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# Eco-engineering urban infrastructure for marine and coastal biodiversity: which interventions have the greatest ecological benefit?

Strain, EMA

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Complete List of Authors:	Strain, Elisabeth; Sydney Institute of Marine Science Olabarria, Celia; Universidade de Vigo, Departamento de Ecología e Biología Animal Mayer-Pinto, Mariana; University of New South Wales, BEES Cumbo, Vivian; Macquarie University Faculty of Science Morris, Rebecca ; University of Melbourne School of Ecosystem and Forest Sciences Bugnot, Ana; The University of Sydney, School of Biological, Earth and Environmental Sciences Dafforn, Katherine; University of New South Wales, School of Biological, Earth and Environmental Sciences; Heery, Eliza; University of Washington Firth, Louise; University of Plymouth Brooks, Paul; University College Dublin, School of Biology and Environmental Science Bishop, Melanie; Macquarie University,
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12 interventions have the greatest ecological benefit?

13

14 **Authors:** Strain E.M.A<sup>1\*</sup>, Olabarria, C.<sup>2</sup>, Mayer-Pinto, M.<sup>1,3</sup>, Cumbo, V.<sup>1,4</sup>, Morris, R.L.<sup>5</sup>,  
15 Bugnot, A.B.<sup>1,3</sup>, Dafforn, K.A.<sup>1,3</sup>, Heery, E.<sup>6</sup>, Firth, L.B.<sup>7</sup>, Brooks, P.<sup>8</sup>, Bishop, M. J.<sup>1,4</sup>  
16 <sup>1</sup>Sydney Institute of Marine Science, 19 Chowder Bay Road, Mosman NSW 2088, Australia  
17 <sup>2</sup>Departamento de Ecoloxía e Bioloxía Animal, Facultade de Ciencias do Mar, Campus  
18 Lagoas-Marcosende, Universidade de Vigo, 36310 Vigo, Spain  
19 <sup>3</sup>Evolution and Ecology Research Centre, School of Biological, Earth and Environmental  
20 Sciences, University of New South Wales, Sydney, NSW 2052, Australia  
21 <sup>4</sup>Department of Biological Sciences, Macquarie University, Sydney, NSW, 2109, Australia  
22 <sup>5</sup>Centre for Research on Ecological Impacts of Coastal Cities, School of Life and  
23 Environmental Sciences, The University of Sydney, NSW 2006, Australia  
24 <sup>6</sup>Department of Biology, University of Washington, Box 351800, Seattle, Washington,  
25 98195, US

26 <sup>7</sup> School of Biological and Marine Sciences, Plymouth University, Drake Circus, Plymouth,  
27 PL4 8AA, United Kingdom

28 <sup>8</sup> School of Biology and Environmental Science & UCD Earth Institute, University College  
29 Dublin, Ireland

30 \* Email for correspondence: strain.beth@gmail.com

31

32 **Running title:** Eco-engineering marine urban infrastructure

33

### 34 **Summary**

35 1. Along urbanised coastlines, urban infrastructure is increasingly becoming the dominant  
36 habitat. These structures are often poor surrogates for natural habitats, and a diversity of eco-  
37 engineering approaches have been trialled to enhance their biodiversity, with varying success.

38 2. We undertook a quantitative meta-analysis and qualitative review of 109 studies to  
39 compare the efficacy of common eco-engineering approaches (e.g. increasing texture,  
40 crevices, pits, holes, elevations and habitat-forming taxa) in enhancing the biodiversity of key  
41 functional groups of organisms, across a variety of habitat settings and spatial scales.

42 3. All interventions, with one exception, increased the abundance or number of species of one  
43 or more of the functional groups considered. Nevertheless, the magnitude of effect varied  
44 markedly among groups and habitat settings. In the intertidal, interventions that provided  
45 moisture and shade had the greatest effect on the richness of sessile and mobile organisms,  
46 while water-retaining features had the greatest effect on the richness of fish. In contrast, in  
47 the subtidal, small-scale depressions which provide refuge to new recruits from predators and  
48 other environmental stressors such as waves, had higher abundances of sessile organisms  
49 while elevated structures had higher numbers and abundances of fish. The taxa that

50 responded most positively to eco-engineering in the intertidal were those whose body size  
51 most closely matched the dimensions of the resulting intervention.

52 4. **Synthesis and application:** The efficacy of eco-engineering interventions varies among  
53 habitat settings and functional groups. This indicates the importance of developing site-  
54 specific approaches that match the target taxa and dominant stressors. Furthermore, because  
55 different types of intervention are effective at enhancing different groups of organisms,  
56 ideally a diversity of approaches should be applied simultaneously to maximise niche  
57 diversity.

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59 **Key words:** Artificial structure, crevice, complexity, depression, habitat-forming species,  
60 microhabitat, protrusion, rockpool, seeding

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62

63 **Introduction**

64 Of the many human activities presently contributing to habitat loss and species extinctions,  
65 urbanisation is generally considered to have one of the greatest impacts across local to  
66 regional scales (Lotze *et al.* 2006; Grimm *et al.* 2008). Over 50% of the human population  
67 now lives in urbanised areas (United Nations Population Fund 2007), with areas within 100  
68 km of the coastline particularly heavily developed, housing over 40% of the global  
69 population and 60% of its largest cities (>5 million inhabitants, Firth *et al.* 2016a). The urban  
70 ecological footprint extends beyond city boundaries and increasingly sprawls into marine and  
71 coastal waters (Duarte *et al.* 2008). In addition to introducing pollutants, such as heavy  
72 metals, nutrients, artificial light and sound, to marine and coastal habitats (Daoji & Daler  
73 2004; Halpern *et al.* 2008), urban environments introduce infrastructure (Dafforn *et al.* 2015).  
74 This infrastructure is used for a range of purposes including coastal protection (e.g. seawalls,

75 breakwaters, groynes), boating or recreational activities (e.g. marinas, piers, pontoons),  
76 supply of energy or resources (e.g. oil, gas platforms) and enhancement of fisheries yield  
77 (e.g. artificial reefs).  
78  
79 Urban infrastructure impacts on natural ecosystems in a variety of ways, including habitat  
80 loss and fragmentation, as well as modification of ecological connectivity, ecosystem  
81 functioning and services, and the physico-chemical environment (Fischer & Lindenmayer  
82 2007; McKinney 2008; LaPoint *et al.* 2015; Bishop *et al.* 2017). The net effect is urbanised  
83 ecosystems that are fundamentally different in structure and function to the natural habitat  
84 which they displace (Airolidi *et al.* 2015; Gittman *et al.* 2016; Heery *et al.* 2017). In some  
85 instances the need for urban infrastructure may be circumvented by adding or restoring  
86 natural habitats that enhance biodiversity and provide essential functions (Sutton-Grier,  
87 Wowk & Bamford 2015; Dethier, Toft & Shipman 2016). For example, the conservation,  
88 restoration and/or establishment of coastal plants, and shellfish and coral reefs that dissipate  
89 wave energy and stabilise shorelines may prevent the need for revetments and seawalls  
90 (Arkema *et al.* 2013) and also enhance fisheries productivity and sequestration of carbon  
91 (Barbier *et al.* 2011). In heavily modified environments, conservation and restoration of  
92 natural habitats may, however, not be feasible, and novel solutions are required (Hobbs,  
93 Higgs & Harris 2009; Lundholm & Richardson 2010). Amongst these, eco-engineering – the  
94 inclusion of ecological principles in the design of infrastructure to enhance its ecological  
95 value (Bergen, Bolton & Fridley 2001) – can benefit terrestrial and marine environments  
96 alike (Chapman & Underwood 2011; Francis & Lorimer 2011). Ideally, ecological values  
97 should be incorporated in infrastructure during the design phase to have greatest effect, but  
98 existing structures may also be modified to promote species of conservation, commercial or

99 functional interest and to enhance native biodiversity (Chapman & Blockley 2009; Dugan *et*  
100 *al.* 2011).

101

102 In terrestrial environments, green walls and roofs have been designed to enhance biodiversity,  
103 restore connectivity to certain faunal groups, and bolster desired ecosystem functions  
104 (Lundholm & Richardson 2010; Francis & Lorimer 2011; Braaker *et al.* 2014). Analogous  
105 approaches can be applied to the design of [urban infrastructure](#) in marine environments  
106 (Chapman & Underwood 2011; Firth *et al.* 2014a). As compared to the largely horizontal and  
107 topographically complex surfaces of natural substrates, marine [urban infrastructure](#) typically  
108 has vertical, smooth, surface that reduces the area for attachment and the diversity of habitat  
109 niches for organisms, and provides fewer refuges from predators, competitors and/or  
110 environmental stressors (Bulleri & Chapman 2010; Loke & Todd 2016). Consequently, one  
111 of the commonly utilised techniques for eco-engineering [marine infrastructure](#) has been to  
112 increase surface area and/or habitat complexity of the hard substrate at a range of scales (mm  
113 to metres) using either additive (i.e. attachment of protruding structures) or subtractive (i.e.  
114 drilling, removal of substrate) processes (Chapman & Underwood 2011). Additive  
115 approaches have utilised both abiotic substrate, and ‘seeding’ with habitat-forming taxa such  
116 as barnacles, bivalves, canopy-forming algae, branching coralline algae or corals (e.g.  
117 Dafforn, Glasby & Johnston 2012; Perkol-Finkel *et al.* 2012; Wilkie, Bishop & O'Connor  
118 2012; Ferse *et al.* 2013). [In the marine environment, the majority of eco-engineering to date](#)  
119 [has been small-scale experimental additions of habitat features to existing urban](#)  
120 [infrastructures](#) (Chapman & Underwood 2011), with relatively few attempts to incorporate  
121 [features into new urban infrastructures](#) (but see Chapman & Blockley 2009, Firth *et al.* 2013  
122 [for some exceptions](#)). These interventions have had varying degrees of success in enhancing  
123 native biodiversity, and in some instances may serve as ecological traps if they lead to

organisms utilising habitats that reduce their fitness (Hale, Treml & Swearer 2015; Hale, Morrongiello & Swearer 2016). Despite this, quantitative studies of the factors that influence the efficacy of such interventions in enhancing biodiversity are lacking.

The efficacy of eco-engineering interventions for enhancing the biodiversity of urban infrastructures is likely to vary across species and environments as well as the spatial and temporal scales of the intervention. The stress gradient hypothesis predicts that positive associations will be greatest in environments where biotic or abiotic stressors are greatest, and weakest in environmentally benign environments (Bertness & Callaway 1994). Hence, interventions that ameliorate abiotic stressors such as temperature and desiccation may be expected to have increasingly strong influences across the intertidal gradient (Bateman & Bishop 2017). Interventions that weaken biotic interactions may be most effective in environments with high predator abundances, or in which competition is intense (Chapman & Underwood 2011; Strain *et al.* in review). Additionally, because responses of organisms to complexity are dependent on body size (Hacker & Steneck 1990; McAbendroth *et al.* 2005), an organism may benefit most from an intervention that adds microhabitats that are a similar order of magnitude to its size (Köhler, Hansen & Wahl 1999). The effects of the interventions can also vary through time depending on the recruitment and growth of the organisms, the mobility of the organism and the successional stage of the community (Firth *et al.* 2016a). For example, the effectiveness of some interventions may only become apparent after sufficient time has elapsed for colonisation to occur (Evans 2016). Alternatively, the efficacy of others may plateau over time, where seeding of structures with biogenic habitats speeds up succession but does not change the endpoint after a number of years (Ferse *et al.* 2013). Studies quantifying how the efficacy of these interventions varies across multiple locations, environments, spatial-scales and time points are lacking.

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150 In this study, we used a meta-analysis and a qualitative literature review to assess sources of  
151 variation in the efficacy of interventions aimed at enhancing the biodiversity of both new and  
152 existing marine urban infrastructure through the creation of novel microhabitats. We expected  
153 that across all scales (ranging from mms to 10s of meters), the addition of complex  
154 microhabitats (i.e. texture, crevices, pits, water retaining, holes, small elevations, large  
155 elevations, seeding) to urban infrastructure would produce an overall positive effect on the  
156 number and abundances of species for specific functional groups (sessile, mobile, benthic,  
157 fish) and habitat-forming taxa (barnacles, bivalves, branching coralline, canopy algae, coral).  
158 Nevertheless, we expected that the magnitude and direction (positive or negative) of effects  
159 of interventions on the abundance and richness of taxa would vary between habitat contexts  
160 (intertidal and subtidal) across which the identity of dominant stressors varies, through time,  
161 between interventions applied to new and existing infrastructure and among functional  
162 groups of organisms, reflecting variation in their niche requirements, and body size.

