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L.B. Firth [a,g,*], R.C. Thompson [b], K. Bohn [a,c], M. Abbiati [d], L. Airoldi [d,h], T.J. Bouma [e], F. Bozzeda [d], V.U. Ceccherelli [d], M.A. Colangelo [d], A. Evans [a,i], F. Ferrario [d], M.E. Hanley [f], H. Hinz [a], S.P.G. Hoggart [b], J.E. Jackson [b], P. Moore [a,i], E.H. Morgan [a,†], S. Perkol-Finkel [b,j], M.W. Skov [a], E.M. Strain [d], J. van Belzen [e], S.J. Hawkins [a,c]

[a] School of Ocean Sciences, Bangor University, Menai Bridge LL59 5AB, UK
[b] Marine Biology and Ecology Research Centre, School of Marine Science and Engineering, Plymouth University, Drake Circus, Plymouth PL4 8AA, UK
[c] Ocean and Earth Science, National Oceanography Centre Southampton, Waterfront Campus, University of Southampton, European Way, Southampton, Hampshire SO14 3ZH, UK
[d] Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Bologna, Via S. Alberto 163, I-48123 Ravenna, Italy
[e] Spatial Ecology Department, Royal Netherlands Institute for Sea Research (NIOZ), Korringaweg 7, P.O. Box 140, 4400 AC Yerseke, The Netherlands
[f] School of Biological Sciences, Plymouth University, Drake Circus, Plymouth PL4 8AA, UK
[g] Ryan Institute, National University of Ireland Galway, Galway, Ireland
[h] Hopkins Marine Station, Stanford University, Pacific Grove, CA 93950, USA
[i] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Aberystwyth SY23 3DA, UK
[j] SeArc—Ecological Marine Consulting, 13 Namirover Street, 69713 Tel Aviv, Israel

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ABSTRACT

Coastal defence structures are proliferating as a result of rising sea levels and stormier seas. With the realisation that most coastal infrastructure cannot be lost or removed, research is required into ways that coastal defence structures can be built to meet engineering requirements, whilst also providing relevant ecosystem services—so-called ecological engineering. This approach requires an understanding of the types of assemblages and their functional roles that are desirable and feasible in these novel ecosystems. We review the major impacts coastal defence structures have on surrounding environments and recent experiments informing building coastal defences in a more ecologically sustainable manner. We summarise research carried out during the THESEUS project (2009–2014) which optimised the design of coastal defence structures with the aim to conserve or restore native species diversity. Native biodiversity could be manipulated on defence structures through various interventions: we created artificial rock pools, pits and crevices on breakwaters; we deployed a precast habitat enhancement unit in a coastal defence scheme; we tested the use of a mixture of stone sizes in gabion baskets; and we gardened native habitat-forming species, such as threatened canopy-forming algae on coastal defence structures. Finally, we outline guidelines and recommendations to provide multiple ecosystem services while maintaining engineering efficacy. This work demonstrated that simple enhancement methods can be cost-effective measures to manage local biodiversity. Care is required, however, in the wholesale implementation of these recommendations without full consideration of the desired effects and overall management goals.

1. Introduction: the problem and current knowledge

In recent years there has been much interest in ecologically sensitive design of coastal defence structures. This is in response to the growing realisation that rising sea levels and stormier seas (IPCC, 2007; Jackson and McIlvenny, 2011; Wang et al., 2012) will prompt proliferation of such structures (Dugan et al., 2011; Firth and Hawkins, 2011) where managed retreat or re-alignment is not an option because important infrastructure, industrial activities and residential property require protection. In this paper we review recent advances in this field since the DELOS project (www.delos.unibo.it) special issue of Coastal Engineering was published in 2005 (e.g. Airoldi et al., 2005; Martin et al., 2005; Moschella et al., 2005; Zanuttigh et al., 2005; see also Burcharth et al., 2007). We synthesise this work and integrate it with our own recent experimental and demonstration studies undertaken in the context of the THESEUS project (www.theseusproject.eu). In response to climate change related sea level rises, the THESEUS project (2009–2014), building on DELOS, examined the application of innovative adaptational technologies to enable safer development and use of the coast whilst ensuring the health of coastal habitats and continued delivery of their ecosystem goods and services. The primary

* Corresponding author at: Ryan Institute, National University of Ireland Galway, Galway, Ireland.
E-mail address: louise.firth@nuigalway.ie (L.B. Firth).
† Deceased.

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objective was to provide an integrated methodology for planning sustainable defence strategies for the management of coastal erosion and flooding by integrating engineering, social, economic and environmental knowledge and practice.

There is a growing consensus that artificial systems are different to natural systems (Bulleri and Chapman, 2004; Chapman and Bulleri, 2003; Firth et al., 2013a; Gacia et al., 2007; Glasby, 1999; Glasby and Connell, 1999; Pister, 2009; Vaselli et al., 2008). The reduced environmental heterogeneity of artificial environments is thought to be one factor explaining the lower epibiotic diversity on artificial structures (Moschella et al., 2005). On a micro-scale (<1 cm), the geological origin of building materials and hence their composition and surface roughness has a significant effect on the structure and functioning of the colonising assemblages (Coombes et al., 2011; Green et al., 2012), whilst at small (<10 cm) to medium scales (1–10 m), crevices, pits and rock pools provide important refuges for many species (Bracewell et al., 2012; Cartwright and Williams, 2012; Chapman and Johnson, 1990; Firth and Crowe, 2008, 2010; Firth and Williams, 2009; Firth et al., 2009; Goss-Custard et al., 1979; Johnson et al., 1998; Skov et al., 2011). The artificial surfaces of most coastal defences lack many of these microhabitats that can be found on natural rocky shores (Firth et al., 2013, in press); thus many species that use these microhabitats are absent from seawalls (Chapman, 2003). Furthermore, when the material used to create the structure is different from that of the natural habitat, species settlement and survival will differ and may be reduced (Davis et al., 2002; Moreira et al., 2006; Coombes et al., 2011; Green et al., 2012). Also, artificial structures are usually characterised by unnaturally high levels of both natural (e.g. storms, sediment scour) and anthropogenic disturbance (e.g. harvesting, trampling, maintenance works). This often results in poor habitat quality and the dominance of opportunistic and invasive species (Airoldi and Bulleri, 2011; Airoldi et al., 2005; Bracewell et al., 2012, 2013; Bulleri and Airoldi, 2005; Bulleri et al., 2006; Firth et al., 2011). Furthermore, in areas where natural shores are gently-sloping, the steeper or vertical surfaces of most types of structure provide a much smaller extent of intertidal habitat, reducing the transition from low to high water from 10s of metres to only a few metres (Chapman, 2003). The number of species will reduce as an inevitable consequence of species–area relationships. When the resident species are more suited to living on gentle slopes, they may not be able to survive on vertical surfaces, especially where wave-action is high. Steeper intertidal slopes may therefore reduce habitat quality in addition to available area, resulting in differences in the composition of the associated communities (Glasby, 2000; Knott et al., 2004; Virgilio et al., 2006; Vaselli et al., 2008). Finally, the construction of artificial structures can alter connectivity of local populations by fragmentation (Goodsell et al., 2007, 2009) or providing stepping-stones, thereby having impacts at a landscape scale.

The above-mentioned differences between artificial and natural rocky shores result in pronounced differences in biological factors such as settlement and recruitment (Bulleri, 2005), competition and predation (Iveša et al., 2010; Marzinelli et al., 2011). Grazing pressure also seems to be consistently higher on artificial than on natural substrates (Ferrario, 2013; Perkol-Finkel et al., 2012). The colonising epibiota (e.g. fucoids, mussels, sabellariid worms) can provide biogenic habitat for small mobile invertebrates, facilitating biodiversity by increasing complexity and heterogeneity of primary substrata (Thompson et al., 1996). Complexity encompasses the absolute abundance of individual structural components that are distinct physical elements of a habitat, per unit area or per unit volume, and heterogeneity encompasses variation in habitat structure attributable to variation in the relative abundance of different structural components (McCoy and Bell, 1991). To date, little research has been carried out investigating the differential importance of biogenic habitats in artificial and natural environments.

The ecological value of shorelines which have been altered to create new hard substrata therefore appears to be lower and the expansion of artificial structures can even lead to genetic diversity loss at regional scales, even if the underlying mechanisms are not yet fully clear (Fauvelot et al., 2009, 2012). Below, we outline simple measures that are intended to redress these differences synthesizing cumulative collective expertise, past research and new studies.

Ecological engineering is a relatively new concept which integrates ecological, economic and social needs into the design of man-made ecosystems. Several studies have shown the effectiveness of simple ecological engineering methods that result in the enhancement of native biodiversity on artificial structures (see Firth et al., 2013 for more details). Habitats of varying complexity (surface roughness, grooves and pits) and configuration (vertical/horizontal) can be easily deployed at different tidal levels (low, mid, high) to the blocks on breakwaters (Borsje et al., 2011; Thompson et al. illustrated in appendix A of Witt et al., 2012). Slabs at lower tidal heights and with greater surface complexity were found to support higher biodiversity (Borsje et al., 2011). Artificial rock pools are easily created in newly constructed seawalls by omitting large sandstone blocks (Chapman and Blockley, 2009) or by fitting habitat enhancement units (custom-made flowerpots) retrospectively to existing seawalls (Browne and Chapman, 2011). These approaches rely on the general consideration that greater habitat complexity leads to greater species richness. The modification of artificial environments can also be implemented to sustain species of conservation or commercial importance. For example, the addition of pits into seawalls resulted in an increase in the commercially exploited limpet *Patella candei*, due to higher microhabitat complexity (Martins et al., 2010). More detail on the various ecological engineering methods can be found in a recent review by Firth et al. (2013).

In this paper we summarise recent experimental work carried out during the THESEUS project in which we: i) tested the effectiveness of simple physical interventions such as the creation of pits, crevices and rock pools on the colonising biota; ii) present demonstration projects of a prototype habitat enhancement unit ("BIOBLOCK") that can be prefabricated and deployed during construction of coastal defence structures or retrospectively post-construction; iii) describe experimental studies to develop techniques to 'garden' native canopy-forming algae of high ecological and conservation value on coastal defence structures; iv) summarise the costs of these interventions; and finally v) outline simple guidelines for achieving particular management goals. We emphasise throughout the need to formulate clear management aims and anticipated outcomes at the design stage of any structure.

2. Physical interventions

2.1. Experimental physical manipulation of the substratum

2.1.1. The creation of artificial rock pools on Tywyn Breakwater, Wales

The construction of a new detached breakwater on the beach at Tywyn, Wales (52°34′N, 04°05′ W) was completed in 2010. In August 2011 artificial rock pools of two different depths were created on the boulders around the base of the new breakwater (Fig. S1a). The purpose of the artificial pools was to provide novel habitat that would not normally be present on the boulders of the breakwater. It was hypothesised that the pools would become colonised by a number of species that were not found on the surrounding boulders. Eighteen artificial pools were created in the horizontal surfaces of the granite boulders using a diamond-tipped drill corer (Fig. S1a), randomly assigned to two treatments (deep and shallow) with nine replicates of each treatment. Deep and shallow pools measured 12 cm and 5 cm deep respectively and 15 cm in diameter. Permanent horizontal and vertical plots of comparable area to the surfaces of the drilled pools were marked on open freely draining rock with drilled holes on the adjacent boulders. In March 2012, all experimental surfaces (emergent rock and pools) were scraped clear and burnt with a flame gun to ensure that substrata were devoid of epibiota (including biofilm).

