Technical Report

Living Seawalls in Boston Harbor: 8 month Biodiversity Assessment

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Executive Summary

Harbors and waterways have long been the hub of development as they provide easy transportation, access to trade, and reliable water for people, farming, and industry. Communities built near rivers, lakes, and coasts could exchange goods, grow economically, and expand more quickly than places without water access (Rodrigue 2024). However, these areas are now becoming increasingly urbanized, with built structures globally impacting over 1 million km2 of natural seafloor habitat. The footprint of marine construction is expected to grow by 23% worldwide over the next 10 years (Bugnot et al. 2021) and so there is an urgent need to develop targeted and effective interventions that mitigate impacts and deliver multiple benefits to a wide range of stakeholders. Nature-based Approaches (NbA) such as living seawalls, which incorporate ecological principles into the design of marine built structures, can reduce their ecological impacts and offer multiple ecological and other benefits.

The Living Seawalls project has developed habitat panels that can be easily attached to marine built structures to add surface rugosity, and microhabitats to enhance biodiversity under a variety of different environmental conditions. Living Seawalls use 3D printing technology to design panels with the pits, crevices and pools of natural shorelines that are then cast using upcycled materials and fitted in customized configurations to new or existing constructions. The accompanying monitoring and evaluation program has revealed that these can increase biodiversity by up to 3 times that of flat surfaces of similar age. These panels have been installed at more than 40 sites around the world since 2018, including Australia, Singapore, Dubai, Gibraltar and the UK. Living Seawalls habitat panels were first installed in the United States at multiple sites in Boston, MA, by the Stone Living Lab (SLL) in November 2024.

This report presents the site selection, design, permitting, monitoring approach, and outcomes from 8 months post-installation biodiversity monitoring of the Boston Harbor Living Seawalls. Two sites in Boston Harbor were selected for installation following the development of a site selection matrix that included the orientation of the seawalls, light availability, wave energy, seawall structural stability, ease of access for installation/monitoring, availability of nearby control sites, visibility and opportunities for education and engagement, and accessibility for environmental justice communities. Fan Pier in the Seaport District and Condor Street Urban Wild in East Boston were selected as the final sites, with two Living Seawalls installations planned for Condor Street Urban Wild on the east- and west-facing seawalls.

Following site selection, the permitting and design for each seawall commenced. The process included obtaining landowner consent, development of engineering design plans detailing existing conditions and proposed modifications, review of the structural integrity of the seawalls, design of durable attachment systems, and submission of permit applications to the City of Boston Conservation Commission, to the Massachusetts Department of Environmental Protection, and to the U.S. Army Corps of Engineers. The time from site selection through design to securing permits was approximately eleven (11) months. As part of the process, Woods Hole Group prepared detailed engineering plans for each site and the SLL Research and Monitoring Committee worked with the Living Seawalls project team to identify relevant panel designs for the local environment and ecology of Boston Harbor. These included designs featuring two sizes of rockpools, swim-throughs, and crevices as well as a flat control panel. Panels were then fabricated by Inland and Coastal Marina Systems in Ireland and shipped to Boston Harbor, which took approximately 6 months.

In parallel, pre-installation biodiversity monitoring commenced at the seawalls in June/July 2024 and included in-situ invertebrate and seaweed sampling (as well as fish and mobile species monitoring with underwater video, not included in this report). Once permits were secured, SumCo Engineering was contracted to install the Living Seawalls panels on each wall. Installation took approximately 5-7 days at each site and the initial phases of the installation of the lowest rows required spring low tide conditions.

After 4 weeks, biodiversity on the panels was primarily composed of diverse microbial biofilms that varied with tidal height. Panel design appeared to have little influence on the development of these initial biofilms, suggesting that subsequent differences in macrofauna among panel designs are driven by the macroscale physical complexity created by the Living Seawalls rather than differences in microbial colonization.

After 8 months, Living Seawalls in Boston Harbor have been rapidly colonized by a diverse range of algae and invertebrates. Biodiversity on the panels included fast-growing ephemeral red and green algae (e.g. sea lettuce), juvenile perennial rockweeds and sugar kelp (at Fan Pier only), periwinkle snails, barnacles, and low abundances of newly settled mussels and other invertebrates. Complex panel designs, particularly the swim-through and rockpool designs, supported greater colonization by perennial rockweeds and showed early signs of developing communities of red algae and kelps. Crevice/ledge and swim-through designs also provided valuable habitat for intertidal snails, while complex designs generally extended the vertical range over which intertidal organisms could persist. Taken together, these results suggest that habitat complexity substantially influences the development of ecological communities on Living Seawalls.

The Living Seawalls also provided important thermal refugia. Complex panel designs generally remained cooler than adjacent flat seawall surfaces during summer conditions, while rockpool panels reduced temperatures during a heatwave event by up to 20°C. These findings suggest that Living Seawalls can enhance the resilience of intertidal communities to increasing thermal stress associated with climate change.

Overall, ecological communities on the Living Seawalls are showing the typical colonization patterns of a New England rocky intertidal habitat. Although communities remain in the early stages of ecological development, species abundances are now broadly comparable to those observed on adjacent seawalls and colonization has proceeded more quickly than anticipated for many organisms. Continued recruitment of long-lived perennial algae and invertebrates suggests these communities are progressing toward more mature intertidal assemblages characteristic of New England rocky shore assemblages. Ongoing quarterly photographic surveys and planned whole-community resampling after two years will determine whether these developing communities ultimately match or exceed the biodiversity and ecological function of nearby conventional seawalls.

These early results demonstrate that Living Seawalls can rapidly create habitat, support the development of diverse intertidal communities, and reduce heat stress on urban waterfront infrastructure, highlighting their potential as a scalable NbA for enhancing ecological outcomes in working harbors.

Sea lettuce, sugar kelp, barnacles, and other organisms colonizing one of the Living Seawall panels at Fan Pier in July 2025, 8 months post-installation.

Main Report

1. Introduction

Globally, marine built structures impact more than 1 million km^2 of natural seafloor habitat, and marine construction activities are projected to increase substantially over the coming decades (Bugnot et al. 2021, Floerl et al. 2021). Like many cities, Boston Harbor is a highly urbanized coastal system where approximately 80% of the Inner Harbor shoreline has been hardened or urbanized (CZM 2025), including extensive seawalls, piers, and other engineered infrastructure. As a result, much of the harbor's intertidal and shallow subtidal habitat is now associated with built structures rather than natural rocky shores. As Boston continues to invest in waterfront redevelopment and coastal resilience strategies to address the impacts of climate change, sea-level rise, and increasing storm intensity, the extent of marine built structures in the harbor is likely to grow. While these structures provide important services for e.g. storm surge and flood protection, they often replace natural coastal habitats with flat, vertical surfaces that support lower biodiversity and provide fewer ecosystem services than natural shorelines (Glasby 1999a, Dafforn et al. 2012, Mayer-Pinto et al. 2018).

As a result, there is a need to develop and evaluate interventions that can reduce the impacts of coastal infrastructure while delivering co-benefits for biodiversity, water quality, education, and recreation. These interventions, often termed Nature-based Approaches (NbA), are increasingly recognized as an important component of sustainable coastal management (Chapman and Blockley 2009, Dafforn et al. 2015a, Dafforn et al. 2015b); however most approaches have been developed and tested in temperate or subtropical regions (Loke and Todd 2015, Firth et al. 2016, Loke et al. 2019, Bishop et al. 2022) and there remains a critical need to evaluate their performance under different environmental, climatic, and regulatory conditions.

One such approach is Living Seawalls, which integrates ecological principles into marine built structures through the integration or retrofit of habitat panels (Figure 1). These panels incorporate pits, crevices, pools, and textured surfaces that mimic key features of natural rocky shorelines, creating refuges and settlement habitat for marine organisms (Bishop et al. 2022). The surface complexity is incorporated into Living Seawalls with 3D printed molds that are cast in concrete to create the panels that are fitted in customized configurations.

Since 2018, Living Seawalls panels have been deployed at more than 40 locations globally, including sites in Australia, Singapore, Dubai, and the United Kingdom. Monitoring across these sites has demonstrated that habitat panels can support biodiversity up to 3 times that of conventional flat seawall surfaces (Bishop et al. 2022). However, ecological and structural performance can vary substantially among regions due to differences in species pools, tidal ranges, water quality, wave exposure and climatic conditions (Clifton et al. 2022, Vozzo et al. 2025, Bauer et al.

2026). Consequently, there is a growing recognition that NbA requires place-based testing to determine whether outcomes observed elsewhere can be replicated in new environmental contexts.

Figure 1: *An early Living Seawalls installation in Sydney Harbor, Australia. (Image credit: Alex Goad).*

Boston Harbor presents a particularly important test case for marine NbA. Unlike many previous Living Seawalls deployments, Boston experiences a cold-temperate climate characterized by large seasonal temperature fluctuations, winter ice formation, freeze-thaw cycles and episodic high-energy storm events. These conditions may influence both the durability of habitat panels and the rates and trajectories of ecological colonization. Understanding how Living Seawalls perform under New England conditions is therefore critical for informing future implementation in the northeastern United States and other seasonally varied and cold-climate coastal regions.

In addition to ecological performance, demonstration projects are essential for developing practical pathways to implementation as well as social license (Dafforn et al. 2026). While interest in NbA continues to increase among municipalities, regulators, and others, uncertainty remains regarding permitting requirements, engineering specifications, maintenance obligations, costs, and long-term performance (Dodds et al. 2025, Allen et al. 2026). Rigorously designed demonstration projects can reduce these uncertainties by providing locally relevant evidence, informing regulatory review processes, and creating case studies for wider adoption. In Boston Harbor, the Living Seawalls project provides an opportunity not only to evaluate ecological outcomes, but also to better understand the engineering, permitting, and other logistical considerations required to scale marine NbA within a complex urban waterfront (Vozzo et al. 2024).

The Living Seawalls habitat panels were first installed in Boston Harbor by the Stone Living Lab (SLL) in November 2024. This installation was the first in the United States. This report presents the site selection process, engineering design, permitting pathway, installation, monitoring framework, and ecological outcomes from the first 8 months following installation. We expected that sections of seawall receiving habitat panels would support more biodiversity than unmodified sections of seawall, and that habitat panels containing complex features would support more biodiversity than flat panels. Biodiversity is expected to further increase over longer time scales, as communities continue to develop. The report provides the first assessment of Living Seawalls in a cold-temperate North American harbor and contributes important evidence regarding the feasibility, performance, and implementation of marine NbA in Boston Harbor and similar urban coastal environments.