163

164 **Methods**

165 *Literature search*

166 We searched the literature using Google Scholar and Web of Science for manipulative and  
167 mensurative field studies in intertidal and subtidal estuarine and coastal marine systems that  
168 examined the ecological effects of adding microhabitats to urban infrastructure (i.e. directly  
169 to structures or to settlement panels) either during construction or by retrofitting. The search  
170 terms included ('microhabitats\*: texture\*, roughness\* crevices\*, cuts\*, fissures\*, grooves\*,  
171 pits\*, rockpools\*, tidal pools\*, rock pools\* flowerpots\* holes\*, ridges\*, elevations\*, towers\*,  
172 raises\*, relief\*, mimic\*, rope\*, ribbons\*, brushes\*') and ('seeding\*, transplants\*, planting\*,  
173 epoxy\*, glue\*, habitat-forming\*, barnacles\*, bivalves\*, mussels\*, oysters\*, canopy\*, kelps\*,

coral\*, branching coralline\*, corticated turf\*, branching turf\*) on ('artificial habitat\*, artificial reefs\*, artificial structure\*, tiles\* or settlement plates\*'). We also searched the reference and citation lists of each article identified using the same search terms.

We selected studies for the analyses that compared between otherwise similar urban infrastructure with and without the intervention: (1) the number of species per unit area (i.e. species density); (2) the abundance of all species within one or more functional groups: sessile algae and invertebrates (hereafter 'sessile'), mobile invertebrates (hereafter 'mobile'), all sessile algae and sessile and mobile invertebrates combined (hereafter 'benthic') and fish (hereafter 'fish'); and/or (3) the species density and total abundance of key habitat-forming taxa (see Table 1 examples). For each study, the nature of the intervention was classified according to whether it added texture, crevices, pits, intertidal water retaining features, subtidal holes, elevations, or habitat-forming species (see Table 1 for definitions) to urban infrastructure. For studies that tested the effects of multiple types of intervention or single types of intervention, across multiple sites each intervention and site was used as a replicate for the analyses (see below for further details).

### *Data extraction*

We found 388 studies through the literature search, from which 109 were suitable for inclusion in our meta-analysis (Table S1) after exclusions (i.e. lack of controls, data on single species or a subset of species from a functional group, confounding with other factors, relevant data not presented either in text or graphs). For each study, we recorded the sample size, and the mean and standard deviation (when reported) of the number and/or abundance of each functional group on urban infrastructure receiving the intervention and on otherwise similar unmanipulated substrate (control). In instances where data were presented in the

figures, we used GetData Graph Digitizer version 2.25.0.32 ([www.getdata-graph-digitizer.com](http://www.getdata-graph-digitizer.com)) to extract means and standard deviations. We also recorded the geographical location of each study, the time interval after which the intervention was fitted or built (in months; hereafter ‘time’), the type of intervention either retrofitted or built (hereafter ‘method’), the area across which the intervention was applied (m<sup>2</sup>) and the dimensions of the unit of intervention (i.e. depth of crevices, pits, holes, intertidal water retaining features and height of elevations and habitat-forming taxa), where available.

*Data analysis*

For studies reporting means, standard deviations and sample sizes (or from which these data could be extracted from figures), we calculated the effect size of the various interventions on variables of interest (i.e. abundance and number of species) as Hedge’s *g* standard mean difference (SMD) (Hedges 1981). We chose the SMD effect size in the meta-analysis rather than the log ratio because these data contained many zeros (i.e. no species observed and/or no variance observed between replicates within the same treatment), (Borenstein *et al.* 2010). For the analysis, the effects of interventions were tested against the control using a random effects model as there was significant heterogeneity between studies (determined by measuring heterogeneity via Cochran’s *Q*, and testing it against a  $\chi^2$  distribution with *n*-1 degrees of freedom, where *n* is the number of studies). The model was fitted using the Hedges random effects estimator (Hedges 1981).

For studies that tested the effect of interventions at different sites, we treated each site as a separate study in the meta-analysis. We tested for links between these by adding study identity as a moderator in the model. When sites from the same study were linked, the results were adjusted by adding study identity as a moderator in a multilevel random effects model.

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225 For each functional group and habitat-forming taxa we assessed how the magnitude and  
226 direction (positive or negative) of effects varied with the size of the intervention area ( $\text{m}^2$ ), the  
227 depth or height of the unit of intervention (either the depression or elevation in mm to m), the  
228 time after implementation of the intervention that monitoring was done (months), method  
229 (retrofitted or built) and differences between zones (intertidal or subtidal) and the type (Table  
230 1) by adding these terms separately, as moderators in the models. Similarly, for each type of  
231 intervention, we assessed how the magnitude and direction of effects varied across the  
232 functional groups or habitat-forming taxa by including intervention type (Table 1) as  
233 moderators in the models. For the water retaining features, only data on the species number  
234 was presented in the studies, and not the species abundances. Therefore, we could not  
235 compare the effects of water retaining features on species abundances to the other  
236 interventions (i.e. texture, crevices, pits, small elevations, or seeding) in the analyses.

237

238 For studies that did not present the variance between replicates, we substituted in the  
239 maximum standard deviation from studies on the same intervention (Furukawa *et al.* 2006;  
240 Strain *et al.* 2014). There were no detectable differences in effect sizes between the studies  
241 with and without standard deviations (based on overlapping 95% confidence intervals). We  
242 also tested and found no differences in the effects of the microhabitats between the  
243 manipulative (97%) or mensurative (3%) studies (data not shown).

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245 We checked whether there was a significant correlation between the effect size and sample  
246 size, as a measure of publication bias using qualitative tests (weighted frequency histogram,  
247 funnel plots and Q–Q normality plots of effect sizes). We also assessed the number of studies  
248 required to increase the p-value to above 0.05, using the Rosenthal's fail-safe number test

(Tables S2-3). All analyses and plots were undertaken using the R package, *metafor* (Viechtbauer 2010) in R gui 3.1.1 (R Core Team 2016).

In addition, we undertook a qualitative review that included studies that did not present data that could be extracted for the analysis (i.e. only written statements about their results). For each type of intervention, we calculated the proportion of studies reporting significant versus non-significant results. We tested for differences in the proportion of significant studies between intertidal and subtidal zones, or among functional groups or habitat-forming taxa using  $\chi^2$  proportions tests.

For both the overall meta-analysis and qualitative review, we used the data from the final sampling period of each study. We only performed analyses on interventions with three or more studies (Tables S2-6).

**Results**

Of the 109 studies from which data were extracted, 23% focused on texture and 21% on crevices. The remaining studies, focused on pits, water retaining features, subtidal holes, small elevations, large elevations and seeding, each contributed between 3-12% to the total number of studies used in the review. 67% of studies described interventions that were retrofitted to existing structures, with the remainder describing interventions that were incorporated at the design stage (Table S1). Of the studies describing interventions at the design stage, 72% were on artificial reefs (Table S1). The studies were not evenly distributed around the globe (Fig. 1) and much (60%) of the research was conducted in Australia (Sydney), Israel (Red Sea), Europe (various locations) and North America (east coast).

The studies were published between 1946 and 2016, with a sharp increase in number through time, mainly between 1990 and 2016 (Fig. 2). This trend is likely to be driven in part by the increasing urbanisation of marine coastlines across the globe and the strong associated interest in eco-engineering approaches. Each intervention type had studies from multiple laboratories, years and countries, indicating the review conclusions are not strongly biased towards an individual country or time point (Table S1).

Most types of intervention (all but the addition of large elevations) significantly enhanced the number and/or abundance of species for at least one key functional group and/or habitat-forming taxon relative to the control (Figs. 3, 4, 5; Tables S2-S6). Interestingly, in only one instance - the addition of texture to the subtidal – was the abundance of a group (the barnacles) significantly reduced relative to the control (Figs. 3-5). The most effective interventions in increasing the number of species were water retaining features (mean [ $\pm$ SE] difference for sessile and benthic species =  $5.0 \pm 4.4$ ) and intertidal pits (mean [ $\pm$ SE] difference for benthic species =  $4.7 \pm 2.1$ ) and to a lesser extent intertidal crevices (mean [ $\pm$ SE] sessile species =  $2.2 \pm 1.6$ ), and subtidal soft interventions (mean [ $\pm$ SE] difference in fish species =  $1.6 \pm 2.0$ ) and seeding (mean [ $\pm$ SE] difference in sessile and fish species =  $2.4 \pm 2.8$ ). There were no detectable differences in effects of retrofitted or built interventions on the number or abundances of species, so these methods were pooled for the final analyses (Tables S2-S3).

For many of the interventions (texture, crevices, pits, subtidal holes, small elevations and large elevations, soft structures and seeding), the area of the intervention had a weak non-significant positive effect on the number of species (Table S2-S3). In contrast, for intertidal water retaining features, there was a significant positive effect of intervention area on the

number of species for each of the functional groups (Table S2). There was no relationship between area of intervention and abundances of species for any of the interventions (Tables S2-S3). As predicted, the effect of most of the interventions (texture, crevices, pits) differed between zones (Tables S2-S6). In contrast, there were no clear effects of the height or depth of the unit of manipulation (i.e. depression or elevation), or the time (months) of the intervention on the species number or abundance (Tables S2-S3).

Overall the results from the meta-analysis and the qualitative review showed similar trends (Table 2). For each intervention we highlight the results of the meta-analysis where available and the results from the qualitative review where there was insufficient information presented to undertake the meta-analysis.

*Effect of intervention type on the number and abundances of species by functional group*

The efficacy of the interventions in enhancing the species number and abundance of key functional groups varied among categories (Figs. 3, 4; Table S4-S6). For sessile organisms, the meta-analysis demonstrated that crevices, water retaining features, or seeding in the intertidal zone resulted in greater increases in the number of species than any of the other interventions tested, in either the intertidal or subtidal zone ( $Q_4 = 40.0$ ,  $p < 0.001$ , Fig. 3, Table S2). In contrast, the cover of sessile species displayed a greater positive response to intertidal seeding and the addition of subtidal texture than to the other interventions ( $Q_3 = 8.3$ ,  $p = 0.049$ , Fig. 4, Table S3). For the mobile species, the qualitative review found that a greater proportion of studies displayed significant effects of intertidal crevices, pits or subtidal holes on abundances ( $\chi^2_3 = 10.4$ ,  $p = 0.015$ ) but not numbers of species ( $\chi^2_3 = 7.3$ ,  $p > 0.05$ ), relative to the other interventions (Figs. 3, 4; Tables S4-S5). For fish, the meta-analysis suggested subtidal soft features and seeding were most important for enhancing both the number ( $Q_4 =$

36.0,  $p < 0.001$ ) and abundances of species ( $Q_i = 15.6$ ,  $p = 0.004$ ) relative to the other interventions tested (Figs. 3, 4; Tables S2-S3). As expected, the qualitative analysis also showed that in a greater proportion of studies, intertidal water retaining features enhanced the number of fish species as compared to the other interventions assessed ( $\chi^2_{24} = 12.7$ ,  $p = 0.013$ ; Fig. 3; Table S4).

Across the different interventions, intertidal water retaining features and seeding (irrespective of zone) were the only habitats that significantly enhanced the number of species for multiple functional groups (Figs. 3, 4; Table S4). The meta-analysis demonstrated that intertidal water retaining features significantly increased the number of sessile, benthic and fish species, but not mobile species relative to controls ( $Q_3 = 9.2$ ,  $p = 0.036$ , Fig. 3, Table S2). Seeding resulted in a significantly higher number ( $Q_i = 13.4$ ,  $p = 0.009$ ) and abundance ( $Q_i = 36.8$ ,  $p < 0.001$ ) of intertidal sessile species and subtidal fish but not intertidal mobile species or subtidal sessile species (Figs. 3, 4; Tables S2-S3).

