0067932

Marine Ecology. ISSN 0173-9565

ORIGINAL ARTICLE

Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts

Thomas A. Schlacher[1], Dave S. Schoeman[2], Jenifer Dugan[3], Mariano Lastra[4], Alan Jones[5], Felicita Scapini[6] & Anton McLachlan[7]

1 Faculty of Science, Health and Education, University of the Sunshine Coast, Maroochydore DC, Qld, Australia
2 School of Biological and Conservation Sciences, University of KwaZulu-Natal, Durban, South Africa
3 Marine Science Institute, University of California, Santa Barbara, CA, USA
4 Departamento de Ecologia y Biologia Animal, Universidad de Vigo, Vigo, Spain
5 Marine Ecology, Australian Museum Sydney, Sydney, NSW, Australia
6 Dipartimento di Biologia Animale e Genetica, Universita di Firenze, Firenze, Italy
7 College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Oman

Keywords
Climate change; coastal conservation; coastal management; macrobenthos sampling; sandy shores.

Correspondence
Thomas A. Schlacher, Faculty of Science, Health and Education, University of the Sunshine Coast, Maroochydore DC, Qld 4558, Australia.
E-mail: tschlach@usc.edu.au

Conflict of interest
The authors declare no conflict of interests.

Abstract

Escalating pressures caused by the combined effects of population growth, demographic shifts, economic development and global climate change pose unprecedented threats to sandy beach ecosystems worldwide. Conservation of beaches as functional ecosystems and protection of their unique biodiversity requires management interventions that not only mitigate threats to physical properties of sandy shores, but also include ecological dimensions. Yet, beach management remains overwhelmingly focused on engineering interventions. Here we summarise the key outcomes of several workshops, held during the 2006 Sandy Beach Ecology Symposium in Vigo, Spain, that addressed issues of climate change, beach management and sampling methodology. Because efficient communication between managers and ecologists is critical, we summarise the salient features of sandy beaches as functional ecosystems in 50 'key statements'; these provide a succinct synopsis of the main structural and functional characteristics of these highly dynamic systems. Key outcomes of the workshops include a set of recommendations on designs and methods for sampling the benthic infaunal communities of beaches, the identification of the main ecological effects caused by direct and indirect human interventions, the predicted consequence of climate change for beach ecosystems, and priority areas for future research.

Problem

Coastal zones contain diverse and productive habitats important for human settlements, development and local subsistence. More than half the world's population lives within 60 km of the shoreline, and this could rise to three quarters by the year 2020 (UNCED 1992). This population surge in the narrow coastal strip, coupled with economic progress and development, extraction of resources, and increasing demands for recreational opportunities, is the ultimate driver for escalating pressures on the world's ocean shores, which are dominated by sandy beaches. Thus, much of existing and future human pressures on global ecosystems are directed at sandy beaches.

Beaches are already under threat from a wide range of human activities and this will increase in the 21st century (Figs 1–3; Brown & McLachlan 2002; Schlacher *et al.* 2006, 2007a). In addition to direct anthropogenic impacts on beaches, global climate change is predicted to have dramatic, widespread and long-lasting consequences for

© 2008 The Authors. Journal compilation © 2008 Blackwell Publishing Ltd

0067933

Fig. 1. Environmental values of sandy beaches. a: sandy shores dominate the open coastlines of the world's oceans (a – Eastern Australia, b – Tonga); c,d: beaches provide habitat to unique suites of invertebrates (c – talidrid amphipods, *Megalorchestia* spp., California) and nesting sites for endangered birds and turtles (d – killdeer chick, *Charadrius vociferous,* California); e: sandy coastlines are hotspots for coastal development (e – Eastern Australia); f,g,h: beaches are prime sites for tourism and human recreation (f – New Zealand, g – Eastern Australia), including recreational fishing (h – South Africa). Photo credits: Thomas Schlacher (a,b,e,f,g), Dave Hubbard (c,d) and Anton McLachlan (h).

the world's marine ecosystems, particularly when coastlines are retreating inland in response to rising sea levels (Feagin *et al.* 2005; Harley *et al.* 2006). Thus, management and conservation of the unique ecological features and processes of beaches have become critical and pressing issues.

Many current and future conservation and mitigation measures on sandy shores require active management of threats. Yet, management of beaches has traditionally focused almost exclusively on maintaining and restoring physical and geomorphological features important for coastal defence (Fig. 3) – ecological aspects are rarely considered (James 2000b; Micallef & Williams 2002). There may be several reasons for this state of affairs: (i) the Cinderella status of beach conservation may partly arise from the lower public profile that ecological aspects of beaches enjoy compared with other iconic marine ecosystems such as coral reefs; this is highly paradoxical as more people use beaches than any other type of shore - but they seldom appreciate their ecological features; (ii) in many situations, there are critical gaps in basic ecological information required for conservation planning on beaches; and (iii) coastal managers are generally not sufficiently engaged with ecologists (and vice versa), and beach management consequently lacks ecological dimensions. Also, because defensible and efficient management interventions must be underpinned by robust scientific data, it is important to standardise scientific methods as far as possible.

This paper reports on the outcomes of three workshops, held during the 2006 Sandy Beach Ecology Symposium in Vigo, Spain, that addressed several of the above issues.

0067934

Fig. 2. Impacts of recreational activities, beach cleaning and erosion issues. a: human trampling destroys the sensitive vegetation of foredunes (Eastern Australia); b,c: use of off-road vehicles is generally not compatible with conservation of ecological features of beaches and can kill invertebrates (b – California, c – Eastern Australia, d – ghost crab *Ocypode ceratophthalma* crushed by 4WD vehicle, Eastern Australia); e: beach raking removes organic material that normally supports invertebrate consumers and may slow formation of embryo dunes (Eastern Australia); f,g,h: high seas (f) causing beach erosion (h) compounded by human modifications (g) of natural dune systems (f – South Africa, g – California, h – Eastern Australia). Photo credits: Thomas Schlacher (a,c,d,e,h), Jenny Dugan (b,g) and Department of Agriculture & Environmental Affairs, KwaZulu-Nata, South Africa (f).

These workshops were convened by Mariano Lastra and chaired by Alan Jones (Climate Change), Dave Schoeman (Methods) and Thomas Schlacher (Management). To facilitate communication between beach managers and ecologists, we summarise the salient features of sandy beaches as functional ecosystems in 50 ‘key statements’; these present the shared views of all authors of this paper and provide a succinct synopsis of the main structural and functional characteristics of these highly dynamic ecosystems.

Structure and Function of Sandy Beach Ecosystems

Coastal managers may not have access to the specialised ecological literature on sandy beaches. Therefore, a concise synopsis of the main physical and ecological attributes of beaches, one that also includes the principal management implications for the conservation of their ecological features, is considered a practical tool. To this end, the following statements summarise the key features of sandy beach ecosystems globally; further information can be found in McLachlan & Brown (2006) and Defeo & McLachlan (2005).

Physical features

1 Sandy beaches worldwide are defined by their sand, wave and tide regimes.

2 Beaches range from narrow and steep (reflective) to wide and flat (dissipative), as sand becomes finer and waves and tides larger; most beaches are intermediate between these extremes.

0067935

Fig. 3. Beach erosion threatening human infrastructure, management responses to shoreline instability and oil pollution. a: buildings located in ecologically sensitive dune areas and located too close to dynamic shoreline position (Eastern Australia); b–d: shoreline erosion can destroy (b – SW-France) or severely threaten (c – South Africa, d – California) the viability of human infrastructure on sandy coasts; e–g: human interventions to combat shoreline erosion include ecologically harmful engineering solutions such as seawalls (e,f – California) and beach nourishment (g – California); h: oil spills can have dramatic ecological effects on sandy shores (h – Galicia, Spain after the sinking of the 'Prestige' in 2002). Photo credits: Thomas Schlacher (a), Jenny Dugan (d,e,f,g), Mariano Lastra (b,h) and Department of Agriculture & Environmental Affairs, KwaZulu-Nata, South Africa (c).

3 Sand particle size is determined by the geological source and subsequent sorting by waves and currents.
4 Narrow and steep reflective beaches are more prevalent in the tropics, whereas flat and wide dissipative beaches are more common in temperate regions.
5 Dissipative beaches are erosional, whereas reflective beaches are accretional.
6 Large volumes of seawater are flushed through the porous sands of ocean beaches.
7 Filtration volumes are higher on reflective beaches, mainly driven by wave action and lower on dissipative beaches where tidal action drives water throughput.
8 The sand body of most beaches is well flushed and oxygenated; only under conditions of fine sand and low water throughput, can stagnant conditions develop in deeper layers.
9 Beaches are closely linked to nearshore surf zones and coastal dunes through the storage, transport and exchange of sand.
10 Sand transport is the highest in exposed surf zones and sand storage often the greatest in well-developed dunes.

Ecology

11 Sandy beaches generally lack attached plants in the intertidal zone.
12 Abundant phytoplankton composed of uniquely adapted species is common in dissipative surf zones where it forms an important component of the food webs.

0067936

13 The intertidal areas of beaches are not marine deserts but provide habitat for a wealth of animals buried beneath the sand surface.

14 The porous sand body harbours small interstitial organisms (bacteria, protozoans and small metazoans) forming a distinct food web.

15 Larger invertebrates of the sandy beach include polychaete worms, clams, whelks and crustaceans, which can be scavengers, predators, filter- or deposit feeders.

16 Beach species include marine forms below the drift line and air-breathing forms around and above the drift line.

17 Most species typical of beaches are found in no other environment.

18 Key adaptations of invertebrates on sandy beaches are: mobility, burrowing ability, rhythmic (*e.g.* tidal, circadian, semilunar, lunar, seasonal) behaviour, orientation mechanisms and flexibility to cope with rapidly changing conditions.

19 Intertidal swash and sand conditions are most variable and dynamic on microtidal reflective beaches.

20 The composition and abundance of invertebrate assemblages are controlled primarily by the physical environment; reflective beaches support low diversity and abundance, whereas these increase under dissipative conditions.