All colonising animals and algae were identified and counted monthly in the pools and on the adjacent emergent substrata plots for ten months. Due to differences in surface area between deep (742 cm^2) and shallow

pools (412 cm^2), separate one-way ANOVAs with factor Habitat (two levels: pool, rock; fixed and orthogonal) were carried out for each of deep and shallow pools separately. GMAV version 5 for Windows was used for ANOVA computations (Underwood and Chapman, 1998). Cochran's test was used to test for heterogeneity of variances, and Student–Newman–Keuls (SNK) procedure was used to make post-hoc comparisons among levels of significant terms. Data were square root transformed where necessary to remove heterogeneity in variances.

A total of 21 species colonised the boulders (pools & emergent rock) between March 2012 and January 2013. Shallow pools supported significantly greater species richness than emergent substrata (Table 1, Fig. 1) whilst deep pools supported similar numbers of species as the emergent substrata. Furthermore, the identity of species differed among habitats with emergent substrata generally supporting barnacles, mussels, green algae and gastropods whilst pools supported mussels, anemones, annelids, gastropods and few barnacles (A. Evans, pers. obs.). The creation of pools is an effective way of providing important habitat for intertidal organisms in artificial environments (Browne and Chapman, 2011; Chapman and Blockley, 2009). In the case of Tywyn Breakwater, the creation of shallow pools provided habitat with greater species richness than deeper pools, possibly due to the greater scouring by gravel and pebble retention in deeper pools.

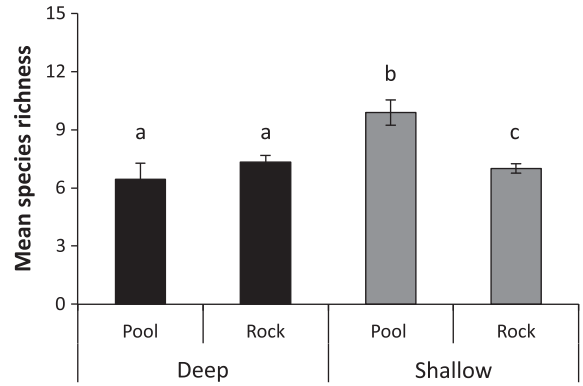

Fig. 1. Drill-cored rock pools at Tywyn, Wales. Mean species richness (n = 9 ± SE) in drill-cored rock pools compared to adjacent emergent substrata. Analyses were performed separately for deep (black bars) and shallow pool (grey bars) habitats due to differences in area among the two. The adjacent emergent substrata were of comparable area to either deep or shallow pools.

2.1.2. The creation of artificial pits on Plymouth Breakwater, England

Plymouth Breakwater, situated 3.2 km from Plymouth Hoe (50°19′N, 4°08′W) is a 1.56 km detached structure, the structure is ca. 3 m above chart datum and extends to ca. 10 m into the subtidal. The seaward side is protected by cast concrete wave-breaker units which are rectangular frustums measuring 6.85 m × 3.20 m at the base and 2.35 m high (Fig. S2a). These wave-breaker units are replaced periodically as they are eroded by the sea. During the casting of the wave-breaker units, surface complexity was added by drilling pits (14 mm and 22 mm diameter) to a depth of 25 mm (Fig. S1b). Each pit had a slight angle so that water was retained. Pits were drilled within a 100 cm × 100 cm area, within each area a total of 100 pits were drilled, each separated by 10 cm. In total eight sets of 14 mm and eight sets of 22 mm pits were drilled. 8 control quadrats of 100 × 100 cm with no pits were also monitored. A one-way design with factor Treatment (3 levels: control, no pits; small, 14 mm and large, 22 mm) (24 patches in total) was used to compare among treatments.

All colonising animals and algae within each quadrat (100 × 100 cm) were identified and counted two years after the deployment of the blocks. Data were analysed using a non-parametric Kruskal–Wallis test. Multiple Mann–Whitney U tests were used to conduct post hoc comparisons using a Bonferroni adjusted *p*-value for multiple comparisons of 0.05/3 = 0.016.

A total of 33 species were observed in the treatments on Plymouth Breakwater (functional groups included algae, anemones, hydroids, ascidians, bryozoans, annelids, bivalves, sponges, gastropods and barnacles). Six of the 10 functional groups were unique to the drilled pits (anemones, annelids, ascidians, bivalves, hydroids and sponges). The Kruskal–Wallis test showed a significant difference in species richness ($H(2) = 10$, $p < 0.05$) Table 2 and the post hoc test revealed that both the 14 mm and 22 mm pits had significantly greater species richness compared to the control plots while there was no difference between the two treatments (Fig. 2, Table 2). These results indicate that even a simple intervention such as adding pits can significantly increase the number of species found on the wave breaker units.

2.1.3. Incorporating habitat features in the construction of a new seawall at Shaldon, England

Surface roughness and novel habitats (pits, pools) can be added to seawalls during construction (Chapman and Blockley, 2009; Chapman and Underwood, 2011). This can be done by increasing the areas of mortar between blocks and manipulating the wet mortar to create desired habitats. The construction of a new sea wall at Shaldon at the mouth of the Teign Estuary in South Devon, England (50°32′N, 03°30′W) was completed in May 2010 as part of a major tidal flood defence scheme. The site is situated in a sheltered estuarine location with strong tidal currents. To achieve a visually attractive structure with minimal negative environmental and aesthetic impact, the new seawall was clad with local stone (Naylor et al., 2012). During the construction of the new seawall, millimetre-scale horizontal grooves (13 replicates), centimetre-scale pits (14 replicates) and recessed crevices (12 replicates). Untreated areas of mortar were also established as controls (8 replicates) (Fig. S3). The wall was designed with an even number of replicates. However, due to the local hydrodynamics after construction the bed level of the foreshore rose unevenly resulting in some replicates being "lost" (e.g. see Fig. S3b). The data presented are from all the available treatments.

Table 1
Drill-cored rock pools at Tywyn, Wales. 1-way ANOVA results for comparison of species richness in (a) deep and (b) shallow drill-cored rock pools compared to emergent substrata on Tywyn Breakwater.

(a) Deep				(b) Shallow	
Source	DF	MS	F	MS	F
Habitat	1	3.56	0.98	0.49	18.1***
Error	16	3.64		0.03	

NS = Not significant
*** P < 0.001.

Table 2
Artifical pits on Plymouth Breakwater, England. (a) Kruskal–Wallis test results for species richness for treatments of 22 mm pits, 14 mm pits and control plots on Plymouth Breakwater. (b) Mann–Whitney U post-hoc comparison results for control plots compared to 22 mm pits, control plots compared to 14 mm pits and 22 mm pits compared to 14 mm pits. Statistically significant results following Bonferroni correction.

a) Kruskal–Wallis test		
Source	df	*H*
Treatment	2	10.32**
b) Mann–Whitney U Post hoc comparisons		
Comparison	*U*	
Control v 22 mm pits	6.5**	
Control v 14 mm pits	5.5**	
22 mm v 14 mm pits	31.5	

P = 0.005/3 = 0.016.
** P < 0.01

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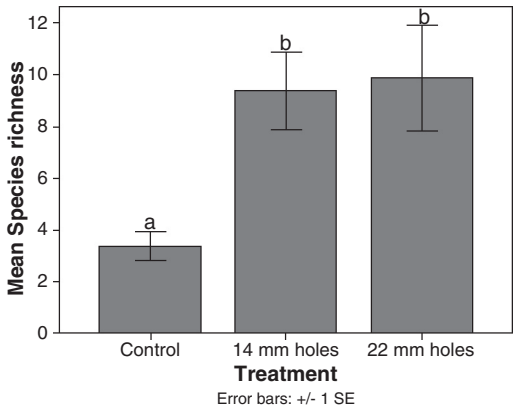

Fig. 2. Artificial pits on Plymouth Breakwater, England. Mean species richness (n = 32 ± SE) in the control plots, the 14 mm drilled hole plots and the 22 mm drilled hole plots on the wave-breaker units on Plymouth Breakwater.

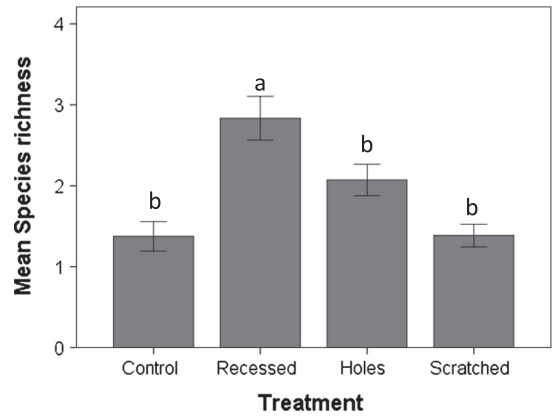

Fig. 3. Novel habitats on Shaldon seawall, England. Mean species richness in the control plots (n = 8 ± SE), recessed treatments (n = 12 ± SE), the pit treatments (n = 14 ± SE) and the scratched treatments (n = 13 ± SE).

Both control and treated areas were created by omitting a brick and filling the void with mortar. Grooves were added by scratching at the surface of the wet mortar with a trowel. The pits were made by pushing a stick of 2.5 cm diameter into wet mortar to a depth of 2.5 cm, at a slight angle down so as to retain water. The recesses were moulded by manipulating the mortar by hand to create a pool with a lip to retain water. All colonising animals and algae were identified and counted in the treatments in December 2011 (nineteen months after the construction of the wall). Data were homogeneous and were analysed using one-way ANOVA. Student–Newman–Keuls (SNK) procedure was used to make post-hoc comparisons among levels of significant terms.

A total of five species were observed on the wall (functional groups included algae, gastropods and barnacles). Barnacles were unique to the recesses while other groups were present across all treatments. The recesses supported greater species richness than the other three habitats (controls, pits and grooves), which did not differ significantly from each other (Table 3, Fig. 3). The higher number of species associated with recesses was probably due to a combination of a greater area and the amount of water retained. Although the increase in diversity is only modest, these results clearly indicate that the addition of new habitats to seawalls can enhance biodiversity. In this particular installation the surface was high in the intertidal frame (approximately MHWN). Manipulation lower in the tidal frame might lead to differences among treatments. The addition of water retaining features can be achieved on larger scales during the construction phase of a new seawall in order to increase the number of species that will potentially colonise.

