Buoyant Ecologies:
Research, Collaboration, and Resilience at the Edge

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Buoyant Ecologies is a collaborative research platform that brings together architects, marine ecologists, and fabricators to address the implications of sea level rise through innovative approaches to designing and constructing resilient waterfront structures. This paper describes how the project's unique collaborative structure incorporates expertise from ecological researchers and industry manufacturers to promote recursive, interdisciplinary feedback loops between speculative thinking and pragmatic knowledge.

1. INTRODUCTION

Current climate change models offer a range of projections for sea level rise due to increases in global warming. In 2012, the U.S. National Oceanic and Atmospheric Administration published an assessment confirming that there is a 90% chance that global mean sea level rise by the year 2100 will fall within the range of 0.2 to 2.0 meters.[1] More recent studies project even greater increases, up to 15 meters by the year 2500.[2] Regardless of the precision of these models, even the lowest estimates present grave challenges for coastal cities. In the United States, nearly 40% of the population lives in coastal regions vulnerable to sea level rise; globally, the world's eight of the ten largest cities are coastal cities.[3]

This paper describes the research and pedagogical framework of Buoyant Ecologies, an ongoing collaborative research platform that brings together architects, marine ecologists, fabricators, and public regulatory agencies to address the realities and implications of sea level rise through innovative approaches to designing and constructing waterfront structures. The project begins with the premise that cities must accept the eventuality of sea level rise and actively develop new alternatives to the conventional ways that humans occupy urban waterfronts. Resisting two common urban responses to sea level rise—the construction of fixed seawalls and defensive barriers, and the impulse to retreat to higher ground—this project instead explores more resilient approaches to waterfront structures that can both adapt to rising sea levels and enhance the surrounding ecosystem.

The paper focuses on the first phase of the Buoyant Ecologies project: the development of material strategies for the construction of buoyant, sessile (or stationary) structures, using customized fiber-reinforced polymer (FRP) composite substrates, commonly known as fiberglass. The project seeks to develop high-performance envelopes constructed of custom-contoured FRP panels that, through their variation in topography, are optimized to provide a range of scalar habitats for marine life (both animals and plants), thereby contributing to the biodiversity of the ecosystem at large. As this kind of research necessitates knowledge and expertise far outside the realm of traditional architectural design, the project's collaborative nature—and the integration of collaborative workflows into the pedagogy of an architecture studio—becomes paramount. This paper describes the project's collaborative structure and how an integrated approach to architectural design, science, and manufacturing can facilitate a unique and productive feedback between speculation and empirical testing. It argues that such a pedagogy enables speculative thinking and pragmatic knowledge to inform each other in ways that would not be possible without an expanded field of expertise, and that this kind of feedback is essential for architects looking to expand design agency beyond the traditional limits of the discipline.

2. RESEARCH FRAMEWORK

Floating structures offer several advantages in regard to coastal resilience. Buoyancy decouples a structure from the ground, eliminating its vulnerability to flooding; in this regard, buoyant vessels are essentially invulnerable to sea level rise. Furthermore, buoyant structures can perform as wave attenuation devices, mitigating coastal erosion and helping to protect shorelines from flooding and storm surge events. However, environmental and regulatory groups—particularly in the San Francisco Bay, the site of this research—typically frown upon the construction of floating structures, as they are considered "fill" that encroaches on the Bay, reduces natural light, and threatens the health of underwater ecologies. This project seeks to invert that assumption by arguing that the underside of floating structures can perform as an upside-down benthic habitat for marine life, and that this surface can be optimized to provide multi-scalar habitats that maintain or increase biodiversity.

The project began in 2014 with an architectural design studio at California College of the Arts, run in collaboration with the Pier 9 Workshop, a state-of-the-art fabrication facility operated by the design technology giant Autodesk on the San Francisco Embarcadero.[4] Autodesk was interested in prototyping visions of a floating extension to the workshop as way to expand their facility's public presence and outreach to the city. The studio instructors sought to position this project as a critique of the defunct Google Barge, which had just recently suffered a very public banishment from San Francisco after failing to secure the approval of city and state regulators.[5] Rather than proposing the structure as a conventional building on top of a conventional barge, the team began to imagine a more integrated approach that would merge material and ecological performance into a new kind of architectural typology.

