Evaluating Methods to Enhance Oyster Production with Alternative Substrates, Retrofits, and Hatchery Holding Times

A Report to the Maryland General Assembly, Governor, and Secretary of Natural Resources in Response to Senate Bill 830 (2022)

Submitted by
University of Maryland Center for Environmental Science (UMCES)

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About this Report

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About this Report

This report is in response to Senate Bill 830 (2022) that instructed the University of Maryland Center for Environmental Science (UMCES) to evaluate the following topics in collaboration with Smithsonian Environmental Research Center, Virginia Institute of Marine Science, appropriate State and federal agencies, and industry and other stakeholders:

1. The types of substrate, including fresh shell, fossilized shell, combinations of shell, and alternative substrates, that are most appropriate for use in oyster harvest areas;

2. The benefits, including habitat–related benefits, of using stones of various sizes in oyster restoration areas;

3. Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates;

4. The potential for retrofitting existing structures, such as riprap revetments, that are unrelated to oyster restoration but that use materials similar to artificial reefs, to include oyster plantings,

5. The effect of spat size upon deployment on oyster abundance.

The five chapters of this report correspond to these five topics.

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About this Report

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This research was supported by many individuals and groups. We thank Victoria and Robert T. Brown of ShopCove Aquaculture LLC and Eric Wisner of Eric Wisner Oysters LLC for use of their leases to undertake the alternative substrate field trials and John Jacobs, Director of Cooperative Oxford Laboratory, for use of their pier and sanctuary for the alternative substrate field trials and hatchery holding time tests. In addition, we are grateful for the donation of materials from Dagsboro Materials, New Brick and Tile of Easton, SeaKing Corporation, SeaWatch Inc., Vulcan Materials Company, and Wittman Wharf Seafood Inc.

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Appendices available in the electronic version of this report available at:

https://www.umces.edu/alternative-substrate-for-oysters
https://www.umces.edu/shores-symposium

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Executive Summary

The Eastern Oyster (*Crassostrea virginica*) is important for Maryland because it provides food, supports the seafood industry, and is a keystone species in Chesapeake Bay. Commercial fishing and aquaculture of oysters are important for local economies, working waterfronts, and Maryland's cultural heritage. Oysters create reefs that enhance recreational fishing, promote biodiversity, and improve water quality. Declines in oyster abundances in the last century resulted in loss of jobs, loss of reefs, and loss of the support that oysters provide to the Chesapeake Bay ecosystem and the health of its waters.

In an effort to restore oyster populations, Maryland has become a world-wide leader in large-scale oyster restoration. Restoration efforts, along with the growing commercial fishing and aquaculture industries, all require the use of oyster shells to maintain and expand oyster populations and productivity. Yet, fresh (reclaimed) oyster shells are in short supply, hampering growth of all sectors – restoration, commercial fishing, and aquaculture.

While ongoing efforts are being made to keep and recycle shells within Maryland, alternative materials are being used or considered for use, including shells (e.g., Clam, Whelk, fossil dredged Eastern Oyster, or weathered Pacific Oyster shell) and non-shell materials (e.g., clean crushed concrete, river rock, granite). These materials – anything other than the fresh shell of the Eastern Oyster – are called "alternative substrates."

There are many questions about alternative substrates that will affect their use: Which alternative substrates are best for harvesting areas? What are the benefits of stones in restoration areas? How are alternative substrates used in other regions? Can existing man-made infrastructure like riprap be retrofitted with oysters using materials other than shell? To answer these questions, Senate Bill 830 (2022) instructed the University of Maryland Center for Environmental Science (UMCES) to evaluate the many uses of alternative substrates for oysters. The bill also required an assessment of the holding time of oyster spat (juvenile oysters) in the oyster hatchery with the aim of increasing efficiency of hatchery production.

