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Metrics to assess ecological condition, change, and impacts in sandy beach ecosystems

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ABSTRACT

Complexity is increasingly the hallmark in environmental management practices of sandy shorelines. This arises primarily from meeting growing public demands (e.g., real estate, recreation) whilst reconciling economic demands with expectations of coastal users who have modern conservation ethics. Ideally, shoreline management is underpinned by empirical data, but selecting ecologically-meaningful metrics to accurately measure the condition of systems, and the ecological effects of human activities, is a complex task. Here we construct a framework for metric selection, considering six categories of issues that authorities commonly address: erosion; habitat loss; recreation; fishing; pollution (litter and chemical contaminants); and wildlife conservation. Possible metrics were scored in terms of their ability to reflect environmental change, and against criteria that are widely used for judging the performance of ecological indicators (i.e., sensitivity, practicability, costs, and public appeal). From this analysis, four types of broadly applicable metrics that also performed very well against the indicator criteria emerged: 1.) traits of bird populations and assemblages (e.g., abundance, diversity, distributions, habitat use); 2.) breeding/reproductive performance *sensu lato* (especially relevant for birds and turtles nesting on beaches and in dunes, but equally applicable to invertebrates and plants); 3.) population parameters and distributions of vertebrates associated primarily with dunes and the supralittoral beach zone (traditionally focused on birds and turtles, but expandable to mammals); 4.) compound measurements of the abundance/cover/biomass of biota (plants, invertebrates, vertebrates) at both the population and assemblage level. Local constraints (i.e., the absence of birds in highly degraded urban settings or lack of dunes on bluff-backed beaches) and particular issues may require alternatives. Metrics – if selected and applied correctly – provide empirical evidence of environmental condition and change, but often do not

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reflect deeper environmental values per se. Yet, values remain poorly articulated for many beach systems; this calls for a comprehensive identification of environmental values and the development of targeted programs to conserve these values on sandy shorelines globally.

1. Introduction

Sandy beaches and coastal dunes provide a diverse range of ecosystem services to society (Dugan et al., 2010; Schlacher et al., 2014a). The range of services provided by beach systems creates, however, diverse expectations (e.g. recreation, real estate, wildlife conservation) by the public (McLachlan et al., 2013). These public demands on beach systems need to be addressed by politicians, and people have increasingly divergent views on how these demands should be met by coastal authorities (Maguire et al., 2011). Fundamentally, challenges in beach management arise from a duality of purposes: beaches need to function as sites of intense recreation and other human uses ('development'), whilst also constituting unique habitats and ecosystems that require protection from excessive use (i.e., 'conservation' McLachlan et al., 2013).

Traditional modes of beach management have focused almost exclusively on restoring sand budgets, maintaining beach width, and protecting human infrastructure (Nordstrom, 2000; Nordstrom and Mauriello, 2001; Schlacher et al., 2006). Conversely, the conservation of habitats, species and ecological functions is often a minor aspect of 'beach management' or is technically inadequate (Peterson and Bishop, 2005). Even when the political will does exist to conserve ecological components of beaches, implementation by authorities can be hampered by uncertainty about how to measure ecological change in a way that it can be linked to management and engineering interventions (Field et al., 2007).

Beach management decisions should be based on empirical data (Micallef and Williams, 2002). Ideally, these data should be scientifically robust, presentable in a form that can be interpreted by non-specialists, and link to ecological features with public appeal. We suggest that these basic requirements could be met by a careful selection of metrics (synonymous here with 'variables' or 'indicators') that would work for many beach assessments and monitoring programs. Selecting ecologically meaningful, robust, cost-effective, and appealing metrics is, however, not trivial. There now exists a substantial body of published work documenting human impacts on beach ecosystems (Schlacher et al., 2014a and references therein), measured using a large number of diverse metrics: this diversity can pose complex choices for environmental managers.

Physical properties commonly measured for beach systems encompass aspects of the size, configuration, geometry, and sediment properties of the shore (Barnard et al., 2012; Harris et al., 2011a; Ortega et al., 2013; Revell et al., 2011; Schlacher and Morrison, 2008; Schlacher et al., 2012; Schlacher and Thompson, 2012; Schlacher et al., 2008c; Thompson and Schlacher, 2008). Coastal strand and dune plants alter the shore by capturing windblown sand, thereby promoting the formation of new coastal topography, the accumulation of sand, and the creation of habitats for other biota (Dugan and Hubbard, 2010; Nordstrom et al., 2012).

Metrics that capture functional processes in beach systems mainly include variables related to the processing of organic matter, nutrient remineralisation and flows, and animal behaviour and activity (Barreiro et al., 2011, 2012; Dugan et al., 2003; Dugan et al., 2011; Garrido et al., 2008; Gómez et al., 2013; Huijbers et al., 2013; Lastra et al., 2008; Scapini, 2013; Schlacher et al., 2010, 2013b). Trophic metrics encompass aspects of predator–prey interactions and foraging ecology (Manning et al., 2013; Peterson et al., 2006, 2013; Schlacher et al., 2014b), and stable isotope markers to reconstruct diets (Bergamino et al., 2012), and to trace the transfer of contaminants from estuaries to beach systems (Schlacher and Connolly, 2009).

Because the first biological response to anthropogenic disturbance is often a behavioural one, changes in animal behaviour are often sensitive and suitable indicators (Scapini et al., 2005; Schlacher et al., 2013a). Vertebrates generally react strongly to direct human interferences or to modifications of their habitat, as illustrated by shifts in the behavioural profile of shorebirds disturbed by vehicles on beaches (Schlacher et al., 2013a, 2013c; Weston et al., 2014), and reduced feeding efficiency of fishes foraging in more turbid surf zones off nourished beaches (Manning et al., 2013). Examples of behavioural changes in invertebrates include altered burrowing performance following beach nourishment (Manning et al., 2013; Viola et al., 2013), changes to orientation on armoured coastlines (Nourisson et al., 2014), or compression of home ranges in ghost crabs exposed to vehicle traffic (Schlacher and Lucrezi, 2010).

The most commonly-used structural biological metrics encompass the occurrence, distribution, and population size of single species (e.g. Gómez and Defeo, 2012; Schlacher et al., 2007b), or the structural properties of communities (e.g. Walker et al., 2008). Metrics at the community level usually comprise compound measures of 'quantity' (e.g., total abundance, biomass, cover) and various statistics of 'diversity' (e.g., species richness, diversity indices, species turnover – beta diversity); these are usually measured for subgroups of the beach biota that are, by convention, categorised by body size: i) microscopic protists (Azovsky et al., 2013); ii) 'small' (0.063–1 mm) meiofauna (Schlacher and Hartwig, 2013); and iii) 'larger' (>1 mm) invertebrates, most of which live beneath the surface of the sand (Defeo and McLachlan, 2013; Harris et al., 2011b; Jaramillo et al., 2012; Schlacher et al., 2011b; Walker and Schlacher, 2011). Vulnerable invertebrates of the upper beach near the dunes and driftline are especially sensitive indicators, particularly for monitoring local extirpations and habitat loss (Hubbard et al., 2013).

The surf zones of beaches are important habitats for a diverse fish and invertebrate fauna, that underpin regionally important fisheries (Bennett and Attwood, 1991; Beyst et al., 1999; Haynes et al., 2011; McLachlan et al., 1996). Studies investigating the effects of fishing on beach biota usually use part of the standard suite of variables used in other fisheries assessments (e.g., population size, landings, size structure; Schoeman, 1996) and, more recently, also assess the links between the population dynamics of beach fisheries species and climate variability (e.g. Ortega et al., 2012).