21 More species can colonise physically benign dissipative beaches, but fewer, mainly robust crustaceans, can establish populations in the harsh conditions on reflective beaches.

22 The effects of biological interactions (*e.g.* competition, predation) are often overshadowed by physical factors on reflective beaches, but can become more influential on dissipative beaches.

23 For any morphodynamic type, tropical beaches are more species rich, whereas temperate beaches tend to support higher abundance and biomass.

24 The fauna of the lower beach may extend their distribution seawards into the surf zone; outside the surf zone, the seabed becomes more stable and a distinct fauna appears.

25 Sandy beach species can have wide geographic ranges across which they respond to latitudinal environmental gradients.

26 Beaches that receive inputs of drift algae, plants and animal carcasses support a variety of unique air-breathing crustaceans and insects.

27 Populations can be isolated amongst beaches and connectivity between beaches occurs through the dispersal of mobile individuals and planktonic larvae.

28 Planktonic linkages between beaches may be crucial in situations where rich populations on dissipative beaches seed more sparse populations on distant reflective beaches.

29 Sandy beach surf zones can support rich zooplankton, particularly shrimps and prawns.

30 Sandy beach surf zones serve as important nursery and foraging areas for fishes.

31 Beaches are important nesting areas for marine turtles and shorebirds.

Beaches as ecosystems

32 Top consumers in sandy beach food webs are fish and birds: beaches are critical foraging areas for higher vertebrates of both commercial importance (finfish) and conservation significance (birds).

33 Food webs of sandy beaches are based on marine sources such as phytoplankton, stranded algae and plants, and carrion.

34 Beach ecosystems are important in processing large quantities of organic material and recycling nutrients back to coastal waters.

35 The porous sand body plays a key role as a great digestive and incubating system that filters water, mineralises organic matter and recycles the nutrients.

36 The high productivity of dissipative systems is tightly linked to rich surf-zone phytoplankton and microorganisms.

37 Beaches interact closely with coastal dunes both physically and biologically.

38 Beaches link terrestrial aquifers with coastal waters through the discharge of groundwater rich in nutrients.

Beach management

39 Sandy coasts are severely impacted by human activity, both directly and indirectly; beaches are squeezed between rising sea level on the marine side and expanding human populations and development on the landward side.

40 Sandy beaches have great socio-economic value as recreational resources and are key components of many tourist destinations.

41 Some dissipative beaches have huge bivalve populations that support commercial and artisanal/recreational fisheries.

42 Sandy coasts, including surf zones, beaches and dunes, must be managed as functional units.

43 Intertidal beaches and surf zones are little disturbed by moderate recreational activity, but are impacted by off-road vehicles, grooming and other intense forms of use.

44 Beaches are susceptible to pollution that impacts the water filtration and purification process.

0067937

45 Sheltered beaches are generally more sensitive to pollution than exposed beaches.

46 Foredunes are highly susceptible to damage; even low-intensity recreational activities disturb their fragile vegetation and nesting animal species.

47 Extensive dissipative beaches are often backed by large dune systems and are important repositories for sandy beach and dune biodiversity.

48 All elements of sandy coasts, from the dunes to the surf zone, are susceptible to the impacts of major engineering structures that affect sand storage and transport.

49 Conservation strategies must embrace all beach types to adequately represent a full range of unique beach elements and processes.

50 Beach management must incorporate conservation of critical ecological features and processes in addition to sand budgets.

Sampling Methodology: Standardising Sampling Designs for Quantifying the Community Structure of Infaunal Macrobenthos on Ocean-exposed Sandy Beaches

Introduction

Ocean-exposed sandy beaches are dynamic and variable environments, displaying a high degree of temporal and spatial heterogeneity at various scales. As a result, the macrobenthos tend to be patchily distributed, with dense aggregations (patches or bands) interspersed among areas of low abundance or uninhabited sand. This patchiness, coupled with the small size of most beach fauna, and their rapid burrowing, introduces considerable difficulties when designing sampling programmes to study intertidal community ecology.

Collection of samples is relatively simple; it generally involves little more than excavating sediment from the intertidal and sieving it in the swash to separate organisms from the sand. In contrast, sampling design (*i.e.* how these samples are to be distributed across the sampling universe) is more complicated, and more often is structured according to the experiences and conventions of the sampling team than based on theoretical principles or standardised approaches. Nevertheless, there are obvious advantages to good sampling designs and standardising techniques. A main benefit is that results of different research teams are better comparable, which is an essential goal, if beach ecologists are to answer 'big' questions in their field.

Here, we report on the outcomes of the workshop on field-sampling designs and collection protocols for ecological benthos research on ocean-exposed sandy beaches. This workshop aimed to achieve consensus on methods and terminology. A full consensus was, however, not always possible amongst all participants, who work in contrasting settings, each with their own physical challenges. What emerged was a code of 'best practice' for sampling strategies designed primarily to characterise macroinfaunal community structure (*i.e.* abundance, biomass, diversity, species composition).

It must be stressed that the recommendations put forward here are a compromise between basic statistical requirements and the logistical constraints of field operations. As such, they are guidelines and not absolute rules; there will be circumstances under which these recommendations are impractical. For example, impact assessments, as well as population and behavioural studies require specialised designs, which were not covered in this workshop. Also, where long-term data sets have followed non-standard approaches, advantages associated with preserving the integrity of the time series might take precedence over compliance with a new strategy. Despite such constraints, beach ecologists are strongly encouraged to follow the recommendations provided below as far as possible.

General sampling issues

1.1. Definition of a sampling unit

There is no single, conventionally accepted definition of a sampling unit in marine benthos research. In some cases, a sampling unit is a single quadrat, core or grab, each of which has clearly defined spatial limits; in others, it is a haul or trawl, which is less clearly defined spatially. The only real aspect of uniformity is that, ideally, replicates of the sampling unit should be distributed randomly throughout the sampling area (sampling universe), if that is logistically feasible. Randomisation is a critical requirement that allows sample statistics to be representative in terms of the actual community characteristics present and that minimises bias.

Community structure on ocean-exposed sandy beaches is spatially highly variable in two dimensions: along the beach (parallel to the shoreline) and across the beachface (from the dunes to the swash). At local scales, this spatial variation is most pronounced across the environmental gradient from the dunes to the swash, but is often less predictable along the shore. To quantify sources of variability in community descriptors along environmental axes, other disciplines often use stratified-random sampling designs. This approach is, however, often considered impractical on beaches because across-shore strata can usually not be readily defined *a priori.* Instead, sandy beach ecologists have traditionally used an alternative strategy by taking a sequence of samples arranged at uniform intervals along a line running parallel to the across-shore gradient. This design covers the entire intertidal. Such designs are described in the statistical literature as being systematic as opposed to randomised. The assumption here is that, provided enough across-shore levels are sampled, each of the likely across-shore 'niches' present on the gradient (and which should, therefore, have been reflected by strata, if a stratified random approach had been taken) will be represented in the pool of across-shore samples. Such lines of systematically placed samples are conventionally termed transects.

Definition: Transect
In sandy-beach ecology, transects are shore-normal lines of samples that usually run from a point at least as high as the drift line downshore to a point near the low-water mark or lower. Along each transect, samples (biological, environmental, or both) are taken at several systematically arranged levels of the intertidal slope.

It should be noted that systematic transect-sampling designs result in spatial autocorrelation among the individual samples (*i.e.* cores, quadrats, or the like) that comprise the transect. This autocorrelation means that individual samples are statistically non-independent and, therefore, cannot be treated as replicates. For these reasons, data obtained from an individual transect are routinely pooled, thereby integrating the across-shore variability and providing a point estimate (a single value, without confidence intervals). Such a pool of samples combined across the different levels of a transect line can, therefore, be viewed as the elementary sampling unit in macrobenthos community research on sandy beaches. This sampling unit provides information for a single, short stretch of beach only. Consequently, to estimate along-shore variability, these sampling units (across-shore transects) must be appropriately replicated.

It is unfortunate that no consistent terminology for such a pool of samples has emerged from the sandy beach literature. For instance, if, at each intertidal level of a transect, three quadrats have been positioned at 1-m intervals along the shore, one fieldworker might correctly refer to this design as a single transect with repeated samples at each level, while another might equally correctly refer to it as three individual transects spaced 1 m apart. Irrespective of the differences in description, because the uniform (systematic) distribution of samples means that observations are not mutually independent, and that data will therefore routinely have to be pooled, both researchers are referring to a sampling unit. To eliminate further confusion associated with the term 'transect' we propose the term 'sampling station' as a more appropriate descriptive name for a point on a beach at which across-shore samples are collected.

Definition: Sampling Station
In sandy-beach ecology, a sampling station is a short (no more than a few metres wide), along-shore stretch of beach from which samples are drawn with the express aim of describing features of that stretch of beach only. These samples could comprise one or more across-shore transects; alternatively, some other sampling design could be employed in an attempt to more explicitly capture information about the along- and/or across-shore variability.

It is important to note that transects (as defined above) are not the most efficient method of expending sampling effort across the shore. For example, instead of arranging the multiple (three or more) samples at each across-shore level of a transect systematically, their positions could be randomised. The advantage here is that if this design can be repeated at several sampling stations, hypotheses regarding differences among sampling stations may be investigated using a two-way (sampling station x intertidal level) mixed-effects ANOVA (or linear mixed models). A similar situation arises, if the intertidal levels are designated in both across- and along-shore dimensions and the positions of samples are randomised along both of these axes. Such increasingly sophisticated approaches change neither the number of levels sampled across the shore at an individual sampling station, nor the amount of total sampling effort, but they nevertheless provide significant advantages in terms of analytical power. In common with most other studies in benthic ecology that employ randomised designs, in this situation, the sampling unit becomes the core or quadrat and not the sampling station.

