague, the Netherlands: W. Junk.

Friedrich, R. & Reis, S. (2000) *Tropospheric Ozone Abatement*. Berlin, Germany: Springer-Verlag.

Gibbs, R.J., Matthews, M.D. & Link, D.A. (1971) The relationship between sphere size and settling velocity. *Journal of Sedimentary Petrology* **41**: 7–18.

Gourlay, M. (1968) Beach and dune erosion tests. Delft Hydraulics Laboratory Report No. M935/M936, the Netherlands.

Gowen, R.J., Mills, D.K. Trimmer, M. & Nedwell, D.B. (2000) Production and its fate in two coastal regions of the Irish Sea: the influence of anthropogenic nutrients. *Marine Ecology Progress Series* **208**: 51–64

Griffiths, C.L., Stenton-Dozey, J.M.E. & Koop, K. (1983) Kelp wrack and energy flow through a sandy beach. In: *Sandy Beaches as Ecosystems*, ed. A. McLachlan & T. Erasmus, pp. 547–556. The Hague, the Netherlands: W. Junk.

Gustavson, K., Garde, K., Wangberg, S.-A. & Selmer, J.-S. (2000) Influence of UV-B radiation on bacterial activity in coastal waters. *Journal of Plankton Research* **22**: 1501–1511.

Hader, D.P. (1997) Effects of UV radiation on phytoplankton. In: *Advances in Microbial Ecology*, ed. J.G. Jones, pp. 1–26. New York, USA: Plenum Press.

Hegge, B., Elliot, I. & Hsu, J. (1996) Sheltered sandy beaches of southwestern Australia. *Journal of Coastal Research* **12**: 748–760.

Hill, B.J. (1977) The effect of heated effluent on egg production in the estuarine prawn *Upogebia africana* (Ortmann). *Journal of Experimental Marine Biology and Ecology* **29**: 291–302.

Hosier, P.E., Kochhar, M. & Thayer, V. (1981) Off-road vehicle and pedestrian track effects on the sea-approach of hatchling Loggerhead Turtles. *Environmental Conservation* **8**: 158–161.

IPCC (1990) *Climate Change: the IPCC Scientific Assessment*, ed. J.T. Houghton, G.J. Jenkins & J.J. Ephraums. Cambridge, UK: Cambridge University Press.

IPCC (1992) *Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment*, ed. J.T. Houghton, B.A. Callander & S.K. Varney. Cambridge, UK: Cambridge University Press.

IPCC (1996*a*) *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. R.T. Watson, M.C. Zinoyowera & R.H. Moss. Cambridge, UK: Cambridge University Press.

IPCC (1996*b*) *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J.T. Houghton, L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, N. Harris, A. Kattenberg & K. Maskell. Cambridge, UK: Cambridge University Press.

IPCC (2001*a*) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J.T. Houghton, Y. Ding, D.J. Griggs, M. Nogeur, P.J. van der Linden & D. Xiaosu. Cambridge, UK: Cambridge University Press.

IPCC (2001*b*) *Climate Change 2001: Impacts, Adaptations and Vulnerability. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J. J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken & K.S. White. Cambridge, UK: Cambridge University Press.

IPCC (2001*c*) *Climate Change 2001: Mitigation. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. B. Metz, O. Davidson, R. Swart & J. Pan. Cambridge, UK: Cambridge University Press.

Jaramillo, E., Contreras, H. & Quijon, P. (1996) Macroinfauna and human disturbance in a sandy beach of south-central Chile. *Revista Chilena de Historia Natural* **69**: 655–663

Komar, P.D. (1983*a*) Coastal erosion in response to the construction of jetties and breakwaters. In: *Handbook of Coastal Processes and Erosion*, ed. P.D. Komar. Boca Raton, Florida, USA: CRC Press.

Komar, P.D. (1983*b*) The erosion of Siletz Spit, Oregon. In: *Handbook of Coastal Processes and Erosion*, ed. P.D. Komar. Boca Raton, Florida, USA: CRC Press.

Kraus, N.C. & McDougal, W.G. (1996) The effects of seawalls on the beach: Part 1, an updated literature review. *Journal of Coastal Research* **12**: 691–701.

Kyle, R., Robertson, W.D. & Binnie, S.L. (1997) Subsistence shellfish harvesting in the Maputaland Reserve in northern KwaZulu-Natal, South Africa: sandy beach organisms. *Biological Conservation* **82**: 173–182.

Leonard, L., Clayton, T. & Pilkey, O. (1990) An analysis of replenished beaches design parameters on US east coast barrier islands. *Journal of Coastal Research* **6**: 1057–1068.