Beach vertebrates (including those of the functionally linked surf zones and dunes) comprise an underappreciated but highly diverse fauna of birds, reptiles, mammals, fishes, and amphibians (Peterson et al., 2013). Many vertebrates found on beaches are functionally dependent on these habitats, as poignantly illustrated by threatened bird and turtle species that nest only on ocean beaches and in the supralittoral zones and dunes behind beaches (Maslo et al., 2011; Schlacher et al., 2014a, 2013a; Schoeman et al., 2014; Wallace et al., 2011). Consequently, population sizes, distributions, nesting activities, and breeding success of birds and marine turtles are frequently-used metrics (Dugan and Hubbard, 2006; Dugan et al., 2003, 2008; Maslo et al., 2011; Nel et al., 2013).

The above précis of the diversity of variables put forward in the literature illustrates the challenges inherent in identifying which metric, or set of metrics, is best suited to undertake empirical data collections designed to assess the effects of human activities on ecological properties of beach ecosystems. Reviews about the type and severity of ecological impacts linked to particular human activities on beaches are available (Brown et al., 2008; Defeo et al., 2009; Schlacher et al., 2007a, 2014a). However, what many coastal managers and conservation practitioners do not have is information about which indicators to use for the issues they commonly encounter on beaches. No published advice on how to select metrics for environmental evaluations of sandy beach ecosystems exists: the literature on beaches lacks a 'guide' (or basic set of criteria and framework) that practitioners can use to make better-informed decisions concerning what features or attributes to measure in order to address a specific environmental, management or conservation issue on sandy shores. We aim to address this gap by constructing a framework that helps with metric selection; this framework is based on transparent criteria that are linked to common environmental management issues for ocean beaches, surf zones and coastal dunes.

2. Methods

Our primary objective is to bring rigour to the selection of metrics that will be useful across a range of management scenarios that regional and local authorities regularly face on sandy shores. This requires three complementary elements to be in place: 1.) knowledge of the main categories of broad issues that most likely require interventions by regional and coastal authorities; 2.) a list of metrics that could be used in environmental assessments for sandy beach ecosystems; and 3.) a system for evaluating how well individual metrics perform in two areas: a.) the number and type of issues for which they can sensibly provide useful empirical data, and b.) the scores they achieve when judged in their performance against a set of criteria that are commonly employed for ecological indicators.

Throughout the paper we use the term 'metric' as being synonymous with 'indicator' or 'variable'. Our definition of 'sandy—beach system' encompasses the non-vegetated part of the sandy shoreline located between the swash and the dunes but, importantly, also extends to the dunes landwards of it and the surf-zone seawards of it: both of these compartments are functionally closely linked to the beach between the tide marks. Thus, 'beach systems', as used here and elsewhere (McLachlan and Brown, 2006), represent a tripartite dune-beach-surf unit. Whilst many of the metrics included here would also pertain to more sheltered shores (i.e., mudflats, estuarine beaches), the reported scores apply to high-energy, exposed ocean beaches.

2.1. Issues

We consider six categories of issues: coastal erosion; habitat loss; recreation; fishing; contamination (litter and chemical pollution); and wildlife conservation. These are the types of issues that coastal authorities (mostly at local and regional level) are frequently required to address and manage, and we identified them from three complementary sources: 1.) recent syntheses of threats to sandy beaches (Brown and McLachlan, 2002; Brown et al., 2008; Defeo et al., 2009; Dugan et al., 2010; Nordstrom, 2008; Nordstrom et al., 2011; Schlacher et al., 2007a, 2008b, 2006); 2.) workshops held on the topic of beach management during the last three International Symposia on Sandy Beaches (Spain, 2006; Morocco, 2009; South Africa, 2012); and 3.) our experience, both as professional scientists and through frequent interactions with coastal management authorities. We explicitly exclude the general effects of climate change (e.g., ocean warming and acidification), because tangible responses to these threats are beyond the remit of regional and local authorities.

2.2. Metrics

The range of metrics in any system is essentially infinite, or at least exceptionally large. Thus, a sensible selection is required that reflects current and past practice in the field, while also encompassing emerging technologies. In this context, the list we present is drawn from published accounts (reviewed in Defeo et al., 2009; Schlacher et al., 2014a) and from identifying functional traits that have been shown to be important on beaches (e.g. respiration Coupland et al., 2007). This yielded a list of 37 metrics. Of these, four metrics represent physical attributes of the system (e.g., foredune dimensions, beach geometry, filtration rate, grain size), and 33 represent biological and ecological traits and processes; the latter range from changes in invertebrate behaviour to the nesting frequency and breeding success of vertebrates (Table 2). There are more ($n = 24$) metrics that represent structural attributes (e.g., width of the intertidal, population size of meiofauna) than metrics that represent functions ($n = 13$; e.g., respiration and scavenging rates). Metrics were numerically scored (see below) on the extent to which they could reflect changes and impacts to the system caused by a particular anthropogenic stressor: scores ranged from 0 (no link to stressor or unsuitable) to 5 (strong and persistent link) and are further defined in Table 1.

Governments are widely mandated to manage pathogen-related health risks to swimmers and other recreationists on beaches. Risks are usually assessed by regularly monitoring the levels of faecal indicator bacteria in the surf-zone of beaches in comparison to legislated health standards (Halliday and Gast, 2011). Such monitoring of human health risks is not intended to reflect ecological conditions per se and is therefore not included in the evaluation of ecological metrics in this paper.

2.3. Criteria

We use four performance criteria that emerge as a common theme in the literature on ecological indicators (summarized in Schlacher et al., 2011a): 1.) '*sensitivity*' — this reflects the degree and consistency with which a metric responds physically or biologically to a human stressor; 2.) '*practicability*' — this reflects whether measurements can be taken within reasonable logistical constraints and without risk to personnel; 3.) '*cost*' — this reflects the financial resources required per unit of measurement/replication; and 4.) '*public appeal*' — this reflects the likelihood and degree of acceptance and uptake by the public and politicians. Each metric was scored from 1 (worst) to 5 (best) against each criterion; definitions of scores are given in Table 1.

2.4. Scoring and assessment process

The core principle underlying our method used to evaluate metrics in terms of their performance against indicator criteria and against a set of common environmental issues was to use *crowd wisdom*. The philosophical and empirical underpinning of the approach is the premise that a collection of people can generally produce a more accurate, aggregate prediction than individuals (Surowiecki, 2005). Crowd wisdom is best suited for problems that involve optimization (the situation at hand here), and we sought consensus of scores among the authors. In terms of process, three of

Table 1
Definitions of criteria used to assess metrics using numerical scores ranging between 5 (‘best’) to 0 (‘worst’).

Target issue
5 = Always strongly reflects changes caused by a particular pressure; very well-known mechanistic links to issue;
4 = Often strongly reflects changes caused by a particular pressure; known mechanistic links to issue;
3 = Generally reflects only limited aspects of changes caused by a particular pressure; uncertain mechanistic links to issue;
2 = Seldom reflects limited changes caused by a particular pressure; tenuous and uncertain mechanistic links to issue;
1 = Rarely reflects any changes caused by a particular pressure; no or unknown mechanistic links to issue;
0 = Unsuitable

Sensitivity
5 = Strong and consistent changes in response to pressure, supported by extensive peer-reviewed literature;
4 = Strong and consistent changes in response to pressure, supported by at least one peer-reviewed scientific study;
3 = Changes small and/or variable, mixed support from the literature;
2 = Plausible, based on sound theoretical expectation, no published study in support though;
1 = No relevant data or empirical evidence to suggest a response to pressure;
0 = Published evidence that variable does not respond to the pressure in question;

Practicability
5 = All aspects of the study can be undertaken with minimal equipment and training. No significant risks involved. No on-site requirement for vehicle or vessel (e.g., measuring dimensions of foredunes);
4 = Does not require equipment that is not readily available in a basic environmental laboratory. Some training required. All associated risks are small and manageable. No on-site requirement for vehicle or vessel (e.g., bird counts);
3 = Does not require equipment that is not readily available in a standard environmental laboratory. Some advanced training required. Some hazardous activities possible. No on-site requirement for vehicle or vessel (e.g., collections of intertidal invertebrates);
2 = Requires specialized equipment and/or skills not available in a standard environmental laboratory. Can involve risky activities. Vehicle or vessel required on site. (e.g., fish netting in the surf zone; collections of venomous and/or protected reptiles in dunes);
1 = Requires highly specialised skills and equipment (at least some of which must be custom-built). Variable risk (can be severe). Vehicle or vessel required (e.g., collection of fish in the surf zone using inflatable boats);
0 = Extremely hazardous or unmanageable risks. (e.g., taking benthic cores on SCUBA in heavy surf).