2. Environmental conditions and ecology of Boston Harbor

2.1 Local environmental conditions

Boston Harbor represents a dynamically evolving urban estuary. The shoreline pre-colonization was a mix of salt marsh and cobble habitats (Richburg and Patterson III 2005). The current shoreline is a mix of marsh, mixed coarse substrate, beach, and human built marine infrastructure (Bell et al. 2005, Bowen et al. 2019, Putnam et al. 2024).

Tidal currents in Boston are dominated by the semidiurnal tide (two flood and two ebb tides each day) and vary considerably throughout the Harbor sites due to the complex geomorphology, islands, channels, and bathymetry that make up the outer and inner harbors. Typical tidal current velocities range from 0.5 to 1.5 m/s (1-3 knots) depending on the location within the Harbor (Signell 1992, CO-OPS 1999). For example, the inner harbor velocities may be between 0.1 to 0.4 m/s, the main navigation channels have tidal velocities that reach 0.5-1.0 m/s, while currents in constricted passages can be up to approximately 1.5 m/s (3 knots). These current velocities increase under coastal storm conditions where storm surge can combine with tidal currents.

Wave exposure throughout Boston Harbor is highly varied. Wave heights and energy increase from the protected inner harbor to the outer harbor. The inner harbor experiences low energy, with significant wave heights generally less than 0.5 meters, due to the protection afforded by the numerous harbor islands and peninsulas and short wind generated wave fetches. Meanwhile the outer harbor (Brewster Islands, Nantasket Roads) can experience wave heights exceeding 3-4 meters during coastal storm events. The two Living Seawalls sites are in quiescent wave environments, where waves generated by vessel wakes far exceeds the naturally generated waves in the areas.

While there are multiple freshwater inputs, salinity is typically ~33-35 ppt. Water temperatures typically span from 15.6oC (60oF) in the summer to -1oC (30oF) in the winter (NOAA Buoy 44013 historical record). During the study period, Boston experienced an extreme summer heatwave in August 2025 when air temperatures approached 38oC (100oF) across the region and Boston Harbor water temperatures were 21oC (70oF). Temperatures on the unmodified seawall reached 52.7oC (127oF), substantially higher than the 30-40oC (86oF-104oF) during June and September 2025. Surface temperatures exceeding 50oC (122oF) are physiologically stressful for many intertidal organisms and can reduce growth, cause reproductive impairment or mortality.

2.2 Local ecological communities

The intertidal of Boston Harbor consists of a wide variety of community types - from salt marshes composed of cordgrass, crabs, and killifish to seagrass beds full of amphipods, isopods, shrimps, crabs, and juvenile fish. The intertidal seawalls of Boston Harbor broadly mimic the rocky intertidal found throughout New England. They are colonized by rockweeds and bladder wrack (Ascophyllum and Fucus), barnacles, irish moss (Chondrus crispus), and a variety of other green and red algae and invertebrates. Seawalls host fish and crabs that eat small amphipods and other invertebrates. The diversity and abundance of these organisms on seawalls is, however, limited with many common intertidal species missing (Cryan et al. 2021) and recovery from disturbance on seawalls at roughly half the rate as rocky shores (Lockwood 2020). Seawalls create a vertical habitat that is devoid of many of the features found in the rocky intertidal, including water retaining rockpools, cracks and crevices that would otherwise serve as refuges for mobile organisms, and more.

3. Site selection in Boston Harbor

Two sites in Boston Harbor were selected for installation of three seawalls following the development of a site selection matrix that included the following:

1) Seawall orientation and light availability - vertical seawalls with minimal overhangs were prioritized to maximize comparability with Living Seawalls installations elsewhere in Australia, Europe, and Asia. Sites with sufficient light availability were preferred, as shading and overhanging structures can influence community development and may favor non-native sessile invertebrates over algae (e.g. Glasby 1999b, Miller and Etter 2008).

2) Accessibility for installation and monitoring - sites that could be safely and reliably accessed for panel installation and long-term ecological monitoring by staff, graduate researchers, and undergraduate students were prioritized. Accessible sites also provide greater opportunities for student training, public outreach, and community engagement activities.

3) Availability of nearby control sites - Suitable nearby control (unmodified seawall) sites were required to enable robust evaluation of the ecological effects of the Living Seawalls panels. Selecting controls in closer proximity to installation sites helped ensure that sites experience similar environmental conditions, including hydrodynamics, larval supply, and the abundance of mobile species. Effective Before-After Control-Impact (BACI) requires that treatment not be confounded with differences between treatment and controls (Larsen et al. 2019). Thus, our approach ensured valid assessment of the Living Seawalls' potential benefits.

4) Visibility and opportunities for education and engagement - sites with high public visibility, substantial pedestrian traffic and good viewing opportunities were prioritized to maximize education, outreach, and community engagement outcomes.

5) Accessibility for environmental justice communities – sites were selected to ensure that the benefits of Living Seawalls are accessible to communities across Boston, including environmental justice communities that often face disproportionate climate and flood risks. Preference was given to sites adjacent to publicly accessible parks and waterfront spaces to support equitable access.

6) Relatively low wave energy - sites exposed to relatively low to moderate wave energy were prioritized to promote panel stability, installation longevity, and researcher safety. These conditions are also broadly comparable to other global installation sites in terms of physical processes.

7) Structural stability – candidate seawalls were required to be structurally sound and not nearing their end of service life. Installing panels on stable, well-maintained infrastructure maximizes the likelihood that ecological monitoring can be conducted over the long term without disruption from major repair or replacement works.

Fan Pier in the Seaport District and the seawalls surrounding the Condor Street Urban Wild park in East Boston were selected as the final sites (Figure 2), balancing the above criteria. Two Living Seawalls installations were planned for the east- and west-facing seawalls at Condor Street Urban Wild.

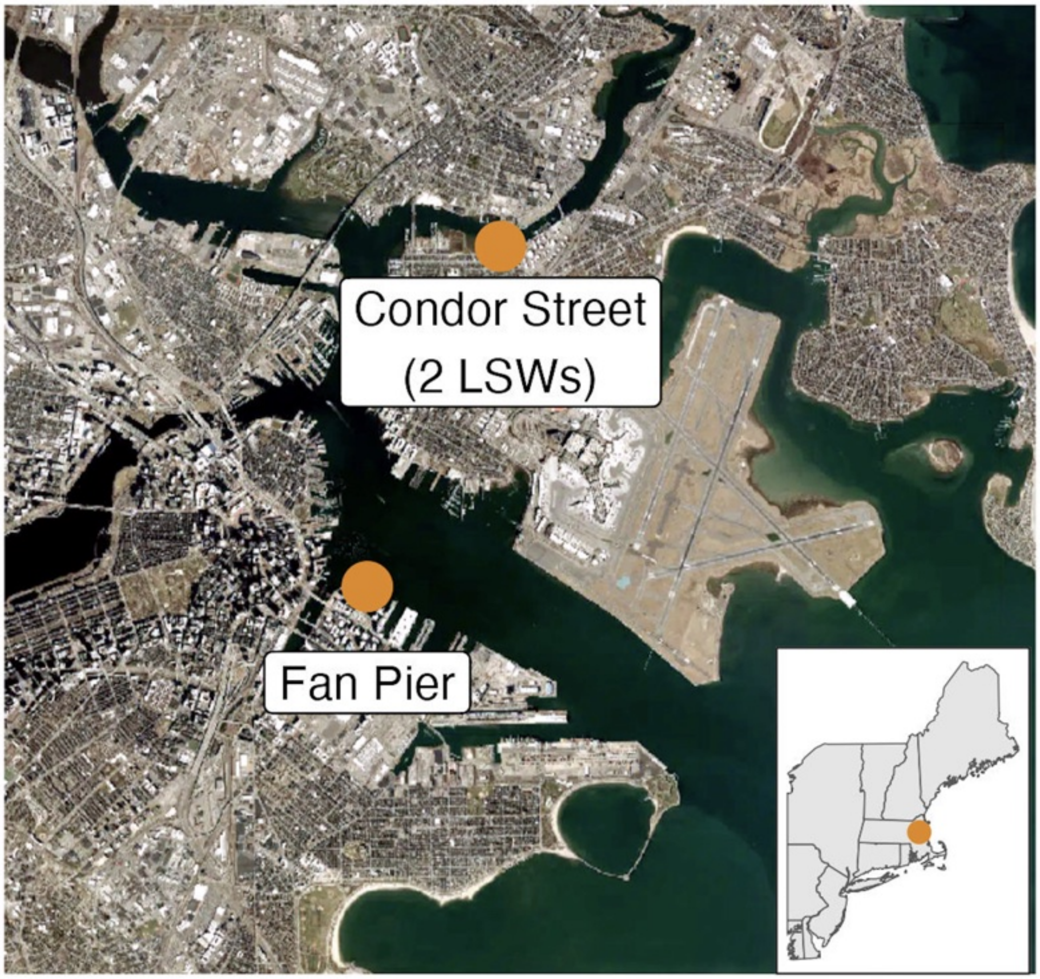

Figure 2: *Map of the three Living Seawalls installations across Boston Harbor with orange points showing selected sites, Fan Pier in the Seaport District and Condor Street Urban Wild. Inset shows the Northeast Seaboard of the US with the location of Boston Harbor marked.*

4. Panel design selection for Boston Harbor and fabrication

We selected 5 different panel designs to apply at each site in Boston Harbor (Figure 3). We prioritized abstract forms and also included one design that showed extremely high fucoid grown in the Plymouth, UK installation because *Fucus* spp. and the fucoid *Ascophyllum nodosum* are key foundation species in the New England rocky intertidal (Menge 1976).

Panel designs chosen included the small rockpool, large rockpool, crevice/ledge, swim-through, and flat control designs. Small and large rockpool: These represent a range of rockpool size found in estuaries. They have been quickly colonized by invertebrates and algae at other global locations and provide shelter from drying out and temperature stress. Crevice/ledge: These provide a cool, moist microhabitat and have been shown to protect invertebrates from predators. Swim-through: These are designed to provide habitat for small fish and have been dominated by fucoid algae at cooler climate installations. Control: This is included to assess the benefits of complex panel designs against a flat surface of identical material type.

