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Ecological enhancement of coastal engineering structures: Passive enhancement techniques

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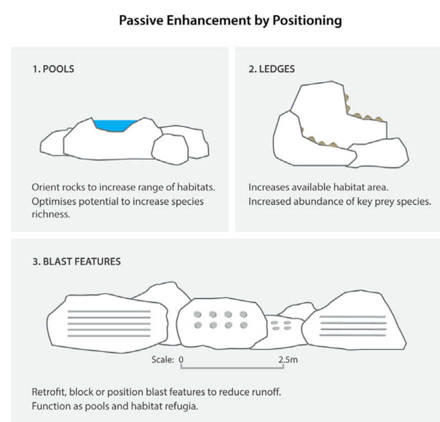
HIGHLIGHTS

- Rock properties can improve habitat suitability and heterogeneity for gastropods.
- Novel ecological sampling measured richness and abundance on geomorphic features.
- Passive positioning of ledges significantly increased limpet abundance in two years.
- Rock type exerts a strong control on geomorphic and habitat features present.
- Selecting suitable features in passive positioning rock armour has clear ecological benefits.

GRAPHICAL ABSTRACT



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ABSTRACT

The rock type used in coastal engineering structures impacts biodiversity, but its effect has been understudied to date. We report here on whether different combinations of rock material and rock mass properties can improve habitat suitability and early phase ecological outcomes on coastal engineering structures. We examine two coastal engineering schemes that used different granites during construction. At site one, Shap granite boulders with a high number of cm-dm^2 surface features (e.g. ledges) were deliberately positioned during construction (called passive enhancement), to a) maximise the provision of cm-dm scale intertidal habitat and b) determine which scale of habitat is best for ecological enhancement. At site two, Norwegian granite boulders were installed without passive enhancement, allowing for a direct comparison. Passive positioning of Shap granite boulders led to an increase in limpet (*Patella vulgata*, Linnaeus, 1758) abundance within two years but few limpets were recorded on the non-enhanced Norwegian granite. Positioning of boulder thus exerts a strong control on the mm and mm-dm scale geomorphic features present, with clear ecological benefits when suitable features are selected for and optimally positioned (i.e. passive enhancement) to maximise habitat features. An *EcoRock* scoring matrix was developed to aid in the selection of the most ecologically suitable rock materials for coastal engineering worldwide; this can help improve habitat provision on engineered structures in a rapidly warming world.

1. Introduction

Hard coastal engineering structures (e.g. sea walls, rock revetments, breakwaters, outfalls) typically use fresh, unweathered rock or concrete

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that typically lack micro- (mm) and meso-scales (cm-m) surface complexities (Coombes et al., 2015). The lack of surface topographic complexity is the main reason for emerging global evidence that such structures are poor ecological surrogates for the natural rocky shores they purport to replace, since they typically support fewer species with lower abundances (Bulleri et al., 2005; Moschella et al., 2005; Firth et al., 2014b). This alters community interactions, ecological function and ecological connectivity (Bishop et al., 2017; Strain et al., 2017). This is amplified by the fact that new structures lack the biological, chemical and physical weathering that alters the properties of rock and marine concrete, rendering them more ecologically favourable (Coombes et al., 2013a). Yet there is an increased use of hard coastal structures worldwide (Firth et al., 2014b) due to flooding and erosion pressure resulting from sea level rise and rapid urbanisation (Jackson and McIlvenny, 2011; Neumann et al., 2015).

Whilst growing research demonstrates how ecological outcomes can be improved by *actively* designing or retrofitting artificial hard coastal structures to deliver positive gains in ecosystem services (Bulleri et al., 2005; Coombes et al., 2015; Evans et al., 2016; Firth et al., 2014b; Strain et al., 2017), important gaps remain. One notable gap is research on the most ecologically suitable rock and concrete material types for coastal and marine engineering applications. Work on testing novel concrete mixes is rapidly advancing (Dennis et al., 2016; Perkol-Finkel and Sella, 2014) for use in different types of concrete engineering (e.g. antifer concrete blocks (Hooman Mousavi et al., 2017), sea dikes (Scheres and Schüttrumpf, 2019) and concrete blocks (Firth et al., 2014b)), where clear ecological gains can be achieved. However, less research has considered the contribution of inexpensive *passive* enhancements, such as the choice of different rock materials (Coombes and Naylor, 2012; MacArthur, 2019; Sempere-Valverde et al., 2018) or the surface features and positioning of the boulders used. The key differences between active and passive enhancement are outlined in Box 1. The research reported here addresses this gap, focussing specifically on the surface features and positioning of boulders used to enhance ecological suitably of coastal engineering structures.

A lack of suitable microhabitats subjects intertidal organisms to substantial abiotic thermal and desiccation stress at low tide and impacts on the distribution and physiology of rocky intertidal species (Lee and Li, 2013; Rickards and Boulding, 2015). Fine-scale (μm-cm) surface roughness can improve the early phase colonisation (<1.5. years) and ecological engineering potential of different types of rock armour and concrete (Coombes et al., 2015). Surface roughness positively affects the build-up of marine biofilms, increases primary productivity and enhances community development by encouraging the settlement of barnacle larvae and littorinids (Chabot and Bourget, 1988; Coombes et al., 2015; Sempere-Valverde et al., 2018). Materials with rougher surfaces thus improve the ability of communities on artificial structures to emulate those on natural substrata (Cacabelos et al., 2016).

Box 1

Ecological enhancements are either active or passive and both must remain within the realms of engineering suitability.

a) ***Active ecological enhancement*** mimics the geomorphological complexity of natural rocky shores, including modifying the chemistry/composition of marine concrete to better suit ecology (Perkol-Finkel and Sella, 2014); use of mm-cm scale surface textured concrete to encourage rapid species colonisation (Coombes et al., 2015; Loke et al., 2014) and; retrofitting rock armour and sea walls with holes (Evans et al., 2016; Firth et al., 2014b) and pools (Browne and Chapman, 2011) to mimic microhabitats and rock pools, all at multiple scales (i.e. mm-cm, cm-dm, dm-m).
b) ***Passive ecological enhancement*** makes informed decisions on choice of rock material, selecting boulders with many surface features and, crucially, boulder positioning to ensure the natural surface heterogeneity features (pools, cracks and ledges) are exposed on boulder tops, maximising their ecological value (Naylor et al., 2017b). Enhancements are simple, inexpensive and implemented during the design, construction and repair phases of infrastructure. Material choice includes selecting rock armour materials that are, for example, rich in calcium, light in colour and/or rough surfaced (i.e. chemically or physically) to maximise ecological suitability (Coombes et al., 2011; Coombes et al., 2013b; MacArthur, 2019).

Scaling up, rock mass properties such as joints and other discontinuities provide important crevice habitats for species (Harper and Williams, 2001; Naylor et al., 2012) at the cm-dm scale on natural rocky shores. These crevice habitats provide important microclimate refugia from climate-related stressors, on both natural rocky shores (MacArthur, 2019) and eco-engineered designs for maritime engineering applications (e.g. MacArthur et al., 2019). Given the widespread use of rock armour in coastal engineering worldwide, and the rapid growth of ecological enhancement and eco-engineering studies, it is important to determine how much of this ecological and biogeomorphological understanding from natural rocky shores has been tested as part of ecological enhancement science. To do this, we examined to extent to which rock-materials were considered as part of ecological outcomes as part of recent ecological enhancement and rocky shore ecology research (2010–2019 in Google Scholar and Web of Science, in April 2019).