In contrast, the addition of texture, crevices, pits, subtidal holes or soft structures to urban infrastructure only enhanced the species number or abundance of a single functional group (Figs. 3, 4; Tables 1, S2). The meta-analysis showed the addition of subtidal texture only significantly enhanced the cover of sessile species (Figs. 3, 4; Table S2). Intertidal crevices increased the number of intertidal sessile species and pits increased the number of benthic species, but the qualitative analyses suggested both of these interventions in many studies also resulted in higher abundances of mobile species (Figs. 3, 4; Tables S2, S4). Subtidal holes only significantly increased the abundances of mobile species (Figs. 3, 4; Tables 1, S3), while the addition of soft habitats significantly increased the number and abundances of fish species (Figs. 3, 4; Tables 1, S2-S3).

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*Effect of intervention type on the number and abundance of habitat-forming taxa*

As predicted, many of the interventions significantly increased the abundance of habitat-forming taxa (Fig. 5; Tables S3, S6). For barnacles ( $Q_i = 7.8$ ,  $p = 0.049$ ) and bivalves ( $Q_i = 8.8$ ,  $p = 0.048$ ), the meta-analysis showed the addition of intertidal crevices and pits resulted in higher cover and/or counts relative to the other interventions tested (Fig. 5; Tables S3). In contrast, for corals, the addition of subtidal pits had the greatest benefits of all the interventions considered ( $Q_i = 10.5$ ,  $p = 0.006$ ; Fig. 5; Tables S3). The qualitative analysis also showed in a greater proportion of studies the addition of texture resulted in increased cover of branching coralline ( $\chi^2_5 = 18.0$ ,  $p = 0.003$ ; Fig. 5; Tables S6), while small elevations lead to higher cover of canopy-forming algae ( $\chi^2_5 = 18.0$ ,  $p = 0.003$ , Fig. 5; Table S6) relative to the other interventions tested.

Overall, the addition of pits had the greatest benefits for multiple groups of habitat-forming taxa (Fig. 5; Tables S3, S5). The meta-analysis showed intertidal pits significantly increased the abundances of barnacles and bivalves ( $Q_i = 88.7$ ,  $p < 0.001$ , Fig. 5, Table S3). The qualitative review suggested this intervention could also lead to higher cover of branching coralline algae while subtidal pits significantly increased the cover or counts of barnacles, branching coralline algae and corals (Fig. 5; Table S6). The addition of texture to the intertidal resulted in significantly higher counts and cover of barnacles, branching coralline and slightly more bivalves and in the subtidal increased cover of branching coralline algae, but there were no detectable effects of this intervention on the other taxa ( $Q_i = 30.7$ ,  $p < 0.001$ ; Fig. 5; Table S3). Crevices had significantly higher counts of barnacles and cover of bivalves when situated in the intertidal, but there were no detectable effects of this intervention on other intertidal taxa or in the subtidal ( $Q_i = 25.0$ ,  $p < 0.001$ ; Fig. 5; Table S3,

S5). The qualitative analysis showed that a greater proportion of studies demonstrated intertidal water retaining features resulted in significantly higher numbers of species of branching coralline and canopy-forming algae ( $\chi^2_2 = 11.9$ ,  $p = 0.008$ ; Fig. 5; Table S6), and small elevations increased the cover of intertidal canopy-forming algae ( $\chi^2_2 = 5.6$ ,  $p = 0.049$ ; Fig. 5, Table S6) relative to the other interventions. Interestingly, there were no clear benefits of seeding on the abundances of new recruits of bivalves, coral or canopy-forming algae ( $Q_3 = 2.4$ ,  $p > 0.05$ ; Fig. 5; Table S3).

## Discussion

The effective use of eco-engineering as a tool for enhancing the habitat value of urban infrastructure requires knowledge of when and where interventions have greatest influence. Despite this, most eco-engineering studies in marine environments have focused on a single type of microhabitat-enhancing intervention, at one or few sites (e.g. Chapman & Blockley 2009; Browne & Chapman 2014; Firth *et al.* 2014a). Studies in natural systems demonstrate how the responses of species assemblages to microhabitats can vary across environmental gradients (e.g. Firth *et al.* 2014b; McAfee, Cole & Bishop 2016) and among taxa (e.g. Bateman & Bishop 2017). Our study provides the first cross-study, quantitative assessment of how the effectiveness of different interventions applied to marine urban infrastructure varies among groups of organisms and environmental settings. As predicted (see reviews by Dafforn *et al.* 2015; Dyson & Yocom 2015; Firth *et al.* 2016a), overall microhabitat-enhancing interventions had a positive effect on the abundance and number of species across the studies. Nevertheless, the magnitude of their effects varied considerably, from zero to highly positive according to the type of intervention, the target taxa, and tidal elevation.

398 In the intertidal, thermal and desiccation stresses have long been implicated in setting  
399 distributional limits (e.g. Wolcott 1973; Harley 2003) and the persistence of organisms can be  
400 contingent on the availability of microhabitat refugia from such stressors (Silliman *et al.*  
401 2011; Firth *et al.* 2016b; McAfee, Cole & Bishop 2016). Perhaps not surprisingly then, the  
402 intertidal interventions with the largest influence on sessile organisms, including barnacles,  
403 bivalves, branching coralline and canopy-forming algae, and on mobile organisms, were  
404 crevices, pits, and water retaining features, each of which provide shading and moisture  
405 retention at low tide (Fig. 6, Table 5, Garrity 1984; Underwood & Jernakoff 1984). Similarly,  
406 fish, which in the absence of water retaining features cannot persist in the intertidal zone at  
407 low tide, were strongly influenced by water-retaining interventions. In contrast, the addition  
408 of small elevations had little, if any, effect on intertidal organisms, despite their capacity to  
409 enhance surface area for attachment. In the intertidal, the groups of organisms that responded  
410 most strongly to a particular type of intervention were those whose body size most closely  
411 matched the dimensions of the unit of intervention (Fig. 6, Hacker & Steneck 1990;  
412 McAbendroth *et al.* 2005). For example, small-scale enhancements, such as adding texture,  
413 pits and crevices, were most effective for smaller bodied organisms such as barnacles and  
414 bivalves. In contrast, larger [interventions](#) such as rock pools could also support larger species  
415 such as branching coralline, canopy-forming algae and fish (Fig. 6).

416

417 Similarly, subtidal interventions that added depressions, as opposed to [elevations](#), generally  
418 had greatest positive effects [on](#) the majority of taxa. Whereas in the intertidal such  
419 [interventions](#) serve to retain moisture, in the subtidal they may be more important in  
420 providing refuge from large-bodied predators, such as fish, which can exert considerable top-  
421 down control on the biota on marine infrastructure (Connell & Anderson 1999; Clynick,  
422 Chapman & Underwood 2007; Ferrario *et al.* 2016). Depressions can also serve as protection

from high wave exposure that can challenge the attachment strength of organisms and interfere with feeding behaviour (Moschella *et al.* 2005; Bulleri & Chapman 2010). In contrast, the **elevated** structures formed by seeding marine infrastructure with large-bodied habitat-forming taxa or soft structures (e.g. rope) had greater positive influence on subtidal fish than depressions. Such larger-bodied taxa may not fit within the bounds of depressions, and instead, **elevated** structures may provide shelter and food resources for these (Hair & Bell 1992; Fernández *et al.* 2009). However, in the subtidal, a relationship between the body-size of organisms and the dimensions of the interventions that produced the most positive effect sizes was not demonstrated (Fig. 6).

Although most of the eco-engineering interventions that we reviewed manipulated microhabitats through the addition and/or subtraction of abiotic habitat, approaches that add **biotic** microhabitat through seeding with habitat-forming species may serve to provide additional benefits (Dafforn *et al.* 2015). Not only may such interventions add habitat, and mitigate the effect of abiotic and biotic stressors on associated organisms (Dafforn, Glasby & Johnston 2012), but they may also play an important role in carbon sequestration (e.g. macroalgae), nutrient cycling and/or maintain clean waters (e.g. filter feeders). Nevertheless, the establishment of habitat-forming taxa remains a challenge on some **urban infrastructure** (Bulleri & Chapman 2010). For example, while transplant of the canopy-forming algae *Cystoseira barbata* onto breakwaters is technically feasible, survivorship can be limited by grazing, which is more intense than on natural rocky reefs (Perkol-Finkel *et al.* 2012; Ferrario *et al.* 2016). Additionally, because the location of infrastructure is often in areas that suffer from high pollutant loadings and poor water quality, environmental conditions may limit the growth and survivorship of habitat-forming species (Falace, Zanelli & Bressan 2006; Ng *et al.* 2015).

448

449 Although our meta-analysis demonstrated predominantly positive effects of microhabitat  
450 interventions on the abundance and number of species of key functional groups of organisms,  
451 very few of the studies identified and analysed, provided assessment of the proportion of  
452 species that were native, non-native or cryptogenic (of unknown origin; e.g. Dafforn, Glasby  
453 & Johnston 2012; Sella & Perkol-Finkel 2015). In highly urbanised environments, with a  
454 long history of shipping and exploitation, the high proportion of species that are cryptogenic  
455 can complicate such assessments (Bishop & Hutchings 2011). Nevertheless, despite such  
456 difficulties, a large body of literature suggests that subtidal urban infrastructures support  
457 more non-native species than nearby rocky reefs (Dafforn, Glasby & Johnston 2012; Airolidi  
458 *et al.* 2015) and sedimentary habitats (Heery *et al.* 2017). Assessing the extent to which  
459 native, non-native and cryptogenic species benefit from interventions would help to identify  
460 maladaptive scenarios which lead to proliferation of unwanted pest species, as well as  
461 approaches that limit such risk. For example, interventions that manipulate microhabitat  
462 through the addition of biotic (i.e. habitat-forming species) as opposed to abiotic structure,  
463 may lessen risk of rapidly colonising pest species from dominating structures, by pre-empting  
464 space that they may otherwise occupy (Dafforn, Glasby & Johnston 2012).

465

466 Our analysis revealed that the majority of eco-engineering interventions involved patch-scale,  
467 short-term manipulations of individual microhabitat types. These small-scale interventions do  
468 not recreate the properties of contiguous natural habitats, due to their comparatively large  
469 edge to interior ratios and small areas (Bender, Contreras & Fahrig 1998). Interventions at the  
470 scale of the entire structure remain rare, and consequently, our knowledge of how  
471 biodiversity benefits relate to the scale of the infrastructure remains poor. As some mobile  
472 species, such as grazers or fish, might require a minimum habitat area in order to effectively

forage (Perkins *et al.* 2015), it is expected that a positive relationship between the area of interventions and their effect on biodiversity might emerge as larger-scale interventions are attempted. Additionally, because the majority of monitoring associated with such interventions was also at the patch scale, and rarely extended beyond 12 months (but see Ferse *et al.* 2013) our understanding whether such eco-engineering approaches have biodiversity benefits that extend beyond the site of the intervention or over longer timeframes remains largely unknown. None of the studies tested the benefits of providing habitat complexity at multiple scales.

The studies assessing the efficacy of eco-engineering interventions came primarily from developed countries in North America, Europe and Australasia. Although this may be a function of both the distribution of coastal ecologists monitoring eco-engineering interventions, and the distribution of eco-engineering interventions themselves, we suspect that the latter is the key driver of this non-random distribution. In terrestrial environments, socioeconomic status is a key indicator of the uptake of eco-engineering interventions such as green walls and roofs, which correlates with factors such as level of education, willingness to pay for environmental improvements, and the resources available for creating an ecological ideal (Kinzig *et al.* 2005; Francis & Lorimer 2011). While such studies are not yet available for the marine environment, we expect similar drivers for the uptake of marine eco-engineering. Quantification of the economic benefits of marine eco-engineering interventions relative to any additional costs associated with their incorporation into structures would help to increase the support for broader-scale implementation.

While the eco-engineering of marine urban infrastructure has made significant advances in the past few decades, there has been little consideration of how specific local scale abiotic

factors (e.g. pollution, temperature, wave exposure) or biotic interactions (e.g. predation, competition, facilitation) influence species interactions and distributions (Bulleri & Chapman 2010). This is despite predictions of ecological theory that positive interactions will strengthen across gradients of biotic (e.g., competition, predation, facilitation) and/or abiotic (e.g., temperature, desiccation) stress, while negative interactions will weaken (Bertness & Callaway 1994). Although our review clearly shows that the effects of complex microhabitats are generally positive, the differing effect size of many of the interventions between intertidal and subtidal zones, and between groups of species, highlights the important role that interactions with the environment can play in determining the outcome of eco-engineering (Table S7).