These initial conversations, although entirely hypothetical and speculative, were critical for catalyzing the partnerships and interdisciplinary feedbacks that continue to inform the research. Speculation about a floating structure's ability to foster ecological growth led to the Benthic Lab at Moss Landing Marine Laboratories, a research group focused on the benthos, or the bottom layer, of marine habitats. These ecologists, led by lab director John Oliver, are experts in the communities of invertebrate animals that accumulate on underwater surfaces, and they immediately recognized an opportunity in embracing such growth on the underside of a floating structure. Similarly, research into fiberglass, a material commonly used in boatbuilding, led to Kreysler & Associates, a composites manufacturer in American Canyon, California, who had just recently completed the fabrication of the FRP facade for Snohetta's new extension to San Francisco Museum of Modern Art. With years of FRP fabrication experience in both marine and architectural realms, founder Bill Kreysler reinforced the notion that a large-scale floating structure fabricated from FRP composites was buildable. Together these two partners helped transform a rudimentary hypothesis—what if a floating building could help the surrounding ecosystem rather than harm it?—into a viable research premise.

3. OPTIMIZED UPSIDE-DOWN BENTHOS ON CUSTOMIZED FIBER-REINFORCED POLYMER SUBSTRATES

The expertise of the Benthic Lab ecologists relates to understanding the tremendous impact of benthic communities of invertebrates on broader ecological health and resilience. These small animals are notable for colonizing any hard substrate—rocks, concrete sea walls, steel piers, docks, boat bottoms, and so on. Their unchecked growth, commonly referred to as "fouling communities," is often viewed as a nuisance; boats are regularly scraped clean to remove the barnacles and other organisms that compromise hydrodynamic performance. Nevertheless, as prey for larger fish and mammals, benthic invertebrates represent an essential part of the food chain, and the biodiversity of these communities directly affects the health of the broader ecosystem and its long term resilience in adapting to the effects of climate change.[6] As with many ecological systems, benthic communities are threatened by the presence of invasive species, which tend to be dominant and result in entirely homogeneous colonization; this is particularly acute in San Francisco Bay, which contains the most non-native species of any coastal estuary worldwide.

This research seeks to address the problem of biodiversity not by eliminating invasives—which is virtually impossible at this point—but by recognizing the latent opportunities of upside-down "fouled" surfaces like boat bottoms, docks, and other waterfront structures. The central premise of the research inverts the notion that fouling is a nuisance, instead embracing it as an untapped opportunity to facilitate diverse communities of invertebrates that contribute to the ecosystem's overall diversity. The hypothesis proposes that the geometry of underwater surfaces can be designed to produce "hillocks" and "valleys" of variable sizes, optimized to produce multi-scalar habitats for different species. This customized topography protects smaller organisms from larger predators and therefore maintains a degree of biodiversity otherwise impossible with flat or smooth boat bottoms that are easily colonized by non-native species. The design of these topographies makes use of statistical models that relate rugosity (magnitude of a surface's "bumpiness"), slope, dimensions of hillocks and valleys, and other parameters to anticipated ecological growth over time.

Fiber-reinforced polymer composites, commonly used in marine applications, offer several advantages for testing this hypothesis. Unlike steel or concrete, fiberglass is entirely resistant to corrosion in salt-water environments. New technologies of computational design and digital fabrication enable the production of highly differentiated topographies that would otherwise be very difficult to make; file-to-factory workflows translate digitally modeled geometry to robotic fabrication machines that can carve customized molds and formwork at a very high degree of complexity and precision. Furthermore, when fabricated in several layers with balsa wood cores or internal corrugated rib structures, composite materials have excellent structural capacity, which is further enhanced by double-curvature. In an opportune synthesis of performance criteria, these qualities of corrosion resistance, customizability, and structural strength render FRP an ideal material with which to test the hypothesis of an optimized ecological substrate.