The search string used aimed to account for a variety of enhancement types as well as studies on natural shores: ("ecological enhancement*" OR "ecological engineering") AND ("coastal defence*" OR "rock armour" OR "rock revetment") AND ("microhabitat*" OR "rock pool*" OR "roughness" OR "texture*" OR "groove*" OR "pit*" OR "water holding*" OR "material" OR "substrate*"). Sixty-four, non-duplicate studies were identified as relevant and included in Table A1. Seven studies were found in the Web of Science search that were already included in the Google Scholar results (Evans et al., 2016; Firth et al., 2014a; Firth et al., 2014b; Hall et al., 2018; Loke et al., 2017; Naylor et al., 2017b; Ostalé-Valriberas et al., 2018). Much research examines *active* enhancement of artificial coastal structures, such as artificial or drill cored rock pools ($n = 7$) (Evans et al., 2016; Firth et al., 2013) and textured tiles, blocks and panels ($n = 13$) (Coombes, 2011; Loke et al., 2019; MacArthur et al., 2019). Fewer studies addressed the ecological value and suitability of rock armour ($n = 4$) or rip rap breakwaters ($n = 4$) than for other features like seawalls ($n = 23$).

In the examined literature, only Sempere-Valverde et al. (2018) compared the geological controls on the ecological suitability of rock armour. Naylor et al. (2017b) identified passive positioning of rock armour during construction to maximise the ecological suitability of coastal structures. Selection and positioning of boulders to optimise for pits, grooves, crevices, ledges and pools (Fig. 1), that act as important microhabitat features and refuges for intertidal organisms, increased habitat heterogeneity, and thus improved species richness and abundance (Evans et al., 2016; Firth et al., 2012; Schaefer et al., 2018). Recent work on concrete tiles has also demonstrated that mm – cm designs are the most ecologically suitable, and can provide important microclimate refugia (MacArthur et al., 2019).

We examine here the influence of boulder roughness, geomorphic features and positioning on early stage colonisation of rock armour by testing the hypotheses that:

1) Inherent rock surface complexity (rock mass properties) at a range of spatial scales (cm – dm) positively influences early stage colonisation on coastal engineering rock armour;
2) Careful positioning of natural and artificial features on coastal engineering rock armour enhances the development of ecological communities within 2 years.

The work presented here examines the influence of passive positioning on ecological enhancement of rock armour revetments. To do this we constructed a novel ecological sampling method to allow species richness and abundance to be measured for individual geomorphic features, to identify which type and scale of geomorphic and rock mass properties influence early phase colonisation. Field sampling compared the influence of different geomorphic feature types, rock type and the presence of quarried features on species richness and abundance.

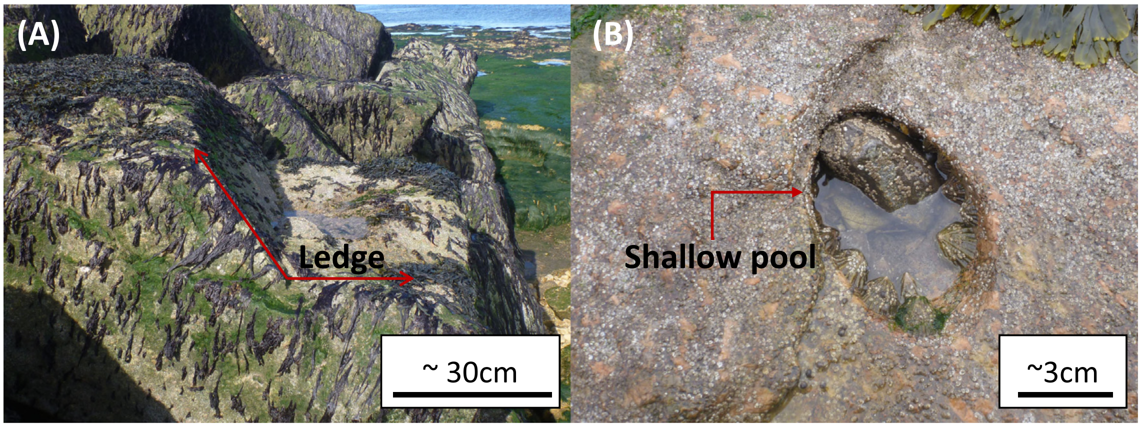


Fig. 1. Example of boulders with (A) ledge and (B) water retaining feature.

These factor into the development of an *EcoRock* scoring matrix, a multi-scale assessment tool combining rock material and rock mass properties. It can assist researchers and practitioners in selecting the most ecologically suitable rock materials for improving ecological outcomes for intertidal rock armour worldwide. Full details of the *EcoRock* scoring matrix can be found in MacArthur (2019) and the effects of the presence of geomorphic features and boulder positioning on ecological outcomes are discussed below.

2. Materials and methods

We performed field-tests of passive enhancement methods (Experiments 1–3) on rock armour revetments at Hartlepool Headland and Skinningrove in England (Fig. 2).

2.1. Description of field testing: experiments 1–3 sampling sites

The construction of the Hartlepool Headland coastal defences (54°41′48.3″N 1°10′31.4″W) spanned 2015 to late 2017. It consisted of an enhanced textured seawall and an 800 × 10 m Shap Granite rock armour revetment, underlain and fronted by a Magnesian Limestone intertidal shore platform (Naylor et al., 2017b). At Skinningrove (54°34′22.7″N 0°54′00.2″W), 23 km southeast of Hartlepool, a sandy beach is backed by a 310 × 10 m Norwegian Granite rock armour revetment installed in 2015. It is the nearest installation of rock armour of comparable age and shore position to the Hartlepool Headland scheme (Fig. 2). Hartlepool is the largest known operational ecological enhancement of UK coastal infrastructure (Naylor et al., 2017b) and both sites have potential to contribute to the understanding of ecological enhancement of rock materials used in hard coastal structures.

Previous studies (Coombes et al., 2011, 2015; McGreevy, 1985) suggested limestone to be the most ecologically suitable rock material due to its light colour, chemistry, porosity and ecological engineering potential. However, engineering and cost constraints precluded widespread use of limestone at Hartlepool (although locally available smaller dimension Carboniferous limestone was used to fill void spaces to improve ecological suitability). Shap granite was selected for its durability, availability and cost (Naylor et al., 2017b) despite being a less ecologically favourable rock (Coombes et al., 2011).

Mitigation requirements under the UK transposition of the EU habitats and bird directives (Council of the European Union, 1979; EC, 1992) required there to be no adverse effects of the construction on the integrity of the site and its importance as a feeding ground for waterbirds (-Naylor et al., 2017b). In response to this requirement, recommendations were made to optimise the selection and positioning of the granite rock armour to optimise its ecological suitability and reduce existing habitat loss from the construction. This resulted in the development of a passive enhancement strategy to minimise future habitat loss resulting from coastal squeeze under sea-level rise scenarios (Jackson and McIlvenny, 2011). This paper is the first known multi-scale (mm – dm^2) assessment of ecological suitability of rock armour materials.

Field measurements for the experiments were taken two years after installation at both sites in June and September 2017.