2.1.4. Manipulation of the rock sizes in gabion baskets: Wales and the Netherlands

Rock-filled gabion baskets and mattresses are often used in artificial coastal defences (Fig. S4). They potentially have important habitat-forming value as they are analogous to natural boulder shores. Although rocks of varying sizes are commonly used for the construction of gabions, no previous work has studied the interaction between rock size and gabion colonisation. To test whether the colonising epibiota would vary with stone size, gabions were filled with stones of different sizes and deployed at the mid tidal level on the boulder shore at Trefor, Wales (52°59′N, 04°25′W) and at the lower mid tidal level on the soft-bottom shore (median grain size 160 ± 25 μm) at Viane in the Eastern Scheldt, the Netherlands (51°36′N, 04°01′E). Gabions measured 50 cm × 50 cm × 30 cm. They were manufactured from 7.6 cm × 7.6 cm mesh opening in 0.3 cm diameter zinc-coated wire with PVC coating. Three treatments were randomly allocated to gabions: (1) small rocks (6–10 cm) only; (2) large rocks (>18 cm) only; (3) mixture of different sizes of rocks (between 6 and 18 cm). Each of the treatments was replicated five times. It was hypothesised that gabions containing a mixture of stone sizes would support higher species richness and total abundance than gabions containing either small or large stones only. The response variables were measured differently at each site and as a result are discussed separately.

At Trefor, Wales, gabions were deployed for twelve months until April 2012, when they were dismantled and each rock was removed and visually inspected for epibiota. All individuals were identified to species-level and counted. One-factor ANOVA was used to compare both species richness and total abundance with factor Treatment (three levels: small, large, mix; fixed & orthogonal). GMAV version 5 for Windows was used for ANOVA computations (Underwood and Chapman, 1998). Cochran's test was used to test for heterogeneity of variances, and Student–Newman–Keuls (SNK) procedure was used to make post-hoc comparisons among levels of significant terms. Data were square root transformed where necessary to remove heterogeneity in variances.

At Trefor, a total of twelve species colonised the gabions. There was no significant difference in species richness among treatments (Table 4a, Fig. 4a) with the gabions comprising small stones only supporting similar numbers of species (mean 7.6) to those comprising a mixture of stones (mean 9.0) and large stones only (mean 7.8). Similar functional groups (barnacles, gastropods, bivalves, crabs, anemones and annelids) were found across all treatments. There were significantly greater numbers of individuals in the 'small' treatment than in the

Table 3
Modified sea wall at Shaldon, England. 1-way ANOVA results for comparison of species richness among treatments.

Source	DF	MS	F
Treatment	3	5.45	10.88***
Error	43	0.50	

*** P < 0.001.

Table 4
Gabion baskets at Trefor, Wales. One-way ANOVA results for comparison of (a) species richness and (b) total abundance among gabions containing different rock sizes.

(a) Species richness				(b) Total abundance	
Source	DF	MS	F	MS	F
Treatment	2	2.87	3.44	39,654	8.62**
Error	12	0.83		4,601	

NS = Not significant
** P < 0.01.

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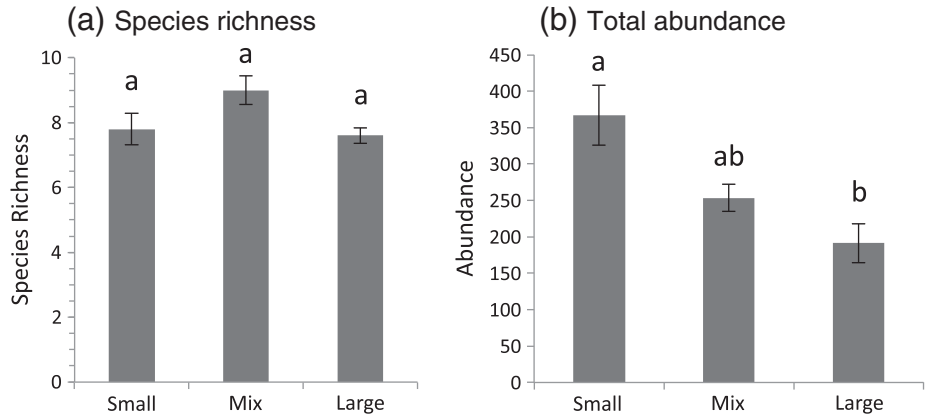

Fig. 4. Gabion baskets at Trefor, Wales. (a) Mean species richness and (b) mean total abundance of individuals in each of the three treatments. Small = small stones only; Mix = mixture of different sizes; Large = large stones only. (n = 5 ± SE).

'large' treatment but no significant difference among the 'mix' treatment and either the 'small' or 'large' treatments (Table 4b, Fig. 4b).

At Viane, gabions were deployed for sixteen months and in September 2012 species richness on the top horizontal surface of the gabions was estimated by counting all species that were visible (without dismantling the gabions). One-factor ANOVA was used to compare species richness with factor Treatment (three levels: small, large, mix; fixed & orthogonal).

Here, the gabions were colonised by fourteen different species. There were no significant differences among the three treatments ($F_{2,12} = 0.48$, $P > 0.05$) suggesting that there were no clear effects of differences in habitat texture such as surface area, related to the use of different rock sizes. Similar functional/taxonomical groups are found across treatments (algae, hydroids, echinoderms, gastropods, bivalves, annelids, crabs and barnacles). It must be noted that this was simply a visual inspection of the top horizontal surface of the gabion and a full survey of the biota living within each gabion is essential to accurately assess patterns of species richness in relation to the different treatments.

2.2. Demonstration projects

2.2.1. The deployment of precast prototype BIOBLOCK at Colwyn Bay, Wales

A new coastal defence scheme including the construction of rock revetment and a shore-perpendicular groyne was completed on the north-facing beach at Colwyn Bay (53°17 N, 03°42 W) in 2012. A prototype habitat enhancement unit, called the BIOBLOCK was installed into the new groyne in February 2012. The BIOBLOCK is a large, precast habitat-enhancement unit comprising multiple habitat types that would not normally be present on the boulders of a structure (Fig. S5). BIOBLOCKs can replace any given boulder in so-called 'riprap' structures (breakwaters, low-crested structures, rock groynes, rock revetment) and can be installed either during construction or retrospectively. Their purpose is to provide habitat whilst still dissipating wave energy. The prototype unit was 1.5 m × 1.5 m × 1.1 m, weighed 5.4 tonnes and comprised novel habitats (rock pools, pits, crevices) in the vertical and horizontal faces (Fig. S5). On the horizontal top face of the block, artificial rock pools were created with differing diameters (large: 25 cm diameter and small: 15 cm diameter) and depths (deep: 20 cm and shallow: 10 cm) with three replicates of each combination (12 pools in total). Pits and ledges were incorporated into the remaining four vertical sides. On two of the vertical faces of the unit, four patches (25 cm × 25 cm) of sixteen evenly spaced pits (deep: 5 cm and shallow: 2 cm) (two of each on each face = 8 patches in total). On the other two vertical faces, ten horizontal crevices (5 cm × 5 cm × 100 cm) were evenly spaced along the length of the face (20 crevices in total, Fig. S5). It was hypothesised that species richness would be greater on the BIOBLOCK than on the surrounding boulders and that species richness would be greater in the large deep pools than the other habitat types on the BIOBLOCK. All biota in the different habitats (pools, pits, crevices, emergent concrete, boulders) were identified and monitored monthly for thirteen months from March 2012 to March 2013. Due to the different sized sampling areas in each of the novel habitats of the BIOBLOCK, it was not possible to compare the colonising epibiotic assemblages using standard sampling units (e.g. quadrats) and formal statistical techniques.

A total of fifteen species were observed on the BIOBLOCK and adjacent boulders during the first thirteen months. Not all species were observed in each month, as some were mobile and/or transitory. The BIOBLOCK consistently supported greater species richness than the adjacent boulders. Functional groups represented across all months on the BIOBLOCK included algae, barnacles, shrimps, annelids, crabs, ctenophores and gastropods whilst those represented on the adjacent boulders included algae, barnacles and crabs. There was a dramatic increase in species richness on the BIOBLOCK between September 2012 and March 2013 (Fig. 5). After thirteen months, the BIOBLOCK supported a total of ten species whilst the adjacent rocks supported only four species (Fig. 5). On the BIOBLOCK, the large deep pools supported a total of five species, followed by the small shallow pools and ledges (four species each), big shallow pools, small shallow pools and deep pits (three species each), and shallow pits supporting the lowest species richness (two species, Fig. 6). The vertical and horizontal faces of the adjacent rocks supported four species each (Fig. 6).

It appears that the greater variety of novel micro-habitats on the BIOBLOCK supported greater species richness than comparable adjacent

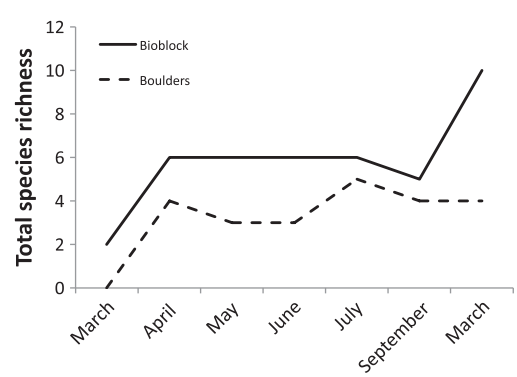

Fig. 5. The BIOBLOCK at Colwyn Bay, Wales. Comparison of total species richness among the BIOBLOCK (n = 1) and adjacent comparable boulder at intervals between March 2012 (1 month after deployment) and March 2013 (13 months after deployment).

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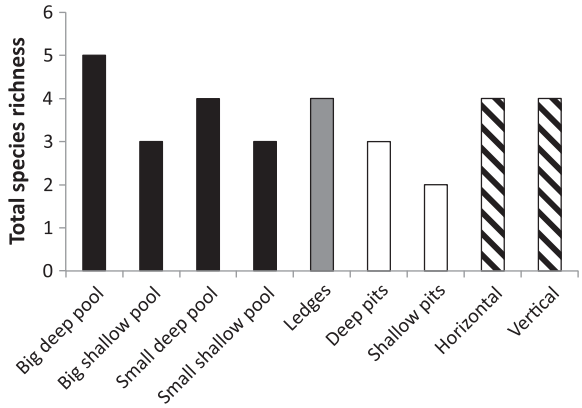

Fig. 6. The BIOBLOCK at Colwyn Bay, Wales. Comparison of total species richness among the different habitat types on the BIOBLOCK and both vertical and horizontal surfaces of adjacent boulder.

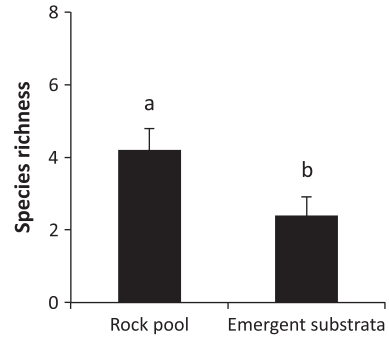

Fig. 7. In-filled cores at Penrhyn Bay, Wales. Mean species richness in artificial pools and adjacent emergent substrata (n = 5 ± SE).

boulders, primarily because of the availability of multiple habitat types on the BIOBLOCK. Thus, precast habitat-enhancement units such as the BIOBLOCK should incorporate multiple novel habitat types (pools of differing depths and diameters, pits of differing depths, ledges and overhangs) to maximise species diversity. It must be noted that this was a prototype demonstration project and that a fully replicated experiment followed by long-term, sustained monitoring (Hawkins et al., 2013a, 2013b) is essential to accurately assess patterns of distribution and abundance in relation to the different habitat types.