4. PEDAGOGICAL FRAMEWORK

The primary vehicle for the Buoyant Ecologies research has been a series of three advanced architectural design studios at California College of the Arts (CCA) in San Francisco. These studios, led by Adam Marcus, Margaret Ikeda and Evan Jones, serve as a venue for speculative inquiry supported by outside expertise of ecologists and manufacturers, as well as empirical testing through full-scale prototypes of the optimized FRP substrate. The architecture studio becomes the primary site for the interdisciplinary feedbacks in which the designers, scientists, and industry partners each catalyze each other to consider ideas and strategies that otherwise may not emerge in a less collaborative framework.

The 2014 studio sited on San Francisco's Embarcadero was followed by two subsequent studios in 2015 and 2016, in which students designed speculative ecological research and education centers for Middle Harbor Shoreline Park, a public reserve located within the Port of Oakland. The Port constructed the park in the early 2000s as an amenity for the adjacent West Oakland neighborhood and as a prototype for how to integrate ecologically restored wetlands into the port's industrial infrastructure.[7] The shift to this particular site and context reflected a desire to situate this research within broader regional and national conversations on resilient coastlines as a defense against increasingly volatile climate patterns and rising sea levels.[8] It also began an ongoing partnership with the Port of Oakland, which as the fifth largest port in