This context dependence means that there can be no uniform definition of a sampling unit for beach ecology. Irrespective of the context, however, samples from a sampling station provide information only for that particular point along the beach and not of the entire beach. In common with any other ecological study, capturing spatial and temporal variability on sandy beaches requires true replication of these sampling stations over appropriate scales.

An inability to define a uniform sampling unit does, however, not imply that uniformity of sampling approaches is not required. For example, a caveat specific to beach sampling is that while macrofaunal abundance and biomass can be estimated for a sampling station from either pooled samples on a transect (as a point estimate without error) or from a more sophisticated sampling design (possibly as an estimated mean with associated error), species richness should be inferred only from the cumulative pool of species encountered in all samples

0067939

taken at a sampling station (Jaramillo *et al.* 1995; Schoeman *et al.* 2003, this volume) Moreover, irrespective of sampling design, researchers should ensure that whenever they use transect lines, individual shore-normal sampling lines are not so close together that sampling on one line disturbs the fauna on adjacent sampling lines. This disturbance can be avoided either by sampling several lines simultaneously, working consistently upshore or downshore, or by ensuring that buffer zones of at least 5 m are placed between sampling lines. Also, researchers should attempt to conform to the minimum sample area and number of across-shore levels recommended below. Arguably, the maximum along-shore extent of a sampling station should not cover more than one aspect of a rhythmic shoreline (a cusp, a horn, or a point intermediate between these). If sampling over a greater range of along-shore variability in physical features is desirable, entire sampling stations should be appropriately replicated.

Recommendation 1

In sandy-beach ecology, as in most other disciplines, a sampling unit is context-dependent, and is, therefore, impossible to define uniformly. Although the term 'transect' is used in many different senses, it should henceforth be applied only to a shore-normal line of samples. To avoid possible confusion in terminology, we recommend the use of the term 'sampling station' to describe a point on a beach at which a uniform sampling effort is expended over standardised levels across the shore. A sampling station should, in most cases, not encompass more than one aspect of a rhythmic shoreline and should be seen as representative of only that part of the beach. If spatial and/or temporal trends are to be assessed, these sampling stations must be appropriately replicated in space and time.

Shape of sampling device (circular *versus* quadrangular)

Samples are conventionally taken from a sampling station on a beach using sample frames placed along a transect either at a fixed number of equally spaced sampling levels or at a set distance apart across the intertidal (Schoeman *et al.* 2003). Sample frames for the collection of sand and faunal samples can either be quadrangular or circular, and are used to demarcate the area of sand to be excavated. Empirical studies suggest little effect of sampler shape (De Grave & Casey 2000). There are, nevertheless, several practical advantages of circular frames over quadrangular ones. Circular frames (generally called cores) have a smaller surface-area-to-volume ratio, so should be expected to damage fewer specimens than a quadrangular frame of similar area; they are more readily constructed from a wider range of easily available materials (pipes of various types); if small, they can be designed so that they are closed at the top to prevent mobile animals from escaping the sampling device (this may be modified in various ways to allow air to escape, while the core is being inserted into the sediment and to create a vacuum that assists in retaining the sediment while the core is extracted); and they are easily operated by non-expert assistants. Finally, whereas the contents of circular frames can generally be removed intact from the ground by extracting the core, those of quadrangular frames are usually excavated using a shovel, and this adds to the likelihood that specimens will be damaged. Of course, it is possible to make a core with a quadrangular cross-section, and such a device would have many of the advantages of a circular core, but quadrangular cores have not been frequently used in sandy beach ecology.

Recommendation 2

Circular frames are recommended; in most instances, these will take the form of large cores.

Size of sample frame

Many sandy beach species are patchily distributed at several spatial scales (Gimenez & Yannicelli 2000; Defeo & McLachlan 2005). It is, therefore, important that the area of a single sample is large enough to capture small-scale variability in the distribution of the organisms. This can be most easily achieved by collecting several small cores; this reduces the probability of collecting only from a single patch of organisms (or a gap), as might happen with a single large core. However, there is a lower limit to the size of a core. Cores that are small relative to the size of the organisms will damage more specimens causing problems in identifications as well as density and biomass measurements (De Grave & Casey 2000).

There are few general rules regarding the size of sampling devices other than that they efficiently capture the abundance and diversity of specimens in the habitat, and that they provide estimates with acceptable accuracy. Both requirements can be met by taking large numbers of samples, which favour the use of small sampling devices (to minimise sampling effort). But, when the sampling device is very small relative to the scale of patchiness, zeroes can dominate the data set, and even a precise estimate can routinely include zero within its confidence interval. This situation can result in nonsensical analyses, often with poor analytical power (where power is the likelihood

0067940

that the statistical test will reject false null hypotheses). Power can be increased to some extent by employing analyses that are more sophisticated than conventional ANOVA (they allow error distributions other than Normal to be specified), but a simpler approach is to ensure that the mean abundance is not near zero, and this can be achieved by selecting sampling devices that are large enough to include, on average, 10–30 specimens. Another pragmatic consideration is that the sampling device should also be large enough to include at least five specimens of the largest organism likely to be encountered. This is of course not always possible on beaches where the size of the largest specimen is generally unknown because a great majority of organisms are buried in the sand and very large organisms are rare.

For ocean-exposed sandy beaches, a reasonable minimum sampling area per intertidal level seems to be ~0.3 m^2 (Schoeman *et al.* this volume), which corresponds closely with the recommendation by Eleftheriou & Moore (2005) that individual quadrats should be no smaller than 0.25 m^2. This can be achieved by pooling a number of smaller cores to encompass as much of the small-scale variability as possible. However, as very small cores damage organisms, and are likely to result in zero counts, a compromise must be reached between the area per sample and core size. This compromise is driven by the abundance, patchiness and maximum body size of organisms likely to be encountered at a sampling station.

Recommendation 3
The minimum area sampled at each across-shore level at a sampling station should approximate 0.3 m^2. This could be achieved using either three 0.1 m^2 cores or several smaller cores. Fifteen 16-cm diameter cores make up ~0.3 m^2 and this seems to be a useful standard on beaches. However, where large-bodied forms are likely to be common, six 25-cm diameter cores, or three 36-cm diameter cores are recommended; cores larger than this are generally impractical. Where individual cores routinely return zero counts, some form of pooling will generally be required.

Depth of coring

In studies that seek to quantify the diversity and structure of macrobenthic communities, the aim of sampling is to capture the largest possible fraction of resident organisms. Therefore, if attributes of entire communities are to be estimated, cores must penetrate deep enough to capture the majority of species.

Recommendation 4
Cores should be taken to a minimum depth of 25 cm, unless it can be demonstrated that the largest part of the infauna does not burrow deeper than this.

Sieve mesh size

Because the conventional definition of macrofauna involves specimens being retained on a mesh of 1-mm aperture, this has become the most widely used mesh size in sandy beach research, and it represents a sensible standard (McLachlan & Brown 2006). Smaller mesh apertures (*e.g.* 500 μm) are largely impractical to use in the field on all but the finest-sand beaches. In considering the relative merits of open- and closed-topped sieves (box sieves *versus* sieve bags), the ability of sieve bags to prevent contamination of samples by surf-zone species during sieving in the swash, and their greater area of mesh surface, makes these the preferred gear type.

Recommendation 5
Sieve bags with a mesh aperture of 1 mm are recommended for sampling macrofaunal communities of ocean-exposed sandy beaches.

Total sample area, number of lines and number of levels per sampling station

The balance between sampling effort expended and information obtained is a universal problem in ecology. On beaches, where the sampling window is generally constrained to the low-tide period, there is a practical limit to the amount of sand that can be processed at a sampling station in one day. This limit depends on the personnel available, the coarseness of the sand, and the width of the shore, among other factors. In practice, these constraints have limited total sampling coverage to 5–10 m^2 per sampling station per day (Jaramillo *et al.* 1995; Schoeman *et al.* 2003; McLachlan & Brown 2006). The question is whether this sample effort is adequate to achieve reasonable estimates of community characteristics of the benthic community at a sampling station.

At present there are no data to model the exact sample area required to measure community parameters accurately for different types of beaches and assemblages (Schoeman *et al.* 2003, this volume). However, some generalised rules can be inferred from existing analyses of data that are available for microtidal beaches of the intermediate morphodynamic type (Schoeman *et al.* this

0067941

volume). On these beaches, an acceptable balance between the bias and precision for estimates of species richness is reached at a sample area of ~4 m^2. This can be scaled down on narrower, low-diversity beaches, but needs to be increased on wider, high-diversity dissipative shores.

The required sample area per sampling station can be achieved by various arrangements of cores along and across the shore at a sampling station. Distinct patterns and boundaries in the across-shore distribution of species are generally less pronounced on sandy beaches compared with rocky shores. Moreover, on narrow, reflective beaches, the distribution patterns of individual species tend to merge or disappear, whereas on flatter, more dissipative shores, they become more distinct and complex as habitat heterogeneity increases (Defeo & McLachlan 2005). Because community-level studies require that species are captured from all areas of the shore, it is desirable to provide also guidelines on the minimum number of across-shore levels to be sampled.

Given the recommendations on sampling-frame size and the sample area per level (~0.3 m^2), and considering generalisations of both zonation and of total sampling effort, a suite of sampling strategies is recommended for adequately capturing information regarding the across-shore gradient in community descriptors at individual sampling stations over a range of beach types (Recommendation 6).

