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Biodiverse built environments:
High-performance passive systems for ecologic resilience

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EXECUTIVE SUMMARY

Perhaps the biggest challenge facing humanity is to sustainably manage human-dominated ecosystems. This is particularly relevant in coastal regions, where waterfront development has replaced tidal ecosystems and the associated ecological functions. Natural buffers, such as marshes, oyster reefs and mangrove trees, are some of the most ecologically productive habitats, yet have seen a continuous decline throughout the 20th century. These tidal ecosystems are critical in maintaining good water quality, diverse habitats, and structural shoreline integrity. As a result of losing these underpinnings of the environment, natural systems are failing to cope with the stressors stemming from coastal communities, and biodiversity is being lost at a rate far exceeding any other time in human history.

This research aims to shift the coastal construction industry, and more broadly, *built environments*, toward environmentally friendly practices. The approach taken herein capitalizes on *passive systems* - those materials and geometries that capitalize on natural bioclimatic factors without the need for operational energy input. High-performance versions utilize embedded material and formal logics to amplify the beneficial returns of passive systems. In this project, we expand the category of these high-performance passive systems to include biodiversity as design criteria in the development of architectural and landscape structures.

By first examining the seawall industry as an embedded player in coastal infrastructure and construction practices, this work seeks common ground through partnerships with community, economic and environmental stakeholders. These collaborations have created opportunities to advance this discussion and achieve milestones introducing new designs and materials into an existing industry and regulatory context. Ultimately, this effort requires collaboration among designers, architects, engineers, contractors, scientists, and regulatory offices at municipal, state and federal levels.

This project advanced a prototype for an engineered-living wall panel derived from mangrove trees and applied it to a constructed waterfront. The goals of the engineered-living shoreline are to restore a tidal ecotone containing a hierarchy of habitats embedded in the panels and to improve the environment by establishing preferred conditions for *foundation species* - those species that disproportionately engineer the environment and create suitable conditions for other species. Because conventional seawalls (concrete, metal, wood, composite) lack tidal habitat, they tend to degrade the environment and create conditions that facilitate invasive species. The present work aims to design a living seawall and collaborate with industry partners to make it economically sustainable.

The method to develop the panels relies on biomimetic designs built on parametric models of natural systems and manifested through novel fabrication techniques. Computer numeric control (CNC) fabrication techniques can deliver optimized geometry to increase the return on investment with these passive technologies, and the casting technique in this project presents new opportunities for cost-effective production of forms that mimic the complexity of natural designs.

Through two pilot studies, the living seawall panels were installed in 2016 and 2018 and monitored for biological recruitment over two years. These “Mangrove Reef Walls” demonstrated a distinct performance advantage over conventional seawalls in terms of habitat creation and waterfront aesthetic value. The advantage was particularly noticeable when applying the panels over a corrugated aluminum seawall, where virtually no biological growth existed on the wall prior to installation. In this regard, one of the outcomes of the project was a critical perspective on the materiality of seawalls; as the industry shifts toward corrugated sheet pile construction composed of vinyl or metal, the new walls host little to no biological recruitment. Although detrimental in many ways, concrete seawalls do support some oyster development but lack structural complexity. The results indicated that form and materiality both play a significant role in supporting healthy tidal environments.

The two pilot studies also explored the feasibility of utilizing silicone mold liners to create the texture and depth of root forms derived from mangrove and oyster patterns. The projects were used to determine the limitations of the silicone material, in terms of weight and formal composition. Although feasible for smaller-scale installations, the molds require additional structural support and handling equipment if they are to be used in large-scale applications.

The prototype developed with this work will ultimately be used to inform the production of a large installation of panels in a separately funded project to study the longterm ecological benefits of the wall panels. In this regard, the project may impact how state and federal agencies recommend engineered-living alternatives to construction projects on both inland and coastal waterfronts. Ultimately, the work has a transformative capacity that, through design, can contribute to wide range of disciplines and potentially affect how we build our cities.

Lastly, the project overlapped with the COVID-19 pandemic, which presented numerous delays and disruptions. Collaborators faced labor shortages and supply chain disruptions that created challenging circumstances within which to advance the project. For a period of time, entities that were involved in the project were forced into “survival mode,” which demonstrated the fragile nature of our interconnected global economy. Suddenly, resources were limited and the prospect of introducing new challenges to an existing industry was temporarily halted. These factors exposed how quickly our construction technologies retreat to entrenched methods, particularly with no incentive to change. The experience only further reinforced the need for more integrated approaches to sustainable systems to avoid value engineering out nature when crises emerge.

01

INTRODUCTION

The objectives of this project included the design and production of a full-scale prototype of an eco-friendly wall panel to be installed over an existing seawall. Through this process, students, practitioners, and interdisciplinary partners collaborated to evolve bio-criteria and design constraints for the seawall panels, which included feedback from a first-generation prototype. The second prototype was developed and installed during the first 12 months of the project, with periodic monitoring occurring over the following 36 months to document the recruitment and development of multiple key indicator species. The present work included collaboration with an industrial partner to evaluate the scaling potential of the technology, particularly within the context of existing seawall construction technologies and well-established installation practices. In this regard, the contributions of the completed work herein provided feedback on methods to produce and install the panels within a coastal context that includes social, economic, environmental and practical considerations.

This report introduces the context for the work and an overview of the panel research, production and installation that took place during 2018-2022. The next section, *Coastal Communities,* covers the environmental challenges that have arisen due to human activities along coastlines. In *Waterways and Walls,* the typology of the seawall-lined Florida canal is introduced. *Living Seawall Concept* outlines the proposed shift in construction toward biodiverse built environments through the lens of the panel design and project installation. Finally, *Future Work* outlines some future directions for the research.

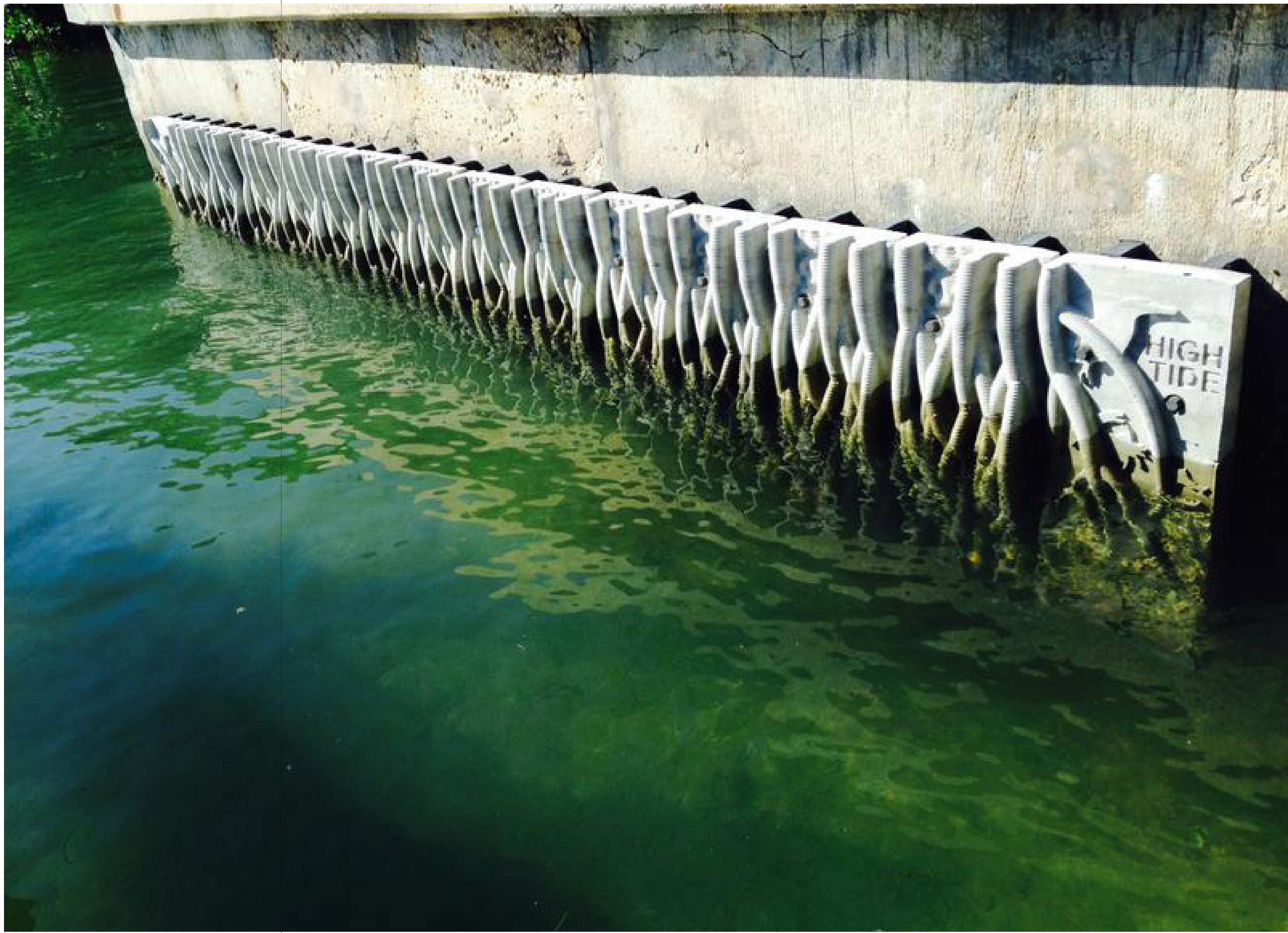


Figure 1. Prototype panels installed on Manasota Key in Englewood, FL in 2016. Image credit: WGCU Radio, Fort Myers

02 COASTAL COMMUNITIES

Over half the world population lives on or near coastlines,[1] putting immense development pressures on these environments.

