Learning from nature to enhance ecoengineering of marine infrastructure

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Abstract

The global sprawl of urban centres is replacing complex natural habitat 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. The development of new technologies such as 3-Dimensional printing allows for the construction of artificial structures that closely mimic the complexity of natural habitats. In order to maximise the ecological value of such technologies, however, 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 systematic literature review and meta-analysis, we compiled information on diversity and function in rock pools on natural rocky shores and built structures to assess the potential ecological benefits of water retaining microhabitats. Qualitative assessment revealed that rock pools on both natural and artificial shores hosted species that were not present on emergent rock. Furthermore, rock pools 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. Our meta-analysis showed higher species richness in rock pools compared to emergent surfaces on built structures, but this was variable between locations. 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 improve these recommendations is discussed.

Keywords. ecological engineering, urbanization, rocky shore, rock pool, ecological function, diversity, meta-analysis

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 and others 2008; Alberti and Marzluff 2004; Grimm and others 2008; Sala and others 2000). Targeted modifications in the design of built environments are critical for species conservation and the recovery of lost diversity and function (Bergen and others 2001; Dafforn and others 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 and others 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 and others 2016; Firth and others 2016). With the development of new technologies such as 3-Dimensional printing, our capacity to design successful “Blue” engineered structures is only limited by our ecological knowledge. In an effort to exploit available ecological knowledge to make cost-effective decisions for future interventions, we conducted a systematic review and synthesis of the current understandings of water retaining features as a common used 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 shores (Thompson and others 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 and others 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 and others 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 and others 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 and others 2002), mitigation strategies to manage and reduce associated impacts are essential.

Designs with defined targets (e.g. increase fish diversity) that are informed by ecological knowledge have the potential to provide valuable habitat in highly modified environments. To achieve this, ecologists are incorporating ecological goals and principals into the design of foreshore infrastructure (Bergen and others 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 (Chapman 2003; Chapman and Underwood 2011; Mering and Chambers 2014). On land, 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, aim to increase diversity and ecosystem function (Chapman 2003), rather than to benefit particular species (but see Martins and others 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 and others 2016; Firth and others 2016; Firth and others 2014a; Firth and others 2014b). This type of intervention has been favoured because natural rock pools can support greater diversity than emergent rock (Evans and others 2016; Firth and others 2014a; Firth and others 2013), and therefore have the potential to increase overall diversity of habitats. For example, water retaining features added to breakwalls hosted greater diversity than the surrounding emergent rock (e.g. Firth and others 2013). However, past surveys and experiments with natural and artificial rock pools have found conflicting patterns. Contrary to expectations, natural rock pools have, in some locations, been less diverse than emergent rock (e.g. Araujo and others 2006; Segovia-Rivera and Valdivia 2016). Similarly, Pinn and others (2005) found water retaining features on artificial structures less diverse that emergent rock. The future addition of water retaining features to artificial structures therefore requires further investigation and qualification of the characteristics that are important to successfully enhancing native biodiversity and particular taxa.

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 and others 2016), placed at different tidal heights. Sizes and depth have also been manipulated to assess effects on diversity (Browne and Chapman 2014; Firth and others 2014b). To achieve maximum outcomes with cost-effective applications, progress in Green and Blue engineering needs to be informed by observations of natural systems and learn from past attempts. Here we propose a decision path for managers considering the addition of water retaining features to built infrastructure. This is informed by a literature review and meta-analyses where we compiled the results of previous interventions on built structures and the ecological processes and mechanisms occurring in natural habitats. We investigated (i) whether adding water retaining features to artificial structures can increase diversity and/or functioning, and (ii) which physical characteristics could be manipulated to maximize the diversity and functions supported by these features.

Methods

Literature search and data extraction

We did a literature review in the Web of Science™ on studies that examined ecological parameters (e.g. diversity, abundances, biomass, animal behaviour 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 then searched the reference list of each selected study for any other relevant articles, resulting in a total of 348 articles.

To evaluate the potential for water retaining features to be designed for ecological benefits, we selected studies that evaluated the diversity and function 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.

To assess whether the addition of water retaining features results in an increase in total biodiversity on built structures, previous studies have compared biodiversity and species composition within and outside rock pools, as opposed to the use of control sites (as discussed in Chapman and others 2017). The idea behind this approach is that a greater ecological diversity and/or species exclusively found in rock pools would reflect in an increase in diversity at the level of the structure. Therefore, we tested whether rock pools increase intertidal diversity with (i) a qualitative literature review of species only found in rock pools, and (ii) a meta-analysis comparing number of taxa within and outside pools. Very few studies have measured ecological processes and function (e.g. productivity, grazing, predation) (see results), therefore these variables were investigated with a qualitative review.

The relationships between number of taxa and design metrics such as tidal height, depth, volume and area of pools were also assessed using meta-analyses. Other design metrics, including substrate complexity, incline and material, distance between pools and light incidence, have been poorly defined and studied in natural rocky shores, and never evaluated from built infrastructure. They were therefore assessed here with a qualitative review of the literature.

All meta-analyses in this study were based on number of taxa as this was frequently reported (see results) and the main goal of previous interventions was to increase diversity on artificial structures (see introduction). Contrasts between studies require comparable methodologies and therefore studies were included in the meta-analysis if they did representative community sampling (i.e. by sampling all the organisms in a benthic quadrat or all fish collected by hand net). Studies were excluded if they sampled a single taxon or species (e.g. Jorger and others 2008; Schreider and others 2003). As we included manipulative and observational experiments in the analyses, it was necessary to filter out studies surveying "young" communities, as opposed to established assemblages. Therefore, for the purpose of this study, we defined "mature" assemblages as those older than 1 year. For statistical reasons, we also excluded studies where critical information (raw data, or mean, number of replicates and standard error or deviation) was missing. Data extraction from graphs was done using WebPlotDigitaliser (arohatgi.info/WebPlotDigitizer). We also extracted the location (name of the district/area) of the study, latitude, the type of structure (natural rocky shore vs built structure) and the total surface area (for benthic assemblages) or volume (for fish) of the sampling unit.

Some studies sampled all organisms in each rock pool (sampling size not standardised), while others standardised their sampling by using quadrats (standardised studies were found for benthic assemblages only). Based on this, we estimated the volume of the rock pool sampled for fish and the area sampled for benthic assemblages (i.e. sampling effort). Studies that did not contain sufficient information to calculate sampling effort were excluded from the meta-analysis. Benthic assemblages and fish were analysed individually and sampling effort was included as a random variable in the models evaluating the effect of tidal height and depth. When evaluating the effect of area and volume for benthic assemblages, standardised and not-standardised studies were evaluated separately, resulting in two analyses per design metric.

Data analysis for studies included in the meta-analysis

When comparing number of taxa between rock pools and emergent rock, some studies reported mean and errors per location sampled, while others reported those for different sites within a location (e.g. several groynes in the same location used by Pinn and others 2005). Each site or location was considered a replicate, hence several data points per study were included in the meta-analyses. To account for non-independence in the data, study identity and location (nested in study identity) were included as random factors in a multi-level model (Noble and others 2017) using rma.mv (*metaphor* package) in R 3.3.3. The effect size of number of taxa between rock pools and emergent rock was calculated using the log transformed ratio of means (using "ROM" in *metaphor* package in R). The type of structure (artificial vs natural) was also included as a fixed predictor in the model. Sensitivity analysis was performed using the leave-one-out method, by removing one study or one location at the time to detect data points with strong effects in the results (Borenstein and others 2009).