Recommendation 6

Given that a sampling station comprises replicate (uniform or, preferably, randomly placed) cores taken at each of several across-shore levels, the following set of strategies is recommended for different types of beaches.

beach width (drift line to low-tide swash line) and morphodynamic type	minimum total sample area (m^2) per sampling station	minimum number of across-shore levels per sampling station
<20 m, 'atidal'/microtidal reflective	2	7
20–50 m, microtidal reflective/intermediate	3	10
50–100 m, microtidal intermediate/dissipative	4	13
100–150 m, micro/mesotidal dissipative	5	17
150–200 m, meso/macrotidal intermediate /dissipative	6	20
>200 m, meso/macrotidal dissipative	8	27

Timing of sampling within the tidal cycle

Most researchers sample beaches during low tide. At this point, almost all of the fauna are buried and least mobile, and structural features of the beach are most evident. Nevertheless, some researchers start working just after high tide and sample at stations above the receding swash line until low tide. This approach provides a longer sampling window and, it has been argued, more readily captures deep-burrowing fauna. However, quantitative comparisons (T. Vanagt, personal communication) do not support the latter assertion and, in fact, suggest that swash-riding fauna are disproportionately represented in such samples. For these reasons, the low-tide approach is preferred. Nevertheless, where the timing of low tide places unreasonable constraints on sampling, work can begin as the tide recedes. In such cases, cores should however not be taken from sediments seaward of a position at least 3 m landward of the upper limit of the swash, as measured over a 15-min period. This should be sufficient to avoid contamination by tidal migrants.

Recommendation 7

Samples for the purpose of determining community structure of macrobenthos should be taken during the low tide, if logistically feasible.

Timing of sampling within the year

To capture the typical characteristics of a community, it is important to exclude species that might recruit to a beach but do not persist long enough to become permanent residents. To achieve this, sampling should be conducted outside of known recruitment peaks, particularly those of highly synchronised, r-selected species.

Recommendation 8

Samples for the purpose of determining community structure of macrobenthos should be taken during times of the year when recruitment is the lowest.

Possibility of incapacitating specimens prior to sieving

As most beach fauna are prodigious burrowers, soft-bodied forms may escape the meshes of a sampling sieve during processing. One approach to reduce the likelihood of escapes is to soak the excavated sediment in preservative prior to sieving. This means either contaminating the beach with large volumes of chemicals or transporting large volumes of sediment back to the laboratory for processing.

0067942

Both practices have obvious drawbacks. Moreover, because very few sampling programmes in beach ecology have used this approach in the past, starting now would introduce unnecessary issues of compatibility across studies.

Recommendation 9
Incapacitating specimens in bulk samples before extraction is discouraged, unless circumstances demand otherwise.

Additional considerations

As with sampling programmes in any other environment, there are decisions to be made at various points. Each has pros and cons. For example, whether to use formalin or alcohol as a preservative depends on whether biomass determination is important or not. Similarly, many beaches have clear microhabitats such as runnels or macrophyte wrack lines that require special consideration during the design of a sampling programme. Benthic fauna associated with wrack lines can be incorporated within the standard sampling design, but flying invertebrates have to be sampled separately or disregarded. Runnels are similarly problematic, because a sample level corresponding with a runnel will not reflect the general intertidal gradient as the benthos remain submerged at low tide. These issues are largely peripheral to this discussion and must be carefully resolved on a case-by-case basis.

Recommendation 10
Study-specific issues must be resolved on a case-by-case basis, with due regard for compatibility with other studies.

Recording environmental variables

Because sandy beaches are physically dynamic environments and the fauna is thought to respond primarily to variations in environmental attributes (McLachlan & Dorvlo 2005), characterisation of environmental conditions is a critical requirement in all studies of community ecology on sandy beaches. For this reason, in addition to sampling the fauna, most research groups seek to characterise the beach on the basis of physical features (McLachlan 1980; Wright & Short 1984; Masselink & Short 1993; McLachlan *et al.* 1993; Short 1996; Soares 2003; McLachlan & Dorvlo 2005). McLachlan & Brown (2006) suggest that a sampling station should be described by at least the following:

1. Statistics from sediment samples taken at the drift line, the mid shore and the low-water swash line, as well as the surf zone, if possible.
2. A description of wave, wind and tidal regimes.
3. All data required for the determination of beach morphodynamic state (*i.e.* modal wave height and period, beach slope, sediment grain size, max. tidal range).
4. General qualitative and quantitative geomorphological information regarding prominent beach features such as foredunes, cusps, beach length, *etc.*
5. Measures of the swash dimensions and climate.
6. Depth of reduced layer, if present.

The additional variables listed below are also useful:

1. Matched sediment samples for each biological sample level.
2. Structural complexity of the habitat, including both natural features such as runnels and wrack deposits, as well as anthropogenic features such as vehicle tracks, footprints.
3. Exposure ratings similar to those used by rocky-shore ecologists; these include variables such as wave fetch and predominant wind and swell directions.
4. Sediment moisture and organic content, as well as penetrability of the sediment.
5. Biomass of wrack cover.

Technical innovations may also aid in the capture of environmental data. For example, video footage of swash can be used to estimate associated parameters in the laboratory. This allows greater effort to be expended on sampling the fauna. Further technical developments will also allow other standard variables to be evaluated with less effort. The use of novel equipment is encouraged where it does not unduly compromise comparability with historical data.

An important point here is that environmental variables must be sampled in a manner that matches biological sampling. Where all cores from a sampling station are pooled, relatively few measures of environmental variables are needed (pooled samples from the drift line, mid shore and low-water swash), but as the sampling design for biological variables becomes more complex, care must be taken to ensure that samples of environmental variables are comparably representative of the sampling station.

Recommendation 11
The minimum set of environmental variables to be sampled at a station is listed by McLachlan & Brown (2006) and these measurements should be routinely collected. These data should be complemented by measures of locally important variables. In this respect, measures of habitat heterogeneity, energy subsidy and anthropogenic disturbance are most important. Care must be exercised to match biological and environmental samples so that they are equally representative of the sampling station.

0067943

Novel sampling devices and techniques

Several novel sampling devices and techniques emerged during workshop discussions and symposium presentations. Tools like 'monster tricycles' for sampling the surf zone, 'swash boxes' for sampling highly mobile swash-riding species and 'sticky traps' for sampling winged insects show great promise, but most need more development before being included in the toolbox of the general sandy beach ecologist. More conventional techniques like pitfall traps, bait pumps, burrow counts, standard visual counts and epibenthic sleds are valuable additions to most sampling programmes, but are difficult to include in a standardised manner; instead they tend to be used to answer specific questions beyond the scope of this discussion.

Concluding remarks on sampling methodology

Ocean-exposed sandy beaches are unusual habitats that need specialised sampling approaches, but there is a general lack of methodological studies for this habitat. Given these limitations, the above recommendations are intended as best-practice guidelines to be used in studies of benthic community ecology on beaches. But these guidelines cannot be static. More information is needed to improve our sampling approaches and all researchers are encouraged to contribute to this by conducting pilot and methodological studies and making the results as broadly available as possible, preferably in the peer-reviewed literature.

Issues and Challenges in Sandy Beach Management

Introduction and context

Human impacts on beaches are not modern phenomena: mankind has used and 'managed' coasts throughout its history of settling the world's shorelines (Nordstrom 2000). However, burgeoning global population growth, demographic shifts towards the coast, and economic prosperity and development are today placing pressures on beaches that act at unprecedented scales and magnitudes (Brown & McLachlan 2002; Schlacher *et al.* 2006, 2007a). Thus, managing beaches to reconcile the rapaciously increasing demands for recreational and financial benefits gained from sandy shorelines with a need to conserve the unique ecological features and processes of beaches has become a critical issue.

Beach management is a multi-faceted and complex endeavour that encompasses environmental, economic, social and cultural dimensions as a minimum set (Bird 1996; Micallef & Williams 2002). Because its objectives are defined by a plethora of drivers (*e.g.* financial considerations, economic gains, nature conservation, coastal defences), and depend on the specific socio-cultural context and human aspirations, management frameworks and interventions are often geographically distinct to meet local and regional needs. Nevertheless, most beach management incorporates elements of: (i) protection against coastal hazards; (ii) maintenance of economic benefits derived from beaches; (iii) safeguarding or enhancing human recreational opportunities; (iv) regulation of resource extraction including fisheries; and (v) protection of habitats and biodiversity (James 2000a,b; Scapini 2002).

Coastal biologists are now recognising the ecological significance of beaches (Schlacher *et al.* 2006, 2007a), but this is not always the case within the broader scientific and coastal management community. Beach management often focuses only on the physical attributes and processes of beaches, particularly those related to managing sand budgets and the stability of the shoreline (Figs 2 and 3; James 2000b). In contrast, conservation of ecological features and processes does, in many cases, not form part of routine beach management. Consequently, the impacts on ecosystems are rarely included in impact assessments. Because beaches support the livelihoods of many and diverse sectors of the community and are crucial coastal features in terms of shoreline protection, a wide range of stakeholders have active, but not necessarily corresponding, interests in these systems. Therefore, management of sandy coasts will have to operate increasingly within the framework of Integrated Coastal Management (ICM) to achieve sustainable outcomes.

Conservation of beaches will require the application of conservation tools established in other marine systems and, possibly, the development of new approaches. For example, zoning of use types and intensities has long underpinned environmental conservation, and marine protected areas (MPAs) have proven to be effective in many settings. Indeed, MPAs are key management tools for biodiversity conservation (Barrett *et al.* 2007), and systematic conservation planning (SCP) provides spatially explicit criteria for their design (Margules & Pressey 2000; McDonnell *et al.* 2002; Meir *et al.* 2004; Murdoch *et al.* 2007; Stewart *et al.* 2007). On beaches, attempts at conservation planning are, however, often impeded by a lack of spatial information about the ecological values to protect. Alternative approaches that use physical and geo-morphological habitat properties as surrogates for biodiversity may be possible solutions (Banks & Skilleter 2005), but still require some knowledge about the link functions between habitat properties and ecological attributes on beaches; these are available on the macro-scale (Defeo & McLachlan 2005; McLachlan & Dorvlo 2005), although for local and

0067944

regional applications, the suitability and efficacy of surrogates need to be verified.