The goals of eco-engineering may range from enhancement of biodiversity, to enhancement of specific ecosystem services, such as fisheries productivity, carbon sequestration, maintenance of water clarity and/or nutrient cycling (Chapman & Underwood 2011). The results of this meta-analysis will assist managers and stakeholders in identifying solutions that best match their specific goals. As different groups of organisms responded most strongly to different types of intervention, eco-engineering projects aimed at maximising biodiversity might benefit from the creation of a variety of different types of microhabitats on any given structure, that increase the breadth of niche space available to organisms (Connor & McCoy 1979). In contrast, projects aimed at enhancing fisheries productivity may wish to target those interventions - the addition of water-retaining features to the intertidal or habitat-forming species or structural mimics to the subtidal – that maximise fish abundance. Nevertheless, studies examining the efficacy of eco-engineering interventions in enhancing ecosystem services are rare, and only one study (Loke & Todd 2016) has tested the effects of utilising mosaics of multiple types of interventions. However, this study did not quantify the

benefits of adding a mosaic of interventions vs. individual interventions for enhancing the richness for multiple functional groups or habitat-forming taxa (Loke & Todd 2016). Further research is urgently needed on these topics. Recent advances in computation design software and three-dimensional printing technology now allow for bespoke eco-engineering designs to be cheaply and readily developed for individual sites (Loke *et al.* 2014). Such techniques also offer great potential for re-creating structures/surfaces that are more akin to natural shorelines.

Although the results of this study indicate that eco-engineering interventions enhance the abundance and richness of ecological communities associated with urban infrastructure, it is unclear to what extent these interventions mitigate the impact of replacing natural with artificial habitat. In addition to local-scale impacts on biodiversity, urban infrastructure can impact ecological processes over larger scales by modifying ecological connectivity (Bishop *et al.* 2017) and through the cumulative effects of multiple developments (Dethier, Toft & Shipman 2016). Given that eco-engineering interventions are unlikely to fully compensate for impacts of urban infrastructure, the feasibility of ‘nature-based’ approaches, which entail restoration, conservation or creation of habitats that provide the desired functions of infrastructure, should first be investigated prior to the decision to build new structures (Sutton-Grier, Wowk & Bamford 2015; Dethier, Toft & Shipman 2016). Where it is not possible to avoid the construction or removal of infrastructure, eco-engineering approaches, which are mindful of site characteristics, the local species pool, and project goals, can assist in minimising the ecological footprint.

#### **Author contributions**

ES and MB conceived the ideas, designed methodology and led the writing of the manuscript.  
ES analysed the data. All authors collected the data, contributed critically to the drafts and  
gave final approval for publication.

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- 762



Fig. 1: Map showing the geographic location of the studies. The number of studies at each location is indicated by the size of the circle.

187x112mm (150 x 150 DPI)

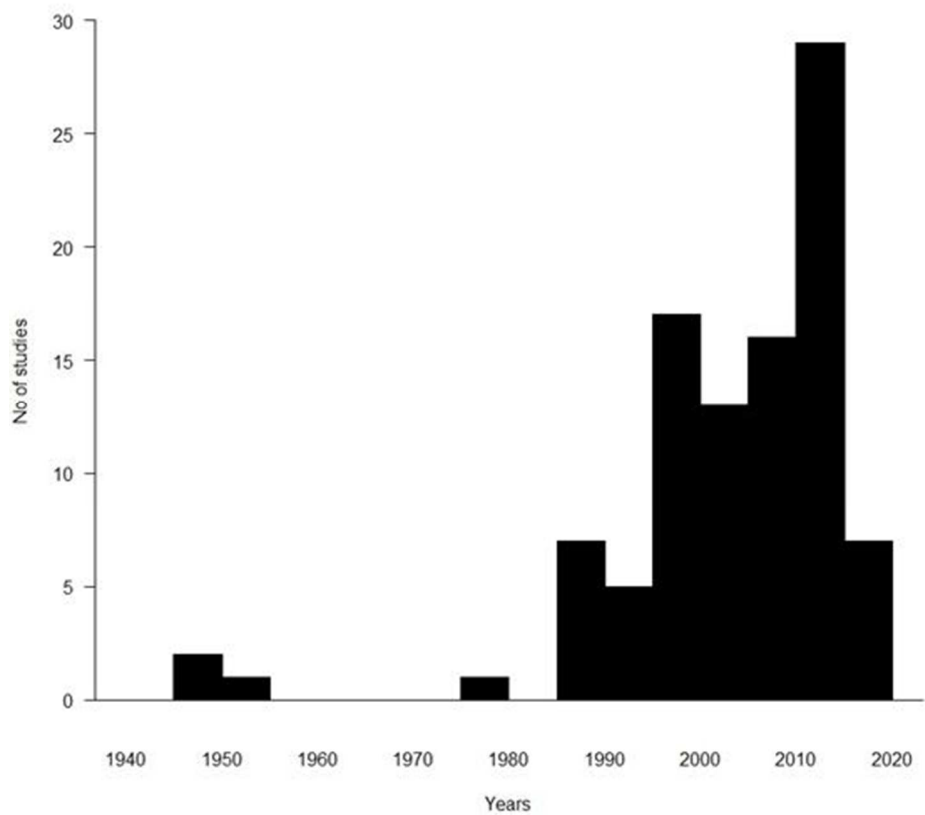


Fig. 2: Number of studies used in the review by year of publication (n = 109). Bins are 5 years wide.  
126x104mm (120 x 120 DPI)

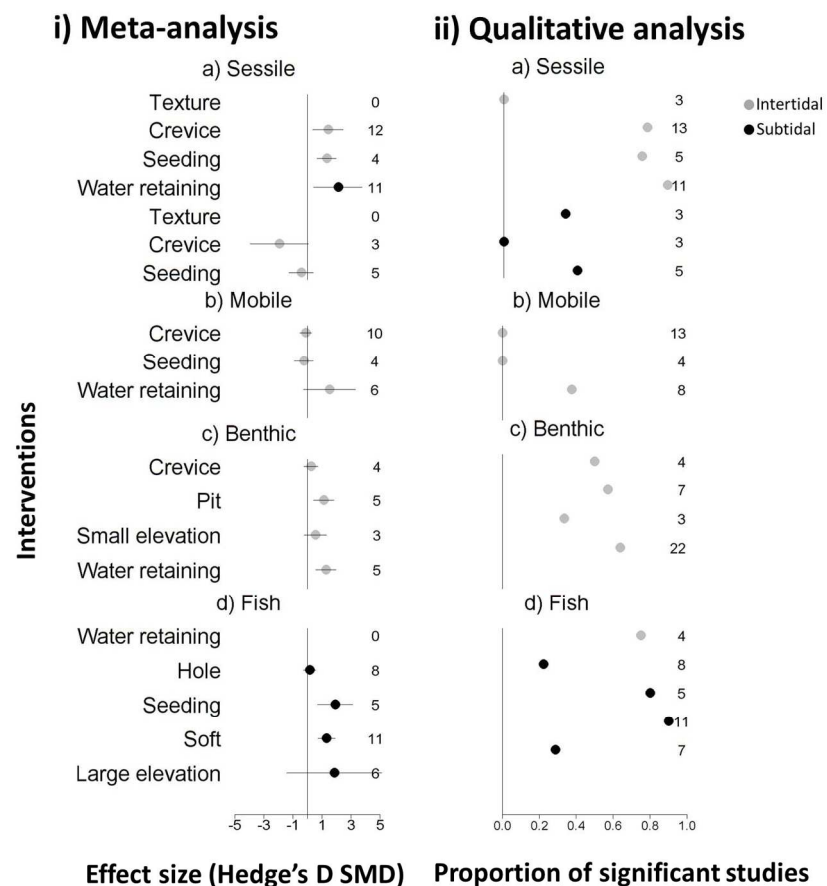
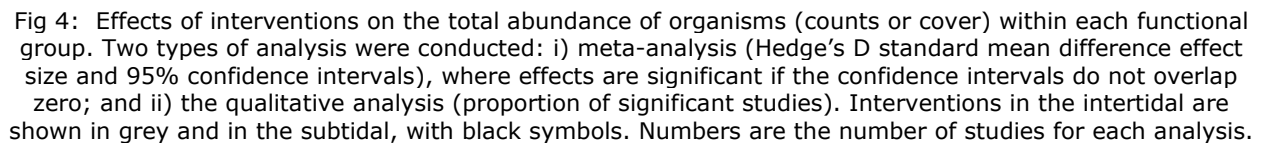


Fig. 3: Effects of interventions on the number of species (per unit area) of each functional group. Two types of analysis were conducted: i) meta-analysis (Hedge's D standard mean difference effect size and 95% confidence intervals), where effects are significant if the confidence intervals do not overlap zero; and ii) qualitative analysis (proportion of significant studies). Interventions in the intertidal are shown in grey and in the subtidal, with black symbols. Numbers are the number of studies for each analysis.

276x372mm (150 x 150 DPI)



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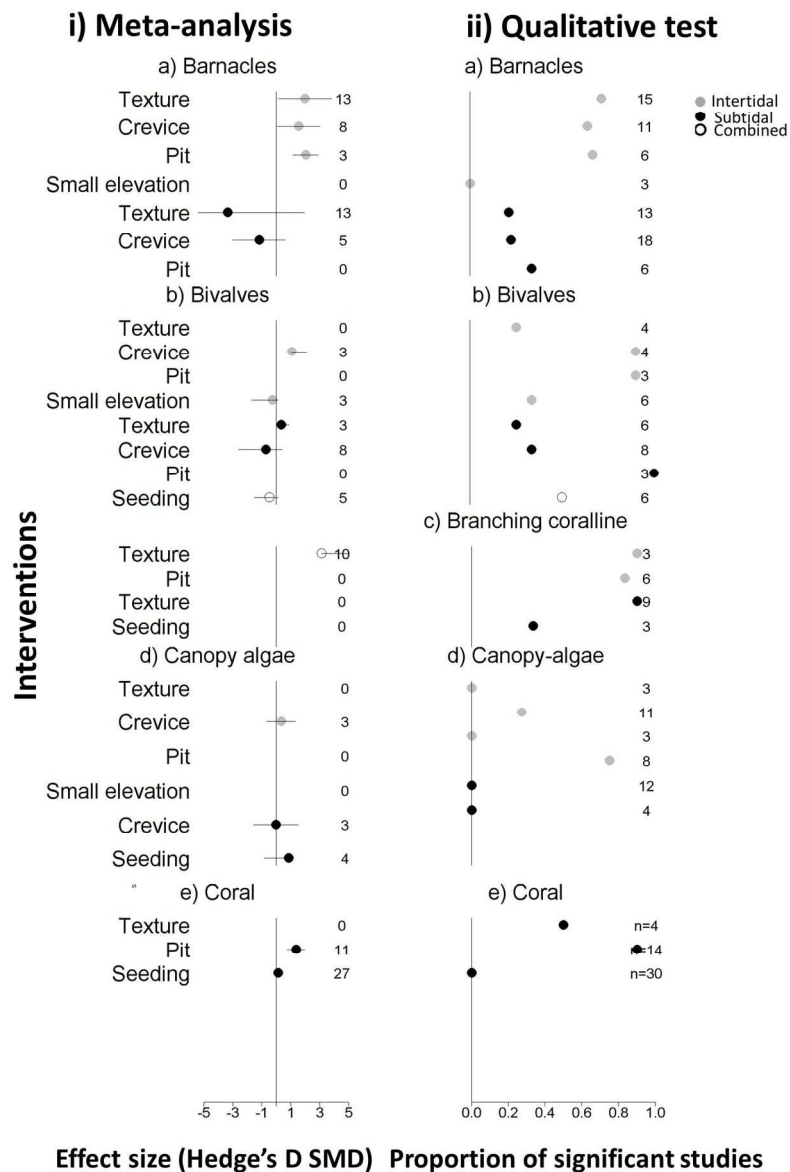


Fig 5: Effects of interventions on the abundance (counts or cover) of organisms of habitat forming taxa. Two types of analysis were conducted: i) meta-analysis (Hedge's D standard mean difference effect size and 95% confidence intervals), where effects are significant if the confidence intervals do not overlap zero; and ii) the qualitative analysis (proportion of significant studies). Interventions in the intertidal are shown in grey, in the subtidal with black symbols, and in both zones, with white symbols. Numbers are the number of studies for each analysis.

