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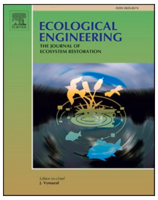

The BioGeo Ecotile: Improving biodiversity on coastal defences using a multiscale, multispecies eco-engineering design

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ABSTRACT

Hard coastal defences support lower biodiversity than natural rocky shores. Ecological enhancement on coastal structures can improve biodiversity by increasing habitat heterogeneity. Most studies have investigated the effect of only one type of texture on intertidal biodiversity. There is a lack of eco-engineering designs that mimic the complexity of natural rocky shores and are scalable for real world applications and commercial manufacturing. To address these gaps, we developed a novel, multiscale (mm-cm), multispecies design called BioGeo Ecotile that is scalable and readily manufacturable. The hybrid design combines previously tested eco-engineering features (pits, holes, grooves and crevices), providing habitats for a range of intertidal organisms. To test the success of the design, Ecotiles and smooth tiles were deployed on rock armour and flood walls along Edinburgh's coast, Scotland. Post-deployment, data on species presence and abundance were collected at the start and end of the second settlement season. Textured Ecotiles supported higher species richness ($F_{3,55} = 21.18$, $p < 0.001$) and colonisation than smooth tiles and adjacent rock armour. Ecotiles supported more mobile species, some of which (crabs) were not recorded on the other treatments. Material type (concrete vs rock) significantly affected community composition, where concrete was dominated by fucoids and rock by barnacles. In this temperate setting, the Ecotiles have enhanced biodiversity of rock armour achieving practical conservation goals. This is the first known retrofit of tiles onto rock armour in the UK. The tiles can be scaled up to whole walls or rock armour units. We demonstrate that a science-design approach can achieve ecological and engineering goals simultaneously, which can accelerate widespread implementation of eco-engineering in large-scale projects.

1. Introduction

Human activity, including coastal urbanisation (McGranahan et al., 2007) and land reclamation (Hansom et al., 2001) have resulted in a proliferation of hard coastal structures (Hansom et al., 2017; O'Shaughnessy et al., 2020). Ocean sprawl has led to degradation of coastal, estuarine and marine (hereafter coastal) habitats and associated ecosystem services (Barbier et al., 2011; Bishop et al., 2017; Firth et al., 2016; Heery et al., 2017). Current and future climate change impacts will further exacerbate the effects (IPCC, 2021). For example, sea level rise can cause coastal squeeze in rocky shores (Jackson and Mcilvenny, 2011) which often leads to further development of hard coastal defences.

Seawalls and rock armour lack the structural complexity of natural rocky shores (Lawrence et al., 2021; O'Shaughnessy et al., 2020), resulting in reduced habitat heterogeneity and biodiversity of intertidal organisms (Airoldi and Beck, 2007; Bulleri and Chapman, 2010a; Moschella et al., 2005). Ecological enhancement of coastal defences can lessen these impacts (Naylor et al., 2012). Also called *greening the grey* or *eco-engineering* (Bergen et al., 2001; Naylor et al., 2017a), this approach incorporates or retrofits green habitat elements on hard grey infrastructure to improve ecological value. This is applied where more nature-based solutions are not socially, economically or technically feasible (Firth et al., 2020; MacArthur et al., 2019).

Previous studies (Strain et al., 2018; O'Shaughnessy et al., 2020; (Evans et al., 2021b)) show that adding structural complexity using texture, such as pits, holes, grooves, supports higher species richness, abundance and diversity. Most eco-engineering studies investigating the

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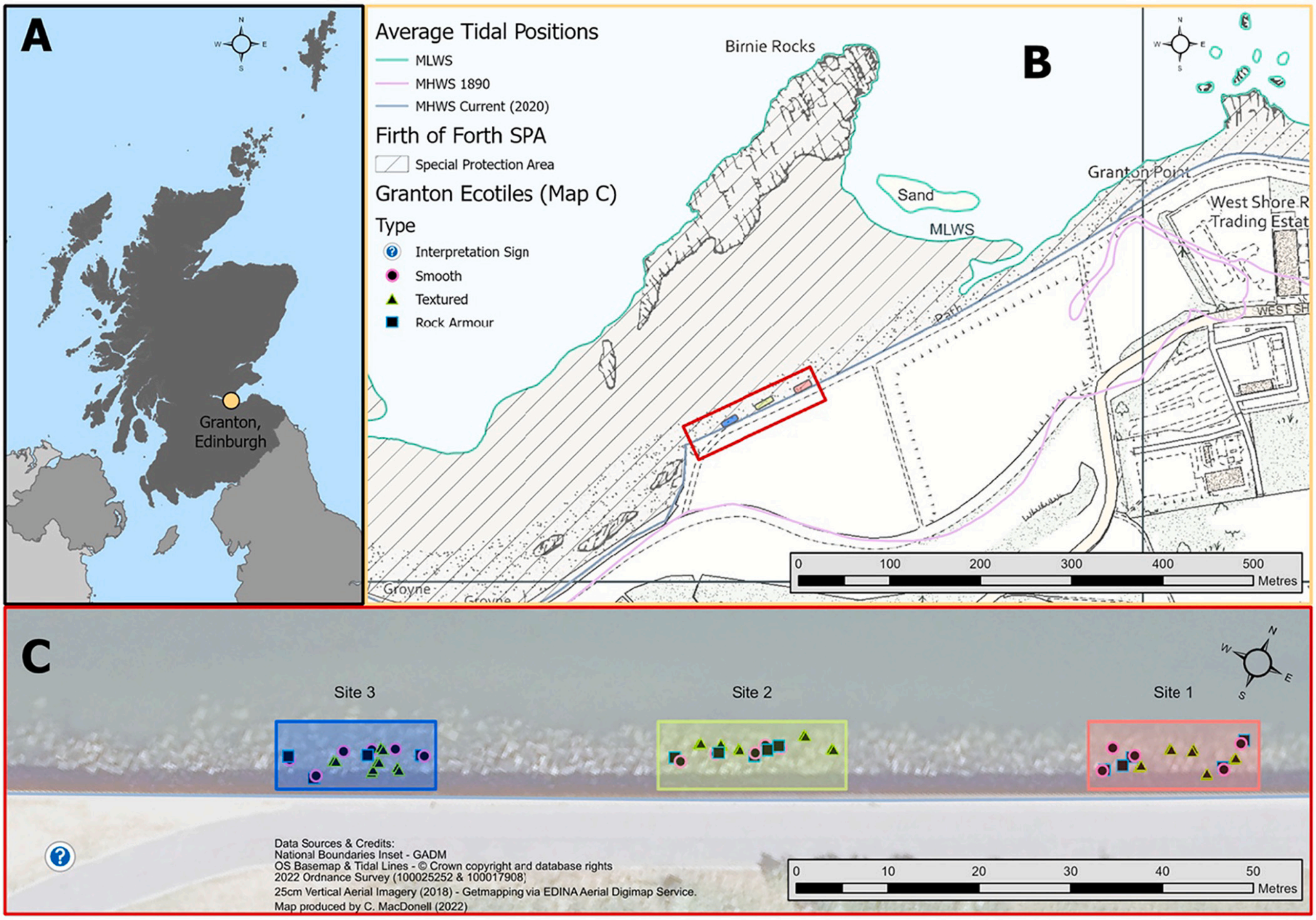