The broad objectives of the workshop were to scope critical issues in beach management and to foster collaboration between scientists working on sandy beach ecology and coastal managers. Communication between scientists, managers and the general public is seen as crucial to achieve sustainable conservation outcomes for beaches. The workshop aimed to highlight the critical issues in decision-making for coastal conservation and planning. It first identified the major environmental values of sandy beaches, and then assessed the range of pressures and impacts faced by these systems. Participants highlighted knowledge gaps for beach management and future research priorities to address these. Finally, a set of four principles was proposed to guide integrated sandy beach management.

Environmental values of sandy beaches

Sandy beaches cover a wide range of environmental values (Fig. 1; Table 1). Because these values generally depend on the specific cultural, economic and environmental context, it is not practical to prioritise them.

Table 1. Environmental values of sandy beaches[a].

value	mainly human (socio-economic)	mainly environmental (ecological)
recreation & tourism	X	
cultural/historical connections	X	
wilderness quality/experience	X	
education & research	X	
sport & entertainment venues	X	
transport corridors	X	
boating (craft launching, jet skies)	X	
fishing and shellfish harvesting	X	
mining	X	
maintaining human health & well-being	X	
real estate	X	
military installations	X	
storm protection (properties, infrastructure, dunes)	X	X
wildlife (birds & other larger, easily visible fauna)	X	X
seawater filtration & nutrient recycling – water quality	X	X
bequest value	X	X
nursery and foraging sites for fishes	X	X
biodiversity		X
habitat		X
nesting and foraging sites for birds and turtles		X
intrinsic ecological value		X

[a] Because environmental values strongly depend on the specific social and cultural context, they are not ranked or prioritised in this table.

Issues and pressures

The ultimate cause of detrimental impacts on sandy beaches is human population growth. In particular, it is the disproportionate growth and geographic expansion of coastal populations – the '*bush to beach phenomenon*' – and an increasing focus on leisure activities, that place escalating pressures on sandy beaches (Figs 1–3). There are, however, a number of proximate and direct causes for environmental degradation that can be readily identified (Table 2). Some of these are interrelated or are generated outside the sandy beach systems (*e.g.* reductions of sediment supply in watersheds, sewage, *etc.*).

Science gaps in sandy beach management

Beach management needs to incorporate ecosystem features and processes explicitly, but this is not always possible due to gaps in communication and ecological knowledge. Yet, environmentally defensible management must be underpinned by science to achieve outcomes that encompass multiple uses that are sustainable. Several critical gaps in environmental information on beaches were identified during the workshop (Table 3).

The Four Principles

A major recommendation of the workshop is the adoption of the following four principles. These can be used to focus beach management to integrate physical and ecological aspects of beach systems in developing best practice:

1. Sandy beaches provide a wide range of ecosystem services and values that cannot be supplied by any other ecosystem and beaches harbour a unique biodiversity.
2. Sandy beaches are under threat worldwide, being squeezed between rising sea levels from the marine side and expanding human populations and development on the landward side.
3. Sandy beaches, including the dunes and the subtidal areas, must be maintained as intact coastal ecosystems that support both key ecological processes and sustainable, multiple uses by humans.
4. Long-term commitment from scientists, managers and the public is critical for the development and adoption of ecologically-based management policies for sandy beaches.

0067945

Table 2. Main pressures on sandy beaches.

pressure		key reference(s)
recreational activities	vehicles (ORVs)	Godfrey & Godfrey (1980), Schlacher *et al.* (2007b), Schlacher & Thompson (2007, 2008)
	trampling (walking), sunbathing, swimming, equestrian use	Rickard *et al.* (1994), Moffett *et al.* (1998)
	camping (beaches & dunes)	Hockings & Twyford (1997)
	surf-zone activities (jetskies, boats)	Davenport & Davenport (2006)
	high human concentrations	de Ruyck *et al.* (1997), Fanini *et al.* (2005, 2007)
	recreational fishing, bait collecting	Defeo & de Alava (1995), McLachlan *et al.* (1996)
pollution	sewage and stormwater discharge	Boehm *et al.* (2003)
	litter	Derraik (2002)
	eutrophication (harmful algal blooms)	Paerl (1988)
	heated effluent (thermal pollution)	Barnett (1971)
	oil and other chemicals	de la Huz *et al.* (2005)
construction	buildings, infrastructure, roads, communications: habitat loss/deterioration	Nordstrom & Jackson (1998), Nordstrom (2000)
	dams: reduction in sediment supply	Willis & Griggs (2003)
	groins, seawalls, revetments, breakwaters: disruption of sediment transport	Komar (1998)
ecologically harmful beach management	grooming	Llewellyn & Shackley (1996), Dugan *et al.* (2003)
	nourishment	Peterson *et al.* (2006), Speybroeck *et al.* (2006)
	armouring	Dugan & Hubbard (2006)
resource exploitation	fisheries	Defeo (2003)
	mining	McLachlan (1996)

Climate Change and Sandy Beach Ecosystems

Rationale and context

Arguably, global climate change is the foremost environmental, social and economic challenge of the 21st century. Ample evidence has in the last decades accumulated showing that human emissions of atmospheric greenhouse gases have led to fundamental changes in the world's climate and oceans (Solomon *et al.* 2007); these changes are predicted to become larger and more widespread by the end of this century (Meehl *et al.* 2007). This recent climate change has propagated to a multitude of ecological effects that span an array of ecosystems, ecological organisations and geographic areas (Walther *et al.* 2002).

Climate change also poses major threats to coastal ecosystems (Harley *et al.* 2006). Beaches, in particular, are likely to experience the impacts of sea level rise, changes in storm and wave regimes and altered sediment budgets (Jones *et al.* 2008). Accelerated erosion of beaches and landward recession of shorelines because of climate change are the key issues for sandy beach ecosystems in the future (Slott *et al.* 2006). Globally ~70% of beaches are already receding, 20–30% are stable, while 10% or less are accreting (Bird 2000). Impacts on beaches are likely to be exacerbated by rapidly increasing human population densities in the coastal zone and widespread transformation of coastlines to urban areas (Nordstrom 2000; Finkl & Krupa 2003).

Existing geo-physical models can be applied to predictions of climate-related changes for sandy beaches (Zhang *et al.* 2004). However, no equivalents exist for the ecological effects of climate change on beaches. Therefore, models that can predict the ecological responses of beaches to climate change and the effects of societal interventions to combat shoreline change are required. Such models are best developed within an ecological framework that specifically addresses climate change issues for sandy beaches; this was the chief rationale for this workshop.

This summary report first provides a brief overview of the major physico-chemical changes likely to impact most strongly on sandy beaches (*i.e.* sea-level rise, episodic events, extreme weather events, pH changes), followed by a synopsis of predicted impacts of climate change on sandy beaches. It concludes with an outline of future research directions that were regarded as particularly critical to advance the development of robust impact assessments and human interventions to climate change on sandy shores.

1.1.1. Sea level rise

The rate of observed sea level rise accelerated from the 19th to the 20th century with a rise of 0.17 (0.12–0.22) m in the last century (Miller & Douglas 2006). This global rise shows regional variation where some regions

0067946

Table 3. Information gaps and resulting research priorities required for management of sandy beaches that incorporates the conservation of ecological attributes.

- predictive capabilities
  - recovery trajectories of impacted areas (*e.g.* removal of sea walls, constructions, piers, *etc.*)
  - effects of dune restoration on adjacent beaches
  - impacts of invasive species
  - sensitivity and resilience of individuals, populations, assemblages and whole ecosystems
  - carrying capacity (social and ecological)
  - effects of nourishment
- identification of ecological responses and impacts
  - suitability and performance of 'indicator' species
  - natural variability *versus* impact effects (*e.g.* ORVs, nourishment, groynes)
  - reversing impacts (best-practice in restoration)
  - effects on organism health and performance (development, response to parasites and diseases, physiology, behaviour)
  - acute (pulse) *versus* continuous (press) disturbance
  - spatio-temporal scales (*e.g.* regional variation)
  - interaction among impacts, cumulative impacts and non-linearities
- linkages and connectivity
  - linkages with higher trophic levels (*e.g.* fish, birds)
  - energetic linkages amongst functional guilds
  - ecosystem-wide processes (*e.g.* nutrient recycling, productivity, ecotonal coupling, cross-system fluxes)
  - connectivity among metapopulations on different beaches
- management information needs (including economic and ecological values of beaches)
  - design of monitoring programs to track changes on short, medium and long time scales
  - contingency programs to respond to catastrophic events (*e.g.* oil spills)
  - implications of hard *versus* soft solutions in shoreline protection
  - policies for designing/developing beaches for specific purposes
  - public and political perception of problems
  - valuation (economic/ecological/social, cultural heritage, archaeological)
  - conservation needs and goals

(*e.g.* western Pacific, eastern Indian Ocean) experienced increases several times the global average (Bindoff *et al.* 2007). There is also an increased incidence of extremely high sea levels (storm surges), supported by observations of more frequent extreme high water events at a broad range of sites worldwide since 1975 (Bindoff *et al.* 2007). By the last decade of the 21st century, global average sea level is projected to be higher by 0.18–0.59 m under the five scenarios modelled by the IPCC (http://www.ipcc.ch), most of it driven by thermal expansion of the oceans (Meehl *et al.* 2007). Irrespective of the exact magnitude of sea level rise (including regional variations), accelerated erosion of beaches and landward retreat of shorelines are virtually certain (Zhang *et al.* 2004), with massive and potentially calamitous flow-on effects for coastal societies worldwide (Nicholls & Tol 2006). This landward migration of shorelines will result in extensive habitat losses on beaches where human development arrests natural inland migration of the shoreline (Feagin *et al.* 2005).

