Blue Ceramics: Co-designing Morphing Ceramics for Seagrass Meadow Restoration

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ABSTRACT

Seagrass meadows are twice as effective as forests at capturing and storing carbon, but human activities have caused them to gradually disappear over the last few decades. We take a nature-centered design approach on contextual inquiry and collaborative designs methods to consolidate knowledge from marine and material sciences to industrial design. This pictorial documents a dialogue between designers and scientists to co-create an ecological intervention using digital fabrication to manufacture morphing ceramics for seagrass meadow restoration.

Authors Keywords

restoration; digital fabrication; ceramic; morphing materials; participatory design

CSS Concepts

• Human-centered computing~ Human computer interaction (HCI)~ Interactive systems and tools~ User interface toolkits

*The first three authors contributed equally to this work.

INTRODUCTION

As the effects of climate change continue to intensify, seagrass meadows face challenges largely due to the human activities in coastal marine environments [16]. Seagrass meadows are vital for healthy marine ecosystems [Fig. 1], and they store large amounts of "Blue Carbon" [7]. With seagrass on the decline [19], interdisciplinary work between design and science is needed to address one of key challenges in seagrass restoration: a lack of conservation tools [16]. In this pictorial, we show the mutual efforts between designers and marine scientists to develop new conservation tools to reduce challenges around seagrass restoration by centering the environment as a stakeholder.

In recent years, post-humanist thought within the field of design has shifted the focus of human-centered design (HCD) methods from the individual stakeholder to the larger natural world [6]. Our project builds on this by taking a nature-centered design approach [14] adapting HCD methods such as contextual inquiry, and collaborative design [17] for an environmental stakeholder —the seagrass meadow system. Throughout the initial research exploration and problem definition, we collaborated closely with several marine scientists from concept creation to virtual usability testing to co-design and fabricate an ecological intervention with morphing ceramics. The result is "Blue Ceramics," a modular system of ceramic tiles for restoring seagrass meadows. Our goal for this pictorial is to present how the design opportunities identified through collaborative design methods inspired and informed the initial hardware development for ecological interventions. We hope to bring attention to how HCD methods can be used to explore opportunities that bring in humans as part of the environment to create more sustainable and resilient futures for people and plants.
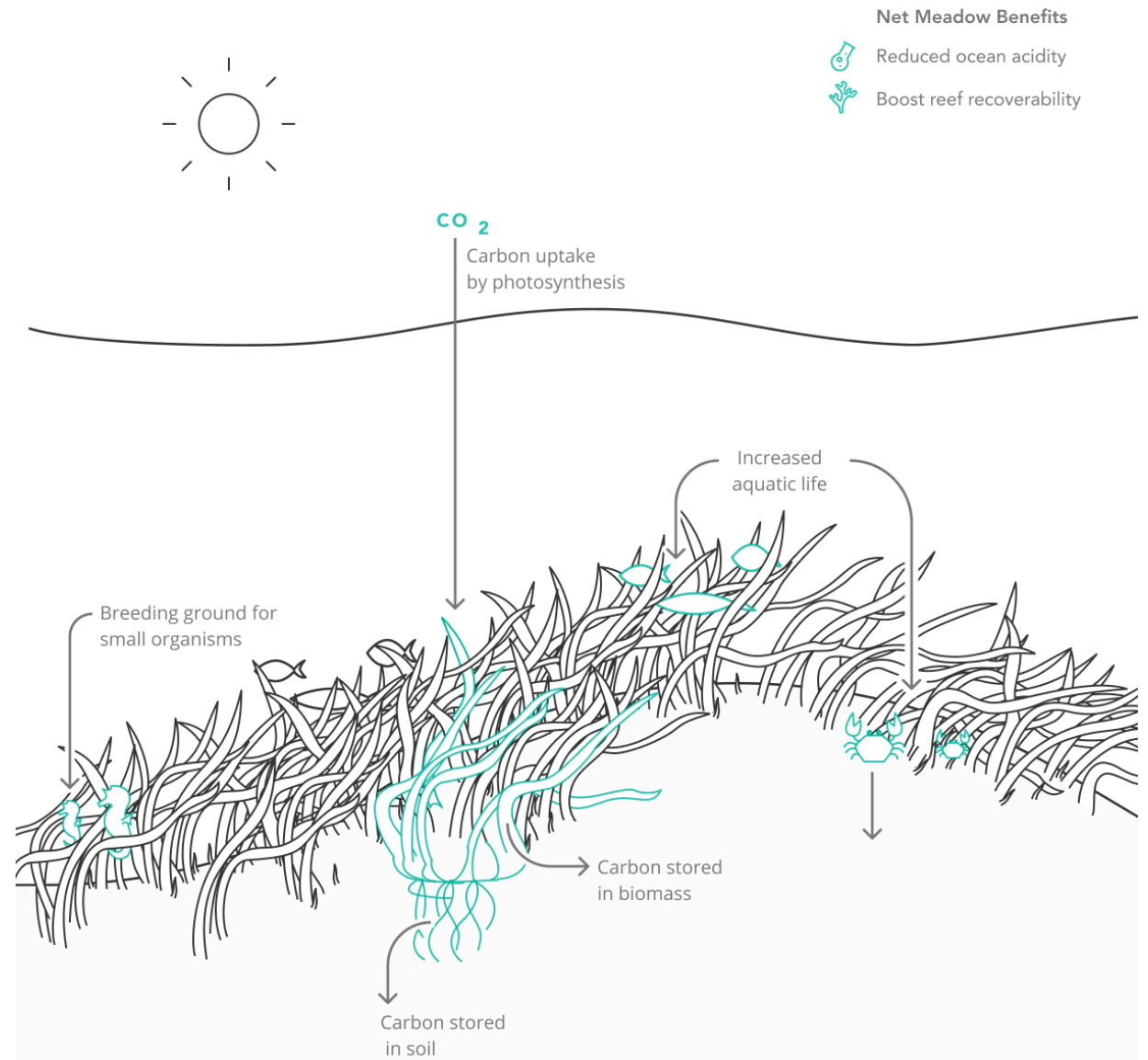

Figure 1. Stable seagrass meadows are able to trap large amounts of Carbon in their roots and biomass. They also support commercially valuable species such as crabs, oysters, fish by providing breeding grounds and safety from predators.