At the same time, the world is losing coastal ecosystems faster than the tropical rainforests.[2,3] In this regard, human-altered landscapes have an ecological footprint on an unprecedented scale, such that the world is witnessing extinction rates thousands of times higher than normal “background” levels, and up to a quarter of species face extinction in the coming decades.[4] Much of this is due to habitat destruction and losses due to land conversion in sensitive areas.

Tidal wetlands, reefs and shorelines create natural filters and thriving habitats that form the foundation to coastal ecology, yet these productive habitats have been nearly completely converted into hardened edges (seawalls and riprap) in some densely urbanized Florida coastal counties.[5] Much of the negative impact of waterfront development stems from two critical aspects of urbanized waterfronts- the loss of structural complexity at the shoreline and the depletion of biological systems that create and enhance it. Exacerbating the problem, waterfronts with seawalls have been shown to facilitate the spread of invasive species.[6,7]

In Florida, coastal and inshore water quality has become a primary concern as it threatens to undermine communities that rely on the environment for economic wellbeing and quality of life. Pollution from water-based activities and runoff from land sources continue to degrade marine environments, contributing to food-web contamination, harmful algal blooms (HABs) and significant impacts to coastal economies and communities.[8,9]

Hydrological systems (natural and human-made) are interconnected across the state, with political and social issues often at the center of debate when it comes to managing the environment. Without natural shoreline filters and effective regional watershed management, coastal waterways become catchment basins for agricultural and urban runoff, which fuels HAB events and prompts die offs of fish, shellfish, manatees and other species. No longer able to be ignored, starving manatees are now a common sight in the Indian River Lagoon, with over 1000 dead from starvation and other causes in the past year alone.[10] Water quality and the environment’s capacity to absorb nutrients and support numerous species is critical to the future of these coastal areas.

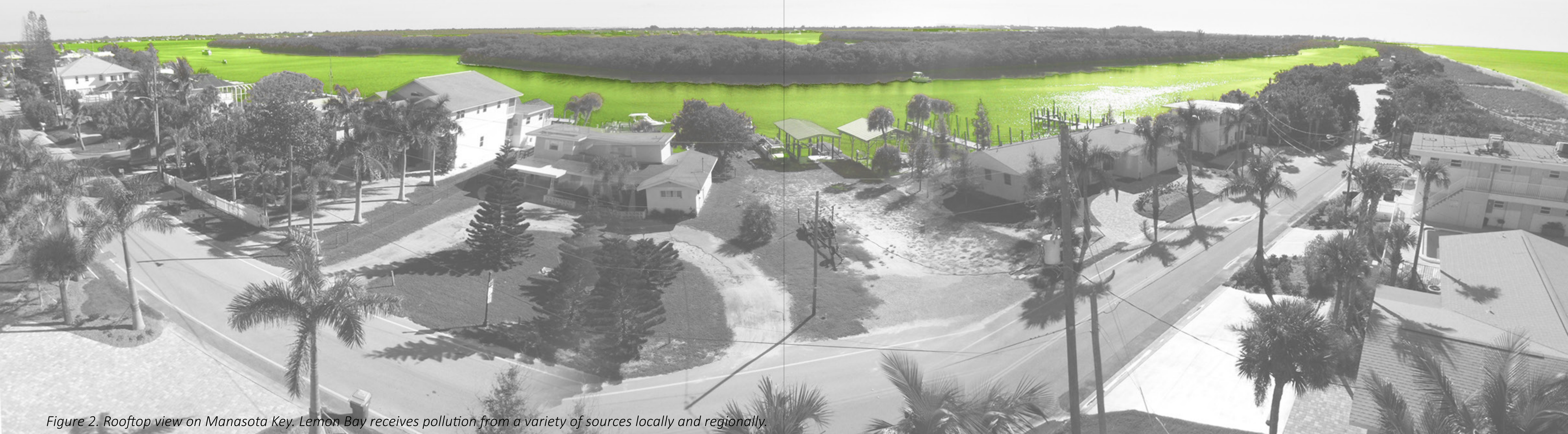


Figure 2. Rooftop view on Manasota Key. Lemon Bay receives pollution from a variety of sources locally and regionally.

Studies have shown human-made structures have the potential to support diverse marine life and increase the filtration capacity of altered shorelines well beyond that of existing natural edges.[11]

Seawalls, piles and other dock structures create surface area; however, these structures are relatively featureless vertical conditions and thus lack the structural complexity of natural intertidal habitats. Distribution of diverse habitats allows for more diverse species assemblage to occupy the shoreline,[12] indicating that the design of artificial habitats across various human-made structures will encourage oyster colonization and have cascading effects on water quality and biodiversity of other marine habitats.

Furthermore, studies show supporting evidence that extending the available habitat across areas of human-altered landscapes would provide a simulacrum of the historical natural shoreline. One survey found that replacement of large swaths of landscape (50-80%) causes dramatic decline in species richness within human-altered shoreline environments, whereas fragmentation that permits patches of habitat to exist within proximity to each other (i.e. "habitat matrix") has little to no effect on most species.[13] Thus, modified urban waterfronts could provide the scaffold for natural processes across large spatiotemporal landscapes and establish mechanisms to support ecosystem-scale functions.

Figure 3. Comparison of natural mangrove shoreline and urbanized waterfront, Manasota Key, Englewood, FL.

Without natural shoreline filters and effective regional watershed management, coastal waterways become catchment basins for agricultural and urban runoff, which fuels harmful algal blooms (HABs) and prompts die offs of fish, shellfish, manatees and other species. Historical septic systems remain a major source of excess nutrients in lagoons and bays. Compounding the issue, oyster extent declined by 64% (biomass reduced by 88%) in U.S. coastal waters during the 20th century,[14] thus significantly reducing the environmental capacity to withstand stressor events and regenerate over time.

Research has shown HAB events to reduce the survival of early stages of oysters and therefore reduce oyster recruitment, and the reduction of overall numbers coupled with lower survival rates make restoration of self-sustaining populations of natural or introduced species much more difficult,[15] thus requiring new tools to establish ecological processes and efficiently transfer excess nutrients into productive biomass.

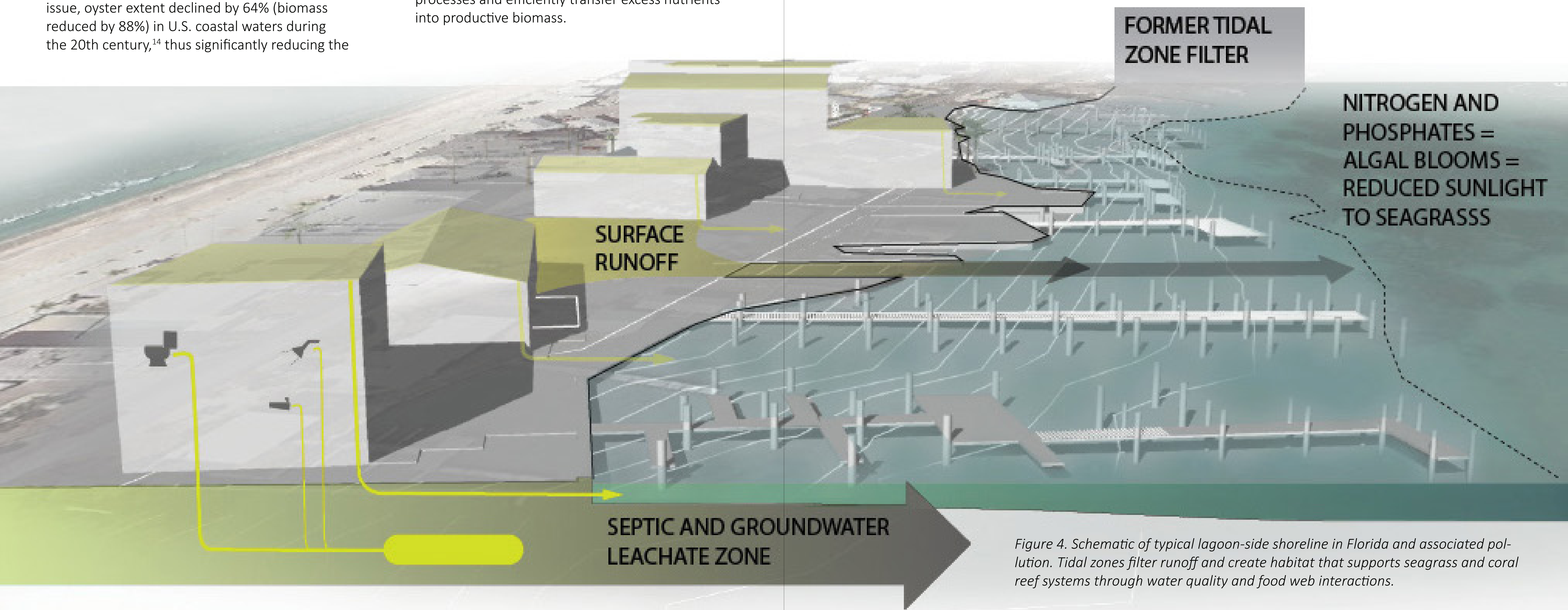


Figure 4. Schematic of typical lagoon-side shoreline in Florida and associated pollution. Tidal zones filter runoff and create habitat that supports seagrass and coral reef systems through water quality and food web interactions.

