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Timing of deployment does not affect the biodiversity outcomes of ecological enhancement of coastal flood defences in northern Europe

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A R T I C L E I N F O

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A B S T R A C T

Timing of installation is an important factor when planning the deployment of ecological enhancements to intertidal coastal and marine infrastructure. Such nature-based solutions (NbS) are increasingly used worldwide, so understanding whether the timing of deployment affects colonisation success is crucial to enhance their success and identify any ecological sensitivities that must be taken into consideration during construction. To date, none of the previous marine eco-engineering studies globally have looked specifically at timing. An unexpected COVID19 interruption in retrofitting Ecotiles designed to improve urban marine biodiversity provided a unique window of opportunity to address this research gap. We examined if time of deployment affects the early colonisation (within 18 months) success of eco-engineering enhancements. Thirty concrete tiles (Ecotiles) cast with a novel multi-scale, multi-species textured formliner were deployed on rock armour in three sites along the coast in Edinburgh, Scotland, at two different time periods (early March and late May 2020). After two settlement seasons, the colonisation success of 85% of the studied species did not vary between the times of deployment. Early colonisation success of intertidal species equalised within two settlement seasons of deployment, along with an overall increase in species richness. Crucially, these results also show that summer construction periods designed to reduce impacts on overwintering birds, do not adversely impact intertidal species during their peak (spring-summer) recruitment period in northern Europe. This novel result provides further support for widespread use of eco-engineering to enhance large coastal infrastructure projects and achieve ecological goals in northern Europe. More widely, this work contributes to the understanding of the impact of deployment timing on the success of similar NbS worldwide.

Introduction

Research has shown that artificial defence structures poorly resemble natural rocky shore habitat (e.g. [1,2]), leading to lower intertidal species diversity and abundance on artificial structures [3]. Ecological enhancement [4], also referred to as eco-engineering or greening the grey [5,6], has been widely recognised as a nature-based solution (NbS) [7] and has been successfully used worldwide to alleviate the negative ecological impacts of coastal infrastructure. Active ecological enhancements [8] have been primarily applied as retrofits to existing structures [9,7] where additional 3D features are manually drilled into rock materials (e.g. [10,11]), such as rock pools (e.g. [12–14]). They have also been constructed as 3D printed units [15] or precast textured concrete tiles using formliners designed to improve biodiversity (e.g. [16–18]), by replicating naturally rocky shores (e.g. [19,17]) and/or as science-design interventions to improve biodiversity and people-nature interactions in cities [20]. Artificial structures lack habitat heterogeneity, so adding structural complexity and texture is recognised as an effective way to support higher species richness and abundance [17,21,22]. However, positive results can vary based on other biogeographic factors, including latitude and tidal zone [23], where ecological success can vary due to biotic and abiotic and anthropogenic factors (e.g. pollution).

Timing of deployment is an important factor when evaluating the design and implementation of marine ecological enhancements, as it may be closely related to the recruitment periods and seasonal variation of species [9]. For example, Strain et al. [23] noted that in temperate regions (such as in this study), the main ecological settlement season for recruitment and growth of intertidal species is from early spring (March) to late autumn (October). As construction of coastal infrastructure within the UK is limited to this time frame, with overwintering protected bird species and adverse sea conditions making construction during the

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winter difficult, understanding how timing of deployment affects colonisation success within the settlement season is important.

Currently, there are no research articles specifically on the timing of deployment of ecological enhancements, however a few experimental ecology studies have investigated the effect of timing of seasonality or disturbance on species colonisation on artificial panels (e.g. [24–26]). Timing of deployment of ecological enhancements can be compared to timing of disturbance, as in most of the studies disturbance equals clearance and so colonisation restarts from zero [27]. Species recruitment varies between seasons due to species recruitment peaks [28,29] and so seasonality (timing of disturbance/ deployment) determines the species composition in early colonisation of intertidal [27,25] and subtidal species [30,26]. For example, in the Adriatic Sea, disturbance in late spring and summer on breakwaters caused overgrowth of macroalgae as compared to disturbance in January, which did not differ from undisturbed controls [27]. In later stage colonisation (after one year) the effect of timing diminishes and communities converge to a common structure [24,25]. As ecological succession proceeds, species richness and abundance tend to increase with time (>12 months) [31,10,17] since deployment and other factors (growth, predation, competition) become more important in determining the community structure [25, 30].