2.2.2. The in-filling of cores to create artificial rock pools at Penrhyn Bay, Wales

During construction of coastal defence structures, cores are often drilled in boulders to test their density (Fig. S2e). These boulders are then placed within the structure to function as normal. When these boulders are placed with the cores running vertically, they can be in-filled with concrete to retain water and thus function as artificial rock pools. In June 2012, nine cores were found and in-filled with concrete to a depth of 10 cm on the eastern breakwater at Penrhyn Bay, Wales (53°19 N, 03°45 W). The experiment ended after nine months in March 2013 when pools and adjacent emergent substrata of comparable area were visually inspected and all epibiota identified.

To test for differences in species richness between the two habitats, one-factor ANOVA was carried out with factor Habitat (two levels: pool, emergent substrata; fixed & orthogonal). Homogeneity of variances was established using Cochran's test and Student–Newman–Keuls (SNK) procedure was used to make post-hoc comparisons among levels of significant terms.

Only five cores retained water sufficiently to function as rock pools. A total of eight species colonised the boulders (pools and emergent rock) throughout the experiment. Pools supported significantly greater species richness (including barnacles, shrimp, gastropods and algae) than emergent substrata (barnacles and gastropods only) (Table 5, Fig. 7). Coralline algal germlings and shrimp were found in the artificial pools. It must be noted that this was a demonstration project and that a fully replicated long-term experiment is essential to accurately assess patterns of distribution and abundance in relation to the different habitat types.

Table 5
In-filled cores at Penrhyn Bay, Wales. One-way ANOVA results for comparison of species richness between pools and emergent substrata.

Source	DF	MS	F
Habitat	1	8.12	5.41*
Error	8	1.54	

* $P < 0.05$.

3. Biological interventions

3.1. Gardening experiments in the North Adriatic, Italy

We examined the feasibility of using artificial substrata to sustain populations of vulnerable species where their habitats are under threat. We experimented with species of *Cystoseira*, which are amongst the most representative, ecologically valuable and at the same time threatened canopy-forming taxa in the Mediterranean Sea (Benedetti-Cecchi et al., 2001; Gianni et al., submitted for publication; Perkol-Finkel and Airoldi, 2010). Our approach was intended to optimise the value of artificial coastal defence structures as substrata for possible forestations (Gianni et al., submitted for publication), without compromising their original purpose of maintaining beaches for tourism.

We transplanted juveniles of *Cystoseira barbata* into four habitats (Natural stable bedrock, Seaward artificial, Landward artificial, and Native unstable source bedrock) along the Adriatic Sea (Italy), and tested whether position (Horizontal or Vertical) and presence of surrounding adults could influence the successful establishment in each habitat (see details of the methods in (Perkol-Finkel et al., 2012)). The percentage of juveniles of *C. barbata* that survived out of those transplanted (five juveniles per plot, four plots in each of 2 areas for each habitat) was greater at most artificial sites examined compared to the native source sites where severe habitat loss was ongoing (PERMANOVA: $F_{1,72} = 7.77$, $P < 0.05$). There were no detectable effects of substratum position or presence of surrounding adults on juvenile growth. These results suggest that artificial coastal defence structures could potentially sustain populations of *C. barbata* despite the greater proportion of steeply sloping surfaces compared to natural habitats (Bulleri, 2005; Chapman and Blockley, 2009). Furthermore, the lack of adult canopies would not be a limiting factor when managing new populations on newly built man-made infrastructures.

The survival of *C. barbata* juveniles was highest on landward, sheltered sides compared to exposed seaward sides of the breakwaters, with average survival >30%, in comparison to ca. 9% in the seaward artificial habitats. The higher flow speed on seaward compared to landward sides of breakwaters can cause greater dislodgment of fucoid macroalgae (Jonsson et al., 2006). Indeed, the different sides of marine structures (e.g. seaward and landward) provide distinct habitats for the growth of a variety of macroalgae and invertebrates (e.g., Bacchiocchi and Airoldi, 2003; Bulleri et al., 2006; Burt et al., 2009). Such differences in aspect must be considered for achieving desired species growth on artificial structures.

Although it was possible to transplant *C. barbata* juveniles onto coastal structures built along rocky coastlines, results were not as promising when structures were located along sedimentary coastlines (Airoldi et al., 2005). A pilot caging experiment at two breakwaters and two natural rocky sites (four plots per treatment per site, see details of the methods in Perkol-Finkel et al., 2012) showed that survival (PERMANOVA caging × habitat: $F_{1,18} = 47.45$, $P < 0.05$) and cover

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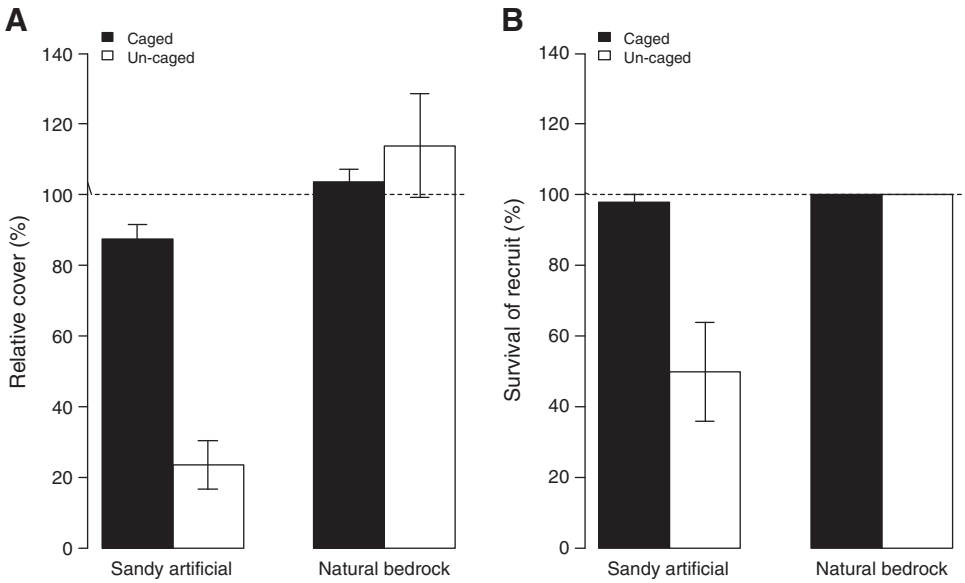

Fig. 8. Gardening experiments, Italy. (A) Mean relative cover (%) and (B) mean survival (%) of *Cystoseira barbata* juveniles after 8 days in relation to initial cover/counts respectively of caged (1 mm mesh size cage, solid bars) and un-caged (open bars). *C. barbata* juveniles were transplanted onto two breakwaters at Marotta (sandy artificial) vs. two natural bedrock areas in La Vela (natural bedrock). Dashed lines are 100% values representing the baseline of initial cover/counts. (n = 4 ± 1SE).

(PERMANOVA caging × habitat: $F_{1,18} = 5.87$, $P < 0.05$) of *C. barbata* transplants along sedimentary coastlines was limited by greater biotic disturbance compared to natural rocky sites (Fig. 8). We repeated the caging experiments at a variety of sites both along the Italian coast and along the coast of Croatia, to achieve a better interspersion of the treatments and test for the generality of our findings. The results were fairly consistent among widely geographically distributed sites (Ferrario, 2013).

Underwater video surveillance showed that loss of *C. barbata* from artificial structures in sandy habitats is related to disturbance by a variety of organisms, including small hermit crabs, mullets and wrasses (Ferrario, 2013). Although many of these species were present in natural rocky sites, there were comparatively fewer interactions with *C. barbata* juveniles in natural reefs relative to artificial structures (Ferrario, 2013). One possible explanation is that artificial structures set on sedimentary shorelines might attract a greater abundance of predators compared to nearby natural habitats, similar to what is thought to occur in systems such as seamounts (Rowden et al., 2010a, 2010b).

3.2. Biotic complexity on artificial structures in the North Adriatic, Italy

The meiofauna communities associated with epibiota on both natural and artificial substrata were investigated across 400 km of the Northern Adriatic coast. In the Adriatic Sea, the epibiotic communities of artificial structures are generally species poor and dominated by the mussel *Mytilus galloprovincialis* which can form wide monospecific beds (hereafter M), or mussel beds plus algae (hereafter M + A) (Bacchiocchi and Airoldi, 2003; Bulleri and Airoldi, 2005), representing habitats with complexity only and complexity with heterogeneity respectively. Harpacticoid copepods were chosen as a target assemblage because it is generally the dominant taxon on hard bottoms in this region.

The study was carried out on the west coast of the North Adriatic Sea at three locations characterised by the presence of numerous artificial coastal defence structures in close proximity to natural rocky reefs: Sistiana (45°46′N, 13°37′W) close to Trieste; Gabicce (43°57′N, 12°45′W); and Conero (43°30′N, 13°37′W). Two sites of each substrata type (natural and artificial) were selected at each of the three locations. Three replicate cores (5 cm internal diameter) were taken. Mussels in each sample were counted. Total surface area of mussels (SAM), surface area of each species of Algae (SAA) and total surface area of algae (SAAt) per sample were calculated. Total surface area (SAT) was obtained by summing SAM and SAAt for each sample. Univariate variables were analysed by a four-factor analysis of variance (ANOVA) with factors Substrata (two levels: natural, artificial; fixed and orthogonal), Location (three levels: Sistiana, Gabicce, Conero; random and orthogonal), Site (two levels: random and nested in Substrata x Location), and Habitat (two levels: M, M + A; fixed and orthogonal).

Species richness was significantly greater in M + A than M habitats at all locations, with Conero having greater species richness than the other two locations (SNK test) (Table 6, Fig. 9A). Abundance was significantly greater in M + A than M at Gabicce and Conero (Table 6, Fig. 9B). These results are not due to secondary surficial area provided by mussels or by number of mussels. SAM and number of mussels were both significantly greater at Sistiana than at Gabicce and Conero (Table 7, Fig. 10A,B) but by the complexity and heterogeneity added by the algae. In fact, differences occurred also between natural and artificial with abundance in M + A habitats at Conero being higher on artificial substrata than natural substrata. In this case samples were characterised by the presence of *Corallina officinalis*, the most complex algae among all others.

Table 6
Biotic complexity, Italy. ANOVA examining effect of substrata, location, and habitat (M and M + A) on species richness.4.