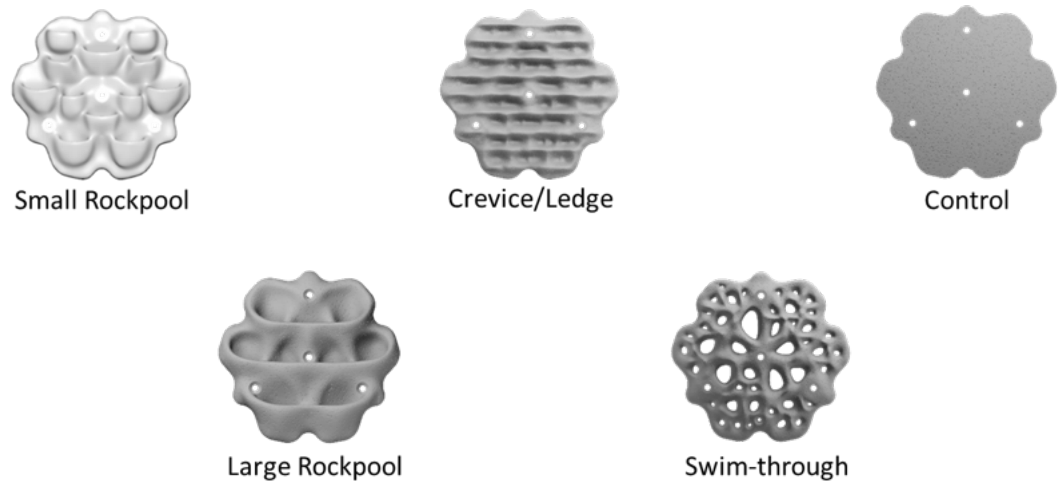

Figure 3: *Images of panel designs selected to test biodiversity enhancement.*

Panels were fabricated by Inland and Coastal Marina Systems (ICMS) in Ireland and shipped to Boston Harbor, which took approximately 6 months. Panels are composed of glass reinforced concrete leftover from pontoon construction by ICMS (Figure 4).

Figure 4: *Images of panel fabrication. (Image credits: Alex Goad.)*

5. Permitting

Following site selection, the permitting and design for each site commenced, concurrently with the panel fabrication. The process included obtaining landowner consent, development of engineering design plans detailing existing conditions and proposed modifications, review of the structural integrity of the seawalls, and submission of permit applications to the City of Boston Conservation Commission, to the Massachusetts Department of Environmental Protection, and to the U.S. Army Corps of Engineers.

Securing permits began by obtaining permissions from relevant landowners to access and modify sites. The project then moved through the City of Boston's Conservation Commission, where approvals were sought for a three-year demonstration. A Chapter 91 license was also required to ensure compliance with Massachusetts' public waterfront access regulations. At the federal level, the U.S. Army Corps of Engineers reviewed the project under Section 10 of the Rivers and Harbors Act, where a key challenge emerged: the potential presence of a migratory bird species in the project area. This triggered additional scrutiny and necessitated careful documentation and potential mitigation planning to avoid ecological disruption.

The time from site selection to securing permits was approximately eleven (11) months. As part of the process, Woods Hole Group prepared detailed engineering plans for each site.

6. Panel Installation

Panels were installed by SumCo Engineering in structured arrays spanning the intertidal zone at each site, enabling comparison across elevation gradients and panel designs. Installation methods included anchoring panels ~10 cm away from the seawall to account for variations in surface using stainless steel lag and bolt systems.

6.1 Fan Pier, Seaport

During mid-November of 2024, a total of 120 habitat panels were installed along a 13 m section of seawall at Fan Pier in the Seaport District of Boston. The panels spanned a vertical range of approximately 3 m, from the low to high intertidal elevations (Figure 5).

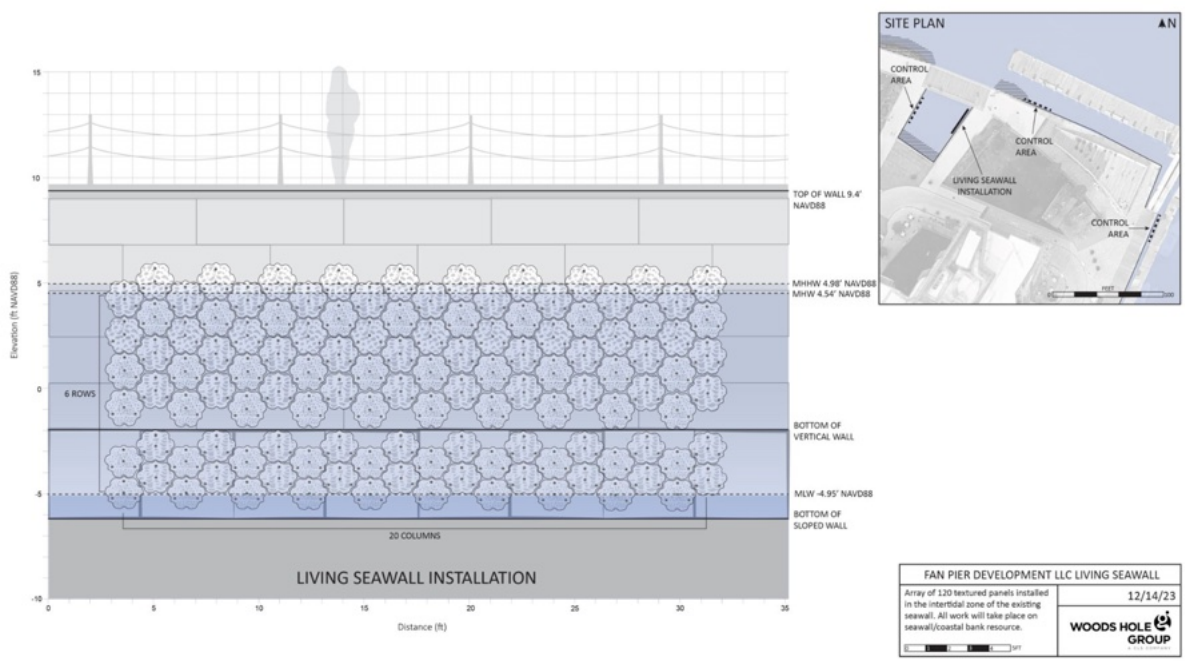

Figure 5: *Engineering design plan for the Living Seawalls installation at Fan Pier, Seaport.*

6.2 Condor Street Urban Wild, East Boston

During early November of 2024, a total of 120 habitat panels were installed in 3 rows along two 13 m sections of the east and west facing seawalls at Condor Street Urban Wild in East Boston. The panels spanned a vertical range of approximately 1.5 m, from the mid to high intertidal elevations (Figure 6).

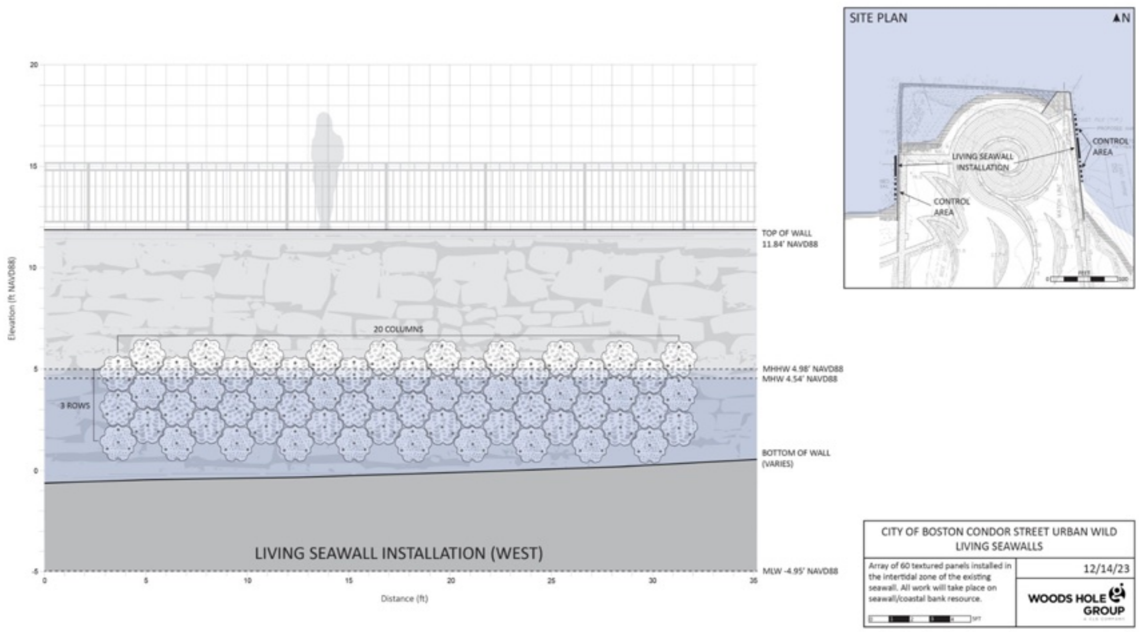

Figure 6: *Engineering design plan for the west-facing Living Seawalls installation at Condor Street Urban Wild, East Boston.*

7. Ecological Monitoring Framework for the Living Seawalls

7.1 Site-scale sampling

To assess the ecological outcomes of Living Seawalls, we examined how the ecological community changed pre- versus post- installation and relative to other changes in the environment and control (unmodified) seawall sites. This followed a modified Before-After Control-Impact (BACI) design where parallel sampling is done at both the site of a prospective ecological change and unmodified biologically similar control sites and used standard methods for Difference-in-Difference analysis (Larsen et al. 2019). As the biology of seawalls is not as well understood as other marine systems, we surveyed multiple control sites near each installation to create a more robust understanding of the ecological outcomes.

We surveyed invertebrate and seaweed communities on Living Seawalls installations and control seawalls in June/July 2024 (pre-installation) and June/July 2025 (~8 months post-installation). We collected additional photo quadrats every 3-4 months that will be analyzed for subsequent publications.

