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Responses of ghost crabs to habitat modification of urban sandy beaches

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ABSTRACT

Sandy beaches in highly urbanised areas are subject to a wide range of human impacts. Ghost crabs are a commonly used ecological indicator on sandy beaches, as they are key consumers in these systems and counting burrow openings allows for rapid assessment of population size. This study assessed the pressures of urbanisation on sandy beaches in the highly urbanised estuary of Sydney Harbour. Across 38 beaches, we examined which physical beach properties, management practices and human induced habitat modification best predicted ghost crab distributions. Of all variables measured, the frequency of mechanical beach cleaning was the most important predictor of crab abundance, with low burrow densities at the highest cleaning frequency and the highest densities at beaches cleaned at the intermediate frequency ($\leq$3 times per week). These results indicate that ghost crab populations in Sydney Harbour are more robust to the impacts of urbanisation than previously thought.

1. Introduction

The alteration of natural habitats by rapidly expanding human populations has caused impacts to ecosystems around the globe (Defeo et al., 2009). Populations in coastal areas are growing significantly faster than anywhere else (Schlacher et al., 2007b) which, coupled with increases in leisure time and higher human settlement in coastal areas, has resulted in escalating pressures on coastal areas around the world (Schlacher et al., 2008). Some of the most vulnerable habitats to the threats associated with high populations are sandy beach ecosystems, with their high social, recreational and economic values combined with important ecological functioning (Defeo et al., 2009; Schlacher et al., 2008).

Sandy beaches are dynamic environments, governed by a variety of physical and biological factors at different temporal and spatial scales (Defeo and McLachlan, 2005). Unconstrained, beaches can be resilient, changing shape and size naturally in response to storms and variations in wave action and currents (Schlacher et al., 2007a). Human modifications of sandy beaches interfere with these natural processes, thereby limiting their resilience and typically having negative impacts (Brown and McLachlan, 2002). Beaches in urban areas are now considered to be trapped in a 'coastal squeeze' between the impacts from human activities on the terrestrial side and the manifestations of climate change on the ocean side (Schlacher et al., 2007a).

Threats to beaches include a wide range of anthropogenic processes, ranging from habitat loss as a result of development and shore armouring, the over exploitation of resources (e.g., fishing and mining) to recreation activities and coastal management practices (Defeo et al., 2009). Coastal engineering practices such as land reclamation, development and shore armouring often result in the destruction of ecologically important natural habitat. These processes involve the conversion of natural habitat, such as the native dune systems, into hard substrates like sea walls, with the potential for strong changes to the ecological values of these environments (Nordstrom, 2004). Recreational use of off-road vehicles on beaches and associated trampling can negatively affect beach habitats (Reyes-Martínez et al., 2015; Schlacher et al., 2007a), but even lower impact activities, such as swimming in the surf zone, can affect the activities of macrofauna and inhibit the feeding

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of higher order predators in the intertidal (Brown and McLachlan, 1990).

Increased use of beaches for recreational purposes has led to the intensification of beach cleaning practices, especially in urban areas. This process involves the use of heavy machinery to drag a large rake or sieve across the surface of the sand to remove debris from the surface layer. This process is designed to remove human waste and debris, however is non-selective and results in the removal of much of the surface layer including washed up organic material known as wrack (Brown and McLachlan, 2002). Sandy beaches often lack large attached plants and, consequently, *in situ* primary production is usually low (Schlacher et al., 2013a) with the exception of the beaches that support high accumulations of surf diatoms (Campbell, 1996). As a result most sandy beaches are reliant on wrack to fuel local food webs (McLachlan and Brown, 2006). The wrack supports a diverse array of organisms, including invertebrate macrofauna that may consume the wrack, meiofauna associated with sediments and predators such as shore birds (Dugan et al., 2003). The removal of wrack from these ecosystems can greatly reduce the abundance of sandy beach fauna (Defeo et al., 2009; Dugan and Hubbard, 2010; Gilburn, 2012). Despite these known impacts, the practice is used frequently by coastal managers around the world as an easy and efficient tool to maintain the aesthetic quality of sandy beaches for human use.

While known to be threatened by a range of human impacts, sandy beaches are poorly studied relative to other marine habitats. One potential solution to address the shortfall in environmental data on sandy beaches is to develop rapid assessment methods to provide measures that can predict the health of the ecosystem as a whole. These include monitoring the abundance of indicator species whose abundance is assumed to correlate with known ecosystem functions or decline with known threats. Such methods have widely been used in other ecosystems, but have rarely been used in sandy beaches despite the fact they are some of the most vulnerable to threats from urbanisation (Barros, 2001).

