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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