Number of Species				Number of individuals	
Source	df	MS	F	MS	F
Substrata (Su)	1	107.56	3.70	360,400.00	0.44
Location (Lo)	2	126.72	5.71*	5,056,000.00	58.95**
Habitat (Ha)	1	220.50	30.77*	3,599,200.00	1.77
SuxLo	2	29.06	1.31	811,670.00	9.46*
SuxHa	1	0.89	0.09	1,744,100.00	1.26
LoxHa	2	7.17	0.48	2,029,400.00	20.06**
Site (Si)(SuxLo)	6	22.19	2.55	85,769.00	0.24
SuxLoxHa	2	9.56	0.64	1,389,100.00	13.73*
Si(SuxLo)xHa	6	15.03	1.72	101,170.00	0.28
Res	48	8.72		359,620.00	
Total	71				

NS: P > 0.05.
* P < 0.05.
** P < 0.01.
*** P < 0.001.

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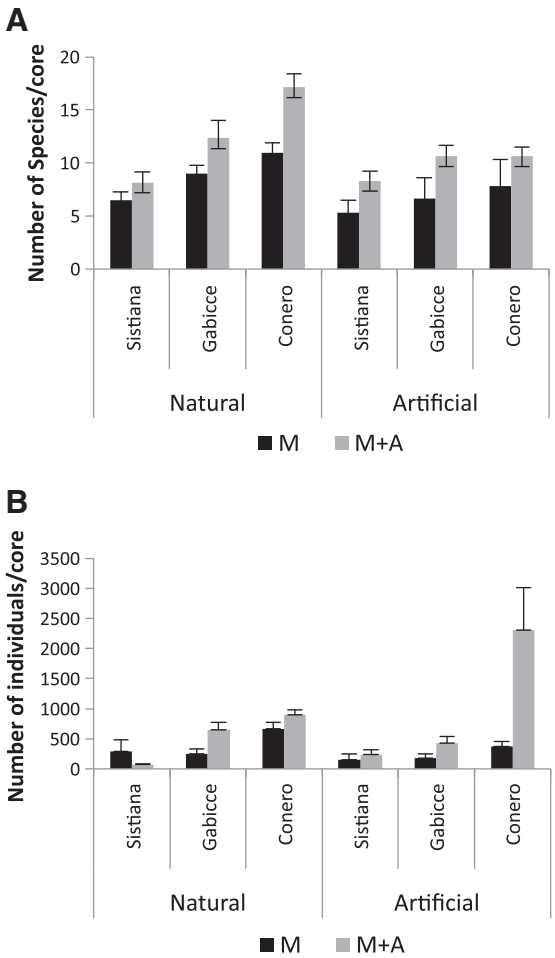

Fig. 9. Biotic complexity, Italy. (A) Mean species richness and (B) mean number of individuals per core (19.63 cm^2). Data are averaged across replicates and sites (n = 6 ± SE).

It appears that richness and abundance of harpacticoid copepods are mainly driven by the number and complexity of epibiota settled on both natural and artificial structures. Proliferation of artificial substrata along the coast may facilitate connectivity and spread of harpacticoid copepods. These patterns could also apply to other associated animal assemblages (e.g. amphipods, polychaetes) increasing complexity and richness of the trophic webs on artificial hard structures.

Table 7
Biotic complexity, Italy. ANOVA examining the effect of substrata, location and habitat (M and M + A) on differences in number of mussels and total mussel surficial area.

Mussels surficial area				Number of mussels	
Source	df	MS	F	MS	F
Surface (Su)	1	4.30	0.003	660.06	0.71
Location (Lo)	2	10534	17.08**	8313.4	25.76***
Habitat (Ha)	1	15095	5.34	304.22	13.17*
SuxLo	2	1665.70	2.70	931.1	2.89
SuxHa	1	21.89	0.04	50	1.35
LoxHa	2	2829.50	2.73	23.10	0.03
Site (Si)(SuxLo)	6	616.88	0.51	322.75	1.29
SuxLoxHa	2	524.91	0.51	37.04	0.05
Si(SuxLo)xHa	6	1036.00	0.86	750.86	3.00
Res	48	1206.30		249.97	
Total	71				

NS: P > 0.05.
* P < 0.05.
** P < 0.01.
*** P < 0.001.

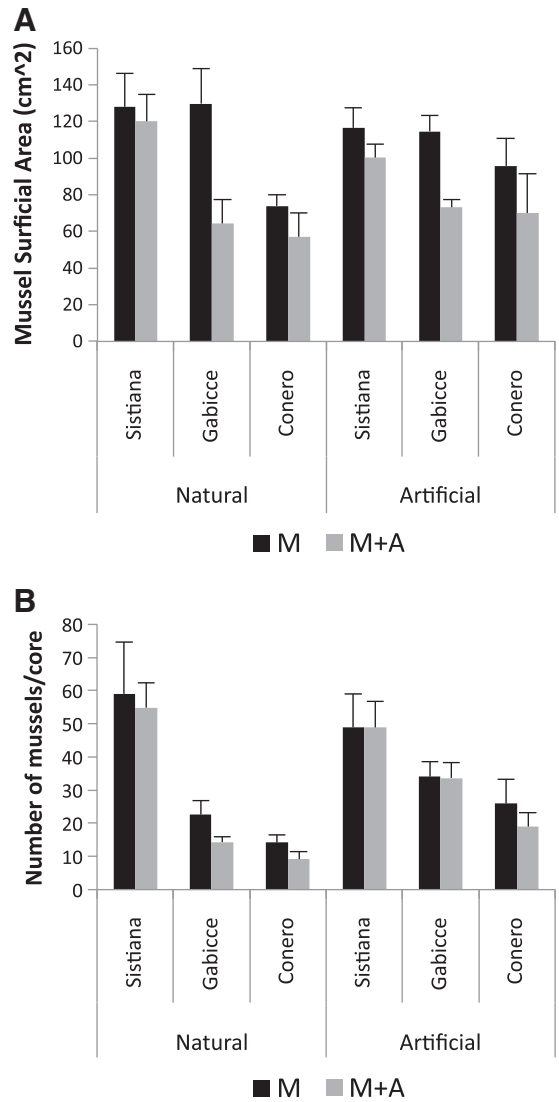

Fig. 10. Biotic complexity, Italy. Mean mussel surficial area and (B) mean number of mussels per core (19.63 cm^2). Data are averaged across replicates and sites (n = 6 ± SE).

4. Costs of interventions and effect on performance

Any intervention to an artificial structure has the potential to modify the engineering performance of the structure and comes at a financial cost. If interventions are incorporated at the construction phase, they can often be more imaginative, larger scale and cheaper than if made retrospectively. A variety of interventions were tested as part of the THESEUS project and described in this paper. Engineers were consulted prior to the implementation of these interventions in order to ensure that potential effects on the performance of the structures were negligible. Table 8 gives an overview of the potential effects on performance and costs associated with these interventions.

5. Overview

There are a number of reasons why artificial structures will never support the diversity of natural rocky shores: limited extent both vertically and horizontally, being on the interface of sandy habitats inevitably leading to scouring, as well as having less complex topographies reducing habitat and microhabitat diversity which in turn limits species diversity. Artificial structures are often newly installed or temporary, thus succession has not run its full course.

Table 8
Summary of the potential effect on performance and cost implications of interventions described in this paper.

Structure	Effect on performance	Cost implications
Drilled rock pools on Tywyn Breakwater, Wales	Drilling 18 rock pools on the breakwater equated to removing 1% of the total volume, as such can be regarded as having a negligible impact on the strength of the structure. However pools may accelerate the rate of fracturing.	The drilling of these rock pools required two men for two days and cost £860. This is a low cost option.
Drilled holes in wave-breaker blocks on Plymouth Breakwater, England	Drilling 100 pits on the concrete breakwater block equated to removing 0.00025% of the total volume, as such can be regarded as have a negligible impact on the strength of the structure. However pits may accelerate the rate of fracturing.	In freshly cured concrete 100 pits can be drilled in 1 h therefore making this low cost option
Modified seawall at Shaldon, England	The seawall at Shaldon was constructed in two parts, there is an inner core that provides the strength of the structure and an outer facing added to improve the aesthetics of the structure. The modifications were made to the rock facing and as such will not affect the strength of the wall.	The total project cost £6.5 million and the estimated cost of the trial was £20 K representing 0.3% of the coast of the entire project Naylor et al., 2011). However the enhancements were a requirement for planning permission.
Gabions filled with different sized rocks	It was not anticipated that the size of the rock used in the gabions will have any effect on the performance of the gabions.	The approximate cost of the gabion baskets and quarried rock was £500. Gabions are a cheap form of coastal defence. It took 3 people approximately 10 h to fill all of the gabions.
Precast concrete BIOBLOCK in groyne at Colwyn Bay, Wales	The primary function of the BIOBLOCK was to dissipate wave energy. The BIOBLOCK was cast to weigh 5.4 tonnes. This is on the heavy side of the types of boulders that are typically used in coastal defence structures in the UK (3–6 tonnes). The positioning of a BIOBLOCK in the place of a boulder is considered to have a negligible effect on the structure. However pits and pools may accelerate the rate of fracturing.	Only 1 BIOBLOCK was deployed at Colwyn Bay as a demonstration project. The mould, concrete and delivery cost approximately £2000. If BIOBLOCKs were available as a product, it is anticipated that they would be a similar cost to a typical boulder.
In-filled cores in groyne at Penrhyn Bay, Wales	The in-filling of cores in boulders is not expected to have any negative effect on the performance of the structure.	The cost of the in-filling the cores was less than £3 per core. It took two people approximately two hours to in-fill nine cores.
Gardening of *Cystoseira* spp. onto subtidal breakwaters in Italy	The gardening of canopy-forming algae is not expected to have any negative effect on the performance of the structure.	At present the technique has only been tested in small-scale experiments. In our experimental tests the costs for a small patch of 15 × 15 cm was about 6 €. We are now testing methodologies to expand the tests at larger scales and reduce the associated costs.

Large complex structures such as the Breakwater at Plymouth, UK (built in the 1800s) have, however, most of the attributes of natural rocky shores because of their size and longevity. As structures become smaller and less complex, differences increase—especially if the disturbance regime is high due to scouring or poor and repetitive maintenance.

Whilst the primary objective of coastal defence structures is to modify hydrodynamic and sedimentary regimes to protect sensitive areas or improve recreational conditions, any structure placed in the sea will become colonised by marine organisms. Colonisation of new habitats must be recognised as an important change to biodiversity in terms of both habitats and species in coastal areas. Furthermore, it cannot be avoided. It is possible, however, within the limits set by the primary necessity of engineering performance of the structure, to modify selected design features to enhance growth of selected organisms or achieve greater species richness. Thus, structures can be used to maximise secondary management end points (where perceptions of desirability or undesirability are intended as value judgment related to societal goals and expectations, Table 9).

Burcharth et al. (2007) identified the following examples of secondary management goals:

- Provision of suitable habitats to promote living resources for exploitation of food (such as shellfish and fish);
- Provision of suitable habitats to promote living resources that are the focus for recreational (such as angling, snorkelling) or educational (such as appreciation of marine life—rock pooling or ornithology) activities;
- Provision of suitable habitats that help conserve endangered or rare species or species of conservation importance;
- Provision of suitable habitats to promote diverse rocky substrate assemblages for conservation or mitigation purposes.