MOTIVATION

This project originally set out to explore the opportunities for ceramics in coral reef restoration, but early on we pivoted to seagrass. Coral reefs near seagrass meadows are more resilient to the effects of climate change [16], but little design attention focuses on the humble seagrass [5]. As seagrass meadows decline, it's unknown how the animals living in them will adapt to the changes [19]. Restoring seagrass meadows is critical to the ocean ecosystem. However, current restoration methods are either too broad or too narrow for repairing areas of meadows that need replenishment [16]. We set out to solve this challenge by identifying potentially improved restoration solutions, and carried out the initial lab test with physical prototypes.

DESIGNING FOR SEAGRASS

Seagrasses play a key role in reducing the sediment in the water through their blade structure. The blades provide resistance against the current trapping sediment and increasing water clarity and the amount of sunlight they receive [3]. When a seagrass meadow system starts to decline, it usually happens in small patches. These are known as "cold-spots" and cause downstream effects such as increased ocean acidity, loss of breeding grounds for key species, and algal blooms [12]. Our intervention targets these cold-spots at different levels to reduce erosion and seed loss through sediment traps. This has the added benefit of providing structure for seagrass roots to regrow. The overall system is designed to increase seagrass meadow resiliency by stopping seed and plant loss at the leverage point, vital to restoration efforts. This provides a space to help facilitate seagrass meadow restoration by exploring ways to keep the sediment stable with an intermediary structure.
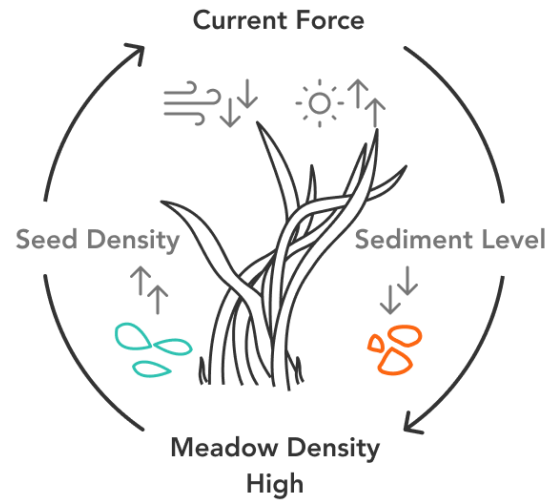

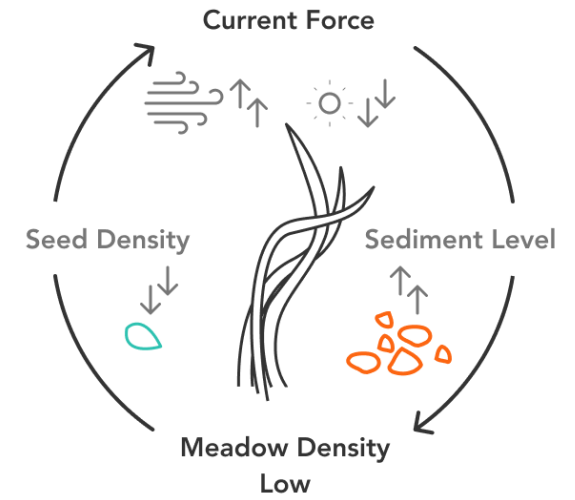Figure 2. Higher meadow density increases current resistance reducing current flow

Figure 3. Lower meadow density provides less resistance increasing current flow
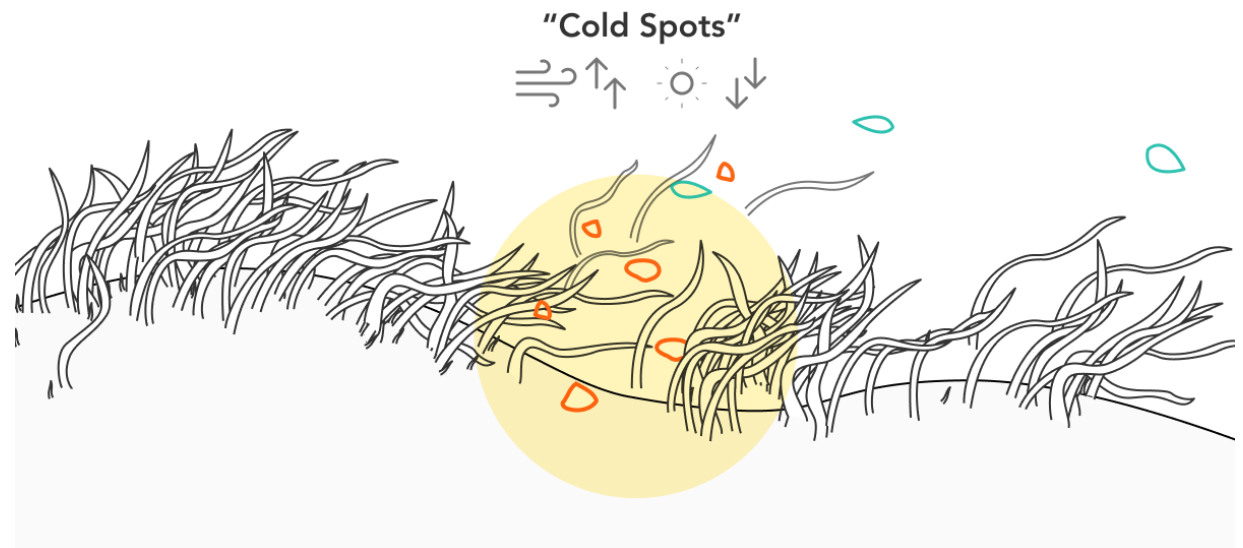

Figure 4. Cold spots reveal the sediment and seeds that was trapped by the seagrass roots. The increased currents remove these decreasing water clarity, and prohibiting regrowth.

