Pilot Report 2022-02

Modifications of Coastal Protection Structures to Enhance Biodiversity and Ecosystem Services

January 2022

Lucy A. D. Lockwood, Robert Chen

School for the Environment, University of Massachusetts Boston

Project funding by the Stone Living Lab in response to RFP#19-1

Stone Living Lab

stonelivinglab.org

Stone Foundation Boston Harbor Islands Living Laboratory for Coastal Resilience

Pilot Project Report

January 25, 2022

Modifications of Coastal Protection Structures to Enhance Biodiversity and Ecosystem Services

Lucy A. D. Lockwood, M.S.

Robert F. Chen, Ph.D.

ABSTRACT

Construction of seawalls, breakwaters, jetties, and other forms of human-engineered coastline has increased globally in response to coastal development pressures. Shorelines "hardened" by such protection structures alter intertidal and shallow subtidal marine ecosystems, affecting the vital ecosystem services provided. The negative impacts of hard coastal protection systems (CPS) have spawned research into CPS design features that could provide better-quality habitat for intertidal and shallow subtidal marine organisms. Substrate material and surface topography are two important design features which were experimentally tested using concrete and granite tiles deployed in the lower intertidal region of Dorchester Bay, Massachusetts. In two concurrent experiments, concrete tiles with cut crevices of varying depth and width, and concrete tiles embedded with the shells of one of the common local bivalve species, *Mytilus edulis, Mercenaria mercenaria,* or *Crassostrea virginica*, were mounted in frames perpendicular to the water's surface. Additional tiles of local granite were included to replicate the historic seawalls of the region. Smooth concrete tiles served as controls in both experiments. The 50 experimental tiles were monitored and photographed over a period of 14 months to assess differences among the treatments in surface area colonized by marine invertebrates and macroalgae, and differences in overall species richness and community composition. The dominant colonizers across all treatments were the snail *Littorina littorea*, the barnacles *Semibalanus balanoides* and *Amphibalanus* improvises, and the red crustose algae *Hildenbrandia rubra*. Intense herbivory pressure by *L. littorea* limited macroalgal species *Porphyra umbilicalis*, *Ulva* sp., and *Ascophyllum nodosum* to crevice areas, both the crevices cut into the tiles and those afforded by the embedded shells and colonizing barnacles. Community composition differed slightly between the tiles with crevices and those with embedded shells, but differences among crevice types and among shell types were not significant. The tiles with crevices and with embedded shells had greater species richness and proportion of area colonized than did the smooth concrete tiles, the granite tiles, or the discs of $CaCO_3$ enhanced concrete.

Overall, the presence of crevices, provided by cutting grooves into flat tiles or embedding shells into tiles increased the abundance, species richness, and survivability of both macroalgae and invertebrates.

I) RATIONALE

Sea-level rise combined with warmer sea and air temperatures and greater intensity storms now threatens inhabited coastal areas around the globe (Melillo et al., 2014; Fleming et al., 2018; Kulp and Strauss, 2019; Taherkhani et al., 2020; Xie et al., 2019). The pressures of larger coastal populations and surging development combine with these threats to produce ever higher demand for protection along the world's shorelines, including those in New England (Climate Central, 2019; Colenbrander et al., 2019; Doggett, 2015; Tiernan, 2019; Union of Concerned Scientists, 2019; Jin et al., 2015; Neumann et al., 2015). So called "hard" or "grey" engineering solutions fortify shores against wave energy and storm surges by means of concrete, stone, or steel seawalls, breakwaters, bulkheads, or revetments (Bishop et al., 2017; (Jin et al., 2015; Pranzini, 2018; Rangel-Buitrago et al., 2018; Williams et al., 2016; Munari et al., 2011). The ecological impacts of hard coastal protection structures (CPS) have become a source of concern as the amount of hardened shoreline has continued to grow (Firth et al., 2016; Chapman and Bulleri, 2003; Choi et al., 2018). Multiple studies have documented deleterious changes to the intertidal and shallow subtidal marine communities on and adjacent to CPS (Bozek and Burdick, 2005; Dethier et al., 2016; J. Dugan et al., 2017; J. E. Dugan et al., 2008; Vaselli et al., 2008; Airoldi et al., 2015; Lovall et al., 2017; Bulleri and Ecology, 2005). To improve ecosystem co-benefits, "soft eco-engineering" (Morris et al., 2018),"nature-based", or "green" approaches are now being considered by integrating natural protection features, such as salt marshes (Vuik et al., 2016; Narayan et al., 2017; Shepard et al., 2011), mangroves (Zhang et al., 2012), sand dunes (Fernández-Montblanc et al., 2020), and beaches (Hanley et al., 2014). Still, in heavily populated urban environment, the economic value of space may make using mostly vertical seawalls to protect urban infrastructure the only available option. The question remains, can we make a better seawall?

The intertidal and shallow subtidal regions provide important ecosystem services (Barbier, 2012; Littles et al., 2018). In New England, the coastal food webs include a range of invertebrates, such as crustaceans and smaller forage fish, that support larger commercially important fish species (Amara and Paul, 2003; Lazzari and Tupper, 2002; Magill and Sayer, 2002; Quammen, 1984; Rossong et al., 2011; Rountree and Able, 1997; Seitz et al., 2014; Silva et al., 2010; Staudinger et al., 2020; Suca et al., 2018). These shoreline regions also provide critical habitat for the reproductive and juvenile stages of many of marine species including commercially important ones including lobster while multiple commercially important species of shellfish spend their entire life cycle there (Goldstein and Watson, 2015; Jones and Shulman, 2008; Rossong et al., 2011; Wahle and Steneck, 1991). Intertidal and shallow water coastal areas also support many avian species, from shorebirds to ducks to fish-eaters such as osprey (Ellis et al., 2007). The numerous sessile filter-feeders that inhabit these regions improve water quality by removing organic matter from near shore waters (Bracken et al., 2012; Pather et al., 2014; Grizzle et al., 2008). Coasts also provide quality of life amenities in the form of boating, swimming, and shoreline recreation; and are associated with positive health benefits for those living and recreating around them (Hooyberg et al., 2020; Bell et al., 2015; Depledge and Bird, 2009; Garrett et al., 2019; Grellier et al., 2017; Wheeler et al., 2012; White et al., 2013, 2014).

In Massachusetts and other New England states, substantial amounts of the coast have already been hardened through the use of CPS, including seawalls, revetments, bulkheads, breakwaters, and jetties (Gillespie 2013; Fontenault et al., 2013). Recent estimates are that sixty percent of Boston Harbor shoreline is hardened (Fontenault et al., 2013). Most of New Hampshire's eighteen miles of ocean-facing coast is hardened (Blondin, 2017; Rice, 2015). With sea level slowly but inexorably rising along the coast (just over 3 mm annually in Boston), it is unclear whether purely soft coastal protection systems, such as salt marshes and beach nourishment, will prove capable of providing protection in the face of rising waters and increased storm intensity (Temmerman et al., 2012; Boon et al., 2018; FitzGerald and Hughes, 2019; Roman, 2017; Vousdoukas et al.,2020). Thus, it is reasonable to assume that the amount of hard CPS in New England, and the world, will remain high in coming decades.

Given the importance of intertidal and shallow subtidal habitats and the ecosystem services they provide, the negative impact on coastal ecosystems that CPS have had worldwide, and that thousands of kilometers of CPS-hardened shoreline exist and will continue to exist for decades or longer, a global need exists for proven techniques for designing or retrofitting existing CPS to improve the quality of habitat they provide (Airoldi et al., 2020). The past five years has brought forth a wide variety of research efforts aimed at increasing biological diversity and productivity on CPS. While some patterns are emerging, much remains unclear in terms of treatments that reliably produce biologically-friendly structures, particularly within the framework of realistic engineering and budgetary constraints, and work in the temperate Northwest Atlantic remains limited.

II) RESEARCH OBJECTIVES

The **overall goal** of this pilot project was to assess whether innovation in the surface structure or surface composition of vertical concrete shoreline seawalls could enhance intertidal biodiversity compared to plain vertical concrete seawalls and bulkheads, many of which exist around Boston Harbor and along coasts throughout the world. This initial research aimed to test the efficacy of and refine the design of two approaches to improving habitat quality on concrete seawalls and similar structures for ecologically important intertidal marine organisms. Both experiments altered the vertical structure surface using simple, low-cost materials and techniques which could be equally applied to new installations or the retrofitting of existing ones. The design intention was to keep marine habitat-supporting alterations at the structure's surface, implementing them through the addition of an outer layer of tiles or added concrete skim-coat, for example. This would allow concrete coastal protection structures to be built or repaired according to established coastal engineering principles and designs for the core while providing much improved marine habitat on ocean-contacting surfaces.

Specific research objectives were:

A) To test whether the addition of horizontal crevices (of varying width and depth) in vertically mounted concrete tiles increased biodiversity (species abundance, and richness) on the tile surface compared to tiles without crevices.

B) To test whether the inclusion of shells of local intertidal shellfish species (clam, mussel, oyster) in the surface layer of vertically mounted concrete tiles increased biodiversity (species abundance, and richness) on the tile surface compared to plain concrete tiles and to tiles of local granite, as both concrete and granite have been used extensively for seawalls and bulkheads around Boston Harbor.