Studies reporting the effects of design metrics on number of taxa used a mix of raw data, means and errors. Hence, a logarithmic transformation was used to control for the differences in the distribution of variances. To assess the relationships between design metrics and number of taxa, linear models were used (*nlme* package in R), with "study identity" and "site" as random predictors to account for non-independence (Nakagawa and Santos 2012) and the design metric of interest as a fixed predictor. For analyses where the level of the factor "study identity" was lower than 4 (Zuur and others 2009), this was considered a fixed factor and the analyses were done using a linear model ('lm' function in R). The number of replicates per data point (1 for raw data points, >1 for means) was included as *weights* in all models. For benthic assemblages, tidal height was reported as a categorical and/or continuous variable, so two separate analyses were performed to test for consistency in the effect of tidal height. When evaluating the relationships between number of taxa and size, area and volume were log transformed, as the species-area relationship predicts a log-log relationship (Connor and McCoy 1979).

Results of qualitative literature review and meta-analysis

The qualitative literature review found 32 studies that directly compared ecological parameters between rock pools and emergent rock, with 12 of them studying diversity and composition of mature assemblages. Twenty-five articles focussed on natural rocky shores, while 7 focussed on built infrastructure. In a separate search, we found design metrics evaluated in 129 studies, with tidal height being the variable most studied (76 studies focussed on natural rocky shores, 6 on built infrastructure and 4 included both), followed by depth (46 natural, 7 built and 1 both), size (reported as volume and/or area, 42 natural and 2 built), structural complexity (21 natural, 2 artificial and 3 both), light incidence (6 natural and 2 built), distance between pools (5 natural), material (2 natural) and incline (1 natural, Fig. 1a). Vertebrates (mainly fish) were the taxa most studied, followed by invertebrates and algae, while a great number of studies analysed benthic assemblages, which included invertebrates and algae (Fig. 1b). The ecological variables most frequently reported were biodiversity parameters, such as number of taxa and abundance/cover of organisms (Fig. 1c). Other variables reported include physical variables such as temperature, salinity and pH and ecological processes such as recruitment, grazing and predation. Functioning and behaviour were poorly studied, with only 17 and 6 studies respectively (Fig. 1). The distribution of non-indigenous species in rock pools was only evaluated in 7 studies.

Finally, 22 articles were selected for the meta-analyses (Supplementary material 1), including 16 studies on natural rock shores, 5 studies on built structures (all breakwaters) and 1 in both natural and built habitats (using Bioblock®). All studies used for the comparisons of the number of taxa between rock pools and emergent rock focussed on benthic assemblages, whereas studies that evaluated the relationships between design metrics and number of taxa focussed on benthic and fish assemblages.

Effect of rock pools on diversity and function

We compared the number of taxa between rock pools and emergent rock at 38 sites (each a replicate) included in 21 locations extending over 20 degrees in latitude and gathered from 6 studies (Figure 2, Supplementary Material 1). These studies were done on natural rocky shores (14), breakwaters (13) and one study on a Bioblock®, and the great majority (5) were observational, with only one manipulative experiment

Most studies used in the meta-analyses reported greater diversity in pools than on emergent rock (but see Pinn and others 2005), but our meta-analysis also showed significant heterogeneity in the data (Test for Heterogeneity Qe = 138.55, df=36, $p < 0.0001$) due to the great variability in the effect sizes between sites (Fig. 2). Number of taxa of benthic organisms was more abundant in water-retaining features than on the emergent surface on built structures ($z = 2.76$, $n = 19$, $p = 0.0058$, Fig. 2), but this was not observed in natural rocky shores ($z = 1.38$, $n = 19$, $p = 0.17$, Fig. 2). Additionally, the sensitivity analyses showed spatial variation in the results, as one location (Elmer) and one study (Firth and others 2013, which includes the location Elmer, among others) contributed most of the differences found on artificial structures. Leaving any of them out from the analysis changed the significance of the results (without Elmer: $n = 37$, $z_{Art} = 1.78$, $p_{Art} = 0.07$, without Firth and others 2013: $n = 29$, $z_{Art} = 1.05$, $p_{Art} = 0.29$, Supplementary Material 2).

Number of taxa, however, is a simplified measure of diversity and does not account for species identity. Our qualitative literature review showed that rock pools provide habitat for a variety of species not found on emergent rock. For example, a rocky shore study in Portugal observed two algal species that were unique to rock pools, but overall a greater number of taxa were found on emergent rocks than in rock pools (Araujo and others 2006). Lintas and Seed (1994) also found a greater number of taxa in mussel beds on emergent rock than in rock pools on natural shores, but six species were exclusively found in rock pools (an anemone, a polychaete worm, a gastropod, a bryozoan and two species of copepods). Similar patterns were found for built structures, where water retaining features were colonised by unique species, i.e. not found on the emergent surface. For example, on the high shore of seawalls in Sydney Harbour, ascidians and sponges were only found in constructed rock pools (Chapman and Blockley 2009). Evans and others (2016) found that adding rock pools to a breakwater supported groups completely absent from emergent surfaces, such as fish, ascidians, bryozoans, hydroids and sponges. Rock pools can, however, benefit non-indigenous species as well. Andrew and Viejo (1998) found a greater prevalence of the non-indigenous algae *Sargassum muticum* in rock pools than on emergent rock in Spain.

Our literature review showed that rock pools also have different functional characteristics and processes than emergent rock. Grazing intensity was two times greater in rock pools than on emergent rock in natural rocky shores of England, due to a species of limpet that often migrated to rock pools for feeding purposes (Noel and others 2009). Therefore, organisms not usually reported in the pools might be directly or indirectly benefiting from the presence of these habitats.

Tidal height

Some studies comparing the number of benthic taxa between tidal heights of rock pools reported tidal height as meters above the lowest tidal mark, others as a categorical variable (i.e. low, medium, high), and some used both. The organisms studied were fish and benthic assemblages, which were analysed separately due to the differences in sampling effort (see methods for more details). As a result, we obtained 26 and 52 data points from 3 and 4 studies to assess the relationships with fish and benthic diversity, respectively, using tidal height as a continuous variable, and 49 data points from 8 studies for benthic assemblages using a categorical variable. This information was gathered from a total of 20 locations (Supplementary Material 1).

The meta-analyses showed that number of taxa for fish and benthic assemblages were negatively related to tidal height (Table 1, Fig. 3). Even though the number of studies is low for some analyses, these are still meaningful as the number of replicates used in this study are greater than in any previous study and we applied new analyses to the raw data from some studies that were not previously considered by the authors of those studies (Daryanavard and others 2015; Goss-Custard and others 1979; Metaxas and others 1994; Wolfe and Harlin 1988). In addition, our meta-analyses included sampling effort in the models to standardise the data, a procedure which has not been done by previous studies.

Species composition also changed with tidal height. For example, some fish species occurred in rock pools at all tidal heights, while others were present only at some heights of the shore (Davis 2000; Gibson 1972). Dominance of algal groups in rock pools was also related to tidal height (Araujo and others 2006; Green 1971). Huggett and Griffiths (1986) found that rock pools located at the low shore were dominated by bivalves and sponges, whereas pools at the high shore were dominated by algae and grazers.

