ARTICLE IN PRESS

Ecological Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Learning from nature to enhance Blue engineering of marine infrastructure

A.B. Bugnot*, M. Mayer-Pinto, E.L. Johnston, N. Schaefer, K.A. Dafforn

Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Kensington 2052, Australia

ARTICLE INFO

Keywords:
Ecological engineering
Urbanization
Rocky shore
Rock pool
Ecological function
Diversity
Meta-analysis

ABSTRACT

The global sprawl of urban centres is replacing complex natural habitats with relatively flat and featureless infrastructure that supports low biodiversity. In a growing countermovement, artificial microhabitats are increasingly incorporated into designs for “Green” and “Blue” infrastructure. In order to maximise the ecological value of such interventions, we need to inform the designs with observations from natural systems and existing Green and Blue infrastructure. Here, we focussed on water retaining features mimicking intertidal rock pools, as this is a widely used intervention in coastal ecosystems. Using a meta-analysis and a qualitative literature review, we compiled information on diversity and function of rock pools on natural rocky shores and built structures to assess the potential ecological benefits of water retaining microhabitats and the design metrics of rock pools that affect diversity and function. Our meta-analysis showed higher species richness in rock pools compared to emergent surfaces on built structures, but this was variable among locations. The qualitative review revealed that rock pools on both natural and artificial shores generally hosted species that were not present on emergent rock and can also host non-indigenous species, suggesting that the addition of these features can sometimes have unwanted consequences and local ecological knowledge is essential to implement successful interventions. Relationships between species richness and design metrics, such as height on shore, volume, surface area and depth of pool were taxa-specific. For example, results from the meta-analysis suggest that building larger, deeper pools could increase diversity of fish, but not benthic organisms. Finally, this study highlights major gaps in our understanding of how the addition of rock pools and design metrics influence diversity and the variables affecting the ecological functioning of rock pools. Based on the knowledge gathered so far, recommendations for managers are made and the need for future studies to add knowledge to expand these recommendations is discussed.

1. Introduction

Natural habitats are shrinking and fragmenting due to the addition of built infrastructure, e.g. buildings and roads, seawalls and breakwaters, leading to a significant decline in biodiversity and ecosystem services in urbanised areas (Airoldi et al., 2008; Alberti and Marzluff, 2004; Grimm et al., 2008; Sala et al., 2000). Targeted modifications in the design of built environments are critical for species conservation and the recovery of lost diversity and function (Bergen et al., 2001; Dafforn et al., 2015b). A common form of modification has been the addition of microhabitats, such as roost-boxes on buildings for birds and bats (e.g. Brittingham and Williams, 2000; Goldingay, 2009) and water-retaining features on foreshore structures that aim to mimic natural rock pools (e.g. Chapman and Blockley, 2009; Firth et al., 2014a). Due to economic, logistical and engineering limitations, past designs of these features have tended to be simplistic and do not reflect the variability in size, shape and structural complexity of natural habitats (e.g. Browne and Chapman, 2014; Chapman and Blockley, 2009; Evans et al., 2016; Firth et al., 2016). With the development of new technologies such as 3-Dimensional printing, our capacity to design successful “Blue” and “Green” engineered structures is only limited by our understanding of ecological systems. In an effort to exploit available ecological knowledge to make cost-effective decisions for future interventions, we conducted a systematic review and meta-analyses and synthesised the current understandings of water retaining features as a common intervention in coastal ecosystems. On the basis of this study, we provide recommendations for new designs and/or modifications of urban marine infrastructure to increase biodiversity and ecological function and minimise ecological impacts.

Urbanised coastal areas have come to resemble “grey islands”, with many natural habitats replaced and/or fragmented by infrastructure built for protection from land erosion and flooding (Bulleri and Chapman, 2010). These structures occasionally become fouled and attract fish life, and have been considered analogous to natural rocky

* Corresponding author.
E-mail addresses: a.bugnot@unsw.edu.au (A.B. Bugnot), m.mayerpinto@unsw.edu.au (M. Mayer-Pinto), e.johnston@unsw.edu.au (E.L. Johnston), n.schaefer@unsw.edu.au (N. Schaefer), k.dafforn@unsw.edu.au (K.A. Dafforn).

https://doi.org/10.1016/j.ecoleng.2018.03.012
Received 24 July 2017; Received in revised form 1 February 2018; Accepted 28 March 2018

Please cite this article as: Bugnot, A., Ecological Engineering (2018), https://doi.org/10.1016/j.ecoleng.2018.03.012

shores (Thompson et al., 2002). However, assemblages on built structures differ in species identity and composition to those found on natural rocky shores, being less diverse (Chapman, 2003; Chapman and Bulleri, 2003) and supporting more non-indigenous species (Airoldi and Bulleri, 2011; Connell, 2001). One of the reasons for these differences is that built structures are typically subjected to greater disturbances and stressors than natural rocky shores (e.g. Airoldi et al., 2005; Airoldi and Bulleri, 2011). Furthermore, there are structural dissimilarities between rocky shores and built structures (Glasby, 1999). For example, breakwaters usually lack the variety of crevices, pits and rock pools found on natural rocky shores (Aguilera et al., 2014). These "irregularities" on natural rock surfaces provide a variety of microhabitats, which are used as refuge from predation and ameliorate the effects of disturbances and daily environmental fluctuations due to tidal cycles in the intertidal zone (Bertness et al., 1981; Fairweather, 1988; Garrity, 1984; Gray and Hodgson, 1998; Sebens, 1991). In addition, built structures are made of materials foreign to natural environments, such as concrete, plastic and treated wood, which have been shown to affect settlement of organisms (e.g. Anderson and Underwood, 1994; Glasby, 2000). As coastlines continue to be developed and require increasing infrastructure to protect valuable assets (Asif and Muneer, 2007; Thompson et al., 2002), mitigation strategies to manage and reduce associated impacts are essential.