The effect of timing of deployment is under-researched to date. We address this important research gap by investigating if and how the timing of deployment of eco-engineering enhancements in the intertidal zone affects early colonisation patterns. In Edinburgh, Scotland, the deployment of Ecotiles in spring 2020 was interrupted by a COVID-19 lockdown, which opened an ecological window of opportunity to test timing as a factor of ecological enhancement [32]. We compared colonisation results after one and two settlement seasons, comparing results between two different times of deployment during the first settlement season (tiles deployed early March and end of May 2020). An innovative transdisciplinary science-design-manufacturing process was used to design textured formliners (moulds used to cast textured concrete) called Ecotiles that mimicked the characteristics of natural rocky shores [20]. Biogeomorphic processes were used to create a multiscale, multispecies ecoformliner to cast marine concrete tiles (300 × 300 × 60 mm) at a commercial pre-cast concrete manufacturing facility [33]. These were deployed on north facing rock armour units in the upper intertidal zone on the coast at Edinburgh (Fig. 1). The main experiment [20] assessed the effect of texture, material, slope and aspect of the ecological enhancement on intertidal species colonisation. Key findings of Kosová et al. [20] were that the textured Ecotiles had higher colonisation and species richness than smooth control tiles and adjacent rock after two settlement seasons. However, we assess here whether deployment timing affects settlement on the Ecotiles after two settlement seasons (i.e. within 15–18 months post-deployment). We hypothesised that:

(1) The tiles deployed at the start of the settlement season (March) have higher species richness and individual species colonisation on the Ecotiles compared to those deployed during the summer settlement season (late May).
(2) Species richness and presence on the Ecotiles increases with time from deployment due to ecological succession.

Understanding the ecological impacts of deployment timing is of importance when assessing the success of such NbS in succession, community composition and biodiversity outcomes. This research is equally important for future applications of ecological enhancements on engineered structures to ensure that construction timing is optimal for early-stage colonisation. Studies of this nature are crucial for evaluating the sensitivity of rocky intertidal colonists to construction-related disturbance and to determine if future restrictions or mitigations are required. Ecological enhancements are increasingly built into engineering schemes (e.g. recent schemes include Port of San Diego, USA

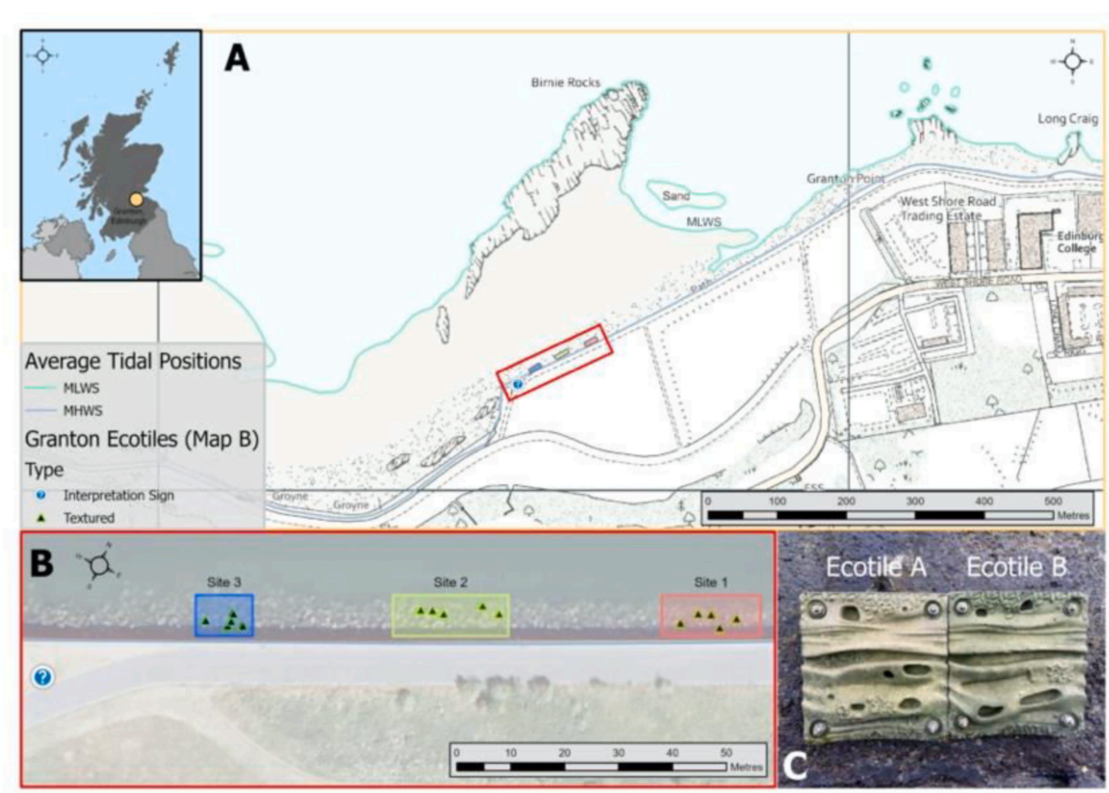

Fig. 1. Showing (A) the study site at Granton, Edinburgh, UK; (B) Five Ecotiles A and five Ecotiles B were deployed at each of the sites 1, 2 and 3; (C) Detail of Ecotile A and B where each tile is 300 × 300 mm.