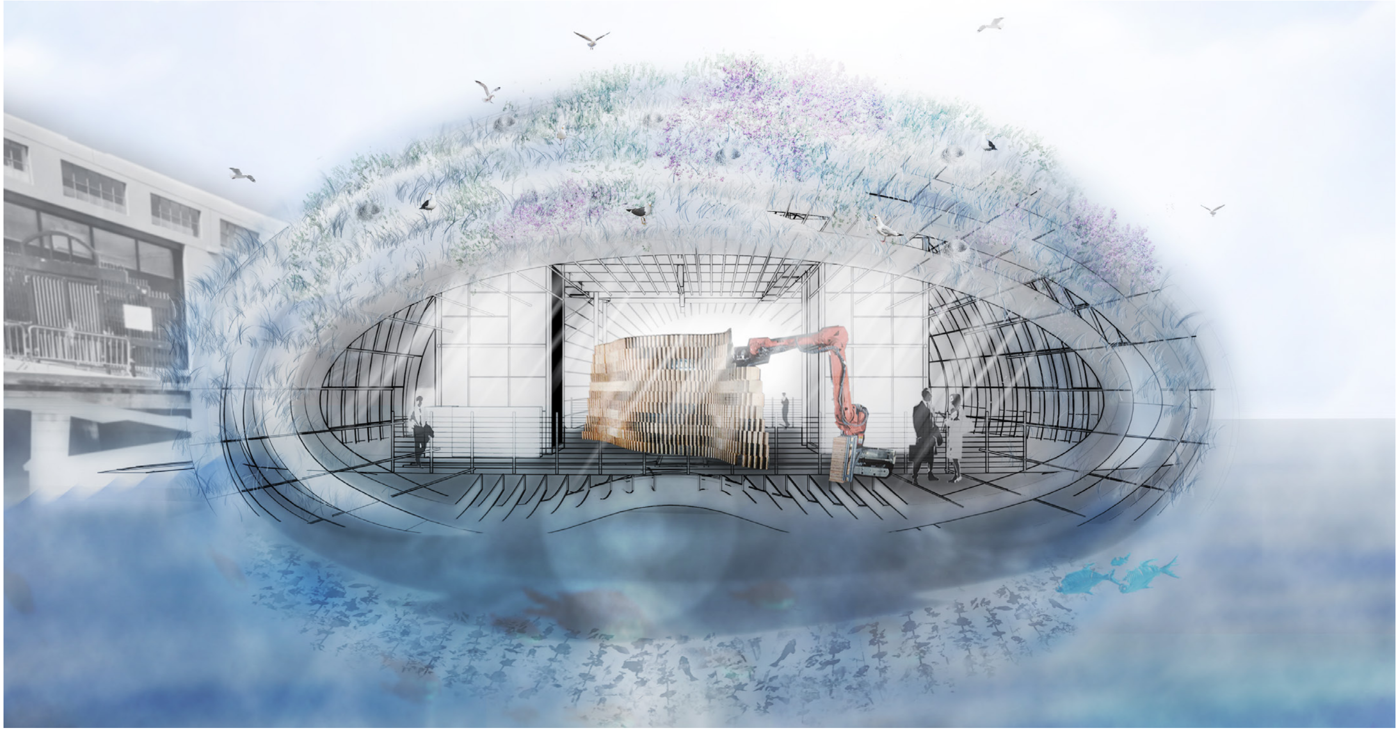


Figure 1: “Adaptive Creature,” by Jill Chin-Han Chao, Hung-yi Chou, and Sanna Lee. This project from the first Buoyant Ecologies studio proposes a monocoque FRP structural shell that provides an ecological substrate both below and above the water. Its speculation about tidal habitats above the waterline inspired the Benthic Lab ecologists to consider additional ways for the substrate to perform beyond subsurface growth medium.

the United States and one of the most significant contributors to the Bay Area economy, recognizes the acute urgency of developing resilient strategies in response to sea level rise.

The studio structure maximized interaction with experts outside of the traditional boundaries of architectural academia. Visits to both Benthic Lab and Kreysler & Associates consisted not only of tours of the facilities but also interactive design charrettes in which students presented their in-progress proposals to the research partners. These visits were supplemented by regular video teleconference sessions in CCA’s studio space to provide feedback at critical moments in the semester where ecological and material performance assumptions required validation or further explanation. As part of CCA’s Integrated Building Design curriculum of comprehensive design studios, students also met regularly with professional consultants from practice: building energy experts, structural engineers, mechanical engineers, and facade consultants. Finally, all design reviews included representatives from each of the research partners—architects, ecologists, and fabricators—as well as other stakeholders such as the Port of Oakland and the San Francisco Bay Conservation and Development Commission (BCDC), the region’s primary regulatory agency for coastal development.

5. INTERDISCIPLINARY FEEDBACKS

The structure of the Buoyant Ecologies studio was designed to encourage recursive feedback loops between designers, ecologists, and fabricators. These interactions ranged from predictable exchanges of knowledge and expertise to more unpredictable conversations and discoveries that opened up new directions for the research. The more conventional interactions typically consisted of architecture students presenting design ideas and ecologists offering pragmatic suggestions about how to improve the design and integration of the optimized substrate surfaces into the larger building proposal, or fabricators offering advice about material parameters and fabrication constraints. While critical for advancing the work, this type of knowledge exchange can be highly informative but is not truly *collaborative* in the sense that there is a bidirectional back-and-forth that generates new ideas or trajectories for the research. Rather, it was the unpredictable moments of interdisciplinary feedback—when pragmatic expertise and speculative design thinking began to inform each other—that proved essential for crafting the overall research trajectory.

Three examples of this interdisciplinary dynamic demonstrate pivotal moments in the project when design speculations initiated new directions for pragmatic and technical research. An early example occurred in the first studio, towards the middle of the semester as the architecture students began to develop their building proposals with drawings, models, and—importantly—perspective renderings of the outer hulls of their floating buildings. Architects often take their representational skills for granted, but the students’ ability to visualize the corrugated and textured FRP topographies was revelatory for the Benthic Lab ecologists. Taking the cue from Kreysler that the composite shells can accommodate large spans, several of the schemes extended the FRP substrate above the waterline to form not only the vessel hull, but also walls and roof structure (Figure 1). Once manifest in visual form through renderings and study models, this notion of a fiberglass substrate on both bottom *and* top sparked a number of conversations

Figure 2: "Augmented Tides" by Rafael Berges and Jared Clifton. The project proposes a series of modular "tidal columns" that initiated broader discussions about potential integration of the optimized ecological substrate into wave attentuation and erosion control devices.