Functioning of rock pools was also observed to vary with tidal height, but the direction of these relationships varied depending on the species. Primary productivity was found to be greatest in pools at mid-heights in Portugal (Alvera-Azcarate and others 2003) and at the lowest pools in the United Kingdom (Martins and others 2007). Annual production of fish was also observed to vary with tidal height, but the direction of the relationship varied for different species (Mgaya 1992). Growth of an invasive algae *Codium fragile* was greater in lower pools in Canada (Scheibling and Melady 2008).

Depth

The meta-analyses included 69 rock-pools from 10 different locations gathered from 7 studies for fish and 27 rock pools from 3 locations and 3 studies for benthic assemblages (Supplementary material 1). Even though the number of studies and locations for benthic assemblages are low, their inclusion is still informative as the number of replicates used in this study are greater than in any individual study and our analyses used raw data from 3 studies that were not previously considered by the authors of those studies. In addition, our meta-analyses included sampling effort in the models to standardise the data, a procedure which has not been done by previous studies. Rock-pool depths ranged from less than 1cm to 2 meters. For fish assemblages, the number of taxa was significantly related to depth (Chi^2 = 15.06, $p = 0.002$, Fig. 4). In contrast, the number of taxa of benthic assemblages was not related to depth (F = 0.42, $p = 0.52$, Fig. 4).

Even though no effect was observed on number of taxa of benthic assemblages, Wolfe and Harlin (1988) and White and others (2015) found that assemblage composition was related to depth. A study done in Australia, with rock pools ranging from 5 to 40-cm deep, found that the grazer snail *Cellana tramoserica* was more abundant in deeper pools, whereas the algae *Hilderbrandia prototypus* was more abundant in shallower pools (Astles 1993). Tubeworms, molluscs and crustaceans were observed to colonise shallow (22 cm) water retaining features added to seawalls in Sydney, while opportunistic algae were dominant in deeper (38 cm) pools (Browne and Chapman 2014). In addition, the distribution and abundances of the non-indigenous gastropod *Zeacumantus subcarinatus* were also affected by depth, but the patterns observed were complex. Densities of *Z. subcarinatus* when present were negatively correlated with depth (Hendrickx and others 2015). In contrast, a manipulative experiment where built rock pools were added to a breakwater found no effect of depth on the structure of assemblages (Evans and others 2016). Primary productivity varied with depth in pools from 2 to 24-cm deep, with deeper pools having greater productivity when located on the upper shore (Martins and others 2007). The relationship between depth (range of depth studied not reported) and growth of two fish species varied depending on the species, with one species, *Clinocottus globiceps*, showing no significant trends and another, *Oligocottus maculosus*, showing a negative relationship (Mgaya 1992).

Size (volume and area)

The relationships between number of taxa in fish assemblages and size was evaluated using volume and area. The relationships between number of fish species and volume was assessed using 73 data points reported by 8 studies from 14 locations, and diversity and area using 69 data points reported by 7 studies from 10 locations (Supplementary material 1). To obtain an unconfounded relationship between number of taxa and size of rock pools, surveys should standardise sample effort. All of these studies, however, sampled all fish in each rock pool, so sampling was not standardised.

The relationships between number of benthic taxa and size of rock pools was assessed from 4 locations gathered from 4 studies, 2 of which used standardised sampling and contributed 18 data points to the analysis (Goss-Custard and others 1979; Metaxas and others 1994), and 2 which contributed a total of 16 data points but used non-standardised sampling (Underwood and Skilleter 1996; Wolfe and Harlin 1988). Even though the number of studies and locations are low, the number of replicates used in this study are greater than in any previous study and we have performed analyses on benthic data as 3 out of these 4 studies (Goss-Custard and others 1979; Metaxas and others 1994; Wolfe and Harlin 1988) have reported raw data but did not assess the relationships between size of rock pools and number of taxa. Data obtained ranged from 7.1 to 876 m^2 and 0.0003 to 14300 m^3 in volume.

Number of fish species showed a significant, positive log-log relationship with both volume and area (Table 2, Fig. 5), as expected based on the richness-area relationship (Connor and McCoy 1979). However, the number of taxa of benthic organisms did not show a significant relationship with volume or area (Table 2, Fig. 5).

Our literature review showed that the effects of rock pool size on assemblage composition of benthic organisms and fish varied in space and time (Bussell and others 2007; Jordaan and others 2011; Martins and others 2007), as well as with species identity (Davis 2000; Mgaya 1992; Zhuang 2006). In addition, effects of size of the pool were also observed within species, as length of fish was significantly correlated to volume in pools from 300 l to 4.6×10^6 l (Emmerson 1985). The relationships between productivity and size were evaluated in two studies. Primary productivity was found to be positively correlated with pool volume, but not with area (for pools ranging from 0.03 to 1.9 m^2, Martins and others 2007), while annual production of fish was not related to area or perimeter of rock pools (sizes of pools samples not reported, Mgaya 1992).

Other variables

Twenty-seven studies have evaluated complexity of the substratum and implemented a range of definitions for complexity, from surface rugosity (e.g. Daryanavard and others 2015; Macieira and Joyeux 2011), presence of rock, rubble and sand (e.g. Griffiths and others 2006; Mahon and Mahon 1994) and presence of pits and crevices (e.g. Cunha and others 2008; Dumas and Witman 1993). Studies evaluating the effects of fine-scale surface complexity (e.g. rugosity, small pits) on a series of ecological variables, such as diversity (e.g. Davidson and Grupe 2015; Griffiths and others 2006), species composition (e.g. Daryanavard and others 2015; Matias 2013), behaviour (Mayr and Berger 1992; Nakamura 1976) and primary production (Matias 2013), among others, found varying results. Griffiths and others (2006) found that the addition of rocks (sizes not reported) to natural pools resulted in an increase in number of species and abundances of fish, but no effect was observed on size distribution of fish among pools. In contrast, abundances of fish were only weakly related to the percentage cover of rocks and no relationship was observed with number of species and biomass in South Africa (Marsh and others 1978). The relationship between densities of fish and rugosity differed between species in a study in California (Davis 2000). Algal assemblages, however, were negatively affected by the presence of rocks (5-8 cm in diameter) due to a scouring effect (vanTamelen 1996).

The metrics light incidence, distance between pools, material and incline of the substratum inside pools have been poorly evaluated before (8, 5, 2 and 2 studies, respectively), and studies have evaluated a range of response variables. The effect of light incidence on ecological communities in natural rock pools has been poorly studied, and was never evaluated on water retaining features on built structures. Previous studies have shown that shaded rock pools have different algal assemblages than those that are illuminated the whole day, with light favouring Cyanophytae and Chlorophyceae at the expense of Rhodophyceae and Phaeophyceae (Gustavss 1972). However, UV exposure can also have negative effects on algae and fish. Coralline algal species showed photo-inhibition related to irradiance fluctuations in rock pools (Williamson and others 2014). The fish *Girella laevifrons* also showed signs of stress when exposed to UV radiation, by increasing oxygen production, decreasing body weight and actively searching for refuge (Pulgar and others 2017).