(Econcretech), Porto Ferrol, Spain (Econcretech) and North Portsea Island in the UK [34], yet the timing of construction of large-scale coastal engineering schemes is often restricted to certain seasons of the year. In temperate regions, this is often the summer months to avoid disturbing habitat of overwintering birds and, for construction reasons, to avoid harsher wave conditions at other times (e.g. [35,34]). Construction then typically occurs during the key settlement season for intertidal species with unknown impacts on settlement success [34]. This means construction can typically occur during the key settlement season for intertidal species – providing further impetus/need for the research questions tested here.

Methods

Site description

The Ecotiles were deployed within the intertidal zone on north facing dolerite rock armour coastal protection structures at the edge of Gypsy Brae recreation ground in Granton, Edinburgh, Scotland, UK (55°58′51.3″N 3°15′34.9″W). Tiles were bolted by contractors who routinely repair coastal structures, following a clear protocol for deployment which they were trained to in during March 2020 (for further details se Kosová et al. [20]; Fig. 2). Tiles on the rock armour units were positioned in the upper intertidal zone, below mean high water spring. The site is located within the Firth of Forth Special Protection Area (SPA), which is an area with special importance for protection of both non-migratory, migratory and overwintering vulnerable bird species [36].

Experimental design

In spring 2020, 30 Ecotiles were deployed on rock armour with 10 tiles at each of three sites spaced ~40 m apart to allow each site to be compared statistically (Fig. 1.B). Five replicates of each type (textured A, textured B; see Fig. 1.C) were deployed [37]. The experiment was nested within a larger scale experiment of 90 tiles [20]. The Ecotiles at site 1 were deployed in early-mid March 2020 (a few weeks before barnacle settling in the inner Forth estuary at Blackness in May 2018; [17]) and the tiles at sites 2 and 3 were deployed in late May 2020 (see timeline Fig. 3), resulting in 5 tiles deployed per tile type in early-mid March 2020, and 10 tiles per tile type in late May 2020. The difference in time of deployment was due to restriction of construction work during the COVID lockdown and created an opportunity to test the different timing of deployment within one settlement season. Data on species percentage cover and count were collected at the start of the second settlement season (mid-March; after 1 settlement season) and at the end of the second settlement season(mid-September 2021), using a 250 × 250 mm quadrat on the 300 × 300 mm tiles to avoid edge effects [38,39].

Statistical analyses

Data on colonisation of Ecotiles A and B were analysed to assess the effect of timing of deployment. Here, only the Ecotiles are assessed with the wider study finding Ecotiles A and B performing significantly better than smooth concrete tiles and rock armour [20]. Generalized linear models (GLMs) were used to test whether there is a significant effect of timing of deployment on species richness (with Poisson distribution) and presence (with binomial distribution) and whether they increase with time from deployment. The optimal model was selected using backwards/forwards model selection using Akaike Information Criterion (AIC; [11,40]). An ANOVA test was used to determine the significance of the optimal factors (two-factor timing of deployment; two-factor tile type; three-factor site; continuous slope and aspect) in affecting species richness and individual species colonisation. A post-hoc Tukey test was applied to compare species richness between months of collection (March vs September 2021).

Community composition of sessile species was analysed using non-metric multidimensional scaling (NMDS) and ordination was applied using Bray-Curtis dissimilarities [38]. The ordination tested the correlation (envfit) between species structure and environmental variables (site, slope, aspect, time of deployment, tile type) 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 [24,41,42,30]. Data were statistically analysed in 4.1.1 (R [43]) with packages 'vegan' [42] for community analysis, 'ggpubr' [44] and 'ggplot2' [45] for graphical representations.

Results

Species richness

Model selection showed that whilst the timing of deployment was included in the optimal model after 1 settlement season (March 2021), it was not a significant factor after 2 settlement seasons (September 2021; Fig. 4). After 1 settlement season, the timing of deployment was a significant factor determining the variation in species richness ($F_{1,28} = 9.14$, $p < 0.01$), with the Ecotiles deployed in late May having a higher number of species than on Ecotiles deployed in early March. However, by the end of the second settlement season, timing was not a significant factor explaining variation in species richness (Fig. 4). For both monitoring periods (Fig. 4), other factors (tile type A and B; site 1, 2 and 3; slope and aspect) were tested but were not retained in the optimal statistical model and thus were not significant factors when comparing Ecotiles A and B. Overall, there was a significant increase in species richness between 1 and 2 settlement seasons on both Ecotile designs (ANOVA: $p < 0.001$).