274x374mm (150 x 150 DPI)

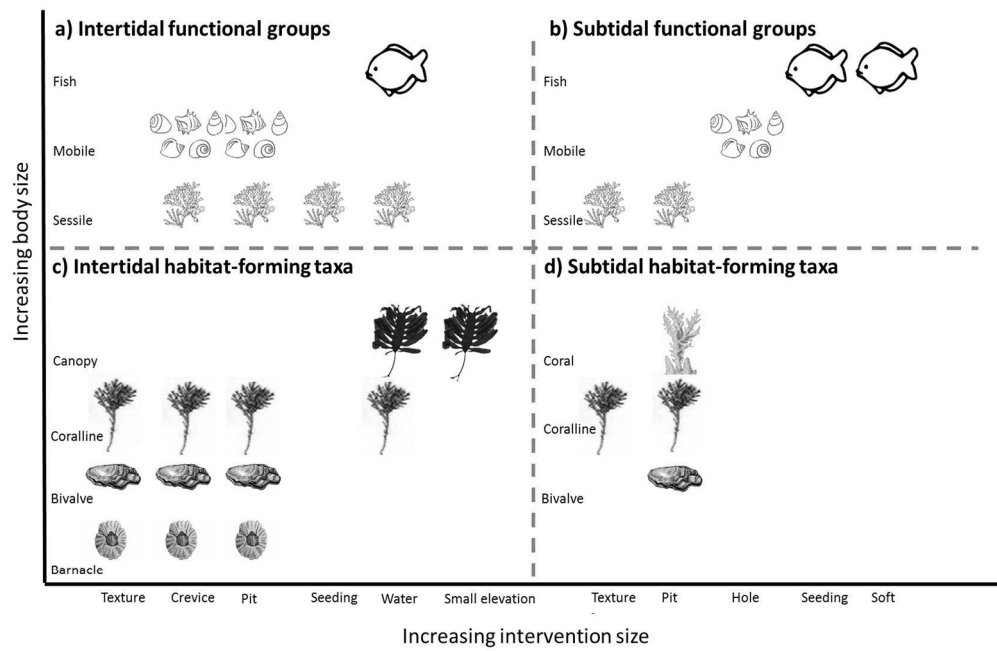





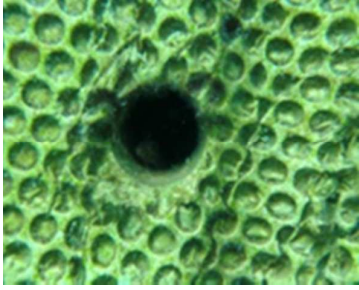






Fig 6. Conceptual diagram summarising the a) intertidal functional groups, b) subtidal functional groups, c) intertidal habitat-forming taxa and d) subtidal habitat-forming taxa that responded most strongly (i.e. greatest positive effect size) to the different categories of eco-engineering intervention. Functional groups are: fish, mobile invertebrates (mobile), and sessile algae and invertebrates (sessile); habitat-forming taxa are: canopy-forming algae (canopy), coral, branching coralline algae (coralline), bivalves and barnacles. Interventions are ordered from left to right on the x-axis, and biota from bottom to top on the y-axis, according to their increasing size.

286x187mm (150 x 150 DPI)

**Table 1:** Categories of intervention defined for the meta-analysis and qualitative literature review.

Classification	Description	Image
Texture	micro-scale manipulation applied to an entire intertidal or subtidal surface that produces depressions and/or raises of $\leq 1$ mm	
Crevice	intertidal or subtidal depression with a length to width ratio $>3:1$ , and depth of $>1$ mm	
Pit	intertidal or subtidal depressions with a length to width ratio $<3:1$ and depth of $>1$ mm to 5 cm. This may or may not hold water.	 Photo: L. H. L. Loke
Intertidal water retaining features	intertidal depressions or features including a) flower pots and b) rockpools with a length to width ratio $<3:1$ that hold water ( $\geq 5$ cm depth) when the tide retreats	<p>a) flowerpot</p>  <p>b) rockpools</p>

		
Subtidal holes	subtidal depressions with a length to width ratio $<3:1$ and $\geq 5$ cm depth	
Small elevations	intertidal or subtidal protruding structures (i.e. raises, ledges or ridges) $\geq 1$ mm high and $< 0.5$ m high in dimension	
Large elevations	intertidal or subtidal protruding structures (i.e. raises, ledges, ridges) $> 0.5$ m high in dimension	
Soft structures	subtidal flexible, protruding materials such as rope, ribbon or twine ( $>0.1$ m in length)	
Habitat-forming taxa	taxa that provide structural habitat to associated organisms (i.e. barnacles,	

	bivalves, coral, canopy-forming algae, branching coralline algae)	
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**Table 2:** Outcome of meta-analyses and qualitative (underlined and in brackets) review. For each intervention we highlight the results of the meta-analysis where available and the results from the qualitative review where there was insufficient information presented to undertake the meta-analysis (see figures for full results). Interventions are scored according to whether they had significant positive (+), negative (-) or non-significant (ns) effects (at  $\alpha = 0.05$ ) relative to controls.

Response	Number of species				Abundance of species				Number of species or abundance of habitat-forming taxa				
Microhabitat	Sessile	Mobile	Benthic	Fish	Sessile	Mobile	Benthic	Fish	Barnacles	Bivalves	Branching coralline	Canopy algae	Coral
<b>Intertidal</b>													
Texture	<u>(ns)</u>				+				+	-	+	<u>(ns)</u>	
Crevice	+	ns	ns		+	<u>(+)</u>	ns		+	+		ns	
Pit			+			<u>(+)</u>	ns		+	<u>(+)</u>	<u>(+)</u>	ns	
Small elevation			ns				ns		<u>(+)</u>	ns		<u>(+)</u>	
Water-retaining	+	ns	+	<u>(+)</u>					ns	ns	+	+	
Seeding	+	ns			ns	<u>(ns)</u>				ns			
<b>Subtidal</b>													
Texture	<u>(ns)</u>				+				-	+	+		<u>(ns)</u>
Crevice	ns				ns				ns	ns		ns	
Pit									<u>(ns)</u>				+

Hole				ns		+		ns					
Large elevation				ns				+					
Seeding	ns			+	ns	ns		ns		ns	ns	ns	ns
Soft structure				+				+					

Table S1: Details of the studies included in the meta-analysis.

Category	Author (year)	Location	Retrofitted (R) or Built (B)	Outcome	Structure	Tidal heights	Response variables measured	Time	Intervention area	Manipulation height or depth
Texture (25)	1. Abdo 2015 2. Abdus-Samad 2013a, b 3. Andersson <i>et al.</i> 1999 4. Bers & Wahl 2004 5. Berntsson <i>et al.</i> 2000a 6. Berntsson <i>et al.</i> 2000b 7. Berntsson <i>et al.</i> 2004 8. Cacabelos <i>et al.</i> 2016 9. Davies, Matz & Vize 2013 10. Diaz-Pulido & McCook 2004 11. Dobretsov & Railkin 1996 12. Guarnieri <i>et al.</i> 2009 13. Harlin & Lindbergh 1977 14. Hawkins 1998 15. Hills, Thomason & Muhl 1999	1. USA 2. USA 3. USA 4. Sweden 5. Germany 6. Sweden 7. Sweden 8. Sweden 9. Portugal 10. USA 11. Australia 12. Russia 13. Italy 14. USA 15. Hong Kong 16. USA 17. Germany 18. UK 19. Germany 20. Netherlands 21. Israel 22. USA 23. Argentina 24. Egypt 25. Australia	1. R 2. R 3. R 4. R 5. R 6. R 7. R 8. R 9. R 10. R 11. R 12. R 13. R 14. R 15. R 16. R 17. R 18. R 19. R 21. R 22. R 22. R 23. R 24. R	1. Increase in sessile cover 2. Increase in sessile cover 3. Increase sessile cover 4. NS 5. NS 6. NS 7. NS 8. NS 9. NS 10. Increase in coral cover 11. NS 12. Increase in bivalve counts 13. NS 14. Increase in branching coralline cover 15. Increase in sessile, branching coralline cover 16. Increase in barnacle counts 17. Increase in barnacle counts 18. Increase in barnacle counts 19. Increase in	Tiles	Mid-lower intertidal or subtidal	No. & abundance of sessile algae & invertebrates, Abundances of barnacles, bivalves, branching coralline, canopy-forming algae, & coral	mean= 7, range = 1 – 24 months	0.36-625cm <sup>2</sup>	0.002 – 1 mm

	16. Köhler, Hansen & Wahl 1999 17. Moschella <i>et al.</i> 2005 18. Ogata 1953 19. Paalvast 2015 20. Perkol-Finkel & Sella 2014 21. Pomerat & Weiss 1946 22. Savoya & Schwindt 2010 23. Thomason <i>et al.</i> 2002 24. Vucko <i>et al.</i> 2014			branching coralline cover 20. NS 21. NS 22. NS 23. NS 24. Increase in sessile , branching coralline cover 25. NS						
Crevise (23)	1. Bourget, DeGuise & Daigle 1994 2. Chapman & Blockley 2009 3. Chapman & Underwood 2011 4. Chabot & Bourget 1988 5. Coombes <i>et al.</i> 2015 6. Dugan <i>et al.</i> 2011 7. Dudgeon & Petraitis 2005 8. Firth <i>et al.</i> 2014a	1. USA 2. Australia 3. Australia 4. USA 5. UK 6. Australia 7. USA 8. UK 9. USA 10. Germany 11. USA 12. USA 13. Singapore 14. Singapore 15. Netherlands 16. USA 17. Italy	1. R 2. B 3. B 4. R 5. R 6. B 7. R 8. B 9. R 10. R 11. R 12. R 13. R 14. R 15. R 16. R 17. R 18. R	1. NS 2. Increase in sessile richness 3. NS 4. Increase in barnacle counts 5. Increase in sessile richness, barnacle counts 6. Increase in sessile, mobile richness 7. NS 8. NS 9. NS 10. Increase in barnacle, bivalve cover	Tiles, Breakwaters, Seawalls	Mid-lower intertidal or subtidal	No. & abundance of sessile algae & invertebrates, No. of sessile & mobile invertebrates, Abundances of barnacles, bivalves & canopy-forming algae	mean = 9.7 months range = 0.1 – 36 months	0.0005-3.45 m <sup>2</sup> / 0.01-4.7 cm depth	

	9. Goff 2010 10. Köhler, Hansen & Wahl 1999 11. Lapointe & Bourget 1999 12. Lemire & Bourget 1997 13. Loke & Todd 2016 14. Loke <i>et al.</i> 2016 15. Paalvast 2015 16. Pech, Ardisson & Bourget 2002 17. Perkol- Finkel <i>et al.</i> 2012 18. Pomerat & Weiss 1946 19. Sherrard <i>et</i> <i>al.</i> 2016 20. Smith, Johnston & Clark 2014 21. Van Tamelen, Stekoll & Deysher 1997 22. Walters & Wethey 1996 23. Watanuki & Yamamoto 1990	18. USA 19. UK 20. Australia 21. USA 22. USA 23. Japan	19. B 20. R 21. R 22. R 23. B	11. NS 12. NS 13. Increase in mobile counts 14. Increase in mobile counts 15. Increase in bivalve cover, mobile counts 16. NS 17. NS 18. NS 19. Increase mobile richness, counts 20. Increase in barnacle cover 21. Increase in canopy counts 22. Increase in barnacle counts 23. NS						
Pit (10)	1. Edmunds,	1. Japan and	1. R	1. Increase in coral	Tiles/Seawalls	Mid-	No. & abundance	mean =	0.01-	