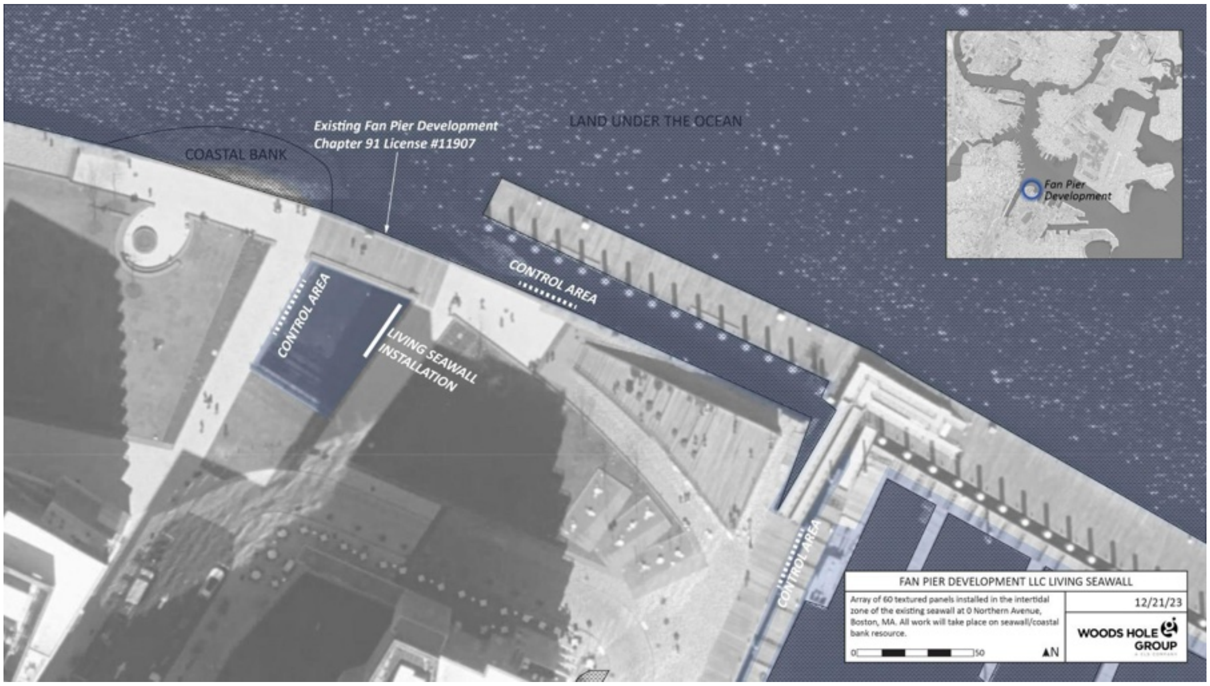

Figure 7: BACI design of site selection for sampling at Fan Pier.

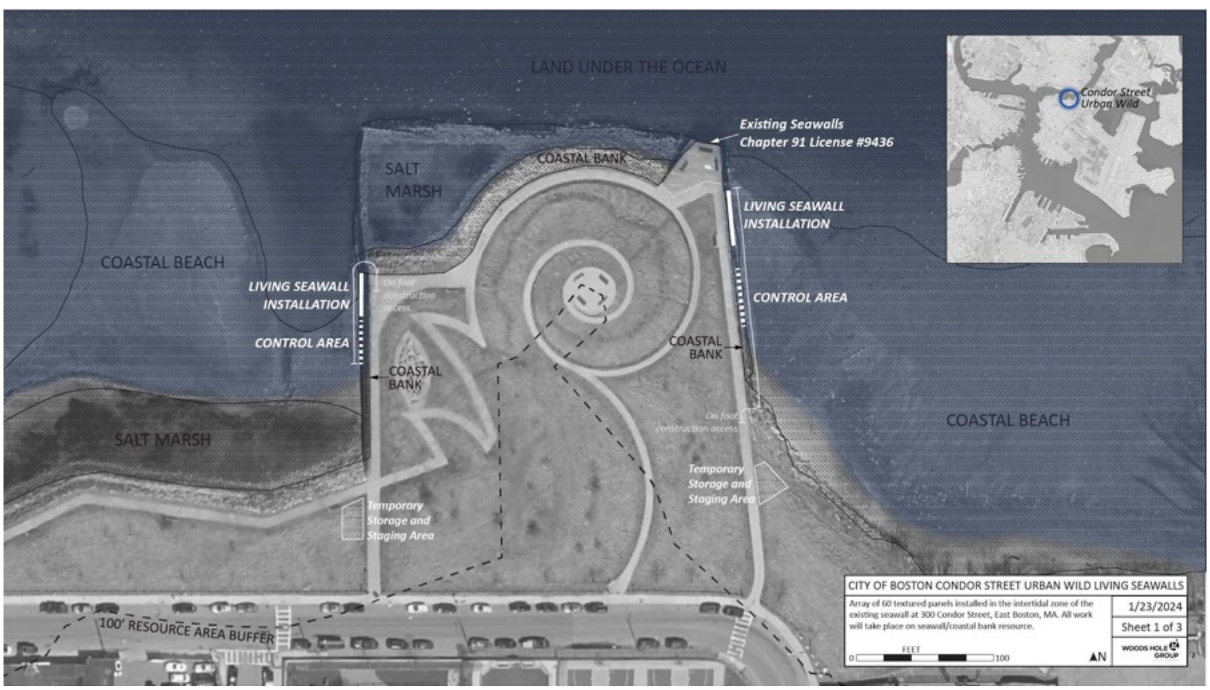

Figure 8: BACI design of site selection for sampling at Condor Street Urban Wild. Two Living Seawalls were installed on the east and west sides of the park.

For all surveys, we used 25 x 25 cm quadrats with 25 uniformly spaced points. Under each point, we assessed both primary (i.e. attached directly to the substrate) and secondary (i.e. growing on top of other species) cover of species. This allowed us to assess percent cover of different species or aggregated functional groups (e.g., red algae, bivalves, etc.). Mobile species within each quadrat were counted by species to determine abundance. Last, we noted sessile species present in the quadrat but not counted under an intersecting point to calculate species richness for an entire quadrat. As many of the species we recorded in 2025 were either new small settlers or taxonomically indeterminate in the field (e.g., one cannot tell different green algae apart without sectioning them and putting them under a compound microscope), many species and analyses were done at higher taxonomic levels than species - e.g. Family or functional group.

We also compared differences in the ecological communities among tidal elevations on each Living Seawalls installation and control seawall. In the intertidal zone, different communities occur at different heights on the shore because the tide determines how long each area is submerged or exposed each day. From the high to low water mark, communities are typically characterized by barnacles, then rockweeds and bladder wrack (Ascophyllum and Fucus), mussels, then irish moss (Chondrus crispus), and finally a mixture of other red algae, soft bodied sessile invertebrates (i.e. tunicates), and kelps at the low elevation. Therefore, at each site, we sampled 10 randomly chosen points at six (Fan Pier) and three (Condor Street Urban Wild) different tidal elevations in June/July 2024 and again in June/July 2025.

At Fan Pier, we sampled at lowest-, low-, mid-low, mid-, high- and highest-intertidal zones. We combined these as three tidal elevations (low, mid, high) to compare to control seawall sites. At Condor Street Urban Wild, the installation did not cover the full intertidal zone and so we sampled at mid-, high- and highest-intertidal zones. For ease of interpretation, we refer to these as low-, mid- and high- zones, respectively. At each tidal elevation we assessed biodiversity using the quadrat sampling protocol as above. Results were analyzed using difference-in-difference models (Larsen et al. 2019) with ordered beta regression to account for percent cover data and zero inflation (Kubinec 2023), although we present the results qualitatively here.

Our expectation was that, relative to control seawalls, we would see less perennial algae (e.g., fucoids and irish moss) and invertebrates (e.g., mussels and barnacles) on the Living Seawalls, which take >1 year to recolonize. We also expected extensive growth in more ephemeral species (e.g., sea lettuce). These ephemeral species tend to dominate while perennials slowly colonize. The perennials ultimately become the primary spaceholders and competitive dominants unless extensively grazed (Lubchenco 1978).

7.2 Panel-scale sampling

To assess the effectiveness of different complex panels in providing habitat for algae and invertebrates, we compared ecological communities among panel designs (Figure 8). In this report we focus on the Fan Pier installation because it provides the most complete representation of panel performance across the full intertidal gradient. Quadrat surveys were conducted using the methods described above, with 4 replicate panels of each design sampled at each of six tidal elevations. Results were analyzed with cover as a response and panel design, tidal elevation, and their interaction as predictors using ordered beta regression as above (Kubinec 2023). Results are presented qualitatively across the six tidal elevations (lowest, low, mid-low, mid, high, and highest) to illustrate how panel performance varies across the intertidal zone.

Figure 9: *Quadrat sampling on the Fan Pier Living Seawalls installation.*

Microbial biofilm formation can influence the identity of macrofauna that settle and colonize a new substrate (Schuster et al. 2019). As microbes are highly sensitive to environmental conditions - even at scales of millimeters - we also examined the impact of panel design on microbial biofilm formation in the month following panel deployment. Microbial biofilms on all seawall panels at Condor Street Urban Wild were sampled weekly for four weeks post-installation, and are currently being resampled annually. Samples were obtained by swabbing a standardized $20cm^2$ area on each panel next to a randomly chosen microhabitat. We did this to represent each panel's specific micro-topography. DNA was isolated using a phenol-chloroform extraction protocol, and the 16S rRNA gene was sequenced on an Illumina MiSeq platform. Raw amplicon sequences were processed in QIIME 2 using the DADA2 pipeline for quality control, denoising, and obtaining Amplicon Sequence Variants (ASVs), which were used for all subsequent analyses.

7.3 Impacts of panel design on thermal buffering

Electric Blue Temperature Loggers (https://electricblue.eu/, ENV29v7.3M6 loggers) were deployed at the high, mid, and low heights on the east and west facing Living Seawalls installations at Condor Street Urban Wild in June 2025 with Z-Spar (A-788 Splash Zone Compound). Data collected from June 2025-May 2026 are presented in this report to highlight how surface temperatures changed on the Living Seawalls panels and the nearby control seawalls over time and during the August 2025 heatwave experienced by Massachusetts.

8. Results

8.1 Ecological outcomes on the Living Seawalls

Eight months after installation, biological communities on the Living Seawalls panels were dominated by early-successional algae, but several perennial algal and invertebrate taxa had also established. Across both sites, species abundances on the Living Seawalls panels were generally comparable to those observed on adjacent seawalls prior to installation, indicating fairly rapid colonization following installation.