When developing this research program, we consulted and collaborated with numerous representatives of the oyster commercial fishing, aquaculture, and restoration sectors, state and federal employees, as well as citizens and scientists from across the nation and world. In each year of this project, a virtual symposium was held to help us gather current information and identify knowledge gaps that could be filled during our evaluations. We are grateful to all who contributed to this effort.

The most important overall finding is that alternative substrates can be used to successfully enhance oyster productivity and populations in Maryland's Chesapeake Bay. Our evaluation in Maryland waters show that alternative substrates perform well in terms of Eastern Oyster spat settlement and survival, both in the laboratory and in the Bay. In addition, there are decades of successful use of alternative substrates for enhancing oyster fishery production and restoration in states along the U.S. Eastern seaboard and Gulf coasts.

This Executive Summary provides highlights of the findings by topic of the Senate Bill 830 (2022). The methods and detailed results associated with these findings are described in the five chapters of this report that correspond to the five topics in the bill. The highlights are:

Chapter 1. The types of substrate, including fresh shell, fossilized shell, combinations of shell, and alternative substrates, that are most appropriate for use in oyster harvest areas;

In a laboratory experiment on alternative substrate, we found that:

- Oyster spat successfully settled and survived on all 10 substrates after six weeks in numbers that ranged from a mean of 0.13 spat/cm^2 (49 spat per container) for limestone to 0.41 spat/cm^2 (192 spat per container) for Pacific Oyster shell.
- Pacific Oyster shell, dredged Eastern Oyster shell, clean crushed concrete and Havre de Grace stone had the highest mean spat abundances after six weeks while limestone and granite had the lowest spat abundances.
- Substrates with the highest mean spat survival from week 3 to week 6 of the experiment were limestone (88%), Pacific Oyster shell (86%), fresh Eastern Oyster shell (84%), and dredged Eastern Oyster shell (80%). Those with lowest survival were Atlantic Surf Clam shell (54%), granite (51%), river rock (46%), and Havre de Grace stone (44%).
- Of the 10 substrates and 11 metals tested, aluminum was the only metal that was detected to be leaching from substrates into the water and this occurred only in the containers with clean crushed concrete and Whelk shell. Aluminum concentrations in the water of these containers remained lower than levels that could negatively impact marine life after six weeks.

We conducted a field evaluation of alternative substrate and found that:

- Wild spat were found on all seven substrates that were recovered from all three rivers (Nanticoke, St. Mary's and Tred Avon Rivers), with abundance levels differing between the river systems. Spat sets on the substrates were high in the St. Mary's and Tred Avon Rivers.
- Within the St. Mary's and Tred Avon Rivers, there was no statistical difference between the abundance of spat on fresh Eastern Oyster shell and the alternative substrates. In other words, the alternative substrates and fresh Eastern Oyster shell performed equally well when spat sets were high.
- The amount of clean, exposed substrate with no mud deposited on it had a significant, positive impact on how many live oyster spat were found – more spat were found in trays with less mud.
- Stone substrates weighed about twice as much as the shell substrates given the same surface area. This has implications for transportation and handling.
- The unusually high abundances of spat on all substrates in the St. Mary's and Tred Avon Rivers may have resulted, in part, because the clean substrates were deployed just before oyster spawning season. Planting clean Eastern Oyster shell just before the oyster spawning season is a technique used to increase spat set by commercial fishermen and aquaculturalists, and it appeared to be effective for alternative substrates as well.

In a cost and emissions analysis of substrates, we found that:

- Barge transport costs were substantially lower than truck transport costs, even when comparing transport costs for a heavier material like Havre de Grace stone ($401/100 miles by barge) with a lightweight substrate like Whelk or Atlantic Surf Clam ($890/100 miles by truck).