Cost
5 = Gratis or negligible cost (e.g., volunteers collect and process data without supervision);
4 = Small cost (e.g., bird counts by ornithological groups, with some supervision).
3 = Moderates cost (e.g., geo-surveys and sediment analyses).
2 = High cost (e.g., full biodiversity survey of various beach habitats)
1 = Very high cost (e.g., isotope pulse-chase experiments to measure carbon cycling on multiple beach types).
0 = Prohibitively expensive (e.g., high-resolution linked ocean-atmosphere general circulation model including all surf zones, globally)

Public appeal
5 = Iconic species or habitats of great public concern, and for which the public is prepared to fight (e.g., turtles, birds of prey);
4 = General public appeal and of great conservation concern (e.g., shorebirds, fish and some mammals);
3 = Public support possible, but not overly strong (e.g., dune vegetation, protected insect species);
2 = Public largely ignorant; occasional interest possible (e.g., beach invertebrates if usable for bait or food);
1 = Public indifferent (e.g., invertebrates not usable for bait or food, nutrient cycling, respiration rates);
0 = Public antagonism (e.g., feral predators/scavengers).

the authors (TAS, DS, AJ) first assigned preliminary scores for each metric. Scoring in this step used the criteria listed in Table 1 that were cross-checked against specific studies from the literature where required. A brief justification was provided in each case for the numeric value assigned (e.g., “*numerous studies demonstrating a strong negative effect of off-road vehicles on shorebirds and benthic invertebrates*”). In a second step, these draft scores were critiqued and re-evaluated by the full group of remaining authors, working independently. Finally, we synthesized all scores and critiques, arriving at final scores that represent a shared view. Generally, this consensus represents the mode of individual scores that individual authors had assigned for each combination of metric x issue or performance criterion, moderated only in cases where additional evidence or arguments - backed up by published case studies - became available.

Whilst consensus reflects shared expertise and collective intelligence, it is possible for groupthink to bias the result (i.e. a psychological phenomenon within a group where conformity and consensus can lead to incorrect outcomes; Janis, 1982). To safeguard against intrusion of strong groupthink, we used the maxim of vigilant appraisal in the form of three procedures known to act against groupthink: 1.) the lead authors explicitly assigned other group members the role of ‘critical evaluator’; 2.) each author assessed scores separately and independently; and 3.) the lead authors did not influence the scoring and evaluation by others. Despite these safeguards (conceptually resembling a Delphi process sensu MacMillan and Marshall, 2006), we cannot exclude the possibility that synoptic scores might partially represent an *argumentum ad populum* (i.e., a fallacy that concludes a proposition to be true because many believe it (Damer, 2013)). We are nevertheless confident in asserting that the scores accurately represent a consensus that reflects the best understanding currently held by those contributing to the group outcomes, and one that is based upon a foundation of logic and systematic, published evidence wherever available.

It is, however, important to recognise that a number of unavoidable caveats emerge using the above method: 1.) the published scores should be viewed as the most probable midpoints of ranges (i.e., higher or lower scores are possible); 2.) all scores reflect a ‘global’ scenario that is likely to apply in many situations on many beaches (i.e., specific local conditions may well alter the scores, but any major departure will need to be well justified); 3.) the scores are neither prescriptive nor static (i.e., we expect them to change over time as new scientific evidence and techniques becomes available — a key property of the scientific method).

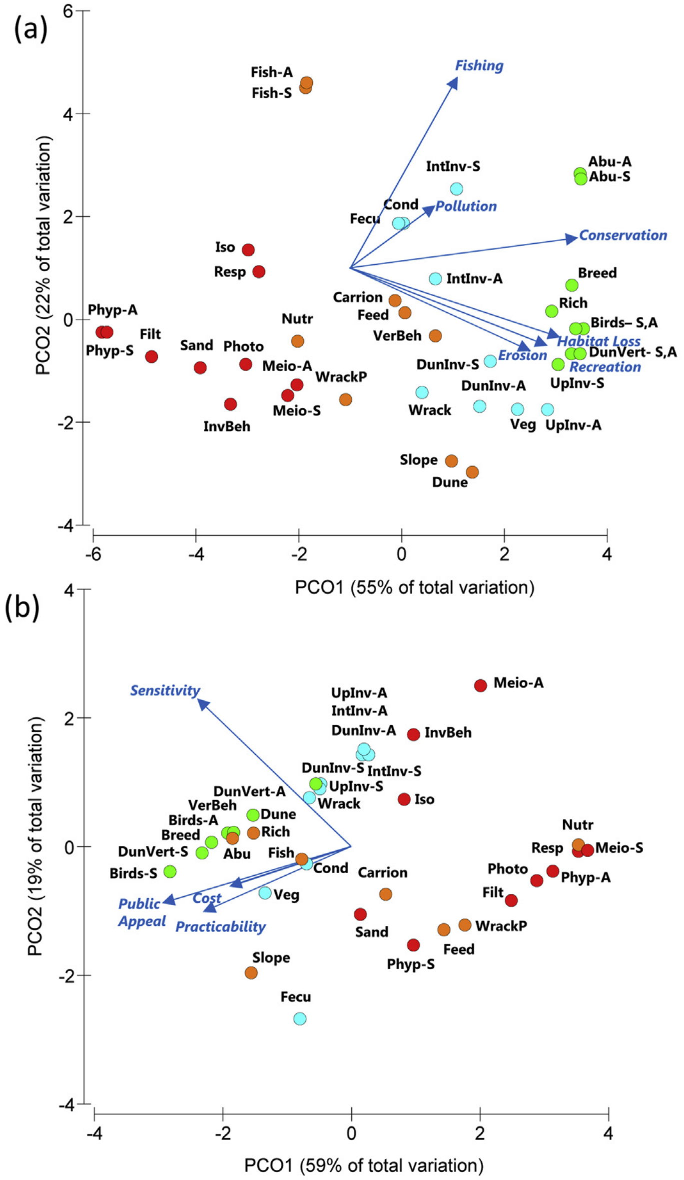
3. Results

3.1. Addressing issues

Evaluation of the suite of metrics in terms of how well a particular metric can assess a particular environmental issue shows a very wide range of suitability scores (Table 2, Fig. 1a). A cluster of metrics, comprising phytoplankton and filtration rates, was assessed as to only rarely reflect any aspect of the pressure or to be only tenuously linked to an issue of concern. Six types of metrics scored highly: 1.) aggregate measures of abundance/biomass/cover of biota, 2.) shorebirds, 3.) breeding/reproductive success; 4.) species richness, 5.) dune vertebrates, and 6.) macroinvertebrates of the upper beach. Measurements of abundance/biomass/cover of biota, at both the species and assemblage level, are thought to be applicable in most situations, chiefly because anthropogenic modifications to habitats and direct pressures on species result in significant changes to the ‘quantity’ of biological entities in most beach systems; similarly, estimates of species richness will also be

Table 2
Metrics scored based on their ability to consistently reflect changes and impacts to the system linked to a particular anthropogenic stressor, or their capacity to yield ecologically-meaningful data for a particular management issue of interest. Scores range from 0 (unsuitable or no link to stressor) to 5 (strong and persistent link) and are further defined in Table 1; ranks are based on mean scores across the six issues (ranked from 1 = greatest ability).