Fig. 2. A-C. Where A. Cross section view of the rock armour at low tide, MHWS is located just above the rock armour along the wall and MLWS is seaward of the low tide in this image (see Fig. 1); B. Colonisation of Ecotiles after 1st settlement seasons (March 2021) C. Colonisation of the same tiles after the second settlement season (September 2021).

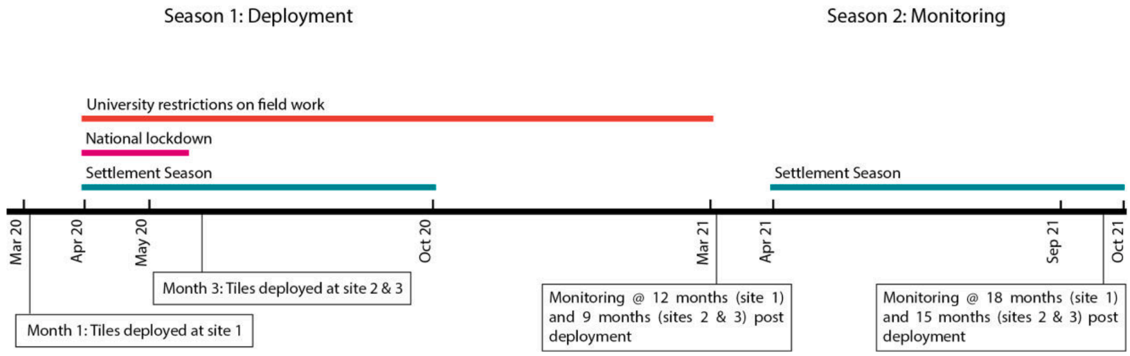

Fig. 3. Project timeline – Ecotile deployment between 11 and 13 weeks apart in settlement season 1 and data collection at two-time intervals (March and September) at the start and end of settlement season 2. Red arrowed lines denote periods of COVID-19 lockdowns where no travel was allowed (NB. From May 2020 to February 2021 fieldwork was also not allowed at the University of Glasgow, which prevented monitoring before March 2021).

Colonisation by individual species

A total of 16 species were found on the Ecotiles, with 9 species after 1 settlement season (March 2021) and 14 species after 2 settlement seasons (September 2021; Table 1). The effect of time of deployment was tested on individual species. Only 2 species groups were affected by timing of deployment per monitoring period (22% of species after 1 settlement season, 14% after 2 settlement seasons). After 1 settlement season, deployment timing was important factor for *Enteromorpha* sp. ($F_{1,27} = 1.07, p < 0.05$) and for *Littorina littorea* ($F_{1,28} = 5.03, p < 0.05$). Both species showed higher colonisation on the Ecotiles deployed in late May 2020 but the difference did not persist into mid-September 2021 towards the end of the second settlement season. After 2 settlement seasons, (15 and 18 months post-deployment), barnacle species ($F_{1,27} = 8.00$, $p < 0.01$) and green algae ($F_{1,28} = 6.46$, $p < 0.05$) showed significantly more colonisation on May-deployed Ecotiles. Other factors (tile type, site, slope and aspect) were initially included in the model selection but the best-fit GLMs only included timing of deployment.

Community structure

Although deployment timing was not found to be significant after 1 settlement season, site was significant for sessile community structure. Non-metric multidimensional scaling (NMDS) showed that sessile community structure was significantly correlated with site in March 2021 (envfit: $R^2 = 0.18$, $p < 0.01$; Fig. 5.A) and September 2021 ($R^2 = 0.15$, $p < 0.05$; Fig. 5.B). PERMANOVA analysis of data after 1 settlement season (March 2021) showed that there was a significant variation between communities based on site ($R^2 = 0.16$, $F_{2,29} = 3.09$, $p < 0.05$), slope ($R^2 = 0.13$, $F_{1,29} = 3.09$, $p < 0.01$) and aspect ($R^2 = 0.09$, $F_{1,29} = 3.55$, $p < 0.05$), with tile type and time having no significant effect on community composition ($p > 0.05$). The results of PERMANOVA after 2 settlement seasons (September 2021) showed that none of the studied factors, including time of deployment, significantly affected the sessile communities ($p > 0.05$).

Discussion

Ecological engineering of coastal infrastructure has been recognised as a NbS to the issue of low biodiversity on artificial rock structures. However, there is little information on how the timing of deployment at different points within a settlement season affects colonisation success and biodiversity outcomes. We show that species richness, colonisation and community structure were not significantly affected by the time of deployment of the Ecotiles after two settlement seasons in Edinburgh contrary to our hypothesis (1) above. For hypothesis 2, we find that the number of species on all tiles increased significantly between 1 and 2 settlement seasons. That species richness increases with time since deployment [10] due to ecological succession, is a common observation [46].