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25cm Vertical Aerial Imagery (2018) - Getmapping via EDINA Aerial Digimap Service.
Map produced by C. MacDonell (2022)

Fig. 1. Map showing (A) Granton, Edinburgh, Scotland; (B) Ecotile deployment sites at Gypsy Brae in Granton, the current and historic tidal positions in the Firth of Forth Special Protection Area; (C) site 1 (red), 2 (yellow) and 3 (blue)and position of Ecotiles, smooth tiles and rock armour sampled. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ecological effects of texture have analysed a limited number of texture scales per treatment (e.g. mm-scale, Coombes et al., 2015; and cm-scale Loke and Todd, 2016; Strain et al., 2018). Exceptions are the tiles directly replicating natural rocky shores (mm – cm scale topographic complexity), pioneered by MacArthur (2019) and extended by (Evans et al., 2021a). Recent work by MacArthur et al. (2019) and Lawrence et al. (2021) identify a key eco-engineering research gap and recommend design and testing of multiscale designs (i.e., mm – cm scales) combining a range of textures to provide the greatest ecological and bioprotection benefits. For example, MacArthur et al. (2019) showed the importance of incorporating both mm-scale and cm-scale habitat features to optimise biodiversity and bioprotection outcomes in temperate climates (Coombes et al., 2015; MacArthur et al., 2019). Adding texture using ecoformliners also provides habitats with moisture (MacArthur et al., 2019), shade and protection from biotic and abiotic stressors at all tide levels, successfully mimicking natural rocky shores (Chapman and Blockley, 2009; Strain et al., 2018).

Despite the recent advances in eco-engineering, there is limited research targeting specific species. Notable exceptions include work on barnacles as habitat-forming and bioprotective species (e.g. Coombes et al., 2015; MacArthur et al., 2019) and prey species for salmon (Sawyer et al., 2020) and birds (Naylor et al., 2017b). Other key habitat-forming and ecosystem engineering species have thus far attracted limited attention, for instance, macroalgae *Fucus* spp. (Rinne and Salovius-Laurén, 2020) that act as bioprotective agents of artificial structures (Bone et al., 2022; Coombes et al., 2013; Gowell et al., 2015). *Fucus* spp. show reduced fecundity on artificial structures compared to natural shore (Drakard et al., 2021). However to date, no designs appear to have considered the specific requirements, such as small (< 5 mm) pits or grooves to encourage establishment and reduce grazing risks of early-stage seaweed species. Designing for habitat-forming species as a part of multiscale, multispecies designs could optimise ecological outcomes.

Other factors influencing intertidal biodiversity on coastal defence structures include material type (Coombes et al., 2011), aspect, exposure, slope (Chapman and Blockley, 2009), disturbance (Airoldi and Bulleri, 2011) and elapsed time from deployment (Evans et al., 2016). For example, UK based eco-engineering studies testing enhancements on different rock types showed variations in species richness between material types (Coombes et al., 2013; Hall et al., 2018; Moschella et al., 2005). However, the influence of material type varies geographically. In temperate regions, appropriate material type can enhance ecological conditions, such as improving water holding capacity. This can apply over short (months post-deployment) and long (> 100 years, i.e. biodiversity over the engineering design life of structures) timescales ((Coombes et al., 2011; Naylor et al., 2012). In sub-tropical and tropical regions, short-term (2–8 months) trials sugggest material type has limited ecological impact (Cacabelos et al., 2016; Hartanto et al., 2022). Further testing of these effects on ecological colonisation are required.

Here, we present a novel multispecies eco-engineering design to address several of these gaps. The BioGeo Ecotile combines successful components of previously tested surface textures (see Fig. 1 and Table 1). The hybrid design incorporates multiple scales (mm – cm; thus multiscale) to support a variety of intertidal species (thus multispecies),

Table 1

Summary of feature types on the Ecotiles (as seen in Fig. 1), their size, intended function, target species and academic papers which found the features to be successful.

Feature in Fig. 1	Feature type	Size	Conservation Evidence category (Evans et al., 2021b)*	Function	Supporting academic papers	Target species	Target species present in feature in our data
A	Barnacles	mm-scale texture on cm-scale barnacle features	This fine scale habitat feature was not included in the directory	Eco-engineering: Barnacles preferentially settle in mm-scale grooves. Ecological studies: Barnacles provide habitat for fucoids.	Coombes et al., 2015; MacArthur et al., 2019; Van Tamelen and Stekoll, 1997	Barnacles Littorinid snails Fucoids	Yes Yes Yes
B	Barnacle biomimicry	mm-scale	Biomimicry was not included in the directory.	Use of empty shells as refuge and creating cm scale roughness to increase habitat complexity	(Barnes, 2000) Cartwright and Williams, 2012; Coombes et al., 2015	Barnacles Littorinid snails	Yes Yes
C	Fine Grooves	width and depth:0.5–1.5 mm	Grooves (1–50 mm depth)	mm-scale roughness	Coombes et al., 2015; MacArthur et al., 2019	Barnacles Macroalgae	Yes Yes
D	Coarse Grooves	width: 2–8 mm; depth: 1–4 mm	Grooves (1–50 mm depth)	cm-scale roughness	Hall et al., 2018	Fucoids	Yes
E	Holes	diameter: 7.5–13.5 mm	Pits (<50 mm depth)	Habitat for smaller mobile and sessile invertebrates	Firth et al., 2014; Hall et al., 2018; Moschella et al., 2005; MacArthur et al., 2019	Periwinkles Mussels	Yes No
F	Pockets	width: 31–61 mm; depth: 18–30 mm	Pits (<50 mm depth)	Habitat for larger mobile invertebrates	MacArthur et al., 2019	Periwinkles Mussels Crabs	Yes Yes Yes
G	Crevice	width: 15–26 mm; length: 250 mm; depth: 17–38 mm	Crevices (>50 mm depth)	Habitat for larger mobile invertebrates, mimicking ledges	Firth et al., 2014; MacArthur et al., 2020	Limpets Crabs	Yes Yes

* Only depths were reported in this Conservation Evidence Directory (Evans et al., 2021b), rather than all dimensions. As our crevice was a long feature (250 mm) we opted to call it a crevice as it is a more spatially persistent landform feature.

as suggested by MacArthur et al. (2019). The Ecotile is based on eco-engineering studies either using test tiles (Evans et al., 2021a; Loke and Todd, 2016; MacArthur et al., 2019), direct replication of natural rocky shore geomorphology (MacArthur et al., 2019), or manipulating boulders to add and optimise features (Hall et al., 2019; MacArthur et al., 2020; Naylor et al., 2017b). The BioGeo Ecotile designs replicate natural shore geomorphology (holes, crevices, grooves, pockets) and include biomimicry of sessile organisms (barnacles) living on rocky shores (MacArthur et al., 2019; Metcalfe, 2015). Based on the results of Coombes et al. (2015), this included biomimicry of ecological processes (i.e. dead barnacle casts) to facilitate barnacle and seaweed establishment and provide sheltered habitat for littorinids.

Uniquely in the field of eco-engineering, the Ecotile also had three human-focused design objectives: (a) To be scaled up using design principles such as tessellation (Metcalfe, 2015) to enable upscaling of repeatable patterns from two designs (textured Ecotile A and Ecotile B) to whole wall or rock armour units (Naylor et al., 2022a). (b) To be readily manufactured by co-developing the design with concrete technologists and pre-cast manufacturers to optimise buildability. Poundfield Products provided textured pre-cast products to an engineering scheme at Hartlepool (Naylor et al., 2017b). And (c) to convey the functional goal of the Ecotiles by bringing biogeomorphological features through design and interpretation (e.g. biomimicry, designed by Metcalfe, 2015 and tested by MacArthur et al., 2019; Naylor et al., 2022a) and so increase people-nature interactions in cities (Soga and Gaston, 2020).