- For substrates for which total costs were available, costs ranged from about $16,000 per acre of oyster bottom for fresh and dredged Maryland Eastern Oyster shell to $55,000 per acre of oyster bottom for granite.
- The most important factors determining air pollutant emissions were distance from the origin to the destination and the weight of the substrate. The per acre emissions are much lower for substrates that can be sourced close to the destination.
- Dredged Maryland Eastern Oyster shell had the lowest transport cost and lowest air pollution emissions during transport whereas granite and river rock had the highest transport costs and highest air pollution emissions per 100 miles.

Chapter 2. The benefits, including habitat–related benefits, of using stones of various sizes in oyster restoration areas;

We conducted field studies and statistical analyses and found that:

- Sonar measurements showed that reefs constructed with stones provide reef habitat structure. The reef structure metrics of cluster height and rugosity were highest on reefs constructed with stone in all tributaries.
- Mean oyster abundances at restoration sites created with stones were two to five times higher than the restoration target of 50 oysters per square meter. This demonstrates that stones can be used to rehabilitate areas with poor oyster habitat. In addition, in one of the three tributaries studied (Harris Creek), oyster abundances were significantly higher at sites created with stones than at natural and spat-on-shell reefs.
- Numerous (>24) species were identified from the DNA sequences in water over stone reefs in all three tributaries, suggesting that stone reefs support biodiversity.
- Stone size had variable influence on oyster restoration benefits in the Tred Avon River: smaller stones (2-4”) supported higher oyster abundances than larger stones (3-6”) but there was no clear difference in cluster height, rugosity, or biodiversity between stone sizes.

Chapter 3. Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates;

In a virtual symposium, we found that:

- There is a longstanding, widespread, and successful use of alternative substrates for enhancing oyster fishery production and restoration in large, subtidal areas along the U.S. Eastern seaboard and Gulf coasts. Limestone, river rock, granite, clean crushed concrete, dredged Eastern Oyster shell, Knobbed Whelk (“conch”) shell, and Atlantic Surf Clam shell have been used successfully.
- The size of the substrate is important for different applications. Small sizes of stones (1 to 2 inches) are regularly used in harvest areas, whereas larger stones are used in sanctuaries.
- In multiple states, stones are used in sanctuaries, and these sanctuaries are located so that water currents carry oyster larvae out of the sanctuaries to harvest areas in an effort to increase production in the oyster industry.
- Suction dredge boats, an innovation in the aquaculture industry, can be used to reclaim and recycle Eastern Oyster shells.

Chapter 4. The potential for retrofitting existing structures, such as riprap revetments, that are unrelated to oyster restoration but that use materials similar to artificial reefs, to include oyster plantings;

Results of a virtual symposium indicate that:

- Retrofitting coastal structures such as riprap, seawalls, and pilings with habitat-forming materials for Eastern Oysters can lead to oyster growth and survival, and produce measurable benefits for biodiversity, shoreline stability, and water quality.
- Success was demonstrated in small-scale (meters) to large-scale (kilometers) projects, showing that Eastern Oysters can colonize even heavily modified environments when designs promote larval settlement.
- Joint design by engineers, ecologists, and planners coupled with performance monitoring are necessary to ensure both ecological success and structural reliability.
- Permitting is a current constraint. Streamlining this could be done by developing Maryland-specific guidelines that define performance metrics and creating a policy/regulatory framework that defines different types of oyster additions (like veneer on existing breakwater or expanding the toe of the breakwater).
- There is a vibrant community eager to advance projects that link ecological uplift with shoreline restoration. Maryland is well-positioned to lead in this emerging field, given its scientific expertise, restoration infrastructure, and policy support.