Figure 5. Detail view of red mangrove tree roots in southwest Florida. Rhizomatic networks create habitat, stabilize soils and filter water. Image credit: Jonathan Hall

Red mangrove trees are a tropical and subtropical species of coastal vegetation that occupy tidal zones. The distinct aerial root systems serve multiple purposes; they stabilize the trees and shoreline during tropical storms and hurricanes and simultaneously create habitat above and below the waterline. The arching forms provide shelter and nursery area for many species, and the roots become a substrate for a wide variety of marine life, forming the basis to a food web that is a 'lifeline' to seagrass and coral reef ecosystems.[16] In contrast to seawalls, the roots trap sediment and reduce wave energy at the shoreline, thus reducing suspended sediment in the water column.[17] Translating this geometry into a constructed edge may replicate some of the functions of mangrove trees.

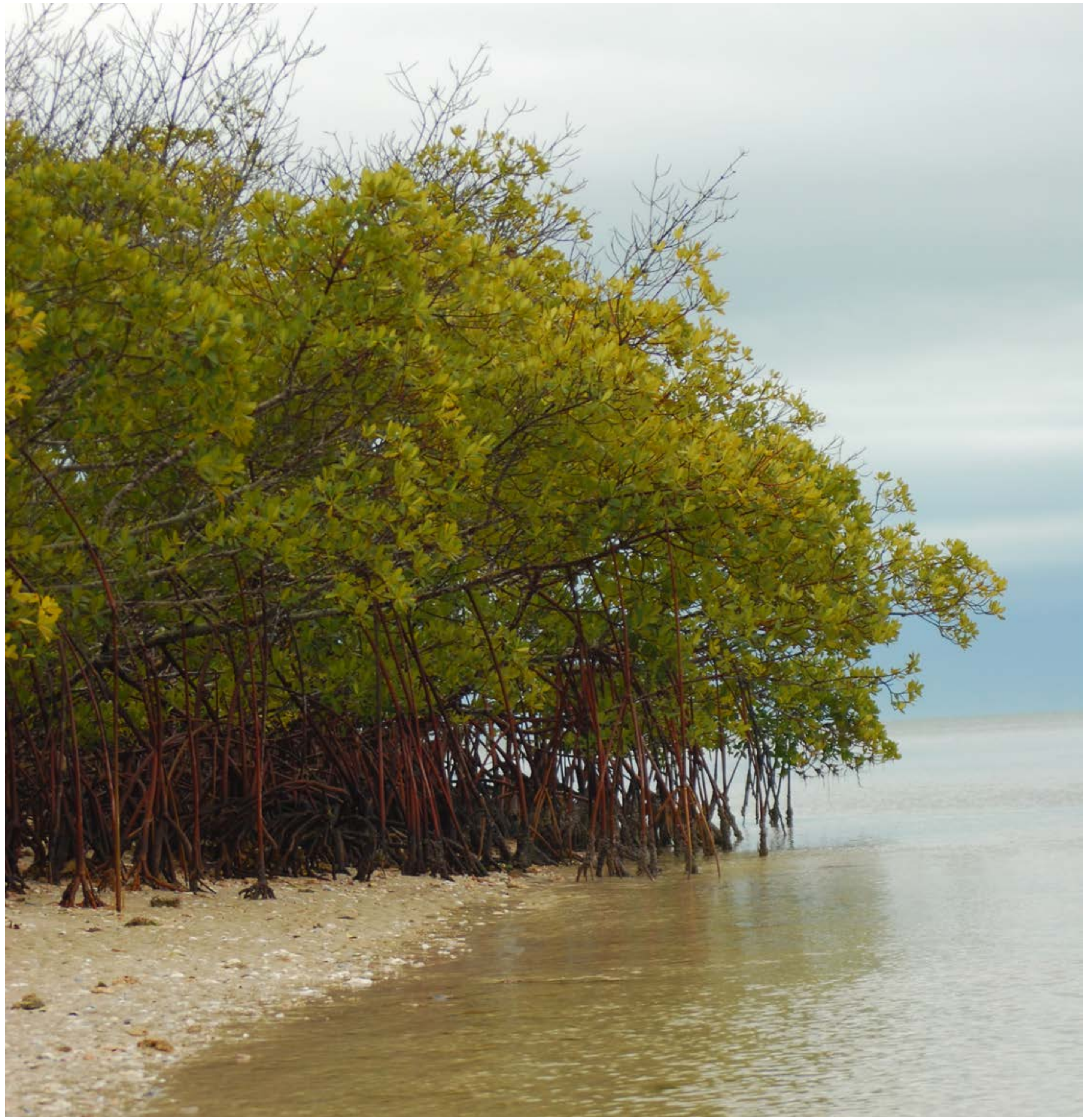


Figure 6. Mangrove edges near waterway channels are the most ecologically productive areas in the forest.

Figure 7. Low tide view of mangrove trees growing over an oyster reef substrate, Southwest Florida.

Figure 8. Low tide view of oyster reef assemblage composed of Eastern oysters with barnacles.

Oyster reefs are often found in tandem with mangrove trees and play an outsized role in stabilizing shorelines and filtering water. A single healthy oyster can filter up to 50 gallons of water per day.[18] Many thousands of oysters across even a small reef cleanse the water of a variety of pollutants. Oysters occupy specific intertidal areas and require a substrate within this zone to become established.

Seawalls offer very little surface area for oysters to become established, and certain materials are more hospitable than others. Seawalls composed of materials other than concrete tend to have less growth due to the lack of calcium carbonate and smoother substrate.

03 WATERWAYS AND WALLS

Florida has tens of thousands of miles of canals and waterways, many of which are lined with concrete seawalls. These vertical and featureless walls replaced tidal habitats and have contributed to the decline of the coastal environment.[19] In addition to creating conditions for accelerated erosion in some areas, seawalls lack suitable structural complexity and make baitfish and foraging fish overly vulnerable to predator species. Regardless, some counties along Florida's Atlantic Coast have converted between 75-100% of tidal shorelines into hardened edges- mainly in the form of seawalls and riprap.[20]

Although living shorelines are an ideal solution for many urbanized shorelines, the harsh reality is they are impractical in most Florida canals, which are the dominant landscape feature of many coastal areas. Dredged and channelized, canals mostly prohibit conventional living shorelines due to limited width, deeper water, and the presence of boat dockage. Tidal vegetation, such as mangrove trees, would require extensive wetland terraces to grow in these environments and would compromise waterfront access. Furthermore, restrictions that apply to mangrove trees when planted on a homeowner's property (the "Mangrove Trimming and Preservation Act") have made individuals resistant to planting the trees when possible, for fear of losing waterfront views and property value. Other factors, such as virtually no incentives, make it unlikely that property owners will commit to living shorelines any time soon.

The vast network of canals created during early years of development in Florida converted existing wetlands into waterways that greatly increased the available linear shoreline- a result driven by the economics of waterfront property. [Figure 9 & 10] In some areas, the available shoreline on the lagoon side is 10-20 times what may have existed historically. In this regard, opportunities exist to transform these shorelines into productive landscapes.