	Nozawa & Villanueva 2014 2. Firth <i>et al.</i> 2014a 3. Loke & Todd 2016 4. Loke <i>et al.</i> 2016 5. Moschella <i>et al.</i> 2005 6. Nozawa, Tanaka & Reimer 2011 7. Martins <i>et al.</i> 2016 8. Paalvast 2015 9. Skinner & Coutinho 2005 10. Walters & Wethey 1996	The Philippines 2. UK 3. Singapore 4. Singapore 5. UK 6. Japan 7. Portugal 8. Netherlands 9. Brazil 10. USA	2. B 3. R 4. R 5. R 6. R 7. B 8. R 9. R 10. R	counts 2. Increase in benthic richness 3. Increase in mobile counts 4. Increase in mobile counts 5. NS 6. Increase in coral counts and cover 7. Increase in barnacle branching coralline cover 8. Increase in barnacle and bivalve cover 9. Increase in barnacle counts 10. Increase in barnacle counts		Lower intertidal or Subtidal	sessile and mobile invertebrates, Abundances of barnacles branching coralline & bivalves	22.24 range = 1-85 months	625cm <sup>2</sup> /0.01-2 cm	
Intertidal water retaining (11)	1. Browne & Chapman 2011 2. Browne & Chapman 2014 3. Chapman & Blockley 2009 4. Evans <i>et al.</i> 2015 5. Evans 2016 6. Firth <i>et al.</i> 2013 7. Firth <i>et al.</i> 2014a 8. Heath & Moody 2003	1. Australia 2. Australia 3. Australia 4. UK 5. UK 6. UK 7. UK 8. Australia 9. UK 10. Australia 11. UK	1. R 2. R 3. B 4. R 5. R 6. B 7. B 8. B 9. R 10. R 11. B	1. Increase in benthic, canopy, branching coralline richness 2. Increase in sessile richness 3. Increase in sessile, canopy, branching coralline richness 4. Increase in sessile richness 5. Increase in sessile, fish, canopy richness	Breakwaters, Groynes, Seawalls	Intertidal	No. & abundance sessile and mobile invertebrate species No. of species of branching & encrusting coralline & canopy-forming algae, & bivalves	mean = 12 months range = 7-18 months	0.007-0.04 m <sup>2</sup> /0.05-0.38 m depth	

	9. Moschella <i>et al.</i> 2005 10. Morris 2016 11. Pinn, Mitchell & Corkill 2005			6. Increase in sessile, benthic, fish canopy, branching coralline, richness 7. Increase in benthic richness 8. Increase in benthic and fish richness 9. Increase in benthic richness 10. NS 11. NS						
Subtidal hole (9)	1. Brotto, Krohling & Zalmon 2006 2. Code 1999 3. Gratwicke & Speight 2005 4. Hixon & Beets 1989 5. Hixon & Beets 1993 6. Hunter & Sayer 2009 7. Kellison & Sedberry 1998 8. Langhamer & Wilhelmsson 2009 9. Sella & Perkol-Finkel 2015	1. Brazil 2. Bonaire 3. USA 4. Hawaii 5. USA 6. UK 7. USA 8. Sweden 9. Israel	1. B 2. B 3. B 4. B 5. B 6. B 7. B 8. R 9. B	1. NS 2. NS 3. Increase fish counts 4. Increase fish counts 5. Increase fish counts 6. Increase mobile counts 7. NS 8. NS 9. Increase mobile, fish counts	Reefs, Offshore platforms	Subtidal	No. & abundances mobile invertebrates, No. & abundances of all fish	mean = 12 months, range = 1-24 months	1-30 m <sup>2</sup> /1-24.5 cm diameter.	
Small elevation	1. Goff 2010 2. Loke & Todd	1. USA 2. Singapore	1. R 2. R	1. NS 2. Increase in	Reefs, Tiles	Intertidal	No. & abundances of algae, sessile	average = 9 months,	0.05-3.45 m <sup>2</sup> /	

(4)	2016 3. Margiotta <i>et al.</i> 2016 4. Soniat, Finelli & Ruiz 2004	3. USA 4. USA	3. B 4. B	benthic richness and counts 3. Increase in bivalve counts 4. Increase in bivalve counts			invertebrates & mobile invertebrates, Abundances of bivalves & canopy-forming algae	range = 1 – 18 months	0.01-0.5 m high	
Large elevation (6)	1. Bortone, Martin & Bundrick 1994 2. Gratwicke & Speight 2005 3. Lingo & Szedlmayer 2006 4. Reed <i>et al.</i> 2006 5. Rilov & Benayahu 1998 6. Wilhelmsson, Yahya & Ohman 2006	1. USA 2. USA 3. USA 4. USA 5. Israel 6. Sweden	1. B 2. B 3. B 4. B 5. B 6. B	1. NS 2. NS 3. NS 4. NS 5. NS 6. NS	Reefs	Subtidal	No. & abundance of fish	average = 5.3 months, range = 1-16 months	0.81-1.99m/0.5-11m high	
Soft (7)	1. Gorham & Alevizon 1989 2. Gratwicke & Speight 2005 3. Fernández <i>et al.</i> 2009 4. Hair & Bell 1992 5. Kellison & Sedberry 1998 6. Rountree 1990 7. Sherman, Gilliam &	1. USA 2. British Virginia Islands 3. Italy 4. Australia 5. USA 6. USA 7. USA	1. B 2. B 3. B 4. B 5. B 6. B 7. B	1. Increase fish richness, counts 2. Increase fish richness, counts 3. Increase fish richness, counts 4. Increase fish richness, counts 5. Increase fish richness, counts 6. Increase fish richness, counts 7. NS	Reefs	Subtidal	No. and abundances of fish	average= 8.6 months, range = 1-24 months	?/0.3-10 m high	

	Spieler 2002									
Seeding with bivalve (3)	1. Clynick, Chapman & Underwood 2007 2. Sellheim, Stachowicz & Coates 2009 3. Wilkie, Bishop & O'Connor 2012	1. Australia 2. USA 3. Australia	1. R 2. R 3. R	1. Increase fish richness, counts 2. NS 3. Increase sessile richness, cover, mobile richness counts	Jetties/tiles	Intertidal or subtidal	No. & abundance of algae & sessile invertebrates, No & abundance of mobile invertebrates, Abundances of recruits & other bivalves	average = 14.8 months, range = 1-18 months	0.01-400 m²	
Seeding with canopy-algae (3)	1. Arenas <i>et al.</i> 2006 2. Dafforn, Glasby & Johnston 2012 3. Reed, Schroeter & Huang 2006	1. UK 2. Australia 3. USA	1. R 2. R 3. R	1. NS 2. Increase in sessile richness, cover, canopy, branching coralline cover 3. NS	Reef/tile	Subtidal	No. & abundance of sessile algae & invertebrate, Abundances of recruits & branching coralline algae	average = 4.8 months, 1.5-12 months	0.1-0.15 m²	
Seeding with coral (7)	1. Clark & Edwards 1995 2. Clark & Edwards 1999 3. Edwards <i>et al.</i> 2015 4. Ferse 2008 5. Ferse <i>et al.</i> 2013 6. Heyward <i>et al.</i> 2002 7. Quinn 2009	1. Maldives 2. Maldives 3. Maldives 4. Indonesia 5. Indonesia 6. Australia 7. USA	1. R 2. R 3. R 4. R 5. R 6. R 7. R	1. NS 2. Increase fish richness, counts 3. NS 4. Increase fish richness, counts 5. NS 6. NS 7. NS	Reef/tile	Subtidal	No.& abundances of all fish, Abundances of recruits, & coral	average = 17.3 months, 1.5-36 months	0.1-50 m²	

Table S2: Effects (Hedges g standard mean difference) of microhabitats: texture, crevice, pit, intertidal water retaining, subtidal hole, elevation, soft, and seeding on number and abundances of species (cover or counts) by functional group: sessile; mobile; benthic or fish. Results show each microhabitat category, response variable, the number of studies, overall estimate of effect size (overall), 95% lower confidence interval (LC), higher confidence interval (HC), Rosenberg fail-safe number of experiments required to overturn the results (Fail safe no), and the effects of the moderator study identity [Q-value], and overall estimates for the effects of size of the artificial structure (m<sup>2</sup>), size of the manipulation (depth or height cm to m) time (months) type (retrofitted or built) and zone (intertidal or subtidal). Effects are significant if confidence intervals do not overlap zero. The overall estimates are based on the last date of sampling. ns p>0.05, \* p<0.05, \*\* p<0.01, \*\*\* p<0.001. NA = no test.

Microhabitats	Response variable	No of studies	Zone	Overall	LC	HC	Fail safe no	Q-value	Size	Depth/Height	Time	Type	Zone
Texture	Sessile cover	15	Subtidal	0.792**	0.338	1.246	62	1.166ns	0.001ns	NA	-0.102ns	NA	NA
Crevice	Total number	25	Intertidal - Subtidal	0.434ns	-0.112	0.987	NA	2.187ns	0.001ns	0.145ns	0.042ns	1.115ns	1.129ns
Crevice	Total counts	9	Intertidal - Subtidal	-0.102ns	-0.438	0.235	NA	0.782ns	-0.269ns	-0.839ns	0.115ns	1.232ns	0.268ns
Crevice	Sessile number	15	Intertidal - Subtidal	0.911ns	-0.095	1.915	NA	3.904ns	0.599ns	0.045ns	-0.008ns	NA	-1.962*
Crevice	Sessile number (intertidal)	12	Intertidal	1.360***	0.621	2.448	32	NA	NA	NA	NA	NA	NA
Crevice	Sessile cover	9	Subtidal	-0.334ns	-0.736	0.049	NA	0.778ns	-0.004ns	-0.56ns	0.124ns	NA	NA
Crevice	Sessile counts	6	Subtidal	-0.02ns	-0.423	0.383	NA	0.016ns	NA	-0.005ns	-0.005ns	NA	NA
Crevice	Mobile number	10	Intertidal	-0.148ns	-0.542	0.247	NA	0.123ns	-0.116ns	-0.116ns	-0.12ns	NA	NA
Crevice	Benthic number	4	Intertidal	0.223	-0.266	0.712	NA	7.266ns	1.481ns	0.179ns	-0.279	NA	NA
Pit	Total number	5	Intertidal	1.096**	0.398	1.794	29	5.04ns	1.426	-1.799ns	0.1ns	NA	NA
Water retaining	Total number (adjusted for)	11	Intertidal	1.251***	0.554	1.947	250	31.84***	0.002***	-0.004ns	-0.003ns	0.912ns	NA

	study)												
Water retaining	Sessile number (adjusted for study)	11	Intertidal	2.101*	0.401	3.738	30	37.633**	0.004*	-0.051n	-0.002ns	4.831ns	NA
Water retaining	Mobile number	6	Intertidal	1.498ns	-0.287	3.284	NA	10.92**	-0.014**	-0.101***	-0.008*	0.001ns	NA
Water retaining	Benthic number (adjusted for study)	5	Intertidal	0.9603*	0.0287	1.8918	250	19.7161**	0.0011**	0.0185ns	-0.001ns	3.741ns	NA
Hole	Total number	9	Subtidal	0.104ns	-0.276	0.483	NA	0.748ns	-0.006ns	-0.005ns	0.022ns	NA	NA
Hole	Total counts (adjusted for study)	6	Subtidal	0.526*	0.143	0.909	44	0.398ns	0.017ns	0.023ns	-0.029ns	NA	NA
Hole	Fish number	8	Subtidal	0.131ns	-0.295	0.556	NA	1.788ns	-0.014ns	-0.004ns	0.02	NA	NA
Hole	Fish counts	18	Subtidal	0.204ns	-0.131	0.537	NA	0.493ns	-0.013ns	-0.005ns	-0.016	NA	NA
Hole	Mobile invertebrate counts (adjusted for study)	3	Subtidal	1.508*	0.044	2.972	24	5.689*	-0.107*	-0.107*	NA	NA	NA
Small elevation	Benthic number	3	Intertidal	0.535ns	-0.223	1.294	NA	NA	0.961**	-1.306ns	-0.123ns	NA	NA
Small elevation	Benthic counts (adjusted for study)	3	Intertidal	-1.12ns	-4.333	2.092	NA	12.836***	0.961**	6.943***	0.655**	NA	NA
Large elevation	Fish number	6	Subtidal	0.028ns	-0.543	0.601	NA	2.165ns	-0.662ns	0.033ns	0.017ns	NA	NA