Before considering any interventions, we advise that the secondary management goals and outcomes are clearly thought through. Tables 9 and 10 summarise the possible secondary management goals and outlines potential interventions to achieve particular goals. In the appendix we illustrate the outcomes of particular interventions to inform practitioners.

Since Moschella et al. (2005) considerable progress has been made in developing ecological engineering interventions worldwide. Particular progress has been made in Australia (Bulleri and Chapman, 2010; Chapman and Underwood, 2011) and during the course of

Table 9
List of secondary management goals for artificial coastal defence structures and guidelines on how to achieve them.

Management goal	*Guidelines*
Minimise change to native diversity and maintain status quo	If structures are built in a rocky setting, mimic as close as possible the natural conditions (i.e. use hard local rock). If structures are built in a sedimentary setting, design to mitigate as much as possible changes to these habitats (e.g. by maximising water flow at the landward or using reef units that prevent build-up of fine sediments at the landward side).
Increase local species diversity for recreation, education, tourism	Use mixture of local rock types; ensure heterogeneity of rock is high. If rock pools are common in the area incorporate water-retaining features.
Promote target species (e.g. for commercial or conservation purposes)	This will vary with the species in question. Consider regional environmental context and distance from source population. Ensure that the ecology of the species is well understood before conducting transplants.
Reduce the likelihood of spread of non-native species	Minimise constructions close to areas that are particularly susceptible to vectors of introductions (e.g. ports), minimise the amount of maintenance work or other severe disturbances and promote the establishment of diverse native assemblages

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Table 10
Consider potential levels of intervention possible or necessary in order to achieve the secondary management goal. It is important to recognise that (a) some factors are uncontrollable whilst (b) others are controllable.

(a) Factors which are uncontrollable & context-dependent	(b) Factors which are controllable through design
Biogeographic setting and potential species pool	Rock hardness: Soft rock (e.g. limestone), hard rock (e.g. granite) or mixture of soft and hard rock
Larval recruitment regime	Habitat heterogeneity: High, low or none. This can be done by drilling pits and crevices or by installing BIOBLOCKs
Sediment supply and dynamics	Water-retaining features: Large volume, small volume or none. This can be done by drilling, in-filling existing holes or installing BIOBLOCKs
Wave action	Gardening of target species: Transplantation success of adult or juvenile individuals may be strongly affected by abiotic conditions (including wave action) or biotic conditions (i.e. grazing pressure)
Tidal range	Tidal level: If possible, the structure can be placed at varying tidal levels
Vectors of introduction of non-indigenous species	Manage maintenance and disturbance to epibiotic communities. Consider factors like distance from other structures and general landscape context

the THESEUS project. Simple cost effective interventions can provide habitats for target species and biodiversity, without compromising the engineering function of the structure. The rules are simple:

i. Match the natural topographic complexity to mimic the mosaic of habitats operating at a variety of scales from 10 m down to less than 1 cm to enhance settlement and survival of native species. This includes creating intertidal pools to retain water wherever possible;
ii. Minimise scouring and maintenance, and;
iii. Actively manage desired target species if natural colonisation potential is low.

Any structure placed in the sea will lead to the loss or modification of natural habitats with impacts on adjacent sedimentary habitats and their associated species (Martin et al., 2005). Therefore, interventions above should be viewed as at best mitigating the impacts of construction projects designed for coastal protection. Any benefits can only be viewed as secondary objectives to the primary aim of coastal protection. But with foresight and accumulating understanding and knowledge from best practice, simple and cost-effective measures can be used to achieve multiple ecosystem services such as local biodiversity maintenance or provision of harvestable species.

Among the factors that affect the growth of species on artificial structures, some are uncontrollable and context dependent, whilst others are controllable through careful design and planning (Table 10, Burcharth et al., 2007; Moschella et al., 2005). It is advantageous to incorporate any modifications during the construction stage as modifications made at this time can be done on a larger scale, can be incorporated into the design of the structure and take advantage of heavy plant machinery that is present on the construction site. It will enable greater flexibility to work with contractors, local councils and agencies and reduce the costs of their incorporation. If it is not possible to incorporate modifications at the construction phase, there are also ways to engineer artificial habitats retrospectively, even if on a smaller scale.

More broadly, with increasing anthropogenic pressure on our coasts, then any planned interventions need to be seen in the broader context of marine spatial planning and integrated management of the coast and its resources. Smart but sensitive design of structures can reduce impacts without compromising their primary purpose, whilst providing opportunities for multiple secondary objectives thereby ensuring an ecosystem-based approach to coastal defence.

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Appendix A. Guidelines

In this appendix we suggest guidelines for the creation of desired habitat types: (i) as part of the quarrying and or concrete casting process, (ii) during construction and (iii) retrospectively. Furthermore the consequences of positioning a structure in relation to tidal height and/or potential sources of non-native species (e.g. ports and marinas) are considered. We also discuss the need to have an ecologically planned lifetime maintenance that would reduce the development of weedy and invasive species.

A.1. Modifications as part of the quarrying or concrete casting process

The type and placement of materials during construction can provide analogues to desired habitat types. The geology of rock used can have a significant effect on the colonising communities (Green et al., 2012) and/or on the rate of natural erosion and weathering. The natural erosion of softer rocks (e.g. limestone) may provide important micro-small scale habitat that is not available on harder rocks (e.g. granite) (Fig. S2b, Firth et al., in press; Moschella et al., 2005). Water is sometimes retained either on or around the bases of the boulders and concrete units of coastal defences (Fig. S2c, d, Firth et al., in press; Pinn et al., 2005) which can support diverse communities.

Quarried boulders are sometimes drill-cored to check the density of the rock (Fig. S2e). If these boulders are then placed vertically, the core can be in-filled with concrete to a desired depth, such that it will retain water and function as a rock pool. Furthermore, quarried

boulders often have longitudinal grooves as an artefact of the drilling process (Fig. S2f). The grooves can provide a valuable refuge for many organisms (see Borsje et al., 2011). When units are constructed of concrete, they can be modified easily and cheaply during the casting process to create desired habitats such as pits, crevices and rock pools (Figs. S1b, S2a).

Recommendations to utilise artefacts of the quarrying and construction process:

To achieve greater availability of habitat and species diversity, where possible:

- Consider regional context, and use rock materials local to the region or as close as possible mimics of adjacent rocky habitats;
- If the natural rocks in the region have complex surfaces, consider reproducing them on the structures by i.e. using boulders with drilled depressions that mimic the natural ones;
- If the natural rocks in the region have rock pools, consider reproducing some natural depressions facing upwards, as they will retain water and support communities typical of that environment. Another option could be to place boulders/units in such a way that they retain water at the bases to provide analogues to rock pools;
- If structures are built with a secondary management goal of supporting recreational or educational activities, then consider incorporating a variety of habitats by casting of concrete units.

A.2. Considerations and modifications during the construction process

A.2.1. Consideration of the physical setting

Structures constructed at the mid-tidal level or higher tend to have lower species diversity and abundance than structures placed on the lower shore (Browne and Chapman, 2011; Chapman and Underwood, 2011; Firth et al., in press; Moschella et al., 2005). Microhabitat features will provide refuge from desiccation when incorporated at high shore levels, but the potential pool of colonising species is greater at lower levels (Fig. S6a,b).

Community structure differs in sheltered and exposed environments. Structures that comprise both exposed and sheltered components are likely to provide a greater diversity of habitats for a wider range of species with differing environmental tolerances (Fig. S6c,d). Whilst providing habitat for native species, it is worth noting that artificial structures also have the potential to support greater abundance of invasive species than natural habitats (Fig. S6e,f) especially on more sheltered landward sides (Airoldi and Bulleri, 2011; Bulleri and Airoldi, 2005). When multiple artificial structures are built relatively close to one another, along stretches of coast comprising predominantly soft sediments, these structures can sometimes function as pathways or stepping stones, facilitating the spread and connectivity of both native and non-native marine species. It is worth noting, however, that the resistance of a community to the establishment of non-native species may increase with higher native species diversity (Stachowicz et al., 2002), especially if certain functional groups are present (Arenas et al., 2006). The risk of facilitating the spread of non-native species through the construction of artificial hard structures may thus be reduced through design options that favour the colonisation by native, habitat-forming species.

A.2.2. Engineering modifications

Modifications that are carried out at the construction stage can be carried out on a larger scale, be more creative, and potentially cheaper than those made retrospectively. The type and extent of manipulations possible will depend on the type of the coastal defence works that are being built. In this section we summarise previously published studies and studies that have been carried out by the THESEUS team. We then continue to give generic recommendations that can be adapted to suit the scheme in question.

Seawalls are often built of blocks or bricks. Surface roughness and novel habitats (pits and pools) can be created in seawalls by increasing the areas of mortar between blocks and manipulating the wet mortar to create the desired habitats (Fig. S3a–d). It is possible to build rock pools into vertical seawalls constructed of blocks during the construction process by omitting blocks and replacing them with a lip to retain water (see Chapman and Blockley (2009) for full details). Furthermore, rock pools can be fitted retrospectively onto vertical seawalls using modified planters (see Browne and Chapman (2011) for full details).

In section i we discussed many of the enhancements that can be artefacts of the construction and/or quarrying procedure and can be considered for the construction of rip rap structures (breakwaters, rock groynes, rock revetments). All of the recommendations that are listed above should be also considered here. The previously-mentioned precast habitat enhancement unit (the BIOBLOCK) can be incorporated into coastal defence structures either at the construction stage or retrospectively (Fig. S5) and enhances habitat availability whilst still dissipating wave energy. It can replace any given boulder on a groyne or breakwater. Practical limitations, however, include that the BIOBLOCK needs to be lifted by crane and may require a license depending on local laws. By deploying it during construction, the license can be covered by the overall scheme and cost can be reduced by using cranes that are already on site. See section 4.2.1 for details.

Recommendations for engineering considerations during the construction process:

To promote habitat variety and hence diversity, for e.g. recreational or educational purpose, include:

- Place the structure (groyne, breakwater, seawall) as low down in the intertidal zone as possible;
- Seawalls, jetties, piers or docks are particularly accessible to the public therefore representing ideal targets from an educational and recreational point of view. Options include modifying the mortar and/or the block work to incorporate pits, crevices and rock pools;
- Consider the recommendations in section i and deploy a number of BIOBLOCKS throughout the structure.

Important design considerations to reduce invasion by non-native species include:

- Structures in close proximity to harbours or shipping routes may increase the likelihood for those structures to become colonised by invasive non-native species;
- Avoid proliferation of structures as they may act as stepping-stones to dispersal for both native and non-native marine species;
- Maximise water movement on the landward side (especially in those regions where sheltered hard substrata are naturally rare).