The ecological aims of this study were to evaluate the success of the novel multiscale (mm – cm), multispecies Ecotile design compared to smooth tile and rock armour, for a practical conservation project. This was done by analysing the effects of factors (tile type as a proxy for texture and material, slope, aspect and site) on species colonisation, richness and community composition. The following hypotheses were tested:

(1) The added structural complexity of Ecotiles results in different community structure with higher species richness and colonisation by target intertidal species compared to the smooth tiles and rock armour.
(2) The material type (concrete vs rock) affects species richness, colonisation and community structure, when controlling for texture.
(3) The Ecotile designs enhance intertidal biodiversity; the Ecotiles with texture support target species and ecological functioning.

Assessing the ecological success of the Ecotile design provides underpinning evidence for future scaling up of the readily manufactured design to whole walls to both maximise the biodiversity benefit and convey enhanced function via biogeodesign.

2. Materials and methods

2.1. Site description

Tiles were deployed on northwest facing coastal protection structures owned by the City of Edinburgh at Gypsy Brae recreation ground in Granton, Edinburgh (55°58′51.3”N 3°15′34.9”W; Fig. 1), UK. The rock armour was a hard-wearing dolerite, a dark-coloured, igneous, mafic (high in iron and magnesium) rock of low porosity and typically low surface roughness. The site macrotidal with a tidal range > 6 m (Fitton et al., 2021). It is located within the Firth of Forth Special Protection Area (SPA), an area with habitats of special importance for protection of vulnerable bird species (Woodward et al., 2015). Natural rocky shore was historically reclaimed from the sea making this an ideal site to apply ecological enhancement to provide habitat and improve biodiversity.

2.2. Ecotile design

The Ecotiles were designed based on the results of previous scientific research in the UK (Coombes et al., 2015; Hall et al., 2018; MacArthur, 2019; MacArthur et al., 2019) and the results of baseline surveys conducted in September 2019 in the mid-upper intertidal zone on rock armour and seawall (see Fig. 1B for positioning of tiles relative to tidal range). This allowed the Ecotile design to include natural shore

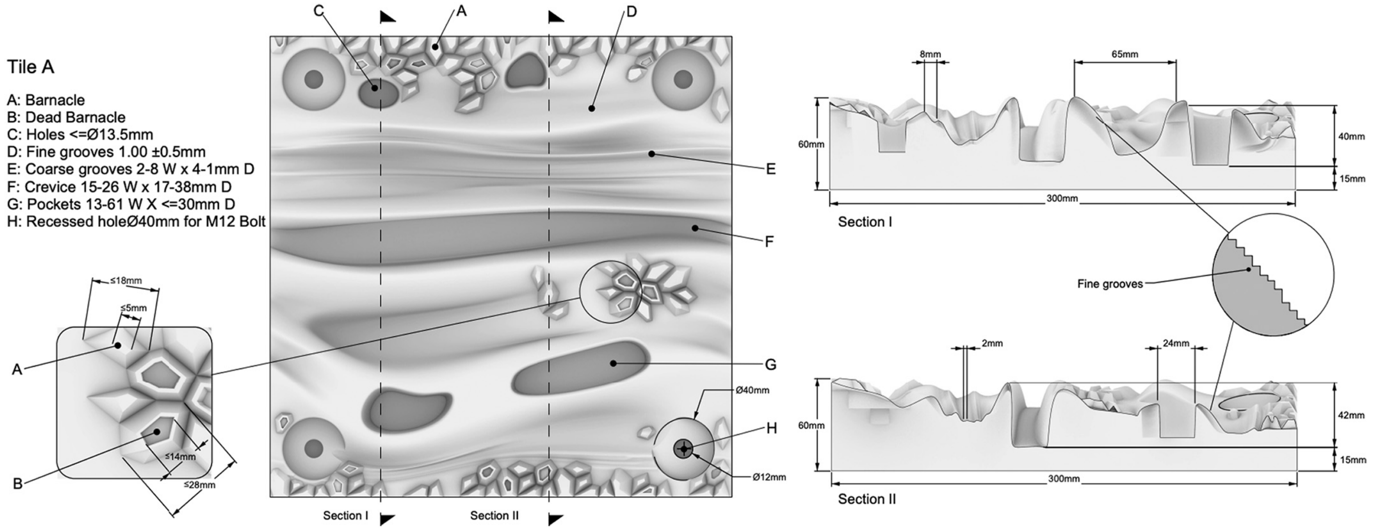

Fig. 2. Multispecies design of Ecotile type A combining natural geomorphological features (holes, grooves, crevices, and pockets) with barnacle biomimicry features described in Table 1. The design was based on previous scientific findings and a baseline survey to maximise biodiversity. Credit: Meshcanics Design.

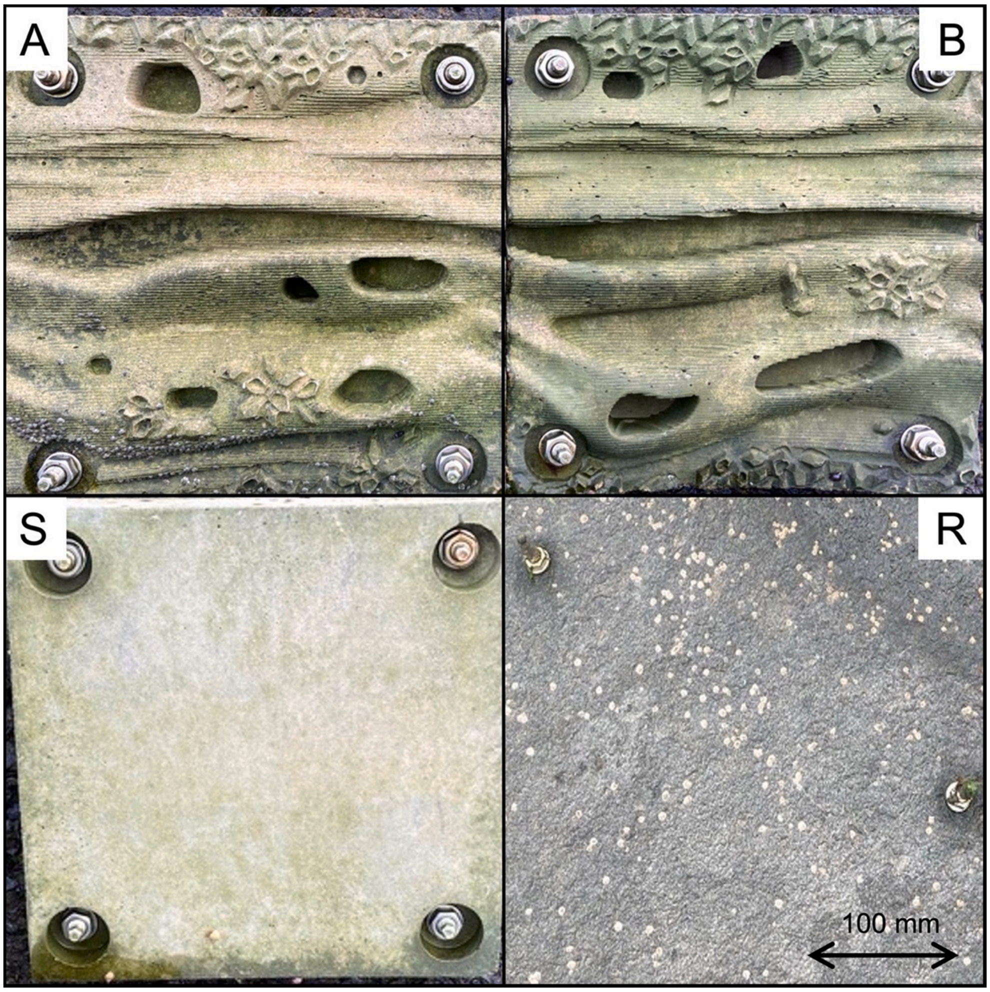

Fig. 3. Tile types: (A) concrete Ecotile A; (B) concrete Ecotile B, and how they can tesselate; (S) concrete smooth tile; (R) rock armour sampling area marked by bolts.

