

Novel eco-engineering of marine piles: 3D-printed habitat panels enhance biodiversity and buffer thermal extremes in a tropical urban estuary

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2 **Novel eco-engineering of marine piles: 3D-printed habitat**
3 **panels enhance biodiversity and buffer thermal extremes in a**
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2. Abstract

Coastal seascapes are increasingly dominated by artificial structures of limited ecological value. This study tested whether 3D-printed eco-engineered wraps, designed to recreate natural intertidal rock-pool habitat, can enhance biodiversity and buffer thermal extremes when retrofitted to marine piles in a tropical urban estuary (Townsville, Australia). Epibenthic assemblages on eco-engineered and control piles were surveyed at 2, 4, 7, 9 and 12 months after deployment, across shaded and sun-exposed orientations and three tidal heights, while temperature was logged hourly inside and outside the rock pools and on control piles. The rock pools were consistently cooler than control surfaces, by approximately 0.8 °C on average and up to 1 °C on shaded aspects, and buffered extremes far more strongly, reducing the highest recorded temperature by up to 6.5 °C. Eco-engineered piles supported a distinct and more diverse assemblage than control piles (functional-group richness 2.8 versus 1.6; Shannon diversity 0.71 versus 0.26), and this difference widened as colonisation proceeded. Control piles converged on a barnacle-dominated monoculture and lost cover late in the study, whereas eco-engineered piles maintained high cover and little bare space (88% versus 60% cover at twelve months). Tube worms were largely restricted to eco-engineered piles, and crabs were frequently observed sheltering within the wraps, although neither was quantified by the survey method. This spatial concordance between thermal buffering and biodiversity indicates microhabitat-scale thermal refuge as a plausible mechanism. Retrofitting piles with eco-engineered wraps can therefore enhance biodiversity and moderate thermal extremes, supporting eco-engineering for ecological enhancement of urban seascapes.

3. Introduction

Coastlines worldwide are increasingly being replaced by artificial structures, including seawalls, breakwaters, groynes, jetties, marinas and piles, as coastal populations expand and hard defences built to protect infrastructure against rising seas, a process collectively termed "ocean sprawl" (Firth et al., 2016; Neumann et al., 2015). The scale of this transformation is considerable: the global footprint of marine built structures was estimated at approximately 32,000 km² in 2018 and is projected to reach around 39,400 km² by 2028 (Bugnot et al., 2021). Hardening is most pronounced in urbanised settings, where built structures occupy more than half ($52.9 \pm 4.9\%$) of the adjacent coastline across 30 major coastal cities worldwide (Floerl et al., 2021). This transformation is expected to accelerate with continued coastal development, sea-level rise and increasingly frequent and intense storms (Bulleri & Chapman, 2010).

Despite superficially resembling the rocky reefs they replace, artificial structures do not function as ecological surrogates for natural hard substrata, instead supporting distinct and generally impoverished epibiotic assemblages (Bulleri & Chapman, 2010; Dennis et al., 2018). Constructed surfaces such as seawalls are typically smooth, steeply sloping and topographically homogeneous, lacking the crevices, pits, overhangs and water-retaining or shaded microhabitats characteristic of natural shorelines. This simplification limits larval survival and the persistence of many taxa, and is associated with a particular paucity of mobile species relative to nearby natural shores (Perkol-Finkel et al., 2019). Artificial structures also tend to favour opportunistic and non-indigenous species, and can act as foci for the establishment and spread of marine invaders (Glasby et al., 2007). The cumulative outcome is biological homogenisation and a loss of ecological value along urbanised coasts, the deficit that ecological engineering has emerged to address.

In response to ocean sprawl, the ecological engineering (hereafter eco-engineering) of artificial structures has emerged as a means of enhancing the ecological value of marine infrastructure, while promoting nature-positive function (Firth et al., 2020; O'Shaughnessy et al., 2020). Framed as the "greening of grey infrastructure" and aligned with the broader agenda of nature-based solutions, the approach seeks to design or retrofit structures so that they support similar, or more, diverse assemblages, reconciling coastal protection with nature-positive outcomes (Airoidi et al., 2021; Dafforn et al., 2015; Firth et al., 2016). In practice, this is achieved largely by reinstating the habitat complexity that built surfaces lack, adding texture, crevices, pits, holes and other features that broaden the range of niches and refuges available to colonising organisms (Strain et al., 2018).

A growing body of evidence indicates that such interventions are frequently effective, with global syntheses reporting that the majority increase the abundance or richness of target organisms relative to unmodified controls (Gad et al., 2026; O'Shaughnessy et al., 2020; Strain et al., 2018). This evidence base is, however, unevenly distributed across structure types and designs, and the benefits of any given design are far from universal. Efficacy varies with the target taxa, the dominant local stressors and the habitat setting, so interventions that succeed on one structure or in one region need not transfer to others (Strain et al., 2018). Together, these imbalances leave substantial gaps for the structure types, design features and environmental settings that remain under-represented in the literature.

Despite expansion in coastal areas, a recent global review identified that seawalls and breakwater-type structures together accounted for almost three-quarters of eco-engineering interventions, whereas pylons and piles were the least recognised and studied, at just 4% (Gad et al., 2026). Design guidance reflects the same imbalance, treating over-water structures such as piers and their supporting piles as a minor category, for which only ecological encasement jackets and synthetic free-hanging ropes have been trialled (O'Shaughnessy et al., 2020). Piles are nonetheless among the most ubiquitous elements of urbanised waterways and support epibenthic assemblages distinct from those of both natural reefs and other artificial structures (Glasby, 1999); their vertical, cylindrical form, orientation and exposure differ markedly from those of seawalls, so designs developed for vertical or sloping walls cannot be assumed to perform equivalently.

Evidence from tropical regions is also scarce, and studies typically report biodiversity outcomes without quantifying the environmental conditions that interventions create, thermal regime among them (Gad et al., 2026). This is a notable omission, because water-retaining, rock-pool-mimicking features are among the designs most likely to ameliorate thermal and desiccation stress: on an eco-engineered seawall in Sydney Harbour, rock-pool and crevice panels that retained moisture and remained cooler than surrounding surfaces supported taxa that were otherwise absent (Bishop et al., 2022). Such designs have rarely been applied to piles, and seldom in the tropics, where thermal stress is most severe (Waltham & Sheaves, 2020).

Accordingly, the objective of this study is to evaluate whether retrofitting marine piles with novel 3D-printed eco-engineered wraps, designed to simulate natural rock-pool microhabitats, enhances biodiversity and moderates thermal extremes compared to unmodified piles in a tropical urban estuary (Ross Creek, Townsville, Australia). Over a twelve-month field experiment, eco-engineered and control piles were compared across shaded and sun-exposed orientations and tidal heights. Specifically, this study aims to: (I) quantify the effect of the eco-engineered piles on

the composition, functional-group richness, diversity and cover of the sessile epibenthic assemblage across twelve months of colonisation; (II) characterise the thermal regime of the eco-engineered microhabitats, including mean temperature, diurnal range and thermal extremes, relative to unmodified surfaces; (III) determine how orientation and tidal height influence both the assemblage and the thermal environment; and (IV) assess the spatial concordance between the biological and thermal responses in order to evaluate thermal refuge provision as a mechanism underlying any biodiversity gains. By pairing repeated biological surveys with continuous temperature logging, this study provides the first integrated assessment of the ecological and thermal performance of eco-engineered piles.

4. Methodology

4.1. Study site

The study was conducted in Ross Creek, a tidal estuary in central Townsville, north-eastern Queensland, Australia (Fig. 1). The study site was located approximately 2.3 km from the creek entrance. Situated within the city centre and flanked by major port and urban infrastructure, the site is representative of a highly urbanised tropical estuary in the region (Waltham & Sheaves, 2018). The eco-engineered wraps were three-dimensionally (3D) printed units designed by Reef Design Lab to recreate natural rock-pool microhabitats and were retrofitted to the support piles of a boardwalk along this stretch of the creek.

The region experiences a dry tropical climate, with mean annual rainfall of approximately 1139.9 mm falling predominantly between December and March, and mean monthly air temperatures ranging from approximately 28 °C in July to 32 °C in January (Tavares et al., 2025). Tides are semidiurnal and mesotidal, with an average mean sea level of 2.023 m and a spring range of approximately 0.7-3.3 m (Maritime Safety Queensland, 2025). The creek receives urban stormwater and carries a high suspended-sediment load, and the shoreline is largely armoured with rock revetment, with remnant mangroves persisting in places.