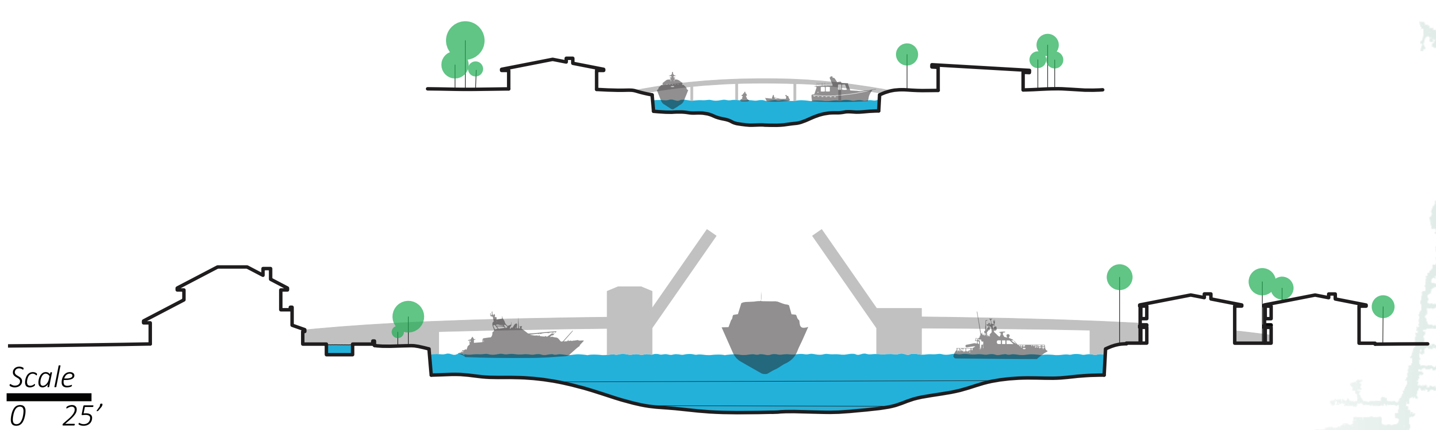


Figure 9. Florida's canals are typically lined on both sides with seawalls and have a deepened navigation channel that makes living shoreline installations difficult.

Waterway Map, Broward County, FL

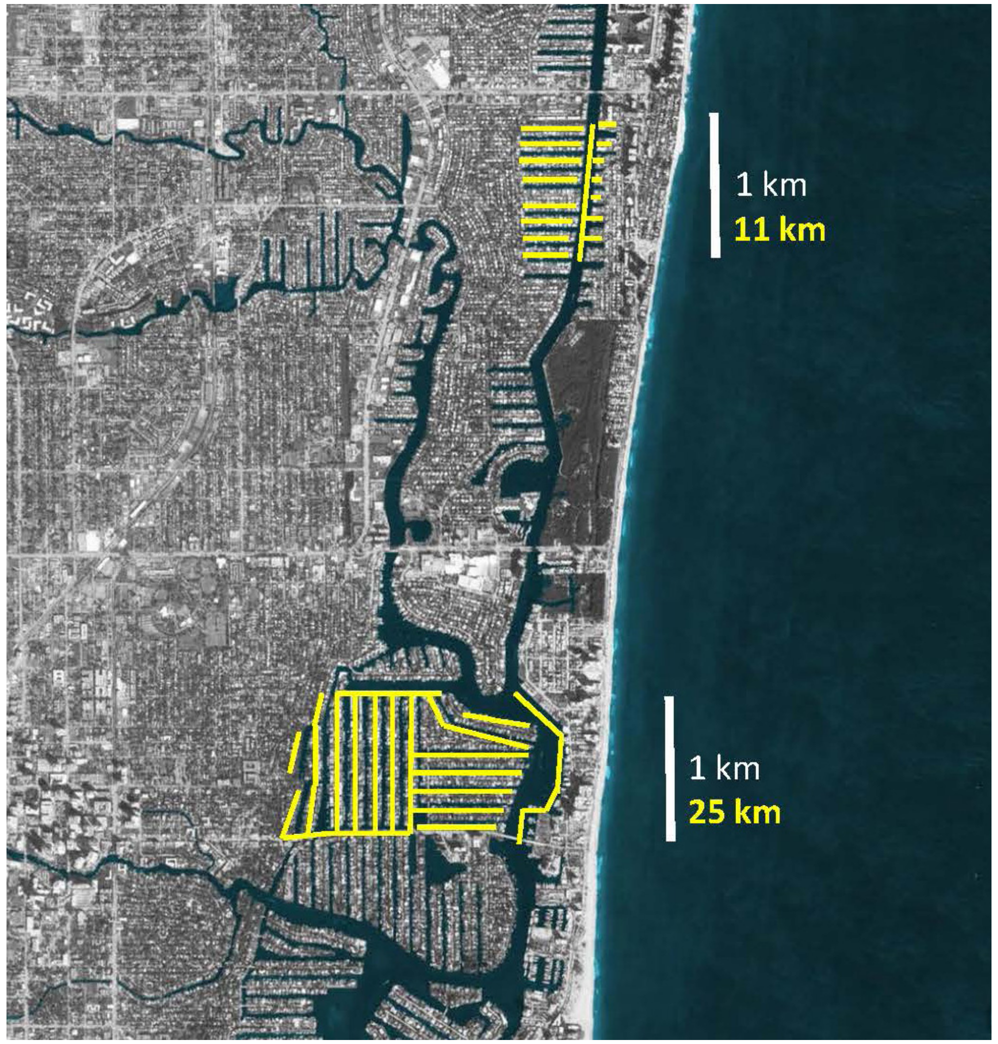


Figure 10. Sampling the available surface area for restoration - Florida has exponentially more linear waterfront when considering a transect to the coastline. The lengths are linear canal measurements; the total shoreline available would be doubled because of the two sides of each canal. From left to right: Marco Island, Treasure Island, Fort Lauderdale Isles/Broward County.

Figure 11. Aging seawall near Englewood, FL. Over time, seawater weakens cement and infiltrates the wall, causing rebar to corrode.

Figure 12. Installed as precast panels with a cast in place cap, concrete seawalls are the most widely used panel type historically. The harsh transition from water to wall precludes any tidal zone for species.

Figure 13. Over the past few decades, vinyl and metal sheetpile seawalls have gained traction. Whereas concrete seawalls host some oyster growth, these walls have little to no biological recruitment and are worsening the impact of seawalls on the marine environment.

Precast and in-situ concrete is the most prevalent material in coastal construction, forming the majority of infrastructural installations and shoreline stabilization systems.[21] Seawalls, bulkheads and other shoreline armoring have proven insufficient in a variety of ways, specifically by replacing tidal ecosystems with harsh transitions that undermine the ecological functioning of shorelines. These approaches are limited in both material and formal attributes, as the choice of building material can play a substantial role in supporting tidal species. Designs rarely incorporate habitat, and concrete as a material can be hostile to marine organisms, particularly during early years of service.

Historically, seawalls were limited to concrete, stone or wood, but in recent decades, corrugated sheet piles in steel or vinyl are being increasingly used. Many factors play a role in seawall material selection, with cost and ease of installation being a primary one. Although corrugated walls have additional surface area resulting from the pleated form, they typically have less biological growth due to the surface smoothness. Additionally, shellfish that utilize calcium carbonate are able to construct shells over concrete walls, whereas corrugated walls have none. The recent shift toward sheetpile seawalls has prompted discussion on ways to improve environmental performance of these structural walls.

Charlotte County Seawalls provided access to multiple active seawall construction sites in SW Florida as part of the collaboration. Figures 11-13 include some of the seawalls and construction sites visited during the project period.

Figure 14. Reef Ball Foundation operates a facility in Sarasota, FL that produces a variety of shapes and sizes of artificial reefs.

Reef Ball Foundation is a well-established organization located in Sarasota, FL and has installed artificial reefs all over the world. The Reef Ball module utilizes marine friendly concrete cast in a fiberglass mold that uses inflatable bladders to create large holes in the form. The units are installed by barge to create artificial reefs that serve as wave breaks. Corals are planted and/or naturally grown on the textured concrete surface. The Reef Ball design was recently incorporated into a living seawall design that uses 8'x10' terraced concrete modules staked into the substrate in front of a seawall. The modules break wave energy and have a variety of relief areas to serve multiple species. The living seawall concept can be scaled in size and proportion to fit a variety of shorelines.