A.3. Modifications incorporated retrospectively

A.3.1. Engineering modifications

Novel habitats can be created on artificial coastal defence structures retrospectively using a variety of methods. Modifications carried out at this stage are generally on a smaller-scale and more expensive than those done at the construction stage. It is possible to create artificial crevices, pits and rock pools by drilling. Pits of varying diameters, depths and distances apart can be easily drilled into boulders, seawalls or concrete units (Borsje et al., 2011; Martins et al., 2010; Witt et al., 2012). Depending on the location and scope of the enhancements, a power source/generator may be required. If it is not possible to use a generator, pits can be pre-drilled into tiles and attached to the desired structure using a battery-powered SDS hammer-action drill (Fig. S1c). Pits can be incorporated on any slope available. Artificial rock pools of varying depth and diameter can be created in the horizontal surfaces of boulders using a diamond-tipped corer (Fig. S1a). A novel way of retro-fitting rock pools is affixing modified

planters (plant pots) to the seawall using stainless steel braces (Browne and Chapman, 2011). This method will only work in the most sheltered environments as planters may be damaged by wave action. Furthermore, planters must fit tightly to the substratum and this method is therefore only recommended where vertical seawalls are available for modification.

Recommendations for engineering considerations that can be fitted retrospectively:

To promote habitat heterogeneity and diversity, where possible

- Incorporate pits either by drilling directly into the substrata or by pre-drilling tiles and affixing them to the substrata;
- Incorporate pools into the horizontal surfaces of boulders by drill-coring. A variety of depths and diameters is advised;
- Incorporate pools into vertical seawalls by affixing modified planters. This is only recommended in low-energy environments and in situations where planters can be fitted tightly to the substratum;
- Habitats created lower on the structure will support greater species diversity than those created higher on the structure.

A.4. Gardening modifications

As artificial coastal defence structures are expected to proliferate alongside with human population (Dugan et al., 2011), and their current ecological value as habitats is often very poor compared to natural habitats (Airoldi et al., 2005; Firth et al., in press; Miller et al., 2009; Moschella et al., 2005; Perkol-Finkel et al., 2006) efforts to garden species of conservation value on their surfaces could help elevate their ecological value without compromising their original function (Perkol-Finkel et al., 2012).

We demonstrated that enhancing canopy-forming algae on artificial structures can be feasible, but requires a greater understanding of the different ecology of these artificial systems. Gardening tended to be more successful on the landward side of the structures, probably due to a greater dislodgment of transplanted individuals on the seaward sides. Neither substratum material nor complexity affected the growth of canopy forming algae. Local environmental and biological settings were the most limiting factors. Gardening was successful on structures built in a rocky seascape, while canopy forming algae were impaired on artificial structures in a sedimentary context, being severely limited by biotic pressure from both fishes and crabs.

Recommendations for gardening considerations:

When planning gardening interventions:

1) Clearly define objectives;
2) Consider regional environmental context and distance from source populations;
3) Use transplantation techniques that do not damage source populations (i.e. intercepting natural recruitment in areas of low survival probability Fig. 8, see also Gianni et al., submitted for publication);
4) Consider actively protecting transplanted species (by e.g. caging) until the establishment of a self–maintaining population;
5) Consider wave regime of the structures. Gardening with canopy-forming algae (or other native habitat-forming species) would be particularly applicable on the landward sides, as these are habitats most susceptible to species invasions. Also, the transplantation of some species may be technically easier in the sheltered conditions of the landward sides, and more effort may be necessary on the seaward side to guarantee the sustained effect of forestation.

A.5. Maintenance considerations

In the long run, ecological considerations in the design of artificial coastal defence structures need to be integrated by careful planning of the project lifetime. Coastal structures are vulnerable to scouring, undermining, outflanking, overtopping, and battering by storm waves. Thus, there is an on-going need for repair and maintenance during the lifetime of the structure. Airoldi and Bulleri (2011) found that maintenance caused a marked decrease in the cover of dominant space occupiers, such as mussels and oysters, and a significant increase in opportunistic and invasive forms, such as microbial films and weedy macroalgae. They also found that if interventions were made at certain times of the year the system recovered to the original state relatively more rapidly than when interventions were done in other periods of the year, reflecting the reproductive biology of the dominant species. It is important to consider the level of maintenance works that may be required at a given site before manipulations are undertaken, in order to assess if they are worthwhile, or whether the level of maintenance will mask the effects of the manipulations. Enhanced marine growth as facilitated by ecological engineering can sometimes elevate the strength and longevity of the structure thus reducing the frequency and magnitude of maintenance work. For example, species that secrete calcium carbonate skeletons (e.g. oysters) can actually strengthen concrete made structures (up to 10 times the original strength, Risinger, submitted for publication). Moreover, biogenic build-up of organisms such as oysters, serpulid or sabellariid worms, barnacles and corals, increases the weight of the structure with time, thus contributing to its stability and robustness (Coombes et al., 2013). A recent study evaluating the recruitment capabilities of 'ecologically active' concrete mixes in different marine environments has demonstrated enhanced marine growth yielding up to 1 kg m^{-2} yr^{-1} of inorganic–calcitic matter (Perkol-Finkel and Sella, in press).

Recommendations for maintenance considerations:

To promote native diversity and reduce the likelihood of establishment of invasive non-native species, where possible

- Repair schedules should be recognised in marine planning strategies to minimise negative ecological effects;
- In general, limit disturbances (from i.e. maintenance, or harvesting), as they will cause significant enhancement of opportunistic and invasive forms, such as biofilms, opportunistic and/or non-indigenous species;
- If interventions are needed, plan and schedule the interventions based on ecological knowledge of the systems (e.g. optimising native species recovery based on knowledge of recruitment windows), as this can help reduce non native species growth;
- Apply principles of ecological engineering for encouraging biogenic build-up, thus reducing the frequency/magnitude of maintenance works in the long run.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.coastaleng.2013.10.015.

References

Airoldi, L., Bulleri, F., 2011. Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban infrastructures. PLoS ONE 6, e22985.

Airoldi, L., et al., 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coast. Eng. 52, 1073–1087.

Arenas, F., Sánchez, I., Hawkins, S.J., Jenkins, S.R., 2006. The invasibility of marine algal assemblages: the role of functional diversity and identity. Ecology 87, 2851–2861.

Bacchiocchi, F., Airoldi, L., 2003. Distribution and dynamics of epibiota on hard structures for coastal protection. Estuar. Coast. Shelf Sci. 56, 1157–1166.

Benedetti-Cecchi, L., et al., 2001. Predicting the consequences of anthropogenic disturbance: large-scale effects of loss of canopy algae on rocky shores. Mar. Ecol. Prog. Ser. 214, 137–150.

Borsje, B.W., et al., 2011. How ecological engineering can serve in coastal protection. Ecol. Eng. 37, 113–122.

Bracewell, S.A., Spencer, M., Marrs, R.H., Iles, M., Robinson, L.A., 2012. Cleft, crevice, or the inner thigh: "Another place" for the establishment of the invasive barnacle *Austrominius modestus* (Darwin, 1854). PLoS ONE 7, e48863.

Bracewell, S.A., Robinson, L.A., Firth, L.B., Knights, A.M., 2013. Predicting free-space occupancy on novel artificial structures by an invasive intertidal barnacle using a removal experiment. PLoS ONE 8 (9), e74457.