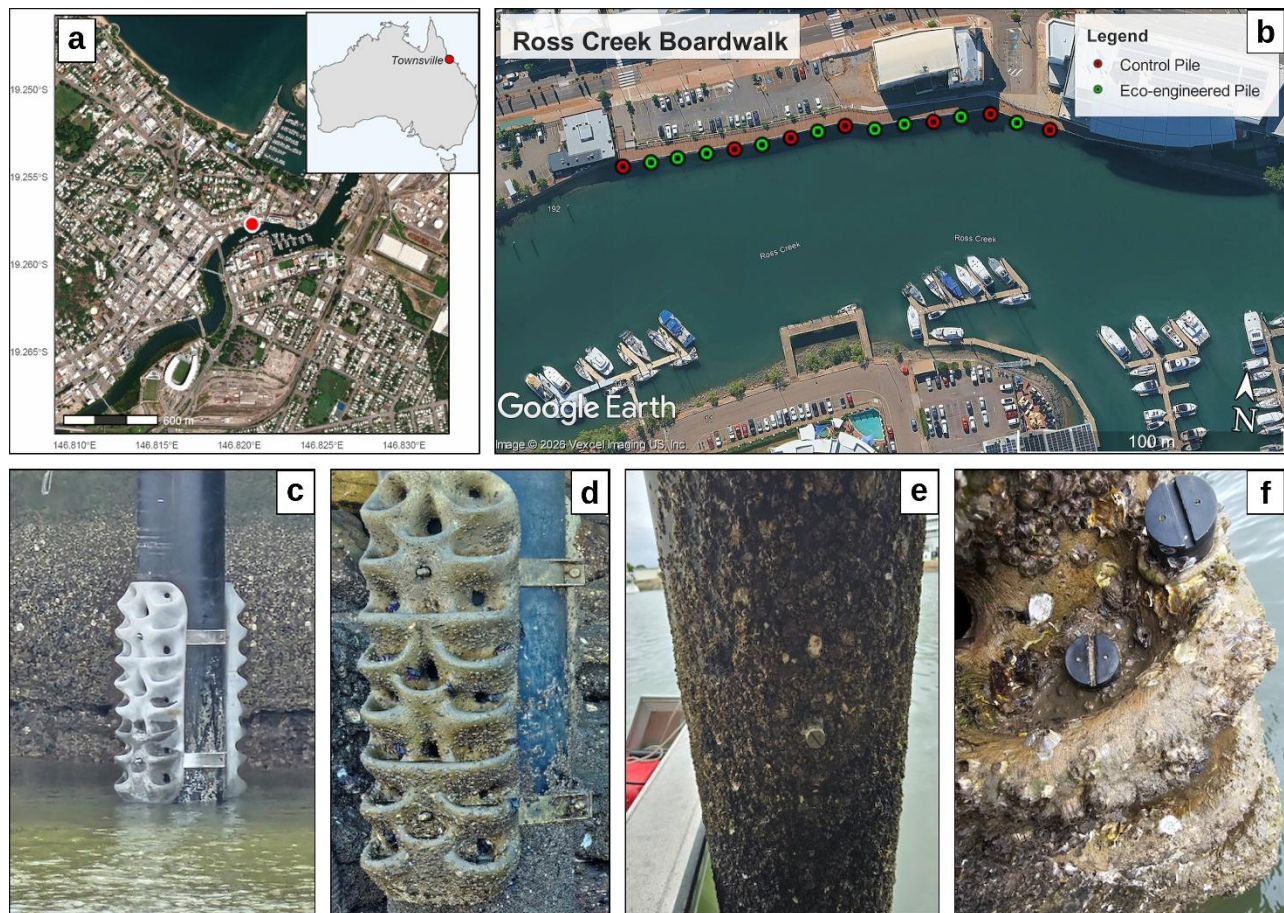


Fig. 1 Study Site and Experimental Setup. (A) Location of the Ross Creek boardwalk study site in Townsville, north-eastern Australia (red circle), with the position of Townsville on the Australian coast inset (basemap imagery: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community). (B) Layout of eco-engineered and control piles on Ross Creek boardwalk (Google Earth, 2026). (C) An eco-engineered wrap clamped to a boardwalk pile at deployment (month 0), showing the moulded concrete rock-pool surface and the clamps securing it to the pile. (D) The same wrap design after seven months of colonisation. (E) An unmodified control pile after seven months, colonised predominantly by barnacles. (F) Close-up of the water-retaining rock pools on a colonised eco-engineered pile, showing two iButton temperature loggers in waterproof housings (Thermochron DS1921G; black discs)

4.2. Eco-engineered piles and experimental design

The boardwalk is supported by 16 piles, of which nine were fitted with eco-engineered wraps while seven were unmodified as controls (Fig. 1B). At each survey event, five eco-engineered and five control piles were selected at random from those available and surveyed. Six quadrats were sampled per pile: one at each of three tidal heights (low, mid and high) on each of two aspects (sun-exposed and shaded).

The eco-engineered piles were modified using three-dimensionally (3D) printed eco-engineered wraps designed by Reef Design Lab as part of the Living Seawall project and cast in

concrete (Fig. 1C). Each wrap was 115 cm tall and 38 cm wide, and its surface was moulded into a rock-pool design of 21 water-retaining depressions ("rock pools") with a mean depth of approximately 7 cm (see Fig. 1C and 1F).

Two wraps were clamped around each eco-engineered pile, giving 18 wraps in total. On each pile, the two wraps were positioned so that their vertical centre was situated at mean tide level, thereby spanning the low to high intertidal zone, and faced in opposite directions: one towards the open creek and sun-exposed, the other towards the adjacent rock-armoured bank and shaded. This created a within-pile contrast in solar exposure, hereafter "orientation", and the equivalent sun-exposed and shaded aspects were distinguished on control piles. At installation, all piles, both eco-engineered and control, were scraped clean to remove existing epibiota, predominantly barnacles, to standardise starting conditions between treatments.

The experiment ran for twelve months, with surveys conducted at approximately two- to three-month intervals, at 2, 4, 7, 9 and 12 months after deployment. While temperature was continuously monitored throughout the whole period.

4.3. *Epibenthic assemblage surveys*

The epibenthic assemblage was surveyed non-destructively using a point-intercept method (Bishop et al., 2022). On each sampling occasion, a 25 × 25 cm quadrat fitted with a regular grid of 25 intersection points was placed against the pile surface, and the sessile organism (or bare substratum) lying directly beneath each point was recorded. Each point therefore represented 4% of the quadrat area, and counts of the 25 points were converted to percentage cover for each category.

Organisms were assigned to four sessile functional groups, distinguished by morphology, growth form and habitat-forming role rather than by trophic function: barnacles, macroalgae, bivalves and tube worms. Functional groups were assigned to species in preference to species-level identification for three reasons. First, the experiment relied on repeated, non-destructive survey campaigns on the same structures on five occasions, which precluded the removal and destructive sampling that species-level identification of encrusting taxa generally requires. Second, several of the colonising taxa cannot be separated reliably in the field and require microscopic examination of skeletal, structural or reproductive features, so field assignment to species would have introduced inconsistency between surveys and observers. Third, functional composition rather than species identity was the ecological response of interest: the eco-engineered piles were designed to provide structural microhabitat, and the question addressed

here is whether they altered the balance of habitat-forming groups occupying the surface, not which particular species colonised it. Richness reported here is therefore functional-group richness, bounded at four, and is not equivalent to species richness.

Mobile fauna, principally gastropods and crabs, were observed on the piles but were not quantified as they moved away as observers approached the piles by boat. Any records falling within quadrats were assigned to a separate "other" category and are not analysed here, since the fixed-point, single-occasion method undersamples motile animals and does not provide a reliable estimate of their abundance. Other Studies of eco-engineered panels on seawalls have quantified both mobile and sessile taxa (Bishop et al., 2022), but those structures are accessible on foot at low tide, whereas the cylindrical geometry of piles and the need to survey from a boat made reliable counts of mobile animals impractical here.

At each survey, quadrats were positioned on both the sun-exposed and shaded aspects of each pile (orientation) and at three intertidal heights: low, mid and high, so that the full orientation × tidal-height combination was sampled on every pile. Quadrats were haphazardly placed at each orientation–height rather than at fixed, permanently marked positions, so that each survey constituted an independent sample of colonising fauna on the available surfaces.