NATURE-CENTERED DESIGN

Our contextual inquiry interviews leverage expert scientific and restoration knowledge to find a design opportunity for seagrass meadow restoration. We conducted one-hour semi-structured interviews via Zoom with five experts in marine science and coastal restoration. Although remote, these interviews took place in their respective research labs and offices. We focused our interview protocol on prompting responses to pain points in their current work or research processes to understand the needs of seagrass meadow systems and obstacles for restoration. The initial interviews with seagrass experts scoped our research to a few key points:

- Lack of restoration tools, particularly with the ability to target specific areas for restoration

- Importance of water clarity to ensure good lighting conditions for seagrass meadow growth

- Increased currents, which scatter seeds and prohibit natural regrowth, and reduce water clarity

These initial interviews also grounded our research in one particular type of seagrass, Eelgrass *Zostera marina*, the most common seagrass in the Northern Hemisphere [15]. Later, we interviewed experts who deploy similar systems for coral reefs about current pain points, and their feedback evolved into our guidelines for transport, assembly, and deployment of the intervention. We then adapted HCD design methods to consolidate the knowledge from these interviews into design opportunities for an intervention centered on the real needs of seagrass meadows [Fig. 5].

We partnered with two experts with experience in coastal restoration for Eelgrass meadow systems to refine the design challenge, intervention goals, and desired impact. Scientist A is a coastal plant ecologist and runs a university research lab focusing on seagrass restoration. Scientist B is a marine biologist working in a marine research laboratory and has previously worked in the field of marine botany.
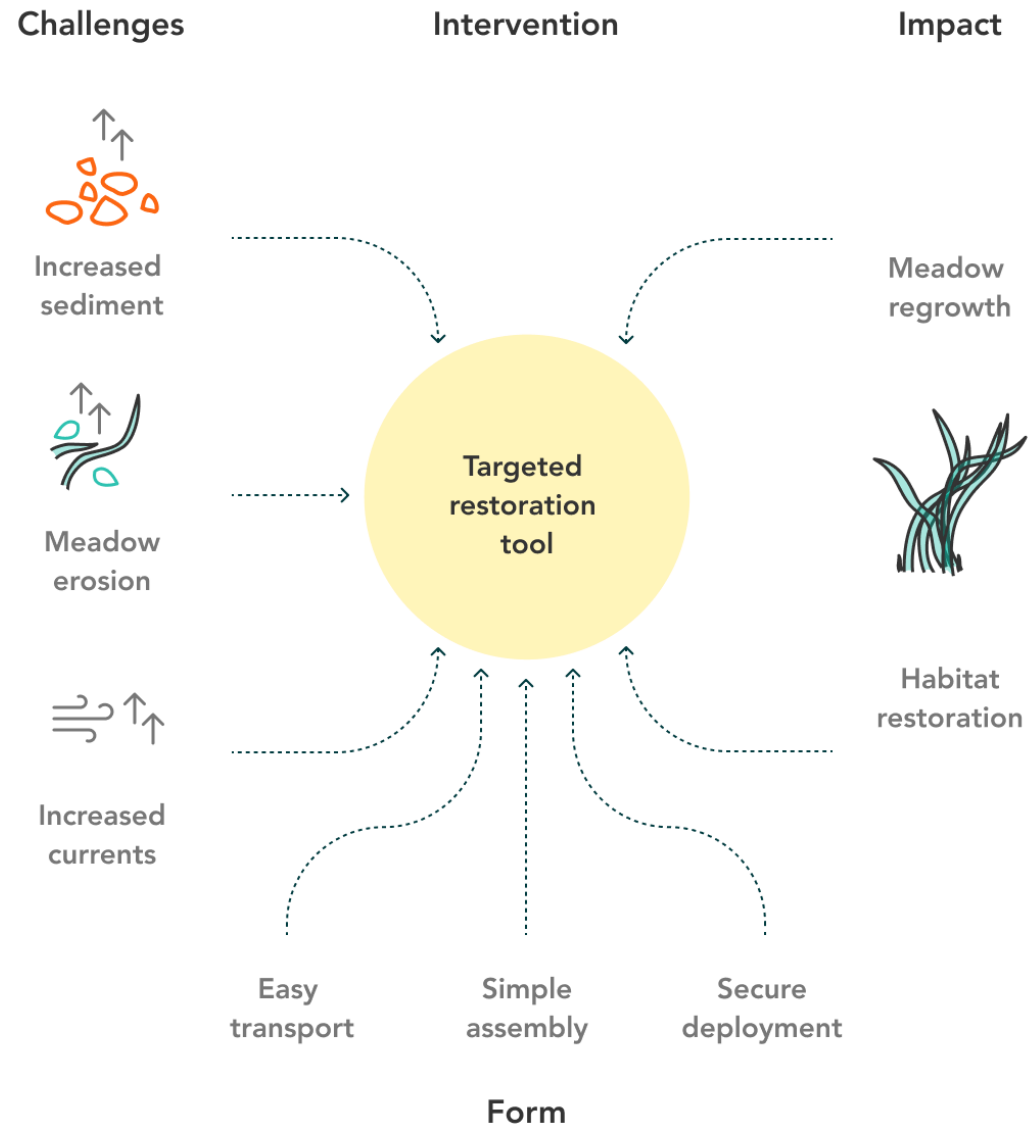

Figure 5. Our research methods helped us scope our intervention design by providing guidelines for impact. This diagram shows how we integrated our knowledge into the final design.