Liddle, M.J. & Moore, K.G. (1974) The microclimate of sand dune tracks: the relative contribution of vegetation removal and soil compression. *Journal of Applied Ecology* **12**: 1057–1068.

Little, C. (2000) *The Biology of Soft Shores and Estuaries*. Oxford, UK: Oxford University Press.

Llewellyn, P.J. & Shackley, S.E. (1996) The effects of mechanical beach-cleaning on invertebrate populations. *British Wildlife* **7**:147–155

Markowski, S. (1959) The cooling water of power stations, a new factor in the environment of marine and freshwater invertebrates. *Journal of Animal Ecology* **28**: 243–259.

Masselink, G. & Short, A.D. (1993) The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. *Journal of Coastal Research* **9**: 785–800.

McKay, W.A., Johnson, C.E. & Branson, J.R. (1986) Environmental radioactivity in Caithness and Sutherland. Part 3: initial measurements and modelling in inshore waters. *Nuclear Energy* **27**: 321–335.

McLachlan, A. (1980) Exposed sandy beaches as semi-closed ecosystems. *Marine Environmental Research* **4**: 59–63.

McLachlan, A. (1983) Sandy beach ecology – a review. In: *Sandy Beaches as Ecosystems*, ed. A. McLachlan & T. Erasmus, pp. 321–380. The Hague, the Netherlands: W. Junk.

McLachlan, A. (1996) Physical factors in benthic ecology; effects of changing sand particle size on beach fauna. *Marine Ecology Progress Series* **131**: 205–217

McLachlan, A. & Harty, B. (1981*a*) Effects of oil on water filtration by exposed sandy beaches. *Marine Pollution Bulletin* **12**: 374–378.

McLachlan, A. & Harty, B. (1981*b*) Effects of crude oil pollution on the supralittoral meiofauna of a sandy beach. *Marine Environmental Research* **7**: 71–80.

McLachlan, A. & Young, N. (1982) Effects of low temperatures on the burrowing rates of four sandy beach molluscs. *Journal of Experimental Marine Biology and Ecology* **65**: 275–284.

McLachlan, A., Dugan, J.E., Defeo, O., Ansell, A.D., Hubbard, D.M., Jaramillo, E. & Penchaszadeh, P. (1996) Beach clam fisheries. *Oceanography and Marine Biology, an Annual Review* **34**: 163–232.

Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore, B., Vorosmarty, C.J. & Schloss, A.L. (1993) Global climate change and terrestrial net primary production. *Nature* (London) **363**: 234–240.

Miles, J.R., Russell, P.E. & Huntley, D.A. (2001) Field measurements of sediment dynamics in front of a seawall. *Journal of Coastal Research* **17**: 195–206.

Moffet, M.D., McLachlan, A., Winter, P.E.D. & de Rouyok, A.M.C. (1996) Impact of trampling on sandy beach fauna. *Journal of Coastal Conservation* **4**: 87–90.

Moore, S.L., Gregorio, D. & Carreon, M. (2001) Composition and distribution of beach debris in Orange County, California. *Marine Pollution Bulletin* **42**: 241–245.

Nauman, J. & Cory, R.L. (1969) Thermal additions and epifaunal organisms at Chalk Point, Maryland. *Chesapeake Science* **18**: 218–226.

Naylor, E. (1965) Effects of heated effluents upon marine and estuarine organisms. *Advances in Marine Biology* **3**: 63–103.

Norton, M.G. & Franklin, F.L. (1980) Research into toxicity evaluation and control criteria of oil dispersants. Fisheries Research Technical Reports, Lowestoft, UK, No. 57: 20 pp.

Peterson, C.H., Hickerson, D.H.M & Johnson, G.G. (2000) Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *Journal of Coastal Research* **16**: 368–378.

Potts, M. (2000) The unmet need for family planning. *Scientific American* **282**: 75–77.

Rakocinski, C.F., Heard, R.W. & LeCroy, S.E. (1996) Responses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, USA. *Journal of Coastal Research* **12**: 326–353.

Ranwell, D.S. (1972) *Ecology Of Salt Marshes And Sand Dunes*. London, UK: Chapman and Hall: 258 pp.

Roberts, C.M. & Hawkins, J.P. (1999) Extinction risk in the sea. *Trends in Ecology and Evolution* **14**: 241–246.

Short, A.D. (1993*a*) *Beaches Of The New South Wales Coast, A Guide To Their Nature, Characteristics, Surf And Safety*. Sidney, Australia: Australian Beach Safety and Management Program, University Printing Service, University of Sydney: 358 pages.