1.1.2. Extreme weather events

Cyclone activity over both hemispheres has changed over the last five decades with a poleward shift in storm track location, increased storm intensity, but a decrease in the total number of storms (Trenberth *et al.* 2007). There is observational evidence for recent increases in intense tropical cyclone activity in the North Atlantic, and this may also occur in other regions. Observations also show a trend towards greater destructiveness, longer lifetimes and greater intensity (Webster *et al.* 2005; Trenberth *et al.* 2007). Similarly, by the end of this century, the total number of tropical cyclones is projected to decrease, but there may be more storms of greater intensity (Meehl *et al.* 2007). Changes in storm characteristics and behaviour will also alter the amount of wave energy. Increases in significant wave height (SWH) have been supported by observations of upward trends in wave height that are strongest in the northwest Atlantic and the northeast Pacific, but trends of smaller waves in the western Pacific tropics, the Tasman Sea and the south Indian Ocean (Bindoff *et al.* 2007). Future projections of storminess and wave climate have large uncertainties, but models show that these factors are critical in reshaping coastlines, possibly leading to accelerated shoreline erosion, including sandy beaches, in the future (Slott *et al.* 2006).

1.1.3. Changes in precipitation

The amount, intensity, frequency and type of precipitation are changing globally (Solomon *et al.* 2007). Available data and models show considerable variation between regions, but widespread increases in heavy precipitation events, even in places where total amounts are less, have been observed, resulting in more floods and altered discharge patterns of freshwater to the oceans (Trenberth *et al.* 2007); the likelihood of more extreme precipitation events is projected to continue in the 21st century (Meehl *et al.* 2007). Since the ecological dynamics of sandy beaches can be linked to freshwater discharge from rivers (Lercari *et al.* 2002), global changes in land-ocean coupling via freshwater outflows are predicted to affect the ecology of beaches.

1.1.4. ENSO

ENSO (El Niño-Southern Oscillation) events have a major influence on key ecological processes in the oceans such as primary productivity, upwelling and the distribution and dynamics of major fisheries species (Lehodey *et al.* 2003, 2006). Although there have been observed changes in El

0067947

Niño evolution in the last decades and a tendency towards more prolonged and stronger El Niños (Bindoff *et al.* 2007), future projections of the amplitude and variability of ENSO events for this century are rarely consistent between models (Meehl *et al.* 2007). Since ENSO events are major drivers for changes in precipitation and consequent freshwater, nutrient and sediment delivery to the nearshore zone, long-term shifts in ENSO strength and frequency may have flow-on effects on beach systems.

1.1.5. Acidification

Oceanic pH is today 0.1 units lower than pre-industrial values, caused by diffusion of increasing atmospheric CO_2 concentrations (Bindoff *et al.* 2007). By the year 2100, pH is projected to decrease by another 0.3–0.4 units (Meehl *et al.* 2007). This acidification of the oceans will cause a 100–150% rise in the concentration of H^+ ions and a simultaneous decrease in carbonate ion levels (Orr *et al.* 2005). Because marine organisms cannot form calcium carbonate shells in undersatured conditions, the ecological consequences of this chemical change are potentially disastrous and will have repercussions for animals of sandy beaches with carbonate shells or exoskeletons (Raven 2005). Model simulations project that carbonate undersaturation will be reached in a few decades at high-latitudes. Therefore, conditions detrimental to marine life could develop within decades (Orr *et al.* 2005).

Ecological impacts on sandy beaches

Workshop participants considered the loss of habitat and associated biota caused by accelerated beach erosion

Table 4. Summary of the main ecological effects predicted to be caused by global climate change.

• effects of increased temperature on biota	
physiological performance, tolerance and survival of organisms	Stillman (2003), Helmuth *et al.* (2005)
geographical shifts in species ranges, increased prevalence of invasive species, altered community structure and dynamics	Harley *et al.* (2006), Ricciardi (2007)
changes in reproductive traits and population dynamics	Philippart *et al.* (2003), Hawkes *et al.* (2007), Saba *et al.* (2007)
altered benthic metabolism (*e.g.* decomposition and mineralisation rates, sediment oxygen saturation, microbial activity, production and respiration)	Hubas *et al.* (2007)
• effects of altered circulation regimes and upwelling	
shifts in nutrient supplies and productivity: food web architecture, trophic dynamics, community structure, nutrient recycling, secondary production incl. fisheries species) on sandy beaches	Hays *et al.* (2005), Barth *et al.* (2007)
altered coastal oceanographic patterns: changes in larval dispersal and/or recruitment of intertidal species	Schoeman & Richardson (2002), Levin (2006)
• effects of sea-level rise and altered storm and wave regimes	
accelerated beach erosion and shoreline retreat	Zhang *et al.* (2004), Slott *et al.* (2006)
habitat loss intertidal & dunes)	Galbraith *et al.* (2002), Feagin *et al.* (2005)
negative ecological impacts of engineering interventions to combat shoreline retreat	Dugan & Hubbard (2006), Speybroeck *et al.* (2006)
altered beach morphodynamics	Stockdon *et al.* (2007)
increased variation in wrack supply	Dugan *et al.* (2003)
direct mortality of beach biota	Milton *et al.* (1994)
changes to dune vegetation *e.g.* plant cover, diversity) – decreased dune stability	Greaver & Sternberg (2007)
• effects of altered precipitation	
changes in sediment supply from inland sources	Masters (2006)
changes in groundwater discharge and interstitial chemistry	McLachlan & Turner (1994), Burnett *et al.* (2003)
increased supply of land-derived nutrients	Gaston *et al.* (2006)
modified dune vegetation and dune stability	Greaver & Sternberg (2007)
• effects of acidification decreased pH)	
tissue acidosis in larger animals causing physiological stress, possibly leading to decreased reproductive potential, slower growth and increased susceptibility to diseases	Langenbuch & Portner (2003), Raven (2005)
reductions or inhibition of calcification rates in calcifying organisms (*e.g.* molluscs, crustaceans, echinoderms, protists, algae) possibly lowering physiological and ecological fitness.	Orr *et al.* (2005), Raven (2005)
decreased supply of biogenic, carbonate sediment to sandy beaches	Feely *et al.* (2004)

0067948

(Feagin *et al.* 2005; Slott *et al.* 2006) as the most immediate and severe ecological threat to beaches caused by climate change (Table 4). Erosion resulting from the combined effects of sea-level rise and changed storm- and wave regimes is likely to trigger most management responses in the short term and medium term (Polome *et al.* 2005).

However, management of large-scale and severe beach erosion and landward migration of shorelines is likely to be diverse; the following scenarios were identified as most likely: (i) do nothing – allow shoreline to recede naturally; (ii) retreat by actively moving back and removing threatened infrastructure; (iii) beach nourishment (soft engineering); (iv) 'hard engineering' using seawalls or other armouring structures; and (v) combined approaches (*e.g.* nourish in front of seawalls). Each of these scenarios is likely to have different ecological consequences for beaches that encompass environmentally 'ideal' approaches (natural shoreline change), moderate ecological impacts (nourishment) and ecologically highly destructive solutions (armouring).

Science gaps and research priorities

The scale and ambit of threats arising from climate change for sandy beaches in the 21st century will require global syntheses of research and interdisciplinary approaches to design management strategies that incorporate the conservation of key ecological attributes of sandy beaches. Several critical gaps in our current scientific knowledge that prevent us from accurately measuring and predicting the anticipated impacts of climate change on sandy beaches were identified and a list of research areas was proposed (Table 5).

Ecologists must be instrumental in the development of conservation and management strategies to maintain the ecological integrity of sandy beaches threatened by climate change. To this end, the following actions were proposed to integrate closer the conservation of ecological features and processes into coastal policy, planning and management interventions on sandy coasts:

1. Raise the public profile of beaches as being diverse ecosystems.
2. Highlight that beaches are extremely vulnerable to climate change.
3. Emphasise that beaches are ecologically linked with other coastal systems.
4. Stress the critical role of human population growth and associated development as underlying causative factors of coastal change.
5. Develop predictive capabilities in sandy beach ecology to forecast the nature and magnitude of ecological changes caused by climate change.
6. Promote the use of adaptive management frameworks.
7. Develop best ecological practice for human interventions to sea-level rise and shoreline retreat.
8. Use management interventions as opportunities for experiments.
9. Provide climate-envelope maps for sandy beach species.
10. Foster integration of global and local research and across disciplines.

Table 5. Research areas[a] proposed that enhance the capacity to measure and predict the ecological impacts of climate change on sandy beaches and linked management responses.

	ecology	management
long-term studies on communities and populations that quantify ecological responses to changes in beach morphology and variability	X	
key ecological traits of individual species (*i.e.* dispersal abilities, reproductive strategies, thermal tolerance, *etc.*)	X	
ability of species to adapt or acclimatise	X	
metapopulation studies	X	
realised and predicted geographic range shifts of biota	X	
habitat requirements of iconic and threatened species (birds, turtles, fish)	X	X
identification of indicator species and their efficacy in monitoring the effects of climate change on sandy beaches	X	X
linkages across ecosystems – ecotonal coupling (*e.g.* dunes, estuaries, reefs)	X	
ecological consequences of alternative societal responses to erosion and shoreline retreat (*e.g.* do nothing, retreat/ setback, nourish, armour)	X	X
scale-dependency and cumulative effects of societal responses to beach erosion	X	X
effects of management interventions to sea-level rise and beach erosion on critical linkages of sandy beaches with adjacent systems (dunes, nearshore, estuaries)	X	X
efficacy of mitigation, rehabilitation and restoration measures	X	X
impacts on economically important fisheries species on beaches	X	X

[a] Not in order of priority.

A central requirement for forecasting the ecological impacts of climate change on sandy beaches is to improve predictive capabilities in the science of beach ecology, inclusive of modelling techniques. Adaptive responses to climate change (*e.g.* interventions to combat erosion and beach retreat) should ideally incorporate environmental outcomes that are ecologically sustainable. This will require close and open collaboration among scientists, managers and policy makers across different levels of the decision-making process, at local, regional, national and international levels. Despite the inherent uncertainties and the long-term nature of climate-change impacts on sandy beach ecosystems, the results of the workshop provide guide principles on future research needs that will enhance society's efforts to respond to climate change in an ecologically responsible and sustainable way.