On sandy beaches, ghost crabs (Crustacea: Brachyura: Ocypodidae) are a widely used indicator species for the health of sandy beach ecosystems (Schlacher et al., 2016), and previous studies have found that their populations are susceptible to human activities on beaches around the world (e.g. Jonah et al., 2015; Schlacher et al., 2011). They are key consumers on sandy beaches (Schlacher et al., 2013b), playing the important ecological role of being apex invertebrate predator and scavenger in these systems, whilst also being important prey for many higher order vertebrate consumers from nearby terrestrial ecosystems (Lucrezi and Schlacher, 2014). Their position as an apex consumer means that their population structure may reflect that of lower trophic levels (Lucrezi et al., 2009b). They also display fossorial habits, constructing deep and complex burrows for shelter which are clearly visible on the surface of the sand, allowing for rapid assessment of population size by counting burrow entrances (Moss and McPhee, 2006).

The aim of this study was to assess beaches in urban areas for the impacts of urbanisation. We examined which variables relating to physical beach properties, management practices and human induced habitat modification best predicted ghost crab distributions in the highly urbanised estuary of Sydney Harbour. Sydney Harbour contains an extensive range of habitats, including over 50 sandy beaches, but a recent extensive review of the state of knowledge for the harbour (Johnston et al., 2015) identified only four research papers that have investigated infaunal communities of beach environments within the harbour (Dexter, 1983, 1984; Jones, 2003; Keats, 1997). Three of these studies were primarily concerned with describing the communities on only a few beaches, whilst the fourth study investigated the impact of an accidental oil spill on the amphipod *Exeodiceros fosser* (Jones, 2003). No studies to date have examined the possible impacts of the extensive habitat modification in this coastal system on sandy beach fauna.

To assess the impacts of urbanisation of ghost crab populations, we modelled burrow densities as a function of variables that described the biotic and abiotic properties of 38 sandy beaches in Sydney Harbour. Predictor variables included those that related to human modification of the beach environments (the presence or absence of a seawall, the level of development surrounding beaches and the mechanical beach cleaning regime maintained at each beach), the productivity of individual beaches (estimated using wrack accumulation and organic content of sediment) and beach morphology (length, beach slope and sediment grain size). Previous studies involving human impacts on ghost crabs have been concentrated on open ocean beaches, and to date there have been no studies on beaches in estuarine environments within a large urban centre.

2. Materials and methods

2.1. Study sites and species distribution

Sydney is Australia's largest city with a population of over 4 million people (Hutchings et al., 2013) and likely to rise to 8.5 million by 2061 (Australian Bureau of Statistics (2013)). Sydney Harbour is located on the eastern coast of New South Wales, Australia (Fig. 1). The harbour is entirely within Sydney's urban area, with the beaches exposed to high levels of human activity. Ninety percent of the harbour's catchment is now urbanised (Hutchings et al., 2013) and more than 50% of the harbour's shoreline comprises artificial structures (Chapman and Bulleri, 2003).

Beaches within the harbour experience a range of wave energy depending on their position within the estuary, from those directly exposed to open-ocean swell to those completely protected from all wave inputs, apart from wakes generated by boats (Kennedy, 2002). Consequently, harbour beaches maintain large amounts of environmental heterogeneity. Thirty-eight sandy beaches were selected for investigation in this study (Fig. 1, Table S1), being located throughout all sections of the harbour, representing a variety of sizes and experiencing a range of urbanisation pressures (Table S1).

We surveyed burrow densities of the Smooth-handed Ghost Crab, *Ocypode cordimanus* Latreille, 1818. This species is found in the Indo-West Pacific and, in Australia, along the northern and eastern coasts, from the north of Western Australia to southern New South Wales (Jones and Morgan, 2002). *Ocypode ceratophthalma* also occurs along the east coast of Australia as far south as Sydney (Barros, 2001), but only *O. cordimanus* is known to occur within Sydney Harbour (Hutchings et al., 2013).

2.2. Classification of beaches by degree of human modification

We identified the level of coastal development and the frequency of mechanical beach cleaning as likely threats to sandy beach communities in Sydney Harbour. Both involve intense modification of natural habitats and have been found to have negative impacts on sandy beach communities worldwide (Dugan and Hubbard, 2006; Gilburn, 2012; González et al., 2014). For each beach, the degree of coastal development was assessed using two measures, the presence of seawalls and the level of urban development on the landward side of the beach.

Beaches were assigned to one of three categories relating to the presence and extent of seawall; none present, partial (i.e., seawall for part of the beach) or complete. Similarly, each beach was categorised into four levels of urban development directly adjacent to the beach (none, low, medium and high), analogous to the