4.4. Surface temperature monitoring

The thermal environment of the surface of eco-engineered and control piles was recorded using Thermochron iButton temperature loggers (model DS1921G; Maxim Integrated/Analog Devices) housed in waterproof casings (Fig. 1F). Loggers were programmed to record hourly from 01 March 2025 to 11 February 2026.

To resolve the thermal effect of the eco-engineered piles at the scale of the microhabitats they create, loggers were deployed in three positions (hereafter "microhabitat"): within the water-retaining rock pools of the eco-engineered piles ("eco inside"); on the outer surface of the eco-engineered piles, between the rock pools ("eco outside"); and on the surface of unmodified control piles ("control") (Fig. 1E and 1F). These positions were replicated across both the sun-exposed and shaded aspects (orientation) on three eco-engineered and three control piles. Loggers were deployed in triplicate at each position, all at mid-tide height; thermal data were therefore collected only at this tidal level.

4.5. *Data Analysis*

Multivariate and univariate analyses were used to test the effects of the eco-engineered piles on the sessile assemblage. Multivariate differences in assemblage composition were tested using permutational multivariate analysis of variance (PERMANOVA) on Bray–Curtis dissimilarity matrices calculated from square-root-transformed percentage covers of the four functional groups (barnacles, macroalgae, bivalves and tube worms); the transformation was applied to prevent the most abundant group (barnacles) from dominating the dissimilarity measure. Because quadrats were sampled at random within each pile rather than as repeatedly marked plots, the pile was treated as the unit of replication. The effects of survey month, tidal height and orientation, and their interactions with treatment, were tested using permutations constrained within piles, whereas the main effect of treatment, which varied among, rather than within piles, was tested separately on pile-level mean covers. Multivariate dispersion was compared among treatments using PERMDISP to confirm that any treatment effect reflected a genuine difference in composition rather than heterogeneity of dispersion; assemblage patterns were visualised using non-metric multidimensional scaling (nMDS), and the functional groups driving treatment differences were identified using similarity percentages (SIMPER) analysis.

Univariate responses, functional-group richness, Shannon diversity, total sessile cover, bare space and the covers of individual functional groups, were analysed using generalised linear mixed models (GLMMs), where pile was treated as a random effect to account for the repeated sampling of each structure, with treatment, survey month, tidal height and orientation, and their interactions, treated as fixed effects. Error structures appropriate to each response were used. Total cover and bare space, recorded as the number of points occupied out of 25, were modelled as binomial responses using beta-binomial distributions rather than being arcsine-transformed, since logistic regression offers greater interpretability and power than transformation for data of this kind, with overdispersion accommodated through the error structure and random effects rather than by transforming the response (Warton & Hui, 2011). Functional-group richness was modelled using a generalised Poisson distribution, which was preferred over the Poisson after the latter showed underdispersion, and Shannon diversity using a Gaussian distribution. Functional groups that were largely confined to one treatment or that colonised only later in the experiment were analysed on the relevant subset of the data; macroalgae and tube worms, which were essentially absent from control piles, were analysed within eco-engineered piles only, where the effects of orientation and tidal height could still be tested. Fixed effects were assessed using Type III Wald tests, and estimated marginal means and pairwise contrasts, with 95% confidence

intervals, were obtained on the response scale, and model adequacy was checked using simulation-based residual diagnostics.

The thermal environment was characterised from three daily metrics derived for each logger: mean, maximum and diurnal range (the amplitude difference between daily maximum and minimum) of temperature. Each metric was analysed using a linear mixed model with microhabitat (control surface, eco-engineered outer surface and eco-engineered rock-pool interior), orientation, and their interaction as fixed effects, and day as a random effect, so that microhabitats were compared within shared days.

No fixed significance threshold was applied (Smith, 2020). Each test is reported with its statistic, degrees of freedom, actual p value and sample size, and interpretation rests on the direction and magnitude of effects, given as estimated marginal means, differences or odds ratios with 95% confidence intervals. All p values are given to two significant figures; values below 0.0001 are reported as $p < 0.0001$. For the permutation tests, the smallest attainable p value is 0.0001 with 9999 permutations and approximately 0.0013 for the pile-level test, where five control and seven eco-engineered piles allow 792 distinct assignments of piles to treatments.

Analyses were conducted in R (Team, 2026) using RStudio (version 2026.05.0), with the vegan, glmmTMB, car, emmeans and DHARMa packages. The study-site map (Fig. 1A and 1B) was produced in R using the sf, ggplot2, maptiles, tidyterra, rnaturalearth, ggspatial and cowplot packages.

5. Results

5.1. *Epibenthic assemblages*

Four sessile functional groups colonised the piles over the twelve-month experiment: barnacles, bivalves (predominantly oysters), macroalgae and tube worms. Other taxa, principally molluscs (snails) and crabs, were observed on the piles during surveys but were not captured by the quadrats and are not considered further. The assemblage that developed on the eco-engineered piles differed consistently from that on control piles in its overall composition, in its diversity and cover, and in the identity and abundance of its dominant groups, with these differences developing over the study and varying with tidal height and orientation.

5.1.1. *Assemblage composition*

Eco-engineered and control piles developed compositionally distinct sessile assemblages, although the degree of separation varied through the study (Fig. 2). The ordination a non-metric multidimensional scaling (nMDS; stress = 0.18) of the square-root-transformed Bray–Curtis dissimilarities among quadrats, shows the two treatments overlapping broadly at the first survey (2 months), when both surfaces still carried sparse, early-colonising assemblages, then separating clearly through the middle of the study (most distinctly at 7–9 months) before converging again by the final survey (12 months). The difference was in the identity of the groups occupying space rather than in the amount of space occupied. Barnacles dominated the available space on both, but control surfaces remained an essentially single-taxon, barnacle-dominated assemblage, whereas eco-engineered surfaces developed a more mixed community in which bivalves, macroalgae and tube worms were prominent. Tube worms were effectively confined to the eco-engineered piles and, together with bivalves and macroalgae, accounted for most of the compositional difference between treatments (SIMPER; Online Resource 1, Table S2); barnacles, despite their abundance, did little to distinguish the two. A small number of quadrats in each survey fell outside the treatment ellipses. These were quadrats with low total cover or dominated by a single group, in which one or two intercepted points determined the entire composition, producing dissimilarities distant from the treatment centroid.

Averaged over the study, this compositional difference was strong and reflected a shift in the assemblage rather than greater variability among eco-engineered piles (pile-level PERMANOVA on pile means, $n = 12$ piles, five control and seven eco-engineered: pseudo- $F_{1,10} = 12.14$, $R^2 = 0.55$, $p = 0.0013$; PERMDISP: $F_{1,10} = 0.03$, $p = 0.86$). The difference was not fixed but changed as colonisation proceeded, and varied with orientation and tidal height (quadrat-level PERMANOVA with permutations restricted within piles, $n = 270$ quadrats: Treatment $\times$ Time $R^2 =$

0.03, Treatment $\times$ Orientation $R^2 = 0.02$, Treatment $\times$ Time $\times$ Tide $R^2 = 0.05$, all $p = 0.0001$). As expected for a developing intertidal community, assemblage structure was shaped most strongly by time since deployment and by tidal height (the two largest sources of variation, explaining 22% and 11% of compositional variation respectively, both $p = 0.0001$), with orientation a smaller but consistent influence ($R^2 = 0.02$, $p = 0.0001$). Full test statistics and degrees of freedom for every term are given in Online Resource 1 (Online Resource 1, Table S2).