In a field trial of retrofit techniques, we found that:

- All retrofits tested—supplemental, integrated, and piling wraps—attracted oyster larvae and supported spat growth, demonstrating that a wide range of materials can enhance habitat value along armored shorelines. The retrofits were deployable by one or two people and lasted for at least three months in a high-energy environment.
- Among the supplemental materials designed to sit on the bottom next to the riprap, spat counts were highest on the Tables, followed by Shoreline Habitat Units (SHU), Oyster Castles and finally Reef Arches with the lowest spat numbers. Among the integrated materials that were placed directly on the riprap, Tufts supported the highest spat abundances, followed by Tridents, HPL riprap stone, and Havre de Grace stone. Inserts had the lowest spat numbers in the group.
- Durability varied across designs: the Table units and Tufts degraded the fastest, whereas several other materials —including SHU units, Oyster Castles, HPL riprap stone, Havre de Grace stone, and Tridents—maintained high structural integrity during the three-month evaluation period.
- Across all approaches, Oyster Castles, HPL riprap stones, Tridents, SHU units, and Havre de Grace stones had the highest total performance scores, suggesting that both integrated and supplemental approaches provide viable, high performing options for oyster habitat that are durable and straightforward to deploy.

Chapter 5. The effect of spat size upon deployment on oyster abundance.

We conducted a large-scale experiment at the Horn Point Oyster Hatchery and NOAA Cooperative Oxford Laboratory and found that:

- Shortly after planting, longer holding times resulted in higher spat survival. Two days after planting, the abundance of spat produced with the 11-day holding time was 23% higher than those with 5- or 17-day holding times. One month after planting, the abundance of spat produced with the 17-day holding time was 26% higher than those with 5- or 11-day holding times. Eight months after planting, there were no longer differences in spat survival based on holding time.
- Over a whole hatchery production year, the 5-day holding time was projected to result in twice the amount of surviving spat than the 11- or 17-day holding time because at least twice the number of batches of spat-on-shell could be produced with the 5-day holding time.
- The 5-day holding time appears to be the optimal holding time because more spat could be produced in a given year. The marginal gains in spat survival at longer holding times did not outweigh the volume of spat that could be produced with the shorter holding time.

Concluding Thoughts

It is clear that the footprint of the 1950s oyster population remains to be filled, and that substrate is needed for any major expansion of the fishery, aquaculture, and restoration sectors that together will support jobs, local economies, and Chesapeake Bay health. In the face of worldwide declines in multiple species of oysters, Maryland's leadership stands out because of its large-scale efforts at oyster enhancement – from large-scale fishery repetition efforts to the large-scale oyster restoration program to the strong support of a growing aquaculture industry. Now that oyster populations are increasing, alternative substrates are needed to form the base of a coordinated effort to continue oyster population and industry expansion. The evaluations in this report show that alternative substrates can be used successfully to enhance oyster production and populations.

Although spat were able to settle and grow on all substrates tested, results of the spat settlement tests should be combined with cost analyses when choosing alternative substrates (see Figure 1C.1). Notably, dredged Maryland Eastern Oyster shell has low substrate costs per acre, the lowest transportation costs, and emits the least amount of air pollution during transport. In addition, dredged Eastern Oyster shell performed well in the spat settlement and survival tests, has a history of successful use in multiple states, and fits the size and shape needed to fill cages in oyster hatcheries.

Pacific Oyster shell that had weathered on land for >5 years also is notable. It was the best overall performer in spat settlement and survival tests, middling in substrate per acre costs, and highest in transportation distance (2,900 miles). Because of the long transport distance, air pollution emission from its transport was at least nine times higher than the other substrates.

In contrast, river rock and granite had decent success in terms of spat settlement and survival but had the highest per acre substrate costs, highest transportation costs per 100 miles, and highest emissions of air pollutants associated with transport per 100 miles. Havre de Grace stone had similar success with spat settlement and survival, but, unlike river rock and granite, it had relatively low transportation costs and low air pollution emissions because it is transported by barge.

In general, stones (such as limestone and river rock) have widespread use in harvest areas and sanctuaries in other states, especially those without a supply of shell. Larger stones (>2") tend to be used in sanctuaries and smaller stones (1-2”) in harvest areas to reduce interference with fishing gear. We found that the use of Havre de Grace stones in oyster restoration areas does appear to support reef structure, oyster abundance, and biodiversity, suggesting that stones are appropriate for a wide range of applications and provide multiple benefits.