Experiment 1 allowed assessment of how two scales of rock properties: a) rock material properties including mm-scale roughness (hereafter called *partial enhancement*) and b) larger, meso-scale (cm-dm's) geomorphic features that had been passively positioned during construction (hereafter, *enhanced*), influenced early stage ecological colonisation. Shap granite was selected at Hartlepool due to its coarse-grained properties that created both fine-scale (μm-cm) and meso-scale (cm-dm's) roughness and its light colour (to increase albedo and reduce desiccation risk, MacArthur, 2019); mm-scale surface roughness is expected to improve barnacle recruitment compared to smoother materials (e.g. Coombes et al., 2015). We then evaluated which cm-dm^{-2} habitat features at Hartlepool are most important for early phase ecology, and thus the optimum physical scale(s) of passive enhancement. **Experiment 2** at Skinningrove compared the ecological performance of a darker, smoother Norwegian granite rock armour (Larvikite) with fewer cm-dm^2 (geomorphic features) to that of the similarly aged Shap granite rock armour (Fig. 2).

Experiment 3 examined whether the quarrying techniques to produce the rock armour boulders provides (cm scale depth) habitat features of ecological value. The quarried blast features are similar in scale to existing retrofitted active ecological enhancements and so were expected to provide favourable ecological results (Hall et al., 2018). Habitat features (Table 2) were identified and each habitat recorded on selected boulders was surveyed for experiments 1 and 2. Species richness and abundance were compared for each experiment.

2.2. Baseline monitoring

The upper intertidal zone of the Magnesian Limestone shore platform fronting the rock armour at Hartlepool was sampled in September 2016 using five 25 × 25 cm quadrats, randomly placed at each of 5 baseline plots ($n = 25$ total), with at least 50 cm between quadrats in each plot. Further details of baseline sampling can be found in Naylor et al. (2017b). In addition, data from the MarClim project (Marine Biological Association, 2019) from a 2008 survey of Hartlepool Headland were used to identify the range of species present prior to construction disturbance. No baseline was conducted at Skinningrove as the sandy beach on which the rock armour sits has no rocky intertidal species present. The nearest baseline data for Skinningrove comes from MarClim survey data at Staithes Cowbar, ~ 8 km from Skinningrove, in 2014.

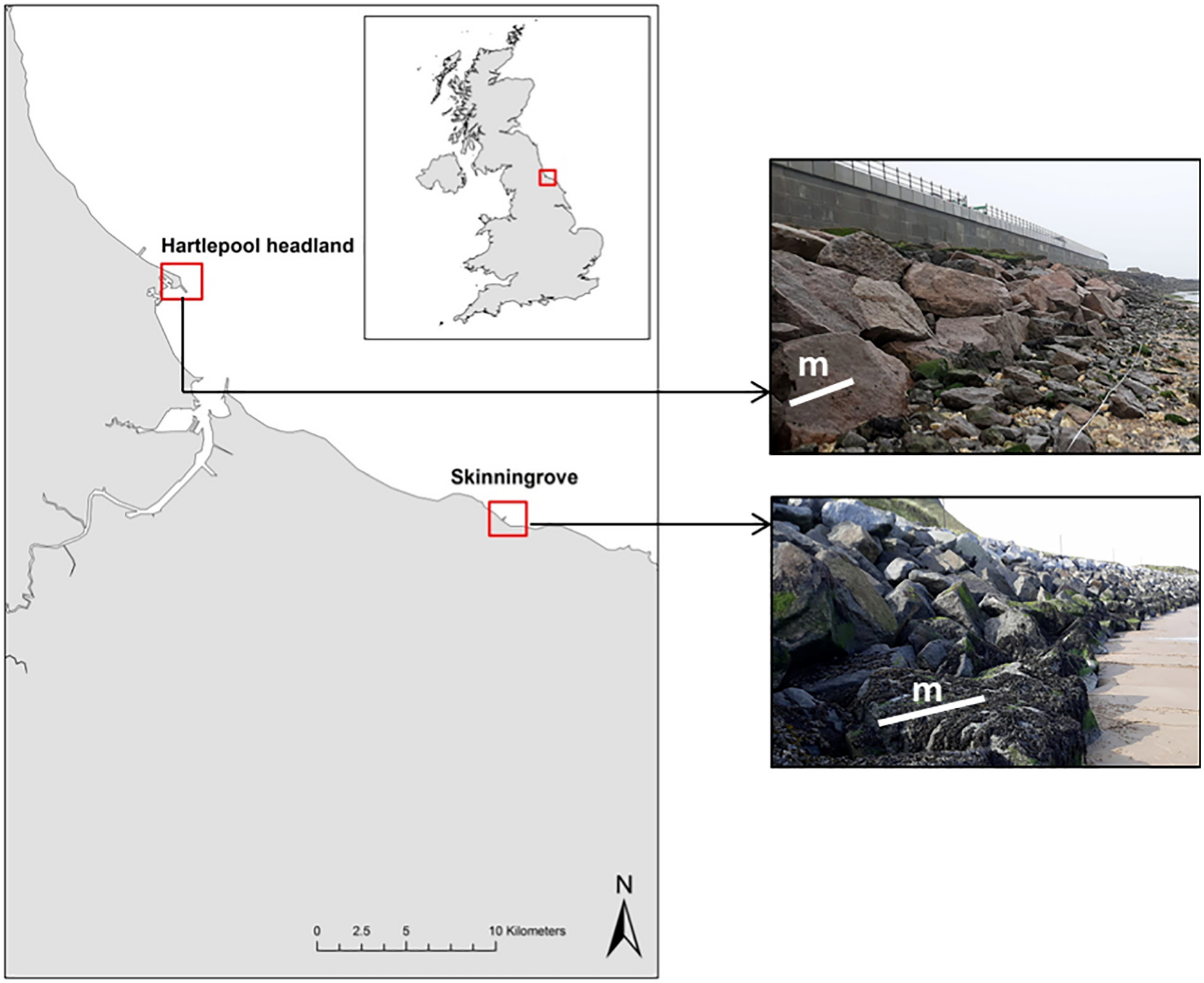


Fig. 2. At Hartlepool, Shap Granite boulders (235 cm ± 10.22 S.E, $n = 31$ boulders) were subject to both partial and enhanced passive enhancement. At Skinningrove, Norwegian granite (144 cm ± 12.75 SE, $n = 10$) had no passive enhancement. Approximate 1 m rulers for scale.