Sessile species community composition was not affected by timing of deployment in either sampling period. Additionally, species richness variations apparent after one settlement season had disappeared by the end of two settlement seasons. This agrees with other studies researching the timing of colonisation onset on ecological succession which show seasonality affecting species composition in early-stage colonisation but communities converge to a common structure within 1 year [24,47,48], although some may take multiple years [25]. With elapsed time from the start of colonisation, other biological factors (e.g. growth, competition, predation) shape the community [25,30]. The wider study shows that texture and material of the ecological enhancement was more important than the timing of deployment when a larger mix of textures and materials were tested [20] providing further evidence that timing of deployment within one settlement season has no impact on ecological conservation outcomes after two settlement seasons.

Our findings suggest that deployment time affects ecological colonisation within one settlement season, with species richness higher in the tiles deployed in May 2020, later in the settlement season. This means that ecological succession happens at varying rates based on the timing of deployment within the peak colonisation season. This agrees with Airoldi and Bulleri [27] who found that disturbance during the spring and summer was more detrimental to colonisation rates and community composition compared to disturbance in the winter. Whilst Airoldi and Bulleri [27] found differences between winter and spring/summer, in this study, we focused on differences within the spring and summer, with the construction of coastal infrastructure more intensive within these seasons. Species richness was linked to different deployment times within the peak settlement season for this region [23]. Depending on the time of disturbance within a year, species will take differing amounts of time to colonise due to their recruitment periods. Our study found that the effects of the timing of deployment on species richness evens out after two settlement seasons, thus the initial impact of the timing of deployment is short-lived (< 18 months) on the success of the Ecotiles in increasing community biodiversity [20].

When considering species-specific affects, the timing of deployment directly affected 4 out of the 16 observed species with a maximum of 22% of species per monitoring period. *Enteromorpha* sp. and *Littorina littorea* were affected after 1 settlement season (9 and 12 months post-deployment). However, neither of these species showed significant difference after 2 settlement seasons (15 and 18 months post-deployment), suggesting that the effect did not persist as time/ecological succession increased. On the other hand, barnacles species and green algal film colonisation were shown to be affected by timing of deployment after two settlement seasons (15 and 18 months from deployment). These species showed higher colonisation on the tiles deployed later in the settlement season (May 2020), suggesting that some species may be