Metric	Erosion	Recreation	Fishing	Habitat Loss	Conservation	Pollution	Rank
A Physical							
A1 Functional							
Filtration rates	1	2	0	1	0	3	35
A2 Structural							
Intertidal width, slope and sand-grain size	5	3	0	5	4	0	22
Foredune dimensions (e.g., height, width)	5	4	0	5	4	0	19
Grain size	3	2	0	0	2	1	34
B Biological – Ecological							
B1 Functional							
Rates and Processes							
Sediment nutrient cycling rates	2	3	1	3	1	4	26
Photosynthesis rates	2	1	0	3	1	4	32
Wrack processing rates	2	4	0	3	3	2	26
Carrion consumption rates	2	4	2	4	3	3	19
Feeding and predation rates	2	4	2	3	4	2	22
Respiration rates	2	2	2	2	1	4	28
Condition and Reproduction							
Tissue stable isotope ratios	1	2	2	2	1	5	28
Condition indices (e.g., body, gonadosomatic)	2	3	3	3	4	4	16
Fecundity	2	3	3	3	4	4	16
Breeding success (birds, turtles, fish)	4	5	3	5	5	4	
Behaviour							
Invertebrate behaviour	2	3	0	2	1	1	33
Vertebrate behaviour	2	5	2	4	4	1	19
B2 Structural							
Plants: wrack and phytoplankton							
Vegetation: dunes and coastal strand	4	4	0	5	5	4	11
Wrack (e.g., amount, composition)	3	4	0	4	3	5	16
Phytoplankton (single species)	1	1	0	0	0	3	36
Phytoplankton (assemblage)	1	1	0	0	0	3	36
Animals							
Invertebrates							
Microbiota and Meiofauna (single species)	3	3	0	2	2	2	31
Microbiota and Meiofauna (assemblage)	3	3	0	2	2	3	28
Macroinvertebrates: supratidal and dunes (single species)	4	4	1	4	5	3	13
Macroinvertebrates: supratidal and dunes (assemblage)	4	4	0	4	5	3	14
Macroinvertebrates: upper intertidal, strandline and driftline (single species)	4	5	1	5	5	5	6
Macroinvertebrates: upper intertidal, strandline and driftline (assemblage)	4	5	0	5	5	5	10
Macroinvertebrates: intertidal (single species)	3	4	5	4	3	3	11
Macroinvertebrates: intertidal (assemblage)	3	4	3	4	3	3	14
Vertebrates							
Dune vertebrates (single species)	5	5	2	5	5	3	6
Dune vertebrates (assemblage)	5	5	2	5	5	3	6
Shorebirds (single species)	5	5	2	5	5	5	3
Shorebirds (assemblage)	5	5	2	5	5	5	3
Surf vertebrates (single species)	2	1	5	0	5	2	24
Surf vertebrates (assemblage)	2	1	5	0	5	2	24
Aggregate measures							
Abundance, cover or biomass (taxon level)	4	4	5	5	5	5	1
Abundance, cover or biomass (assemblage level)	4	4	5	5	5	5	1
Richness (species, taxonomic entities)	4	4	2	5	5	5	6



Abu-A - Abundance, cover or biomass (assemblage level); *Abu-S* - Abundance, cover or biomass (taxon level); *Birds-A* - Shorebirds (assemblage); *Birds-S* - Shorebirds (single species); *Breed* - Breeding success (birds, turtles, fish); *Carrion* - Carrion consumption rates; *Cond* - Condition indices (e.g. body, gonadosomatic); *Dune* – Foredune dimensions (e.g. height, width); *DunInv-A* - Macroinvertebrates: supratidal & dunes (assemblage); *DunInv-S* - Macroinvertebrates: supratidal & dunes (single species); *DunVert-A* - Dune vertebrates (assemblage); *DunVert-S* - Dune vertebrates (single species); *Fecu* - Fecundity ; *Feed* - Feeding & predation rates; *Filt* - Filtration rates; *Fish-A* - Surf vertebrates (assemblage); *Fish-S* - Surf vertebrates (single species); *IntInv-A* - Macroinvertebrates: intertidal (assemblage); *IntInv-S* - Macroinvertebrates: intertidal (single species); *InvBeh* - Invertebrate behaviour; *Iso* - Tissue stable isotope ratios; *Meio-A* - Microbiota and Meiofauna (assemblage); *Meio-S* - Microbiota and Meiofauna (single species); *Nutr* - Sediment nutrient cycling rates; *Photo* - Photosynthesis rates; *Phyp-A* - Phytoplankton (assemblage); *Phyp-S* - Phytoplankton (single species); *Resp* - Respiration rates; *Rich* - Richness (species, taxonomic entities); *Sand* - Grain size; *Slope* - Intertidal width & slope; *UpInv-A* - Macroinvertebrates: upper intertidal, strandline & driftline (assemblage); *UpInv-S* - Macroinvertebrates: upper intertidal, strandline & driftline (single species); *Veg* - Vegetation: dunes & coastal strand ; *VerBeh* - Vertebrate behaviour; *Wrack* - Wrack (e.g. amount, composition); *WrackP* - Wrack processing rates.

Fig. 1. Ordination diagrams (principal coordinates analysis) based on similarities (Euclidean distances on untransformed scores) of metrics in terms of a) links to specific environmental issues, and b) performance against common criteria for ecological indicators (cf. Tables 2 and 3 for individual scores). Colour coding reflects quartiles of ranked mean scores for each set of criteria: Q1 = red, Q2 = orange, Q3 – turquoise, Q4 = green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

applicable in many cases (Table 2, Fig. 1a). Ocean beaches are critical nesting, feeding, and roosting areas for a diversity of bird species, and human activities have been widely demonstrated to have negative outcomes for individual species and whole assemblages of birds on beaches; consequently metrics reflecting shorebird attributes (e.g., abundance, diversity, habitat use, distributions, assemblage structure) are applicable in many situations. Because reproduction and breeding are frequently critical parts of a species' lifecycle, and are often highly sensitive to, for example, human interference (e.g., loss of dunes for turtle and bird nesting; predation of birds by dogs; disturbance of birds, especially of nesting adults and pre-fledgling juveniles), measurements of breeding success and recruitment performance should be very widely applicable in many beach assessments (Table 2, Fig. 1a). Vertebrates associated with coastal dunes, particularly nesting turtles and birds at the interface between the dunes and the beach, are functionally dependent on these habitats for reproduction; hence, changes to the size and structure of vertebrate populations, their distributions, and the composition of vertebrate assemblages are sensible variables to detect anthropogenic pressures in many cases. Macroinvertebrates of the upper beach, including those associated with strandlines, can be particularly sensitive to human activities, due to particular life-history characteristics (e.g., species that brood embryos and hence lack larvae, resulting in low dispersal capabilities), and due to the spatial concentration of anthropogenic habitat changes in this zone. Consequently, invertebrates of the upper beach score highly in adequately addressing multiple issues (Table 2, Fig. 1a).

Assessments of fisheries issues will often require metrics that are very specific to the species or assemblage being targeted (i.e., population dynamics of invertebrates and fishes). Also, fishing often targets species in the surf zone (the exception being clam fisheries that extend into the intertidal), whereas many other pressures are directed more towards the beach above the swash zone and the dunes. Consequently, metrics representing surf-zone fishes (at the population and assemblage level) score highly for fisheries issues, but are otherwise seldom of primary concern for subaerial beaches and dunes (Table 2, Fig. 1a). Metrics that reflect functional aspects of beach systems are particularly important to detect and quantify pollution impacts, notably changes to isotope signature in tissues and the rate at which beach systems process nutrients and organic matter. These functional measures are important complements to structural measures such as changes to the abundance and community structure of assemblages following pollution events (Table 2, Fig. 1a).