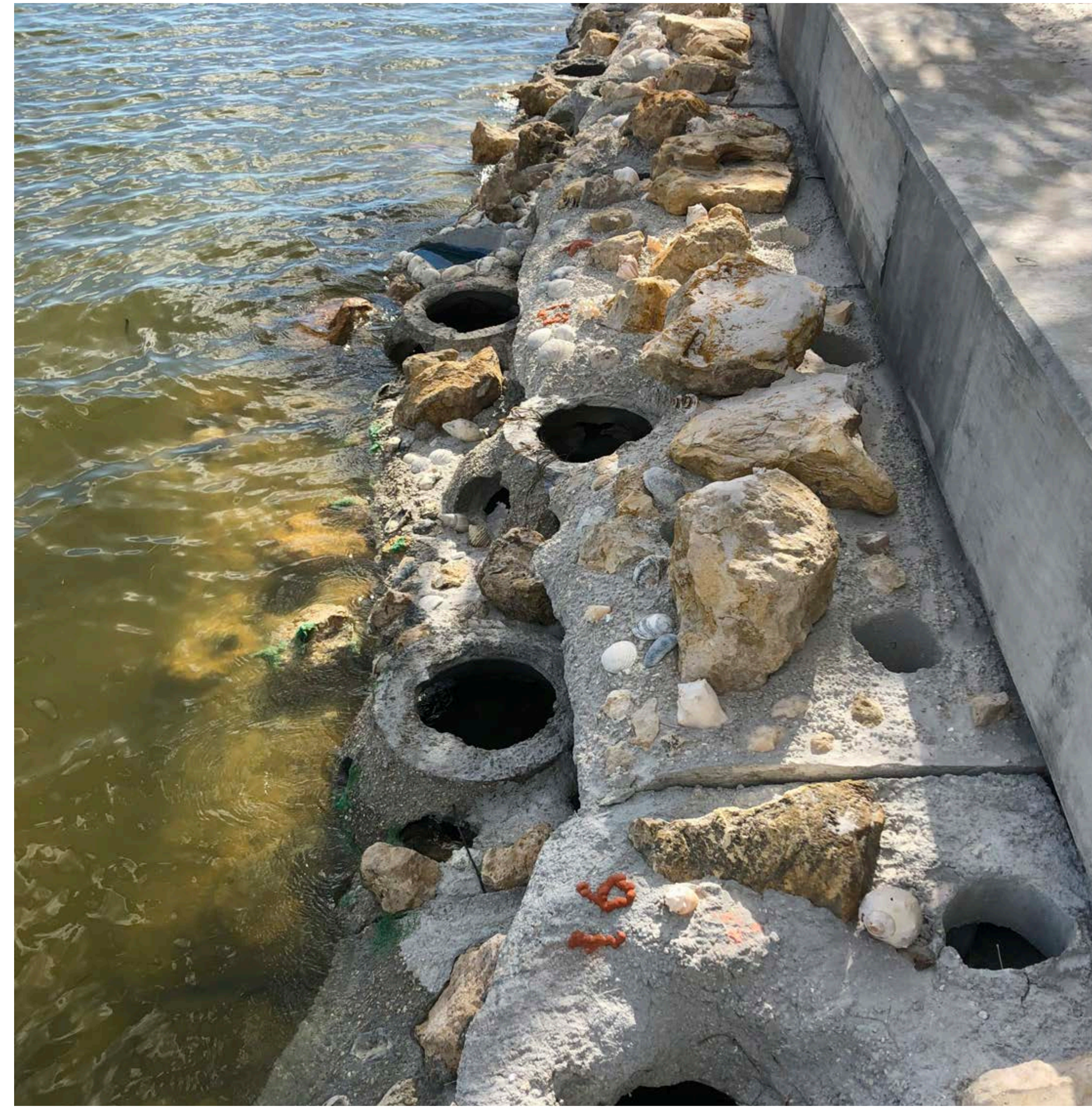


Figure 15. Reef Balls were integrated into a stepped concrete living shoreline installed in Sarasota. Production of the modules involves embedding Reef Balls into slabs of concrete poured over layers of sand to create levels.

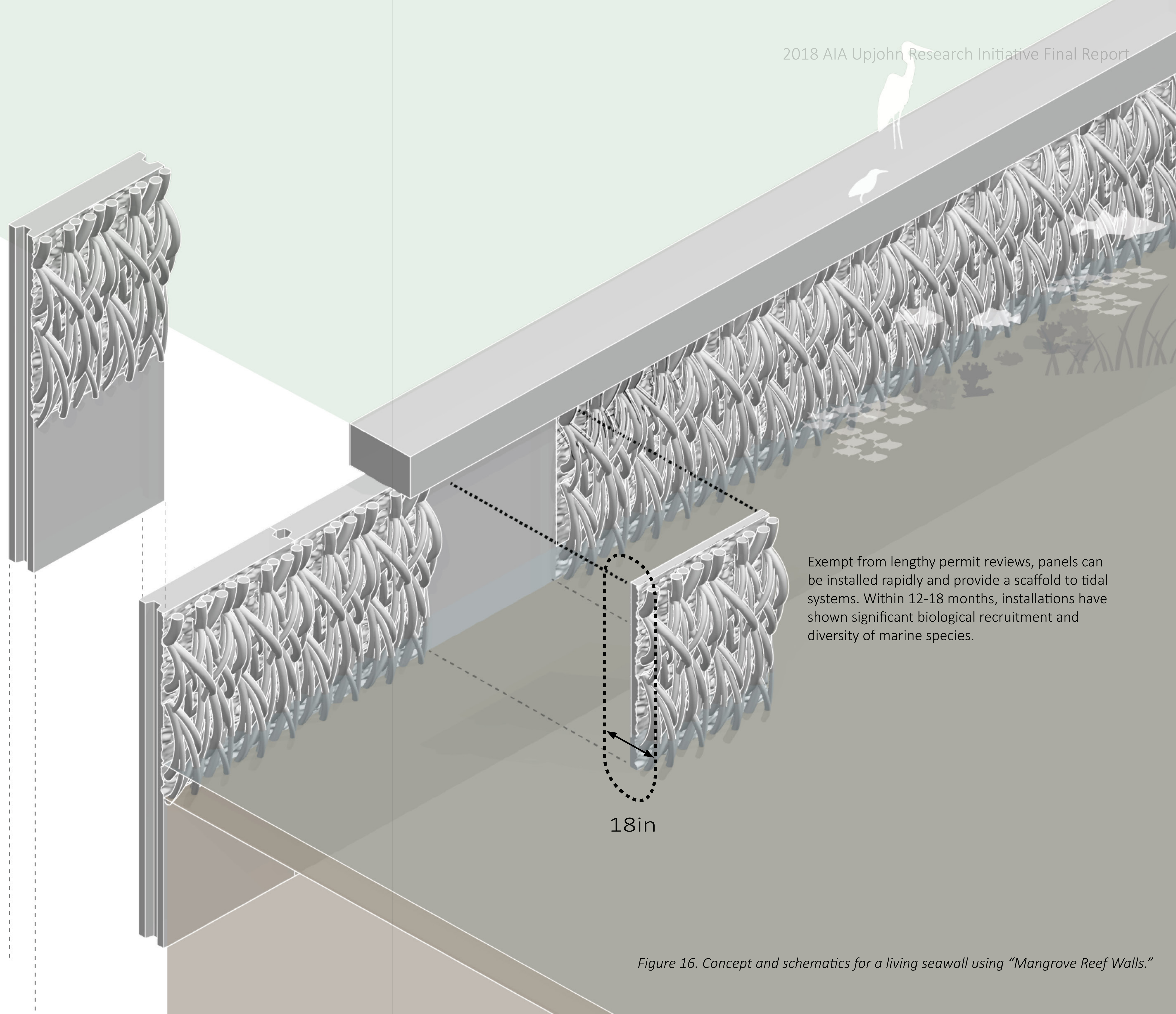
LIVING SEAWALL CONCEPT

Towards *Biodiverse Built Environments*...

The living seawall concept, known as “Mangrove Reef Walls,” aims to integrate biodiversity within an engineered-living seawall. The mangrove-inspired habitat panels capitalize on a passive approach-marine friendly concrete and optimized geometry create conditions for a tidal substrate suitable for fish and shellfish. Additionally, the design mimics the edge of a mangrove forest, where roots overhang tidal streams. This dynamic edge of mangrove forests tends to form transitional zones that contain dense root areas and deeper water channels where numerous species interact.

The design also seeks to collaborate with an existing industry; in contrast to many other environmental restoration technologies (Reef Ball Foundation, Ocean Habitats, etc.), the habitat panels are integral to the seawall - aesthetically and functionally. The panels can be precast in the face of a structural seawall panel or added to an existing seawall face. The root-like elements terminate below the seawall cap, or below it in some cases to provide a shelf for shorebirds that hunt along the top of the panels.

The design and materiality of the panels were both advanced through this study. Through an installation in Fort Pierce, FL, new molds tested the scale and complexity of silicone form liners to achieve more depth in the root-like projections. Panels are exempt from lengthy environmental reviews due to Florida Department of Environmental Protection Code 62.330.050, Section 12 that enables seawall enhancement projects within 18” waterward of the face of an existing seawall. This exemption status further warrants study of these panels, since waterfront property owners are often deterred by the daunting challenge of permitting when considering restorative projects on the water.



Exempt from lengthy permit reviews, panels can be installed rapidly and provide a scaffold to tidal systems. Within 12-18 months, installations have shown significant biological recruitment and diversity of marine species.

Figure 16. Concept and schematics for a living seawall using “Mangrove Reef Walls.”

The panels are biomimetic and utilize digital modeling and fabrication to produce molds that are used to produce precast panels. Parametric computer models were developed to create 3D digital models of oyster textures with roots overlaid. These models were based on actual mangrove root densities found in literature searches. By incorporating scientific papers that determined initial root densities, the models were then adjusted to fit within fabrication constraints, allow for tooling depths, spacing for recruitment over time, etc.

Numerous iterations were developed to mimic the actual mangrove roots, which were then paired with a feasible production methodology. [Figure 15-17] The branching structure is based on an algorithm built to reflect mangrove root arching forms and densities.

The digital modeling process has checkpoints to ensure it can be produced. Digital surfaces are mapped over the roots [Figure 17] to create a surface that can be milled in whole or parts by subdividing it. Panels were developed in layers that could be milled and assembled to produce a master mold. From this master mold, multiple negative molds were cast to be used in producing the panels.