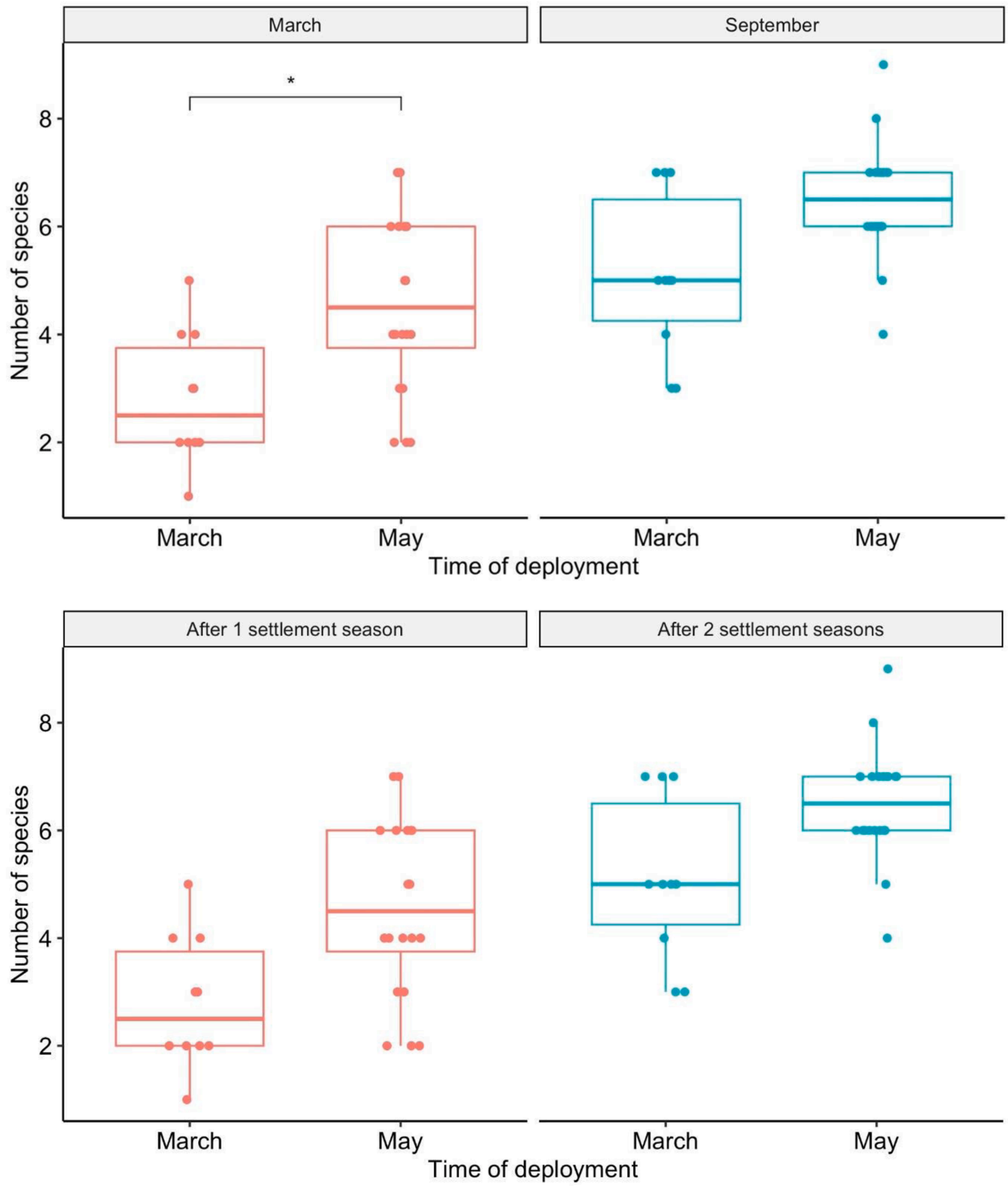

Fig. 4. showing species richness on Ecotiles deployed in March and May 2020 after 1 (9 and 12 months post-deployment in March 2021) and two (15 and 18 months post-deployment in September 2021) settlement seasons. Lines included only for significant differences. Points correspond to raw data.

affected by colonisation differences within one settlement season. As COVID-19 restrictions prevented monitoring over this period, it is not possible to precisely determine the order of early stage colonisation following and during the first settlement season of deployment. However, fucoid seaweed dominated the Ecotiles, showing a higher probability of colonisation with time from deployment (September > March), suggesting an increase in abundance due to typically rapid fucoid growth in summer [49,50]. This concurs with Airoldi and Bulleri [27] who found that when disturbance occurred in late spring/ summer, fucoids dominated post-disturbance recovery. Further sampling is needed to establish if the effect of deployment time on barnacles and green algae film colonisation evens out after further settlement seasons.

Although, timing of installation of ecological enhancement is suggested as a factor to consider [9], no published marine eco-engineering studies have looked specifically at timing. The main ecological settlement season in northern Europe for recruitment and growth of intertidal species is from early spring to late autumn [23]. In this region, winter is suggested as the most appropriate season for rapid ecological succession in temperate intertidal [25] and subtidal rocky shores [24]. However, the deployment of tiles in the winter is often unachievable, with weather limitations and constructure restrictions due to overwintering birds. We found that differing times of deployment within the main recruitment season appears not to affect species colonisation, richness or composition after two settlement seasons (including two winters for rapid ecological succession). This suggests that unless very rapid ecological succession (i.e. < 1 year) is the goal of ecological enhancement, there is no time constraint on the deployment or construction of ecological enhancements aiming for intertidal biodiversity conservation (Fig. 6).

Table 1
Shows a list of species found on the Ecotiles in March and September indicating whether time of deployment had an effect on their early-stage colonisation.

Time of collection		SPECIES NAME	COMMON NAME	Timing of deployment significant?
After 1 settlement season (March 2021; 9 and 12 months post-deployment)	SESSILE	*Fucus vesiculosus*	Bladder wreck	–
		Austrominius modestus and *Semibalanus balanoides*	Barnacles	–
		–	Green algal film	–
		–	Brown algal film	–
		Enteromorpha sp.	Turf green seaweeds	Higher presence on tiles deployed in May $F_{1,28} = 4.74$, $p < 0.05$
		Ulva lactuca	Sea lettuce	–
		Porphyra sp.	Red algae	–
	MOBILE	*Littorina littorea*	Common periwinkle	Higher presence on tiles deployed in May. $F_{1,28} = 5.03$, $p < 0.05$
		Littorina saxatilis	Rough periwinkle	–
After 2 settlement seasons (September 2021; 15 and 18 months post-deployment)	SESSILE	*Fucus vesiculosus*	Bladder wreck	–
		Austrominius modestus and *Semibalanus balanoides*	Barnacles	Higher presence on tiles deployed in May $F_{1,27} = 8.00$, $p < 0.01$
		–	Green algal film	Higher presence on tiles deployed in May $F_{1,28} = 6.46$, $p < 0.05$
		–	Brown algal film	–
		Enteromorpha sp.	Turf green seaweeds	–
		Pomatoceros triqueter	Tubeworm	–
		Mytilus edulis	Blue mussel	–
		Patella vulgata	Limpet	–
		Littorina littorea	Common periwinkle	–
	MOBILE	*Littorina saxatilis*	Rough periwinkle	–
		Anurida maritima	Seashore springtail	–
		Talitrus saltator	Sand hopper	–
		Nucella lapillus	Dog whelk	–
		Carcinus maenas	European green crab	–