3.2. Meeting indicator criteria

'Sensitivity' is an important requirement for any variable used in environmental assessments, stipulating that a metric responds (ideally in a predictable and monotonic way) to the pressure of interest and that the probability and amplitude of the response are sufficiently well documented in the literature. A sizeable number of metrics was deemed as showing strong and consistent changes in response to human pressures, backed up by the peer-reviewed literature; these included three functional measures (breeding success, invertebrate behaviour, vertebrate behaviour) and 16 structural aspects encompassing the following: foredune dimensions, wrack, invertebrates and vertebrates at both the population and assemblage level, compound measurements of abundance/biomass/cover, and species richness (Table 3, Fig. 1b).

Collections of empirical data should also be logistically feasible within reasonable limits and not be unacceptably hazardous — metrics should be 'practicable'. We identified measurements representing dimensions of foredunes (e.g., height, width, integrity) as the metric with the highest score for this criterion (Table 3, Fig. 1b): surveys of foredunes usually require only basic equipment, can make use of free remote sensing data for synoptic surveys, and usually carry minimal risks. Other metrics that are feasible and relatively risk-free are: 1.) quantifying changes in grain size and beach geometry; 2.) collecting basic data on fecundity and reproductive performance (e.g., nesting frequency, number of eggs per nest, hatching and fledging rates); 3.) surveying vegetation of the dunes and strandline (e.g., species composition, recruitment, distributions); 4.) quantifying wrack deposition and composition; and 5.) undertaking basic counts of vertebrates associated primarily with dunes and of shorebirds (Table 3, Fig. 1b).

Most environmental programs are financially constrained, making cost an important consideration. Data on wrack (e.g., biomass, distribution, composition) and shorebird counts can usually be obtained with small investments, particularly when trained volunteers are part of the program (Table 3, Fig. 1b). Ornithological groups and other naturalist societies can contribute valuable data on vertebrate populations and behaviour, and this may also be possible for vegetation surveys (Table 3, Fig. 1b). Metrics concerning any type of invertebrate assemblage - from meiofauna and macrobenthos to dune arthropods — at a useful level of taxonomic resolution - are often expensive to use in modern environmental evaluations (Table 3, Fig. 1b). These metrics are expensive because of high labour costs incurred during sorting and identification. The work also requires highly specialised skills in taxonomy, generally limiting the likelihood of involving volunteers in many cases.

Data are collected to make decisions about the use and management of sandy shorelines. These decisions have, however, complex histories and attributes: politicians must make them, bureaucrats must implement them, and the public is asked to support them. Thus, evaluations that include metrics which the public knows and values highly are, arguably, more likely to translate into conservation and management outcomes that have sustained socio-cultural backing. Components of beach systems that the public generally supports strongly - to the point of passionate advocacy — are vertebrates (fish, birds, turtles) and aspects relating to their 'well-being' and conservation (e.g., health, nesting success, fledgling and hatchling survival) - these are all metrics scoring very highly in our analysis (Table 3, Fig. 1b). Because wider beaches enhance the recreational experience, people generally feel strongly about beach width. The occurrence of nuisance or harmful algal blooms in the surf zone can also be an issue of considerable public concern as can water quality and pollution (Table 3, Fig. 1b).

3.3. 'Performance'

'Performance', when measured in terms of the range of issues that a metric is likely to be useful for, is highly correlated ($r = 0.73$, $P < 0.001$) with 'performance' when measured in terms of meeting a set of indicator criteria (Fig. 2). Four types of metrics are applicable to address several issues (i.e., good issue coverage), and meet indicator criteria at high scores (i.e., good criterion compliance); these metrics are: 1.) bird populations and assemblages on ocean beaches — these can be quantified using an array of variables (e.g., abundance, diversity, distributions, habitat use, assemblage structure, species composition); 2.) reproductive performance, breeding success, or recruitment rates- these are conventionally measured in birds and turtles, but are also highly applicable and meaningful for invertebrates and plants; 3.) vertebrate species that make regular use of dunes and beaches or that are functionally dependent on them for nesting, roosting, or feeding; traditionally, metrics for beach and dune vertebrates at the population level focus on turtles and birds of conservation concern, but mammals and reptiles other than turtles can be included here; and 4.) compound measurements of the abundance/cover/biomass of biota (plants, invertebrates, vertebrates) at both the population and assemblage level.

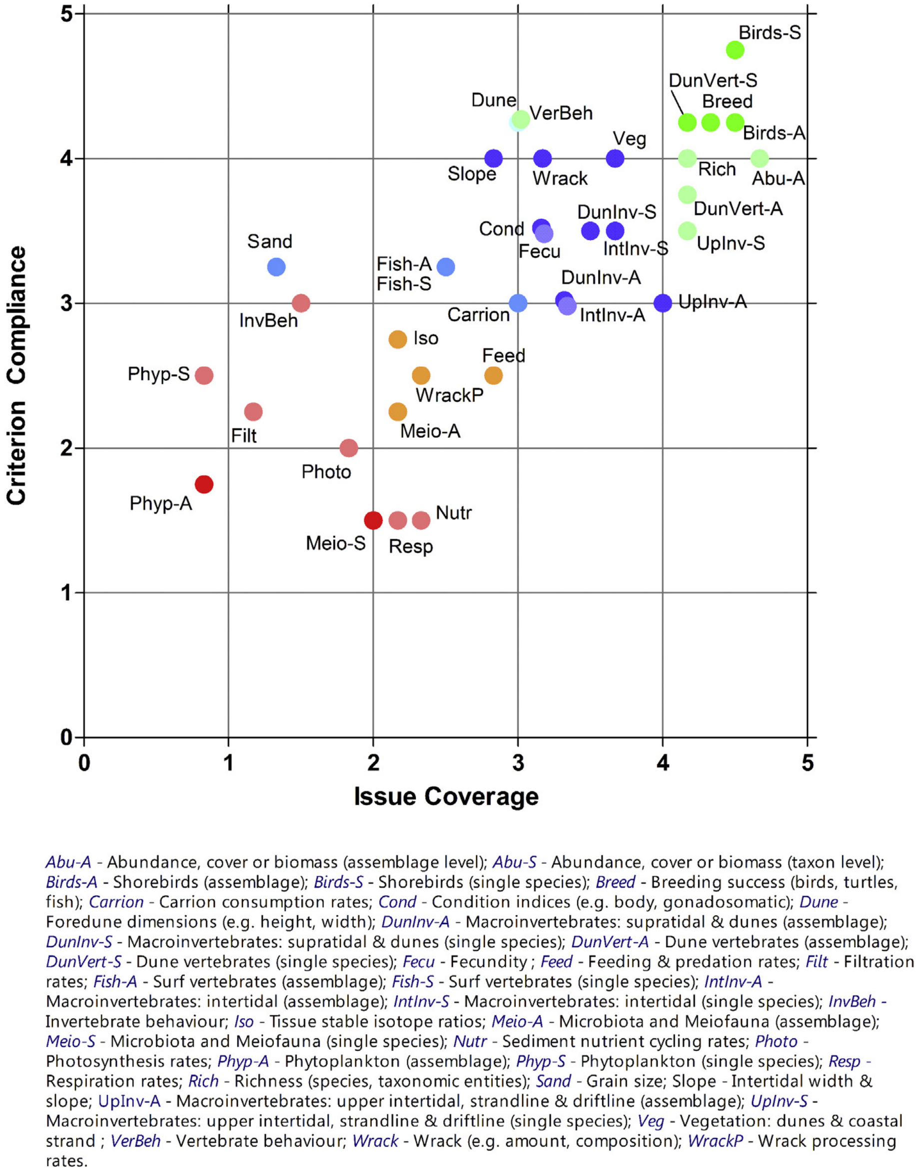
4. Discussion

4.1. From a few common metrics to a systematic selection

How increasingly intense and widespread modifications of coastal systems by humans have impacted dunes and sandy shores has been assessed using several physical, chemical, and biological measures (Carruthers et al., 2013; Defeo et al., 2009; Schlacher

Table 3
Performance of metrics against four criteria widely applied to assess ecological indicators. Scores for each criterion are explained in detail in Table 1, but generally range from 1 (very poor/fail) to 5 (very good); ranks are based on mean scores across the six issues (ranked from 1 = highest performance).