geomorphological habitats, e.g. holes, crevices, grooves, pockets, barnacle mimicry, to increase the species richness, abundance, diversity of key target species (i.e. barnacles, fucoids, invertebrates; Fig. 2). Table 1 summarises the feature types that were incorporated into the design of the Ecotiles. The Ecotiles were designed to be at the maximum safe manual handling weight for ease of retrofitting onto existing structures made from standard marine concrete (300x300x60 mm). The surface area of the tiles, minus the bolt holes, was as follows: Tile A 155,123.70

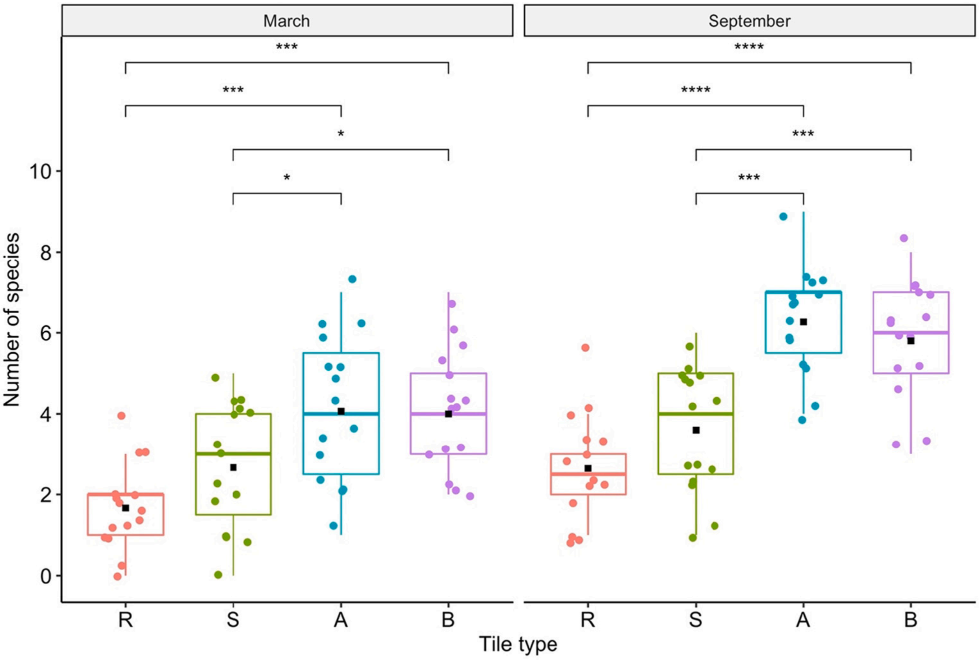

Fig. 4. Species richness on the rock (R), smooth tile (S), Ecotiles (A) and (B) in March and September. Black squares show the mean number of species for each tile. Significant differences between tiles are indicated by stars (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$).

(± 0.04) mm^2, Tile B 157,313.97 (± 0.04) mm^2 and smooth tile 84,973.45 (± 0.01) mm^2. As tile type correlates with surface area, only tile type was used as a factor in data analysis.

2.3. *Experimental design*

The textured Ecotiles A and B, concrete smooth tiles (S) and adjacent rock (R) were compared to test for the effect of texture and material (Fig. 3). In spring 2020, 45 square tiles (300 × 300 × 60 mm) were deployed on rock armour with 15 tiles at each of three adjacent sites spaced ~50 m apart (Fig. 2). Five replicates of each type (textured A, textured B, smooth S) were deployed at each site, individually or in pairs with at least 1 rock armour unit or 2–5 m between tiles. Five rock controls (R) of the same 300 × 300 mm area were marked on adjacent rock at each site (Green and Crowe, 2013). All tiles and rock controls were placed in the same shore position (upper intertidal zone). Tile heights were measured with Leica differential GPS and ranged from 0.5 m to 2.0 m above mean sea level (MSL), with mean and median values being ~equal at 1.34 and 1.39 m, respectively. The average daily inundation across the tile deployment shore heights ranged from a minimum of 5.4 to a maximum 12.7 h/day. Mean and median inundation were both 9 h/day, as measured over 93 tidal cycles using an *Insitu* Water Level Logger from 25th August – 11th October 2022, including the Autumn equinox capturing the maximum annual tidal range in this dataset). The aspect of tiles on rock armour varied between 1 and 350° with a range of slope (10–80°). The tiles were installed on the seawall behind the rock armour. However, due to the high position in the intertidal zone (near mean high water spring), the tiles were only colonised by algal films and will not be discussed further in this paper.

The Ecotiles at site 1 were deployed in March 2020 and, due to fieldwork restrictions during a COVID lockdown, the tiles at site 2 and 3 were deployed in May 2020. This created an opportunity to test the difference in colonisation between different times of deployment, which had not been tested before (Naylor et al., 2022a, 2022b).

2.4. *Data collection*

Ecotiles were monitored for the presence/absence of intertidal species to assess early colonisation. Data were collected in March 2021 (12 months post-deployment for Site 1, and 9 months post-deployment for sites 2 & 3), and in September 2021 (18 and 15 months post-deployment for site 1 and sites 2 & 3, respectively). Organisms were identified to the lowest possible taxa based on non-invasive observation in the field. Abundance of species on the tiles was recorded as percentage cover (%) for sessile species and as counts for mobile species within a 25 cm quadrat on the 30 cm^2 tiles and rock, to avoid any edge effects (Bulleri, 2005). Data on physical characteristics of the tiles, including slope (degrees) and aspect (orientation to North), were collected.

2.5. *Statistical analyses*

Generalized linear mixed-effects models (GLMMs) with Poisson distribution were used to test the hypotheses that species richness was higher on the textured tiles than on the smooth tile and on the rock. Explanatory variables tested were: tile type (4 levels: R, S, A, B; as a proxy for texture and material), site (3 levels: site 1, 2 and 3), aspect and slope of the tiles (both continuous). The optimal model was chosen based on backwards/forwards stepwise model selection. The same analysis was applied to data from March and September. For analysing species richness, the optimal model was tested using Anova and compared using AIC (Hall et al., 2018; Zuur et al., 2009).