Ephemeral algae showed different trajectories at the Condor Street Urban Wild and Fan Pier Living Seawalls installations (Figure 9). At Condor Street Urban Wild, green algae, including the sea lettuce (*Ulva lactuca)* and gutweed (*Enteromorpha intestinalis),* increased from pre- to post-installation on both east- and west-facing Living Seawalls. In the low zone, cover increased from ~20% pre-installation to 60-80% post-installation on Living Seawalls, while remaining at ~20% on adjacent control seawalls. In the mid zone, cover after 8 months was similar to pre-installation levels of ~50% with little change at control seawalls. In the high zone, cover reached ~40% on both Living Seawalls - which was a large increase for the west-facing wall. In contrast, cover on the high zone of the control seawalls was lower and did not change appreciably. At Fan Pier, ephemeral green algae had roughly the same cover pre- versus post- installation on the Living Seawalls at all tide heights. Control seawalls remained statistically the same, although they qualitatively increased at low and mid- heights.

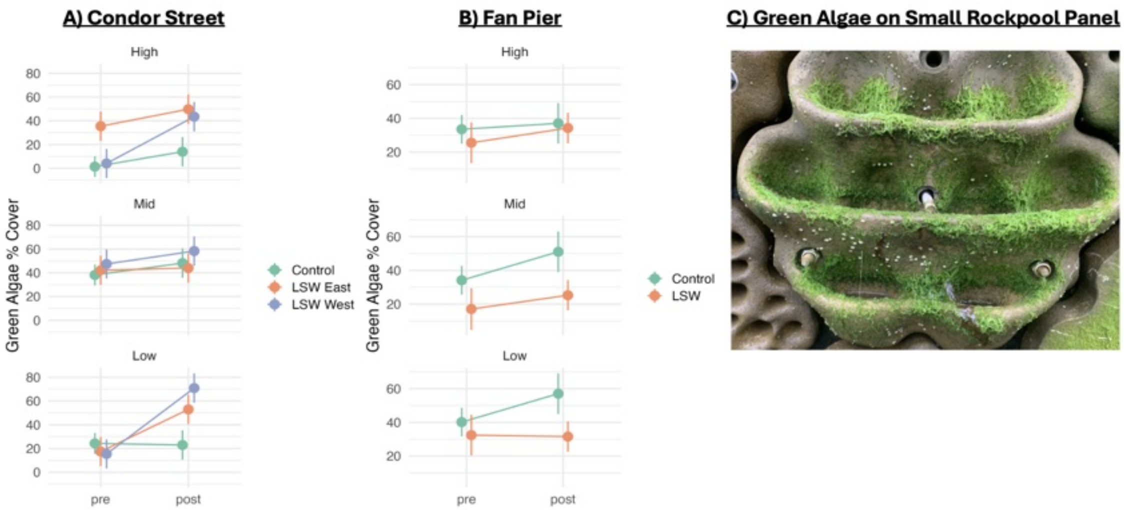

Figure 10: *Abundance of green algae in pre-installation (June/July 2024) versus post-installation and recruitment (June/July 2025) at Condor Street Urban Wild (A), Fan Pier (B), and a representative image of a panel (C). Control lines represent the average over all control seawalls at the site for comparison against the Living Seawalls. Sites are split into high, low, and mid zones, although it should be noted that the three zones of Condor Street Urban Wild are roughly equivalent to partitioning the high and mid zone of Fan Pier (i.e., they are higher in the intertidal). Dots represent means with 95% Confidence Interval error bars.*

Red algae were most abundant at Fan Pier (Figure 10). Ephemeral red algae, dominated by *Porphyra* spp., occupied approximately 40% cover in the high intertidal and maintained high abundances through the middle tidal elevations. In contrast, red algae were either absent, uncommon, or lower on the Living Seawalls compared to the pre-installation and control seawall at Condor Street Urban Wild.

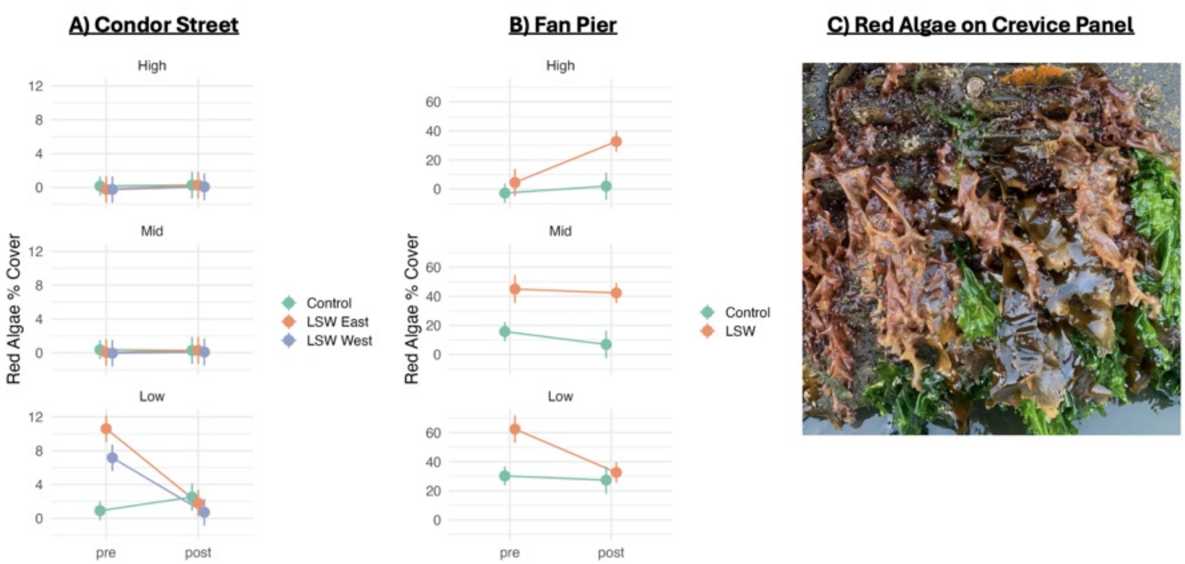

Figure 11: *Abundance of red algae in pre-installation (June/July 2024) versus post-installation and recruitment (June/July 2025) at Condor Street Urban Wild (A), Fan Pier (B), and a representative image of a panel (C). Control lines represent the average over all control walls at the site for comparison against the Living Seawalls. Sites are split into high, low, and mid zones, although it should be noted that the three zones of Condor Street Urban Wild are roughly equivalent to partitioning the high and mid zone of Fan Pier (i.e., they are higher in the intertidal). Dots*

represent means with 95% Confidence Interval error bars. Note also the green algae and juvenile kelp on the crevice/ledge panel alongside the Porphyra and Gratelopia.

Perennial algae and sessile invertebrates occupied less space overall compared to the ephemeral algae, but showed evidence of successful recruitment to the Living Seawalls. At Fan Pier, brown algae such as *Fucus* spp. reached approximately 20% cover across much of the intertidal gradient. Although lower than pre-installation levels, these values indicate substantial recruitment within the first 8 months. Many individuals were juveniles, suggesting continued development of perennial algal communities. Brown algae remained uncommon at Condor Street Urban Wild except on the lowest control seawalls, where cover remained relatively constant.

One notable observation was the recruitment of juvenile sugar kelp (*Saccharina latissima*) at Fan Pier (Figure 11b). Juvenile kelp occurred on Living Seawalls but was not recorded on nearby control seawalls, suggesting that panel microhabitats may facilitate establishment of this foundation species.

Barnacle cover at Condor Street Urban Wild stayed low at 5-10% across all tidal elevations and seawalls, save the low control seawalls where it was ~20% but did not change over time. Barnacle cover was 20% across all tidal heights in Fan Pier, although this was a decrease in the low- and mid-zones. Mussel cover remained low at all sites (< 2%) including controls, although the colonization of mussels on the new panels at all sites was notable (Figure 11a) and surprising given the noted declines in mussel abundance in the Gulf of Maine (Sorte et al. 2017).

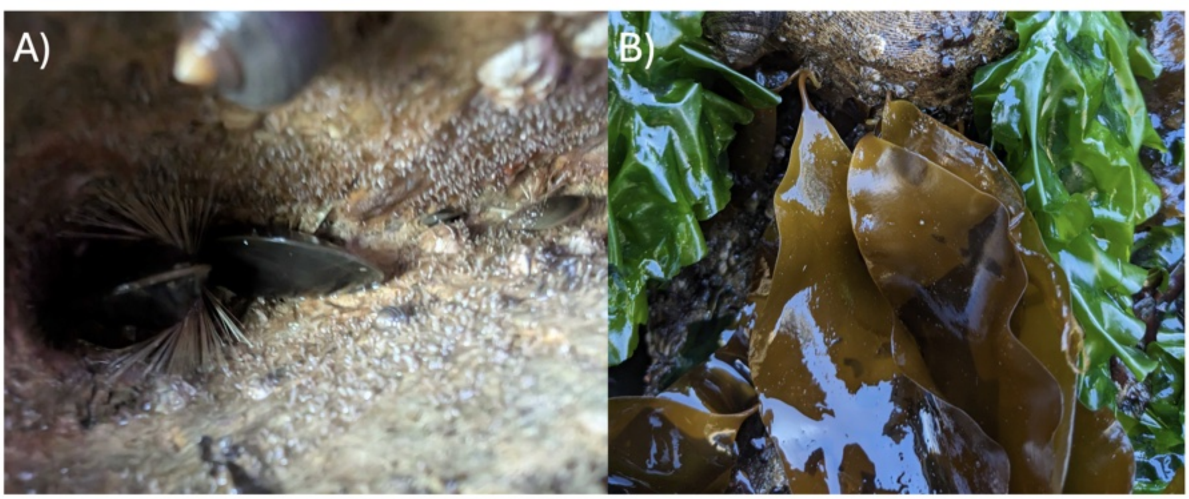

Figure 12: *Newly settled juvenile mussels (A) and sugar kelp (B) at the Fan Pier LSW.*

Overall, communities on Living Seawalls remained in an early successional stage after 8 months. Nevertheless, rapid colonization by ephemeral algae and invertebrates, together with recruitment of longer-lived perennial algal species, indicates that ecological communities are developing along trajectories consistent with mature New England rocky shore assemblages.