Metric	Sensitivity	Practicability	Cost	Public Appeal	Rank
A Physical					
A1 Functional					
Filtration rates	2	3	3	1	31
A2 Structural					
Intertidal width, slope and sand-grain size	3	4	4	5	7
Foredune dimensions (e.g., height, width)	5	5	4	3	2
Grain size	3	4	3	3	19
B Biological – Ecological					
B1 Functional					
Rates and Processes					
Sediment nutrient cycling rates	2	1	2	1	35
Photosynthesis rates	2	2	3	1	33
Wrack processing rates	2	3	3	2	28
Carrion consumption rates	3	3	3	3	22
Feeding and predation rates	2	2	3	3	28
Respiration rates	2	1	2	1	35
Condition and Reproduction					
Tissue stable isotope ratios	4	1	3	3	27
Condition indices (e.g., body, gonadosomatic)	4	3	3	4	14
Fecundity	2	4	3	5	14
Breeding success (birds, turtles, fish)	5	4	3	5	2
Behaviour					
Invertebrate behaviour	5	3	3	1	22
Vertebrate behaviour	5	4	4	4	2
B2 Structural					
Plants: wrack and phytoplankton					
Vegetation: dunes & coastal strand	4	4	4	4	7
Wrack (e.g., amount, composition)	5	4	5	2	7
Phytoplankton (single species)	2	2	2	4	28
Phytoplankton (assemblage)	2	2	2	1	34
Animals					
Invertebrates					
Microbiota and Meiofauna (single species)	2	1	2	1	35
Microbiota and Meiofauna (assemblage)	5	1	2	1	31
Macroinvertebrates: supratidal and dunes (single species)	5	3	3	3	14
Macroinvertebrates: supratidal and dunes (assemblage)	5	2	2	3	22
Macroinvertebrates: upper intertidal, strandline and driftline (single species)	5	3	3	3	14
Macroinvertebrates: upper intertidal, strandline and driftline (assemblage)	5	2	2	3	22
Macroinvertebrates: intertidal (single species)	5	3	3	3	14
Macroinvertebrates: intertidal (assemblage)	5	2	2	3	22
Vertebrates					
Dune vertebrates (single species)	5	4	3	5	2
Dune vertebrates (assemblage)	5	2	3	5	13
Shorebirds (single species)	5	4	5	5	1
Shorebirds (assemblage)	5	3	4	5	2
Surf vertebrates (single species)	4	2	2	5	19
Surf vertebrates (assemblage)	4	2	2	5	19
Aggregate measures					
Abundance, cover or biomass (taxon level)	5	3	3	5	7
Abundance, cover or biomass (assemblage level)	5	3	3	5	7
Richness (species, taxonomic entities)	5	3	3	5	7



Abu-A - Abundance, cover or biomass (assemblage level); *Abu-S* - Abundance, cover or biomass (taxon level); *Birds-A* - Shorebirds (assemblage); *Birds-S* - Shorebirds (single species); *Breed* - Breeding success (birds, turtles, fish); *Carrion* - Carrion consumption rates; *Cond* - Condition indices (e.g. body, gonadosomatic); *Dune* - Foredune dimensions (e.g. height, width); *DunInv-A* - Macroinvertebrates: supratidal & dunes (assemblage); *DunInv-S* - Macroinvertebrates: supratidal & dunes (single species); *DunVert-A* - Dune vertebrates (assemblage); *DunVert-S* - Dune vertebrates (single species); *Fecu* - Fecundity ; *Feed* - Feeding & predation rates; *Filt* - Filtration rates; *Fish-A* - Surf vertebrates (assemblage); *Fish-S* - Surf vertebrates (single species); *IntInv-A* - Macroinvertebrates: intertidal (assemblage); *IntInv-S* - Macroinvertebrates: intertidal (single species); *InvBeh* - Invertebrate behaviour; *Iso* - Tissue stable isotope ratios; *Meio-A* - Microbiota and Meiofauna (assemblage); *Meio-S* - Microbiota and Meiofauna (single species); *Nutr* - Sediment nutrient cycling rates; *Photo* - Photosynthesis rates; *Phyp-A* - Phytoplankton (assemblage); *Phyp-S* - Phytoplankton (single species); *Resp* - Respiration rates; *Rich* - Richness (species, taxonomic entities); *Sand* - Grain size; Slope - Intertidal width & slope; UpInv-A - Macroinvertebrates: upper intertidal, strandline & driftline (assemblage); *UpInv-S* - Macroinvertebrates: upper intertidal, strandline & driftline (single species); *Veg* - Vegetation: dunes & coastal strand ; *VerBeh* - Vertebrate behaviour; *Wrack* - Wrack (e.g. amount, composition); *WrackP* - Wrack processing rates.

Fig. 2. Comparison of metrics based on mean scores of issue coverage and compliance with ecological indicator criteria. Colour coding reflects position of metrics in the bivariate space, ranging from red denoting low criterion and issue compliance (lower left) to green denoting metrics that perform very well (>4, upper right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2007a; Schlacher et al., 2014a; reviewed by Schlacher et al., 2006). Assessments include responses to specific pressures or to more generalized threats arising from the escalating use of beaches and the transformations of dune habitats globally. Examples of specific pressures and the metrics employed to measure their impacts include: nourishment – birds, invertebrates, and fish (Manning et al., 2013; Peterson et al., 2006; Schlacher et al., 2012); beach grooming or raking – birds, invertebrates, beach-nesting fish, and dune plants (Dugan and Hubbard, 2010; Dugan et al., 2003; Martin et al., 2006; Nel et al., 2013); oil spills – invertebrates, birds (Andres, 1997; Schlacher et al., 2011b); coastal armouring – beach zones/habitats, invertebrates, birds, and turtles (Dugan et al., 2008; Jaramillo et al., 2012; Lucrezi et al., 2010; Walker et al., 2008); off-road vehicles – sediment properties, invertebrates, dune plants, and birds (Groom et al., 2007; Lucrezi and Schlacher, 2010; Meager et al., 2012; Schlacher and Lucrezi, 2010; Schlacher et al., 2013a); camping in coastal dunes – dune habitat integrity, plants, and invertebrates (Schlacher et al., 2011a; Thompson and Schlacher, 2008); and trampling – invertebrates (Schlacher and Thompson, 2012). Each of the above provides a straightforward application of a usually small set of metrics to measure the effects of a usually well-defined threat. Similar metrics (i.e., fauna abundance, diversity, distribution, scavenging rates) have also been shown to be suitable to assess ‘compound threats’ that encompass several pressures linked to the urbanisation of coastlines (Hubbard et al., 2013; Huijbers et al., 2013).

It would thus appear that questions arising during the design of ecological impact assessments for dunes and beaches can readily draw on existing published examples that set out the technical details. Although this holds true for several commonly-encountered human threats (e.g., off-road vehicles, armouring, beach nourishment, pollution) it does not present a comprehensive view that employs multiple criteria to select variables under a range of project requirements (e.g., budgets, objectives, types of threat). Therefore, a core objective of this paper was to provide guidance for the selection of metrics that are best suited to assess the condition of beach and dune systems or to measure the impacts of specific human actions. We have presented the outcomes of this evaluation in a set of 'league tables' (Tables 2 and 3), which provide a more complete overview of metrics, including their strengths and weaknesses in specific applications, than has been available in the primary literature.