III) RESEARCH METHODS

Project Overview

Forty-five custom concrete tiles with various surface alterations along with five custom-cut tiles of native granite (50 experimental surfaces total) were deployed in two separate experiments at the mouth of Savin Hill Cove in Boston Harbor in late August of 2019.

A) Crevice Tiles Experiment

Commercial 7”x7” square (18 cm x 18 cm x 4 cm) flat concrete outdoor paving tiles (Pavestone brand) served as the basis for the crevice experiment. Horizontal crevices were cut into the concrete tiles using a table saw equipped with a carbide blade. Four sets of crevice designs were created from combinations of two different widths: 4 mm (“narrow”) and 12 mm (“wide”) and two different depths: 5 mm (“shallow”) and 15 mm (“deep”). Two crevices of the same combination of depth and width were cut on each experimental tile, with each crevice spaced 6cm from the tile edge and 6cm from the other crevice to minimize the influence of either (see Figure 1). Five replicates of each crevice type (narrow-shallow, narrow-deep, wide-shallow, wide-deep) were created. Five of the plain pavers with no crevices served as controls in the experiment.

B) Surface Experiment: Shell-Embedded Concrete and Granite Tile

Using commercial concrete formulated to withstand freezing and salt exposure, custom 8-inch square tiles were poured using commercial molds lined with shells of three abundant native bi-valve species: *Crassostrea virginica* (American oyster), *Mercenaria mercenaria* (hard clam), and *Mytilus edulis* (blue mussel). The shells had previously been sun-dried for over 12 months. After pouring and setting, the tiles were cured for over a month to properly harden the concrete before deployment. In addition to five replicates of each of the three embedded shell types, a set of five plain control tiles with no shells was also poured and cured using the same concrete and molds. Finally, given the extensive historical use of locally quarried granite for seawalls and piers in the region, granite cladding stones quarried from southern New Hampshire were purchased and then, using a table saw and carbide blade, were cut into rough tiles of approximately the same 8”x8” dimensions as the poured concrete ones (see Figure 2).

C) Frames

Galvanized steel L-bar was used to construct ten mounting frames, each holding five tiles (see Appendix A for design). A sacrificial zinc anode was attached to each frame to slow corrosion of the steel under conditions of twice-daily immersion in salt water. UV-stabilized zip ties were used to secure the top and bottom of each tile to the frame. The back of each frame was mounted to two concrete blocks, one at each end of the frame, securing the frame horizontally with the tiles held perpendicular to the sea surface. The steel frames were monitored over the course of the experiment but showed no evidence of significant internal corrosion and subsequent loss of strength.

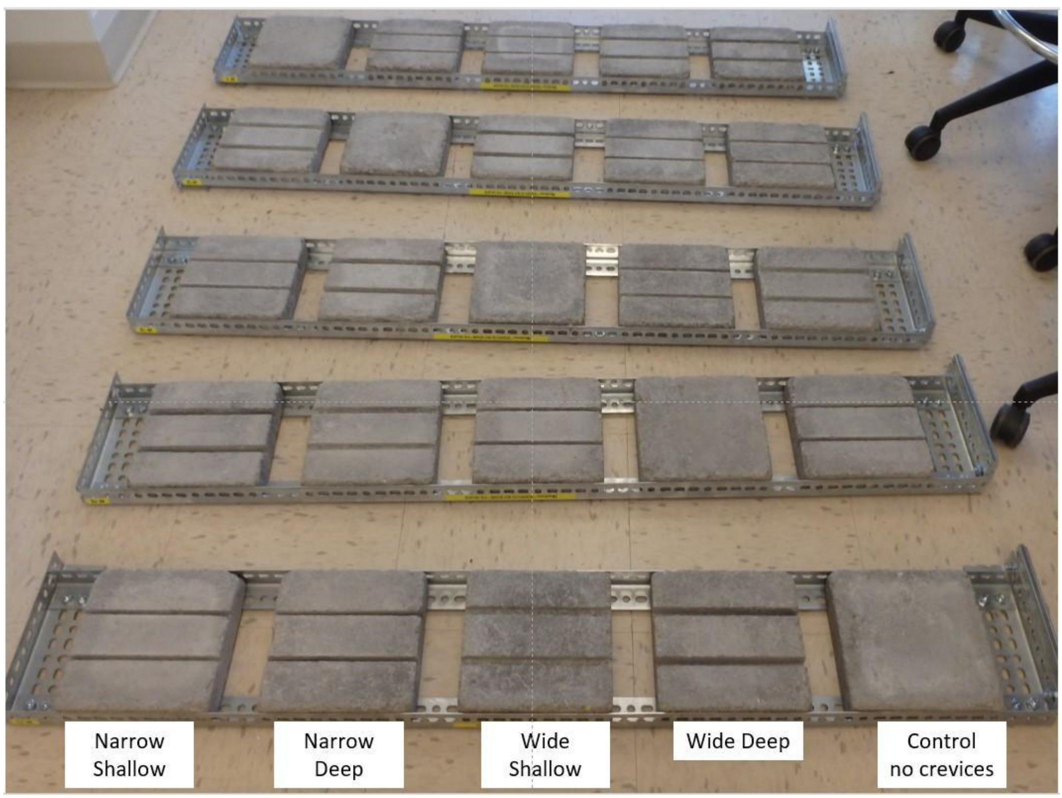


Figure 1 Crevice Tiles before deployment showing the four crevice types and the control. Note how the tile types are shuffled in position within the five frames so that no tile type is in the same position nor adjacent to the same tiles in all the frames.

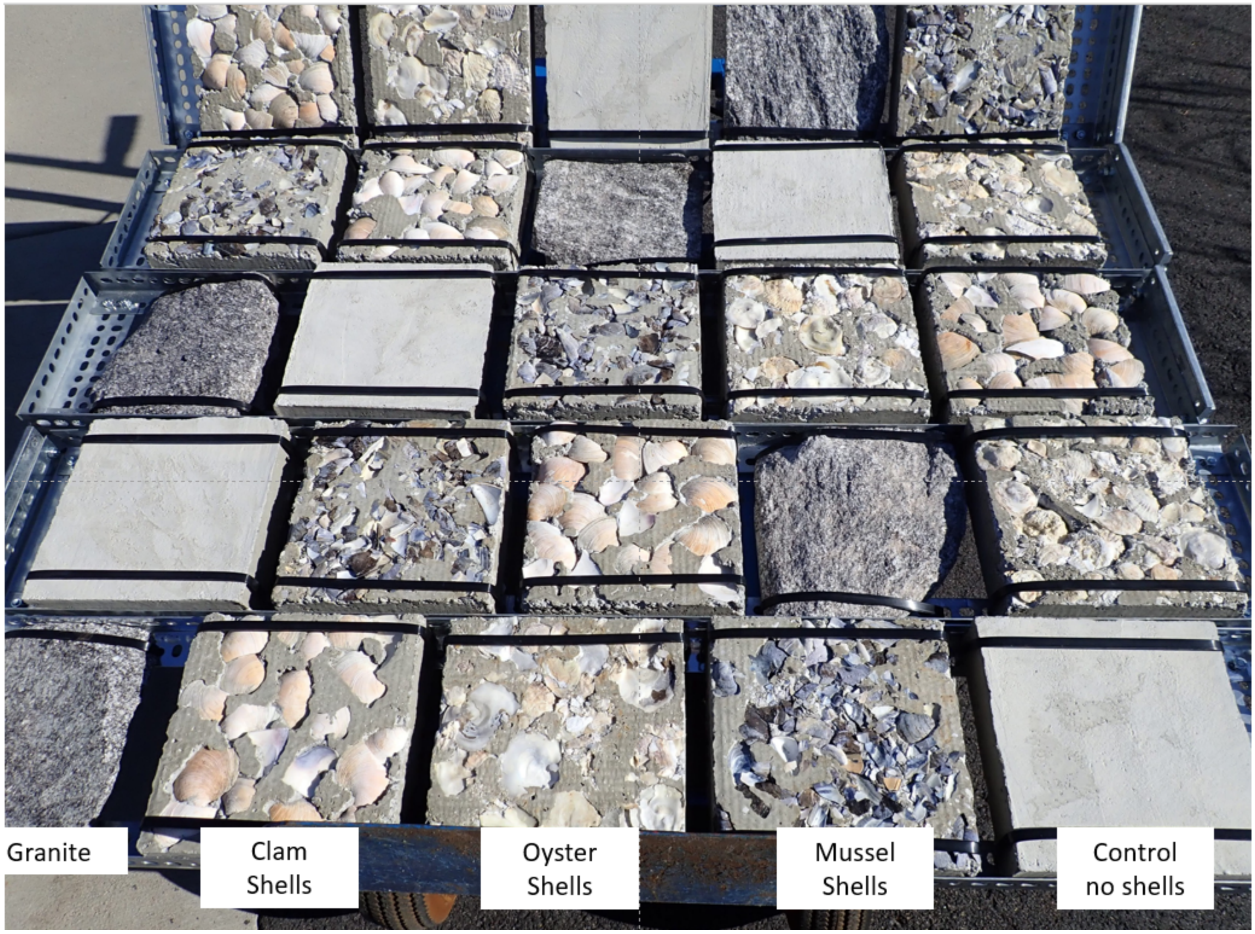


Figure 2 Shell-embedded and granite tiles before deployment. Note altered tile order for each frame.