Distances between rock pools showed variable effects on population dynamics, however no studies evaluated their effect on assemblage composition. When evaluating temporal changes in population dynamics of a copepod, pools between 0 to 40 m apart showed similar patterns of temporal variation, but pools more than 40 m away showed different patterns of temporal variation (Johnson 2001). Population synchrony of an invertebrate species was also negatively related to distance among pools (Pandit and others 2016). In contrast, Engel and others (2004) found that genetic differences of the red seaweed *Gracilaria gracilis* between pools were not related to distance between pools. Only one study assessed the effects of material of rock pools on community structure. Cox and others (2011) sampled rock pools on basalt and limestone natural rocky shores and found different fish assemblages. No studies have, however, evaluated the effect of material of construction when designing water retaining features for foreshore infrastructure. Incline of the pool can influence diversity and functioning as it affects shading and depth, but only one study evaluated this factor. Firth and others (2014a) reported that the relationship between incline and richness varied with functional group, with canopy algae having a positive relationship with slope, while encrusting algae and faunal groups had no clear trends.

Discussion and recommendations

Green and Blue engineering strategies are increasingly being recognised as valuable tools to enhance biodiversity and function in highly modified environments (Dafforn and others 2015b; Schifman and others ; Threlfall and others 2017). Their success and applicability are, however, limited by our understanding of the particular factors driving biodiversity and function. For example, if the objective of an intervention is to maximise ecological biodiversity on a particular structure though the addition of microhabitats, what are the specific characteristics of these microhabitats that maximise biodiversity? This study takes the first steps into answering these questions by gathering the existing knowledge on the effects of the presence and characteristics of rock pools on biodiversity and function. Using a combination of literature review and meta-analyses, we propose the first guidelines for the design of water retaining features on built infrastructure (Fig. 6), which should be updated and improved as new data becomes available.

When evaluating species uniquely found in rock pools, a qualitative review showed that water retaining features can host a set of species absent on the surrounding emergent rock (Chapman and Blockley 2009; Evans and others 2016; Firth and others 2013), showing that their presence has the potential to add a greater range of species to the site for both built and natural habitats, but care should be taken not to facilitate the establishment and/or spread of noxious, invasive species (Dafforn 2017). When comparing number of taxa between rock pools and emergent rock, the results of our meta-analysis suggested that, contrary to the general perception that rock pools contain greater diversity than emergent rock, these patterns are variable in space. This is evidenced by the significant heterogeneity in the data and the sensitivity analyses, which showed that one location (Elmer, UK) was the main driver of the significant differences found in number of taxa for water retaining features. Due to the high variability in the effects of rock pools between sites, it is arguable that the design of Blue engineering strategies should be informed by knowledge of the local environment, flora, and fauna rather than following the general assumption that adding habitat complexity to built structures will increase native species diversity.

Our analyses on rock pools only (and not the emergent surfaces) does suggest that tidal height (in both built structures and natural habitats) affect biodiversity of fish and benthic assemblages, with greater diversity at lower tidal heights. In addition, the literature review also showed evidence of changes in function with tidal height. For example, even though greater biodiversity was always observed in pools in the lower intertidal compared to pools in the higher intertidal, primary productivity peaked at a range of tidal elevations, suggesting context dependant relationships between these two variables. When designing Blue infrastructure that incorporates water retaining features, tidal elevation should be selected based on the desired outcomes of the intervention (e.g. to optimise diversity or function or both). If the main objective is to increase diversity at the site level, water retaining features should be placed at a broad range of tidal heights to provide suitable habitat to a wide variety of species. If resources are constrained, the majority of water retaining features might be placed in the low intertidal zone, to maximise habitat availability in this high-diversity zone. If, on the other hand, the main objective is to increase a particular function of the system, e.g. productivity, the tidal height of these features will be site dependent and developers might choose the most suitable elevation range for the dominant local keystone species.

We observed that deeper, larger pools increased the diversity of fish, however, these results were not reflected in the diversity of the benthic assemblages. These patterns can be explained by the requirements of highly mobile fish (e.g. Davis 2001; Jordaan and others 2011) and behavioural choices (e.g. Davis 2000; Richkus 1981). Also, the lack of trends observed for benthic assemblages might be a result of the low number of locations and studies included in the meta-analyses, mainly due to most studies not standardising sampling nor considering sampling volumes to account for the different sampling efforts between pools. Other studies not included in the meta-analysis due to using categorical classifications of pool sizes showed trends varying greatly in space and time and location (Firth and others 2014a; Zhuang 2006). Based on the information available to date, we recommend that, if the main objective is to increase fish diversity, efforts should be concentrated on building larger, deeper pools (Fig. 6). If, however, the main goal of a modification is to increase overall diversity, water retaining features with a broad range of depths, sizes and structural complexity should be added to the habitat to increase niche variability at the site (Fig. 6). Future interventions should design appropriate monitoring strategies (as discussed by Chapman and others 2017) and make the data publicly available to build on the available knowledge and improve these recommendations as appropriate. In polluted environments in particular, care should be taken to avoid the creation of contaminant traps by varying the pool height to width ratio (e.g. a 3:1 height to volume ratio is an efficient particle trap and may result in contaminated water features, Dafforn and others 2013). Also, shape and size of pools can affect physico-chemical characteristics such as temperature (Kita and others 1985; Martins and others 2007) and desiccation (Altermatt and others 2012), which can, in turn, affect colonisation and establishment of communities. Designs should aim to minimise these effects by using a range of depth and sizes similar to those of local natural rock pools. The relationships between physical parameters of pools and functioning were observed to vary greatly between and within studies, so any designs aiming to maximise particular functional attributes should base their design on local ecological knowledge.

These recommendations do not, however, guarantee to achieve the desired outcomes. The local pool of species available for colonisation can greatly affect the results. This review has found that interventions on foreshore infrastructure may also facilitate the establishment of non-indigenous species. This has also been observed in terrestrial environments where artificial roots have been colonised by non-indigenous birds, insects and mammals (e.g. Le Roux and others 2016; Savard and Falls 1981). With the objective of pre-empting space and avoiding the settlement of undesired species, a recent study added artificial turf to water retaining features (Morris and others 2017). Results showed no differences in the percentage on non-indigenous species between pools with and without turf. Additionally, interventions done so far have been limited to small scales, whereas the effects of interventions at the scale of the site remain unexplored (Chapman and others 2017). Finally, Blue engineering strategies should be implemented in conjunction with measures to control disturbances on these structures. For example, the implementation of maintenance practices that minimise physical damage to ecological assemblages and discourage harvesting of native organisms (Airoldi and others 2005; Airoldi and Bulleri 2011).

Our review revealed that certain design metrics remain almost unexplored. Marine infrastructure is greatly affected by anthropogenic sources of light, such as artificial lighting at night and shading caused by infrastructure during the day. On pilings and pontoons, artificial light affects fish abundance and predation on benthic assemblages (Bolton and others 2017), while daylight intensity and surface inclination influence the presence and competitive dominance of non-indigenous species (Dafforn and others 2012). The effect of light on ecological communities in natural rock pools has been largely overlooked, and has yet to be evaluated on water retaining features on built structures. Inclination of rock pools and its effect on associated assemblages represents another big gap in our understanding, particularly given the demonstrated importance of surface orientation for benthic assemblages (Blockley and Chapman 2006; Dafforn and others 2012; Glasby 2000). Finally, construction material is understood to affect benthic assemblages (e.g. Airoldi and others 2015; Brown 2005; Burt and others 2009; Hawkins and others 2010), but only one study has examined its effect on rock pool communities (Cox and others 2011). We strongly recommend the measurement of such parameters in future studies to inform the design of water retaining features, as well as that of marine infrastructure more generally. In the absence of such information for pools, designs of these features should minimise artificial light, maximise natural light, and as far as possible mimic the surface characteristics of the local coastal geology.