Data on species counts and percentage cover were translated into presence or absence of each species per tile. Logistic regressions (GLMMs with binomial distribution) were run for each species in both months of collection to test the effect of explanatory variables on colonisation by individual species. Model fit was evaluated using analysis of deviance (Anova in R package 'car') with Wald type III test (Fox and Weisberg, 2019). The results of the optimal logistic regression model were used to predict probabilities of presence of each species on the Ecotiles based on the significant factors.

Community composition was analysed for sessile and mobile species separately. Tiles with zero species present, and hence no community,

Table 2

List of species observed during the sampling in March and September on Ecotiles (A and B), concrete smooth tiles (S) and rock armour (R). x indicates presence of species. Blue shading indicates species whose presence was significantly affected by tile type, site, slope and aspect. Dark grey shading indicates the species was not found in given month. * indicates target species that were expected on Ecotiles A and B. Note that the species were not necessarily found on all tiles of the same type.

	SPECIES NAME	COMMON NAME	Presence of species on tiles in March				Presence of species on tiles in September			
			A	B	S	R	A	B	S	R
SESSILE	*Fucus vesiculosus**	Bladder wreck	x	x	x	x	x	x	x	x
	Austrominius modestus and *Semibalanus balanoides**	Barnacle species	x	x	x	x	x	x	x	x
	-	Green algal film	x	x	x	x	x	x	x	x
	-	Brown algal film	x	x	x			x	x	x
	Enteromorpha sp.	Turf green seaweeds	x	x	x	x	x			
	Ulva lactuca	Sea lettuce	x	x	x		■	■	■	■
	Porphyra sp.	Red algae	x	x	x	x	■	■	■	■
	Pomatoceros triqueter	Tubeworm	■	■	■	■	x	x		
	*Mytilus edulis**	Blue mussel	■	■	■	■		x		
MOBILE	*Patella vulgata**	Limpet				x	x	x	x	x
	*Littorina littorea**	Common periwinkle	x	x	x		x	x	x	x
	Littorina saxatilis	Rough periwinkle	x	x			x			x
	Anurida maritima	Seashore springtail	■	■	■	■	x	x	x	x
	Talitrus saltator	Sand hopper	■	■	■	■	x	x	x	x
	*Nucella lapillus**	Dog whelk	■	■	■	■	x			x
	*Carcinus maenas**	European green crab	■	■	■	■	x	x	x	
summary	*Presence of sessile species per tile type*		7	7	7	5	5	6	4	4
	Presence of mobile species per tile type		2	2	1	1	7	6	5	6
	Presence of all species per tile type		9	9	8	6	12	11	9	10

were not used in the community analysis. A non-metric multidimensional scaling (NMDS) ordination was applied using Bray-Curtis dissimilarities (Bulleri, 2005). The ordination was used to test the correlation (envfit) between species structure and environmental variables that determine the Ecotile dis/similarity based on the Ecotile community. Permutational multivariate analysis of variance (PERMANOVA) with 999 permutations was applied to test whether the studied factors explain the variation between communities on the tiles (Evans et al., 2019; Oksanen et al., 2022).

All statistical analyses were carried out using in R package for statistical computing version 4.1.1 (R Core Team, 2022). Specifically, package “lme4” (Bates et al., 2015) was used for the GLMM, “car” (Fox and Weisberg, 2019) for ANOVA, “ggpubr” (Kassambara, 2020) for graphical representation of significant comparisons, “vegan” (Oksanen et al., 2022) to implement NMDS, and “ggplot2” (Wickham, 2016) were used for all graphical representation of the results.

3. Results

3.1. Species richness

The number of observed species per tile ranged between 0 and 7 (mean = 3.1 ± 0.23 SE) in March and between 1 and 9 (mean = 4.6 ± 0.27 SE) in September. Tile type was the only significant factor affecting the number of species present (Fig. 4). The ANOVA test showed species richness differed significantly between tile types in March ($F_{3,56} = 8.61$, $p < 0.001$) and in September ($F_{3,55} = 21.18$, $p < 0.001$). In both months, the lowest numbers of species were on the rock and the highest on the Ecotiles A. Post-hoc ANOVA showed that there was a significant difference between tiles R-A, R-B, S-A, and S—B in both months ($p < 0.05$) (Fig. 4). There was no significant difference between tiles R-S and A-B ($p > 0.05$). Overall, species richness was higher in September than in March with a significant increase on the rock R ($p < 0.05$), tiles A ($p < 0.001$) and B ($p < 0.01$) but not a statistically significant difference on the smooth tiles S ($p > 0.05$).

Table 3

Overview of species that were significantly affected (anova $p < 0.05$) by one of the studied factors, and their probability of presence based on the tile type and other factors. Probability of presence based on tile type is shown in the order of high>low probability (tile types separated by comma have the same probability). Graphs on probability of presence can be found in the Supplementary Materials Fig. S4-S13.

Species	Mobile/ sessile	Month	Probability of presence		
			Tile type	Other factors	Figure in Supp. Materials
Fucus vesiculosus	S	March & September	A, B > S > R	–	S4
Brown algal film	S	March	A, S > B > R	–	S5
Enteromorpha sp.	S	March	B, S > A > R	–	S6
Barnacle species	S	March	R > B > A > S	Slope (steep > gentle)	S7
Barnacle species	S	September	R > B > A > S	Site (2 > 3 > 1)	S8
Pomatoceros triqueter	S	September	B > A > S, R	–	S9
Anurida maritima	M	September	A > B > S > R	–	S10
Nucella lapillus	M	September	A > R > S, B	–	S11
Patella vulgata	M	September	–	Slope (steep > gentle)	S12
Green algal film	S	September	A > B > S > R	–	S13

3.2. Colonisation by individual species

A total of 16 species were recorded throughout the study, with 10 recorded in March and 14 in September. Table 2 shows on which tile type the species were found and the target species for which the Ecotile was designed. In September after 15 and 18 months, all target species (barnacle species, fucoids, littorinid snails, dog whelks and mussels) were found on either or both Ecotiles A and B.

Logistic regression for each species showed that four species in March and seven species in September were significantly affected by either of the studied factors (tile type, site, aspect and slope; Table 3). Supplementary materials provide the predicted probability of presence for the species which showed a significant relationship in both sampling periods.

3.3. Mobile species using textured structure

In September ($n = 7$) more mobile species occurred than in March ($n = 3$). Mobile organisms were observed to utilise the geomorphic features of the textured Ecotiles and hide under the seaweed canopy on both the smooth and textured tiles. On the Ecotiles A and B, mobile species used the structures where water was retained (crevices, holes and pockets). Periwinkles (*Littorina littorea*), springtails (*Anurida maritima*) and tubeworms (*Pomatoceros triqueter*) were often found in the smaller holes and pockets (Fig. S1 (A)). Barnacle species were observed to colonise the grooves and biomimicry features designed for them (Fig. S1 (B)). A few crabs ($n = 8$) were found in September; all except one were on the textured tiles A and B, and none were observed on the surrounding rock armour. The crabs (*Carcinus maenas*) were hiding in the pockets and crevices (Fig. S2) that were designed for them as a shelter.

3.4. Evidence of ecological functioning

Interactions between species and natural ecological functioning were observed on the tiles. Some smooth tiles with high levels of green or brown algae showed limpet (*Patella vulgata*) teeth marks and (Fig. S3 (A)) grazing trails on the tiles even in cases of zero seaweed cover. Limpets were also often seen to congregate around the Ecotiles and were grazing on the seaweed overhanging from the tiles (Fig. S3 (B)). The limpet teeth marks were found only on the surface of smooth tiles and not on the surface of textured tiles (although limpet teeth marks were observed on the smooth sides of both tile types). The dense cover and number of fucoid seaweed holdfasts on the textured tiles likely limits access to graze the tile surface.