8.2 Ecological communities vary with panel design and tidal elevation

Seaweeds and invertebrates at Fan Pier

The Fan Pier installation provided the best opportunity to examine the influence of panel design because Living Seawalls panels spanned a broad intertidal gradient. Across most taxa, complex panel designs supported higher abundances than flat control panels and extended the tidal range over which species could persist (Figures 12-16).

Barnacles responded particularly strongly to panel design (Figure 12). Above the mid intertidal zone, barnacle cover on flat control panels generally remained below 5%, whereas some complex panel designs consistently supported twice the cover in the high and highest intertidal zones. Specifically, small and large rockpool panels performed especially well, supporting barnacle cover of up to 50% in the mid intertidal zone and maintaining substantial cover (~30%) even at the highest elevations.

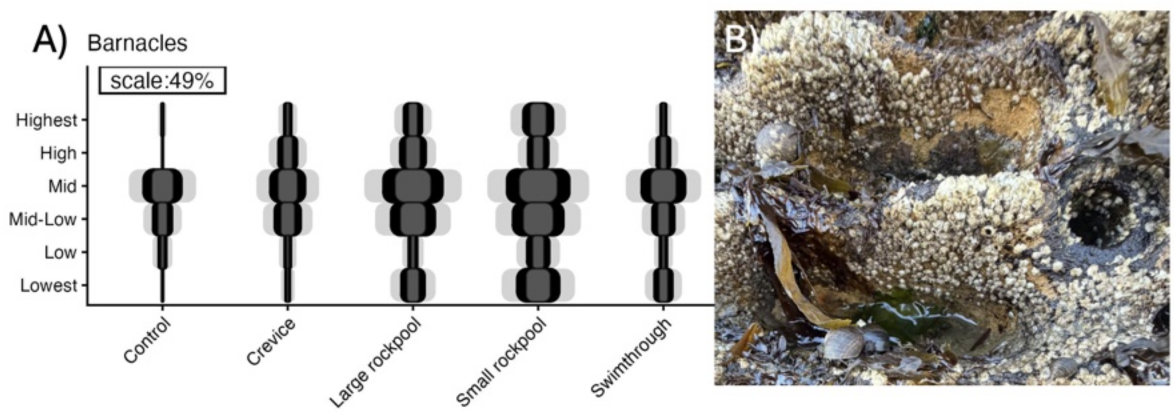

Figure 13: *Barnacle cover at Fan Pier different tidal heights on different panel designs (A) and a representative colonized panel (B). For the data panel (A) the y-axis shows tide height. The width of solid colored bars shows average percent cover. Light grey bars show the upper 95% confidence interval and dark grey bars the lower 95% confidence interval. The scale box at the top provides context for the meaning of bar width - i.e., the width of the scale box equals the number inside.*

Patterns for filamentous green algae were similar to barnacles (Figure 13). Complex panels had greater cover of green algae than flat control panels (10-15% versus 2-5%) at mid and higher intertidal heights. This suggests that enhanced habitat complexity provides suitable conditions for persistence at elevations on a seawall where algae would otherwise be uncommon. At lower intertidal heights, the cover of filamentous green algae on complex panels decreased and was generally replaced by red and brown algae at the lowest intertidal heights apart from on the flat control panels where covers increased with decreasing intertidal height.

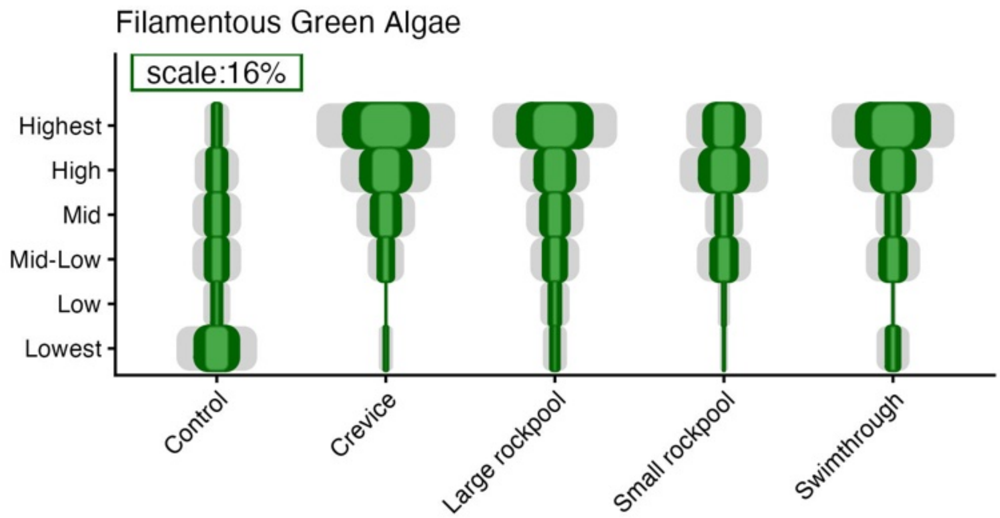

Figure 14: *Filamentous green algal cover at Fan Pier at different tidal heights on different panel designs. The y-axis shows tide height. The width of solid colored bars shows average percent cover. Light grey bars show the upper 95% confidence interval and dark grey bars the lower 95% confidence interval. The scale box at the top provides context for the meaning of bar width - i.e., the width of the scale box equals the number inside.*

Red algae, predominantly ephemeral algae from the genus *Porphyra* had the highest cover of all taxa and this was consistent across most panel designs (Figure 14). At the highest intertidal height, red algae cover was lowest on control panels (~5%) and highest on complex designs (~27% on small rockpools). Red algae cover increased with decreasing intertidal height across all panel designs (25-50%). At mid and low intertidal heights, controls had the highest cover followed by crevice/ledge treatments.

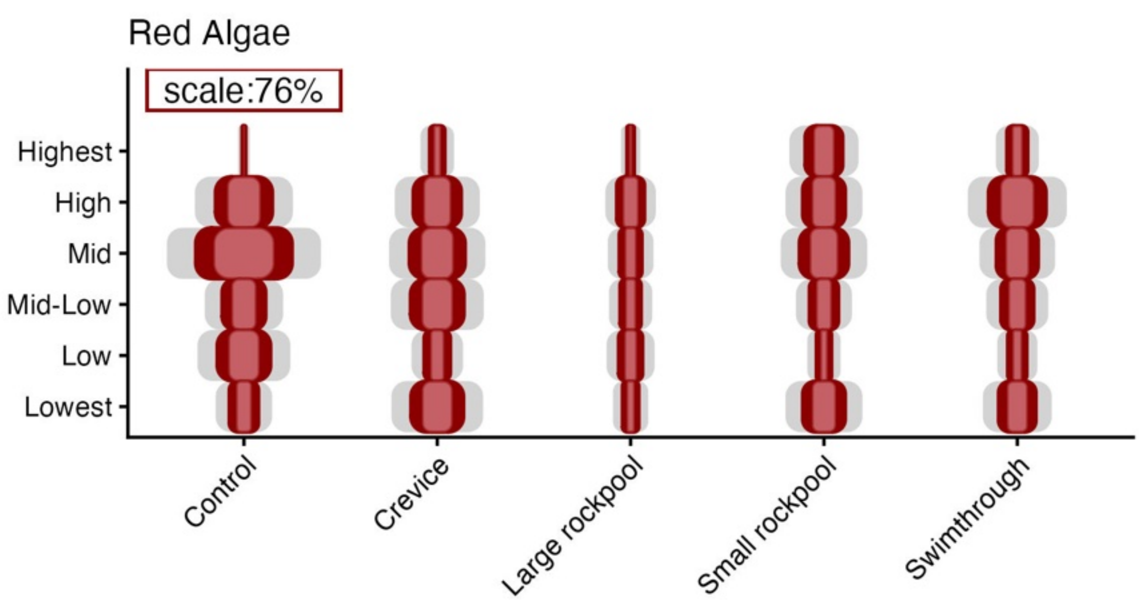

Figure 15: *Red algal cover at Fan Pier at different tidal heights on different panel designs. The y-axis shows tide height. The width of solid colored bars shows average percent cover. Light grey bars show the upper 95% confidence*

interval and dark grey bars the lower 95% confidence interval. The scale box at the top provides context for the meaning of bar width - i.e., the width of the scale box equals the number inside.

Perennial algae responded strongly to habitat complexity across multiple taxa. *Fucus* spp. had their highest cover on complex panels at mid and lower intertidal heights, with cover up to ~20% on large and small rockpool panels. Further, cover was ~15% on swim-through panels at all tidal heights (Figure 15) as compared to <5% on control panels. In the lowest intertidal, irish moss (*Chondrus crispus*) – a typically abundant perennial red alga at low tide heights (Menge 1978) – was found only on complex panels, with up to 15% cover on some small rockpool and crevice/ledge treatments. Last, juvenile sugar kelp was only found on rockpool and crevice/ledge panels.

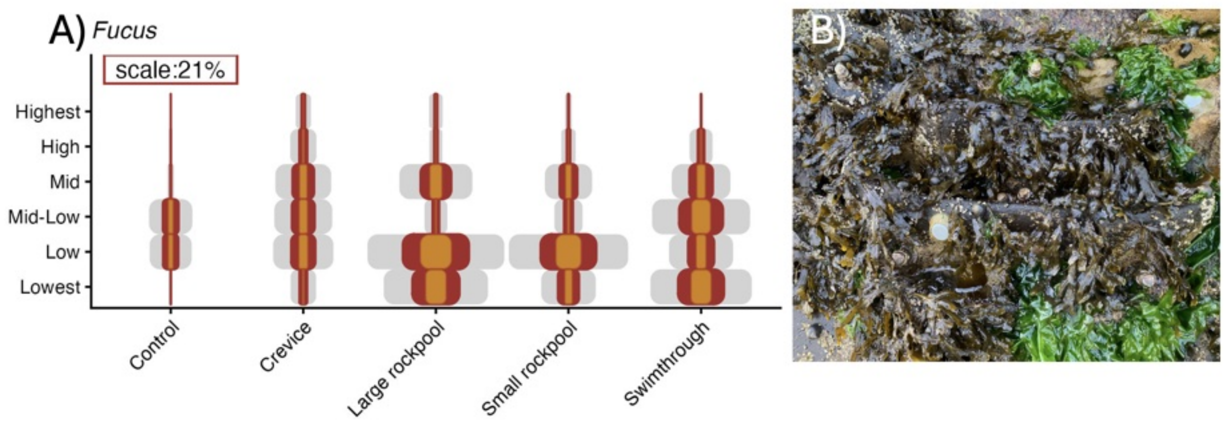

Figure 16*: Fucus spp. cover at Fan Pier at different tidal heights on different panel designs (A) and a representative colonized panel (B). For the data panel (A) the y-axis shows tide height. The width of solid colored bars shows average percent cover. Light grey bars show the upper 95% confidence interval and dark grey bars the lower 95% confidence interval. The scale box at the top provides context for the meaning of bar width - i.e., the width of the scale box equals the number inside.*

Mobile invertebrates also responded to panel design and were dominated by periwinkle snails (*Littorina littorea*) (Figure 16). At Fan Pier, there were very few snails on the control panels (2-3 individuals), although their impact was evident via grazing trails and cleared areas around snails that were visible on the panels. Snails were more abundant on crevice/ledge and swim-through panels at mid to low tide heights (5-10 individuals). While lower in abundance (3-5 individuals), they were often found in the pockets of large and small rockpools at these lower heights as well.