Table 1. Factorial design of the crevice and surface experiments

Crevices		Replicates	Surfaces		Replicates	
Narrow/Shallow	NS	5	Clam	CM	5	
Narrow/Deep	ND	5	Mussel	MU	5	
Wide/Shallow	WS	5	Oyster	OY	5	
Wide/Deep	WD	5	Granite	GR	5	
Control	CC	5	Control	CO	5	
	Total	25		Total	25	

D) Site

The ten frames of tiles were deployed in the lower-mid intertidal zone on a sandbar adjacent to UMass Boston in Savin Hill Cove within Boston Harbor. The frames were placed three meters apart, all at the same approximate elevation of 2.5 feet above MLLW. Emersion time, the period when the tiles and the organisms were out of the water, averaged 4 hours for each tidal cycle, or approximately 8 hours over the course of the twice-daily tidal cycles. The frames were deliberately oriented to face Southwest so the tile surface would be subjected to the challenge of heating and drying by mid-day and afternoon sun when exposed around low tide on hot summer days.

E) Monitoring

The tiles were observed and photographed approximately monthly after deployment in order to track any settlement and growth on the tile surfaces. The photographic protocol, using a Ricoh G900 camera and an Olympus TG-5 camera, included individual full-frame straight-on shots of each tile plus a straight-on shot of each frame of five tiles. As part of the observation process, any interesting or unusual species on a tile was photographed in macro close-up mode and close-ups of all tiles were taken quarterly. Frames were checked monthly for degradation.

F) Photographic Analysis

Photos taken of the tiles in October 2020 with a Ricoh G900 camera were used to determine the percent cover by live barnacles used in the statistical analysis. The photos were sorted, graded, tagged, and catalogued using PhotoMechanic 6.0 software (CameraBist, 2021). The selected photos were then processed for image enhancement and a photo quadrat layer file created using PhotoQuad (Trygonis, V., 2016). Using tools in the PhotoQuad software every tile photograph was carefully analyzed at various zoom levels to identify live barnacles and mark them as regions of interest, coded by barnacle species, from which the percent cover by live barnacles was derived. *Littorina littorea* snails on each tile were assessed as a simple count (since they are mobile percent cover is not applicable) in a separate process.

G) Data Analysis

The statistical analysis was performed using the R programming language v.4.1.1 (R Core Team, 2021) in RStudio v.2021.09.0 (RStudio, Inc., 2021) along with additional code packages written to extend R capabilities. The initial data entry was done using Microsoft Excel for Windows version 14.0.07 (Microsoft Corporation, 2010) and the data file then read into R for the statistical analysis. Using R, summary statistics and initial data visualization for both the Crevice Tile Experiment and the Surface Tile Experiment were computed. The two experiments each included twenty-five observations with balanced data (equal numbers of observations for each level of a factor). For each experiment, multiple linear models were fit using additional regressor terms with the percent of each tile covered by live barnacles as the continuous response (dependent) variable. The different models were then compared using log-likelihood, AIC and other tests. Results from the model with the best fit—tile type as a single categorical independent fixed factor—were then used with ANOVA (Type I) to determine whether significant differences existed in the percent cover of each of the different tile types using an alpha of 0.05. Normality checks (Kolmogorov-Smirnov test, Shapiro-Wilk test, QQ and other plots) and homogeneity tests (Fligner- Killeen, Levene's) were carried out on the data and on the model residuals to confirm that the assumptions of ANOVA were met.

IV) RESULTS

After both experimental sets of tiles were deployed in late August of 2019, sporadic and spatially scattered settlement by *Amphibalanus improvises* (Bay barnacle) occurred across all tile types during the fall. Settlement was quite limited however, and the first monitoring check of 2020 (which took place mid-February due to weather conditions in January) showed no further colonization and a decrease from the fall. This was not surprising as winter is not a period of intertidal recruitment in the Gulf of Maine for the obvious reasons of sub-freezing air temperatures when exposed and the danger of ice-scour during the twice daily tidal changes and during winter storms.

Three months later (after a Covid-19 imposed hiatus), all tiles were covered in *Semibalanus balanoides*, the common Northern rock barnacle, following its typical March-April reproductive period. Barnacles are pioneer species, providing habitat for other invertebrates and food for carnivorous snails. The summer months brought settlement of pioneer seaweeds: the green macroalgae *Ulva sp*. and the red microalgae *Porphyra umbilicalis*. The tiles experienced significant grazing pressure from the abundant herbivorous snail *Littorina littorea*, the common periwinkle, which kept macroalgal settlement limited to the tile crevices and crevices around the barnacles and embedded shells. The intense herbivory along with several heatwaves in August 2020 kept macroalgal growth to a minimum. Algal germlings repeatedly began growing amongst the barnacles and within the crevices but would never progress in size beyond 3-4 cm. Colonial invertebrate species, including *Halichondria panicea* (breadcrumb sponge), *Botrylloides violaceus* (orange sheath tunicate), and several bryozoans, appeared sporadically over the summer but none had established growth by the project's end in October 2020.

Despite the overall limited number of species and limited abundance, differences in settlement and survival were observed among treatments in both experiments. The wider crevices supported more initial settlement and growth of macroalgae, while in both experiments, the plain concrete control tiles, lacking either crevices or shell pieces, had the lowest overall barnacle survival and the least species diversity for the duration of the project.

Barnacles are not only pioneer species, often the first invertebrates to establish on any bare intertidal surface, but with their irregular shells and often densely packed settlement, barnacles provide structure and conditions that facilitate the settlement and growth of other marine species. As hardy as barnacles are, they are not immune to being sheared off hard substrates, eaten by predators, and in summer will succumb due to excessive solar heating. Species abundance in the form of tile surface cover by live barnacles, therefore, was the indicator used to measure the effectiveness of the multiple tile treatments after 14 months.

The experiments were analyzed separately because the difference in tile size and concrete formulation between the two made direct comparisons less meaningful.

A) Crevices

Among the twenty-five tiles deployed for the crevice experiment, the tile surface area covered by live barnacles ranged widely at the conclusion, ranging from a low of less than 9% cover to a high of over 52% cover. The mean percent tile surface cover for the experiment was 31.23 ± 2.59 with SD of 12.97. Table 2 below provides summary statistics for each of the tile types in the crevice experiment. Reviewing the means for each tile type it is notable that all of the crevice tiles had significantly more live barnacle cover at the end of 14 months than did the plain control tile with no crevices. Figures 3 and 4 help visualize the differences in percent cover by tile type in this experiment.

Table 2. Summary Statistics for Crevice Experiment by Tile Type

Tile Type	# of Tiles	Min	Max	Mean	SE (±)	SD	95% CI Lower	95% CI Upper
CC	5	8.67	15.24	12.56	1.1	2.46	10.37	14.76
ND	5	25.68	51.49	34.6	4.6	10.29	25.4	43.8
NS	5	19.18	48.70	32.5	5.25	11.74	22	43
WD	5	25.78	52.56	40.03	4.34	9.7	31.35	48.7
WS	5	28.94	51.66	36.46	4.07	9.11	28.31	44.61