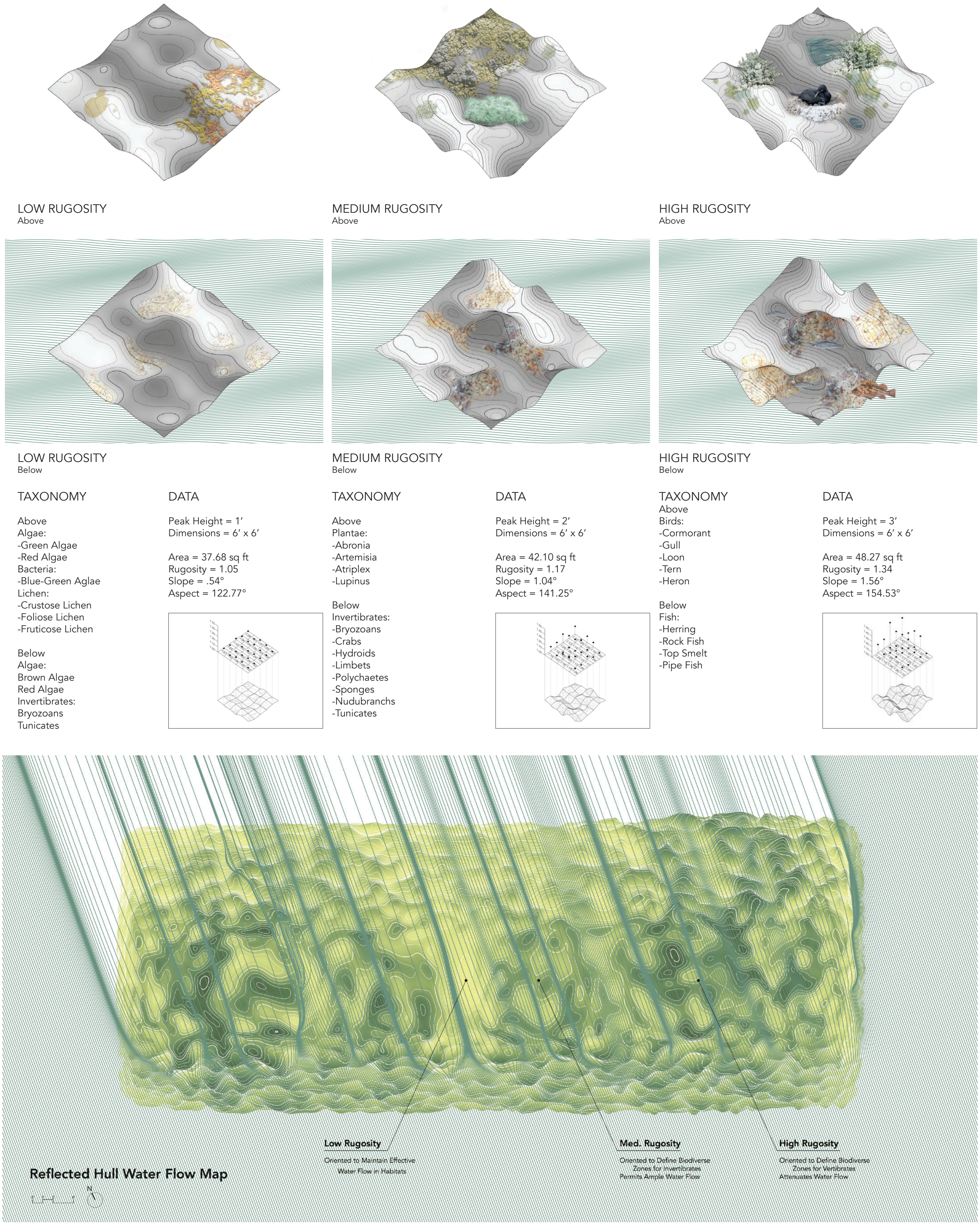
about how the top side could also be optimized to perform ecological functions. These include rainwater collection through carefully designed channels in the surface topography, pockets for plantings, and the notion of circulating salt water onto the roof to create artificial tidal wetlands on the exterior of the building. These ideas, which continued to inform student projects in subsequent studios, originated with the ecologists yet never would have emerged without the design speculations and visualizations produced by the architecture students.