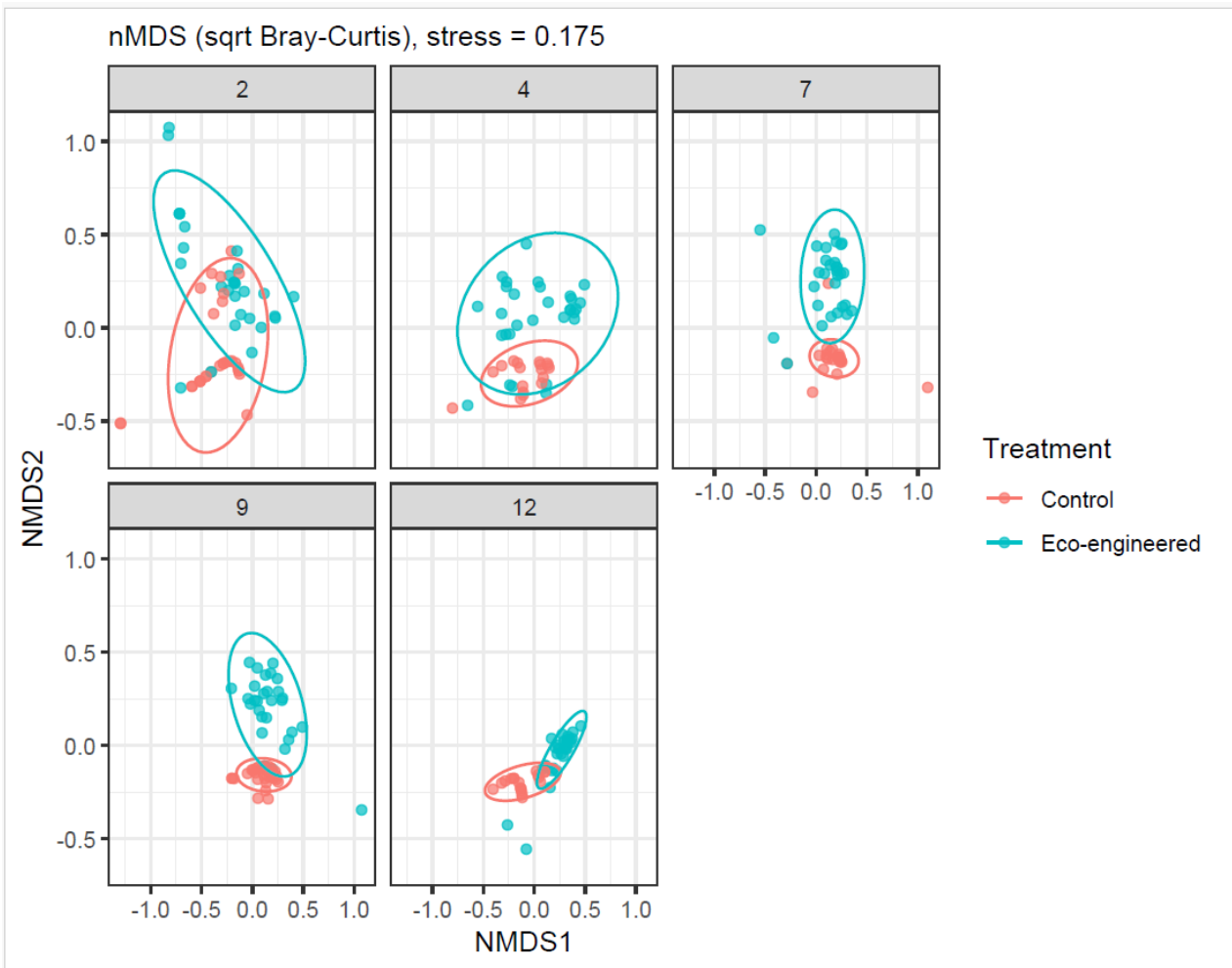


Fig. 2 Non-metric multidimensional scaling (nMDS) ordinations of sessile assemblage composition, shown separately for each survey month (2, 4, 7, 9 and 12 months after deployment), based on Bray-Curtis dissimilarities of square-root-transformed functional-group cover. Each point is a quadrat, coloured by treatment, with ellipses showing 95% confidence regions. All panels derive from a single ordination (stress = 0.175), so positions are comparable across months

5.1.2. *Pile assemblage diversity, richness, and cover*

Eco-engineered piles were consistently more diverse than control piles. Across all five surveys they supported nearly twice the functional-group richness (on average 2.8 versus 1.6 groups per quadrat; $n = 150$ eco-engineered and 120 control quadrats on 12 piles) and more than double the Shannon diversity (0.71 versus 0.26), differences that were already present at the first survey and strongly supported by the models (generalised linear mixed models, Wald χ^2 tests: richness, treatment $\chi^2_1 = 49.6$, $p < 0.0001$; Shannon diversity, treatment $\chi^2_1 = 27.2$, $p < 0.0001$; Fig. 3). This contrast reflected the barnacle monoculture that developed on control surfaces: control assemblages became progressively dominated by a single group and collapsed in diversity, whereas eco-engineered surfaces maintained a mix of groups throughout. The eco-engineered richness advantage also widened as colonisation proceeded (Treatment $\times$ Time, $\chi^2_4 = 11.3$, $p = 0.024$), with weaker evidence of change through time for diversity (Treatment $\times$ Time $\chi^2_4 = 9.2$, $p = 0.056$), and both richness and diversity declined from the low to the high shore (tide: richness $\chi^2_2 = 63.1$, $p < 0.0001$; Shannon diversity $\chi^2_2 = 10.6$, $p = 0.0051$).

Total cover followed a more dynamic trajectory (Fig. 3; beta-binomial GLMM, $n = 270$ quadrats, 54 per survey; values below are model-estimated means with 95% confidence intervals, averaged over orientation and tidal height, and odds ratios are control relative to eco-engineered). Eco-engineered piles already carried more cover than control piles at the first survey (46% [40 to 52] versus 36% [30 to 42]; odds ratio 0.665, $p = 0.029$), but the two converged as space filled rapidly on both treatments through the middle of the study (77% versus 75% at 4 months, $p = 0.62$; 84% versus 81% at 7 months, $p = 0.48$). They then diverged sharply: control cover declined over the final surveys while eco-engineered cover was maintained (88% versus 68% at 9 months, $p < 0.0001$), so that by 12 months eco-engineered piles carried far more cover than control piles (88% [84 to 91] versus 60% [52 to 67]; odds ratio 0.205, $p < 0.0001$). Bare space showed the mirror-image pattern, only slightly lower on eco-engineered surfaces early on (55% versus 64% at 2 months, $p = 0.032$), but far lower by the end of the study (12% [9 to 16] versus 37% [29 to 45]; odds ratio 4.32, $p < 0.0001$), indicating that eco-engineered surfaces not only accrued cover faster but retained it as control surfaces lost it. Across treatments, cover was higher on the shaded, rock-facing aspect and declined toward the high shore (Fig. 3).

