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Human threats to sandy beaches: A meta-analysis of ghost crabs illustrates global anthropogenic impacts.

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A B S T R A C T

Beach and coastal dune systems are increasingly subjected to a broad range of anthropogenic pressures that on many shorelines require significant conservation and mitigation interventions. But these interventions require reliable data on the severity and frequency of adverse ecological impacts. Such evidence is often obtained by measuring the response of 'indicator species'.

Ghost crabs are the largest invertebrates inhabiting tropical and subtropical sandy shores and are frequently used to assess human impacts on ocean beaches. Here we present the first global meta-analysis of these impacts, and analyse the design properties and metrics of studies using ghost-crabs in their assessment. This was complemented by a gap analysis to identify thematic areas of anthropogenic pressures on sandy beach ecosystems that are under-represented in the published literature.

Our meta-analysis demonstrates a broad geographic reach, encompassing studies on shores of the Pacific, Indian, and Atlantic Oceans, as well as the South China Sea. It also reveals what are, arguably, two major limitations: i) the near-universal use of proxies (i.e. burrow counts to estimate abundance) at the cost of directly measuring biological traits and bio-markers in the organism itself; and ii) descriptive or correlative study designs that rarely extend beyond a simple 'compare and contrast approach', and hence fail to identify the mechanistic cause(s) of observed contrasts.

Evidence for a historically narrow range of assessed pressures (i.e., chiefly urbanisation, vehicles, beach nourishment, and recreation) is juxtaposed with rich opportunities for the broader integration of ghost crabs as a model taxon in studies of disturbance and impact assessments on ocean beaches. Tangible advances will most likely occur where ghost crabs provide foci for experiments that test specific hypotheses associated with effects of chemical, light and acoustic pollution, as well as the consequences of climate change (e.g. species range shifts).

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1. Introduction

"I'll try you on the shore"

William Shakespeare: Antony and Cleopatra (1606)

Accelerating environmental impacts on ocean beaches and coastal dunes call for effective environmental planning and biological conservation. These interventions should meet two cardinal criteria: 1.) environmental values and conservation goals must be clearly identified for broad and inclusive segments of the population (Harris et al., 2014; Vivian and Schlacher, 2015); and 2.) management decisions must be based on impact assessments that produce defensible and biologically relevant information (Harris et al., 2015).

A sizeable part of this information comes from documenting the response of organisms (at various levels of ecological organisation ranging from individuals to ecosystems) to human activities or anthropogenic habitat change (Defeo et al., 2009; Schlacher et al., 2007a). On ocean shores, a broad range of animals (e.g. benthic invertebrates, birds, marine turtles) has been used to detect biological effects attributed to an equally diverse spectrum of anthropogenic pressures, ranging from vehicle impacts to urbanisation (e.g. Huijbers et al., 2015b; Marshall et al., 2014; Reyes-Martínez et al., 2015; Walker and Schlacher, 2011).

Ghost crabs (Genera *Ocypode* and *Hoplocypode*) are perhaps the most widely-studied invertebrate indicator species on ocean-beaches (e.g. Barros, 2001). Ghost crabs are attractive as ecological indicators for a number of reasons: i) they are widespread in the subtropics and tropics; ii) they occur on both the non-vegetated beaches and in the dunes backing beaches; iii) they are relatively large, often locally abundant, arguably charismatic, and require no specialised tools to sample; iv) their taxonomy is well known and identification not overly difficult; and v) they construct semi-permanent burrows with clearly visible openings at the beach surface (Lucrezi and Schlacher, 2014; Schoeman et al., 2015). It is the fossorial habits of ghost crabs, in particular, that has led to their widespread adoption as ecological indicators, chiefly because estimates of abundance and body size can be made from counts and measurements of burrow sizes without the need to physically collect the organisms (Barros, 2001).