Browne, M.A., Chapman, M.G., 2011. Ecologically informed engineering reduces loss of intertidal biodiversity on artificial shorelines. Environ. Sci. Technol. 45, 8204–8207.
Bulleri, F., 2005. Role of recruitment in causing differences between intertidal assemblages on seawalls and rocky shores. Mar. Ecol. Prog. Ser. 287, 53–65.
Bulleri, F., Airoldi, L., 2005. Artificial marine structures facilitate the spread of a non-indigenous green alga, *Codium fragile* ssp. *tomentosoides*, in the north Adriatic Sea. J. Appl. Ecol. 42, 1063–1072.
Bulleri, F., Chapman, M.G., 2004. Intertidal assemblages on artificial and natural habitats in marinas on the north-west coast of Italy. Mar. Biol. 145, 381–391.
Bulleri, F., Chapman, M.G., 2010. The introduction of coastal infrastructure as a driver of change in marine environments. J. Appl. Ecol. 47, 26–35.
Bulleri, F., Abbiati, M., Airoldi, L., 2006. The colonisation of human-made structures by the invasive alga *Codium fragile* ssp. *tomentosoides* in the north Adriatic Sea (NE Mediterranean). Hydrobiologia 555, 263–269.
Burcharth, H.F., Hawkins, S.J., Zanuttigh, B., Lamberti, A., 2007. Environmental Design Guidelines for Low Crested Coastal Structures. Elsevier, Oxford, UK.
Burt, J., Bartholomew, A., Usseglio, P., Bauman, A., Sale, P.F., 2009. Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? Coral Reefs 28, 663–675.
Cartwright, S.R., Williams, G.A., 2012. Seasonal variation in utilization of biogenic microhabitats by littorinid snails on tropical rocky shores. Mar. Biol. 159, 2323–2332.
Chapman, M.G., 2003. Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity. Mar. Ecol. Prog. Ser. 264, 21–29.
Chapman, M.G., Blockley, D., 2009. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. Oecologia 161, 625–635.
Chapman, M.G., Bulleri, F., 2003. Intertidal seawalls-new features of landscape in intertidal environments. Landsc. Urban Plan. 62, 159–172.
Chapman, A.R.O., Johnson, C.R., 1990. Disturbance and organization of macroalgal assemblages in the northwest atlantic. Hydrobiologia 203, 191–192.
Chapman, M.G., Underwood, A.J., 2011. Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. J. Exp. Mar. Biol. Ecol. 400, 302–313.
Coombes, M.A., et al., 2011. Colonisation and weathering of engineering materials by marine microorganisms: an SEM study. Earth Surf. Process. Landf. 36, 582–593.
Coombes, M.A., Naylor, L.A., Viles, H.A., Thompson, R.C., 2013. Bioprotection and disturbance: seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. Geomorphology 202, 4–14.
Davis, J., Levin, L., Walther, S., 2002. Artificial armored shorelines: sites for open-coast species in a southern California bay. Mar. Biol. 140, 1249–1262.
Dugan, J.E., Airoldi, A., Chapman, M.G., Walker, S., Schlacher, T., 2011. Estuarine and coastal structures: environmental effects. In: Elliott, M., Dugan, J.E. (Eds.), A Focus on Shore and Nearshore Structures. Treatise on Estuarine and Coastal Science. Elsevier, New York, NY, pp. 1–21.
Fauvelot, C., Bertozzi, F., Costantini, F., Airoldi, L., Abbiati, M., 2009. Lower genetic diversity in the limpet *Patella caerulea* on urban coastal structures compared to natural rocky habitats. Mar. Biol. 156, 2313–2323.
Fauvelot, C., Costantini, F., Virgilio, M., Abbiati, M., 2012. Do artificial structures alter marine invertebrate genetic makeup? Mar. Biol. 159, 2797–2807.
Ferrario, F., 2013. Analysis and development of ecologically based approach0065s to coastal defence. (PhD Thesis) University of Bologna.
Firth, L.B., Crowe, T.P., 2008. Large-scale coexistence and small-scale segregation of key species on rocky shores. Hydrobiologia 614, 233–241.
Firth, L.B., Crowe, T.P., 2010. Competition and habitat suitability: small-scale segregation underpins large-scale coexistence of key species on temperate rocky shores. Oecologia 162, 163–174.
Firth, L.B., Hawkins, S.J., 2011. Introductory comments—global change in marine ecosystems: patterns, processes and interactions with regional and local scale impacts. J. Exp. Mar. Biol. Ecol. 400, 1–6.
Firth, L.B., Williams, G.A., 2009. The influence of multiple environmental stressors on the limpet *Cellana toreuma* during the summer monsoon season in Hong Kong. J. Exp. Mar. Biol. Ecol. 375, 70–75.
Firth, L.B., Crowe, T.P., Moore, P., Thompson, R.C., Hawkins, S.J., 2009. Predicting impacts of climate-induced range expansion: an experimental framework and a test involving key grazers on temperate rocky shores. Glob. Chang. Biol. 15, 1413–1422.
Firth, L.B., Knights, A.M., Bell, S.S., 2011. Air temperature and winter mortality: implications for the persistence of the invasive mussel, Perna viridis in the intertidal zone of the south-eastern United States. J. Exp. Mar. Biol. Ecol. 400, 250–256.
Firth, L.B., et al., 2013. The importance of water retaining features for biodiversity on artificial intertidal coastal defence structures. Divers. Distrib. 19, 1275–1283.
Firth, L.B., Mieszkowska, N., Thompson, R.C., Hawkins, S.J., 2013. Climate change and adaptational impacts in coastal systems: the case of sea defences. Environ. Sci. Process. Impact. http://dx.doi.org/10.1039/c3em00313b.
Gacia, E., Satt, M.P., Martin, D., 2007. Low crested coastal defence structures on the Catalan coast of the Mediterranean Sea: how they compare with natural rocky shores. Sci. Mar. 71, 259–267.
Gianni, F., Bartolini, G.F., Airoldi, L., Ballesteros, E., Francour, P., Guidetti, P., Meinesz, A., Thibaut, T., Mangialajo, L., 2013. Conservation and restoration of marine forests in the Mediterranean sea and the potential role of marine protected areas. Adv. Oceanogr. Limnol. http://dx.doi.org/10.1080/19475721.2013.845604.
Glasby, T.M., 1999. Differences between subtidal epibiota on pier pilings and rocky reefs at marinas in Sydney. Estuar. Coast. Shelf Sci. 48, 281–290.
Glasby, T.M., 2000. Surface composition and orientation interact to affect subtidal epibiota. J. Exp. Mar. Biol. Ecol. 248, 177–190.
Glasby, T.M., Connell, S.D., 1999. Urban structures as marine habitats. Ambio 28, 595–598.
Goodsell, P.J., Chapman, M.G., Underwood, A.J., 2007. Differences between biota in anthropogenically fragmented habitats and in naturally patchy habitats. Mar. Ecol. Prog. Ser. 351, 15–23.
Goodsell, P.J., Underwood, A.J., Chapman, M.G., 2009. Evidence necessary for taxa to be reliable indicators of environmental conditions or impacts. Mar. Pollut. Bull. 58, 323–331.
Goss-Custard, S., Jones, J., Kitching, J.A., Norton, T.A., 1979. Tide pools of Carrigathorna and Barloge Creek. Philos. Trans. R. Soc. Lond. B 287, 1–44.
Green, D.S., Chapman, M.G., Blockley, D.J., 2012. Ecological consequences of the type of rock used in the construction of artificial boulder-fields. Ecol. Eng. 46, 1–10.
Hawkins, S.J., Firth, L.B., McHugh, M., Poloczanska, E.S., Herbert, R.J.H., Burrows, M.T., Kendall, M.A., Moore, P.J., Thompson, R.C., Jenkins, S.R., Sims, D.W., Genner, M.J., Mieszkowska, N., 2013a. Data rescue and re-use: recycling old information to address new policy concerns. Mar. Policy 42, 91–98.
Hawkins, S.J., Vale, M., Firth, L.B., Burrows, M.T., Mieszkowska, N., Frost, M., 2013b. Sustained observation of marine biodiversity and ecosystems. Oceanography 1, e101 http://dx.doi.org/10.4172/ocn.1000e101.
IPCC, 2007. Climate change 2007: the physical science basis—summary for policymakers. Contribution of working group i to the fourth assessment report of the inter-governmental panel on climate change (Paris).
Iveša, L., Chapman, M.G., Underwood, A.J., Murphy, R.J., 2010. Differential patterns of distribution of limpets on intertidal seawalls: experimental investigation of the roles of recruitment, survival and competition. Mar. Ecol. Prog. Ser. 407, 55–69.
Jackson, A.C., McIlvenny, J., 2011. Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts. J. Exp. Mar. Biol. Ecol. 400, 314–321.
Johnson, M.P., Hughes, R.N., Burrows, M.T., Hawkins, S.J., 1998. Beyond the predation halo: small scale gradients in barnacle populations affected by the relative refuge value of crevices. J. Exp. Mar. Biol. Ecol. 231, 163–170.
Jonsson, P.R., et al., 2006. Interactions between wave action and grazing control the distribution of intertidal macroalgae. Ecology 87, 1169–1178.
Knott, N.A., Underwood, A.J., Chapman, M.G., Glasby, T.M., 2004. Epibiota on vertical and on horizontal surfaces on natural reefs and on artificial structures. J. Mar. Biol. Assoc. UK 84, 1117–1130.
Martin, D., et al., 2005. Ecological impact of coastal defence structures on sediment and mobile fauna: evaluating and forecasting consequences of unavoidable modifications of native habitats. Coast. Eng. 52, 1027–1051.
Martins, G.M., Thompson, R.C., Neto, A.I., Hawkins, S.J., Jenkins, S.R., 2010. Enhancing stocks of the exploited limpet *Patella candei* d'Orbigny via modifications in coastal engineering. Biol. Conserv. 143, 203–211.
Marzinelli, E.M., Underwood, A.J., Coleman, R.A., 2011. Modified habitats influence kelp epibiota via direct and indirect effects. PLoS ONE 6, e21936.
McCoy, E.D., Bell, S.S., 1991. Habitat structure: the evolution and diversification of a complex topic. In: Bell, S.S., McCoy, E.D., Mushinsky, H.R. (Eds.), Habitat Structure: The Physical Arrangement of Objects in Space. Chapman & Hall, London, pp. 3–27.
Miller, M.W., et al., 2009. Alternate benthic assemblages on reef restoration structures and cascading effects on coral settlement. Mar. Ecol. Prog. Ser. 387, 147–156.
Moreira, J., Chapman, M.G., Underwood, A.J., 2006. Seawalls do not sustain viable populations of limpets. Mar. Ecol. Prog. Ser. 322, 179–188.
Moschella, P.S., et al., 2005. Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. Coast. Eng. 52, 1053–1071.
Naylor, L.A., Venn, O., Coombes, M.A., Jackson, J., Thompson, R.C., 2011. Including Ecological Enhancements in the Planning, Design and Construction of Hard Coastal Structures: A process guide. Report to the Environment Agency(PID 110461). University of Exeter (66 pp.).
Naylor, L.A., Coombes, M.A., Venn, O., Roast, S.D., Thompson, R.C., 2012. Facilitating ecological enhancement of coastal infrastructure: the role of policy, people and planning. Envron Sci. Policy 22, 36–46.
Perkol-Finkel, S., Airoldi, L., 2010. Loss and recovery potential of marine habitats: an experimental study of factors maintaining resilience in subtidal algal forests at the Adriatic Sea. PLoS ONE 5, e10791.
Perkol-Finkel, Sella, 2013. http://www.ice.org.uk/ICE_Web_Portal/media/Events/Breakwaters%202013/Ecologically-Active-Concrete-for-Coastal-and-Marine-Infrastructure—Innovative-Matrices-and-Designs.pdf (in press).
Perkol-Finkel, S., Shashar, N., Benayahu, Y., 2006. Can artificial reefs mimic natural reef communities? The roles of structural features and age. Mar. Environ. Res. 61, 121–135.
Perkol-Finkel, S., Ferrario, F., Nicotera, V., Airoldi, L., 2012. Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. J. Appl. Ecol. 49, 1457–1466.
Pinn, E.H., Mitchell, K., Corkill, J., 2005. The assemblages of groynes in relation to substratum age, aspect and microhabitat. Estuar. Coast. Shelf Sci. 62, 271–282.
Pister, B., 2009. Urban marine ecology in southern California: the ability of riprap structures to serve as rocky intertidal habitat. Mar. Biol. 156, 861–873.
Risinger, J.D., 2012. Biologically dominated engineered coastal breakwaters. (PhD thesis) Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College. (submitted for publication).
Rowden, A.A., Dower, J.F., Schlacher, T.A., Consalvey, M., Clark, M.R., 2010a. Paradigms in seamount ecology: fact, fiction and future. Mar. Ecol. 31, 226–241.
Rowden, A.A., et al., 2010b. A test of the seamount oasis hypothesis: seamounts support higher epibenthic megafaunal biomass than adjacent slopes. Mar. Ecol. 31, 95–106.
Skov, M.W., Hawkins, S.J., Volkelt-Inge, M., Pike, J., Thompson, R.C., Doncaster, C.P., 2011. Patchiness in resource distribution mitigates habitat loss: insights from high-shore grazers. Ecosphere 2 (5) (art60).
Stachowicz, J.J., Fried, H., Osman, R.W., Whitlatch, R.B., 2002. Biodiversity, invasion resistance, and marine ecosystem function: reconciling pattern and process. Ecology 83, 2575–2590.
Thompson, R.C., Wilson, B.J., Tobin, M.L., Hawkins, S.J., 1996. Biologically generated habitat provision and diversity of rocky shore organisms at a hierarchy of spatial scales. J. Exp. Mar. Biol. Ecol. 202, 73–84.

Underwood, A.J., Chapman, M.G., 1998. GMAV 5, Sydney, Australia: Institute of Marine Ecology. University of Sydney, Australia.
Vaselli, S., Bulleri, F., Benedetti-Cecchi, L., 2008. Hard coastal-defence structures as habitats for native and exotic rocky-bottom species. Mar. Environ. Res. 66, 395–403.
Virgilio, M., Airoldi, L., Abbiati, M., 2006. Spatial and temporal variations of assemblages in a Mediterranean coralligenous reef and relationships with surface orientation. Coral Reefs 25, 265–272.
Wang, J., Gao, W., Xu, S., Yu, L., 2012. Evaluation of the combined risk of sea level rise, land subsidence, and storm surges on the coastal areas of Shanghai, China. Clim. Chang. 115, 537–558.
Witt, M.J., et al., 2012. Assessing wave energy effects on biodiversity: the wave hub experience. Phil. Trans. R. Soc. A 370, 502–529.
Zanuttigh, B., et al., 2005. Environmental design of coastal defence in Lido di Dante, Italy. Coast. Eng. 52, 1089–1125.

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