4.2. Beyond simple metrics

We recognise that the types of metrics and tools that are available for beach studies are expanding, mainly due to advances in instrumentation, molecular methods, and modelling techniques. For example, Baptista et al. (2011) describe a high-resolution and high-accuracy survey system that produces 3-dimensional representations of sandy shore surfaces, which can permit calculations of sand volume and other physical parameters. These types of methods will be particularly useful to document habitat changes in the face of global sea-level-rise (SLR) that is predicted to have major ecological and economic consequences for sedimentary coastlines (Church and White, 2011; Pendleton et al., 2011; Romine et al., 2013). To evaluate the effects of SLR across multiple environmental dimensions, multiple models can be linked as demonstrated by Aiello-Lammens et al. (2011); they integrated geomorphological, habitat, and metapopulation models of the effects of SLR to simulate declines in suitable habitat, carrying capacity, and populations for the Snowy Plover *Charadrius alexandrinus* in Florida (Linhoss et al., 2013; see also Sims et al., 2013). Similarly, integration of models can span socio-economic and geomorphological domains to predict the evolution of shorelines affected by nourishment (Jin et al., 2013). These integrated modelling frameworks can be further augmented with multi-criterion decision analysis to identify preferred management strategies for species threatened by SLR (Linhoss et al., 2013). Developments in genomics technologies (e.g., qPCR, SNP based methods, DNA barcoding, microarrays, metagenetics, metagenomics, transcriptomics) are predicted to transform marine monitoring, having the potential to lead to more cost-effective and reliable taxonomic identifications and assessments of the status of marine waters and sediments (Bourlat et al., 2013).

4.3. Metric selection has a context dependency

We have provided a broad set of criteria and performance measures to select appropriate metrics for beach and dune impact assessments under a range of different scenarios; we contend that these will have general applicability. At the same time, we acknowledge that individual studies will be constrained by often-unique contingencies and political demands, making the choice and use of indicators highly dependent on the socio-cultural context. This context-dependency can, however, also offer opportunities not captured fully by the selection process outlined here. Such opportunities, for example, arise when particular technical expertise is available locally for free or at little cost (e.g., bird-watchers or other naturalists, retired academics keen to contribute to environmental issues gratis, etc.). Conversely, a particular combination of a human action that impinges directly on a threatened species may provide a compelling case for using a particular metric in this instance.

The choice of metrics will also be constrained to a small set of candidate variables in cases where particular parts of the dune-beach habitat complex are disproportionally impacted, or where they contain taxa that are particularly vulnerable. Hubbard et al. (2013) provide a compelling example of this situation along the Californian coast. Here the upper sections of beaches near the strandline have been subjected to significantly higher rates and intensity of habitat loss and alterations, chiefly due to grooming and shore armouring in urbanised sectors of the coast. Biological impacts in this situation are compounded by the fact that the most-altered upper shore is also the sole habitat of isopod crustaceans that have low dispersal ability and low reproductive outputs; the net outcomes are numerous local extirpations of the isopods (Hubbard et al., 2013), which logically, would serve as an excellent metric with which to measure human impacts along this coast (Hurtado et al., 2013). Similarly, on coasts that receive large inputs of plant wrack (seagrass and algae), monitoring the properties and dynamics of these wrack accumulations and the associated fauna is a very good metric in many cases (Dugan et al., 2003). Wrack attributes (e.g., biomass, coverage, biological processing) and fauna associated with driftlines are particularly suitable to gauge the ecological effects of grooming and beach cleaning (Gilburn, 2012). Wrack-associated metrics are, however, less relevant on shorelines that receive negligible wrack inputs and consequently have poorly-developed driftlines; warm-temperate and tropical beaches without significant seagrass or algal beds in the subtidal offshore are often of this type.

Distributions of invertebrates across the beach (from the dunes to the swash) are important and frequently used metrics in beach assessments. Dugan et al. (2013) have conceptually extended the traditional method of describing across-shore distributions of invertebrates from representing essentially static ranges (e.g. Schlacher and Thompson, 2013), by incorporating the dynamic nature of species distributions where animals continually adjust their position in the intertidal in response to changes in physical conditions and, possibly, changes in food supply; these dynamic distributions are termed 'envelopes' (Dugan et al., 2013), and could well be a promising new tool to gauge human changes to sandy beaches.

Environmental assessments routinely use multiple indicators to measure condition and change (Carruthers et al., 2013; Marshall et al., 2014; Williams et al., 2009). For example, to assess the effects of beach grooming, Dugan et al. (2010) employed a suite of indicators that encompassed habitat dimensions, wrack cover, native plant abundance and richness, and plant performance. Whilst multiple metrics can more robustly and comprehensively cover a specific, or multiple, environmental issues of concern, they can further complicate the selection process and interpretation of data by non-specialists.

Dunes and beaches form part of a wider littoral landscape and are functionally connected to the nearshore seascape. As landforms, they are formed and shaped by processes often remote from the site itself, such as sediment delivery and the oceanography of coastal cells (Barnard et al., 2012; Houser, 2009; Orme et al., 2011). Because human changes to landscapes processes (e.g., alterations to wash-overs frequencies following dune reconstruction, sand by-passing scheme at engineered coastal inlets) can have profound ecological effects (Schupp et al., 2013), it is critical that applications of metrics that represent site conditions are embedded and contextualised in a comprehensive description of these broader landscape and oceanographic processes.

There are a number of variables that all assessments of environmental condition and impacts need to take into account and explicitly measure. These comprise some of the key anthropogenic threats to beach systems that often include activities that are known (reviewed in Defeo et al., 2009) to have detrimental environmental effects on beach and dune ecosystems: 1.) grooming/cleaning; 2.) driving of vehicles; 3.) coastal armouring; 4.) the presence of dogs, 5.) nourishment, 6.) recreational use of dunes (vehicles, camping, trampling, etc.); and 7.) temporal and spatial patterns of beach use. For all of these activities it is important to include the history, intensity, frequency and spatial coverage (if known). In all cases, measurements of pressures must be accompanied by measurement of ecological consequences and vice versa (i.e., no environmental assessment should monitor only human-associated stressors without including ecological metrics that are known to respond to these stressors, and measurement of ecological metrics should not occur in isolation without quantifying matched human stressors). In addition, features of the landscape that are likely to have positive effects on dunes and beaches should be described. These include the presence of subtidal seagrass and kelp beds (supply of wrack to beaches), the presence of adjacent rocky shores, estuaries, wetlands (e.g., provision of alternate feeding, roosting, perching sites), and the presence of rocky outcrops and pools (e.g., resting and refuge areas for shorebirds).

Our list of metrics evaluated here contains more structural than functional variables. This does not, however, suggest that structural attributes of the systems are in any respect more important in environmental assessments and monitoring. On the contrary, inclusion of indicators that measure functions and processes is critical in all programs. Recent applications of resilience theory in other ecosystems, which have experienced regime shifts despite extensive monitoring of structural metrics (e.g., coral and seagrass cover) demonstrate that there is a very real danger in measuring only structural variables (Hughes et al., 2010; Thrush et al., 2009). For this reason, numerous authors have now concluded that structural variables alone do not always provide sufficient information about the condition and resilience of ecosystems; this may be due to the existence of feedback loops, alternate regimes and hysteresis in some systems (e.g., Nyström et al., 2012; Olds et al., 2012).

A related concern is the application of physical descriptors of the systems without full inclusion of biological and ecological aspects. For example, the presence, width, or volume of sand on a beach is often viewed as a proxy for an intact ecosystem. While habitat dimensions and properties are relevant, it is the quality and condition of these habitats that is of prime ecological importance. Beaches can have wide intertidal areas, but in many urban settings or where vehicle traffic is intense, these habitats are so strongly altered that they lose key ecological functions and support low biodiversity (Noriega et al., 2012; Schlacher et al., 2008a). As an example, the widespread application of repeated beach ‘nourishment’ or ‘restoration’ activities that add sand for recreation, can significantly degrade the ecological properties of beaches to the point of creating de-faunated sands (Manning et al., 2013; Peterson and Bishop, 2005; Peterson et al., 2006; Schlacher et al., 2012). In other cases, a wider beach can be the result of bare sand areas left from degradation of dune habitat (Dugan and Hubbard, 2010).