We used a collaborative sketching method adapted from the "Homesense Kit Manual" by Audrey Deschamps-Sonsino [4] from the co-creation of IoT products for the home to surface the scientists' knowledge of the key needs of the meadow. These sessions generated a total of nine sketches around speculative solutions. Over Zoom, we started with eight general prompts on seagrass meadows systems, the scientists then identified the three key points for sketching. Using an iPad with a drawing software, the designer shared their screen, and worked through the selected points with the scientist to live sketch how these concerns could be addressed with speculative solutions. The designer had the most context into possible fabrication methods and materials. By creating together, both the scientist and designer could build on each others expertise to visualize the direction and the scale of possible solutions [20]. These sketches served as the initial blueprints in exploring the intervention form. Our fabrication focused on ideas surfaced in two key sketches. The first idea from scientist A focused on a set of structures that mimics how marshes and oyster beds trap seeds and sediments [Fig. 7]. The second idea from scientist B focused on promoting seed sedimentation and germination even under strong currents by providing a stable structure with holes to catch seeds and allow roots to anchor.

INTEGRATING THE RESEARCH INTO FORM

We drew upon the semi-structured interviews and collaborative design sessions to generate guidelines, rules, and principles about seagrass meadow systems, and scope our work for a targeted design opportunity [Fig. 9]. We used the initial research and sketches as the basis for developing the form, and later an environmental simulation. These renders of the form were used as visual artifacts in think-aloud usability testing with the same marine scientists. We prototyped several form designs in the simulation. We showed the variations to our coastal restoration experts before investing in the manufacturing of a particular shape [Fig. 8]. This allowed us to have a grounded discussion around factors such as water clarity, depth, sunlight, seagrass height, and intervention scale.
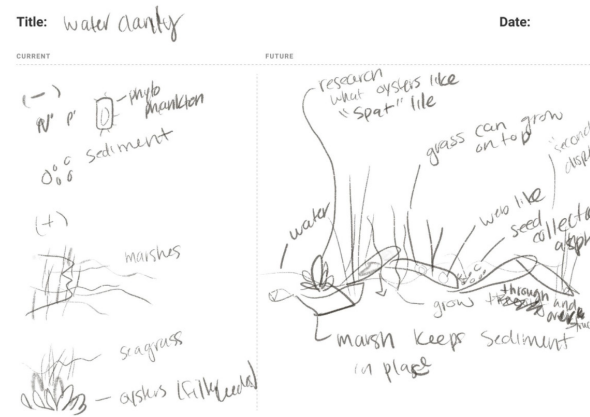

Figure 6. This idea from scientist A focuses on how marshes naturally trap sediment and seeds by sketching a tile network that mimics this ability.
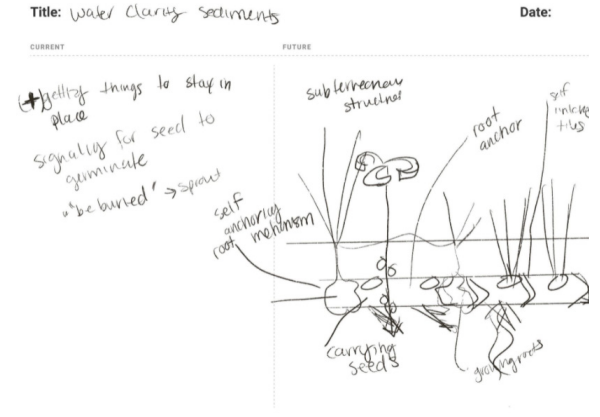

Figure 7. This idea from Scientist B focuses on how to provide a stable structure for seagrass roots in strong currents through an underground grid.
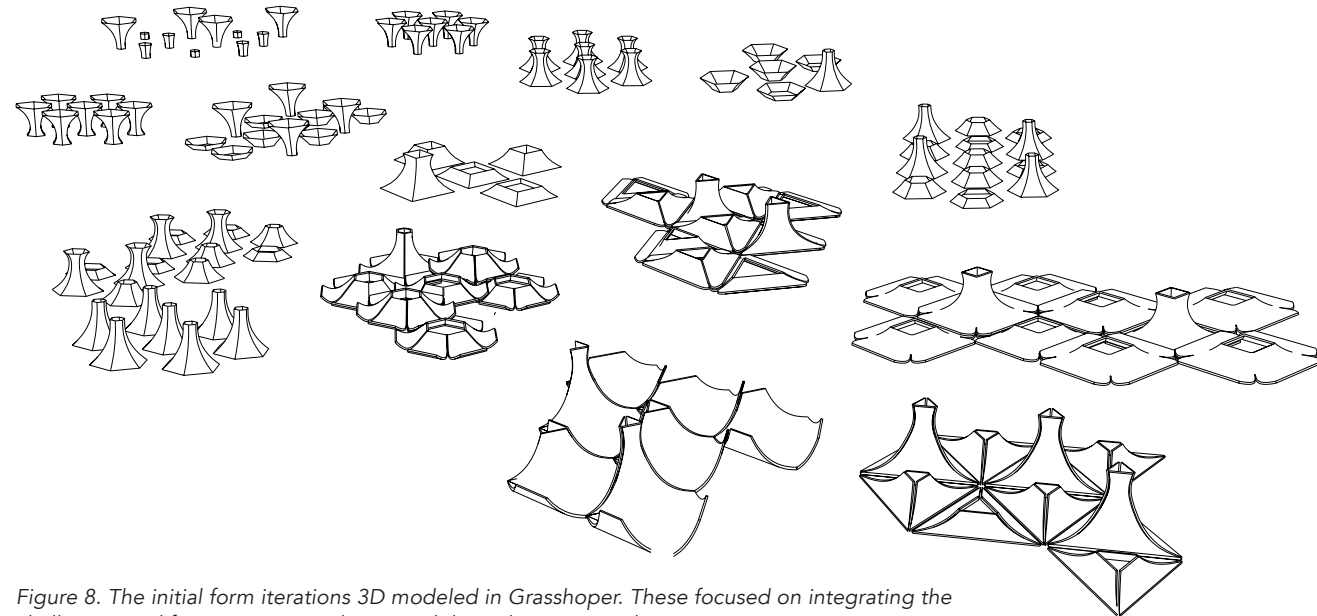

Figure 8. The initial form iterations 3D modeled in Grasshoper. These focused on integrating the challenges and form constraints discovered through our research.