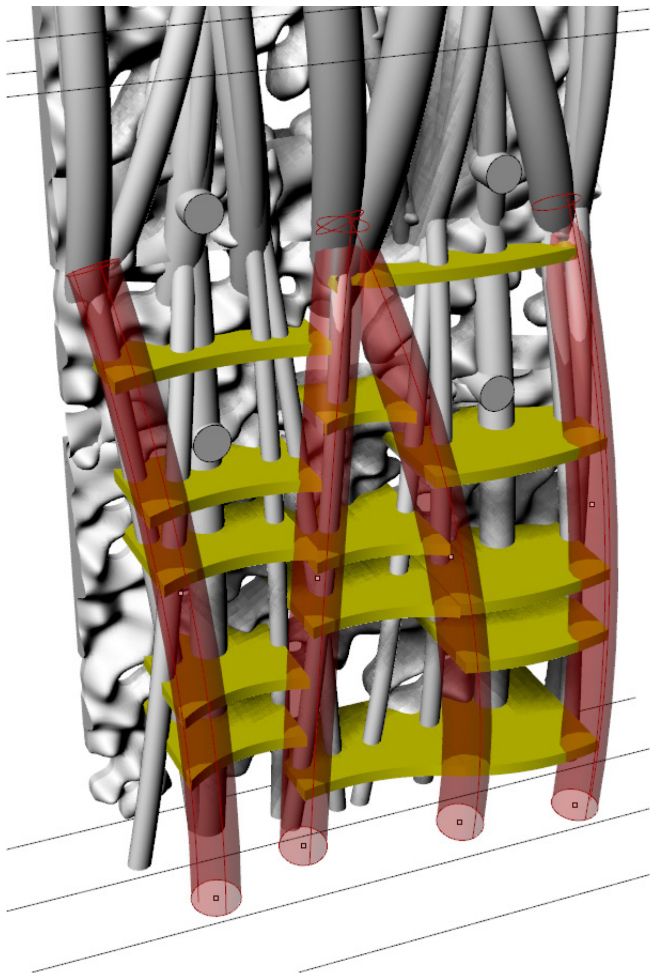


Figure 17. 3D computer model showing the root projections and supporting structure. Mangrove roots vary in diameter and orientation to create similar density to that of natural mangroves.

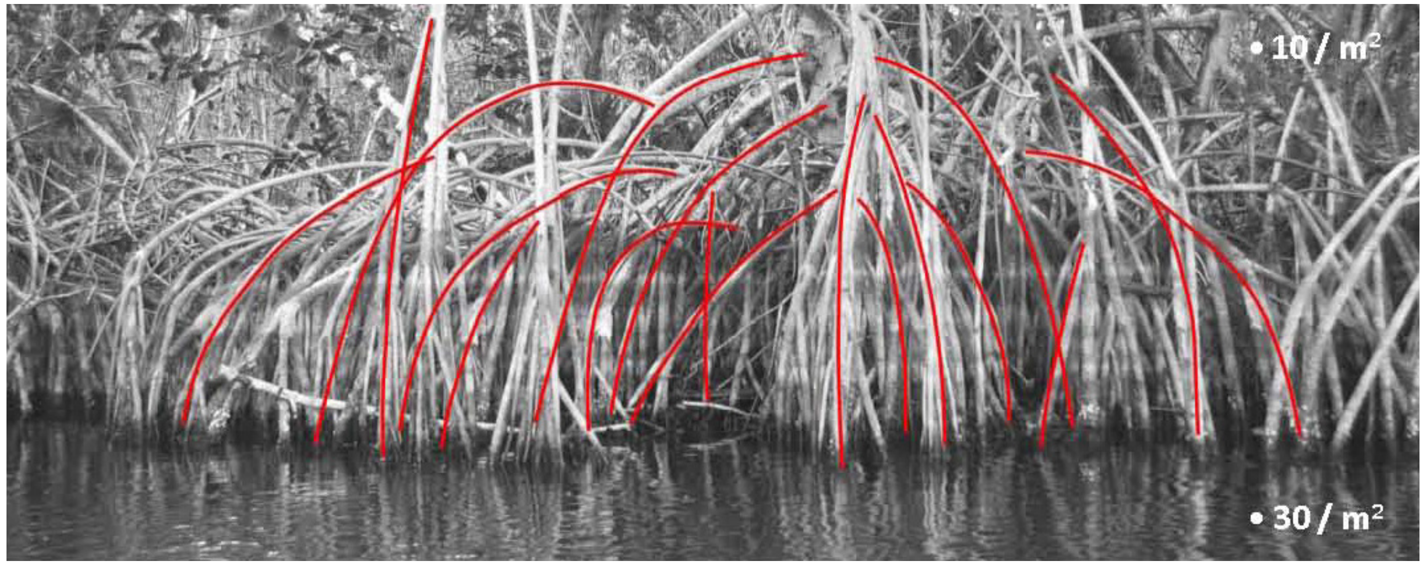


Figure 18. Mangrove root density varies by species and age of a given plot. Medians taken from an established group of tress were used to inform the parametric model.

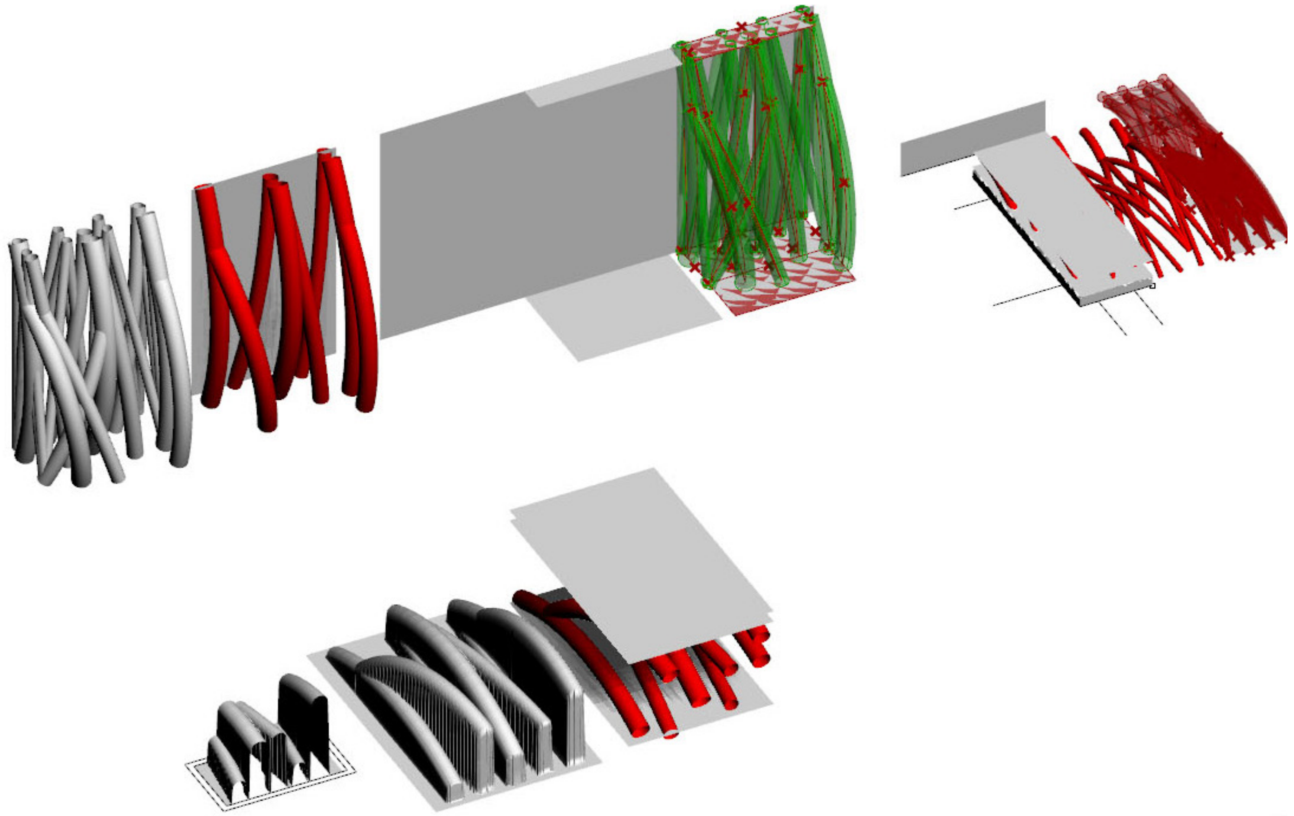


Figure 19. Various stages of digital model development and experimentation in preparation for CNC milling.

Mangrove-inspired panels were first produced in 2016 for the installation in Englewood, FL. The translation from digital model to concrete panel involved prototyping with 3d printers and CNC milling technologies. Master molds were cast using a tin-cure silicone rubber. Multiple designs were developed to test varying degrees of porosity and habitat relief, in addition to a diagrammatic panel that featured multiple recognizable species- green heron, crab, baitfish and snook.