Even though there is a broad number of studies focussing on the ecology of rock pools, the community-level effects of the presence of rock pools and design metrics remain poorly studied. Furthermore, studies on human impacts on ecological communities tend to be focussed on community structure and little is known about impacts on the ecosystem functions that underpin critical services (Johnston and others 2015). Our review uncovered case studies showing that rock pools on natural rocky shores can affect the functioning of communities and can have bottom-up effects that escalate, at least, to the whole habitat. One example from the coast of the United Kingdom, described how limpets migrated from neighbouring emergent rock to graze inside constructed rock pools (Noel and others 2009). As Blue engineering interventions can serve multiple biodiversity and functional objectives (Dafforn and others 2015a), we strongly recommend including measurements of functional properties in future studies. If the goal of the intervention is to increase particular functional aspects of the habitat, designs should be informed by the drivers of the functional parameter to maximise (Fig. 6). As indirect assessment of change in functioning using diversity measures is not accurate (Johnston and others 2015), future studies focussing on water retaining features should incorporate direct measurements of functional variables to inform future interventions.

Conclusions

The fast advance of design and construction technology provides new opportunities to improve and refine ecological interventions based on in-depth observations of natural systems and lessons learnt from existing Green or Blue infrastructure. Clear ecological objectives of the intervention, proposed *a priori*, are crucial in order to inform the most appropriate design for infrastructure - a practice often neglected (Chapman and others 2017; Mayer-Pinto and others 2017). Notwithstanding the aforementioned knowledge gaps, we can use the results of this study in combination with general ecological understandings of intertidal ecosystems, to guide the design of foreshore constructions. The results of this review support the idea that the addition of microhabitats to built infrastructure has the potential to increase diversity and functioning. Some key principles include: a) managers should evaluate if the addition of water retaining features has the potential to achieve the desired outcomes based on knowledge of the local ecological communities, b) to achieve benthic biodiversity outcomes, niche diversity should be maximised by adding water retaining features of varying tidal height, depth, pool volume and area; to achieve fish biodiversity outcomes, deeper bigger pools should be prioritised c) aim for natural dimensions, materials, complexity, light regimes and distance between pools similar to those found locally. Rigorous monitoring, assessment and reporting of ecological outcomes (including open access for raw data) should be done to build our knowledge base and continually improve the proposed framework. As we continue to construct the coast, we emphasize the need for small- and large-scale studies that address critical knowledge gaps and incorporate ecological objectives into our built environment.

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Figure captions

Fig. 1. Number of studies that assessed physical and ecological parameters in intertidal rock pools. (a) Studies evaluating design metrics (tidal height, depth, size, structural complexity (complexity), light incidence (light), distance away from other pools (distance), substrate incline and construction material (material)). (b) Studies focused on vertebrates, invertebrates, algae, protists and all benthic organisms. (c) Studies assessing community diversity (including diversity parameters such as Shannon Index and total number of taxa, total abundances, biomass and multivariate analyses), physico-chemical characteristics of the

pools (temperature, pH, salinity, oxygen, etc.), ecological processes (reproduction, grazing, predation, connectivity, dispersal), ecological functioning (production, respiration, nutrients cycling) and behaviour.

Fig. 2. Ratio between number of taxa in rock pools vs emergent rock for each data point. Grey diamonds represent the estimated value and 95% CI for each group (built structures and natural rocky shore). Data points are ordered by latitudinal gradient. N = number of replicates.

Fig. 3. Number of taxa vs tidal height of rock pools for fish (top) and benthic (bottom) assemblages. For benthic assemblages, studies using tidal height as a continuous variable (meters) are on the left, and using a categorical variable (right) variable. Colours represent different sites.

Fig. 4. Number of taxa vs depth of pool (meters) for fish and benthic assemblages. Colours represent different sites.

Fig. 5. Number of taxa vs size (volume and area, log-log relationship) for fish and benthic assemblages. Studies using standardised (only for benthic) and not-standardised sample size. Colours represent different sites.

Fig. 6. Diagrams of the design of past interventions including water retaining features of similar sizes and depth, and regularly positioned at several tidal heights, and diagrams of the recommended designs of water retaining features to either increase total benthic diversity (animal and algal) or fish diversity. Depth of the pool is represented by colour of pools. Symbols by ian.umces.edu.

Tables

Table 1

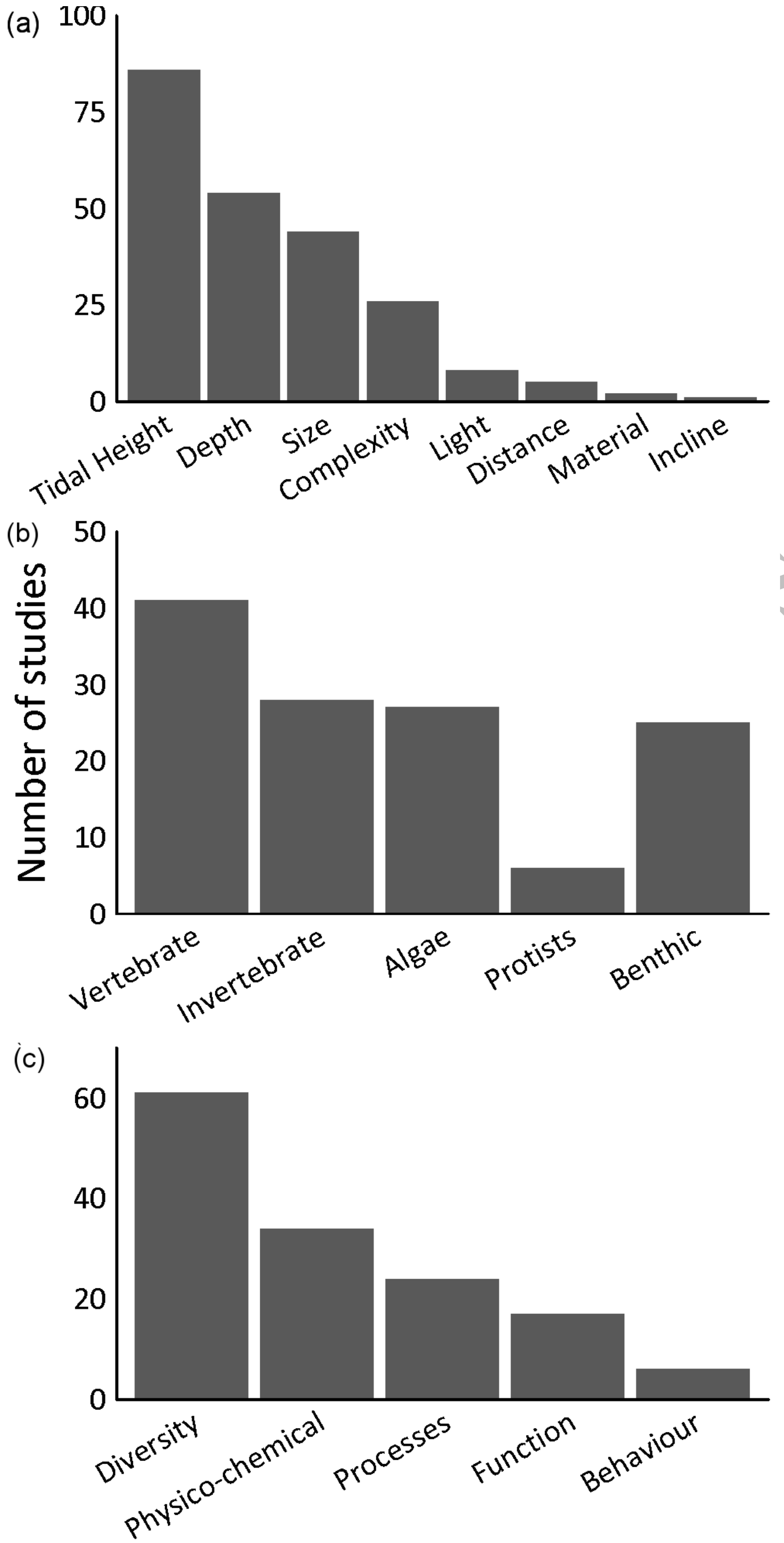
Results from the linear models assessing the effect of tidal height on number of taxa, when using tidal height as a continuous and categorical variable.