Another example of this kind of interaction occurred in the second studio, as the focus of the research shifted to the Oakland site and larger questions of coastal resilience and sea level rise. As the students developed more sophisticated understanding of strategies of resilient design, the projects began to suggest a more integrated approach between fixed structures and buoyant structures, in which the buoyant structures began to perform ecologically at multiple scales. *Augmented Tides*, a proposal by Rafael Berges and Jared Clifton, consists of a U-shaped building that enclosed a courtyard-like lagoon populated with semi-buoyant "tidal columns" (Figure 2). These petri dish-like FRP composite structures are contoured to promote ecological growth of upside-down benthic organisms on the bottom side and also artificial tidal wetlands on the top side. The modular nature of the tidal columns—individual units, as opposed to a single continuous hulls of the first studio—sparked a conversation with Kreysler about the potentials of modular off-site construction. As the project developed and incorporated pragmatic constraints of fabrication, transport, and assembly, its higher level of resolution prompted the Benthic Lab ecologists to speculate about the columns' function as wave attenuation devices to help prevent coastal erosion. Before this point, wave attenuation and erosion control was not a focus of the studio's research, but the notion of networks of smaller buoyant structures as a strategy for preventing erosion has since emerged as a promising application for enhancing coastal resilience.

The third example, from the 2016 studio, demonstrates how the cumulative body of knowledge developed by previous students provides a foundation for subsequent studios to develop further. *SubOrdinate*, a project by Madeline Cunningham and Taylor Metcalf, proposes a "village" of small buoyant and semi-buoyant structures located just offshore of the park. The buildings are fabricated entirely of contoured FRP composite panels, which serve as structure, envelope, and as the optimized ecological substrate for marine habitats above and below the water. In designing the geometry of the FRP envelope, the students utilized an integrated parametric model to input the precise dimensional parameters provided by the ecologists and analyze this geometry according to specific metrics such as rugosity and slope. With input from the Benthic Lab team on statistical correlations between these metrics and the surface's performance as an ecological growth substrate, the students were able to use the model to produce simulations of how these geometries would impact hydrodynamic flows, which correspond to delivery of nutrients and thus provide one way to predict growth over time (Figure 3). This process allowed them to digitally speculate in a highly informed way about the gradated communities of marine species that would emerge along the substrate over time. Although developed within the context of a speculative project, this kind of parametric process represents a significant breakthrough, as it demonstrated to the ecologists the relative ease by which one can develop a streamlined design-simulate-prototype-measure workflow.

6. FULL-SCALE PROTOTYPING & TESTING

The studio curriculum incorporated a series of full-scale prototyping experiments that have provided an empirical basis for the speculative explorations at the building scale. Just as the visionary thinking of the architecture students provoked the Benthic Lab and Kreysler collaborators to think about pragmatic solutions in new ways, the process also occurred in reverse: the pragmatic lessons of fabricating and testing a prototype at full-scale inspired new possibilities for speculation grounded in material and ecological performance.



TAXONOMY

Above
Algae:
-Green Algae
-Red Algae
Bacteria:
-Blue-Green Aglae
Lichen:
-Crustose Lichen
-Foliose Lichen
-Fruticose Lichen

Below
Algae:
Brown Algae
Red Algae
Invertibrates:
Bryozoans
Tunicates

DATA

Peak Height = 1′
Dimensions = 6′ x 6′

Area = 37.68 sq ft
Rugosity = 1.05
Slope = .54°
Aspect = 122.77°

TAXONOMY

Above
Plantae:
-Abronia
-Artemisia
-Atriplex
-Lupinus

Below
Invertibrates:
-Bryozoans
-Crabs
-Hydroids
-Limbets
-Polychaetes
-Sponges
-Nudubranchs
-Tunicates

DATA

Peak Height = 2′
Dimensions = 6′ x 6′

Area = 42.10 sq ft
Rugosity = 1.17
Slope = 1.04°
Aspect = 141.25°

TAXONOMY
Above
Birds:
-Cormorant
-Gull
-Loon
-Tern
-Heron

Below
Fish:
-Herring
-Rock Fish
-Top Smelt
-Pipe Fish

DATA

Peak Height = 3′
Dimensions = 6′ x 6′

Area = 48.27 sq ft
Rugosity = 1.34
Slope = 1.56°
Aspect = 154.53°

Figure 3: “SubOrdinate” by Madeline Cunningham and Taylor Metcalf. The project utilized an integrated, parametric model that incorporated quantitative inputs from the ecologists (above) and generated a simulation of the hydrodynamic flows that would be produced by the variable geometries (below).