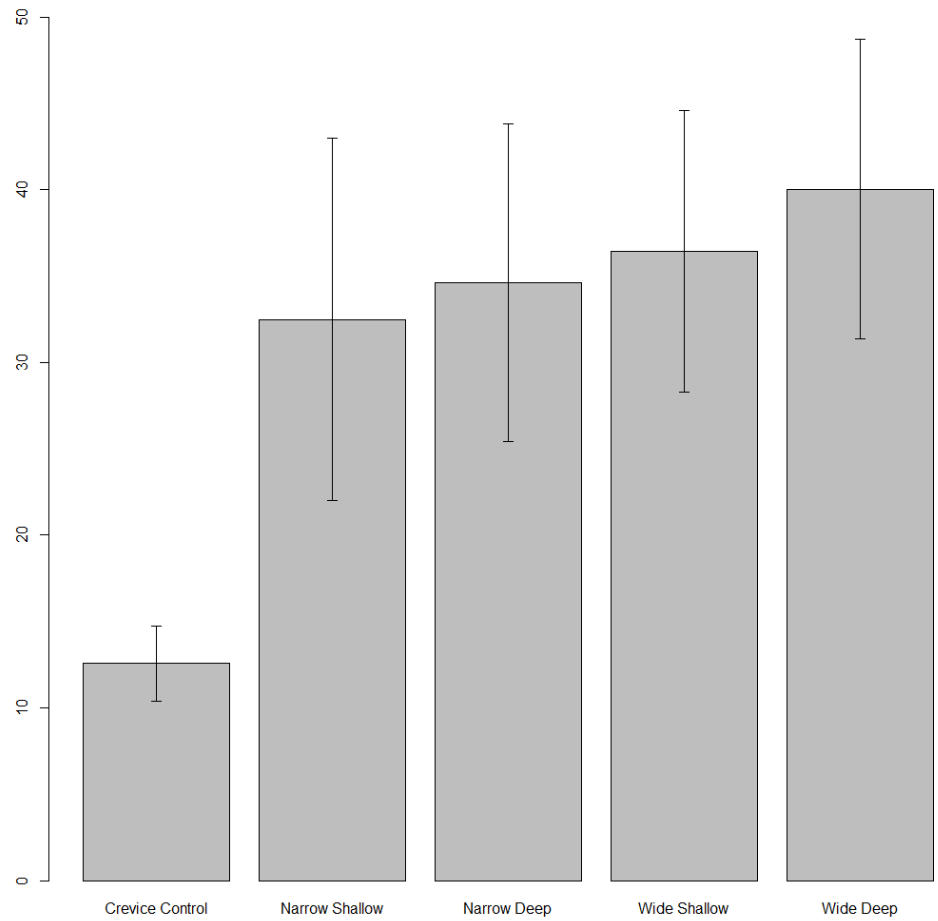


Figure 3 Crevice Experiment Tile Type Means with 95% Conf. Intervals

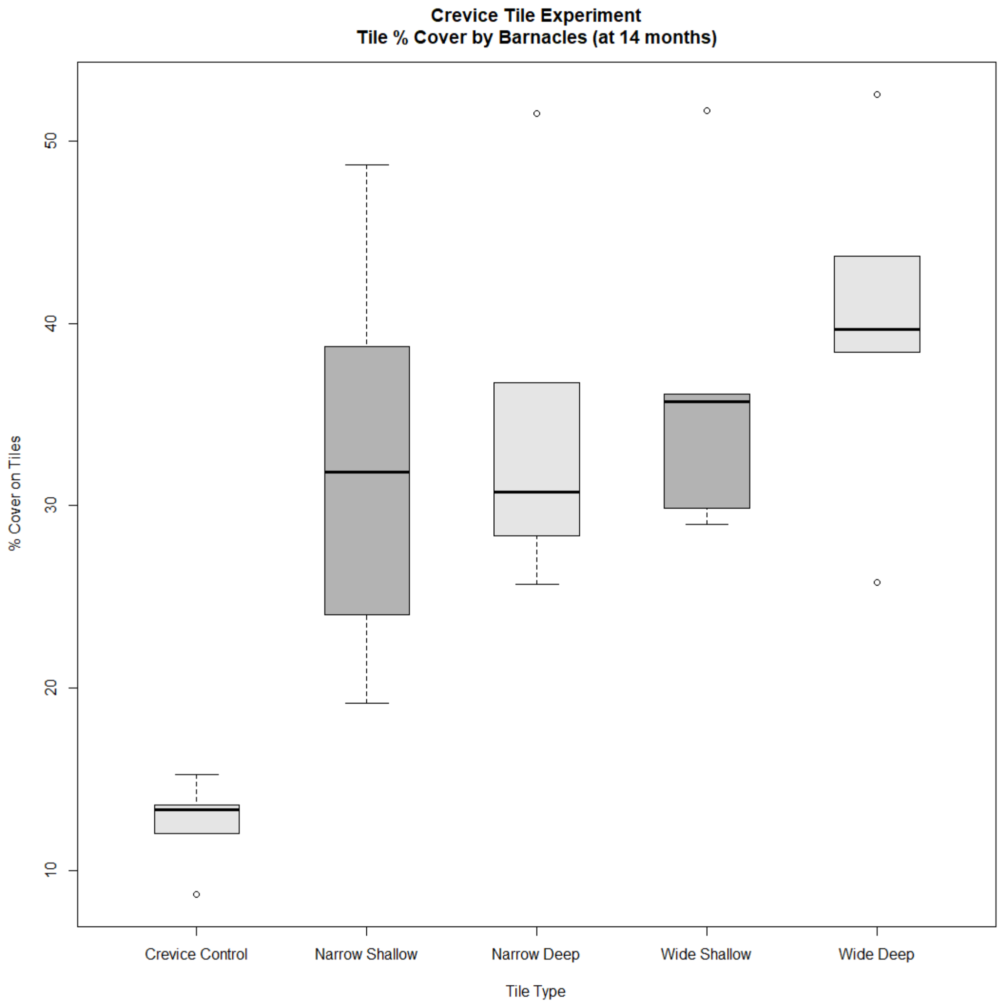


Figure 4 Crevice Experiment Tile Types

The box plot in Figure 4 illustrates the large difference in the cover proportion between the four crevice design groups and the plain control group. Note that for the control group the 95% confidence interval upper and lower bounds have no overlap with those of any of the four crevice groups. This visualization lends support to rejecting the null hypothesis of equal means (and thus no significant difference) in the percent cover after 14 months between the crevice tile groups and the group of control tiles lacking crevices.

Statistical comparison of several fitted models of the cover proportion data supported using tile type as the main effect. A one-way ANOVA confirmed a significant difference in the mean % cover by live barnacles [$F(4, 20)= 6.83$, $p=0.001$] among the five groups in the study. Post hoc analysis using Tukey's HSD test indicated no significant difference among the four crevice designs but significant differences for all crevice groups with the control group (Table 3 and Figure 5).

Table 3. Tukey Multiple Comparison of Meansfor Crevice Experiment by Tile Type 95% family-wise confidence level

Fit: aov(formula = TotalCov ~ TileType, data = creviceTiles)

Tile Type Grp Means Compared	Difference	95% CI Lower	95% CI Upper	P-Value (adj)
ND-CC	22.038	4.556	39.519	0.009
NS-CC	19.933	2.451	37.415	0.021
WD-CC	27.463	9.981	44.945	0.001
WS-CC	23.893	6.411	41.375	0.005
NS-ND	-2.104	-19.586	15.377	0.996
WD-ND	5.425	-12.057	22.907	0.882
WS-ND	1.856	-15.626	19.337	0.998
WD-NS	7.530	-9.952	25.011	0.701
WS-NS	3.960	-13.522	21.442	0.959
WS-WD	-3.570	-21.051	13.912	0.972

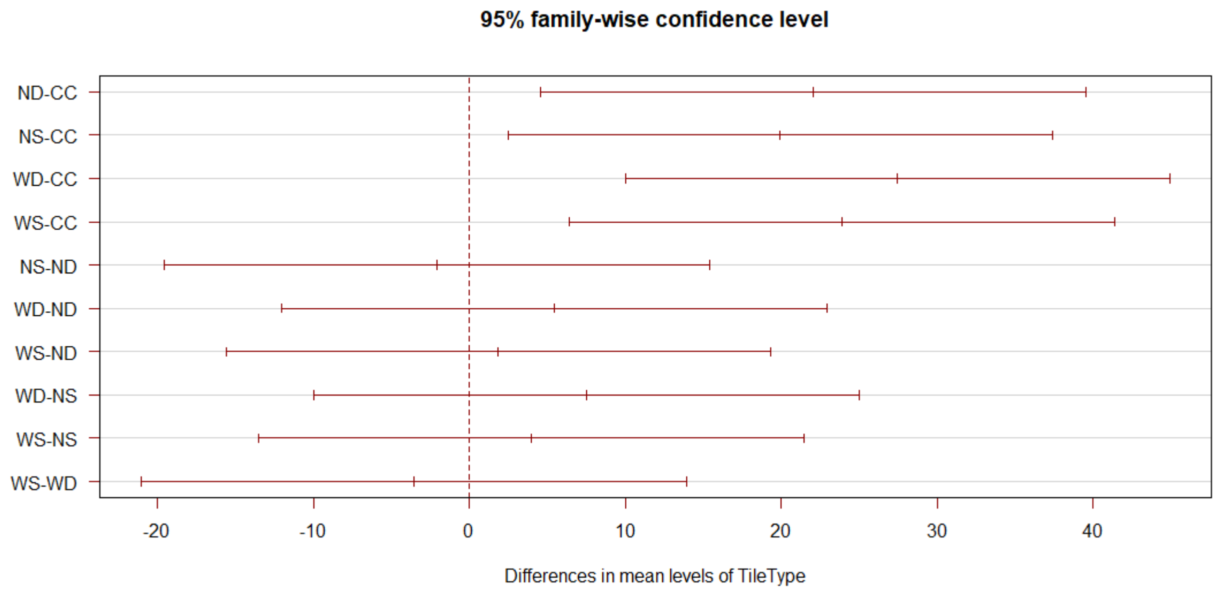


Figure 5 Crevice Experiment Tukey's Test Results

B) Surface Treatments

Among the twenty-five tiles deployed for the surface experiment, the tile area covered by live barnacles at 14 months ranged from a low of less than 10% cover to a high of over 38% cover. The mean percent tile surface cover for this experiment was 20.48 ± 1.34 with SD of 6.72. Table 4 below provides summary statistics for each of the tile types in the crevice experiment. There was lower overall live barnacle cover in the surface tile experiment but also less variability. Once again, the plain control tile group featured the smallest live barnacle coverage at the end of the experiment. Figures 6 and 7 help visualize the differences in percent cover by tile type in this experiment.