Conclusions

We investigated the effect of timing of deployment of eco-engineering enhancements, in this case, multiscale, multispecies textured marine concrete tiles retrofitted onto rock armour units, on intertidal colonisation success to address the knowledge gap in whether the timing of deployment of ecological enhancements on artificial marine structures effects intended biodiversity outcomes. The COVID-19 lockdown of late March 2020 created an unexpected research opportunity, interrupting our Ecotile deployment and showing the benefits of adopting a flexible approach to ecological research. In this environmental setting, our results show there is no ecological impact of varying the timing of deployment of ecological enhancements during the first settlement season of intertidal colonisation and on ecological succession after two settlement seasons. Nevertheless, further work is required to determine the impacts of deployment of ecological enhancements in autumn/winter in this and other environmental settings worldwide. In each location, it is important to assess how much time is required for ecological succession to equalise and if there is inter-annual variation in the nature and rate of colonisation that may be linked to temporal variations in biotic factors, such as larval or spore availability, in a given year [25,30,26]. Furthermore, research is required to determine if deployment time is critical for subtidal structures, with ecological enhancements able to act as shelter for juvenile fish and another motile species (Boakes et al. 2022).

These findings suggest that temperate region deployments of large scale ecological enhancements, constructed across the intertidal settlement season, as part of engineering schemes are likely to achieve similar levels of intertidal species richness and community structure within two settlement seasons of deployment– regardless of when they are deployed during the main spring-summer recruitment period. This is especially important where construction is limited to summer months to reduce impacts on bird populations (such as in the North Portsea and Hartlepool schemes). This is important as summer only construction periods designed to protect overwintering birds does not appear to impact intertidal ecology, including for the key prey species (e.g. limpets [35] and crabs) of internationally protected overwintering birds.

More research alongside the growing number of operational scale installations of ecological enhancements across multi-year construction phases (e.g. [35,34]) is the next step for further exploration of the role of timing on ecological succession and the success of operational enhancements. Academic research alongside these larger scale applications would be a cost and time effective way to (a) enhance our ecological understanding of the effects of timing and inter-annual variability in settlement between species and ecological enhancement designs; (b) measure the ecological success of the NbS enhancements applied to engineering schemes and (c) allow further closing of the science-practice gap in this field [33]. Regionally specific work on the timing of ecological enhancements is key for the success of future projects to “Green the Grey”, incorporate coastal blue-green infrastructure [51] and/or install other coastal NbS to ensure that the timing of construction is ecologically optimal for early-stage intertidal colonisation. This research demonstrates that temporal scale factors influencing ecological success of eco-engineering and related NBS is an important factor to consider, alongside spatial scale issues in this field, such as determining the optimal spatial extent and distribution of ecological enhancements to achieve intended ecological outcomes.

NBS impacts and implications

Environmental – COVID19 created an unexpected interruption in installation of ecological enhancements. This created a window of opportunity to address a key science gap: *Does the timing of deployment affect colonisation success?* Ecotiles were deployed at two separate times during the settlement season and showed similar results after two settlement seasons.

Social – The Ecotiles tested here aimed to improve human-nature interactions in urban ecosystems. Our research found that timing of installation did not affect ecological outcomes, making it easier for practitioners to apply these eco-engineering designs more readily – increasing their use and thus the potential to improve people-nature interactions in cities.

Economic - This paper shows that there are no additional construction constraints adding habitat for intertidal ecology that would otherwise increase or prolong construction periods and thus costs. It provides