3.5. Community composition

The community analysis and non-metric multidimensional scaling (NMDS) ordination was conducted for sessile and mobile species separately in both March and September. In March, there were insufficient numbers of mobile species on the Ecotiles to undertake community composition analysis.

3.6. Sessile community

Non-metric multidimensional scaling (NMDS) showed that sessile community structure was significantly affected by tile type in March (envfit: $R^2 = 0.45$, $p < 0.001$; Fig. 5.A) and September ($R^2 = 0.45$, $p < 0.001$; Fig. 5.B). In March, the difference was driven mainly by barnacle species (1.36) and brown algae film (−0.73). PERMANOVA showed that tile type ($R^2 = 0.30$, $F_{3,56} = 8.68$, $p = 0.001$), slope ($R^2 = 0.06$, $F_{1,56} = 5.04$, $p = 0.001$) and site ($R2 = 0.05$, $F_{2,56} = 2.10$, $p = 0.048$) were statistically significant in determining the species composition on the tiles in March. In September, the difference between community structure on tile types was driven by barnacle species (1.02) and *Fucus vesiculosus* (−0.54). PERMANOVA of the September data showed that tile type was the only studied factor significantly affecting sessile species composition ($R^2 = 0.51$, $F_{3,56} = 19.81$, $p = 0.001$). The results show that tile type was an important determinant, as it explained 30% of variability in March and 51% in September. The NMDS ordinations (Fig. 5A, B) show clustering of concrete tiles (filled symbols) suggesting a difference in composition of communities on concrete tiles vs on the rocks.

3.7. Mobile community

NMDS analysis of mobile species in September showed that site significantly affected the community structure (envfit: $R^2 = 0.11$, $p < 0.05$; Fig. 6), which was driven by *Patella vulgata* (1.71) and *Talitrus saltator* (−0.77). There was a statistically significant difference between tile types ($R^2 = 0.12$, $F_{3,56} = 2.37$, $p < 0.01$) and sites ($R^2 = 0.06$, $F_{2,56} = 1.85$, $p < 0.05$) indicated by PERMANOVA. Tile type and site together explain 18% of variation between the communities on tiles.

4. Discussion

This study tested a novel design aimed at ecological enhancement and combining previously successful features for colonisation by intertidal species. The design was intended to be scaled up to larger units for use in coastal engineering and infrastructure projects. Overall, the Ecotiles showed higher species richness and presence of target species and enhanced community composition compared to smooth tiles and rock armour.

Hypothesis 1. *The added structural complexity of Ecotiles results in different community structure with higher species richness and colonisation by target intertidal species compared to the smooth tiles and rock armour.*

Species richness was significantly affected by tile type, with both

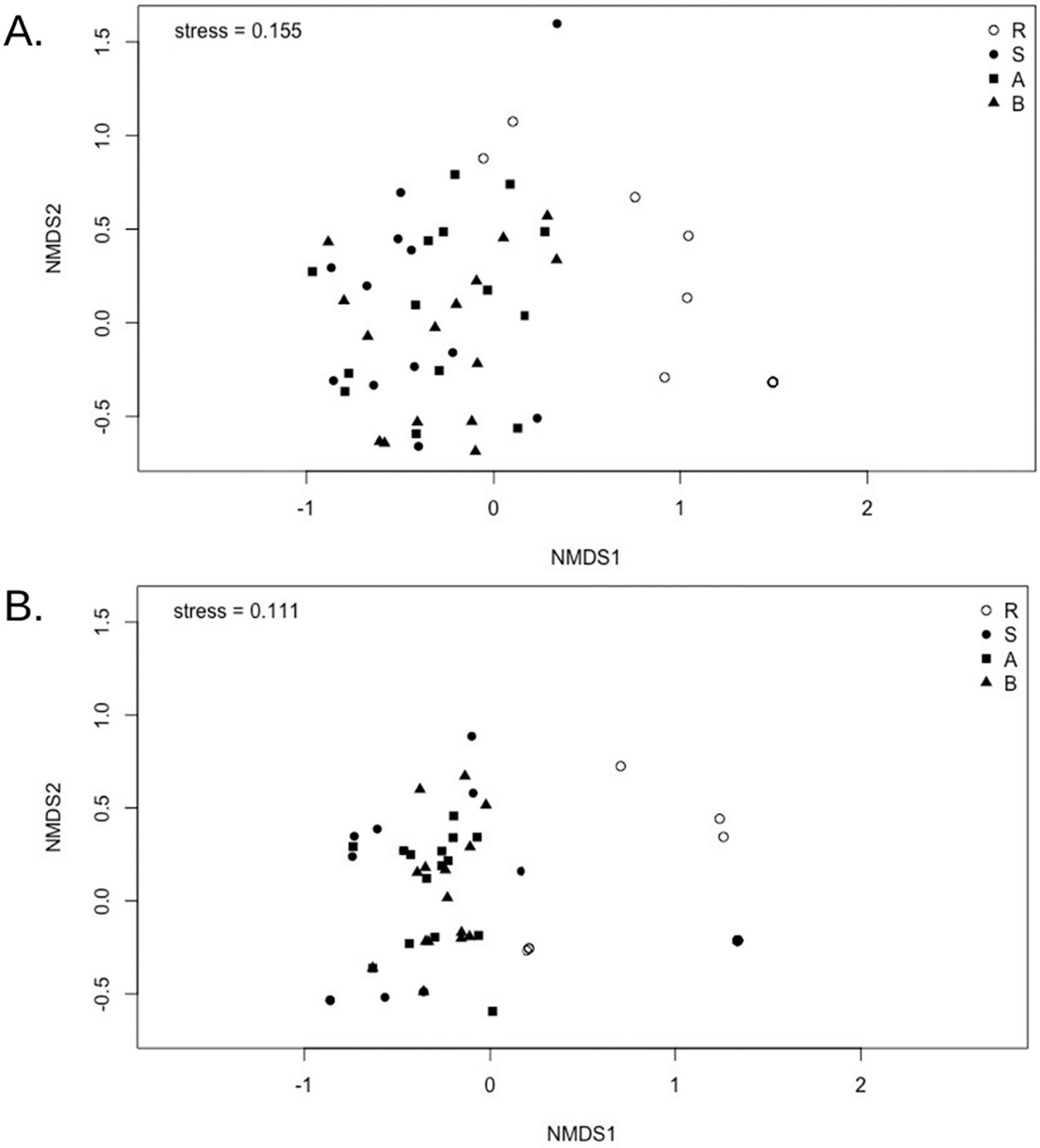

Fig. 5. NMDS ordinations of sessile species assemblages based on tile type A. after 9–12 months in March and B. after 15–18 months in September. Filled symbols represent concrete tiles, empty symbols indicate rock. (R) rock, (S) smooth tile, (A) textured Ecotile A, (B) textured Ecotile B.

textured Ecotiles A and B having the highest number of species recorded. The significant difference between the textured-smooth tiles and the textured tile-rock suggests that texture is an important factor in increasing species richness. This supports our multispecies design and supports MacArthur et al. (2019) who recommended future designs include cm- and mm-scale features to provide different microhabitats for a variety of species. Combination of the mm and cm-scale geomorphic features and barnacle biomimicry creates the high habitat heterogeneity missing on rock armour and seawalls (Moschella et al., 2005; Prendergast et al., 2010).