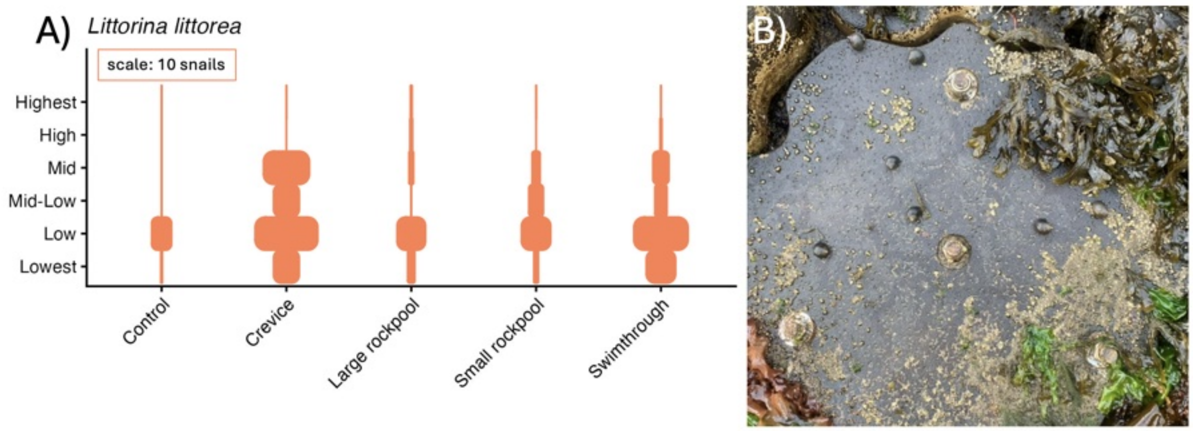

Figure 17: *Periwinkle snail abundances at Fan Pier at different tidal heights on different panel designs (A) and a representative colonized panel (B). For the data panel (A) the y-axis shows tide height. The width of solid colored bars shows average percent cover. The scale box at the top provides context for the meaning of bar width - i.e., the width of the scale box equals the number of snails for a bar of that width. (B) shows a control panel found with a few snails. Note the amount of space they have maintained as clear.*

Taken together, these results suggest that habitat complexity substantially influences the development of ecological communities on Living Seawalls. Among the designs tested, rockpool panels consistently supported the broadest range of taxa and appeared to provide the greatest overall biodiversity benefits. Additionally, some complex panels had taxa-specific responses such as snails clustering in crevices on the crevice/ledge panel and so having a range of designs in the intertidal may be important for overall diversity and heterogeneity in the intertidal.

Adding complex designs effectively increased the vertical extent of suitable habitat across the tidal gradient and generally supported greater cover of green algae in the higher intertidal, that would otherwise have been largely absent. At lower intertidal heights we observed increased cover of perennial brown algae versus ephemeral red algae on complex panels versus controls. Rockpool and swim-through treatments appear to be particularly good panel morphologies for brown algae, some even hosting kelps in addition to fucoids.

Complex panels also supported more periwinkle snails, although more visible signs of snail grazing were seen on control panels. Given that snails preferentially graze ephemeral algae, potentially they are using complex panels as habitat, but spending their time foraging on easier to graze control panels. This could explain lower cover of green algae on control panels.

Microbial biofilm communities at Condor Street Urban Wild

Preliminary analysis of the microbial biofilm communities from the Condor Street Urban Wild Living Seawalls panels (east facing wall) four weeks after installation suggest that bacterial communities are primarily structured by tidal elevation rather than panel design (Figure 17). The first two axes capture 95.1% of the total compositional variance (PC1:

56.3%, PC2: 38.8%). This ordination signal is almost exclusively driven by tidal elevation, as highlighted by the 95% confidence ellipses. The low (green) and high (purple) tide communities occupy entirely separate regions of the ordination space, thus, show the greatest divergence, while the mid tide (orange) communities bridge the gap between the two. Individual panel designs do not follow a clear ordination pattern. Consequently, the differences observed among panel designs for seaweeds and invertebrates are likely driven by the physical habitat complexity created by the panels rather than by differences in microbial biofilm development.

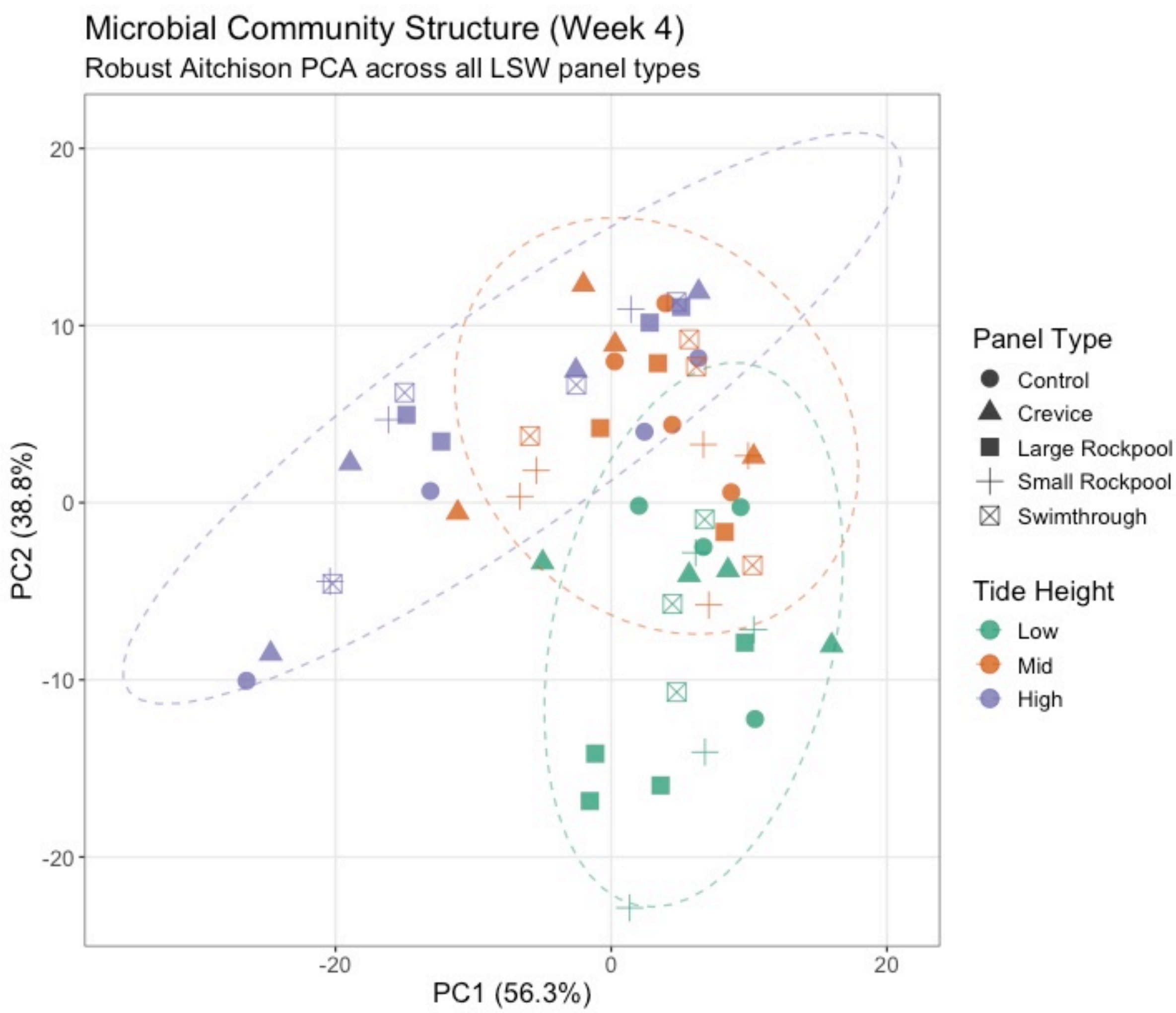

Figure 18: *Microbial community structure at Condor Street Urban Wild four weeks post-installation. Beta diversity is visualized using a Robust Aitchison Principal Component Analysis (RPCA) calculated from 16s rRNA amplicon sequence variants (ASVs). Individual points represent distinct panels, with shapes denoting panel design and colors indicating tidal elevation. Dashed ellipses represent 95% confidence intervals for each tidal zone.*

8.3. Thermal buffering by panel designs at Condor Street Urban Wild

In August of 2025, approximately 10 months post-installation, Massachusetts experienced an extreme heatwave. The effects were particularly evident at Condor Street Urban Wild, where seawalls receive prolonged direct solar exposure. Following the heatwave, substantial declines in biological cover were observed across much of the seawall. Green algae alone persisted within and around rockpool habitats and recovery since the heatwave (observed in June 2026) has been most evident in these areas (Figure 18).