Table 4. Summary Statistics for Surface Experiment by Tile Type

Tile Type	# of Tiles	Min	Max	Mean	SE (±)	SD	95% CI Lower	95% CI Upper
CO	5	9.91	16.61	14.44	1.21	2.7	12.02	16.86
GR	5	12.80	19.00	15.85	1.18	2.64	13.48	18.21
CM	5	15.79	38.57	26.79	4.09	9.16	18.6	34.98
MU	5	20.99	26.88	24.75	1.03	2.31	22.69	26.82
OY	5	12.72	24.85	20.58	2.11	4.72	16.37	24.8

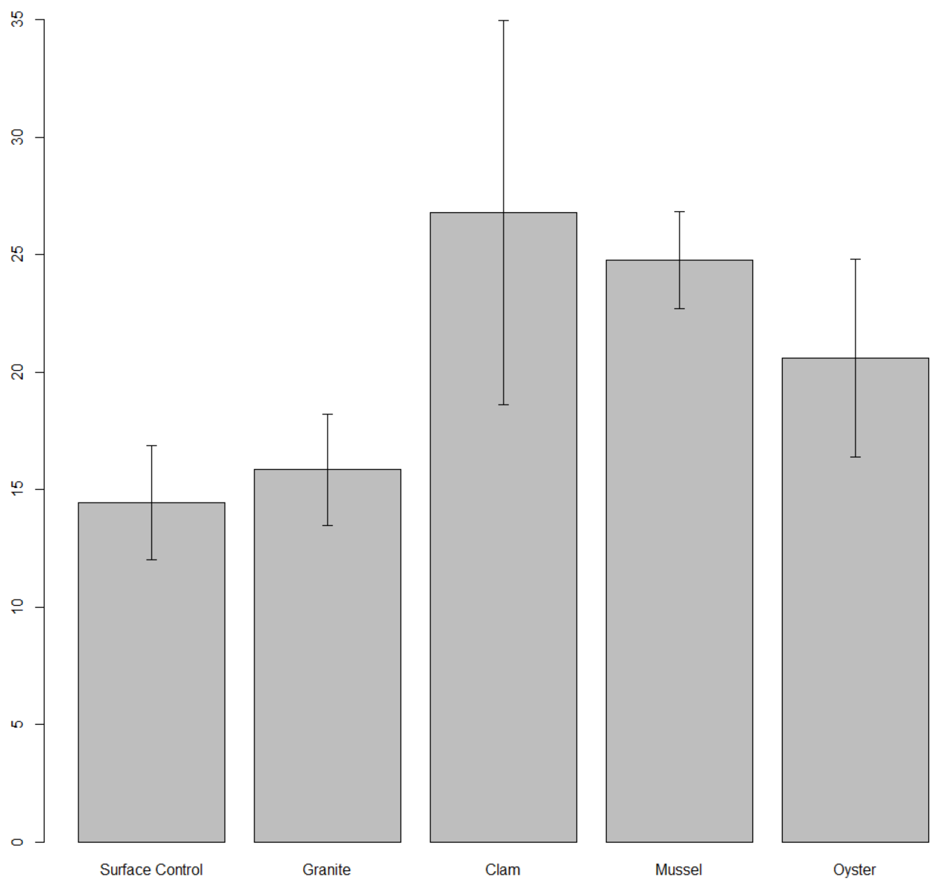


Figure 6 Surface Experiment Tile Type Means with 95% Conf. Intervals

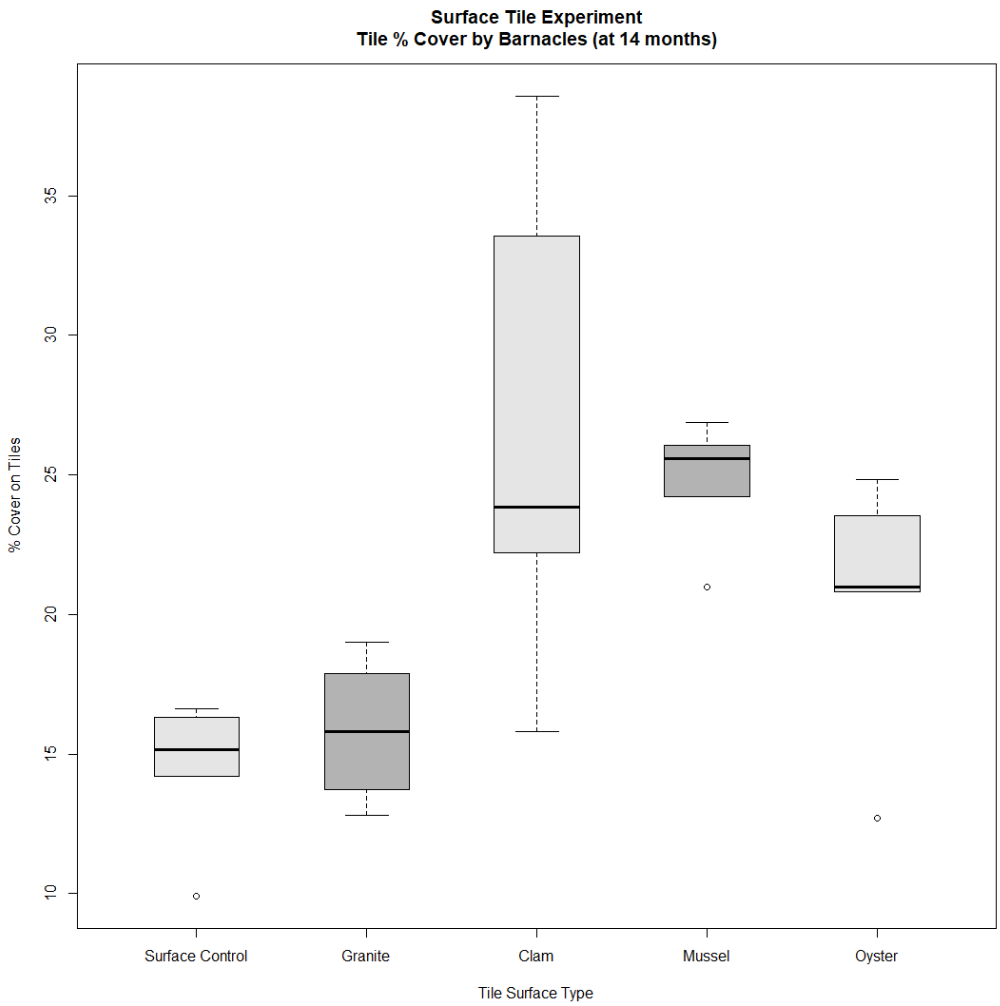


Figure 7 Surface Experiment Tile Types

The box plot in Figure 7 reveals the cluster of the embedded shell tile groups all with mean barnacle cover much higher than that of the control plain concrete tile group. Interestingly, the granite tiles also had lower mean barnacle cover, similar to that of the control group. The control group's 95% confidence interval upper and lower bounds have no overlap with those of any of the three embedded shell groups but do with the granite group. Once again, the visualization lends support to rejecting the null hypothesis of equal means (and thus no significant difference) in the percent cover after 14 months between all of the five groups.

A one-way ANOVA confirmed a significant difference in the mean % cover by live barnacles [$F(4, 20) = 6.83$, $p=0.001$] among the five groups in the study. Post hoc analysis using Tukey's HSD test indicated no significant differences among groups except for both the clam and mussel tile groups with the control group and the clam tile group with the granite tile group (Table 5 and Figure 8).

Table 5. Tukey Multiple Comparison of Means for Crevice Experiment by Tile Type
95% family-wise confidence level

Fit: aov(formula = TotalCov ~ TileType, data = creviceTiles)

Tile Type Grp Means Compared	Difference	95% CI Lower	95% CI Upper	P-Value (adj)
CO-CM	-12.355	-21.844	-2.866	0.007
GR-CM	-10.944	-20.433	-1.455	0.019
MU-CM	-2.038	-11.527	7.451	0.966
OY-CM	-6.208	-15.697	3.281	0.321
GR-CO	1.412	-8.077	10.901	0.991
MU-CO	10.317	0.828	19.806	0.029
OY-CO	6.148	-3.341	15.637	0.330
MU-GR	8.906	-0.583	18.395	0.072
OY-GR	4.736	-4.753	14.225	0.578
OY-MU	-4.170	-13.659	5.319	0.685