Blue engineering designs incorporating ecological goals and principals (e.g. increase fish diversity) and informed by ecological knowledge have the potential to provide valuable habitat in highly modified environments (Bergen et al., 2001; Chapman and Underwood, 2011). To make built structures more suitable for the colonisation and establishment of native species and increase diversity, several design modifications and enhancements have been proposed, aiming at increasing structural complexity and, therefore, diversity of microhabitats. On land, for example, past studies have evaluated the characteristics of artificial roosts that maximise occupancy by targeted species (e.g. Mering and Chambers, 2014). Most interventions in marine environments, however, aimed to increase overall diversity and ecosystem function (Chapman, 2003), rather than to benefit particular species (but see Martins et al., 2010).

The marine intervention that has been most widely applied is the addition of water retaining features, which aims to mimic natural rock pools (Browne and Chapman, 2014; Chapman and Blockley, 2009; Evans et al., 2016; Firth et al., 2016; Firth et al., 2014a,b). The idea behind this approach is that a greater ecological diversity and/or species exclusively found in these features, in comparison to emergent rock, would translate into an increase in the overall diversity at the level of the structure or site. Hence, the success of previous interventions has been assessed by comparing biodiversity and species composition within and outside water retaining features, as opposed to the use of control sites (as discussed in Chapman et al., 2017). Using this approach, previous studies have reported an increase in biodiversity at the structure level after interventions (e.g. Browne and Chapman, 2014; Evans et al., 2016). However, such pattern is not universal and past surveys and experiments in natural rock pools and water retaining features have found conflicting results in terms of diversity and/or have not discussed the presence of unique species in rock pools (e.g. Araujo et al., 2006; Pinn et al., 2005; Segovia-Rivera and Valdivia, 2016). The future addition of water retaining features to artificial structures therefore requires further investigation. Consequently, the first aim of this study was to test whether rock pools host greater diversity than emergent rock and compiled information about the presence of unique species in rock pools using a qualitative literature review and meta-analysis.

Past interventions have been constrained by economical, logistical and/or engineering limitations, resulting in simple designs (e.g. a concrete flowerpot with smooth surfaces, Browne and Chapman, 2014; cylinder-shaped pools drilled in the rock, Evans et al., 2016), placed at constant tidal heights. To achieve maximum outcomes with cost-effective applications, designs should closely mimic the natural rock pools that enhance the desired variables. Progress in Green and Blue engineering therefore needs to be informed by observations of natural systems and learn from past attempts. The second aim of this study was to investigate the physical characteristics of rock pools that can be manipulated to maximise the diversity, processes and functions supported by these features using a qualitative review and, when enough data was available, meta-analyses. Results from this study are summarised in a decision tree to guide managers considering the addition of water retaining features to built infrastructure.

2. Methods

2.1. Systematic qualitative review

We did a literature review in the Web of Science™ on studies that examined ecological parameters (e.g. diversity, abundances, biomass, animal behaviour, processes and various ecosystem function variables) of rock pools on natural rocky shores and built structures. The search was done using the search terms "pool*" AND ("tide*" OR "tidal*" OR "rock*") for the period 01/01/1900 to 22/03/2017. After excluding results from unrelated research areas, we found 1,852 articles. These were further filtered by title and abstract, excluding articles that did not study intertidal rock pools (e.g. freshwater pools). We also searched the reference list of each selected study to capture studies that had not been included in the initial searches or that had been published in journals not indexed in the database we searched.

To evaluate the potential for water retaining features to be designed for ecological benefits, we selected studies that evaluated the diversity (number and identity of species), processes (e.g. grazing and predation) and functioning (e.g. primary and secondary productivity) in rock pools, including those that described the effect of design metrics (size, shape and position of pools) on ecological variables. These included manipulative and observational experiments, on both natural rocky shores and built structures. As a result, 156 studies that were included in our qualitative review.

2.2. Meta-analyses

Thirty-two papers identified in our systematic review (described above) were selected for the meta-analyses, based on the following criteria. Contrasts between studies require comparable methodologies and therefore studies were included in the meta-analyses only if they representatively sampled the local assemblages (i.e. by sampling all the organisms in a benthic quadrat or all fish collected by hand net). Studies that sampled a single or few taxa or species (e.g. Jorger et al., 2008; Schreider et al., 2003) were therefore excluded. Only studies that assessed 'established' or 'mature' assemblages were included in the meta-analyses. This was done to avoid potential confounding factors related to the stage of development of the assemblage. Therefore, for the purpose of this study, we defined "mature" assemblages as those older than 1 year. Studies where critical information (raw data, or mean, number of replicates and standard error or deviation) was missing were also excluded, due to statistical reasons. To standardise differences in sampling procedures (i.e. standardised sampling effort vs non-standardised), we estimated sampling effort as the volume of the rock pool sampled for fish and the area sampled for benthic assemblages. Thus, studies that did not contain sufficient information to calculate sampling effort were excluded from the meta-analysis.

Meta-analyses were done for a specific variable if there were more than 15 relevant data points from at least 6 studies (study identity could then be considered as a random factor – see data analysis for more details; Zuur et al., 2009). However, meta-analyses were also employed in cases where 2 or more studies reported raw data but had not tested the hypotheses addressed here. Limitations in such cases are, however, discussed. As a result, only studies reporting number of taxa for fish and