"I have been working with seagrass restoration for a long time and we didn't come up with anything like this. Just having something different to try is really exciting to me."
— Scientist A on our intervention design
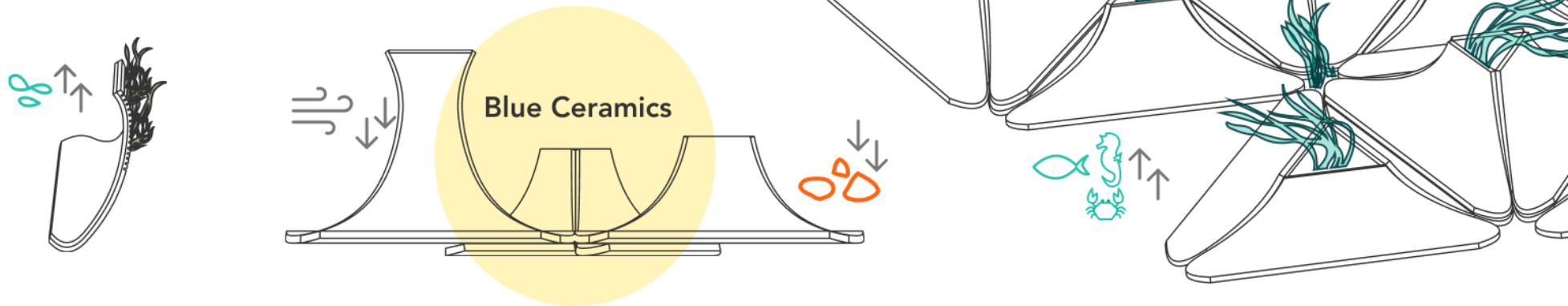
Micro Level ┈┈→
Add texture to increase seed anchoring

Macro Level ┈┈┈┈┈┈┈┈┈┈┈→
Increase topology to reduce current force

Coverage to prevent erosion and decrease sediment levels

System Level
Provide intermediate habitat for small organisms

Facillitate better conditions for meadow regrowth and restoration

Figure 9. Blue Ceramics intervention design. The micro, macro, and system levels reflect how the intervention addresses key leverage points for change within seagrass meadow systems.
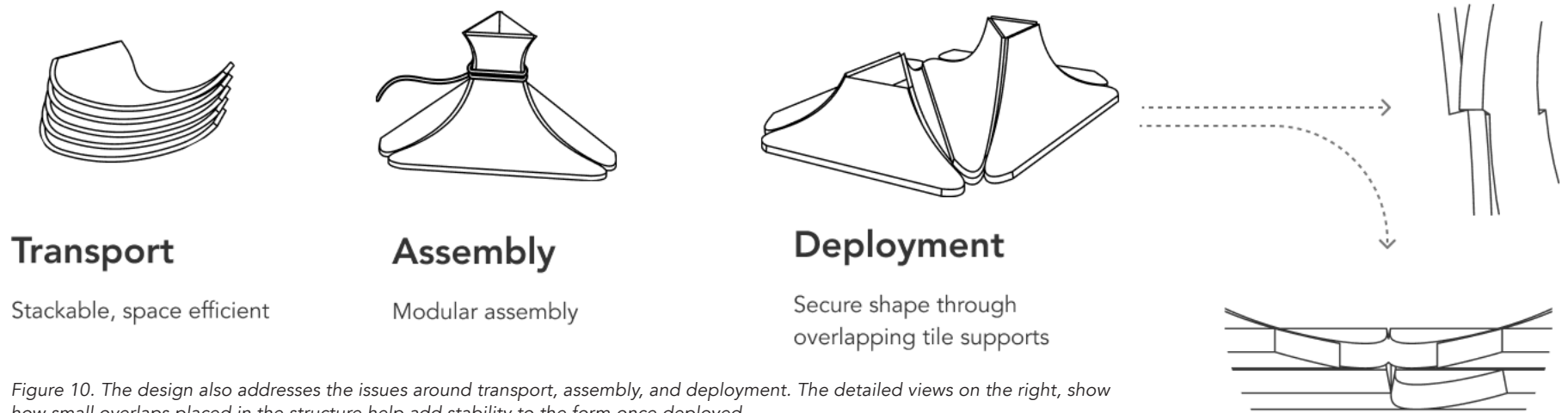
Transport
Stackable, space efficient

Assembly
Modular assembly

Deployment
Secure shape through overlapping tile supports

Figure 10. The design also addresses the issues around transport, assembly, and deployment. The detailed views on the right, show how small overlaps placed in the structure help add stability to the form once deployed.

The environmental simulation, built in Unreal Engine, used the systems information from our research and intervention design. This allowed us to virtually test out the deployment of the intervention —conveying the goals and form details to scientists, designers, and the general public alike. Additionally, the environmental simulation can be used to prototype deployment in different types of underwater environments.