	Continuous			Categorical	
	Estimate	Chi²	*p*	Chi²	*p*
Fish	-0.50 ± 0.17	15.04	0.001		
Benthic	-0.65 ± 0.28	43.49	0.0000	26.54	0.0000

Table 2

Results from the linear models assessing the effect of size (measured as volume and area) on number of taxa for fish and benthic assemblages.

	Volume			Area		
Not standardised	**Estimate**	**Estimate**	**p**	**Estimate**	**Estimate**	**p**
		Chi² =			*Chi² =*	
Fish	1.21 ± 1.05	46.96	0.0000	1.31 ± 1.04	51.00	0.000
Benthic		*F* = 2.08	0.17		*F* = 2.13	0.17
Standardised		**t value**	**p**		**t value**	**p**
Benthic		*F* = 1.75	0.21		*F* = 1.45	0.25



906

907 Figure 1

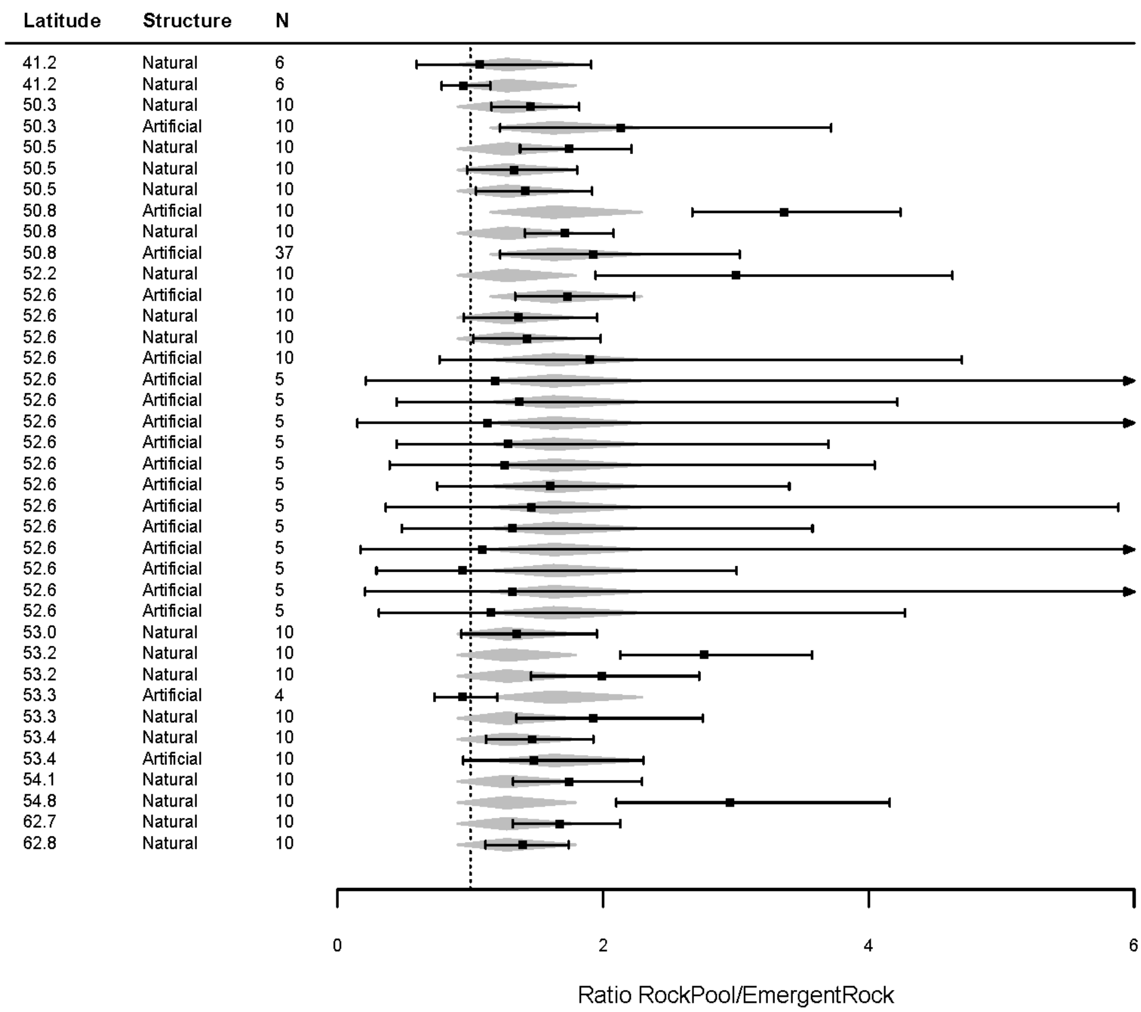

Latitude Structure N
41.2 Natural 6
41.2 Natural 6
50.3 Natural 10
50.3 Artificial 10
50.5 Natural 10
50.5 Natural 10
50.5 Natural 10
50.8 Artificial 10
50.8 Natural 10
50.8 Artificial 37
52.2 Natural 10
52.6 Artificial 10
52.6 Natural 10
52.6 Natural 10
52.6 Artificial 10
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
52.6 Artificial 5
53.0 Natural 10
53.2 Natural 10
53.2 Natural 10
53.3 Artificial 4
53.3 Natural 10
53.4 Natural 10
53.4 Artificial 10
54.1 Natural 10
54.8 Natural 10
62.7 Natural 10
62.8 Natural 10
0
2
4
6
Ratio RockPool/EmergentRock