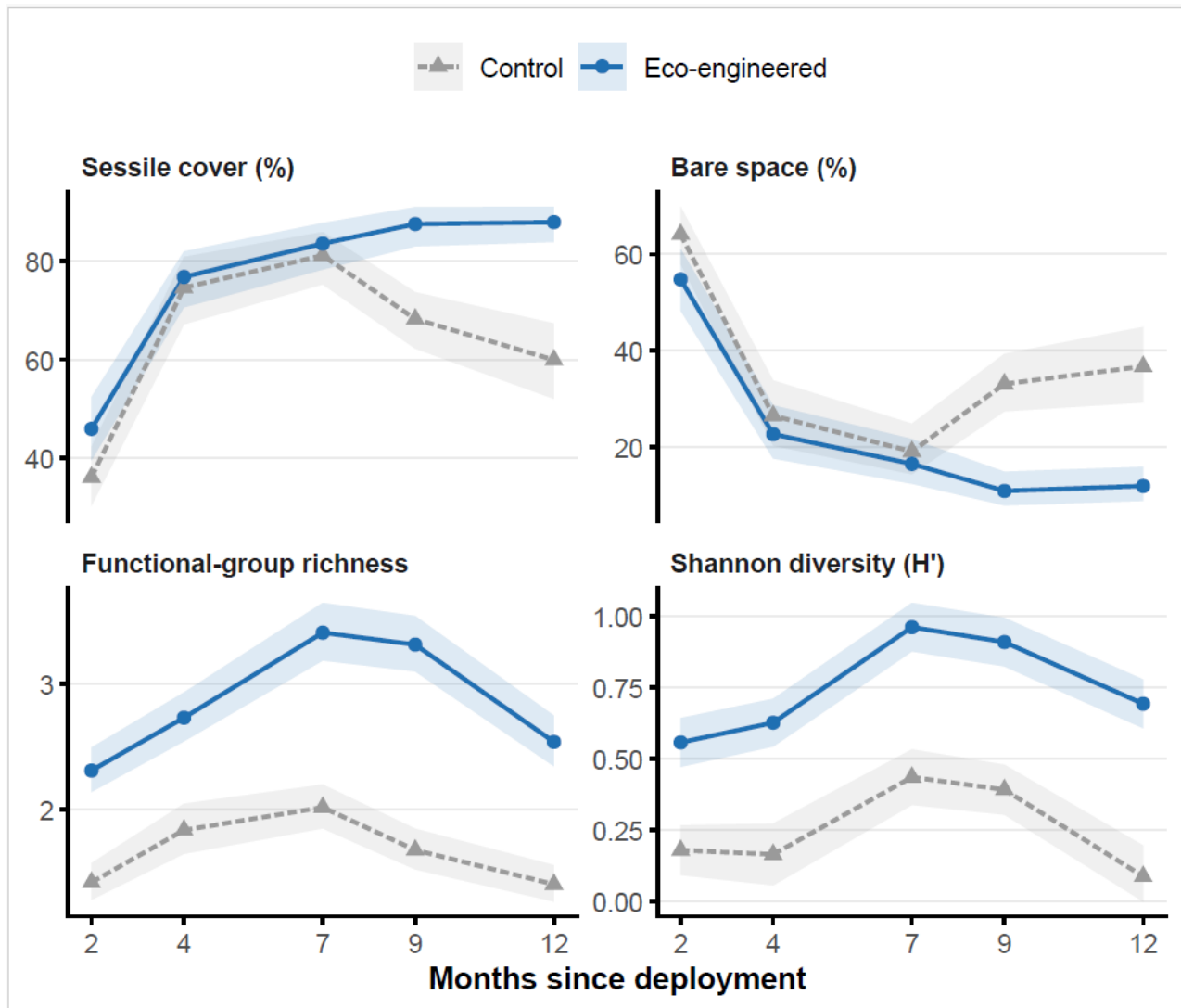


Fig. 3 Sessile assemblage responses on eco-engineered and control piles over the twelve-month experiment: total sessile cover (%), bare space (%), functional-group richness, and Shannon diversity (H'). Points show estimated marginal means from the generalised linear mixed models, averaged over tidal height and orientation, with shaded bands showing 95% confidence intervals (eco-engineered, blue; control, grey)

5.1.3. Functional groups responses

Barnacles were the dominant space-occupier on both treatments and differed little in overall cover between eco-engineered and control piles (beta-binomial GLMM, treatment $p = 0.65$; Fig. 4). What differed was their relative dominance through time: on control surfaces barnacles came to monopolise the available space, whereas on eco-engineered surfaces they remained interleaved with other groups (Treatment $\times$ Time, $\chi^2_4 = 23.0$, $p = 0.00013$). Model-estimated barnacle cover was higher on control than on eco-engineered piles at 4 months (68% versus 53%; odds ratio 1.91, $z = 3.425$, $p = 0.0006$) and at 7 months (62% versus 43%; odds ratio

2.12, $z = 4.386$, $p < 0.0001$), but similar at 12 months (59% versus 63%; odds ratio 0.867, $z = -0.776$, $p = 0.44$). The eco-engineered assemblage was therefore richer not through any reduction in barnacles, but through the addition of other groups alongside them.

The groups that distinguished the two treatments were bivalves, macroalgae and tube worms. Bivalves established later in the study and increasingly favoured eco-engineered piles (Treatment $\times$ Time, $\chi^2_2 = 50.0$, $p < 0.0001$; $n = 162$ quadrats from the 7, 9 and 12-month surveys), reaching far greater cover than control piles by 12 months (Fig. 4). Macroalgae were almost entirely restricted to eco-engineered surfaces, with mean cover of 6.4% on eco-engineered piles versus 1.1% on control piles ($n = 150$ and 120 quadrats), too scarce on control piles to model formally; they were present through the first part of the study but had largely disappeared by the final survey. Most strikingly, tube worms were effectively an eco-exclusive group: they were absent from control piles at every survey (0 of 120 control quadrats, against a mean cover of 8.1% across the 150 eco-engineered quadrats) and, as one of the three groups that together accounted for 70% of the dissimilarity between treatments (SIMPER; Online Resource 1, Table S2), formed the clearest signature of the eco-engineered treatment.

Within the eco-engineered piles ($n = 150$ quadrats on seven piles), these habitat-formers were strongly structured by orientation and tidal height. Tube worms were concentrated on the shaded, rock-facing aspect and in the lower intertidal: model-estimated cover was 11.1% (95% CI 9.3 to 13.1) on shaded surfaces versus 2.4% (1.7 to 3.3) on sun-exposed surfaces (orientation $\chi^2_1 = 90.3$, $p < 0.0001$), and declined from 9.5% on the low shore to 2.3% on the high shore (tide $\chi^2_2 = 52.9$, $p < 0.0001$). Macroalgae showed the opposite orientation preference, being more abundant on the sun-exposed aspect (orientation $\chi^2_1 = 9.3$, $p = 0.0023$; $n = 120$ quadrats from the 2 to 9-month surveys).

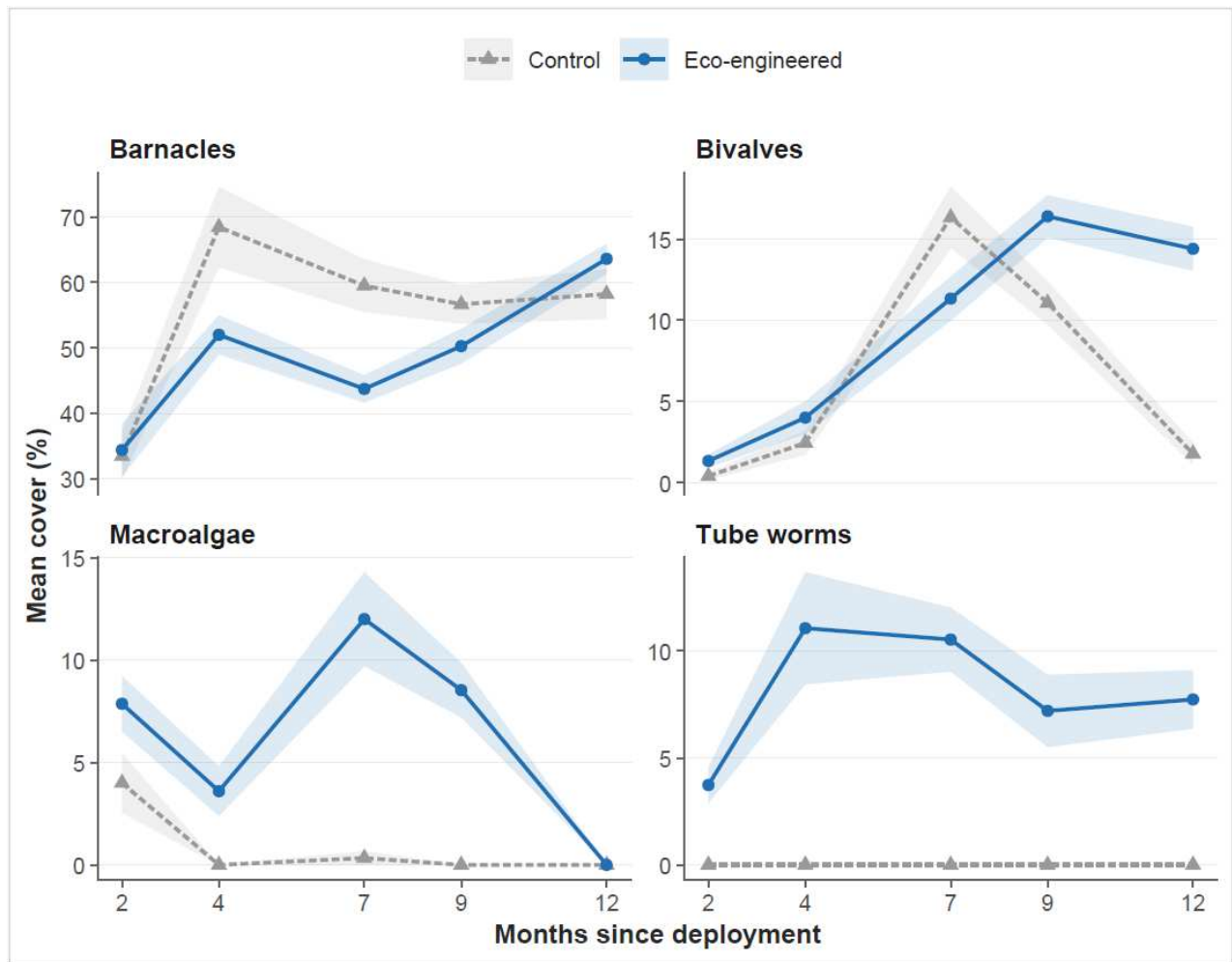


Fig. 4 Mean cover (%) of four sessile functional groups (barnacles, bivalves, macroalgae and tube worms) on eco-engineered and control piles over the twelve-month experiment. Points show mean cover across quadrats, with shaded bands showing ± 1 standard error (eco-engineered, blue; control, grey)