Fig 11. Blue Ceramics environmental render of the full system

Fig 12. Blue Ceramics top view shows how sand is trapped

Fig 13. Blue Ceramics overlap view shows how tiles connect
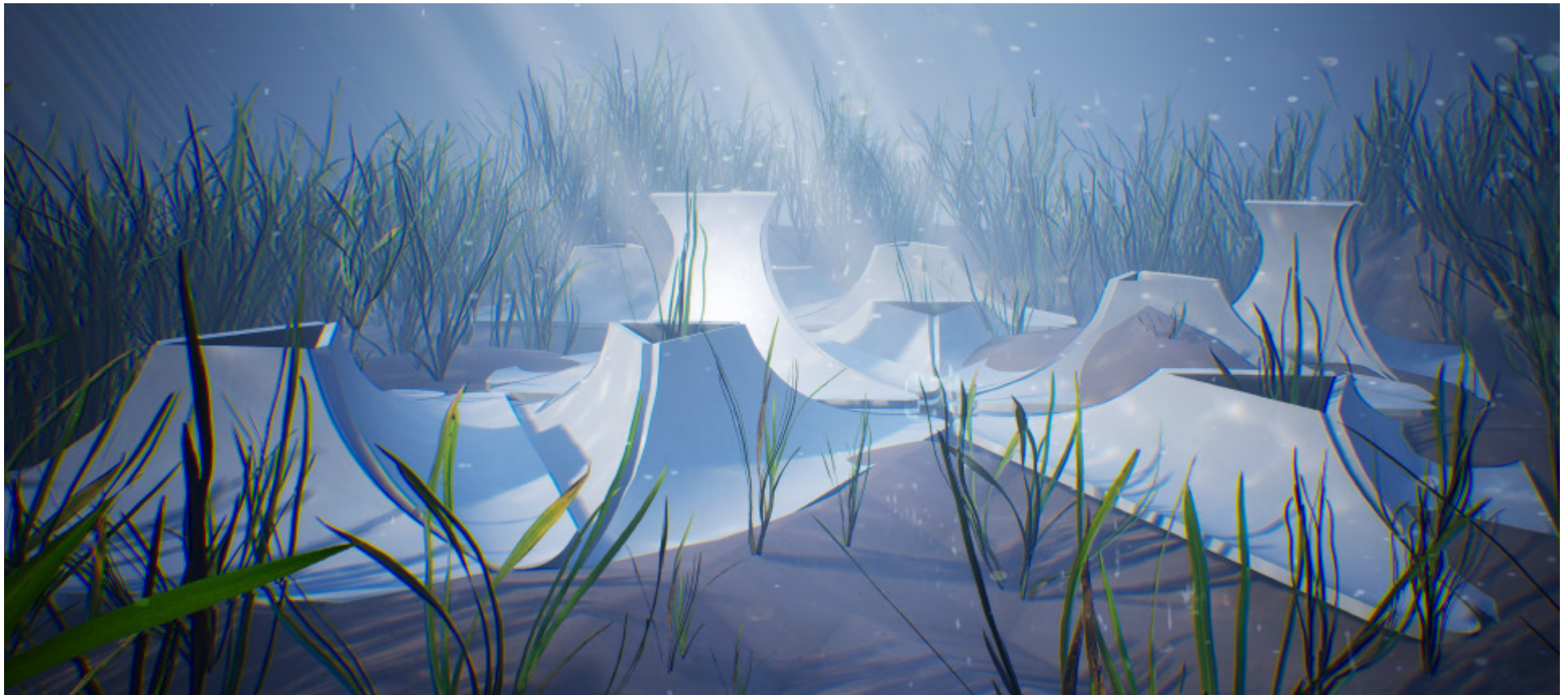
DESIGN RATIONALE

Our intervention design takes into consideration the fabrication material and technologies involved in the manufacturing process. Clay is a natural material, meaning we can develop a process for fabrication, application, and destruction where every step occurs within the same ecosystem [13]. For prototyping purposes, we used commercially available clay bodies to establish a material baseline of the morphing behavior of ceramics [Fig. 14-17]. However, the long-term vision is to develop a "clay ink" from local sands and marsh clays. This ensures the intervention introduces no foreign materials when it breaks down through natural and environmental stressors.

Digital fabrication methods for morphing materials save time and material and have a smaller carbon footprint than other methods [18]. We developed morphing ceramics structures using two different fabrication techniques: CNC and 4D clay printing. Blue Ceramics is envisioned to be deployed in a variety of underwater locations with different environmental constraints. 4D printing provides a route for developing a fabrication process that can be easily modified to fit the specific needs of a specific seagrass meadow, such as height, width, and length[8].

MANUFACTURING MORPHING CERAMICS

Morphing ceramics take advantage of the tension created by two types of clay with differential shrinkage rates that are joined together and then fired to create an isotropic, homogeneous positive reference Gaussian curvature [2, 10]. Our experiments used porcelain and stoneware, which our firing tests showed has a shrinkage rate of 13-15% and 7-8%, respectively. This contrast makes them the ideal candidates for making morphing bi-layer ceramic structures [11, Fig. 18].

Figure 14. Stoneware with Talc exhibits the most highest stable morphing.

Figure 15. Red sculpture exhibits low but stable morphing.

Figure 16. Sculpture clay exhibits high but unstable morphing.

Figure 17. Stoneware without Talc vitrifies before morphing can be achieved.

Porcelain 13-15% Shrinkage

Stoneware 7-8% Shrinkage

Clay Types

Bi-layer structure
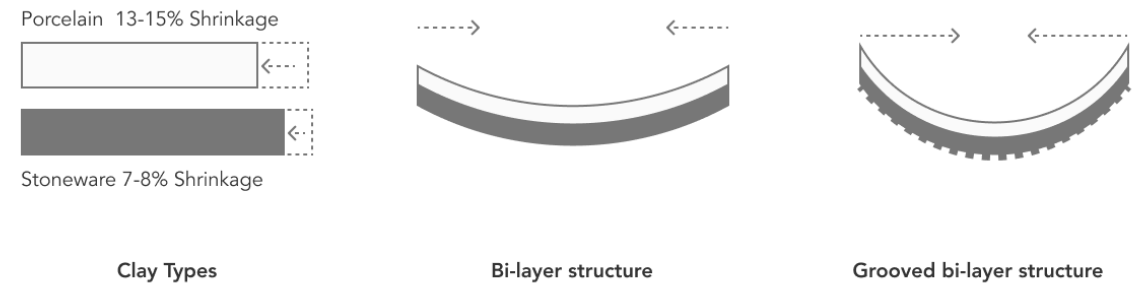
Grooved bi-layer structure

Figure 18. Our initial material tests established the shrinkage rates for our clays using a small test kiln. We used these tests to understand which clays would best be suited for morphing. We moved forward with testing the Stoneware with Talc.