2.3. Field sampling methods

2.3.1. Boulder sampling

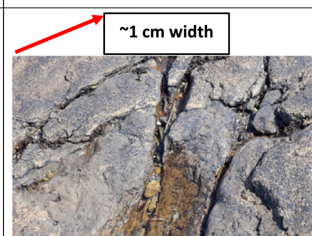
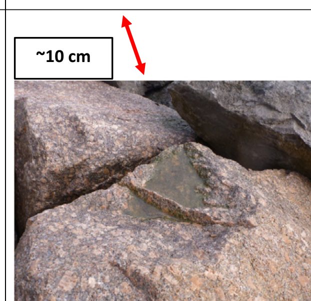
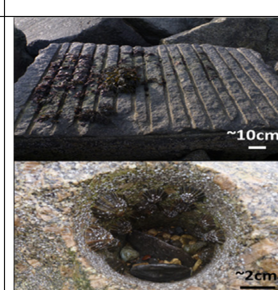
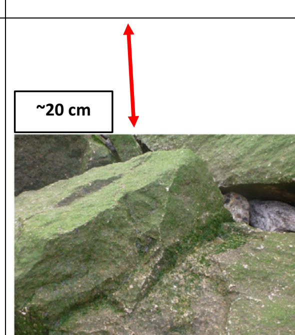
The width of most Hartlepool boulders exceeded two metres (Fig. 1) and this size effectively precluded quadrat sampling to identify species present and habitat complexity. A new field sampling method was developed to span physical scales (cm through dm's) and aimed at measuring links between habitat complexity (i.e. geomorphic features) and ecology – and thus geology, geomorphology and biodiversity interactions (Table 2). This involved stratified random sampling (after Le Hir and Hily, 2005; Sousa, 1979) of 60 m long horizontal, shore-parallel transects laid out along the lowest row of the rock armour (only row safe enough to sample). Sample numbers varied as construction activity, safe access to boulders and tidally restricted site access conditions at Hartlepool limited the number of boulder samples that could be undertaken during field visits (Table 1). The closest partially enhanced/enhanced boulders to each point were then sampled, with a spacing of at least 1.5 m apart (Griffin et al., 2010; Londoño-Cruz and Tokeshi, 2007) (Table 1).

The entire top surface of each boulder was sampled with species recorded as counts of individuals for mobile species and percentage cover estimated to the nearest 5% for sessile species, with surface area varying by boulder. The effect of surface area was not controlled for; however, the number of each geomorphic feature type was noted per boulder sampled, and all statistical tests compare species characteristics to geomorphic features. The presence and location of mobile species was also recorded on boulder surfaces and on/in specific features (Table 2) in order to better establish the link between species and habitat complexity. The count of each feature type (crack, crevice, pool, ledge, other) was recorded, with the feature types used outlined in Table 2. Overhangs and cryptic habitats known to be of high ecological value (Sherrard et al., 2016) were impossible to sample due to health and safety considerations (i.e. too dangerous given boulder size and height of revetment).

Table 1
Sampling details and enhancement types (N) studied at Hartlepool and Skinningrove for each experiment.

Boulders sampled over 60 m transects	
Experiment 1 sample numbers	N = 10 enhanced, $N = 10$ partially enhanced (total $n = 20$) at Hartlepool
Experiment 2 sample numbers	N = 15 enhanced, $N = 15$ partially enhanced (n = 30 Hartlepool), N = 30 non-enhanced Skinningrove
Experiment 3 sample numbers	$N = 6$ and $N = 18$ blastline and blasthole adorned boulders at Hartlepool and Skinningrove, respectively. An equal amount of unadorned “rocks to the left” were sampled

Table 2
Geomorphic feature types ("microhabitats" in ecology) from smallest to largest and their definitions. Scale definitions and further details can be found in MacArthur (2019); photographs by the authors. Boulders used in the photos are from year 0 (<1 year of colonisation), apart from the quarry features which are year 2.

Geomorphic Feature	Definition on boulders	Scale	Photo with approximate scale provided
Surface	The uppermost layer of the boulder.	mm – cm^{-1}	
Crack	A split in the surface of the boulder.	Width between 1 and 2.5 cm and a depth greater than the width. Photo shows cracks on natural rocky shore.	
Pool	Much smaller in scale than those typically found on rocky shores, pools on the boulders were characterised by depressions where water gathered.	<2.5 cm of water gathered. Few of these pools gathered >1.5 cm of water.	
Blast features: Blastlines (top) or Blastholes (bottom)	Quarried features on the rock. Clearly manmade.	Approximately 1–2.5 cm in depth and 1-3 cm in width (blastlines and 5-10 cm width blastholes). Similar scale to retrofitted active ecological enhancements (Hall et al., 2018).	
Ledge	A vertical or near-vertical face that is angled close to perpendicular to the boulder surface.	Varied in height but were typically between 10 and 80 cm.	

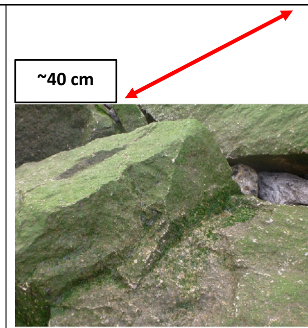
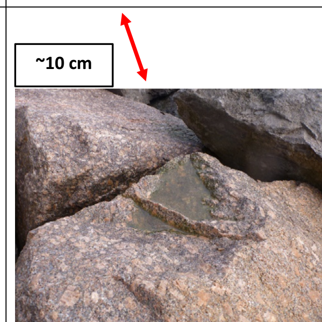
Ledge Adjacent	The area immediately next to the bottom of a ledge.	The immediate surface next to a ledge, so typically followed ledge width and cm-scale.	
Pool Adjacent	The area immediately next to the edge of a pool.	The immediate surface next to a pool, so typically followed pool width and cm-scale.	

Table 1 outlines the Hartlepool sampling strategy where the Shap granite boulders had two scales of enhancement: a) partially enhanced boulders had a base level of enhancement via material choice (i.e. coarse-grained properties for roughness and lighter colour for higher albedo) were randomly deployed without consideration of the presence or orientation of surface features (<20% of surface covered with geomorphic features) and b) enhanced boulders specifically positioned to orient meso-scale geomorphic features upwards (>20% of their surface covered by geomorphic features (Table 2)). Percentage enhancement was estimated visually for the total top surface of individual boulders to categorise boulders into enhanced and partially enhanced.

2.3.2. Experiment 1: passive enhancement for habitat features on rock armour

This experiment aimed to establish whether differences in species abundance and richness occurred between partially enhanced and enhanced granite boulders at Hartlepool. This experiment allowed identification of the optimal approach (i.e. partial or enhanced) and scales (mm – dm^2) of passive enhancement of rock armour.

2.3.3. Experiment 2: ecological comparison of rock type

This experiment aimed to determine whether Hartlepool Shap Granite or Skinningrove Norwegian Granite was more ecologically suitable.

2.3.4. Experiment 3: habitat value of quarried rock features

This experiment aimed to establish whether quarried features in the boulders provide ecological habitat within 2 years of installation. Due to the low abundance and scattered occurrence of these features, sampling was undertaken by walking along the lowest level of the rock armour revetment to sample all boulders displaying these features on the top surface, as well as the nearest unadorned boulder to the left (to function as a control). This resulted in $n = 6$ and $n = 18$ blastline and blasthole adorned boulders at Hartlepool and Skinningrove, respectively, together with an equal number of unadorned control boulders.

2.4. Statistical analyses

The distribution of species richness and abundance data was strongly skewed even after attempts at transformation, so statistical testing for each experiment was conducted using non-parametric Kruskal-Wallis tests and Dunn's test pairwise comparisons, with Bonferroni adjusted *p*-values for multiple comparisons. Analyses were carried out in *R version 3.5.1* (R Development Core Team, 2018).

Multiple Kruskal-Wallis and subsequent post-hoc tests were conducted on species richness and mobile and sessile species abundance per experiment by site. If results showed significance, then the effects of enhancement and geomorphic feature types were discerned for individual sites. The distribution of key prey species (*Patella vulgata*) for internationally important waterbirds was a requirement of the Hartlepool scheme (Naylor et al., 2017b); limpets found on boulder surfaces and features were recorded to inform choice of optimal geomorphic feature types for future *passive* ecological enhancements.