The silicone molds served as concrete form liners and the panels were made from a custom blend of marine friendly concrete. High-strength fast setting grout mix was combined with silica fume and macro-fibers to ensure longevity of the panels and resist saltwater intrusion and corrosion. Oyster flour was added to temper the pH of the concrete, and it’s been suggested that oyster shells used as a substrate can be beneficial in attracting new oysters.

The texture of the panels is a result of the CNC milling process. The selection of bit profile (flat, round, vee, etc.) and design of the toolpath (direction and spacing of the cutting path) was used to create evenly spaced striation across the panels, providing additional surface area and texture. These rough cut patterns also reduce machining time because the number of paths required by the tool to cut the surface is lower than for a smooth geometry.

Figure 20. Panels developed for the Manasota Key installation contained graphics to compliment the habitat panels. Image credits: Jose Beltran

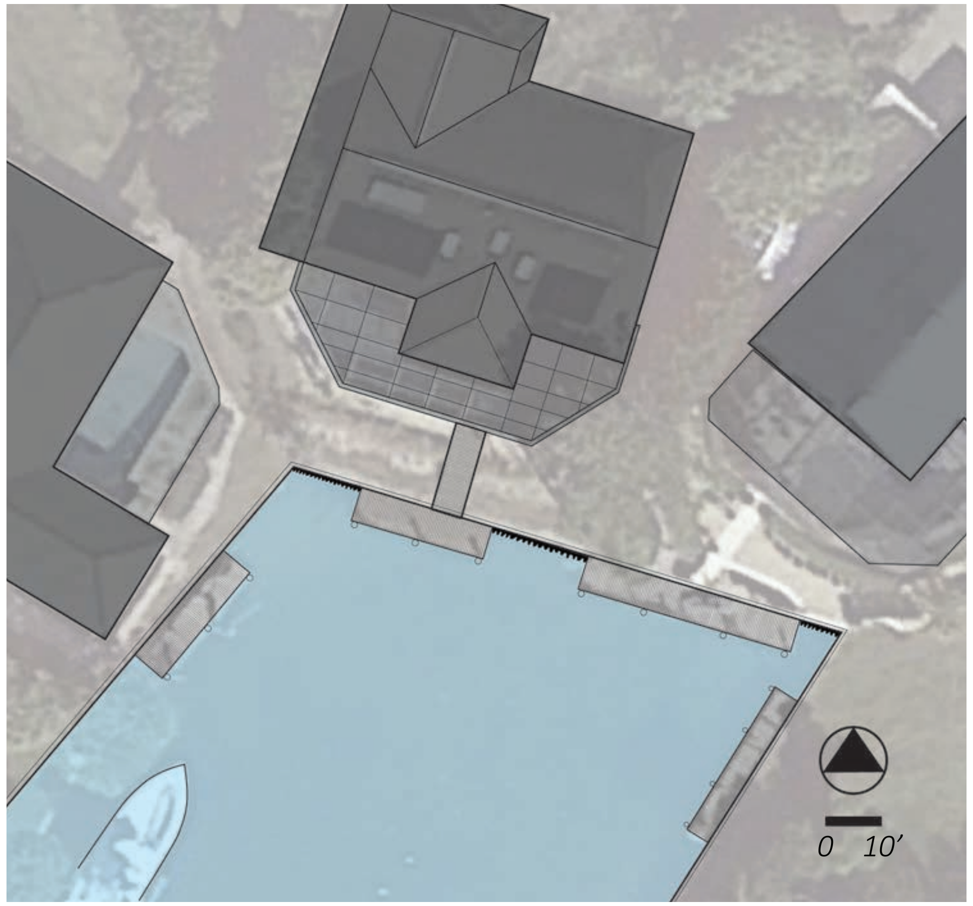


Figure 21. Site plan for the Fort Pierce installation. Panels were placed on an aluminum seawall at the end of a canal.

During summer of 2018, new enlarged panels were installed in Fort Pierce, FL. A famous oceanographer was looking for a research-driven project to transform their seawall into a living shoreline. Panels were designed to fit over the existing corrugated aluminum seawall, which had no biological recruitment, despite having been in service for decades. The project involved collaborating with a landscape architect that created a master plan of native plantings for the grounds above the seawall. Panels for the project were cast with a silicone mold that was the largest and most complex mold to date.

Figure 22. Fort Pierce seawall installation. Landscape architect Meg Whitmer designed native plantings over a limestone berm adjacent to the seawall. Image credit: Dr. Edith Widder, ORCA

Figure 23. Panels for the Fort Pierce installation were 24”x36” and cast with a silicone rubber mold. Roots extended approximately 12” outward from the seawall face. Oyster flour (above left) was added to the concrete mix to be marine-friendly.

Figure 24. Other than a few barnacles (left), the corrugated aluminum seawall had virtually no biological growth prior to installation. The panels were installed summer of 2018 (center) and periodically monitored. After a slow start, the recruitment of oysters and barnacles accelerated to completely cover the panels (right).

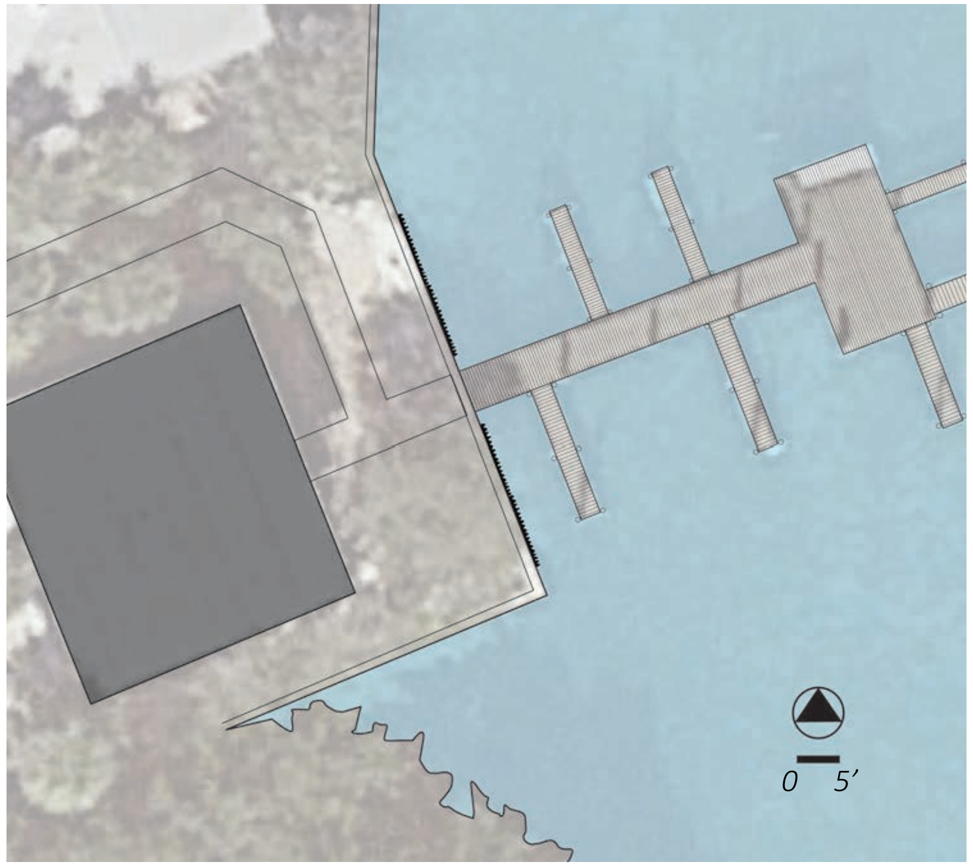


Figure 25. Site plan for the Englewood installation. Panels were installed over an existing concrete seawall.

Prior to the Fort Pierce project, mangrove-inspired panels were installed on Manasota Key in Englewood, FL. These panels were periodically monitored until 2018 and provided feedback to the design and fabrication of the larger panels at Fort Pierce. The panels created structural complexity on the wall in multiple ways: (1) roots project outward from the panel, creating gaps and added surface area, (2) smaller holes and tunnels perforate the panels, (3) gaps between the panels and seawall created larger relief areas behind the panels, and (4) because the panels did not cover the entire seawall, wading birds hunt from the top of the panels and large predatory fish hide below them.

Figure 26. Monitoring of panels installed fall 2016 continued into 2018 and provided feedback for the design of the Fort Pierce installation. Image credit: WGCU Radio, Fort Myers

Figure 27. Habitat panels at the Englewood, FL site were installed in 2016 and monitored through 2018. At 16 months, oyster and other species had grown over the artificial roots similar to natural mangrove roots.