Figure 4: The above full-scale prototypes were submersed upside-down in Monterey Bay for twelve weeks to test relationship between geometry and colonization of species. Comparison of a flat control substrate (left) with a rugose substrate that incorporates variable hillocks and valleys demonstrates proof-of-concept that gradated habitats of invertebrates can be modulated with differentiated geometries.

To date, project partner Kreysler & Associates has produced three sets of 24" by 24" prototypes, all of which have been installed underwater for monitoring and evaluation by the Benthic Lab team. The first set consisted of entirely arbitrary geometries, sampled from the speculative building designs of the 2014 studio. Although uninformed by performative metrics like rugosity and slope, these prototypes were crucial for establishing "proof-of-concept" confirmation that rugose geometries foster gradated habitats of invertebrates that are more diverse than those found on flat, undifferentiated surfaces (Figure 4). Subsequent prototypes incorporated observations about the substrate's performance into a set of typologies for the optimized substrate based on simple, repetitive geometries. These forms—informally dubbed "pyramids," "juicers," "keels"—may at first seem arbitrary and whimsical, but they reflect precise input from the ecologists regarding geometry, dimensions, and slopes for the FRP surfaces (Figure 5). These formal and performative logics then feed back into the students' design workflow, often inspiring and catalyzing the development of formal strategies at a larger scale.

A critical factor in the prototyping process has been the involvement of Daniel Gossard, a graduate Masters student in the Benthic Lab program who has aligned his thesis research with that of the Buoyant Ecologies project. Daniel's expertise as both an ecologist and a diver (he conducts regular dives to monitor the performance of the ecological substrates) has proven enormously important in solidifying the link between ecological performance and architectural design. In the most recent studio, this student-to-student interaction between ecologist and architect has greatly streamlined and enhanced the feedback between disciplines.

7. CONCLUSIONS & NEXT STEPS

With the encouraging results of the initial prototypes, the project partners have commenced work on the next phase of the research: constructing a larger-scale prototype to be deployed at Middle Harbor Shoreline Park in the Port of Oakland as a testing lab and public demonstration project. The "Float Lab," a small vessel with connection points on the underside to attach modular substrate prototypes, will serve several purposes. It will facilitate ongoing testing of the substrate geometries, as well as other types of growing mediums, such as "vertical structures" that mimic the submerged roots of mangrove forests. With a small inhabitable interior space, the vessel will also serve as a prototypical "scale model" of a floating building and encourage conversation about this typology as a potential strategy for resilient design. Finally, as a complement to the Park's mission as a didactic, educational resource, the Float Lab will serve as a pedagogical tool, teaching visitors and increasing public awareness about the challenges of rising sea levels.

Although still in the early phases, this project owes its initial success and momentum to the pedagogical structure of the architecture studios that serve as the primary venue for the research. By incorporating Benthic Lab's scientific knowledge and Kreysler & Associate's material know-how, the collaborative structure triggered a recursive set of feedback loops that transcend the conventional, false binary distinction between visionary thinking and practical knowledge, instead allowing the two to inform each other. As architects work to develop compelling and robust strategies for resilient shorelines, it is critical to develop thoughtful and productive ways of integrating extra-disciplinary expertise into the design process. The Buoyant Ecologies project points to one model for taking on complex, wicked problems such as climate change and sea level rise, which demand a synthetic integration of academia *and* industry, design *and* research, speculation *and* pragmatism.

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Marine Ecology Partner: Benthic Lab / Moss Landing Marine Laboratories — John Oliver, Kamille Hammerstrom, Dan Gossard

Fabrication Partner: Kreysler & Associates — Bill Kreysler, Josh Zabel, Michelle Aquino