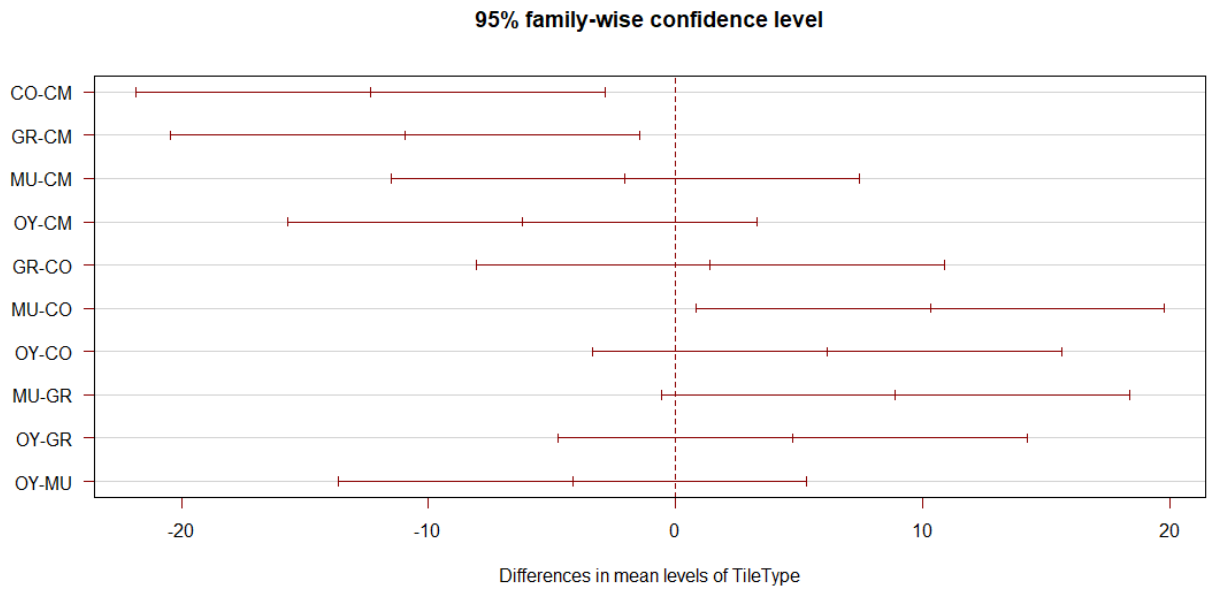
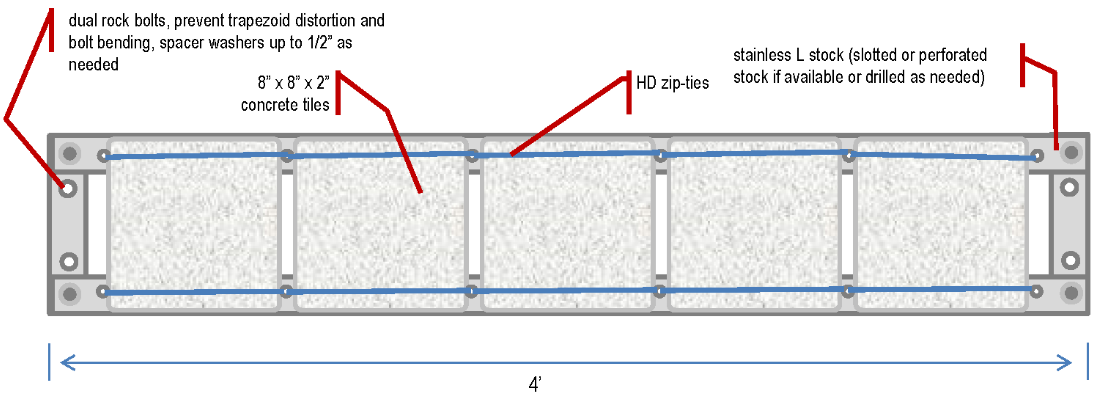


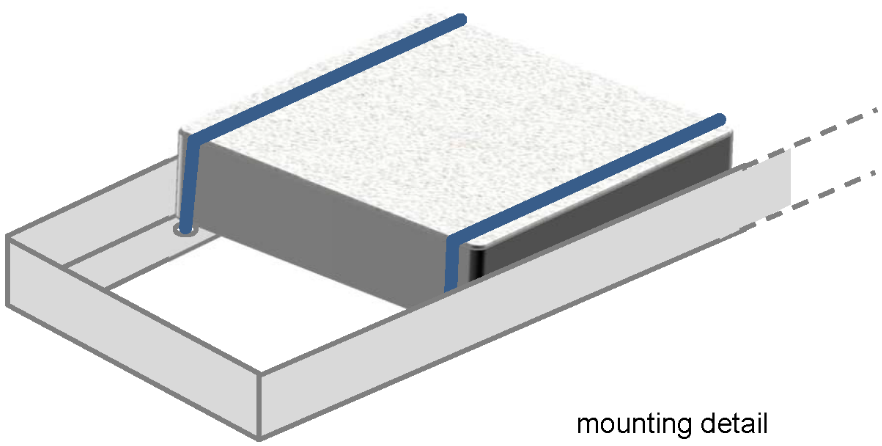
Figure 8 Crevice Experiment Tukey's Test Results

V) CONCLUSIONS

Overall, this pilot project offers several valuable conclusions and observations that will be useful for anyone interested in designing seawalls with additional ecosystem co-benefits. First, the tile manufacturing process and deployment strategy were successful for over 26 months in harsh New England marine, intertidal environment. While tiles were recovered and analyzed after 14 months, cinder blocks, frames, and zinc anodes were left in place for 26 months before recovery. Concrete tiles that were poured for this experiment survived better than commercially available concrete paving tiles or concrete blocks. Zinc anodes protected the much less expensive galvanized steel making expensive stainless steel frames unnecessary. These method developments should prove useful towards the success or any subsequent experimental tile deployments. Second, crevices clearly increase the longer term survival of barnacles on vertical concrete surfaces in the intertidal zone. Barnacles, and eventually macroalgae, showed increased settlement and initial survivability on tiles with crevices or those with crevices and surface roughness provided by integrated shells. Flat surfaces were exposed not just to heat and dryness, but also to intense herbivory by the snail *Littorina littorea*. While it would be interesting to experiment further with the width, depth, and heterogeneity of designed crevices, it is clear that any vertical seawall incorporating crevices in the surface design will provide better habitat for macroalgae and invertebrates than the traditional flat surfaces of granite or concrete. We hypothesize that this success is due to creating cool, moist niches that can also protect barnacles from being sheared off or preyed upon. Finally, there are many variables in the complex intertidal system including seasonality, timing of deployment (i.e., when the seawall is constructed), migratory predators, timing of storm events, and altered physical environments due to adjacent structures, that could affect experimental design and results. In addition, long-term deployments are necessary to examine the impacts of succession and ultimately seawall ecosystem values. Even so, this pilot project was successful in demonstrating the value of non-flat surfaces and lays the groundwork for many more experiments to determine optimal seawall surface designs.

Appendix A
Intertidal Tile Mounting Frame
(not to scale)



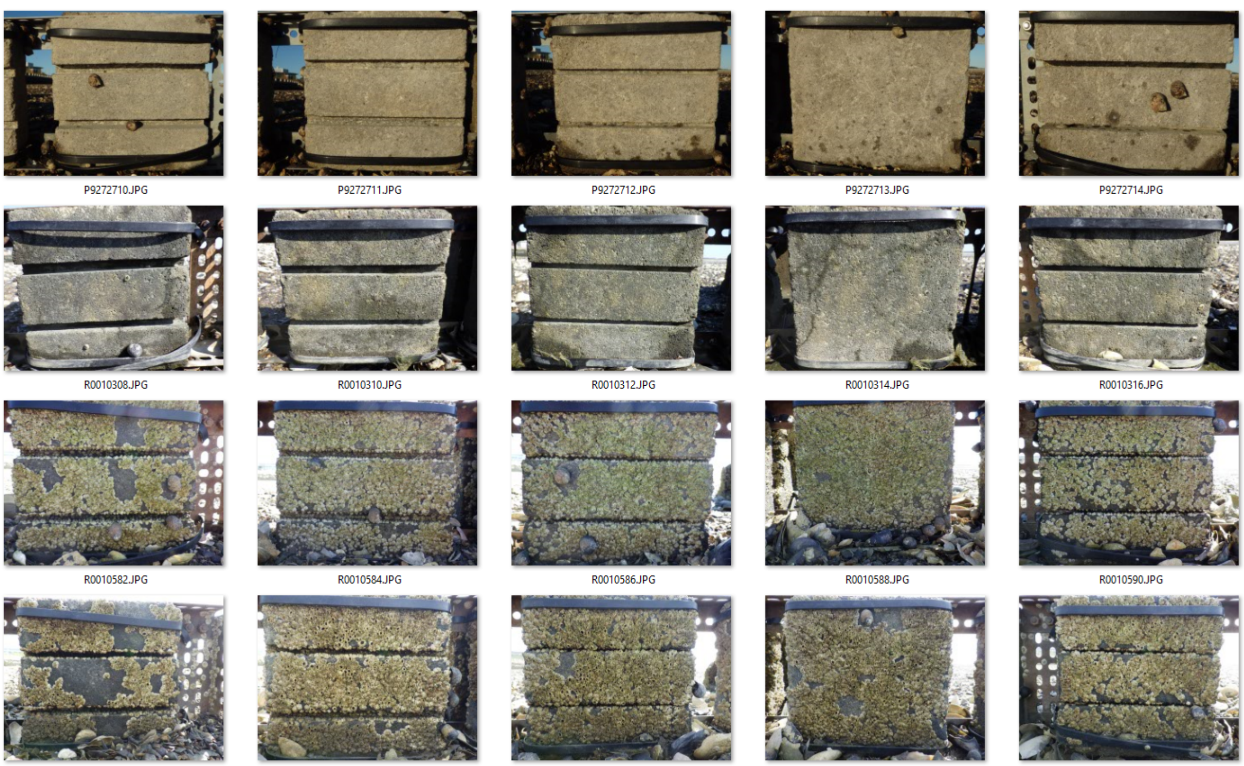


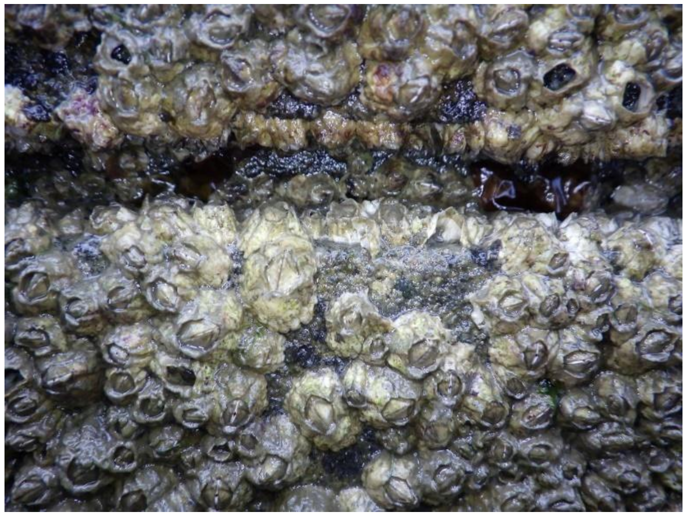
mounting detail

APPENDIX B

Crevice and Surface Tile Experiment Photos

Surface Exp. Control Tile showing recent shearing of barnacles





Wide and Shallow Crevice with multiple Porphyra germalings

Oyster Shell Tile showing Porphyra germling

APPENDIX C

LIST OF SOFTWARE AND R PACKAGES

Software

Git 2.34 open-source version control system, https://git-scm.com/

GitHub Desktop 2.9.6 open-source version control system, https://git-scm.com/

ImageJ 1.52h (Schindelin, J., et al., 2012; Schneider, C. A., et al., 2012)