Short, A.D., ed. (1993*b*) *Beach and Surf Zone Morphodynamics. Journal of Coastal Research, Special Issue No. 15*. Lawrence, USA: Coastal Eduction & Research Foundation: 231 pp.

Short, A.D. (1996) The role of wave height, period, slope, tide range and embaymentisation in beach classification: a review. *Revista Chilena de Historia Natural* **69**: 589–604.

Short, A.D. & Hesp, P.A. (1982) Wave, beach and dune interactions in southeastern Australia. *Marine Geology* **48**: 259–284.

Siegel, P.R. & Wenner, A.M. (1984) Abnormal reproduction of the sand crab *Emerita analoga* in the vicinity of a nuclear generating station in Southern California. *Marine Biology* **80**: 341–345.

Southward, A.J. (1982) An ecologist's view of the implications of the observed physiological and biochemical effects of petroleum compounds on marine organisms and ecosystems. *Philosophical Transactions of the Royal Society of London, Series B* **297**: 241–255.

Swart, D.H. & Reyneke, P.G. (1988) The role of driftsands at Waenhuiskrans, South Africa. In: *Journal of Coastal Research, Special Issue No. 3*, ed. C.W. Finkl, Jr, pp. 97–102. Lawrence, USA: Coastal Education & Reaearch Foundation

Tarazona, J. & Parendes, C. (1992) Impacto de les eventos El–Niño sobre las commundades bentonicas de playa arenosa durante 1976-1986. Paleo ENSO Records International Symposium, Lima, Extended Abstracts, pp. 299–303.

Tarazona, J., Arntz, W., Canahuire, E., Ayala, Z. & Robles, A. (1985) Modificacion producidas durante 'El-Niño' en la infauna bentonica de areas someras del ecosistema de afloriamento peruano. In: *El-Jernomeno El-Niño y su Impacto en la Fauna*

Marina, ed. W. Arntz, A. Landa & J. Tarazona, pp. 55–63. Callao, Peru: Bolletin Instituto del Mardel, Special Issue 1985.

Tarazona, J., Salzwedel, H. & Arntz, W. (1988) Oscillations of macrobenthos in shallow waters of the Peruvian central coast induced by the El-Niño 1982-83. *Journal of Marine Research* **46**: 593–611.

Thomas, M.L.H. (1978) A comparison of oiled and unoiled intertidal communities in Chedabucto Bay, Nova Scotia. *Journal of the Fisheries Research Board of Canada* **35**: 707–716.

Tinley, K.L. (1985) *Coastal Dunes of South Africa*. Pretoria, South Africa: CSIR, South African National Scientific Programmes Report No. 109: 300 pp.

Uchiyama, Y., Nadaoka, K., Rolke, P., Adachi, K. & Yagi, H. (2000) Submarine groundwater discharge into the sea and associated nutrient transport in a sandy beach. *Water Resources Research* **36**:1467–1479.

United Nations (1998) *World Population Prospects: the 1998 Revision, Volume 1*. New York, USA: United Nations Secretariat, Department of Economic and Social Affairs, Population Division: 614 pp.

Van der Merwe, D. (1988) The effects of off-road vehicles (ORVs) on coastal ecosystems – a review. Institute for Coastal Research, University of Port Elizabeth, Port Elizabeth, South Africa: 64 pp.

Van der Merwe, D. & Van der Merwe, D. (1991) Effects of off-road vehicles on the macrofauna of a sandy beach. *South African Journal of Science* **87**: 210–213.

Wigley, T.M.L. (1995) Global-mean temperature and sea level consequences of greenhouse gas stabilization. *Geophysical Research Letters* **22**: 45–48.

Wolcott, T.G. & Wolcott, D.L. (1984) Impact of off-road vehicles on macroinvertebrates of a mid-Atlantic beach. *Biological Conservation* **29**: 217–240.

Wood, C.M. & McDonald, D.G., eds. (1997) *Global Warming: Implications for Freshwater and Marine Fish*. Cambridge, UK: Cambridge University Press: 425 pp.

World Resources Institute (1998) *World Resources 1998–1999*. New York, USA: World Resource Institute, Oxford University Press.

Wright, L.D. & Short, A.D. (1984) Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology* **58**: 93–118.

Wubben, D.L. (2000) UV-induced mortality of zoea I larvae of brown shrimp *Crangon crangon* (Linnaeus, 1758). *Journal of Plankton Research* **22**: 2095–2104.

Wynberg, R.P. & Branch, G.M. (1997) Trampling associated with bait-collection for sandprawns *Callianassa kraussi* Stebbing: effects on the biota of an intertidal sandflat. *Environmental Conservation* **24**: 139–148.