We manufactured uniform test tiles using 2 fabrication methods: 4D printing [Fig. 19] and CNC grooving [Fig. 20]. 4D printing uses commercially available 3D printers to create bi-layered tiles by printing stoneware clay on top of porcelain clay. These tiles morph when fired in a kiln and create an extra "dimension," hence 4D printing. CNC grooving uses a drawing machine to mechanically carve lines into slabs of hand-thrown stoneware clay. They are then cut into tiles with a custom-fabricated cutter and attached to a piece of hand-formed or 3D printed porcelain clay. We used these methods to explore the material properties and morphing behaviors of ceramics. These experiments focused on

1. Testing the mismatched stress in bi-layered ceramics

2. Observing the effects of geometric parameters such as grooving and material thickness on the resulting shape

3. Gathering data to derive and inverse design pipeline

Single Layer Tests

In the initial print tests, we created single-layer tiles with identical dimensions but different print routes. While all samples shrank after firing, it was evident that using a print route perpendicular to the lengthwise direction of the ceramic pieces causes the most shrinkage [Fig. 22]. This result later informed our manufacturing method for bi-layer samples.

Bi-Layer Tests

In the bi-layer tests, we combined clay sheets created through hand-forming, 3D printing, and CNC grooving to deepen our understanding of the relationship between manufacturing methods and morphing behavior. The samples with the largest curvature used the following combinations:

• Printed porcelain with hand-formed stoneware

• Hand formed porcelain with printed stoneware

• Printed porcelain and stoneware printed perpendicularly to each other

This test provided further insight into the impact of print orientation on the resulting curvature [Fig. 21].
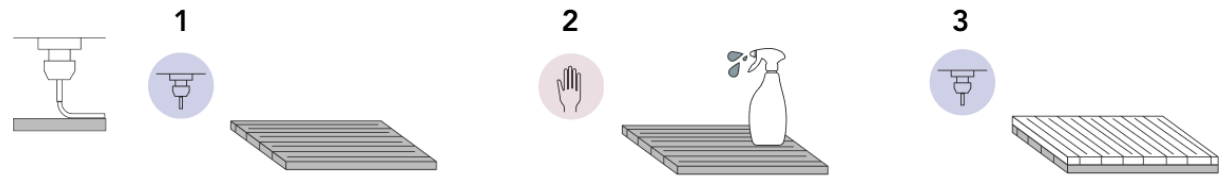

Figure 19. Using a Hyrel printer. 1. Load the printer with stoneware on a route aligned to the x-axis 2.Spray the with water 3. Load the printer with porclein aligned to y-axis.
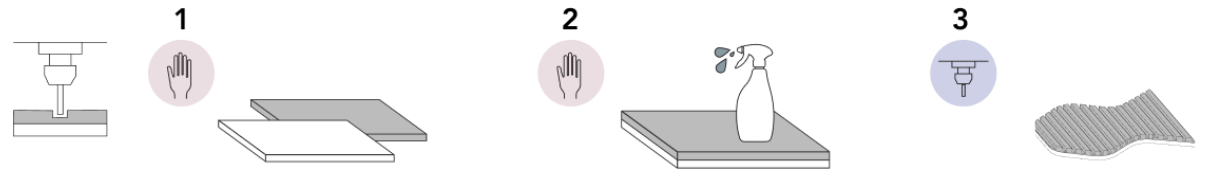

Figure 20. Using a CNC printer. 1. Hand fabricate the porcelain and stoneware slabs 2.Spray the with water 3. Groove the slabs

Figure 21. Left. Bi-layer layer testing of printing orientation

Figure 22. Above. Single layer testing of printing orientation

Grooving Tests

We tested the effects of grooving the surface of clay sheets on the morphing process in parallel with single- and bi-layer tests. Earlier research demonstrated that surface grooves act as tension release points [11], which increases overall curvature. Our tests corroborated these results—samples with dense grooves greatly augmented the resulting morph [Fig. 23].

Figure 23. CNC machine grooving density tests

Needle Adaptations

We also adapted the 3D printer as a grooving instrument by using an extruder head as a needle. By default, the printer holds the needle at 90°, which created rough lines and inaccurate curvatures. However, tilting the needle at a 45° angle creates clean grooves and more accurate curvatures by extension [Fig. 25.] A special adapter was later created to hold the needle in the correct position [Fig. 26].