Our analysis identified a suite of good candidate metrics that relate primarily to the upper parts of beaches and the dunes, especially those at the interface between the dunes and the non-vegetated section of the beach. Of the indicators found to have best issue coverage and criteria compliance in our analysis (coded green in Fig. 2), several indicators with primary terrestrial affinity are well-represented (e.g., dune plants and air-breathing animals). By contrast, many marine indicators (coded red to orange Fig. 2) had some of the lowest scores for coverage and compliance (e.g., phytoplankton, meiofauna). This disparity of indicator strength with elevation across the surf-dune gradient is worthy of further consideration. For instance, it may be related to a higher vulnerability of taxa that occupy the more restricted upper shore habitat, a higher intensity of impacts in this zone, or a combination of both (e.g., Dugan et al., 2013; Hubbard et al., 2013); it could possibly also be influenced by a disparity of research effort across taxa or habitats.

Metric selection must always be practical and take account of biogeography, and differences in landscape features and degrees of urbanisation. Some of the most sensitive indicators from our analysis may not be suitable for use in highly-degraded systems (e.g., endangered birds rarely nest on well-used recreational beaches or in systems lacking dunes). The absence of these faunal elements is, nevertheless, a prime indicator of deleterious environmental condition or change and should be reported as such; more subtle measurements of human impacts on already highly disturbed coastlines will require other metrics. Some of the most sensitive and thus highly rated indicators may not be present in every coastal region (e.g., turtles do not nest on cold-temperature beaches). Within a region, the landscape context can preclude the use of some of the more highly-rated indicators (e.g., the absence of dunes on many bluff-backed beaches precludes the use of any of the dune metrics.

4.4. *Metrics and ecosystem services in beach management*

Sandy beaches are iconic assets, strongly anchored in the cultural narratives and the socio-economic fabrics of coastal societies. This pivotal role of beaches, functioning as diverse and complex socio-economic systems, creates formidable challenges for political decision makers and on-ground beach managers to deliver the full range of functions expected from beaches by society (De Ruyck et al., 1995). Thus, the overriding objective of beach management, or environmental management more broadly, is to create, maintain, or restore ecosystem properties more favourable to human well-being and material benefits (sensu Wallace, 2007).

Management that focuses primarily on maintaining instrumental (‘utilitarian’) environmental values to meet human needs may, however, neglect the protection of ecological features more broadly, irrespective of how well these are measured using any of the metrics reviewed by us (Tables 2 and 3). Nevertheless, the concept of contextualising components and processes of the environment in terms of the benefits they can deliver to human society has gained strong ascendency in delivering the rationale for ecological conservation (Millennium Ecosystem Assessment, 2005).

Ecosystem services are broadly defined as “the benefits people obtain from ecosystems” (Millennium Ecosystem Assessment, 2005); this concept has become widely used to construct or strengthen arguments for the conservation of biodiversity or other ecological elements (Jax et al., 2013). Services provided by beaches meet human needs across many dimensions: economic support, provision of living space and food, recreational opportunities, cultural and spiritual fulfilment, and protection against destructive natural events (Schlacher et al., 2008b). Paradoxically, many of the benefits and services that society expects from beach systems are jeopardised by environmentally-destructive practices (Defeo et al., 2009). Indeed, this paper's main motivation is to assist natural resource managers who wish to assess the consequences of current practices of beach and dune use with greater accuracy and efficacy.

While we have illustrated the utility of a range of metrics that can usefully be applied to measure ecological condition and the effects of human interventions on beach systems, the knock-on effects that any ecological impacts may have on the quality and quantity of ecosystem services still need to be quantified for beaches globally. Our present inability to commodify (monetize) the function of beaches is, however, not invariably an impediment to effective beach conservation (Harris et al., 2013). Managing and conserving beaches to address societal expectations and human values in terms of ‘service delivery’ and ‘monetary values’ is attractive when embedded in a Keynesian worldview, but it is not unproblematic otherwise. Indeed, the concept and application of ecosystem services to argue for biodiversity conservation is not without critics, particularly with regard to issues of social justices, the failure of markets to value nature, and the inappropriateness of commodifying and monetizing symbolic, cultural and spiritual values (Jax et al., 2013; Turnhout et al., 2013; Wallace, 2006).

As an alternative to a management philosophy underpinned by ‘ecological service delivery’, Turnhout et al. (2013) suggest three complementary approaches that appear useful in the context of managing and conserving ecological features of beaches: 1.) recognise and value the diversity of relationship of humans with biodiversity and ecosystems (e.g. continuing traditions, social networks, spirituality – i.e., nurture social–natural relations); 2.) build on existing human-natural relationships to live with biodiversity in ways that are not overly market-orientated; 3.) avoid creating singular measures to represent the complexity and heterogeneous nature of the relationship between humans and nature, but instead value the diversity of relations.

4.5. Metrics and values

Selecting, applying and analysing metrics to gauge the effects of a human activity on beach ecosystems are purely technical activities. They do not, by themselves, produce environmental or conservation benefits - these can only come from embedding the technical activities in a strong and intellectually rigorous conservation framework, followed by translating the outcomes of the technical work into management actions contextualised within that conservation framework. Three steps are critically important in creating the conservation framework and these are applicable in the great majority of cases: 1.) recognizing the *values* comprehensively, 2.) translating these values into *goals*, and 3.) setting *targets* for achieving the goals (Kukkala and Moilanen, 2013).

Whereas some pioneering work exists on setting targets for biodiversity conservation of beach systems (Harris et al., 2013), the more fundamental aspects of identifying values and setting goals (both of which cannot be compromised for effective conservation outcomes) are rare or non-existent for beach systems. It is therefore important that the philosophical and conceptual foundations of environmental values are clearly understood, across the board by stakeholders, before the metrics are selected.

Conservation and management of beaches can be framed in terms of obligations towards other human beings (also as members of future generations) with regards to safeguarding the integrity of ecosystems that are a shared good – a deontological value context (Jax et al., 2013). This view is seldom disputed in beach management practice, but is also seldom explicitly recognized as such. More complex is the question whether non-human entities (i.e., beach ecosystems) have inherent (‘intrinsic’) values that do not depend on human valuations (Rolston, 1994). This question has given rise to on-going debates as to how to incorporate intrinsic values, in addition to the instrumental values that are the product of human attribution (O'Neill, 2003), into conservation practice (Justus et al., 2009; Sagoff, 2009).

Many humans attribute value to non-human nature beyond purely utilitarian perspectives (Jax et al., 2013). The typology of values proposed by Jax et al. (2013) encapsulates this heterogeneity and will be useful in guiding beach conservation and management. It recognizes four classes of values: 1.) *inherent* (‘intrinsic’) moral values (non-human natural beings for their own sake; direct moral obligation towards them); 2.) *fundamental* values (basic conditions of existence and life and on earth); 3.) *eudaimonistic* values (basic condition for a good human life = a life worthy of a human being); 4.) *instrumental* values (valuable as means to something else; in principle replaceable).

The values of sandy beach systems encompass all of the above categories comprehensively. Examples include our moral obligation to protect beach-dependent species and habitats in their own right (intrinsic value); connections to the ‘Land’ and ‘Country’, enabling coastal settlements (fundamental value); leisure activities, aesthetic enrichment, inter-generational justice (eduaimonistic values); provision of fish and shellfish, land for housing, and storm protection (instrumental value).

Notwithstanding the existence of a generalized typology of values that can be associated with beach and dune systems, no comprehensive valuing of beach systems – one that encapsulates the full range of intrinsic, fundamental, eduaimonistic and instrumental values - exists. Globally, environmental values of beach ecosystems are only sketched as isolated fragments, connected neither to conservation nor to socio-economic uses. This fragmented and incomplete understanding of values impedes the development of management and conservation plans, where actions are designed to meet targets, and where targets reflect values accurately and comprehensively. Consequently, a critical necessity is to methodically identify the values that underpin policies for beach management and conservation.

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