Large elevation	Fish counts (adjusted for study)	6	Subtidal	1.835	-1.45	5.12	NA	31.392***	-4.423ns	-0.261ns	0.033ns	NA	NA
Soft	Fish number	11	Subtidal	1.297***	0.71	1.894	110	5.384ns	-0.234ns	-0.161ns	0.019ns	NA	NA
Soft	Fish counts	11	Subtidal	0.680**	0.173	1.187	26	3.546ns	-0.234ns	-0.142ns	-0.015ns	NA	NA
Seeding	Total number	20	Intertidal – Subtidal	1.228***	0.771	1.684	264	1.756ns	-0.001ns	-0.037ns	0.006ns	NA	-0.71ns
Seeding	Total counts	10	Intertidal – Subtidal	0.998ns	-0.065	2.058	NA	0.001ns	0.008ns	-0.013ns	-0.008ns	NA	-2.209*
Seeding	Total counts (intertidal)	11	Intertidal	1.836***	0.745	2.928	16	NA	NA	NA	NA	NA	NA
Seeding	Sessile number	9	Intertidal - Subtidal	1.067***	0.657	1.477	53	1.355ns	3.5ns	13.50ns	-0.026ns	NA	1.328*
Seeding	Sessile number (intertidal)	4	Intertidal	1.3287** *	0.695	1.962 3	65	NA	NA	NA	NA	NA	NA
Seeding	Sessile cover	9	Intertidal - Subtidal	0.771ns	-0.32	1.862	NA	1.316ns	-8.070ns	-3.09ns	-0.083ns	NA	-0.183ns
Seeding	Mobile number	5	Intertidal - Subtidal	0.895ns	-0.223	2.014	NA	6.456ns	-7.144ns	-7.144ns	-0.18***	NA	-2.88***
Seeding	Mobile number (intertidal)	4	Intertidal	0.343ns	-0.231	0.917	NA	NA	NA	NA	NA	NA	NA
Seeding	Mobile counts	5	Intertidal - Subtidal	0.129ns	-0.773	1.031 2	NA	1.211ns	-2.509***	-2.509***	-0.114**	NA	-1.824* *

Seeding	Mobile counts (intertidal)	5	Intertidal	-0.263ns	-0.915	0.39	NA	NA	NA	NA	NA	NA	NA
Seeding	Fish number	5	Subtidal	1.894**	0.675	3.113	33	0.059ns	-0.001ns	-0.003ns	-0.03ns	NA	NA
Seeding	Fish number	5	Subtidal	2.071*	0.252	3.888	17	1.156ns	-0.008ns	-0.416ns	-0.038ns	NA	NA

Table S3: Effects (Hedges g standard mean difference) of microhabitats: texture, crevice, pit, intertidal water retaining, subtidal hole, elevation, height, soft, and seeding on the number of species (water retaining features only) and abundances (cover or counts) of habitat-forming taxa: barnacles, branching coralline, coral and canopy-forming algae. Results show the effects of microhabitats, response variable, the number of studies, overall estimate of effect size (overall), 95% lower confidence interval (LC), higher confidence interval (HC), Rosenberg fail-safe number of experiments required to overturn the results (Fail safe no), and the effects of the moderator study identity [Q-value], and overall estimate for the effects of structure size (m<sup>2</sup>), manipulation size (depth or height cm to m) time (months), type (retrofitted or built) and zone (intertidal or subtidal). Effects are significant if confidence intervals do not overlap zero. The overall estimates are based on the last date of sampling. ns p>0.05, \* p<0.05, \*\* p<0.01, \*\*\* p<0.001. NA = no test.

Intervention	Response variable	No of studies	Zone	Overall	LC	HC	Rosenbergs failsafe no	Study	Size	Depth/Height	Time	Type	Zone
Texture	Total counts	39	Intertidal - Subtidal	4.312ns	-6.456	13.087	NA	0.389ns	0.249ns	NA	- 0.816ns	NA	2.775ns
Texture	Total cover	13	Subtidal	9.276**	2.813	15.739	21	0.041ns	- 0.023ns	NA	-0.41ns	NA	NA
Texture	Counts of bivalves	3	Subtidal	0.325ns	-0.216	0.865	NA	0.091ns	- 0.001ns	0.011ns	0.001ns	NA	NA
Texture	Cover of branching coralline	10	Intertidal – Subtidal	12.489*	5.2	19.778	138	0.848ns	- 0.264ns	NA	- 1.961ns	NA	- 31.446***
Texture	Counts of barnacles	23	Intertidal – Subtidal	0.244ns	-1.412	1.902	NA	0.038ns	- 0.009ns	0.023ns	0.286ns	NA	-4.316**
Texture	Counts of	13	Intertidal	1.969*	0.133	3.807	108	NA	NA	NA	NA	NA	NA

	barnacles (intertidal)												
Crevice	Total counts (adjusted for study)	9	Intertidal – Subtidal	0.739ns	-0.099	1.576	NA	48.056***	- 0.004**	-4.126**	0.972*	1.232ns	-2.774*
Crevice	Total counts (adjusted for study in intertidal)	9	Intertidal	1.356*	0.186	2.525	32	NA	NA	NA	NA	NA	NA
Crevice	Total cover	15	Intertidal – Subtidal	0.218ns	-0.121	0.558	NA	0.775ns	- 0.215ns	-0.206*	- 0.001ns	01.241ns	0.714ns
Crevice	Cover of bivalves	11	Intertidal – Subtidal	0.349ns	- 0.177'	0.877	NA	3.936ns	0.129ns	-0.206*	-1.142*	NA	-2.099*
Crevice	Cover of bivalve (intertidal)	3	Intertidal	1.542**	0.418	2.667	36	3.936ns	NA	NA	NA	NA	NA
Crevice	Counts of canopy-algae (adjusted for study)	6	Intertidal – Subtidal	0.471	-0.289	1.23	NA	13.344*	- 0.611ns	-2.101ns	- 0.207ns	NA	-0.159*
Crevice	Counts of canopy-algae (adjusted for study in intertidal)	3	Intertidal	0.649	-0.596	1.893	NA	NA	NA	NA	NA	NA	NA
Crevice	Counts of barnacles	25	Intertidal – Subtidal	0.001ns	-1.747	1.749	NA	11.145*	- 0.006**	-4.381**	1.151*	NA	-3.868 *
Crevice	Counts of barnacles (intertidal)	8	Intertidal	2.491ns	-0.082	5.063	NA	NA	NA	NA	NA	NA	NA

Pit	Total counts	13	Intertidal – Subtidal	1.238***	0.947	1.528	337	1.883ns	- 5.622ns	7.193ns	- 0.054ns	NA	NA
Pit	Total cover (adjusted for study)	5	Intertidal – Subtidal	2.747*	0.405	5.089	65	40.461***	0.109*	7.508**	- 0.054ns	NA	3.463*
Pit	Total cover (adjusted for study in subtidal)	3	Subtidal	3.249*	0.503	5.994	NA	NA	NA	NA	NA	NA	NA
Pit	Counts of corals	11	Subtidal	1.358***	0.758	1.959	255	0.397ns	- 3.175ns	3.479ns	- 0.054ns	NA	NA
Pit	Counts of barnacles	3	Intertidal - Subtidal	2.014***	1.127	2.9	14	0.127ns	0.348ns	-1.326	0.011ns	NA	-0.347ns
Water retaining	Total density	15	Intertidal	0.358ns	-0.653	0.754	NA	0.739ns	0.001ns	-0.002ns	0.041ns	NA	NA
Water retaining	Canopy algae number (adjusted for study)	3	Intertidal	2.747*	0.405	5.089	25	40.461***	0.001ns	-0.001*	0.109*	NA	NA
Water retaining	Bivalve number	5	Intertidal	-0.451ns	-1.411	0.511	NA	7.45ns	0.001ns	NA	- 0.141ns	NA	NA
Water retaining	Barnacle number	7	Intertidal	-1.287ns	-3.215	0.643	NA	1.19ns	- 0.001ns	-0.001ns	0.164**	NA	NA
Small elevation	Total counts (adjusted for study)	3	Intertidal	0.541ns	-0.074	1.155	NA	49.218***	-6.12ns	-5.283ns	-1.103*	NA	NA
Small elevation	Bivalve count (adjusted for	3	Intertidal	-0.287ns	-1.431	0.855	NA	48.04***	-6.12ns	5.92ns	- 1.331ns	NA	NA

	study)												
Seeding	Total cover (adjusted for study)	5	Intertidal-Subtidal	0.61ns	-0.875	2.095	NA	14.793**	-0.003ns	-2.104ns	-0.04ns	NA	1.273*
Seeding	Total cover (adjusted for study in intertidal)	4	Intertidal	-0.475ns	-3.493	2.545	NA	0.633ns	NA	NA	NA	NA	NA
Seeding	Bivalve cover	5	Intertidal-Subtidal	-0.485ns	-1.056	0.108	NA	2.938ns	NA	NA	NA	NA	NA
Seeding	Coral counts	27	Subtidal	0.113ns	-0.202	0.429	NA	3.373ns	-0.004	0.029**	-0.008ns	NA	NA
Seeding	Canopy cover	4	Subtidal	0.84ns	-0.829	2.509	NA	-0.001ns	-0.002ns	-0.011ns	0.038ns	NA	NA

Table S4: Relative effects of microhabitats: texture, crevice, intertidal water retaining, subtidal hole, elevation, soft structure, and seeding on the number of species within or across functional groups (sessile; mobile; benthic and fish). For the a) meta-analysis the values are the estimate of effect size and (confidence intervals). The effects are significant if the confidence intervals do not overlap zero. For the b) qualitative analysis the number of significant studies is shown against the total number of studies. The overall differences between the intertidal and subtidal microhabitats or the functional groups were tested with Hedges g standard mean differences (SMD) in the case of the meta-analysis or proportions tests ( $\chi^2$ ) in the case of the qualitative analysis. Data is based on the final date of sampling. ns  $p>0.05$ , \*  $p<0.05$ , \*\*  $p<0.01$ , \*\*\*  $p<0.001$ . NA = no test.

Relative effects within functional groups								
	a) Meta-analysis				b) Qualitative analysis			
Functional group	Sessile	Mobile	Benthic	Fish	Sessile	Mobile	Benthic	Fish
Intertidal								
Texture	NA	NA	NA	NA	0/3	NA	NA	NA
Crevice	1.385 (0.421-2.349)**	-0.126 (-0.505-0.254)ns	0.707 (-0.648-2.065)ns	NA	10/13	0/13	2/4	NA
Pit	NA	NA	1.128 (0.063-1.731)*	NA	NA	NA	4/7	NA
Small elevation	NA	NA	0.811 (-1.826-2.319)ns	NA	NA	NA	1/3	NA
Seeding	1.383 (0.073-2.267)*	0.345 (-0.283-0.973)ns	NA	NA	4/5	0/4	NA	NA
Intertidal water retaining	1.771 (0.723-2.838)***	-0.859 (-0.283-0.973)ns	1.541 (0.134-2.948)*	NA	7/11	3/8	14/22	$\frac{3}{4}$
Subtidal								

Texture	NA	NA	NA	NA	1/3	NA	NA	NA
Crevice	0.202 (-0.689-1.093)ns	NA	NA	NA	0/3	NA	NA	NA
Seeding	0.955 (-0.061-1.969)ns	NA	NA	1.899 (1.014-2.784)***	2/5	NA	NA	4/5
Hole	NA	NA	NA	0.134 (-0.472-0.739)ns	NA	NA	NA	2/8
Soft	NA	NA	NA	1.114 (0.601-1.627)***	NA	NA	NA	8/11
Large elevation	NA	NA	NA	-0.001 (-0.843-0.739)ns	NA	NA	NA	2/7
SMD test or $\chi^2$	39.952***	2.782ns	10.063*	35.989***	15.556*	7.243ns	2.113ns	12.863*
Relative effects across functional groups								
	Intertidal sessile	Subtidal sessile	Intertidal mobile	Subtidal mobile	Intertidal benthic	Intertidal fish	Subtidal fish	SMD test or $\chi^2$
a) Meta-analysis								
Crevice	1.973 (0.595-3.351)*	NA	0.439 (-0.937-1.815)ns	NA	1.231 (-0.386-2.847)	NA	NA	13.813**
Seeding	1.94 (0.809-4.692)*	0.791 (-2.204-3.78)ns	2.731 (-0.081-5.542)ns	NA	NA	NA	4.673 (1.337-8.008)**	13.343**
Intertidal water retaining	1.535 (0.331-2.741)*	0.766 (-0.447-	1.263 (0.175-2.351)*	NA	NA	NA	NA	9.204*

		1.978)ns						
b) Qualitative analysis								
Texture	0/3	0/3	NA	NA	NA	NA	NA	1.234ns
Crevice	10/13	0/3	0/13	NA	2/4	NA	NA	17.06**
Seeding	4/5	2/5	0/4	NA	NA	NA	4/5	7.719*
Intertidal water retaining	7/11	NA	3/8	NA	14/22	3/4	NA	15.011**

Table S5: Relative effects of microhabitats: texture, crevice, intertidal water retaining, subtidal hole, elevation, soft structure, and seeding on the species abundances (cover or counts) within or across functional groups (sessile; mobile; benthic and fish). For the a) meta-analysis the values are the estimate of effect size and (confidence intervals). The effects are significant if the confidence intervals do not overlap zero. For the b) qualitative analysis the number of significant studies is shown against the total number of studies. The overall differences between the intertidal and subtidal microhabitats or the functional groups were tested with Hedges g standard mean differences (SMD) in the case of the meta-analysis or proportions tests ( $\chi^2$ ) in the case of the qualitative analysis. Data is based on the final date of sampling. ns  $p > 0.05$ , \*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ . NA = no test.