Microsoft Excel for Windows, Microsoft 365 Apps for enterprise (Microsoft Corp, 2021)

Microsoft Word for Windows, Microsoft 365 Apps for enterprise (Microsoft Corp, 2021)

PhotoMechanic 6.0 (CameraBits, Inc., 2020

PhotoQuad, Trygonis, V., Sini, M., 2012. photoQuad: a dedicated seabed image processing software, and a comparative error analysis of four photoquadrat methods. Journal of Experimental Marine Biology and Ecology 424-425, 99-108. doi:10.1016/j.jembe.2012.04.018

R version 4.1.1 R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

RStudio v. 2021.09.0 (RStudio, Inc., 2021)

R Packages

AICcmodavg
Mazerolle MJ (2020). *AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c)*. R package version 2.3-1, https://cran.r-project.org/package=AICcmodavg.

broom
David Robinson (2018). broom: Convert Statistical Analysis Objects into Tidy Data Frames. R package version 0.4.4. https://CRAN.R-project.org/package=broom

car
Fox J, Weisberg S (2019). *An R Companion to Applied Regression*, Third edition. Sage, Thousand Oaks CA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/.

DescTools
Andri et mult. al. S (2021). *DescTools: Tools for Descriptive Statistics*. R package version 0.99.44, https://cran.r-project.org/package=DescTools.

dplyr
Hadley Wickham, Romain François, Lionel Henry and Kirill Müller (2018). dplyr: A Grammar of Data Manipulation. R package version 0.7.5. https://CRAN.R-project.org/package=dplyr

effectsize

Ben-Shachar MS, Lüdecke D, Makowski D (2020). "effectsize: Estimation of Effect Size Indices and Standardized Parameters." *Journal of Open Source Software*, **5**(56), 2815. doi: 10.21105/joss.02815, https://doi.org/10.21105/joss.02815.

effsize

Torchiano M (2019). effsize: Efficient Effect Size Computation. doi: 10.5281/zenodo.1480624, R package version 0.7.6, https://CRAN.R-project.org/package=effsize.

ggplot2

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. Retrieved from https://ggplot2.tidyverse.org

MASS

Venables WN, Ripley BD (2002). *Modern Applied Statistics with S*, Fourth edition. Springer, New York. ISBN 0-387-95457-0, http://www.stats.ox.ac.uk/pub/MASS4.

openxlsx

Philipp Schauberger, Alexander Walker, Luca Braglia (2019) openxlsx() package version: 4.1.4 https://CRAN.R-project.org/package=openxlsx

readxl

Hadley Wickham and Jennifer Bryan (2018). readxl: Read Excel Files. R package version 1.1.0. https://CRAN.R-project.org/package=readxl

tidyr

Hadley Wickham and Lionel Henry (2018). tidyr: Easily Tidy Data with 'spread()' and 'gather()' Functions.R package version 0.8.1. https://CRAN.R-project.org/package=tidyr

REFERENCES

Airoldi, L., Turon, X., Perkol‐Finkel, S., and Rius, M. (2015). Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. *Diversity and Distributions*, *21*(7), 755–768. https://doi.org/10.1111/ddi.12301

Airoldi, L., Beck, M. W., Firth, L. B., Bugnot, A. B., Steinberg, P. D., and Dafforn, K. A. (2020). Emerging Solutions to Return Nature to the Urban Ocean. *Annual Review of Marine Science*, *13*(1), 1–33. https://doi.org/10.1146/annurev-marine-032020-020015

Airoldi, L., Beck, M. W., Firth, L. B., Bugnot, A. B., Steinberg, P. D., and Dafforn, K. A. (2020). Emerging Solutions to Return Nature to the Urban Ocean. *Annual Review of Marine Science*, *13*(1), 1–33. https://doi.org/10.1146/annurev-marine-032020-020015

Barbier, E. B. (2012). A spatial model of coastal ecosystem services. *Ecological Economics*, *78*, 70–79. https://doi.org/10.1016/j.ecolecon.2012.03.015

Bozek, C. M., and Burdick, D. M. (2005). Impacts of Seawalls on Saltmarsh Plant Communities in the Great Bay Estuary, New Hampshire USA. *Wetlands Ecology and Management*, *13*(5), 553–568. https://doi.org/10.1007/s11273-004-5543-z

Blondin, H. (2017). New Hampshire Inventory of Tidal Shoreline Protection Structures. NH Department of Environmental Services.

Boon, J. D., Mitchell, M., Loftis, J. D., & Malmquist, D. M. (2018) Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions. Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467. Virginia Institute of Marine Science, William & Mary. https://doi.org/10.21220/V5T17T

Bozek, C. M., and Burdick, D. M. (2005). Impacts of Seawalls on Saltmarsh Plant Communities in the Great Bay Estuary, New Hampshire USA. *Wetlands Ecology and Management*, *13*(5), 553–568. https://doi.org/10.1007/s11273-004-5543-z

Bracken, M., Menge, B., Foley, M., Sorte, C., Lubchenco, J., and Schiel, D. (2012). Mussel selectivity for high-quality food drives carbon inputs into open-coast intertidal ecosystems. *Marine Ecology Progress Series*, *459*, 5362. https://doi.org/10.3354/meps09764

Bulleri, F., Chapman, M. & Underwood, A. (2005). Intertidal assemblages on seawalls and vertical rocky shores in Sydney Harbour, Australia. Austral Ecology, 30(6), 655–667.

Bulleri, F. & Chapman, M. G. (2010). The introduction of coastal infrastructure as a driver of change in marine environments. Journal of Applied Ecology, 47(1), 26–35.

Chapman, M., and Bulleri, F. (2003). Intertidal seawalls—new features of landscape in intertidal environments. *Landscape and Urban Planning*, *62*(3), 159–172. https://doi.org/10.1016/s0169-2046(02)00148-2

Choi, C., Jackson, M. V., Gallo‐Cajiao, E., Murray, N. J., Clemens, R. S., Gan, X., and Fuller, R. A. (2018). Biodiversity and China's new Great Wall. *Diversity and Distributions*, *24*(2), 137–143. https://doi.org/10.1111/ddi.12675

Dethier, M. N., Raymond, W. W., McBride, A. N., Toft, J. D., Cordell, J. R., Ogston, A. S., Heerhartz, S. M., and Berry, H. D. (2016). Multiscale impacts of armoring on Salish Sea shorelines: Evidence for cumulative and threshold effects. *Estuarine, Coastal and Shelf Science*, *175*, 106–117. https://doi.org/10.1016/j.ecss.2016.03.033

Doggett, T. D. (2015). The Growing Value of U.S. Coastal Property at Risk. Boston, MA: AIR Worldwide. Retrieved from https://www.air-worldwide.com/Publications/AIR-Currents/2015/The-Growing-Value-of-U-S-Coastal-Property-at-Risk/

Dugan, J. E., Hubbard, D. M., Rodil, I. F., Revell, D. L., and Schroeter, S. (2008). Ecological effects of coastal armoring on sandy beaches. *Marine Ecology*, *29*(s1), 160–170. https://doi.org/10.1111/j.1439-0485.2008.00231.x

Dugan, J., Emery, K., Alber, M., Alexander, C., Byers, J., Gehman, A., McLenaghan, N., and Sojka, S. (2017). Generalizing Ecological Effects of Shoreline Armoring Across Soft Sediment Environments. *Estuaries and Coasts*, 1–17. https://doi.org/10.1007/s12237-017-0254-x

Firth, L. B., Browne, K. A., Knights, A. M., Hawkins, S. J., and Nash, R. (2016a). Eco-engineered rock pools: a concrete solution to biodiversity loss and urban sprawl in the marine environment. *Environmental Research Letters*, *11*(9), 094015. https://doi.org/10.1088/1748-9326/11/9/094015

Firth, L.B., Knights, A.M., Thompson, R.C., Mieszkowska, N., Bridger, D., Evans, A., Moore, P., O'Connor, N.E., Sheehan, E.V. and Hawkins, S.J. (2016b). Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. In Oceanography and Marine Biology: An Annual Review (pp. 193-270). Taylor & Francis.

