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The effects of manipulating microhabitat size and variability on tropical seawall biodiversity: field and flume experiments

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ABSTRACT

Previous studies have shown that concrete tiles on seawalls that incorporate microhabitat size variability (i.e. complexity) can increase species richness compared to unmodified seawalls. In a recent study, we showed that manipulating complexity at the 4–28 mm scale can have an effect on seawall community composition and that the type of structural component (microhabitats such as pits and grooves) can influence assemblage diversity independently of their complexity. It is not known, however, whether these effects will be exhibited at a larger scale; in other words, will the positive relationship be present if the size range of components on concrete tiles is enlarged (8–56 mm). Therefore, in the present study, we examine: (1) the effects of changing the scale of structural manipulation on species richness and, (2) the hydrodynamic properties (i.e. velocity of flow over the whole tile) of different designs. We doubled the size of all x, y and z dimensions to create 400 × 400 × 64 mm concrete tiles (up from 200 × 200 × 32 mm in the previous study) with two different basic designs: 'Pits' and 'Grooves'. These were deployed for one year at two island sites off Singapore's mainland along with 'Granite control' tiles so that we could assess what the existing seawall would host within the same timeframe. Results showed that the 'complex' tiles supported greater richness (S) than 'simple' ones, suggesting that the size range tested here (8–56 mm) is relevant to tropical intertidal communities. Flume experiments revealed similar wave amplitude values over the surfaces of all tile types, including the granite controls, suggesting that intertidal organisms are unlikely to colonise the tiles differentially as a result of cm-scale hydrodynamic differences, i.e. the dominant mechanism underlying this 'complexity-diversity' relationship is unlikely to be due to differences in flow velocities over a 400 × 400 mm tile surface but, rather, is related to resource (e.g. refuge) availability. These results help identify the "scale of effect" of topographic complexity which can be directly integrated into ecological engineering designs to increase biodiversity on tropical seawalls.

1. Introduction

It is predicted that, by the next decade, approximately three quarters of the world's population will reside in 'coastal zones' (within ~100 km inland from the sea)—even though this represents only 10–15% of the global land area (Hinrichsen, 1994; Small and Nicholls, 2003; Bulleri and Chapman, 2015). Coastal land is therefore in high demand and development and seaward land reclamation is occurring at unprecedented scales (Lai et al., 2015). In addition, the risks of accelerated sea level rise and more frequent and intense storms and flooding due to climate change have resulted in an urgent need for greater shoreline protection (French and Spencer, 2001; Temmerman et al., 2013). As a result, man-made coastal defenses, such as seawalls, groynes, and breakwaters are quickly, and at a global scale, becoming the primary means of mitigating such risks (Thompson et al., 2002; Dugan et al., 2011; Gittman et al., 2015).

Extensive coastal armouring occurs in almost all major coastal cities; for example, in Sydney Harbour it represents more than 50% of the shoreline (Chapman and Bulleri, 2003), while in Victoria Harbour, Hong Kong, close to 95% of the coast comprises vertical seawalls (Lam et al., 2009). As habitats, artificial coastal defences such as seawalls differ from natural shores in some fundamental ways. One of the most obvious is the extent and slope of the substratum, which can result in very different wave hydrodynamics and inundation patterns. Compared to seawalls for example, natural (rocky) shores tend to be more gently sloping with longer and wider intertidal extents while seawalls, often built simply as a barrier, are usually very steep (see also review by Bishop et al., 2017–in this issue). Energy from wave impact can be high and dislodges organisms or impedes settlement. Furthermore, vertical steepness results in a contraction of the intertidal zone, causing species that would normally be spaced apart to become superimposed. This change in species distribution can alter competitive interactions and

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community dynamics, thereby influencing the composition and diversity of seawall assemblages (Chapman, 2006; Tyrrell and Byers, 2007; Chapman et al., 2009; Burgos-Rubio et al., 2015; Heery et al., 2017–in this issue). Reduced area and niche overlaps can be particularly disadvantageous for specialist species, which tend to have specific habitat requirements and narrower niche breadths compared to organisms with broader tolerances and flexible requirements (Slatyer et al., 2013). This may explain why artificial structures are often characterised by only a few abundant generalist species (e.g. nerite snails). Contraction of space can be exacerbated by a lack of microhabitats (e.g. pits, rock-pools, overhangs and crevices) and low structural complexity that is typical of the smooth engineered surfaces of seawalls (Moreira et al., 2007; Chapman and Blockley, 2009). Directly or indirectly, together these factors contribute to the depauperate seawall ecosystem (Goodsell et al., 2007; Chapman et al., 2009).

Despite these adverse consequences, only relatively recently have researchers examined the ecological impacts of seawalls, the communities living on them, and/or suggested guidelines for incorporating biodiversity enhancement into the design of artificial coastal defences (Chapman and Bulleri, 2003; Chapman and Underwood, 2011; Firth et al., 2014; Dafforn et al., 2015). With the realisation that these structures cannot be removed, and acknowledging current predictions of climate change, there is now greater interest in maximising the ecological value of coastal armour while still maintaining civil engineering requirements and standards (Chapman and Underwood, 2011; Naylor et al., 2012; Firth et al., 2013). This has been done using a variety of approaches and to varying degrees of success; for instance, by recreating natural shore elements such as pits and crevices on seawalls (e.g. Firth et al., 2016a; Martins et al., 2010; Moschella et al., 2005; Moreira et al., 2007; Borsje et al., 2011), by using different materials and textures (e.g. Coombes et al., 2015; Burt et al., 2009; Moschella et al., 2005), and by adding artificial tide-pools, e.g. by attaching flowerpots (Browne and Chapman, 2011), drill-coring (Evans et al., 2016), removing stone blocks to create cavities (Chapman and Blockley, 2009), and deploying pre-cast units that incorporated these element(s) (e.g. Firth et al., 2014; Perkol-Finkel and Sella, 2015).