Figure 2

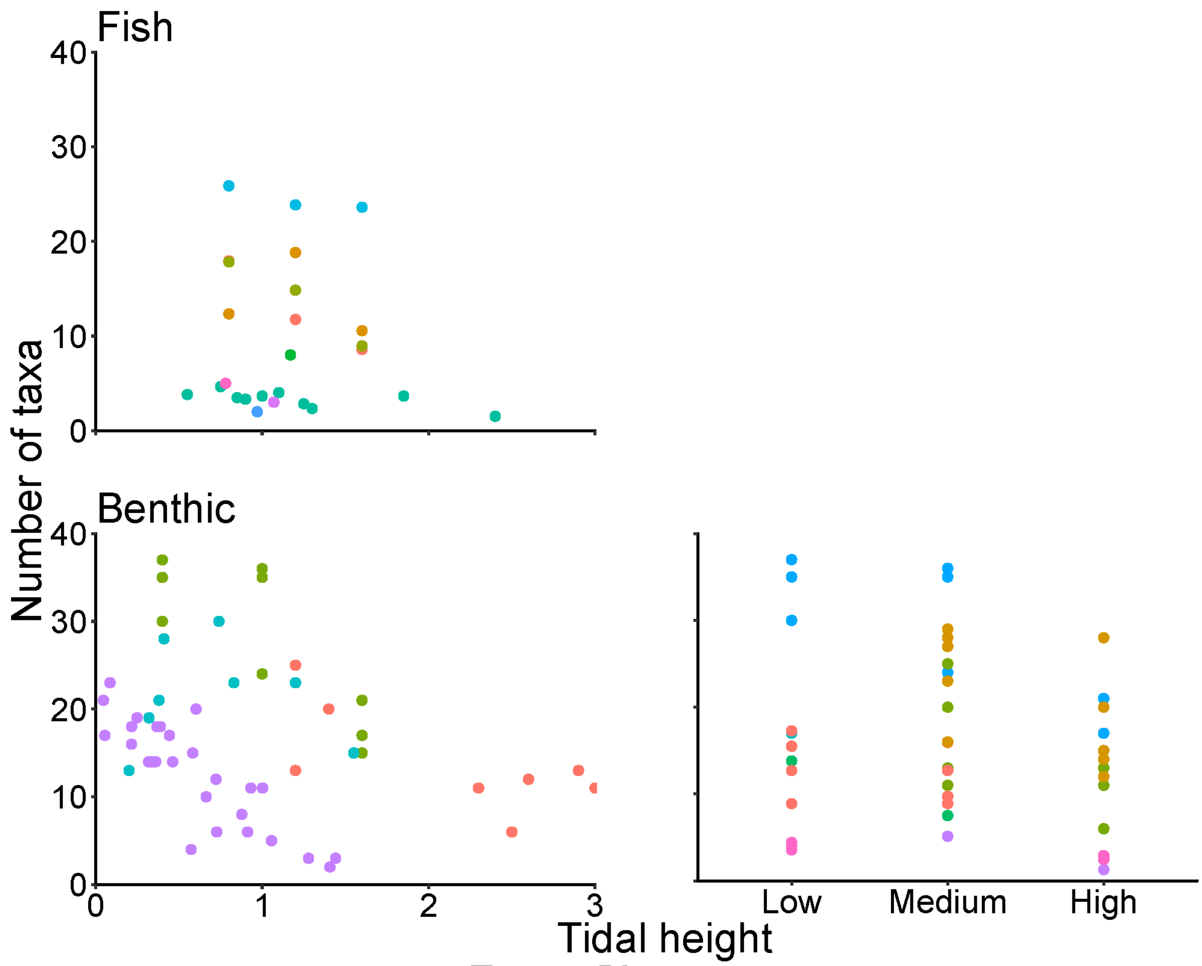
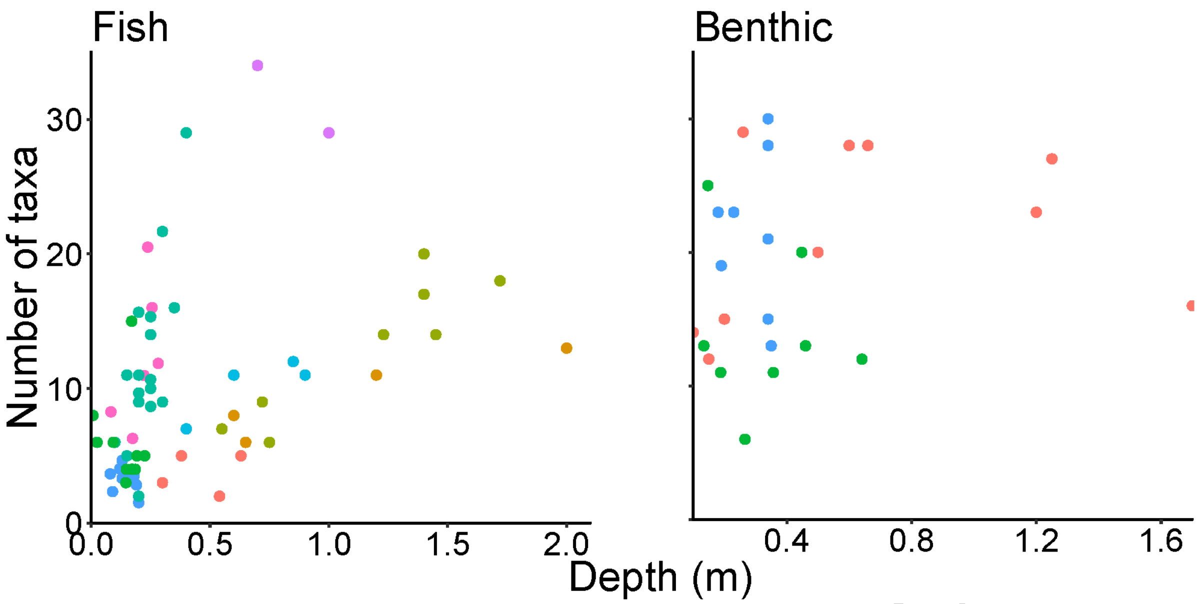