3. Results

3.1. Baseline monitoring of species

A MarClim survey conducted across the shore platform in 2008 at Hartlepool (can be requested from the Marine Biological Association, 2019) recorded a total of 13 species. Of these species, algae contributed the most to species richness (7 species), followed by gastropods (3 species) as listed in Table 3. These results were similar to nearby rocky shores sites at Seaham (11 species, ~23 km) and Roker (10 species, ~32 km). The nearest MarClim site to Skinningrove is shown to be more species rich where a total of 17 species were recorded across the intertidal zone (Staithes, ~8 km).

Field surveys conducted in the mid-upper intertidal zone at Hartlepool in September 2016 (before the platform was covered by the rock armour) recorded 18 species across the shore platform, with an average of 10 species per quadrat (MacArthur, 2019). Abundance results mirrored the earlier MarClim 2008 survey with *Patella vulgata* recorded in high densities on the sampled shore platforms (average of 33.23/m^2). Several species absent in 2008 were recorded in 2016 including *Littorina saxatilis* ($n = 5.76$/m^2) and *Anurida maritima* ($n = 12$/ m^2) (Table 3).

3.2. Passive enhancement using rock mass properties as habitat features on rock armour: experiment 1 (June 2017)

At Hartlepool, natural mid-upper intertidal zone shore platform species richness from $n = 16$ quadrats found an average of 6.75 species (±

Table 3
MarClim survey results based on SACFOR ranking (Burrows et al., 2008) (S=Super Abundance, A = Abundant, C=Common, F=Frequent, O=Occasional, R = Rare) at Hartlepool (2008) with additional species recorded in 2016 mid-upper intertidal zone baseline surveys.

Species	Hartlepool MarClim 2008	Hartlepool Baseline 2016
Laminaria digitata	O	
Fucus spiralis	A	
Fucus vesiculosus	S	C
Fucus serratus	A	
Mastocarpus stellatus	F	
Chondrus crispus	F	R
Palmaria palmate	C	
Actinia equine	A	R
Semibalanus balanoides	A	O
Mytilus edulis	R	R
Patella vulgata	S	C
Littorina littorea	F	R
Nucella lapillus	O	
Ulva sp.		C
Littorina obtusata		O
Littorina saxatilis		O
Melarhaphe neritoides		R
Polydora ciliata		R
Talitrus saltator		R
Rhodothamniella floridula		O
Lithothamnion sp.		R
Verrucaria sp.		O
Anurida maritime		R
Osmundea pinnatifida		R

0.48 SE) per quadrat compared to 3.5 species (±0.52 SE) on enhanced boulders and 4 species (±0.37 SE) on partially enhanced boulders. Six taxa were recorded across the entire transect, with species consistent across both enhancement types apart from one *Littorina littorea* recorded on one enhanced boulder.

Species richness was not significantly influenced by enhancement type ($H[1] = 0.695$, $p=0.405$), likely due to the low average numbers of species found at Hartlepool, particularly on the rock armour compared to baseline values. Apart from the lone L. *littorea*, *Patella vulgata* was the only mobile species present in this experiment, 2 years after installation. Limpets dominated the community at Hartlepool (similar to the natural rocky shore), with enhanced boulders having significantly greater abundance of limpets compared to partially enhanced boulders ($H[1] = 8.483$, $p<0.01$). An average of $n = 81.5$ (±16.43 SE) limpets were observed on enhanced boulders compared to 27.2 on partially enhanced boulders (± 8.47 SE). Importantly, two years after installation limpet abundance on enhanced boulders was comparable to the natural baseline.

Fig. 3a shows the average numbers of habitat features recorded on enhanced and partially enhanced boulders. Enhanced boulders had a greater number of ledges (Table 2), the most common feature recorded on the rock revetment and covered the greatest surface area of both enhanced and partially enhanced boulders (Fig. 3b). The higher number of ledges observed on boulder surfaces is the product of the boulders available, their rock mass properties and their subsequent positioning.

Fig. 3c illustrates the influence of all geomorphic feature types on limpet abundance with abundance higher on enhanced boulder surfaces than on partially enhanced boulders, although this result is not statistically significant ($H[1] = 2.405$, $p=0.121$). When comparing individual feature types between partially enhanced and enhanced boulders, only ledges have a statistically significant influence on limpet abundance ($H[1] = 11.929$, $p<0.001$).

Sessile species, *Fucus vesiculosus, Porphyra umbilicalis, Ulva intestinalis* and *Semibalanus balanoides* were observed at Hartlepool. As expected, barnacle abundance did not differ between enhancement types ($H[1] = 0.052$, $p=0.819$) - the mm-scale partial enhancement of the Shap Granite was present across both types of enhancement: partial and enhanced.

3.3. Experiment 2 (September 2017): comparison of rock-biotic responses across scales (mm – decimetre) between lithologies

Species richness was significantly greater at Skinningrove than Hartlepool ($z = 4.672$, $p<0.001$), with an average of 5.40 (±0.27 SE) species compared to 3.33 (±0.24 SE) at Hartlepool (Fig. 4). This is expected as the MarClim site nearest Skinningrove had a much higher species richness than at Hartlepool. Of the eleven species detected on boulders at Skinningrove, four were mobile species. At Skinningrove, limpets were the most abundant species, with *Littorina littorea* ($n = 1$), *Talitrus saltator* ($n = 30$ across several boulders) and *Ligia oceanica* ($n = 1$) also observed. At Hartlepool, a total of six species were recorded, two were mobile with a single recording of *Nucella lapillus* on a partially enhanced boulder.

Mobile abundance counts at both sites focused solely on limpets as other mobile species were rare and sparsely distributed. Limpet abundance was significantly greater at Hartlepool than Skinningrove ($H[1] = 23.482$, $p<0.001$) (Fig. 4). Hartlepool is a limpet dominated site (e.g. MarClim data in Table 3), with significantly greater numbers of limpets on habitat features ($H[1] = 10.863$, $p<0.001$) and on the surface of boulders ($H[1] = 19.851$, $p<0.001$) than Skinningrove. Experiment 2 found that ledge and ledge adjacent habitat on enhanced boulders made a significant difference on limpet abundance when comparing with partially enhanced boulders at Hartlepool ($H[1] = 9.130$, $p<0.01$ and $H[1] = 6.139$, $p<0.05$ respectively). It is likely that this ledge adjacent habitat provides a more sheltered environment than the surface of the boulder, offering higher humidity as seen in other microhabitats (MacArthur et al., 2019). There were notably less ledges at Skinningrove than Hartlepool (e.g. 8% and 20% average ledge cover on boulder surfaces, respectively), as each boulder had an average of 0.77 ledges compared to 1.73 at Hartlepool ($n = 30$ boulders per site).

At Hartlepool, enhancement did not affect species richness ($H[1] = 1.260$, $p=0.262$), possibly due to the low average species richness of the boulders (3.07 ± 0.33 SE for enhanced and 3.60 ± 0.34 SE for partially enhanced).

Significantly more barnacles were observed at Hartlepool than Skinningrove ($H[1] = 39.110$, $p<0.001$) (Fig. 4). At the mm scale no statistically significant differences in surface roughness were found between the two rock materials (MacArthur, 2019), which has previously been shown to influence settlement rates (Coombes et al., 2015).