Relative effects of microhabitats within functional groups								
	a) Meta-analysis				b) Qualitative analysis			
Functional group	Sessile	Mobile	Benthic	Fish	Sessile	Mobile	Benthic	Fish
Intertidal								
Texture	NA	NA	NA	NA	0/3	NA	NA	NA
Crevice	NA	NA	-0.375 (-1.075-0.323)ns	NA	2/5	5/6	0/3	NA
Pit	NA	NA	-0.234 (-1.217-0.749)ns	NA	NA	4/4	0/3	NA
Small elevation	NA	NA	-2.781 (-4.155-1.406)ns	NA	NA	NA	0/3	NA
Seeding	1.288 (0.008-1.045)*	-0.263 (-0.843-0.317)ns	NA	NA	$\frac{3}{4}$	0/5	NA	NA
Subtidal								
Texture	0.532 (0.019-1.045)*	NA	NA	NA	13/15	NA	NA	NA
Crevice	-0.159 (-0.799-0.481)ns	NA	NA	NA	1/14	NA	NA	NA

Seeding	0.043 (-1.06-1.145)ns	NA	NA	1.933 (0.649-3.216)**	2/5	NA	NA	5/6
Hole	NA	2.192 (1.456-2.928)***	NA	0.131 (-0.518-0.779)ns	NA	2/3	NA	5/18
Soft	NA	NA	NA	0.769 (0.017-1.554)*	NA	NA	NA	9/11
Large elevation	NA	NA	NA	1.164 (-0.159-2.489)ns	NA	NA	NA	1/6
SMD test or $\chi^2$	8.263*	34.881***	1.005ns	15.521**	19.936***	11.688*	Ns	15.03***
Relative effects of microhabitats across functional groups								
	Intertidal sessile	Subtidal sessile	Intertidal mobile	Subtidal mobile	Intertidal benthic	Intertidal fish	Subtidal fish	SMD test or $\chi^2$
i) Meta-analysis								
Crevice	-0.019 (-0.423-0.383)ns	NA	NA	NA	-0.375 (-1.074-0.323)ns	NA	NA	1.116ns
Seeding	2.076 (1.354-3-168)**	1.091 (-1.538-2.071)ns	-7.144 (-24.916-10.627)ns	NA	NA	NA	6.981 (4.013-8.821)***	36.752***
ii) Quantitative analysis								
Texture	0/3	13/15	NA	NA	NA	NA	NA	4.416ns
Crevice	2/5	1/14	5/6	NA	0/3	NA	NA	13.487**
Pit	NA	NA	4/4	0/3	NA	NA	NA	3.51ns

Seeding	3/4	2/5	0/5	NA	NA	NA	5/6	7.834*
Hole	NA	NA	NA	2/3	NA	NA	5/18	1.438ns

Table S6: Relative effects of microhabitats: texture, crevice, intertidal water retaining, subtidal hole, elevation, soft structure, and seeding on the species abundances (cover or counts) or number of species (water retaining features only) within or across functional groups (sessile; mobile; benthic and fish). For the a) meta-analysis the values are the estimate of effect size and (confidence intervals). The effects are significant if the confidence intervals do not overlap zero. For the b) qualitative analysis the number of significant studies is shown against the total number of studies. The overall differences between the intertidal and subtidal microhabitats or the functional groups were tested with Hedges g standard mean differences (SMD) in the case of the meta-analysis or proportions tests ( $\chi^2$ ) in the case of the qualitative analysis. Data is based on the final date of sampling. ns  $p>0.05$ , \*  $p<0.05$ , \*\*  $p<0.01$ , \*\*\*  $p<0.001$ . NA = no test.

i) Meta-analysis						ii) Qualitative analysis				
Functional group	Barnacles	Bivalves	Branching coralline	Canopy-forming algae	Coral	Barnacles	Bivalves	Branching coralline	Canopy-forming algae	Coral
Intertidal										
Texture	0.818 (-3.16-1.525)	0.103 (-0.59-0.797)ns	NA	NA	NA	10/15	1/4	3/3	0/3	NA
Crevice	2.479 (0.0463-4.975)*	1.049 (0.062-2.038)*	NA	0.402 (-0.721-1.524)ns	NA	7/11	4/4	NA	3/9	NA
Pits	0.419 (0.289-3.626)*	5.783 (3.787-7.778)***	NA	NA	NA	4/6	3/3	5/6	0/4	NA
Small elevations	NA	0.023 (-0.318-0.365)ns	NA	NA	NA	0/3	2/6	NA	6/8	NA
Water retaining	NA	NA	NA	NA	NA	0/6	3/6	4/4	6/8	NA
Subtidal										
Texture	-1.349 (-2.628—	0.455 (-0.277-	NA	NA	NA	4/13	3/9	9/9	NA	2/4

	0.072)*	1.186)ns								
Crevice	-1.042 (-2.616-0.534)	0.302 (-0.185-0.787)ns	NA	0.593 (-1.357-2.542)ns	NA	4/15	2/6	NA	0/12	NA
Pits	0.993 (-2.226-4.211)	NA	NA	NA	1.244 (0.005-2.487)*	2/6	3/3	NA	NA	14/14
Seeding	NA	NA	NA	0.195 (-0.749-1.141)ns	0.412 (-0.424)ns	NA	NA	1/3	0/4	0/30
Combined intertidal and subtidal										
Seeding	NA	-0.474 (-1.056-0.108)ns	NA	NA	NA	NA	3/6	NA	NA	NA
SMD or $\chi^2$ test	7.747*	8.778*	12.627*			24.132**	14.826*	18***	17.986**	43.5***
Habitat-forming taxa	Intertidal barnacles	Subtidal barnacles	Intertidal bivalves	Subtidal bivalve	Intertidal branching coralline	Subtidal branching coralline	Intertidal canopy-forming algae	Subtidal canopy-forming algae	Subtidal coral	SMD or $\chi^2$ test
i) Meta-analysis										
Texture	1.973 (0.282-3.664)*	-1.954 (-3.887 - 0.033)ns	0.002 (-3.449-3.448)ns	0.465 (-2.957-3.894)ns	14.831 (5.385-24.274)**	10.267 (5.766-14.768)***	NA	1.289 (-4.593-7.173)ns	1.289 (-5.013-5.578)ns	30.705***
Crevice	1.541 (0.393-2.703)**	-1.334 (-2.786-0.118)ns	0.84 (0.197-2.145)*	-1.468 (-3.193-0.259)ns	NA	NA	-0.854 (-2.197-0.488)ns	-1.257 (-3.061-0.548)ns	NA	24.934***

Pit	0.68 (0.002-1.358)*	1.521 (0.714-2.378)***	NA	2.364 (1.109-3.618)***	0.877 (0.118-1.637)*	NA	NA	NA	1.199 (0.875-1.524)***	88.671***
Seeding	NA	NA	-2.925 (-1.351-2.982)ns		NA	NA	NA	6.174 (-1.210-5.56)ns	3.789 (-1.025-6.0741)ns	2.287ns
ii) Qualitative analysis										
Texture	10/15	4/13	1/4	3/12	3/3	9/9	0/3	NA	2/4	17.588***
Crevice	7/11	4/18	4/4	2/8	NA	NA	3/9	0/12	NA	18.31*
Pit	4/6	2/6	3/3	3/3	5/6	NA	0/4	NA	14/14	21.716***
Water retaining	0/6	3/6	4/4	6/8	NA	NA	NA	NA	NA	11.916**
Small elevation	0/3	NA	2/6	NA	NA	NA	6/8	NA	NA	5.627ns
Seeding			3/6			1/3	NA	1/3	0/4	1.852ns

Table S7: Hypothesized benefits of adding different microhabitats to artificial structures in the intertidal and subtidal zones.

Microhabitats	Benefits in intertidal	Benefits in subtidal	References
Texture	- ↑ settlement spaces	- ↑ settlement spaces	Coombes <i>et al.</i> (2015) Köhler, Hansen & Wahl (1999)
Crevice	- ↑ surface area for attachment - ↑ protection from predators - ↑ moisture - ↓ light	- ↑ surface area for attachment - ↑ protection from predators - ↓ light - ↓ water motion	Chapman & Underwood (2011), Perkins <i>et al.</i> (2015)

	<ul style="list-style-type: none"> <li>- ↓ temperature</li> <li>- ↓ water motion</li> </ul>		
<b>Pit</b>	<ul style="list-style-type: none"> <li>- ↑ surface area for attachment</li> <li>- ↑ protection from predators</li> <li>- ↑ moisture</li> <li>- ↓ light</li> <li>- ↓ temperature</li> <li>- ↓ water motion</li> </ul>	<ul style="list-style-type: none"> <li>- ↑ surface area for attachment</li> <li>- ↑ protection from predators</li> <li>- ↓ light</li> <li>- ↓ water motion</li> </ul>	Loke & Todd (2016), Perkins <i>et al.</i> (2015)
<b>Seeding</b>	<ul style="list-style-type: none"> <li>- ↑ recruitment potential of target organism</li> <li>- ↑ surface area for attachment</li> <li>- ↑ protection from predators</li> <li>- ↑ moisture</li> <li>- ↑ functioning (e.g. filtering or pre-empting space for non-native species)</li> <li>- ↓ light</li> <li>- ↓ temperature</li> <li>- ↓ water motion</li> </ul>	<ul style="list-style-type: none"> <li>- ↑ recruitment potential of target organism</li> <li>- ↑ surface area for attachment</li> <li>- ↑ protection from predators</li> <li>- ↑ functioning (e.g. filtering or pre-empting space for non-native species)</li> <li>- ↓ light</li> <li>- ↓ temperature</li> <li>- ↓ water motion</li> </ul>	Dafforn <i>et al.</i> (2015) Ferrario <i>et al.</i> (2016)
<b>Intertidal water retaining feature</b>	<ul style="list-style-type: none"> <li>- ↑ surface area for attachment</li> <li>- ↑ moisture</li> <li>- ↓ water motion</li> </ul>		Firth <i>et al.</i> (2016c)
<b>Small elevation</b>	<ul style="list-style-type: none"> <li>- ↑ surface area for attachment</li> <li>- ↑ moisture</li> <li>- ↓ water motion</li> </ul>	<ul style="list-style-type: none"> <li>- ↑ surface area for attachment</li> <li>- ↓ water motion</li> </ul>	Goff <i>et al.</i> (2010)
<b>Subtidal hole</b>		<ul style="list-style-type: none"> <li>- ↑ surface area for attachment</li> <li>- ↑ protection from predators</li> <li>- ↓ light</li> <li>- ↓ water motion</li> </ul>	Langhamer & Wilhelmsson (2009)
<b>Subtidal soft structures</b>		<ul style="list-style-type: none"> <li>- ↑ protection from predators</li> <li>- ↑ food supply by attracting mobile and sessile invertebrates</li> </ul>	Hair & Bell (1992); Fernández <i>et al.</i> (2009)