Acknowledgements

This paper benefited greatly from the inputs of the participants who took part in the conference workshops and provided a wealth of inputs, ideas and contributions.

References

Banks S.A., Skilleter G.A. (2005) Intertidal habitat conservation: identifying conservation targets in the absence of detailed biological information. *Aquatic Conservation-Marine and Freshwater Ecosystems*, **15**, 271–288.

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

Barrett N.S., Edgar G.J., Buxton C.D., Haddon M. (2007) Changes in fish assemblages following 10 years of protection in Tasmanian marine protected areas. *Journal of Experimental Marine Biology and Ecology*, **345**, 141–157.

Barth J.A., Menge B.A., Lubchenco J., Chan F., Bane J.M., Kirincich A.R., McManus M.A., Nielsen K.J., Pierce S.D., Washburn L. (2007) Delayed upwelling alters nearshore coastal ocean ecosystems in the northern California current. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 3719–3724.

Bindoff N.L., Willebrand J., Artale V., Cazenave A., Gregory J., Gulev S., Hanawa K., Le Quéré C., Levitus S., Nojiri Y., Shum C.K., Talley L.D. (2007) Observations: oceanic climate change and sea level. In: Solomon S., Qin D., Manning M. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (Eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK: 385–432.

Bird E.C.F. (1996) *Beach Management*. John Wiley, Chichester, New York: 281 pp.

Bird E.C.F. (2000) *Coastal Geomorphology: An Introduction*. John Wiley, Chichester, 322 pp.

Boehm A.B., Fuhrman J.A., Mrse R.D., Grant S.B. (2003) Tiered approach for identification of a human fecal pollution source at a recreational beach: case study at Avalon Cay, Catalina Island, California. *Environmental Science & Technology*, **37**, 673–680.

Brown A.C., McLachlan A. (2002) Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation*, **29**, 62–77.

Burnett W.C., Bokuniewicz H., Huettel M., Moore W.S., Taniguchi M. (2003) Groundwater and pore water inputs to the coastal zone. *Biogeochemistry*, **66**, 3–33.

Davenport J., Davenport J.L. (2006) The impact of tourism and personal leisure transport on coastal environments: a review. *Estuarine, Coastal and Shelf Science*, **67**, 280–292.

De Grave S., Casey D. (2000) Influence of sampler shape and orientation on density estimates on intertidal macrofauna. *Journal of the Marine Biological Association of the UK*, **80**, 1125–1126.

Defeo O. (2003) Marine invertebrate fisheries in sandy beaches: an overview. *Journal of Coastal Research*, **SI 35**, 56–65.

Defeo O., de Alava A. (1995) Effects of human activities on long-term trends in sandy beach populations: the wedge clam *Donax hanleyanus* in Uruguay. *Marine Ecology Progress Series*, **123**, 73–82.

Defeo O., McLachlan A. (2005) Patterns, processes and regulatory mechanisms in sandy beach macrofauna: a multi-scale analysis. *Marine Ecology Progress Series*, **295**, 1–20.

Derraik J.G.B. (2002) The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin*, **44**, 842–852.

Dugan J.E., Hubbard D.M. (2006) Ecological responses to coastal armouring on exposed sandy beaches. *Shore & Beach*, **74**, 10–16.

Dugan J.E., Hubbard D.M., McCrary M.D., Pierson M.O. (2003) The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California. *Estuarine, Coastal and Shelf Science*, **58**, 25–40.

Eleftheriou A., Moore D.C. (2005) Macrofauna techniques. In: Eleftheriou A., McIntyre A.D. (Eds), *Methods for the Study of Marine Benthos*. Blackwell Science, Oxford, UK: 160–228.

Fanini L., Cantarino C.M., Scapini F. (2005) Relationships between the dynamics of two *Talitrus saltator* populations and the impacts of activities linked to tourism. *Oceanologia*, **47**, 93–112.

Fanini L., Marchetti G.M., Defeo O., Scapini F. (2007) Abundance and orientation response of the sandhopper *Talitrus saltator* to beach nourishment and groynes at San Rossore Natural Park, Tuscany, Italy. *Marine Biology*, **152**, 1169–1179.

Feagin R.A., Sherman D.J., Grant W.E. (2005) Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Frontiers in Ecology and the Environment*, **3**, 359–364.

Feely R.A., Sabine C.L., Lee K., Berelson W., Kleypas J., Fabry V.J., Millero F.J. (2004) Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science*, **305**, 362–366.

Finkl C.W., Krupa S.L. (2003) Environmental impacts of coastal-plain activities on sandy beach systems: hazards, perception and mitigation. *Journal of Coastal Research*, **35**, 132–150.

Galbraith H., Jones R., Park R., Clough J., Herrod-Julius S., Harrington B., Page G. (2002) Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. *Waterbirds*, **25**, 173–183.

Gaston T.F., Schlacher T.A., Connolly R.M. (2006) Flood discharges of a small river into open coastal waters: plume traits and material fate. *Estuarine Coastal and Shelf Science*, **69**, 4–9.

Gimenez L., Yannicelli B. (2000) Longshore patterns of distribution of macroinfauna on a Uruguayan sandy beach: an analysis at different spatial scales and of their potential causes. *Marine Ecology Progress Series*, **199**, 111–125.

Godfrey P.J., Godfrey M. (1980) Ecological effects of off-road vehicles on Cape Cod. *Oceanus*, **23**, 56–67.

Greaver T.L., Sternberg L.S.L. (2007) Fluctuating deposition of ocean water drives plant function on coastal sand dunes. *Global Change Biology*, **13**, 216–223.

Harley C.D.G., Hughes A.R., Hultgren K.M., Miner B.G., Sorte C.J.B., Thornber C.S., Rodriguez L.F., Tomanek L., Williams S.L. (2006) The impacts of climate change in coastal marine systems. *Ecology Letters*, **9**, 228–241.

Hawkes L.A., Broderick A.C., Godfrey M.H., Godley B.J. (2007) Investigating the potential impacts of climate change on a marine turtle population. *Global Change Biology*, **13**, 923–932.

Hays G.C., Richardson A.J., Robinson C. (2005) Climate change and marine plankton. *Trends in Ecology & Evolution*, **20**, 337–344.

Helmuth B., Kingsolver J.G., Carrington E. (2005) Biophysics, physiologicalecology,and climate change: does mechanism matter? *Annual Review of Physiology*, **67**, 177–201.

Hockings M., Twyford K. (1997) Assessment and management of beach camping within Fraser Island World Heritage Area, South East Queensland. *Australian Journal of Environmental Management*, **4**, 25–39.

Hubas C., Lamy D., Artigas L.F., Davoult D. (2007) Seasonal variability of intertidal bacterial metabolism and growth efficiency in an exposed sandy beach during low tide. *Marine Biology*, **151**, 41–52.

de la Huz R., Lastra M., Junoy J., Castellanos C., Vieitez J.M. (2005) Biological impacts of oil pollution and cleaning in the intertidal zone of exposed sandy beaches: preliminary study of the “Prestige” oil spill. *Estuarine Coastal and Shelf Science*, **65**, 19–29.

James R.J. (2000a) The first step for the environmental management of Australian beaches: establishing an effective policy framework. *Coastal Management*, **28**, 149–160.

James R.J. (2000b) From beaches to beach environments: linking the ecology, human-use and management of beaches in Australia. *Ocean & Coastal Management*, **43**, 495–514.

Jaramillo E., McLachlan A., Dugan J. (1995) Total sample area and estimates of species richness in exposed sandy beaches. *Marine Ecology Progress Series*, **119**, 311–314.

Jones A.R., Gladstone W., Hacking N.J. (2008) Australian sandy-beach ecosystems and climate change: ecology and management. *Zoologist*, **34**, 190–202.

Komar P.D. (1998) *Beach Processes and Sedimentation.* Prentice-Hall, Englewood Cliffs, NJ.

Langenbuch M., Portner H.O. (2003) Energy budget of hepatocytes from Antarctic fish (Pachycara brachycephalum and Lepidonotothen kempi) as a function of ambient CO2: pH-dependent limitations of cellular protein biosynthesis? *Journal of Experimental Biology*, **206**, 3895–3903.

Lehodey P., Chai F., Hampton J. (2003) Modelling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. *Fisheries Oceanography*, **12**, 483–494.

Lehodey P., Alheit J., Barange M., Baumgartner T., Beaugrand G., Drinkwater K., Fromentin J.M., Hare S.R., Ottersen G., Perry R.I., Roy C., Van der Lingen C.D., Werner F. (2006) Climate variability, fish, and fisheries. *Journal of Climate*, **19**, 5009–5030.

Lercari D., Defeo O., Celentano E. (2002) Consequences of a freshwater canal discharge on the benthic community and its habitat on an exposed sandy beach. *Marine Pollution Bulletin*, **44**, 1397–1404.

Levin L.A. (2006) Recent progress in understanding larval dispersal: new directions and digressions. *Integrative and Comparative Biology*, **46**, 282–297.

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

Margules C.R., Pressey R.L. (2000) Systematic conservation planning. *Nature*, **405**, 243–253.

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.

Masters P.M. (2006) Holocene sand beaches of southern California: ENSO forcing and coastal processes on millennial scales. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **232**, 73–95.

McDonnell M.D., Possingham H.P., Ball I.R., Cousins E.A. (2002) Mathematical methods for spatially cohesive reserve design. *Environmental Modeling and Assessment*, **7**, 107–114.

McLachlan A. (1980) The definition of sandy beachs in relation to exposure: a simple rating system. *South African Journal of Science*, **76**, 137–138.

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., Brown A.C. (2006) *The Ecology of Sandy Shores*. Academic Press, Burlington, MA, USA: 373 pp.

McLachlan A., Dorvlo A. (2005) Global patterns in sandy beach macrobenthic communities. *Journal of Coastal Research*, **21**, 674–687.

McLachlan A., Turner I. (1994) The interstitial enivronment of sandy beaches. *Marine Ecology-Pubblicazioni della Stazione Zoologica di Napoli I*, **15**, 177–211.