3.4. Enhancing habitat value of rock armour using quarried rock features: experiment 3

Sampling was hampered by the paucity of quarried features at Hartlepool and no significant difference was found between the presence of blast holes on boulders and species richness compared to the baseline results from adjacent boulders. However, at Skinningrove enhanced boulders with blast lines had significantly greater species richness than the sampled adjacent boulders with no blast features ($H[1] = 5.503$, $p<0.05$). At Skinningrove, limpets were more abundant on boulders enhanced by quarried features than adjacent boulders ($H[1] = 12.376$, $p<0.001$), yet the presence of limpets within these features was not significant ($H[1] = 1.055$, $p=0.304$). At Hartlepool, the sporadic and rare occurrence of blast features made little difference to limpet abundance.

4. Discussion

The key interactions between geomorphic feature type and species response from the three experiments, along with key recommendations for future research are summarised in Table 4.

The results summarised in Table 4 show that selection of boulders with a large variation in surface texture (i.e. geomorphic feature types) from the mm-dm^2 scale increases the physical complexity of

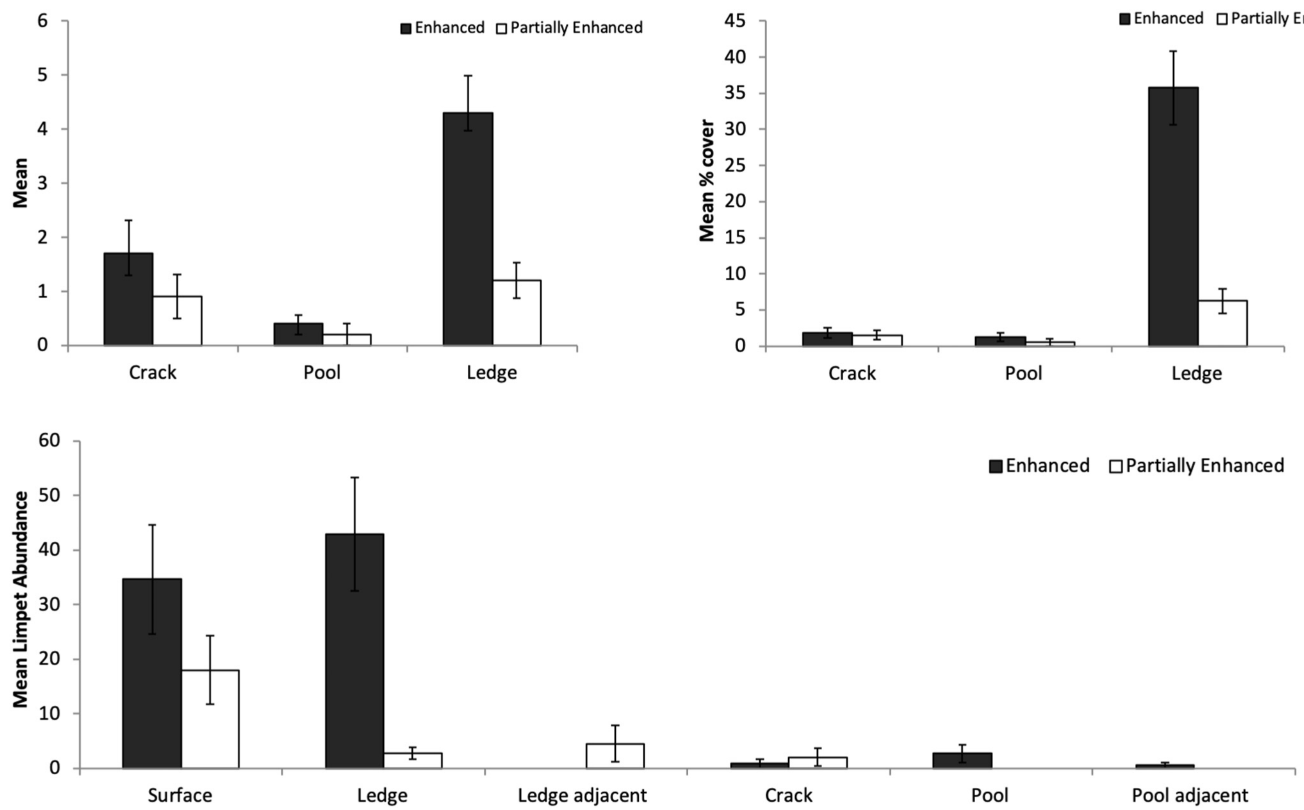


Fig. 3. Evaluating the presence of geomorphic features on boulders at Hartlepool and their influence on key prey species (*P. vulgata*) (a) Mean number of geomorphic features on enhanced and partially enhanced boulders, Hartlepool (b) Mean percentage cover of individual features on enhanced and partially enhanced boulders and (c) Mean limpet abundance per feature type (not accounting for the effects of surface area) on enhanced and partially enhanced boulders, Hartlepool ($\bar{x} \pm$ standard error).

rock armour structures and this assists colonisation. When combined with passive positioning to maximise presence of cm-dm-scale geomorphic features on boulder surfaces, both habitat and refuge provision and ecological suitability is increased. In this study, at the scale of rock armour units, the larger scale (dm-dm^2) surface features lead to statistically higher mobile species abundance. These features are particularly important for limpets at Hartlepool, an important food source for key bird species and a key criterion for mitigation requirements at the site (Naylor et al., 2017b). Ledge and ledge associated features on the Shap granite had significantly higher limpet abundances within 2 years of installation (these features were limited on the Norwegian granite). Limpets were found to congregate on ledges (and ledge adjacent habitat) compared to other geomorphic feature types, with these features statistically more frequent on the top surfaces of the passively positioned boulders. These results clearly demonstrate that our hypotheses; both that complexity at a range of spatial scales positively influences early colonisation and that careful positioning of features enhances the development of ecological communities within two years, can be accepted. Enhancing boulders passively was found to make a significant difference to mobile species abundance within 2 years.