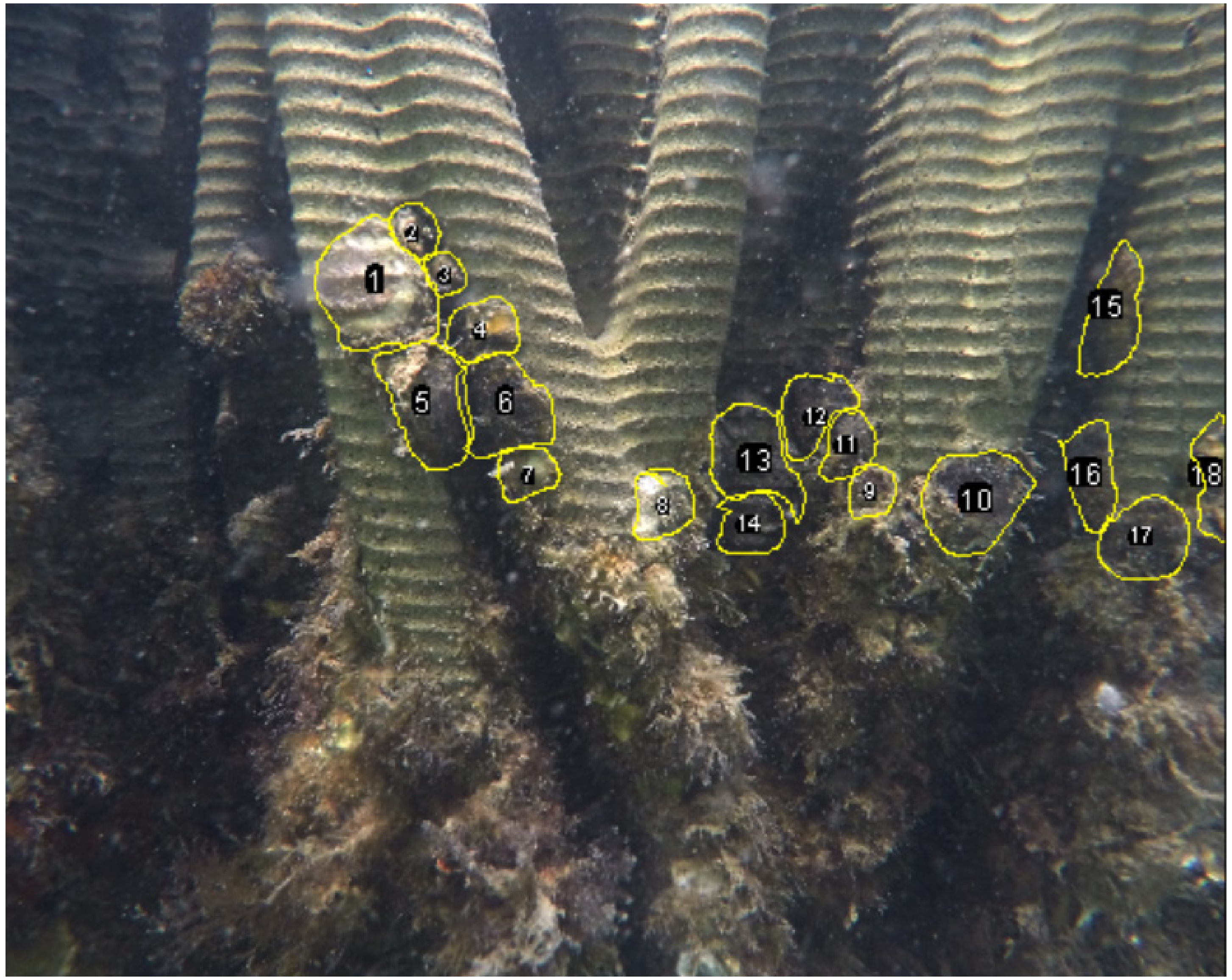


Figure 28. Monitoring of the Englewood site was conducted monthly for 12 months. The above image shows how certain species were identified via images captured with a GoPro camera outfitted with underwater lens filter. In addition to quantifying oyster coverage, other species were documented when they were found on the panels to indicate the diversity of life present. Image credit: Jessene Aquino-Thomas

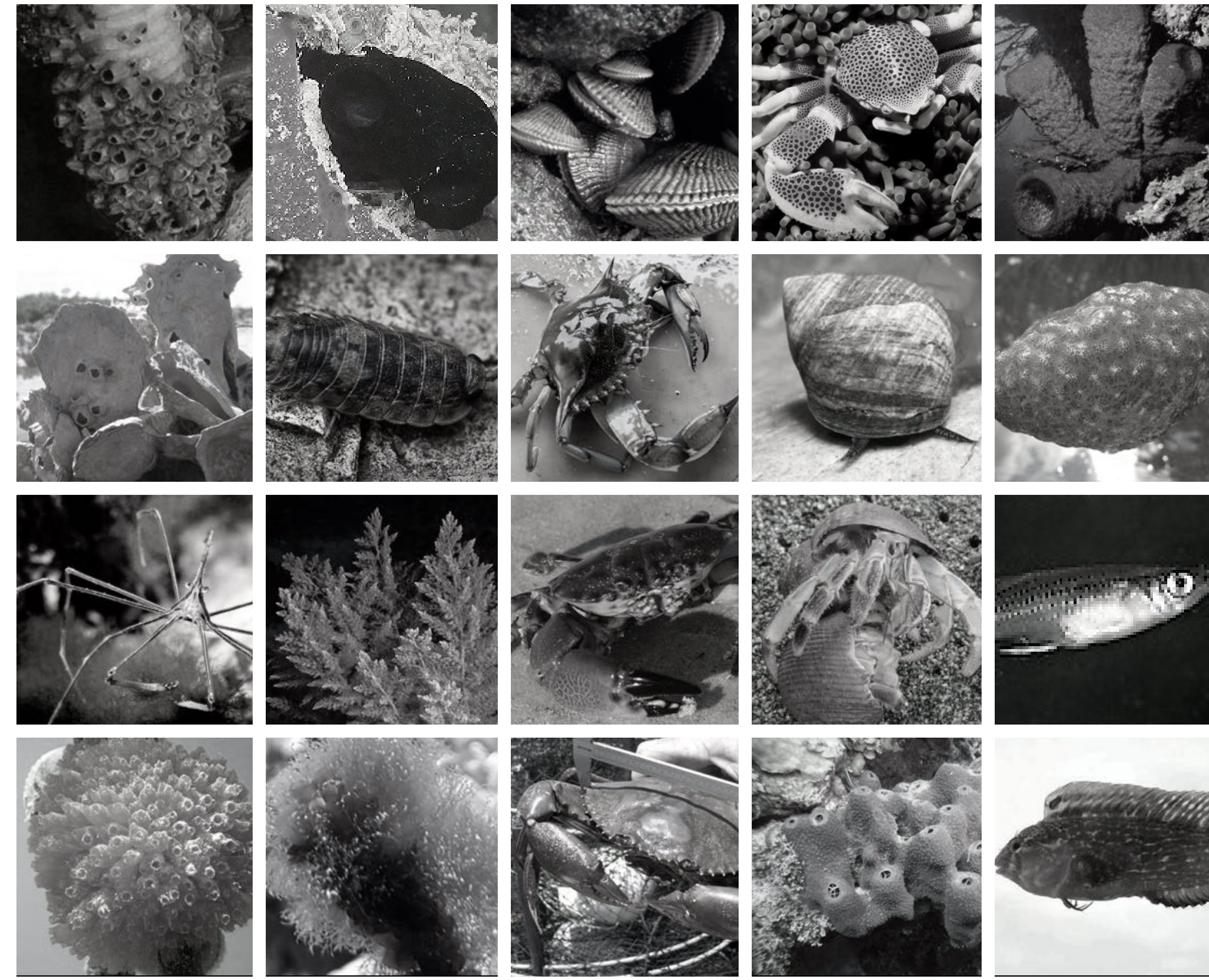


Figure 29. Sample of diversity found on panels during survey work (left to right, top to bottom): barnacles, black tunicate, ribbed mussels, porcelain crabs, fire sponge, eastern and flat tree oyster, sea roach, blue crab, periwinkle and other snails, bryozoans, arrow crab, red algae, small stone crabs, hermit crabs, mangrove gambusia, mangrove tunicate, cotton candy algae, mud crabs, ethereal sponge, Florida blenny. Images sourced from internet

05 FUTURE WORK

Through two project installations and subsequent monitoring, the panels were advanced in scale and materiality with this project. The collaboration with Charlotte County Seawalls provided access to industry standards, as well as providing direct feedback on the proposed integration of the habitat panels within the context of seawall fabrication and installation.

After installation, the projects received some media attention in Florida. Radio coverage and news articles raised awareness of the initiative, which further promoted the environmental issues affecting coastal areas. This media coverage expanded the network of collaborators for the project by connecting the research to new sites and municipalities. New partnerships in Edgewater and Miami have offered further potential to expand the project in scope and scale.

Along with these new project sites, which include an increase in scale of the panels and more robust formwork (including single and double sided molds), future research directions of the work include diversifying the materiality of the panels, focusing on more sustainable concrete technologies, and continuing the partnership with seawall contractors to accelerate the adoption of integrated habitat panels.

Figure 30. Panels precast and awaiting installation at new location in Edgewater, FL.

Figure 31. Half-scale prototype panel testing a double-sided mold and embedded ropes.

Figure 32. Future directions of the research include diversifying the substrate to accommodate multiple species that prefer softer materials.

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