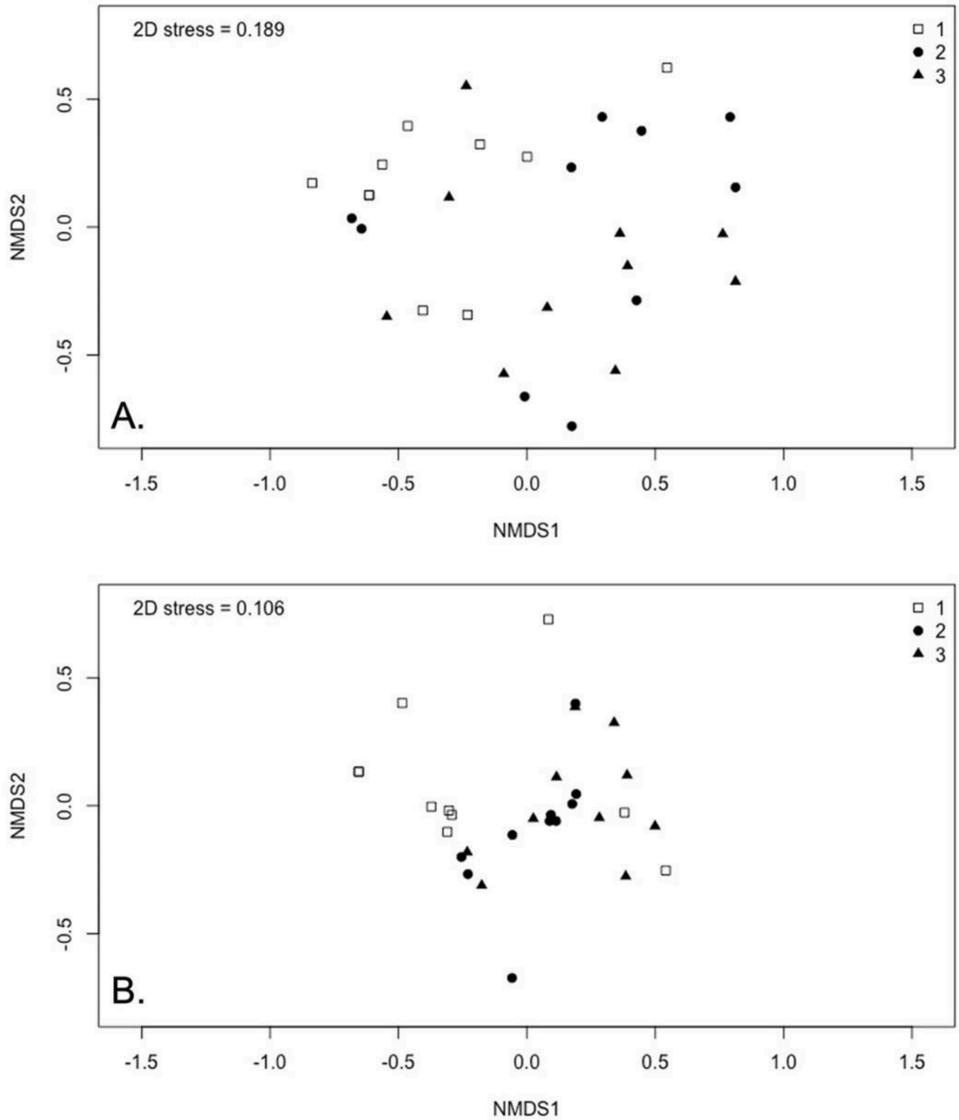

Fig. 5. A-B. NMDS ordinations of multivariate species assemblages based on site 1, 2, 3 after (A) 1 settlement season (9–12 months in March) and (B) 2 settlement seasons (15–18 months in September 2021). The open symbols represent March 2020 deployment (9 and 15 months post-deployment) and filled symbols represent May 2020 deployment (12 and 18 months post-deployment).

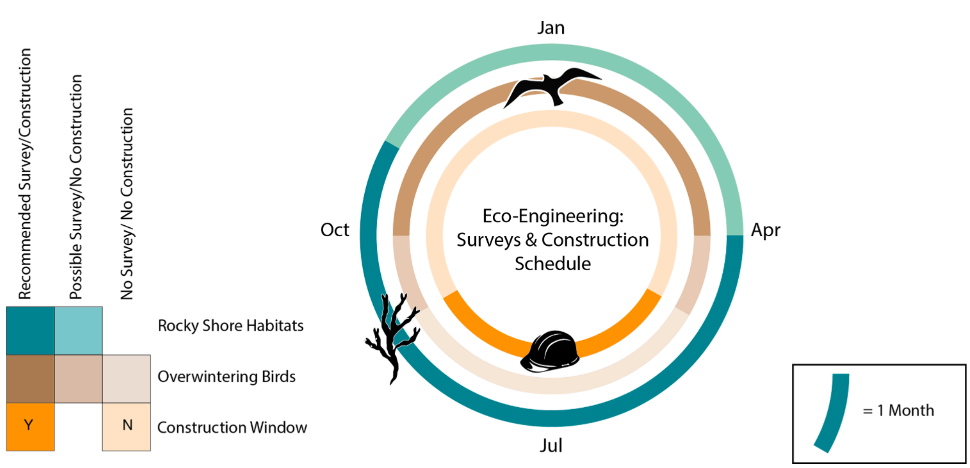

Fig. 6. Diagram illustrating construction and ecological survey windows for deployment of rocky intertidal eco-engineering measures and/or coastal engineering structures where construction needs to occur to not disturb overwintering birds. Rocky shore and overwintering bird survey timings based on recommendations by the Joint Nature Conservation Committee.

further evidence of the ecological benefits of eco-engineering measures, improving the economic case for widespread application of greening the grey.

Construction Window - Naylor et al. Flexible colonisers: timing of deployment of ecotiles does not affect ecological enhancement of coastal flood defences in northern Europe

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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