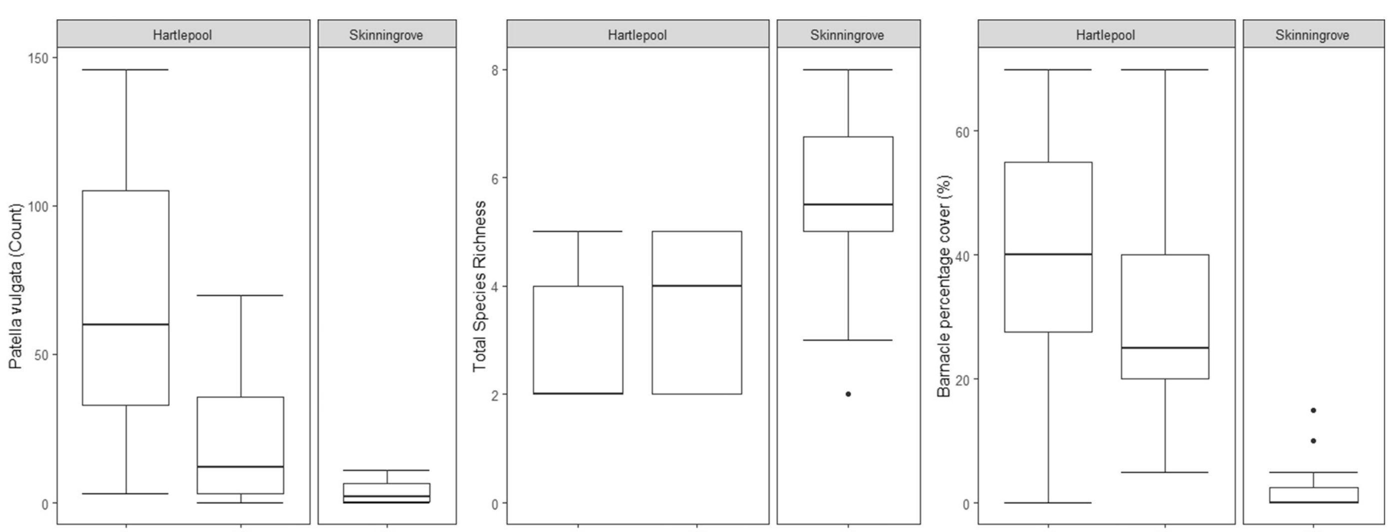


Fig. 4. Limpet abundance, total species richness and barnacle cover (%) on enhanced (E, $n = 15$) and partially enhanced (PE, n = 15) boulders at Hartlepool and non-enhanced boulders at Skinningrove (NE, n = 30).

Table 4
Key ecological results by geomorphic feature type and future recommendations.

Geomorphic feature	Key ecology result	Ecological material choice result	Further work needed
Surface	Barnacle abundance: statistically similar for enhanced and partially enhanced Shap Granite.	mm-cm roughness on light-coloured rocks aids barnacle colonisation (other factors such as larval supply being equal)	Comparisons of multiple rock types at the same site and measurement of other factors (e.g. larval supply): to allow optimal rock type for ecology to be identified.
Crack (Table 2 for scale)	No significance found.	Limited occurrence and importance, (MacArthur, 2019) limited ecological value on natural shores.	No further work required. Focus on larger cm - dm-scale features.
Pool	No significance found.	Small pool size (<1.5 cm depth) and shallow depth may have limited the ecological value for pool species.	Ensuring deeper depressions are positioned upwards or retrofitting pools onto rock armour to ensure greater depth and ecological value.
Pool adjacent habitat	No significance found.	Small pool size and shallow depth may have limited the potential for “humidity halos” around pools	Measure humidity buffering provided by different sized pools in future studies.
Blast features: Blastlines (top) or Blastholes (bottom)	Limpet abundance and species richness greater blast features occur. Adjacent boulders, with poor positioning did not offer the best habitat value.	Features were limited or positioned poorly so they did not retain water or provide shelter reduced ecological potential.	Better positioning or more deliberate modification of existing features e.g. sealing holes to trap water. Further testing of the benefits of these features.
Ledge	Enhanced ledges significantly increase limpet abundance.	Compared to partially enhanced boulders, ledges increased limpet abundance	Passively position to maximise larger, dm-scale ledges to increase surface area of habitat.
Ledge adjacent habitat	Experiment 2: ledge adjacent habitat on enhanced boulders increased limpet abundance compared to partially enhanced boulders.	Likely humidity gains (MacArthur et al., 2019). around edge of ledge as more sheltered microhabitat.	As above and also measure humidity buffering through the tidal cycle to evaluate benefits for reducing dessication (MacArthur et al., 2019)
Overall assessment	Species richness and sessile species abundance likely predominately controlled by wider environmental factors. Mobile species abundance is greatest on passively enhanced and positioned boulders with ledge features.		Further research is needed to test different rock types within one rock revetment.

The naturally porous, calcium-rich, light coloured limestone intertidal platform at Hartlepool was more species rich than enhanced and partially enhanced granite boulders, in agreement with previous findings (Naylor et al., 2017b). The low species richness on both the enhanced and partially enhanced Shap granite compared to the 2016 baseline is likely a result of a lack of suitable geomorphic features such as deep pools but may also likely related to granite mineralogy (e.g. MacArthur, 2019; Coombes et al., 2011) restricting the opportunities for boring species known to improve ecological suitability in calcium-rich rocks like limestone (Coombes et al., 2011; Naylor et al., 2012; Pinn et al., 2008). For example, two species in the 2016 baseline are found predominately on limestone/calcium-rich rocks (*Polydora ciliata, Lithothamnion* sp.) as they chemically bore into the rock to make their homes, which is impossible on granite substrata. The limited porosity and lack of water retaining features thus makes the Shap granite less ecologically suitable than the Magnesian limestone platform - however, as discussed in Naylor et al. (2017b), granite was used in the coastal engineering project on cost and engineering durability grounds. By incorporating more surface features that provide greater water holding capacity and shelter, and selecting the most ecologically suitable granite in the range suitable for engineering requirements (Naylor et al., 2017b), the ecological suitability of coastal engineering structures can be improved.

At both Hartlepool and Skinningrove, species richness remained lower than nearby shore platform baselines after 2 years. We interpret this to be due to a relative lack of water-holding features at both sites and the hardness of the granite compared to more calcium-rich rocks. The pools present on some boulders at Hartlepool were often <1.5 cm deep and did not achieve the levels of species richness associated with natural rock pools (Evans et al., 2016; Jackson, 2014). It follows that retrofitting pools to coastal defence structures such as boulders or concrete surfaces should increase species richness to approach the levels found in natural pools. In addition, more ecologically suitable rocks (MacArthur, 2019) should be chosen where engineering requirements allow.

Blastholes and blastlines are a good example of a quarrying process by-product that can create cm-scale ecological enhancements that can enhance habitat potential since quarried features are comparable in shape and scale to crevices on natural rocky shores and mimiced by active enhancement trial features (Firth et al., 2014b; Hall et al., 2018) and (MacArthur, 2019). However, Hartlepool (Table 2) had few boulders with blastholes and most boulders at Skinningrove had blastlines features that were badly positioned and, in some cases, too shallow (approx. 1.5 cm deep) to substantially influence species recruitment. The Skinningrove quarried features were too high in the tidal frame for effective intertidal organism colonisation or angled too steeply so that water was shed, rather than be retained, so these features made little difference to species richness and abundance.

Although not statistically significant, we suggest that the blasthole and blastline data at Skinningrove provides further evidence highlighting the importance of scale and orientation of surface features when designing and constructing coastal engineering structures with ecology in mind. For example, had the positioning of the blast features been optimised at Skinningrove using passive enhancement construction methods, it is probable that the results would have approached those of previous studies showing holes and grooves *actively* retrofitted on rock armour to substantially influence species diversity and abundance (Evans et al., 2016; Firth et al., 2014b; Hall et al., 2018). Furthermore, more deliberate modification of existing features, such as sealing quarried blastholes to trap water and the planned positioning of rocks with existing blastlines, has the potential to increase the recruitment of specific species and increase species richness. Further testing is required to quantify this potential as part of new build or repairs to coastal engineering schemes. This is especially important as rock armour material typically has lower embodied carbon (per $kgCO_2/t$) than concrete rock armour units (Broekens et al., 2011). Therefore, passive enhancement using locally sourced rocks with blasting artefacts may be a cost and carbon efficient means of improving habitat provision on rock armour.