Tile type was also a significant factor affecting community composition, with a larger effect on sessile species than on mobile species, where site was also significant. The results show that in both March and September there was a significant difference in sessile communities between tile types of different materials. The NMDS suggests that sessile communities on the concrete tiles (A, B and S) showed a similar community structure dominated by seaweed and higher number of species than the rock. The community composition on the rock differed significantly, with dominance by barnacles and showed little or no seaweed unlike on the concrete tiles.

Unlike other eco-engineering studies, we investigated the colonisation success of individual species colonisation for all species found. For the species which showed significant effects by the studied factors (Table 3), tile type was the determinant factor for all, except for limpets. This exception is likely explained by generally low limpet abundance in the area during sampling. As hypothesised, some species (namely fucoids, green algal film, tubeworms, and springtails) were more likely to be present on the textured tiles than on the smooth tiles and the rock. This highlights the importance of improving habitat heterogeneity to support biodiversity, as found previously (Bulleri and Chapman, 2010b; Evans et al., 2021b; Firth et al., 2014).

Barnacles showed the highest colonisation on the rock, and then tiles A and B, and least colonisation on the smooth tiles (Table 3; Fig. S7, S8), lacking the mm-scale roughness barnacles prefer (Coombes et al., 2015; MacArthur et al., 2019). This pattern suggests that barnacle colonisation is determined mainly by texture, as was shown by Coombes et al. (2015). Although the rock armour did not show high structural complexity, the rock had mm-scale roughness an ideal texture for barnacle cyprid

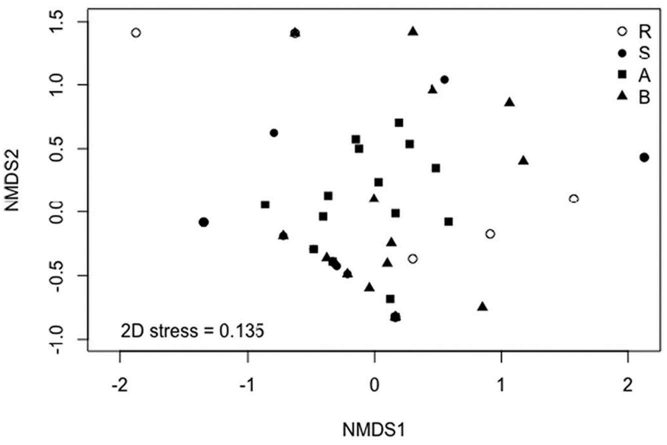

Fig. 6. NMDS ordination of mobile species after 15–18 months in September based on tile type. Filled symbols represent concrete tiles, empty symbols indicate rock. (R) rock, (S) smooth tile, (A) textured Ecotile A, (B) textured Ecotile B.

colonisation (Coombes et al., 2015). Similar to *Fucus vesiculosus,* barnacles are important habitat-forming ecosystem engineers (Smith et al., 2014). Barnacles create structure and biogenic habitats that support colonisation by other species, including *Fucus* species (Van Tamelen and Stekoll, 1997). Also observed in our study, the empty shells of barnacles provide refuge for gastropod species, such as *Littorina* sp. (Barnes, 2000; Cartwright and Williams, 2012). Apart from the ecological benefits, the bioprotective structure provided by barnacles is also beneficial from an engineering perspective (Coombes et al., 2017).

Hypothesis 2. *The material type (concrete* vs *rock) affects species richness, colonisation and community structure, when controlling for texture.*

Material type (rock vs concrete) did not affect species richness. The difference in species richness between the smooth concrete tiles and the rock was not significant. This concurs with other studies testing material types (Cacabelos et al., 2016; Hartanto et al., 2022), suggesting that other factors might be more significant or affect different ecological metrices such as abundance (Dennis et al., 2018).

The sessile community structure was significantly different between the fucoid-dominated concrete tiles and the barnacle-dominated rock, as expected. This suggests that material type was important in determining the community structure, which could be due to the difference in material properties like hardness, albedo, and roughness that are known to affect microhabitat conditions and thus ecological suitability (Coombes and Naylor, 2012; MacArthur et al., 2020). This study has shown that community composition varies between different rock and concrete materials placed in the same environmental setting. Similar findings were found by earlier research (Coombes et al., 2011, Jackson, 2015, Hall et al., 2018 and MacArthur et al., 2020 in the UK). However, contrasting results were found in a tropical setting in Singapore and Azores, Portugal by Hartanto et al. (2022). The difference could be because the majority of species in the tropical study were mobile whereas not as many mobile species were found in the temperate setting. Mobile species are less likely to be affected by the material type as they move around to find their preferred habitat.

In the temperate region of this study, we found that the species richness was not significantly different between the concrete tiles and rock but that different material types support different species. Therefore, use of more than one material type as part of operational engineering schemes may lead to better ecological outcomes than single material type. A good example of this long-term benefit of multiple material types in the Northeast Atlantic region exists at Plymouth Breakwater. There are large differences in community composition, habitat complexity and biogeomorphologically created features (rock pools) between Cornish Granite (barnacle dominated) and Portland limestone (with diverse rock pools and associated species assemblages) (Coombes et al., 2011; Jackson, 2015).

Fucus vesiculosus was the only species which was affected by tile type in both March and September. Fucoids showed similar probability of colonisation on Ecotiles A, B and smooth tiles and reduced colonisation on the rock. This suggests that texture was not as important for fucoids. However, material type is an important factor for fucoid colonisation as shown by the low fucoid colonisation of the rock compared to the concrete tiles.

Hypothesis 3. *The Ecotile designs enhance intertidal biodiversity; the Ecotiles with texture support target species and ecological functioning.*

The multiscale (mm-cm) multispecies design of the Ecotiles succeeded in enhancing intertidal biodiversity. Both Ecotiles A and B performed comparably to each other, and both showed higher colonisation and species richness than the smooth tiles and rock armour. The photographic evidence showed that target species colonised in features as expected based on previous trials in these environmental conditions (Bishop et al., 2022). For example, crabs were found in crevices and pockets, dog whelks and periwinkles in holes and pockets (Firth et al., 2014; Hall et al., 2018; MacArthur, 2019; MacArthur et al., 2020) and barnacles in fine grooves and on barnacle biomimicry sites (Coombes et al., 2015; MacArthur et al., 2019).

The observations of mobile organisms hiding in the features show that species whose body size matches the features respond best to the enhancements, as found by Strain et al. (2018). Therefore, it is important to include a range of sizes of features and texture in the eco-engineering design to accommodate for a higher diversity of organisms and a range of life stages. These microhabitats provide refuge from predators, competitors and environmental stressors, and hence are essential for survival of intertidal organisms (Chapman and Blockley, 2009). Most of the geomorphic features on the textured Ecotiles where the mobile organisms were recorded were seen to retain water, an added complexity that facilitates intertidal organisms to endure long periods of exposure during low tides (Hall et al., 2018; MacArthur et al., 2020).

The results show that the presence of Ecotiles can have wider ecosystem benefits and support ecological functioning. The Ecotiles increased overhanging seaweed growth, which had a knock-on benefit of aggregating limpets around the Ecotiles, which can be a defence mechanisms of limpets against predation (Coleman et al., 2004). The presence of limpets is key in the intertidal zone as they help regulate the lower trophic level by grazing on macroalgae, including fucoids. Hence they control algal populations, prevent overgrowth and allow competition space for other species (Jenkins et al., 1999; Raffaelli et al., 1996).