McLachlan A., Jaramillo E., Donn T.E., Jr, Wessels F. (1993) Sandy beach macrofauna communities and their control by the physical environment: a geographical comparison. *Journal of Coastal Research*, **15**, 27–38.

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

Meehl G.A., Stocker T.F., Collins W.D., Friedlingstein P., Gaye A.T., Gregory J.M., Kitoh A., Knutti R., Murphy J.M., Noda A., Raper S.C.B., Watterson I.G., Weaver A.J., Zhao Z.-C. (2007) Global Climate Projections. In: Solomon S., Qin D., Manning M. *et al.* (Eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK: 747–846.

Meir E., Andelman S., Possingham H.P. (2004) Does conservation planning matter in a dynamic and uncertain world? *Ecology Letters*, **7**, 615–622.

Micallef A., Williams A.T. (2002) Theoretical strategy considerations for beach management. *Ocean & Coastal Management*, **45**, 261–275.

Miller L., Douglas B.C. (2006) On the rate and causes of twentieth century sea-level rise. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, **364**, 805–820.

Milton S.L., Leone-Kabler S., Schulman A.A., Lutz P.L. (1994) Effects of Hurricane Andrew on the sea turtle nesting beaches of South Florida. *Bulletin of Marine Science*, **54**, 974–981.

Moffett M.D., McLachlan A., Winter P.E.D., De Ruyck A.M.C. (1998) Impact of trampling on sandy beach macrofauna. *Journal of Coastal Conservation*, **4**, 87–90.

Murdoch W., Polasky S., Wilson K.A., Possingham H.P., Kareiva P., Shaw R. (2007) Maximizing return on investment in conservation. *Biological Conservation*, **139**, 375–388.

Nicholls R.J., Tol R.S.J. (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, **364**, 1073–1095.

Nordstrom K.F. (2000) *Beaches and Dunes on Developed Coasts*. Cambridge University Press, Cambridge, UK, 352 pp.

Nordstrom K.F., Jackson N.L. (1998) Effects of a high rise building on wind flow and beach characteristics at Atlantic City, NJ, USA. *Ocean & Coastal Management*, **39**, 245–263.

Orr J.C., Fabry V.J., Aumont O., Bopp L., Doney S.C., Feely R.A., Gnanadesikan A., Gruber N., Ishida A., Joos F., Key R.M., Lindsay K., Maier-Reimer E., Matear R., Monfray P., Mouchet A., Najjar R.G., Plattner G.K., Rodgers K.B., Sabine C.L., Sarmiento J.L., Schlitzer R., Slater R.D., Totterdell I.J., Weirig M.F., Yamanaka Y., Yool A. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**, 681–686.

Paerl H.W. (1988) Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnology and Oceanography*, **33**, 823–847.

Peterson C.H., Bishop M.J., Johnson G.A., D'Anna L.M., Manning L.M. (2006) Exploiting beach filling as an unaffordable experiment: benthic intertidal impacts propagating upwards to shorebirds. *Journal of Experimental Marine Biology and Ecology*, **338**, 205–221.

Philippart C.J.M., van Aken H.M., Beukema J.J., Bos O.G., Cadee G.C., Dekker R. (2003) Climate-related changes in recruitment of the bivalve Macoma balthica. *Limnology and Oceanography*, **48**, 2171–2185.

Polome P., Marzetti S., van der Veen A. (2005) Economic and social demands for coastal protection. *Coastal Engineering*, **52**, 819–840.

Raven J. (2005) *Ocean Acidification due to Increasing Atmospheric Carbon Dioxide*. The Royal Society, London: 65 pp.

Ricciardi A. (2007) Are modern biological invasions an unprecedented form of global change? *Conservation Biology*, **21**, 329–336.

Rickard C.A., McLachlan A., Kerley G.I.H. (1994) The effects of vehicular and pedestrian traffic on dune vegetation in South Africa. *Ocean & Coastal Management*, **23**, 225–247.

de Ruyck A., Soares A.G., McLachlan A. (1997) Social carrying capacity as a management tool for sandy beaches. *Journal of Coastal Research*, **13**, 822–830.

Saba V.S., Santidrian-Tomillo P., Reina R.D., Spotila J.R., Musick J.A., Evans D.A., Paladino F.V. (2007) The effect of the El Nino Southern Oscillation on the reproductive frequency of eastern Pacific leatherback turtles. *Journal of Applied Ecology*, **44**, 395–404.

Scapini F., Ed. (2002). *Baseline Research for the Integrated Sustainable Management of Mediterranean Sensitive Coastal Ecosystems. A Manual for Coastal Managers, Scientists and all Those Studying Coastal Processes and Management in the Mediterranean*. Istituto Agronomico per l'Oltremare, Società Editrice Fiorentina, Firenze: 224 pp.

Schlacher T.A., Thompson L.M.C. (2007). Exposure of fauna to off-road vehicle (ORV) traffic on sandy beaches. *Coastal Management Journal*, **35**, 567–583.

Schlacher T.A., Thompson L.M.C. (2008). Physical impacts caused by off-road vehicles (ORVs) to sandy beaches: spatial quantification of car tracks on an Australian barrier island. *Journal of Coastal Research*, **24**, 234–242.

Schlacher T.A., Schoeman D.S., Lastra M., Jones A., Dugan J., Scapini F., McLachlan A. (2006) Neglected ecosystems bear

0067952

the brunt of change. *Ethology, Ecology & Evolution*, **18**, 349–351.

Schlacher T.A., Dugan J., Schoeman D.S., Lastra M., Jones A., Scapini F., McLachlan A., Defeo O. (2007a) Sandy beaches at the brink. *Diversity & Distributions*, **13**, 556–560.

Schlacher T.A., Thompson L.M.C., Price S. (2007b) Vehicles versus conservation of invertebrates on sandy beaches: quantifying direct mortalities inflicted by off-road vehicles (ORVs) on ghost crabs. *Marine Ecology*, **28**, 354–367.

Schoeman D.S., Richardson A.J. (2002) Investigating biotic and abiotic factors affecting the recruitment of an intertidal clam on an exposed sandy beach using a generalized additive model. *Journal of Experimental Marine Biology & Ecology*, **276**, 67–81.

Schoeman D.S., Wheeler M., Wait M. (2003) The relative accuracy of standard estimators for macrofaunal abundance and species richness derived from selected intertidal transect designs used to sample exposed sandy beaches. *Estuarine, Coastal and Shelf Science*, **58S**, 5–16.

Schoeman D.S., Nel R., Soares A.G. (2008) Measuring species richness on sandy beach transects: extrapolative estimators and their implications for sampling effort. *Marine Ecology*, **29** (Suppl. 1): 134–149.

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

Slott J.M., Murray A.B., Ashton A.D., Crowley T.J. (2006) Coastline responses to changing storm patterns. *Geophysical Research Letters*, **33**, L18404.

Soares A.G. (2003) Sandy beach morphodynamics and macrobenthic communities in temperate, subtropical and tropical regions: a macroecological approach. Ph.D. thesis, University of Port Elizabeth 165 pp.

Solomon S., Qin D., Manning M., Alley R.B., Berntsen T., Bindoff N.L., Chen Z., Chidthaisong A., Gregory J.M., Hegerl G.C., Heimann M., Hewitson B., Hoskins B.J., Joos F., Jouzel J., Kattsov V., Lohmann U., Matsuno T., Molina M., Nicholls N., Overpack J., Raga G., Ramaswamy V., Ren J., Rusticucci M., Somerville R., Stocker T.F., Whetton P., Wood R.A., Wratt D. (2007) Technical Summary. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miler (Eds). *Climate Changes 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, U.K.: 19–91.

Speybroeck J., Bonte D., Courtens W., Gheskiere T., Grootaert P., Maelfait J.P., Mathys M., Provoost S., Sabbe K., Stienen E.W.M., Van Lancker V., Vincx M., Degraer S. (2006) Beach nourishment: an ecologically sound coastal defence alternative? A review. *Aquatic Conservation – Marine and Freshwater Ecosystems*, **16**, 419–435.

Stewart R.R., Ball I.R., Possingham H.P. (2007) The effect of incremental reserve design and changing reservation goals on the long-term efficiency of reserve systems. *Conservation Biology*, **21**, 346–354.

Stillman J.H. (2003) Acclimation capacity underlies susceptibility to climate change. *Science*, **301**, 65.

Stockdon H.F., Sallenger A.H., Holman R.A., Howd P.A. (2007) A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology*, **238**, 1–20.

Trenberth K.E., Jones P.D., Ambenje P., Bojariu R., Easterling D., Klein Tank A., Parker D., Rahimzadeh F., Renwick J.A., Rusticucci M., Soden B., Zhai P. (2007) Observations: Surface and Atmospheric Climate Change. In: Solomon S., Qin D., Manning M. *et al.* (Eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK: 235–336.

UNCED (1992) *United Nations Conference on Environment and Development, Agenda 21, Chapter 17: Protection of the Oceans, All Kinds of Seas, Including Enclosed and Semi-Enclosed Seas, and Coastal Areas and the Protection, Rational Use and Development of Their Living Resources*. United Nations Divison for Sustainable Development, New York, 42 pp.

Walther G.R., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C., Fromentin J.M., Hoegh-Guldberg O., Bairlein F. (2002) Ecological responses to recent climate change. *Nature*, **416**, 389–395.

Webster P.J., Holland G.J., Curry J.A., Chang H.R. (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309**, 1844–1846.

Willis C.M., Griggs G.B. (2003) Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability. *Journal of Geology*, **111**, 167–182.

Wright L.D., Short A.D. (1984) Morphodynamics variability of surf zones and beaches: A synthesis. *Marine Geology*, **56**, 93–118.

Zhang K.Q., Douglas B.C., Leatherman S.P. (2004) Global warming and coastal erosion. *Climate Change*, **64**, 41–58.