Fish
Benthic
Number of taxa
Tidal height
0
10
20
30
40
1
2
3
Low
Medium
High

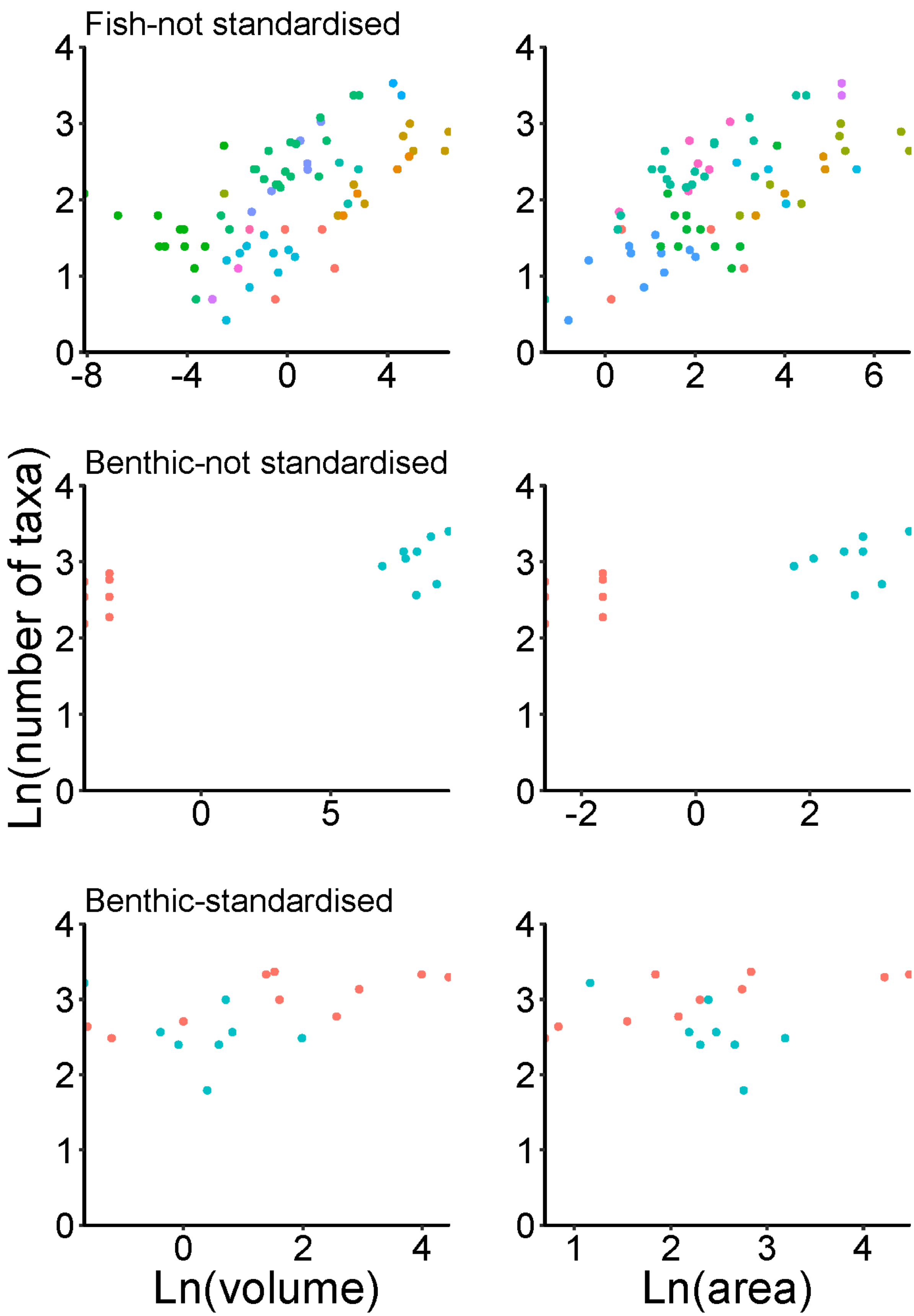
Figure 3



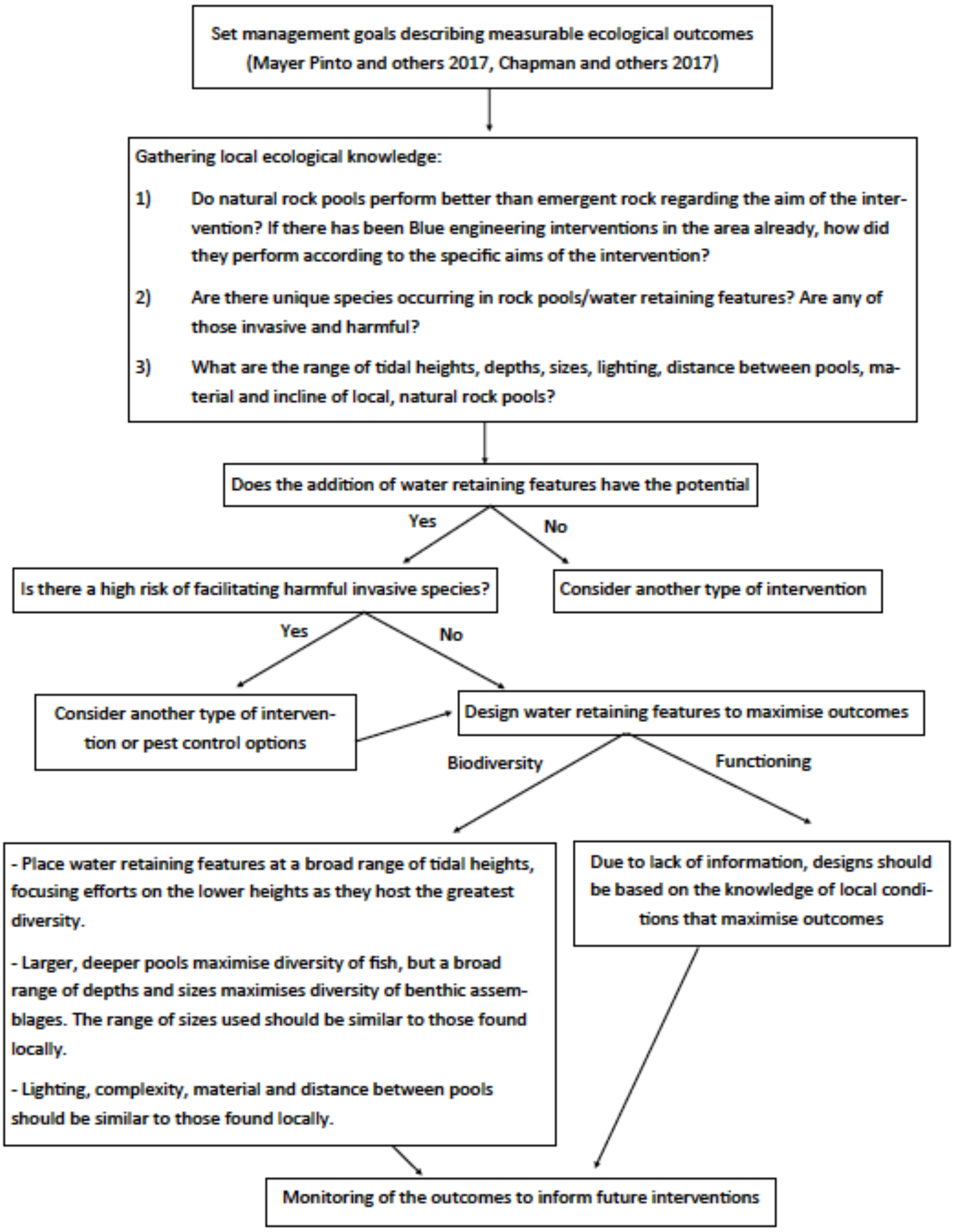
914

915 Figure 4

916



917 Figure 5



Set management goals describing measurable ecological outcomes (Mayer Pinto and others 2017, Chapman and others 2017)
Gathering local ecological knowledge:
1) Do natural rock pools perform better than emergent rock regarding the aim of the intervention? If there has been Blue engineering interventions in the area already, how did they perform according to the specific aims of the intervention?
2) Are there unique species occurring in rock pools/water retaining features? Are any of those invasive and harmful?
3) What are the range of tidal heights, depths, sizes, lighting, distance between pools, material and incline of local, natural rock pools?
Does the addition of water retaining features have the potential
Yes
No
Is there a high risk of facilitating harmful invasive species?
Consider another type of intervention
Yes
No
Consider another type of intervention or pest control options
Design water retaining features to maximise outcomes
Biodiversity
Functioning
- Place water retaining features at a broad range of tidal heights, focusing efforts on the lower heights as they host the greatest diversity.
- Larger, deeper pools maximise diversity of fish, but a broad range of depths and sizes maximises diversity of benthic assemblages. The range of sizes used should be similar to those found locally.
- Lighting, complexity, material and distance between pools should be similar to those found locally.
Due to lack of information, designs should be based on the knowledge of local conditions that maximise outcomes
Monitoring of the outcomes to inform future interventions

Figure 6