5.2. Surface thermal environment

The eco-engineered microhabitats were consistently cooler and more thermally stable than control surfaces, and the buffering strengthened from the open wrap surface to the interior of the water-retaining rock pools. Mean daily temperature declined across this gradient: 25.3 °C on control surfaces, 25.1 °C on the eco-engineered wrap, and 24.7 °C inside the rock pools (linear mixed model with day as a random effect, $n = 270$ control and 330 eco-engineered logger-days per orientation; microhabitat $\chi^2_2 = 1296.6$, $p < 0.0001$; Fig. 5). Accounting for the strong day-to-day and seasonal variation, the rock-pool interiors averaged 0.84 °C cooler than adjacent control surfaces (95% CI -0.88 to -0.80), and this cooling was greater on the shaded, rock-facing aspect (-1.04 °C) than on the sun-exposed aspect (-0.65 °C; microhabitat $\times$ orientation interaction $\chi^2_2 =$

285.0, $p < 0.0001$). The offset persisted year-round: all microhabitats tracked the seasonal cycle together, but the eco-engineered surfaces remained cooler throughout (Fig. 5).

The microhabitats also dampened the daily temperature swing. Mean diurnal range declined from 6.45 °C on control surfaces to 6.23 °C on the wrap and 6.04 °C inside the rock pools, a reduction of about 0.40 °C inside the pools (microhabitat $\chi^2_2 = 62.1$, $p < 0.0001$), roughly half of which was contributed by the pool itself beyond the wrap surface, while day-to-day variability in the range was also lower inside the pools (standard deviation 1.64 versus 2.15 °C), indicating a more stable as well as a cooler microclimate. In contrast to mean temperature, this damping was greatest on the sun-exposed aspect (microhabitat $\times$ orientation interaction, $\chi^2_2 = 13.1$, $p = 0.0014$).

The clearest effect, however, was on thermal extremes. Mean daily maxima inside the rock pools were 1.44 °C below control surfaces overall (95% CI -1.58 to -1.29; microhabitat $\chi^2_2 = 250.2$, $p < 0.0001$; microhabitat $\times$ orientation interaction $\chi^2_2 = 16.2$, $p = 0.00031$), and the buffering of the most extreme temperatures was larger still. The single hottest temperature recorded on a control surface reached 40.5 °C, whereas inside the rock pools the maximum never exceeded 34.0 °C, a capping of the peak by up to 6.5 °C (Fig. 6). These extremes were concentrated on the sun-exposed aspect, where control surfaces reached their highest temperatures and the wraps removed the most acute heat: 40.5 °C on control surfaces versus 34.0 °C inside the pools (a 6.5 °C reduction), compared with a smaller gap on the shaded aspect, where both stayed cooler (37.5 versus 33.0 °C).

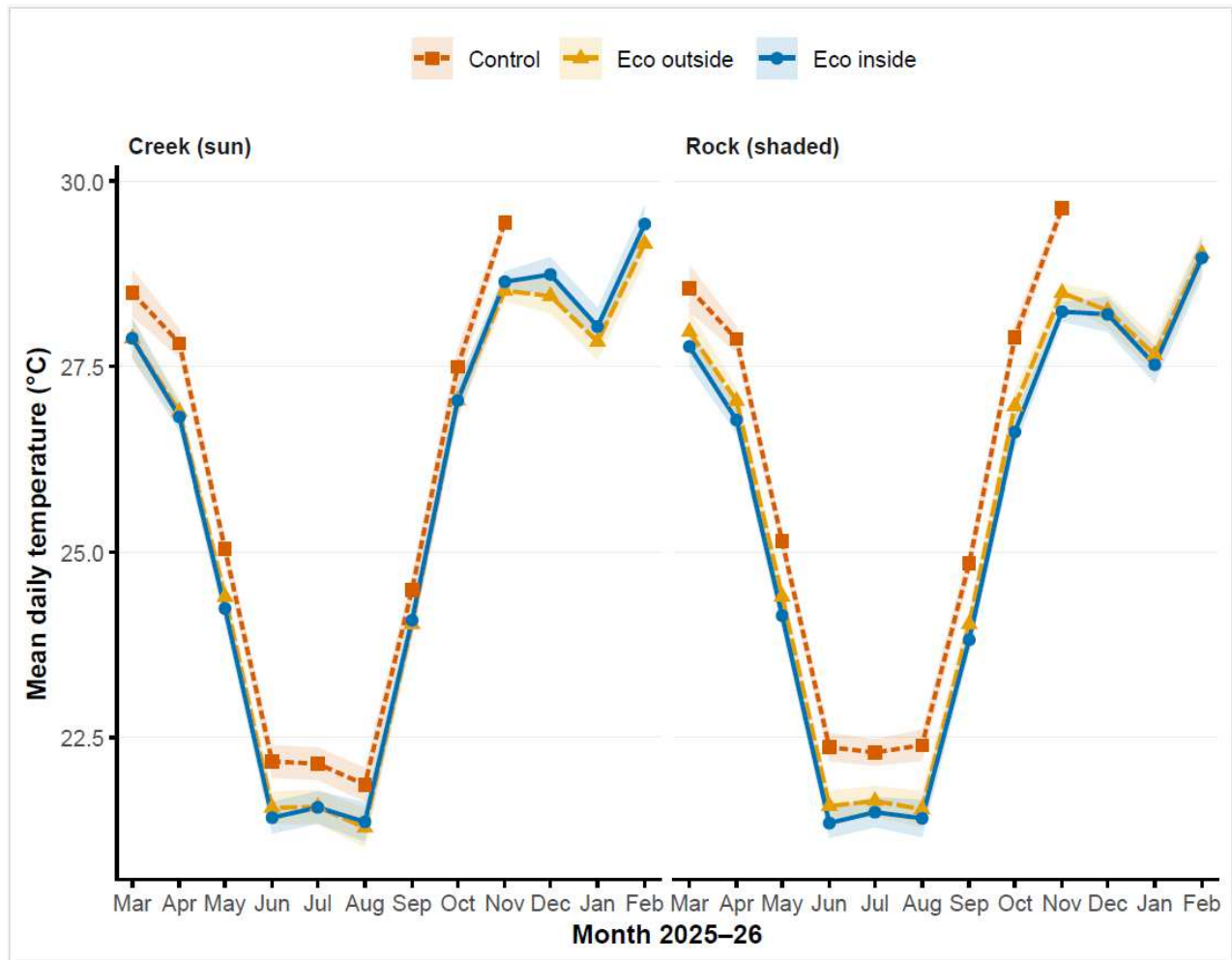


Fig. 5 Mean daily temperature (°C) recorded in three microhabitats (control pile surfaces, the outer surface of the eco-engineered piles ("eco outside"), and the water-retaining rock-pool interiors of the eco-engineered piles ("eco inside")) over the study period (March 2025 to February 2026), shown separately for the sun-exposed (creek-facing) and shaded (rock-facing) aspects. Points show monthly means of the daily means, with shaded bands showing ± 1 standard error (control, red; eco outside, orange; eco inside, blue)