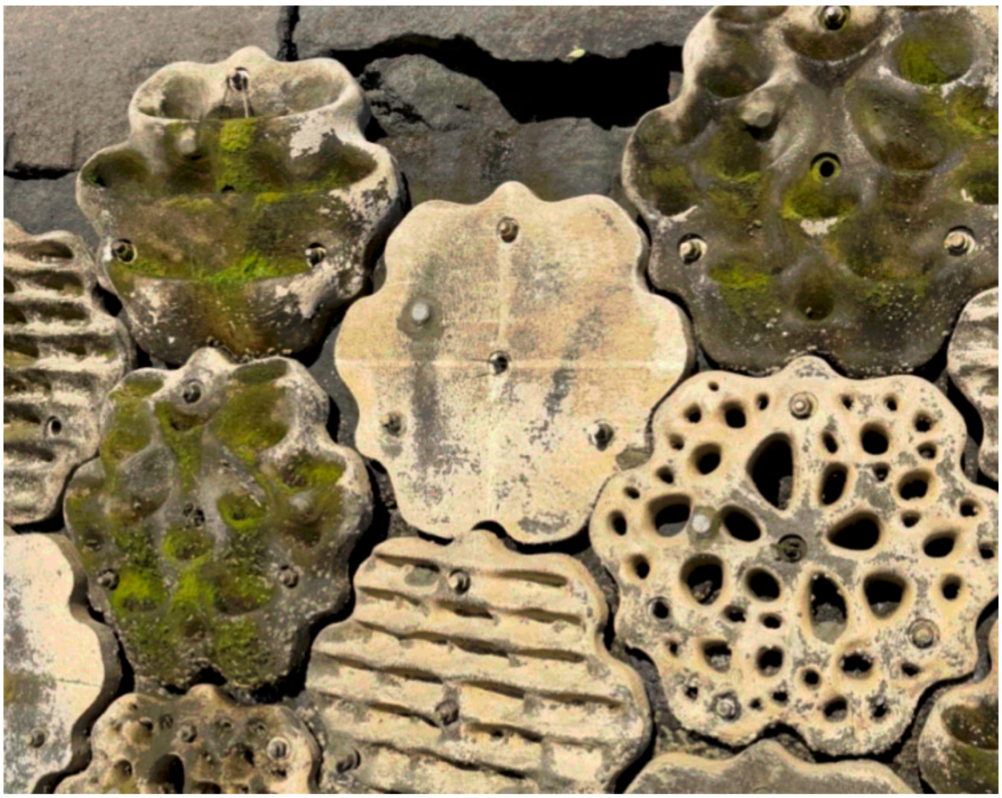

Figure 19: *Condor Street Urban Wild in June 2026. Note the extensive green algae around rockpools, although the control and other panels have not recovered as well.*

Temperature monitoring demonstrated that Living Seawalls panels consistently remained cooler than adjacent unmodified seawall surfaces (Figure 19). This pattern occurred across tidal elevations and seasons, but was most pronounced during summer. Within the Living Seawalls installation, the rockpool panels recorded the lowest average daily maximum temperature during summer and this was ~10ºC (~18ºF) cooler than adjacent seawall surfaces. In the fall and winter, complex and control panels were more similar in surface temperature, but the rockpools consistently had the lowest average daily maximum temperatures.

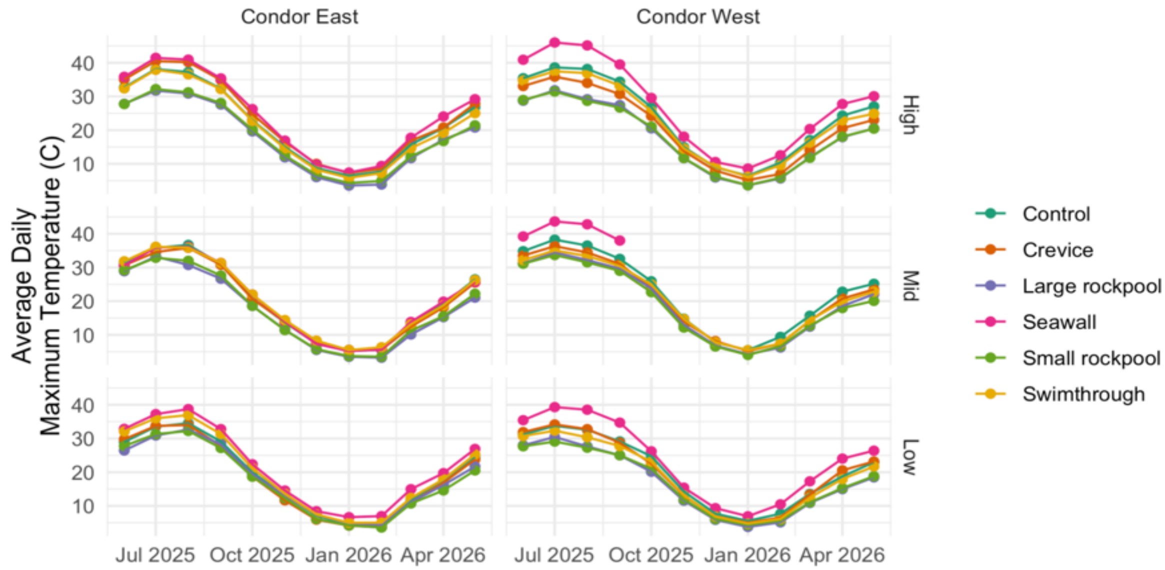

Figure 20: *The average maximum daily temperature by month on different panel designs and the adjacent control seawall at Condor Street Urban Wild.*

To understand the role of Living Seawall panels in ameliorating the most stressful thermal conditions each month, we looked at the largest daily difference between the adjacent seawall and each panel design at the three tide heights (Figure 20). In August 2025, when the heat wave occurred, the rockpool panels reduced the thermal maximum consistently by at least 10ºC and up to 20-25ºC (25-45ºF) on Condor West with maximum seawall temperatures of 52.7ºC (127ºF). These results highlight the capacity of habitat panel designs, particularly rockpools, to create thermal refugia that may increase resilience of intertidal communities under future climate warming.

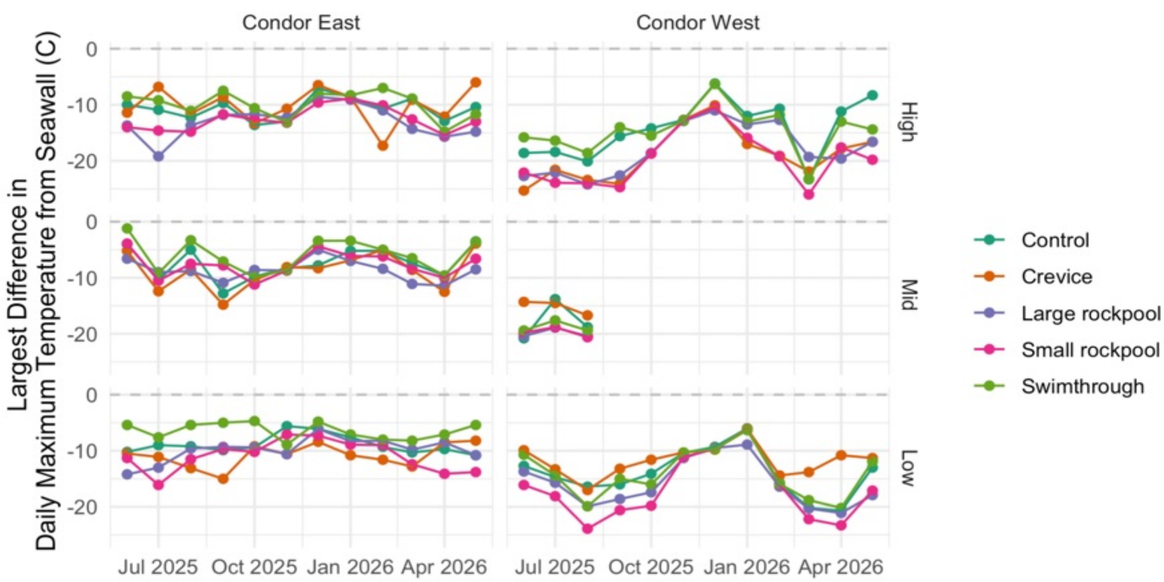

Figure 21: *The largest difference in maximum daily temperature relative to the adjacent seawall for each panel design by month at Condor Street Urban Wild.*

9. Conclusions

Eight months after installation, Living Seawalls in Boston Harbor have been rapidly colonized by a diverse range of algae and invertebrates. Although communities remain in the early stages of ecological development, species abundances are now broadly comparable to those observed on adjacent seawalls and colonization has proceeded more quickly than anticipated for many taxa.

Several key findings emerged eight months after installation:

- Living Seawalls supported rapid colonization by intertidal organisms following installation and communities were similar to surrounding unmodified seawalls.
- Early successional communities were dominated by ephemeral green and red algae, consistent with patterns observed on newly available rocky habitats.
- Perennial species characteristic of New England rocky shores, including *Fucus* spp., *Chondrus crispus*, barnacles, mussels, and juvenile sugar kelp, have begun establishing on complex panels.
- Complex panel designs generally supported greater biodiversity than flat control panels.
- Habitat complexity extended the vertical range over which many species could persist within the intertidal zone.
- Rockpool and swim-through designs were particularly effective at supporting perennial algae and increasing habitat availability.
- Crevice/ledge and swim-through panels provided important refuge habitat for periwinkle snails and other mobile organisms.
- Microbial biofilm development was influenced primarily by tidal elevation rather than panel design.
- Complex panels moderated surface temperatures relative to adjacent seawalls, particularly during summer.
- Rockpool habitats reduced temperatures during extreme heat events by as much as 20°C, demonstrating potential to enhance climate resilience.

Overall, these results indicate that Living Seawalls are functioning as intended in Boston Harbor. The panels are supporting the development of ecologically diverse communities while simultaneously creating microhabitats that reduce thermal stress and expand habitat availability. Although the communities remain in the early stages of succession, continued monitoring will determine whether these communities ultimately match or exceed the biodiversity of adjacent seawalls. Early observations from 2026 already indicate further increases in species diversity, abundance and cover beyond those reported here (Figure 21). Collectively, these findings suggest that Living Seawalls can enhance biodiversity and climate resilience in cold weather urban coastal environments. As communities continue to develop, we anticipate that the installations will support increasingly complex intertidal assemblages that contribute important ecosystem functions and services within Boston Harbor.

Figure 22: *A photo of the mid-intertidal from the Fan Pier installation in June 2026 before sampling. Note the extensive growth of adult perennial brown algae.*

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