Manipulating the structural complexity of seawalls has been proposed as one of the most tractable ways of improving their biodiversity (Larkin et al., 2006; Loke et al., 2015a; Lai et al., 2015). However, complexity comprises multiple parameters that vary in the strength of their effect (Loke et al., 2015a; Lavender et al., 2017–in this issue). Using a theoretical framework (Loke et al., 2015a) and a software tool (Loke et al., 2014) for incorporating complexity into seawalls, Loke and Todd (2016) fabricated concrete tiles with simple and complex structural designs (greater complexity = increased variability in the sizes of four different components types: 'pits', 'towers', 'grooves' and 'crevices') and installed these on seawalls around Singapore. Results showed that, independent of surface area, greater complexity supported greater species richness and different intertidal communities. They also found that the type of structural component can have an effect on community composition and diversity that is independent of complexity. Based on these results, relevant spatial structure was hypothesised to be a critical but limited resource on seawalls in Singapore and resource partitioning was discussed as a potential model responsible for promoting greater diversity on tiles with greater microhabitat size variability (complexity).

Loke and Todd (2016), however, only examined the effects of complexity on biodiversity at one scale (4–28 mm). Even though this size range of 4–28 mm may be biologically relevant to many intertidal organisms, it would be unwise to extrapolate their results to larger (or smaller) scales given that ecological responses are often underpinned by processes and/or mechanisms that are scale-dependent (England and Cooper, 2003). In their review, Jackson and Fahrig (2014) highlight how landscape structure is seldom measured at the true 'scale of effect', i.e. the scale at which it elicits the strongest ecological response. Hence, in the present study we build on Loke and Todd (2016) by testing: (1) the effects of increasing the scale of structural manipulation and, (2) the hydrodynamic properties (i.e. velocity of flow over the whole tile) of the various tile designs. From Loke and Todd (2016) we chose the two designs that supported the greatest diversity, i.e. the 'Pits' and 'Grooves', and doubled the size of all x, y and z dimensions. Hence, the new tiles were 400 × 400 × 64 mm overall (up from 200 × 200 × 32 mm) and the size range of all the components was increased from 4–28 mm to 8–56 mm (Fig. 1). We hypothesised that the 'complex' tiles (now with components ranging from 8–56 mm) would support a greater number of species relative to 'simple' tiles (all components with mean size of 32 mm) of the same surface area. In order to assess if there were any small-scale hydrodynamic differences among tile types that could explain the results of this up-scaled study, we conducted a series of flume studies to measure 3-D flow velocities across each tile.

2. Material and methods

2.1. Tile fabrication

Loke and Todd (2016) created 200 mm × 200 mm × 32 mm (width × length × depth) concrete tiles of four basic designs: 'pits', 'towers', 'grooves' and 'crevices'. They made these into 'simple' and 'complex' tiles using the software programme *CASU* (Loke et al., 2014). For simple tiles, the length, width, spacing and height/depth of each structural component was fixed at 16 mm. For the complex tiles, these dimensions were varied from 4 to 28 mm (while maintaining a mean of 16 mm). In the present study we chose the two designs that had supported the greatest diversity in that study (Loke and Todd, 2016), i.e. the 'Pits' and 'Grooves' and doubled the size of all x, y and z dimensions. Hence, the new tiles were 400 × 400 × 64 mm; the length, width, spacing and height/depth of each structural component was fixed at 32 mm for the simple tiles and the variation increased to 8–56 mm for the complex tiles.

Masters of each tile type were created following Loke and Todd (2016) and we used silicone rubber (Freeman Bluesil™ V-340) for making the moulds from which the concrete tiles were cast. Control tiles were also constructed following Loke and Todd (2016) where granite pieces were cemented together in 400 × 400 mm casts. These were fabricated to mimic the surface of granite rip-rap seawalls where the tiles were installed so that we could assess what the existing unmanipulated seawall would support within the same timeframe, i.e. did the concrete tiles 'enhance' biodiversity on the seawalls? They were not designed to control for different substrate types as this was not within the scope of the project—that is, we did not attempt to compare concrete and granite as this has been done by others (e.g. Burt et al., 2009) and it was not feasible to carve the structural components into granite blocks. The four types of concrete tiles represented two levels of complexity ('Simple' and 'Complex'), and two different structural designs ('Pits' and 'Grooves'). Therefore, in total, five tile types were tested in this study: 'Complex-Groove', 'Complex-Pit', 'Simple-Groove', 'Simple-Pit' and 'Granite control' (Fig. 1). For all the tiles, during casting, painted mild steel flat bars with pre-drilled holes were set within the concrete base of the tiles so that they could be fixed directly onto the seawalls.

2.2. Study sites and field experimental design

Tiles were deployed during the low tides on 5–6 July 2011 along the un-grouted granite rip-rap seawalls at two sites among Singapore's Southern Islands: Pulau Hantu (1° 13′ 34″ N, 103° 45′ 0″ E) and Kusu Island (1° 13′ 22″ N, 103° 51′ 40″ E). Five replicates of each tile type were attached in random order using M8 stainless steel bolts onto the seawalls (spaced ~2.0 m apart and ~0.5 m above Chart Datum) at each site, creating a two-way ANOVA design with 'Tile type' as a fixed