Given the extensive use of ghost crabs as ecological indicators on ocean beaches, a formal review and meta-analysis of this practice is warranted. To this end, here we synthesise the literature and address five broad questions:

1) What are the *types of human pressures* acting on beach-dune systems that have been assessed with ghost crabs?
2.) What is the magnitude of reported ecological *effect sizes* for different stressors?
3.) Which *metrics* (response variables) have been used?
4.) What are the *gaps* in terms of human pressures currently not adequately assessed using ghost crabs?
5.) What *opportunities* exist to advance the use of ghost crabs as ecological indicators on ocean beaches?

2. Methods

Studies that examined the response of ghost crabs to anthropogenic activities (sensu lato) were obtained by first searching the Web of Science, Scopus, and Google Scholar using "ghost crabs" OR "*Ocypode* OR *Hoplocypode* " as key words. From this pool we identified studies reporting on human impact assessments by reading the original documents. Sources from literature searches were supplemented by examining the cited reference lists of publications in hand; this yielded several additional reports from government agencies (e.g. U.S. Fish & Wildlife Service, Natal Parks Board). No filter was applied with respect to the types of impacts. Nevertheless, all studies were required to meet two minimum criteria for inclusion in the meta-analysis: peer-review or an equivalent quality control was likely to have been completed, and quantitative data on changes/differences of at least one response variable could be extracted from a publication (e.g. contrasts in burrow counts between beach sections with and without vehicle traffic). In all cases, we classified the intensity of human use or habitat modification by following the original descriptions provided by the authors of each study, usually representing a 'high impact/use treatment' condition that was compared with a 'low use/reference/control' condition. In most cases it was not possible to quantify or rank the intensity or level of pressure from the original descriptions; hence, all analyses here are performed using a binary classification of 'impact' vs. 'reference', irrespective of differences in impact intensity that may have existed among studies.

We quantified the magnitude of effects on measured ghost crab biological metrics by using the log-response ratio, *ln* R, which is a common statistic of ecological effect sizes in meta-analyses: $ln\ R = \ln(mean_{impact}/mean_{control})$ (Borenstein et al., 2009). 'Impact' refers to sites or beaches that were categorised by authors as being evidently more influenced by a particular human stressor of interest and hence usually represent values from 'impact' groups or 'treatments'. Conversely, 'control' values usually represent localities where the stressor of interest was judged (by the original study authors) to be substantially less influential or absent and hence represent 'reference conditions' in the context of individual studies. Half of the studies in our database did not report sufficient details on samples sizes, variances, statistical tests used, or P-values; in other papers these statistics could not be reliably extracted or inferred from graphs or tables. These omissions precluded the calculation of standardised effect-size statistics such as Cohen's d and Hedges' g (Harrison, 2011) for the majority of studies. For these reasons, we limit our analysis to unweighted one-sample t-tests of the hypothesis that the mean log-response ratio is 0 (*i.e.*, that there is, on average, no effect; i.e. raw response ratio = 1).

The term 'indicator species' has multiple meanings in ecology and environmental science, with little or no consistency of usage amongst authors. Broadly, five main types of usage can be identified to: 1.) measure the biological responses to anthropogenic stressors, pollutants, human activities, management actions, or restoration efforts (i.e. 'indicator species' are used as biological monitors that are thought to react in predictable ways to changes in the environment) (Carignan and Villard, 2002; Diekmann and Dupré, 1997; Jonsell and Nordlander, 2002; Krmpotić et al., 2015; Siddig et al., 2016); 2.) characterize assemblages or habitats (i.e. 'indicator species' are those that are viewed as 'typical' species, showing consistent fidelity to a set of biological or environmental attributes) (Antonelli et al., 2015; De Cáceres et al., 2010; Dufrêne and Legendre, 1997; Hogle et al., 2015; Hwang et al., 2015; Peterken, 1974; Ricotta et al., 2015; Sarrazin et al., 2015); 3.) reflect more than one process, condition, or biological attribute that may or may not be linked to human interventions (i.e. 'indicator species' serve as multiple proxies, the specific meaning being often dependent on the study context) (Lindenmayer, 1999; Niemi et al., 1997; Regehr and Montevecchi, 1997); 4.) act as surrogates for species that are difficult to detect or sample, or to reflect specific environmental