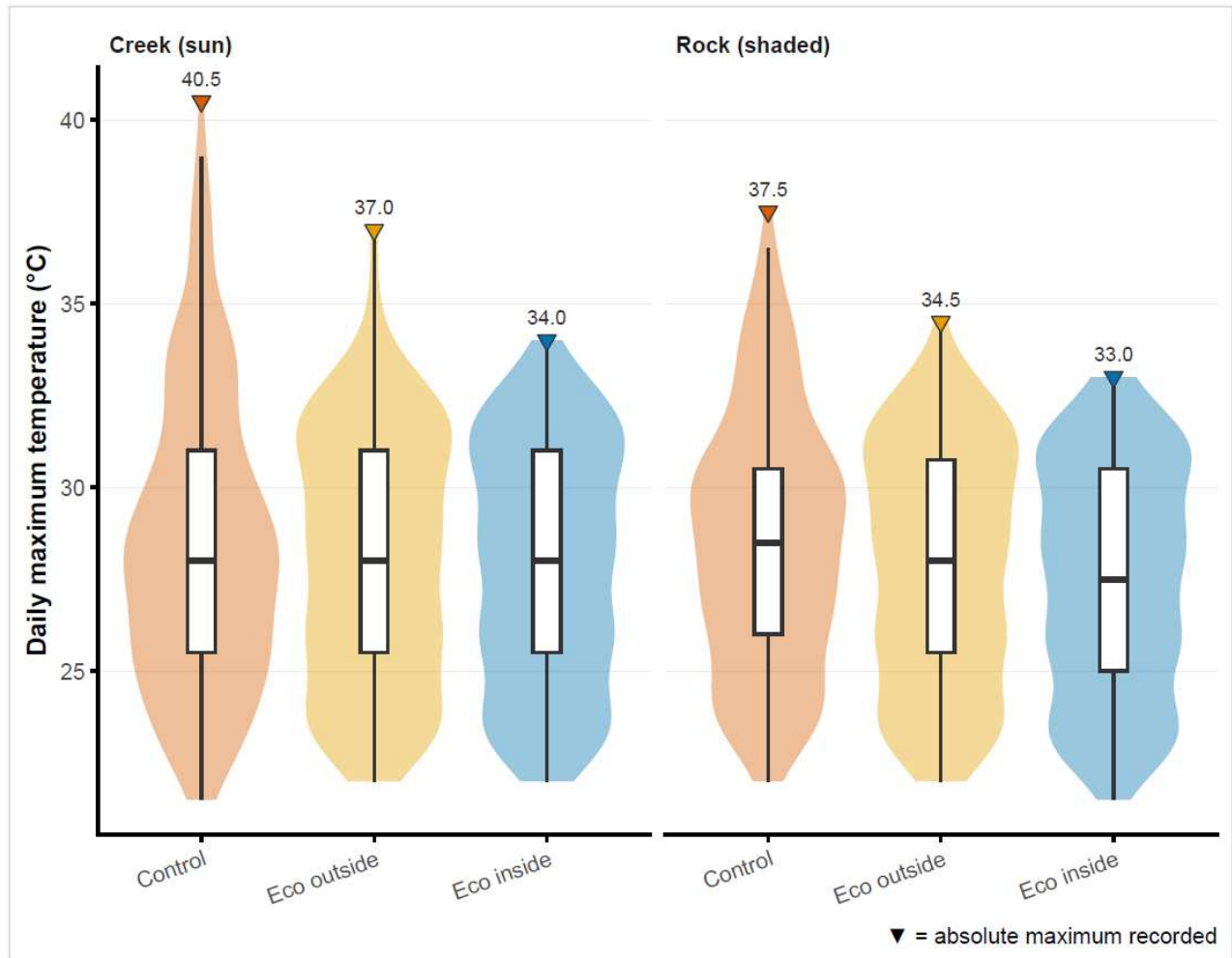


Fig. 6 Distribution of daily maximum temperatures (°C) in the three microhabitats (control pile surfaces, the outer surface of the eco-engineered piles ("eco outside") and the rock-pool interiors of the eco-engineered piles ("eco inside")), on the sun-exposed (creek-facing) and shaded (rock-facing) aspects. Violins show the distribution of daily maxima across the study period; boxplots show the median and interquartile range, with whiskers extending to 1.5 times the interquartile range. Inverted triangles mark the single highest temperature recorded in each microhabitat, with values labelled (°C)

6. Discussion & Conclusion:

This study presents a nature-positive case for retrofitting marine piles with 3D-printed, rock-pool-mimicking eco-engineered wraps, which enhanced biodiversity while simultaneously moderating the thermal environment experienced by colonising organisms. The eco-engineered wraps changed not only how much life the piles supported, but which organisms could persist on them. Control piles followed the trajectory typical of unmodified intertidal structures, converging on a barnacle-dominated monoculture that lost cover late in the study. The wraps, by contrast, sustained a more even assemblage in which several functional groups persisted, including taxa effectively absent from unmodified surfaces. The eco-engineered wraps also created

microhabitats that were consistently cooler, less thermally variable and less prone to temperature extremes than exposed control surfaces, with the water-retaining rock pools providing the greatest buffering. These two outcomes were not independent. The microhabitats that supported the richest assemblages were also the coolest and least thermally variable, and both effects were strongest on shaded aspects and lower on the shore. This spatial concordance is consistent with the eco-engineered wrap providing a thermal refuge from the extremes that characterise unshaded hard surfaces in this tropical setting.

6.1. Enhancement of the epibenthic assemblage

The magnitude of the biodiversity enhancement we observed is consistent with the broader eco-engineering literature, in which the addition of habitat complexity to artificial structures has repeatedly increased the richness and abundance of colonising assemblages (Gad et al., 2026; Strain et al., 2018). The overall increase, however, captures only part of the effect. More revealing was the way the eco-engineered piles restructured the assemblage. Control piles followed the trajectory typical of unmodified intertidal hard structures, developing a high but species-poor cover that converged over time towards a near-monoculture of barnacles. The eco-engineered piles, by contrast, supported a more even assemblage in which barnacles, bivalves, macroalgae and tube worms co-occurred, so that comparable overall cover was partitioned among several functional groups rather than dominated by one. This distinction underlies the diversity results: the eco-engineered piles did not simply add space for the same organisms but provided the structural and microhabitat heterogeneity that allowed groups largely excluded from plain surfaces to establish and persist.

Particularly notable in this respect were the tube worms, which were effectively restricted to the eco-engineered piles and all but absent from control piles, and which concentrated on the shaded, lower-tide microhabitats. Their near-exclusivity indicates that the eco-engineered piles did more than increase the abundance of existing colonisers; they supported taxa that the unmodified control piles could not. This pattern echoes findings on complex eco-engineered panels elsewhere, where water-retaining and shaded microhabitats have supported moisture- and shade-associated taxa that are otherwise absent from exposed artificial surfaces (Bishop et al., 2022). The concentration of tube worms, and of richness and diversity more generally, in the lower and shaded positions is also consistent with the wider observation that the biodiversity benefits of eco-engineering are typically greatest on the lower intertidal zone, where immersion is longer and thermal, and desiccation stress less severe.

6.2. *Thermal buffering and refuge mechanism*

An important finding here is that the eco-engineered wraps reshaped the thermal environment of the piles, in a way that is mechanistically consistent with their effect on biodiversity. On unmodified structures, thermal stress is concentrated in the hours of aerial exposure at low tide, when solar heating drives surface temperatures well above ambient and desiccation acts simultaneously; water-retaining features interrupt both processes by keeping the surfaces they enclose wet and shaded through emersion. Consistent with this, mean cooling inside the rock pools was modest, but the pools damped the daily temperature range and capped thermal extremes, reducing the hottest recorded maximum from 40.5 °C on control surfaces to 34.0 °C.

What matters biologically is where these values sit relative to organismal tolerances. Peak temperatures on control piles approached 40 °C, at or beyond the acute thresholds at which tropical intertidal invertebrates begin to lose function, and mass mortality of barnacles and oysters during heatwaves occurs precisely when extreme air temperatures coincide with midday low tides (Raymond et al., 2022). Experimentally, an increase of only a few degrees in maximum temperature, with almost no change in the mean, is sufficient to halve oyster survival (Scanes et al., 2025), and acute thresholds determined for common intertidal fauna in this estuary indicate that resident species would require thermal refuge for much of the day on unmodified seawall surfaces (Waltham & Sheaves, 2020). By holding maxima some 6 °C lower and shortening the time spent at stressful temperatures, the rock pools widen the thermal margin of the surfaces they create, and reduce the heat load accumulated across the year, relaxing the constraint that most limits colonisation of exposed structures.

These thermal effects were spatially concordant with the biological responses, which points to thermal amelioration as one mechanism underlying the biodiversity gains. The microhabitats that were coolest and least thermally variable, namely the shaded, lower-shore positions and the rock-pool interiors, were also those that supported the richest and most diverse assemblages and the highest cover of the more thermally sensitive groups, notably the tube worms. The same logic links the orientation effect to the thermal data, with the shaded aspect both cooler and more diverse than the sun-exposed aspect. Comparable patterns have been reported on tropical Queensland seawalls, where sun-facing boulder surfaces were up to 15 °C hotter than shaded faces and encrusting oysters occurred only on the cooler, shaded sides (Waltham & Sheaves, 2024), and rock-pool interiors on eco-engineered seawall panels have likewise been shown to cool and to support taxa absent from surrounding surfaces (Bishop et al., 2022). That we achieved comparable buffering on slender, vertical piles, rather than on the broad faces of a seawall or boulder revetment, indicates that these benefits can be delivered even on

the structurally constrained surfaces that piles present, and they are likely to be especially valuable in tropical urban estuaries where baseline temperatures already sit close to the tolerances of the resident biota.