Another design opportunity was revealed through grooving tests with round-tipped needles. This method creates ceramics with richly-textured surfaces, and when done with open-ended grooves, has the added ability to trap seeds and sediment [Fig. 27] We made small test samples to verify this ability by making small test samples in the lab [Fig. 28]]

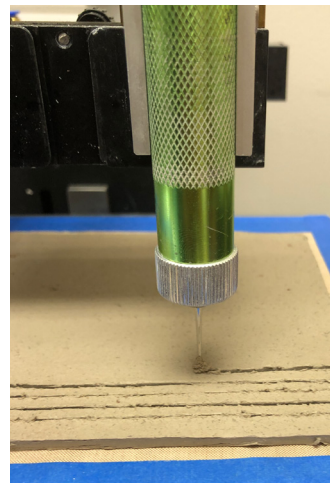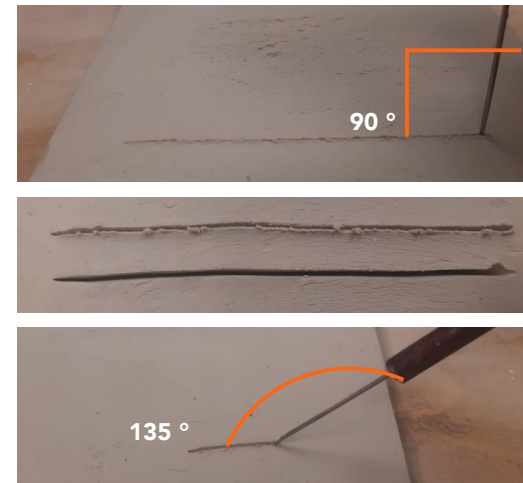
Figure 24. Hyrel printer with orginal printer head.

Figure 25. We noticed that while hand-grooving, we tilt the angle of the needle achieving cleaner edges.
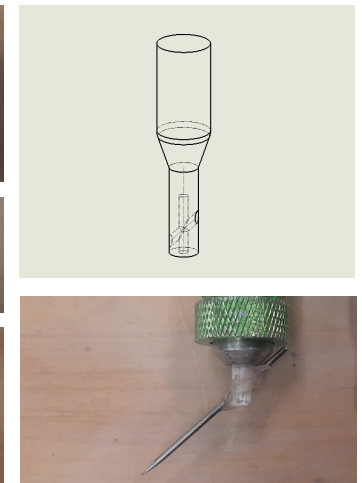
Figure 26. Adapted Hyrel printer head for angled grooving.

Figure 27. Round-tipped grooving design

Figure 28. Round-tipped grooving design showing seeds growing on the tile.

Inverse Design Pipeline

Our lab has developed a program that samples morphed pieces to systematically generate groove patterns that create the desired curvature on a given material [1]. We used this software during the later phases of our manufacturing process to increase the fidelity in relation to the design. We will continue to add tagged data to increase the accuracy of the program's output, and we hope that this will shift the burden of computation away from designers while leaving the freedom to imagine creative shapes [Fig. 29].

Fabrication Tradeoffs

While additive manufacturing saves the efforts of creating an initially flat sheet clay, it can be time-consuming. 3D printing clay is still slow to complete the printing of reasonably sized 3D objects [1]. However 4D printing uses less material overall and is geometrically easy to fabricate [19]. We envision a CNC grooving process on top of a flat sheet of clay through digitally controlled subtractive manufacturing. In combination with the inverse design pipeline, this process sets the stage for scaling the manufacturing process both in quantity and size with the lowered cost of production and time.
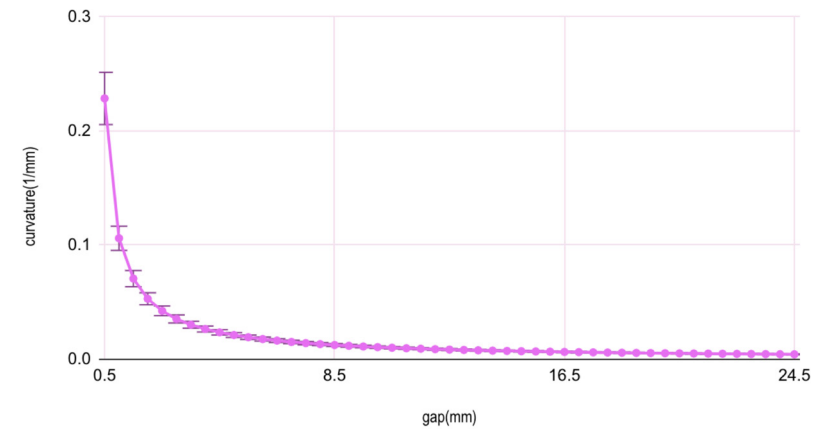

Figure 29. Ceramic samples used to chart the relationship between the grooving and the morphing.

Figure 30. Right. We constructed mid-sized morphing ceramic prototypes of the intervention design. Further testing is needed to build our understanding how the firing process affects morphing on larger tiles.

REFLECTIONS

Digital fabrication of ceramic structures has been explored before [9], however, our focus lies in creating 4D structures for underwater environments. Blue Ceramics is an ongoing project in the early stages, and this work will continue to evolve as more tests are completed. Future materials research should focus on thoroughly understanding the effects of clay material properties and firing temperatures on the morphing process. Early testing with small-scale prototypes validated our assumptions around the form and sediment interaction [Fig. 31-32].

In addition to adapting HCD methods for a natural stakeholder, we had to adapt the methods for remote research as well. Since our focus was surfacing the needs of the seagrass meadow system, we asked the scientists to talk through the tools and processes of their research. While this method could only capture by proxy, it provided our team with the right basis to understand the seagrass meadow system through the eyes of those who understand them the most. However, a key next step is to collaborate with the scientists in field testing to validate our findings in the seagrass meadows.

From collaboratively sketching ideas to building morphing ceramic prototypes, our research brings a new lens on collaboration across disciplines by using familiar design methodologies to target nature instead of humans. This work demonstrates that the nature-centered design process proved to be the perfect framework to translate knowledge between designers and marine scientists to design ecological interventions[14]. This pictorial highlights how our process brings together knowledge at the intersection of many different fields to design a new tool for seagrass meadow conservation. We hope this work broadens the conversation around the potential for design to bring about more sustainable futures.

Figure 32. Right. We placed small form prototypes in a current tank with colored sand to understand current movement over the form and how sediment of different sizes interacted on the form.

Figure 31. Before building large scale prototypes, we designed smaller prototypes of the form design to test design details such as increasing tile overlap and stability.

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