Firth, L. B., Airoldi, L., Bulleri, F., Challinor, S., Chee, S., Evans, A. J., Hanley, M. E., Knights, A. M., O'Shaughnessy, K., Thompson, R. C., and Hawkins, S. J. (2020). Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. Journal of Applied Ecology, 57(9), 1762–1768. https://doi.org/10.1111/1365-2664.13683

FitzGerald, D. M., and Hughes, Z. (2019). Marsh Processes and Their Response to Climate Change and Sea-Level Rise. Annual Review of Earth and Planetary Sciences, 47(1), 481–517. https://doi.org/10.1146/annurev-earth-082517-010255

Fleming, E. J., Payne, W., Sweet, M., Craghan, J., Haines, J. F., Hart, H., … Sutton-Grier. (2018). Coastal Effects. In Reidmiller, D.R. et al. (Ed.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II (pp. 322–352). Washington, DC: U.S. Global Change Research Program. doi:10.7930/NCA4.2018.CH8

Fontenault, J., Vinhateiro, N. & Knee, K. (2013). Mapping and Analysis of Privately-Owned Coastal Structures along the Massachusetts Shoreline. Applied Science Associates, Inc.

Gillespie, A. (2013). Dam and seawall removal gets easier in MA. Frontiers in Ecology Dispatches, 6-66.

Goldstein, J., and Watson, W. (2015). Seasonal movements of American lobsters in southern Gulf of Maine coastal waters: patterns, environmental triggers, and implications for larval release. Marine Ecology Progress Series, 524, 197–211. https://doi.org/10.3354/meps11192

Grizzle, R. E., Greene, J. K., and Coen, L. D. (2008). Seston Removal by Natural and Constructed Intertidal Eastern Oyster (Crassostrea virginica) Reefs: A Comparison with Previous Laboratory Studies, and the Value of in situ Methods. *Estuaries and Coasts*, *31*(6), 1208–1220. https://doi.org/10.1007/s12237-008-9098-8

Hanley, M. E., Hoggart, S. P. G., Simmonds, D. J., Bichot, A., Colangelo, M. A., Bozzeda, F., Heurtefeux, H., Ondiviela, B., Ostrowski, R., Recio, M., Trude, R., Zawadzka-Kahlau, E., and Thompson, R. C. (2014). Shifting sands? Coastal protection by sand banks, beaches and dunes. *Coastal Engineering*, *87*, 136–146. https://doi.org/10.1016/j.coastaleng.2013.10.020

Jin, D., Hoagland, P., Au, D. K., and Qiu, J. (2015). Shoreline change, seawalls, and coastal property values. *Ocean & Coastal Management*, *114*, 185–193. https://doi.org/10.1016/j.ocecoaman.2015.06.025

Jones, P. L., and Shulman, M. J. (2008). Subtidal-intertidal trophic links: American lobsters [Homarus americanus (Milne-Edwards)] forage in the intertidal zone on nocturnal high tides. *Journal of Experimental Marine Biology and Ecology*, *361*(2), 98–103. https://doi.org/10.1016/j.jembe.2008.05.004

Kulp, S. A., and Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, *10*(1), 4844. https://doi.org/10.1038/s41467-019-12808-z

Littles, C. J., Jackson, C. A., DeWitt, T. H., and Harwell, M. C. (2018). Linking people to coastal habitats: A meta-analysis of final ecosystem goods and services on the coast. *Ocean & Coastal Management*, *165*, 356–369. https://doi.org/10.1016/j.ocecoaman.2018.09.009

Melillo, J. M., Richmond, T. & Yohe, G. (2014). Climate change impacts in the United States: Third national climate assessment. U.S. Global Change Research Program. doi:10.7930/J0Z31WJ2

Morris, R. L., Chapman, G. M., Firth, L. B., and Coleman, R. A. (2017). Increasing habitat complexity on seawalls: Investigating large‐ and small‐scale effects on fish assemblages. *Ecology and Evolution*, *7*(22), 9567–9579. https://doi.org/10.1002/ece3.3475

Morris, R. L., Konlechner, T. M., Ghisalberti, M., and Swearer, S. E. (2018). From grey to green: Efficacy of eco‐engineering solutions for nature‐based coastal defence. *Global Change Biology*, *24*(5), 1827–1842. https://doi.org/10.1111/gcb.14063

Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Guerrero, A., Shepard, C. C., Reguero, B. G., Franco, G., Ingram, J., and Trespalacios, D. (2017). The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. *Scientific Reports*, *7*(1), 9463. https://doi.org/10.1038/s41598-017-09269-z

Neumann, B., Vafeidis, A., Zimmermann, J., and Nicholls, R. (2015). *Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment*. https://doi.org/10.1371/journal.pone.0118571

Pather, S., Pfister, C. A., Post, D. M., and Altabet, M. A. (2014). Ammonium cycling in the rocky intertidal: Remineralization, removal, and retention. *Limnology and Oceanography*, *59*(2), 361–372. https://doi.org/10.4319/lo.2014.59.2.0361

Rice, T. (2015). Inventory of Habitat Modifications to Sandy Beaches in the U.S. Atlantic Coast Breeding Range of the Piping Plover (Charadrius melodus) prior to Hurricane Sandy: Maine to the North Shore and Peconic Estuary of New York. Terwilliger Consulting, Inc.

Rossong, M. A., Quijon, P. A., Williams, P. J., and Snelgrove, P. V. R. (2011). Foraging and shelter behavior of juvenile American lobster (Homarus americanus): the influence of a non-indigenous crab. *Journal of Experimental Marine Biology and Ecology*, *403*(1–2), 75–80. https://doi.org/10.1016/j.jembe.2011.04.008

Suca, J. J., Pringle, J. W., Knorek, Z. R., Hamilton, S. L., Richardson, D. E., and Llopiz, J. K. (2018). Feeding dynamics of Northwest Atlantic small pelagic fishes. *Progress in Oceanography*, *165*, 52–62. https://doi.org/10.1016/j.pocean.2018.04.014

Stachowicz, J. J., (2001) Mutualism, Facilitation, and the Structure of Ecological Communities: Positive Interactions Play a Critical, but Underappreciated, Role in Ecological Communities by Reducing Physical or Biotic Stresses in Existing Habitats and by Creating New Habitats on Which Many Species Depend. *BioScience*, 51(3), 235–46. https://doi.org/10.1641/0006-3568(2001)051[0235:MFATSO]2.0.CO;2.

Staudinger, M. D., Goyert, H., Suca, J. J., Coleman, K., Welch, L., Llopiz, J. K., Wiley, D., Altman, I., Applegate, A., Auster, P., Baumann, H., Beaty, J., Boelke, D., Kaufman, L., Loring, P., Moxley, J., Paton, S., Powers, K., Richardson, D., … Steinmetz, H. (2020). The role of sand lances (Ammodytes sp.) in the Northwest Atlantic Ecosystem: A synthesis of current knowledge with implications for conservation and management. *Fish and Fisheries*, *21*(3), 522–556. https://doi.org/10.1111/faf.12445

Taherkhani, M., Vitousek, S., Barnard, P. L., Frazer, N., Anderson, T. R., and Fletcher, C. H. (2020). Sea-level rise exponentially increases coastal flood frequency. *Scientific Reports*, *10*(1), 6466. https://doi.org/10.1038/s41598-020-62188-4

Union of Concerned Scientists, (2019). Underwater: Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate, https://www.ucsusa.org/resources/underwater#ucs-report-downloads

Vaselli, S., Bulleri, F., and Benedetti-Cecchi, L. (2008). Hard coastal-defence structures as habitats for native and exotic rocky-bottom species. *Marine Environmental Research*, *66*(4), 395–403. https://doi.org/10.1016/j.marenvres.2008.06.002

Vousdoukas, M.I., Ranasinghe, R., Mentaschi, L. et al. Sandy coastlines under threat of erosion. Nat. Clim. Chang. 10, 260–263 (2020). https://doi.org/10.1038/s41558-020-0697-0

Vuik, V., Jonkman, S. N., Borsje, B. W., and Suzuki, T. (2016). Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coastal Engineering*, *116*, 42–56. https://doi.org/10.1016/j.coastaleng.2016.06.001

Wheeler, B. W., White, M., Stahl-Timmins, W., and Depledge, M. H. (2012). Does living by the coast improve health and wellbeing? *Health & Place*, *18*(5), 1198–1201. https://doi.org/10.1016/j.healthplace.2012.06.015

White, M. P., Alcock, I., Wheeler, B. W., and Depledge, M. H. (2013). Coastal proximity, health and well-being: results from a longitudinal panel survey. *Health & Place*, *23*, 97–103. https://doi.org/10.1016/j.healthplace.2013.05.006

White, M. P., Wheeler, B. W., Herbert, S., Alcock, I., and Depledge, M. H. (2014). Coastal proximity and physical activity: Is the coast an under-appreciated public health resource? *Preventive Medicine*, *69*, 135–140. https://doi.org/10.1016/j.ypmed.2014.09.016

Williams, A., Giardino, A., and Research, P. E. of. (2016). *Canons of coastal engineering in the United Kingdom: seawalls/groynes, a century of change?* https://doi.org/10.2112/JCOASTRES-D-15-00213.1

Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J., and Smith, T. J. (2012). The role of mangroves in attenuating storm surges. Estuarine, Coastal and Shelf Science, 102, 11–23. https://doi.org/10.1016/j.ecss.2012.02.021