The higher abundance of barnacles at Hartlepool than Skinningrove cannot be attributed to statistical differences in roughness between the two granites, as mm-scale roughness did not vary between the two rock types (MacArthur, 2019). This differs from earlier research showing that the presence of mm-scale roughness improves barnacle colonisation compared to smoother surfaces (Coombes et al., 2015; MacArthur et al., 2019; Raimondi, 1988). Recruiting early colonising species, such as barnacles, is crucial to the development of more complex intertidal communities (Coombes et al., 2015). Albedo (surface reflectivity affected by colour) varies with rock type (Coombes et al., 2011; MacArthur, 2019) and low albedo substrates are known to reduce thermal and desiccation stress of species (Kordas et al., 2014). Observed differences in early colonising species may be a result of albedo (which was statistically different between the two rock types (MacArthur, 2019)), cm-scale roughness which was visually rougher for Shap granite, availability of nearby suitable habitat (i.e. local geomorphology, Herbert and Hawkins, 2006) and biogeographic conditions and/or larval supply (Menge et al., 2010). For example, the influence of local geomorphology and larval supply are likely reasons here, because Hartlepool is fronted by a limestone shore platform that provides an adjacent larval source compared to Skinningrove fronted by a sandy beach.

Our results show that the abundance of early stage colonisers is affected by geomorphic complexity across a range of scales (mm – dm^2). The passive selection of rock materials with a high frequency of geomorphic features across the mm-dm^2 scale, together with ecologically informed positioning of boulders, produces tangible ecological benefits. This passive enhancement technique satisfies the aims of the original scheme at Hartlepool: baseline numbers of limpets have been rapidly achieved within two years, three years sooner than when mitigation monitoring was required. In terms of maximising species richness and biodiversity value of rock armour, quarrying artefacts (e.g. blastlines and blastholes) appear to function similarly to both geologically controlled geomorphic feature types such as ledges, as well as *active* enhancements such as retrofitted grooves on rock armour (Hall et al., 2018). Further enhancement could be achieved by retrofitting features with greater water holding capacity (e.g. Evans et al., 2016) or by sealing the base of blastholes to mimic the biological boring found within natural rock pools.

To identify the contribution of rock type and boulder enhancements to engineered structures, we have developed a scoring matrix called EcoRock, the details, methods and experimental set of which is found in MacArthur (2019). EcoRock outputs for both Shap and Norwegian granite, and other common engineering rock types, are reproduced in Table 5 with the addition of cm-dm scale of geomorphic features. This highlights that cm-dm^2 scale geomorphic features should be considered in combination with rock material properties (Coombes et al., 2011; Coombes and Naylor, 2012; MacArthur, 2019) to determine the true value of boulders for ecological suitability. Careful selection of rock materials based on a combination of rock material and rock mass properties increases the ecological suitability of the resultant boulder (Table 5). Additional parameters, such as aspect (the directional positioning of the boulders), may further influence rock material selection. For example, on south and west facing shores with larger tidal ranges (e.g. south-facing Welsh and English coasts) and warmer micro-climates than the north-eastern aspects studied here, albedo and rock surface temperature may have a greater influence on material choice than other properties. Further field testing is required to test the EcoRock scoring matrix with an engineering-scale *passive* enhancement trial of rocks of different types (and range of geomorphic feature types) placed in the same rock revetment and deliberately positioned for ecological benefit in a range of environmental settings (e.g. aspect, tidal range), to better inform coastal engineering practice.

The EcoRock scoring matrix extends existing design catalogues for eco-engineering (e.g. Naylor et al., 2017a; O'Shaughnessy et al., 2020) by assisting researchers and practitioners in selecting the most ecologically suitable rock materials during the design, tendering and construction phases of coastal, lake or river engineering projects.

5. Conclusion

- This study shows that optimal passive enhancement with significant ecological benefits can be achieved by selecting boulders with high numbers of large scale natural or quarried features (dm scale) and positioning to optimise for ecology. Ecologically informed rock selection and application is thus recommended where natural and nature-based solutions are not feasible, and where rock armour is the preferred option for coastal engineering schemes.
- A multi-scale combination of selecting ecologically suitable material properties (e.g. albedo, mm-scale texture) and positioning of rock mass features (cm-dms scale) is thus an effective and inexpensive method to ecologically enhance coastal engineering structures.
- The EcoRock scoring matrix helps identify the most ecologically suitable rock materials to be used for maritime engineering projects. As the design life of thesee structures is typically 80–100 years, and the ocean continues to warm, this matric can aid engineers in selecting rock materials best suited to help ecology in a warming world.
- Locally sourced light-coloured and calcium-rich bioerodable lithologies (such as limestone), whose surfaces are characterised by natural or engineered cm-dm^2 features that maximise surface roughness across multiple scales, will favour early colonisation rates and

Table 5
Scoring table for ecological (mm scale) and engineering suitability (Low (L) = 1, Moderate (M) = 2, High (H) = 3) for rock material properties from lab experiments on unweathered rock samples. SG = Shap granite, NG = Norwegian granite, CG = Cornish granite, CL (H) = Carboniferous limestone (Hartlepool), CL (W) = Carboniferous limestone (Welsh), ML = Magnesian limestone, BL = Blue Lias limestone, PL = Portland limestone. Lab experiment details found in MacArthur (2019). For Hardness scoring is reversed (1 = High, 2 = Moderate and 3 = Low) as for these factors low hardness is more ecologically suitable (greater biogeomorphic potential). Portland limestone and Cornish granite from Coombes and Naylor (2012) and Coombes (2011). Ecological suitability score is the sum of all variables. Blank space indicates data not collected (Developed from MacArthur, 2019).

Rock material	Igneous			Sedimentary				
	SG	NG	CG	CL (H)	CL (W)	ML	BL	PL
Calcium Content	L	L	L	H	H	H	H	H
Hardness	H	H	H	L	M	L	L	L
Density	M	M	M	M	M	M	M	M
Albedo	M	L	M	M	M	M	L	M
Porosity	L	L	L	L	L	H	L	H
WAC	L	L	L	L	L	H	L	H
Surface roughness (25 mm^2 scale)	H	H	H	M	H	L	M	H
Long-term biogeomorphological potential	L	L	L	M	M	H	M	H
[Lab tests- sum of above variables] Ecological suitability (mm-cm scale)	12	11	12	16	16	20	15	22
Ledge habitat (Field tests)	H	M		M		H		
Pool habitat (Field tests)	L	L		L		H		
Blast features (Field tests)	L	H		L		L		
Ecological suitability with cm-dm's scale features [Lab + Field]	17	17		21		27		
Engineering suitability	H	H	H	H	H	L	L	M
Combined Ecological and Engineering suitability	M	M		M		L		

promote the long-term ecological suitability of rock armour via biogeomorphic ecosystem engineering.

CRediT authorship contribution statement

Mairi MacArthur: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing - original draft, Writing - review & editing, Visualization.**Larissa A. Naylor:**Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.**Jim D. Hansom:** Conceptualization, Methodology, Writing - review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition.**Michael T. Burrows:**Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Search strings and associated list of references used in introductory literature review.

Search strings
("ecological enhancement*" OR "ecological engineering") AND ("coastal defence*" OR "rock armour" OR "rock revetment") AND ("microhabitat*" OR "rock pool*" OR "roughness" OR "texture*" OR "groove*" OR "pit*" OR "water holding*" OR "material" OR "substrate*")

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