Temperature alone does not account for the full pattern. Although the rock pools capped the most extreme temperatures most strongly on the sun-exposed side, biodiversity there remained lower than on the shaded side, indicating that factors beyond peak temperature, including greater exposure on the creek-facing aspect, cumulative thermal dose, immersion time and light, also shape the assemblage. Macroalgae ran counter to the general trend, being more abundant on the sun-exposed than the shaded aspect, implying that light availability rather than temperature governed their distribution. Thermal amelioration is therefore best understood as one of several co-acting mechanisms, operating alongside the additional surface area, structural complexity and cryptic space that the eco-engineered wraps provide.

6.3. *Management Implications*

Marine piles are ubiquitous in urbanised estuaries yet remain one of the least-studied structure types in eco-engineering, and therefore represent a substantial and largely unrealised opportunity for biodiversity enhancement. The eco-engineered wraps tested here were retrofitted to existing, in-service piles without modification to the host structure, demonstrating that the ecological value of hard infrastructure can be improved after construction rather than only at the design stage. This matters given the vast stock of piles already in place in ports, marinas and waterfront developments worldwide, few of which will be replaced within the coming decades. Because the eco-engineered wraps are modular and clamp directly onto standard piles, the approach is in principle readily scalable and transferable to comparable structures elsewhere.

The results also indicate where such interventions should be placed. Benefits were consistently greatest at lower tidal elevations and on shaded aspects, so eco-engineered wraps positioned low on the shore, or on the shaded faces of structures, can be expected to return more per unit installed than those placed high on sun-exposed surfaces. Where budgets or structural constraints limit the number of units, targeting placement in this way is likely to be more effective than distributing them evenly across a structure.

Framed as climate adaptation rather than biodiversity enhancement alone, the thermal results carry a further implication. As heatwaves become more frequent and intense (Marcos et al., 2025), the value of built-in thermal refugia should increase rather than diminish: there is a case that unmodified structures have no capacity to buffer the extremes projected to intensify, whereas features that hold water and shade through emersion will continue to cap peak

temperatures (Waltham & Sheaves, 2024). Retrofitting existing infrastructure is therefore a form of adaptation for the species already occupying urban shorelines, and one that need not wait for structures to reach the end of their design life. And in the case of these modules, they could be unbolted and moved higher on piles in the future with higher sea levels.

Two pathways follow for coastal planning. For the existing stock of piles, retrofit is the only realistic route. For new construction, water-retaining features can be incorporated at the design stage, avoiding the added mass and clamping hardware that retrofit requires and allowing complexity to be built into the structure itself. Embedding such requirements in development approvals and design standards would deliver these outcomes at a scale that voluntary retrofit cannot. Any such application should be bounded, however: eco-engineering compensates only partially for the habitat that hardened shorelines displace, and should not be used to justify further coastal development (Firth et al., 2020).

The ecological return is also likely to be greater than our surveys capture. Crabs and fish were conspicuous around the eco-engineered wraps, using the cryptic, sheltered space that unmodified piles lack, although neither group could be quantified by the point-intercept method used here. The benefits reported for the sessile assemblage should therefore be regarded as a partial account of the value these structures provide.

6.4. Limitations and future directions

Several limitations qualify these findings and indicate priorities for future work. The study was conducted at a single estuary over twelve months, so the generality of the results across estuaries, structure types and longer timeframes remains to be tested. The thermal and biological data were also resolved at different scales, the loggers distinguishing the rock-pool interior but confined to mid-tide height, the biological surveys resolving orientation and tidal height but not the interior of the rock pools, so the link between the cooler microhabitats and the assemblages they support is inferred rather than directly demonstrated. Pairing temperature logging with biological sampling at the same positions, including within the rock pools themselves, would allow this thermal-refuge mechanism to be tested directly.

The survey design also bounds what can be concluded. Scoring the assemblage to functional groups rather than species was necessary for repeatable, non-destructive survey across five occasions, but limits inference about which taxa the eco-engineered wraps actually favoured, and may obscure turnover occurring within groups. Mobile fauna were likewise not quantified: crabs retreated into the eco-engineered wraps' crevices and rock pools as observers approached, and fish aggregated around the structures only at high tide, so neither could be

counted reliably by the point-intercept method. Timed counts, baited remote cameras or trapping would capture these mobile and transient components and give a fuller account of the ecological return on eco-engineering of piles.

There are also constraints arising from the design itself. Because a single wrap design was tested, the contributions of its individual features cannot be separated: the water-retaining rock pools, the additional surface area and the sheltered gap between wrap and pile all covary, and comparing designs that isolate these elements would identify which are doing the work. The eco-engineered wraps are substantial concrete units, weighing approximately 73 kg each, such that a fitted pair with its clamps exceeds 150 kg, and therefore add considerable load to the host pile. They are consequently best suited to structurally sound piles able to bear this additional weight, and may not be appropriate for older, lighter or load-limited structures without engineering assessment. Lighter materials or designs delivering comparable complexity and water retention at reduced mass would broaden the range of piles to which the approach could be applied, and warrant investigation.

A further consideration emerged over the course of the experiment. By the later surveys (months 9 and 12), several of the rock pools had begun to accumulate sediment, in places to a depth of around 5 cm, partially infilling the water-retaining features on which the thermal and biological benefits depend. This suggests that the current design may require modification to promote self-flushing or to limit sediment retention, and, more broadly, that the performance of such features cannot be assumed to be stable over time (a similar sediment accumulation result was found in a separate study, using water-retaining flower pots (Waltham & Sheaves, 2024)). It underscores the need for longer-term monitoring: the differences we documented developed and shifted over the twelve months, the control assemblage declined late in the study, and the rock pools began to infill, all of which indicate that short-term assessments may misrepresent the trajectory and persistence of eco-engineering outcomes. Multi-year monitoring, tracking both the biological assemblage and the physical condition of the habitat features, is essential to establish the durability of the benefits reported here and to guide design improvements.

6.5. Conclusion:

Retrofitting marine piles with 3D-printed, rock-pool-mimicking eco-engineered wraps substantially enhanced the biodiversity of a tropical urban estuary while simultaneously moderating the thermal environment of the colonised surfaces. Over twelve months, the eco-engineered wraps supported a richer, more diverse and more evenly structured sessile assemblage than unmodified piles, which converged towards a barnacle-dominated monoculture,

and their water-retaining rock pools were cooler and markedly less prone to thermal extremes than exposed control surfaces. The cooler shaded and lower-shore microhabitats supported the most diverse assemblages, a spatial concordance consistent with the eco-engineered wraps providing a thermal refuge alongside the additional surface area and structural complexity they offer.

These results identify marine piles, among the most ubiquitous yet least-studied of artificial structures, as a widespread and currently underused opportunity for eco-engineering, and show that their ecological value can be improved by retrofitting existing structures rather than only through maintenance upgrades or new design. The benefits reported here are likely conservative, given that mobile fauna observed around the eco-engineered piles could not be quantified, but their persistence is not assured. The rock pools began to accumulate sediment within a year, a problem also encountered in the tropics with flower-box style rock pools, where sediment accumulation likewise compromised the water-retaining features (Waltham & Sheaves, 2018), and the assemblage continued to change throughout the study. Longer-term, multi-site assessment, coupled with design refinements to maintain the water-retaining features and reduce structural load, will be needed to confirm the durability of these benefits.

The scope for such interventions is considerable. With the global footprint of marine built structures projected to approach 39,400 km² by 2028, the opportunity extends well beyond retrofitting: incorporating water-retaining, rock-pool-mimicking features into new piles and associated infrastructure at the design stage could deliver nature-positive outcomes at a scale that retrofitting alone cannot achieve. Eco-engineering of both existing and future marine infrastructure therefore represents a practical pathway for improving biodiversity outcomes while enhancing climate resilience in rapidly urbanising coastal ecosystems.

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