The intertidal mobile species found at the studied site (limpets, crabs, etc.; Table 2) are important for supporting higher trophic levels, particularly the birds located in the Firth of Forth SPA, an area with special importance for bird species (Naylor et al., 2017b; Woodward et al., 2015). For example, curlews and redshanks feed on crabs (Goss-Custard and Jones, 2009), oystercatchers feed on limpets and eiders mainly prey on blue mussels (Woodward et al., 2015). The increased presence of these intertidal species on the Ecotiles compared to the smooth tiles and rock armour, provides more food resource for the birds in the SPA.

5. Design objectives and scaling up

The Ecotiles tested in this experiment were double the size of those previously tested by MacArthur et al. (2019) and triple the size of those tested by Coombes et al. (2015) showing a progressive scaling to larger test tiles to the maximum size allowable for manual handling. Other research trials applying tiles to rock armour exist. Large numbers of tiles have been deployed in Singapore (Loke and Todd, 2016) and coral fragments have been added to 'seed' test tiles (Toh et al., 2017) – these could conceivably be scaled and applied in operational projects. In

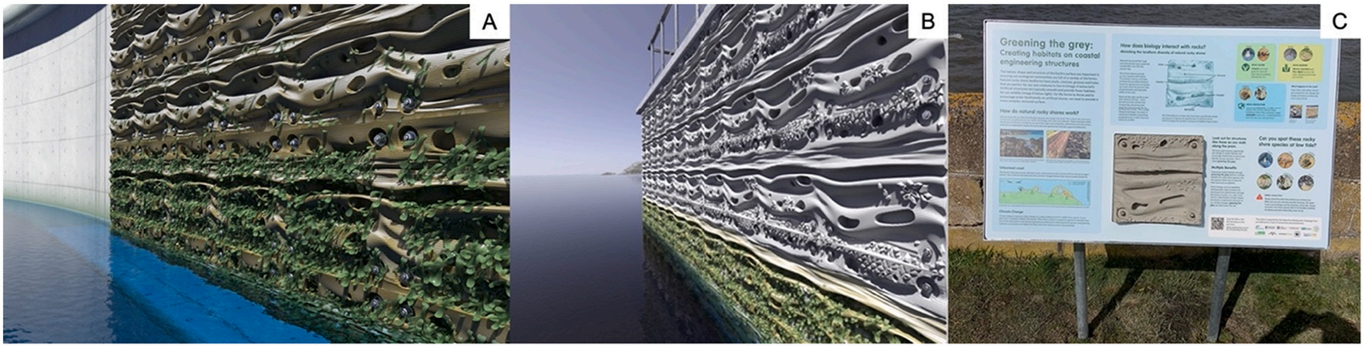

Fig. 7. A-B) Render diagram illustrating how the BioGeo Ecotile can be scaled to a full wall compared to the plain cast concrete wall beside it (Source: Meshcanics) and C) Public interpretation sign explaining the BioGeo Ecotile project (see Fig. 2 for location).

Sydney, the Living Seawalls project (https://www.livingseawalls.com.au) has combined academic science and industrial design to create tiles for retrofitting onto existing infrastructure; scientific tests of these designs are promising (Bishop et al., 2022) and thus could be applied operationally. Designs like these, and the one reported on in this paper, improve the evidence base for potential application of retrofits throughout the design life of coastal engineering assets (Suedel et al., 2021).

Uncommonly seen in eco-engineering studies to date, the Ecotile presented here was designed to be readily scaled up to whole wall or rock armour unit at the design concept stage (Fig. 7). This was similar to the pioneering Seattle seawalls project (Sawyer et al., 2020), which involved academics across science and design fields, along with multiple types of practitioners. Designing and testing the ecologically suitability of small-scale tiles, such as those presented here, thus represents a key evidence-gathering step to underpin the longer-term eco-engineering product design goals, such as ecoformliners for whole wall applications. Few eco-engineering products and studies have had these goals in mind at the outset (this paper, Sawyer et al., 2020). Using smaller test tiles can allow local ecological (and social) feasibility to be evaluated, prior to selecting an eco-engineering product to apply to an operational engineering scheme (e.g. a whole wall application). The design and testing approach used here is gaining momentum. For example, a team at Swansea University is currently undertaking an experiment using small tiles of commercially available (non-eco) formliners and two designed to look like oysters, to test which ones are best suited for use in a replacement seawall (https://www.swansea.ac.uk/bioscience/seacams-2/mumbles-sea-hive-project/).

Collaboration and iterative conceptual and practical discussions with the designer, commercial manufacturer, concrete technologist and commercial installers was pivotal to achieving our second design objective affordability, ease of manufacture and installation (Naylor et al., 2022a). Lastly, the addition of barnacles and biomimicry (i.e. the barnacle casts) on top of the natural geomorphology of the tile design (crevice, grooves and pockets) allowed function to be conveyed through form (Metcalfe, 2015). This, along with a public interpretation sign in the recreation area adjacent to the deployment site (Fig. 7c), helps highlight the presence of nature in cities by increasing visibility. This improves the direct experience of people-nature interactions (Soga and Gaston, 2020) by bringing biogeomorphological features into cities via a multispecies (human and non-human) science-design approach (Canepa et al., 2022; Metcalfe, 2015; Naylor et al., 2022a). Conducting long-term monitoring and to upscale ecological enhancements to full panels, such as the recent scheme using an award-winning Ecoformliner design at Portsmouth, UK (Sheffield et al., 2022) is a key future eco-engineering research goal to facilitate widespread implementation. Transdisciplinary collaborations between academic scientists and designers, as well as designers, engineers and manufacturers from industry is pivotal for creating scalable, readily manufacturable eco-engineering designs that meet multiple design goals: ecological, biogeomorphological and human.

6. Conclusions

In conclusion, the multiscale multispecies BioGeo Ecotile design is successful in supporting intertidal biodiversity. The Ecotiles outperform both smooth tiles and rock armour for species richness after two settlement seasons. Retrofitting multiscale, multispecies habitat enhancement tiles onto rock armour at this UK site increased colonisation and species richness compared to rock armour and smooth tiles.

BioGeo Ecotiles increased diversity, abundance and the presence of species that are a key prey for birds within the Special Protection Area. Statistically significant differences in community composition between material show that different material types support different species in temperate settings. Therefore, we suggest the use of a range of textures and materials in temperate intertidal settings where ecological enhancements are aimed at increasing biodiversity and maximising ecological potential. The target species colonised the features specifically designed for them. This shows that previously tested features can be combined into a multiscale multispecies design and that Ecotiles enhance intertidal diversity when deployed on rock armour. In addition, the BioGeo Ecotile met its design objectives in mimicking the biogeomorphology and colonisation of natural rocky shores, to design for humans and non-humans and to be readily scalable.

Studies like this one strengthen the evidence that eco-engineering reduces the impacts of ocean sprawl (Bishop et al., 2017). This research demonstrates that ecological goals and engineering design objectives can be achieved simultaneously, via a transdisciplinary science-design approach (Naylor et al., 2022a), helping to accelerate widespread implementation of eco-engineering (Suedel et al., 2021) in practical construction and/or conservation projects.

Author statement

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2022.106881.

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