Clean crushed concrete performed well in our spat settlement tests, both in the laboratory and in the waters of Chesapeake Bay, and is used regularly in other states as an alternative substrate for oysters. Cost per acre and transportation costs per 100 miles were on the high end compared to other substrates, but close proximity to planting vessels can make it a cost effective option. We did find that the metal aluminum leached from crushed concrete into the water during our six week experiment, but its levels in the water of our study would not negatively impact marine life.

Hard coastal structures (breakwaters, riprap, concrete structures) can be retrofitted for Eastern Oyster growth and survival, and once retrofitted, produce benefits for biodiversity, shoreline stability, and water quality. Our field trials showed that there are multiple viable ways to retrofit coastal structures for oysters, the success of which depends on the site characteristics, especially the amount of wave energy. Turning hardened shorelines into oyster habitat will benefit the Chesapeake Bay ecosystem, water quality, and shoreline stability.

This research program also provides important insights to increase spat production of oyster hatcheries. For the Horn Point Oyster Hatchery, the 5-day holding time of oyster spat on the setting pier was predicted to result in the highest annual production of oysters – twice that of longer holding times because more batches of oysters could be produced.

Looking forward, it is important to consider the influence of the increasing carbon dioxide in the atmosphere that is predicted to cause acidification (lowering of pH) in Chesapeake Bay (Li et al., 2023). Increased acidification causes oyster shells to dissolve more rapidly. Additionally, not all types of shell dissolve at the same rate (Waldbusser et al. 2011). Dredged Eastern Oyster shell is more resistant to dissolving than weathered shell, and weathered shell is more resistant than fresh shell. Use of dredged/weathered shell or stone/concrete substrates may help extend the benefits of replenishment and restoration efforts further into the future.

This report was written for general audiences and our next step is to prepare scientific publications based on the results of these evaluations. These publications will include additional analyses, detailed technical information, and additional references that are available upon request until published in peer-reviewed scientific journals. The peer-review process is a unique feature of science that ensures high confidence in results and their interpretation, and is an important part of confirming and sharing the new knowledge that was discovered during this research program. Once published, the peer-reviewed publications also will be available upon request.

Moving from these evaluations to in-water implementations, we recommend monitoring the performance of alternative substrates for spat set, oyster abundance and growth, cost, durability, ease of use, and effectiveness for a given application (e.g., lack of interference with harvest gear, or reef height above bottom in sanctuaries). Systematic and coordinated assessments can help identify the most effective – and cost effective – use of alternative substrates that will best support the growth of commercial fishing, aquaculture, and restoration of oyster production and populations in Maryland’s Chesapeake Bay.