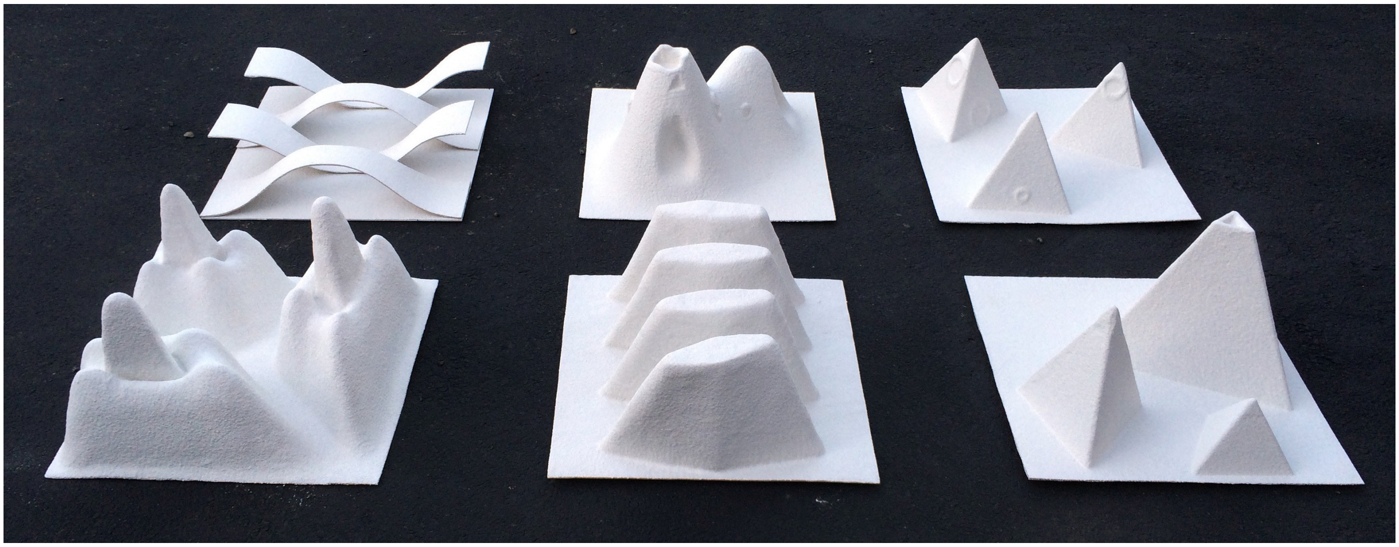

Figure 5: The second round of full-scale FRP substrate prototypes incorporated lessons from earlier tests. The geometric typologies are based on precise dimensional and slope metrics provided by the Benthic Lab ecologists.

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CCA Buoyant Ecologies Studio, 2014: Hayfa Al-Gwaiz, Behnaz Banishahabadi, Welbert Bonilla, Jill Chin-Han Chao, Hung-yi Chou, Tyler Jones-Powell, Sanna Lee, Mikaela Leo, Maryam Nassajian, Yasmine Orozco, Melissa Perkinson, Jude Simon, Blake Stevenson, Dustin Tisdale

CCA Buoyant Ecologies Studio, 2015: Rafael Berges, Trishala Umesh Chandra, Kuan-Lun Chen, Jared Clifton, Keith Edwards, Kenneth Hu, Vaama Joshi, Susan Lopez, Shirin Monshipouri, Betty Nip, Min Joo Noh, Omar Soliman, Susan Wing, Ka Ki Yam

CCA Buoyant Ecologies Studio, 2016: Fernanda Bernardes, Gina Bugiada, Bryany Burke, Madeline Cunningham, Taylor Metcalf, Mrnalini Mills-Raghavan, Georine Pierre, Stephany Rattner, Carlos Sabogal, Arash Sedaghatkamal, Nicole Van Malder

ENDNOTES

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4. For documentation of the 2014 Buoyant Ecologies studio, see Ikeda, Margaret, Evan Jones, and Adam Marcus, *Buoyant Ecologies: New Visions for San Francisco's Waterfront* (2015).

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7. For an overview of the history of the site and design of Middle Harbor Shoreline Park, see David Gates & Associates and Thurston Design Group, *Middle Harbor Shoreline Park Master Plan* (1999).

8. Resilience can best be defined as the elastic ability to return to stability after the shock of a crisis or natural disaster. Conversations about architecture's role in constructing resilient cities increased in the aftermath of Hurricane Sandy in 2012, when cities began to recognize increasing vulnerability to the effects of climate change. For a general overview of principles of resilient design, see Rachel Minnery, "Resilience to Adaptation," *Architect* (August 4, 2015), accessed January 29, 2016, http://www.architectmagazine.com/aia-architect/aiafeature/resilience-to-adaptation_o