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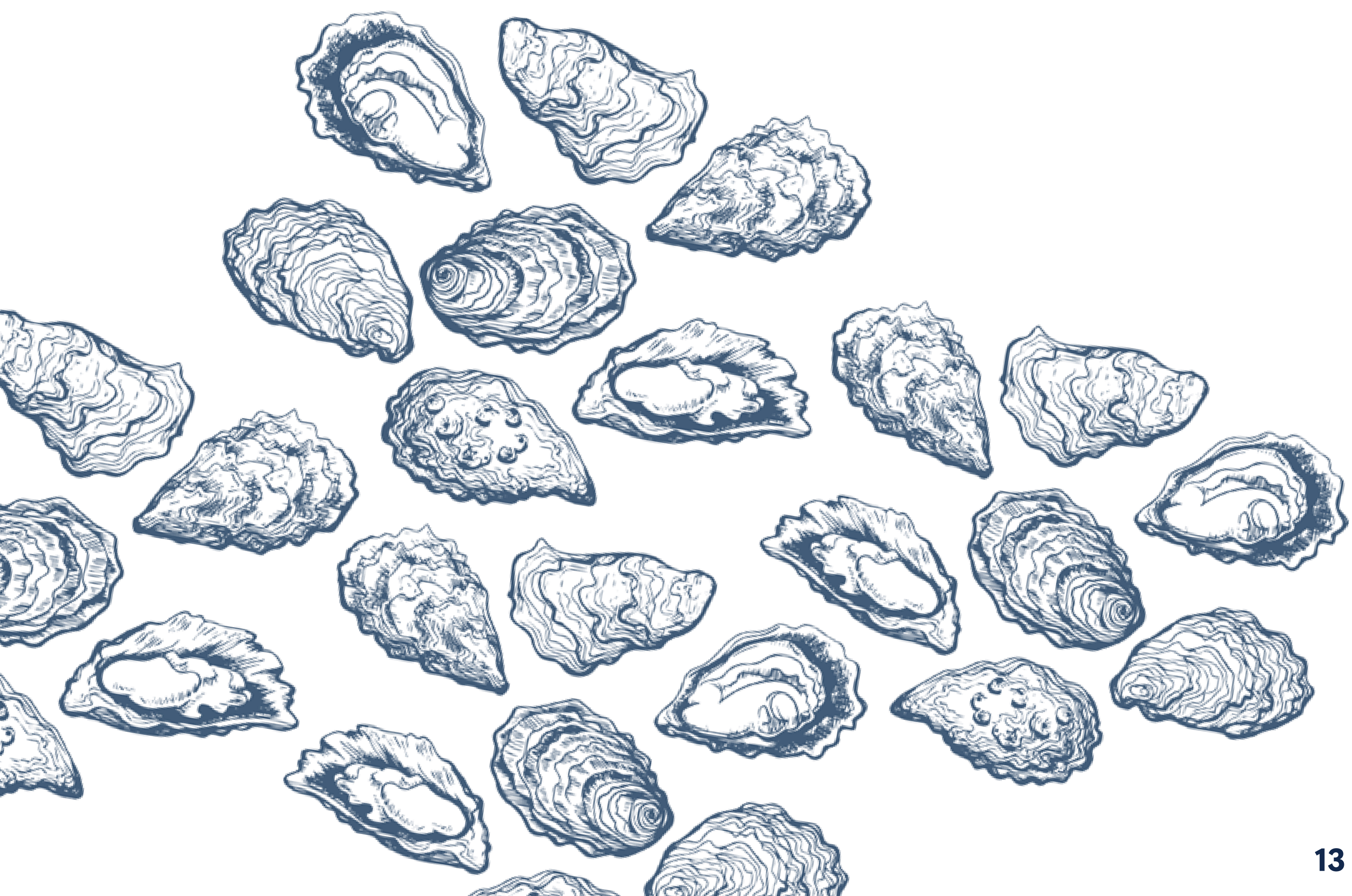
Chapter 1: Evaluation of Alternative Substrates



Chapter 1: Evaluation of Alternative Substrates

Introduction

The use of Eastern Oyster shell is essential for sustaining commercial fishing and aquaculture industries in Maryland. The material enhances oyster productivity by providing hard habitat that oyster larvae require to settle and grow, keeping the oyster grounds from being buried by sediment, and providing shells that oyster hatcheries need to produce spat-on-shell. Now that demand for Eastern Oyster shell has outpaced supply in Maryland, alternative substrates such as other types of shell and stone are being explored to supplement fishery, aquaculture, and restoration needs.

In this study, three complementary efforts – a laboratory study, a field study, and a cost and emissions analysis – were made to evaluate the types of substrate, including fresh shell, fossilized shell, combinations of shell, and alternative substrates that were most appropriate for use in oyster harvest areas like commercial fishing grounds and bottom leases. This chapter contains three sections, one for the laboratory study (Section A), one for the field study (Section B), and one for the costs and emissions analysis of fresh Eastern Oyster shell and alternative substrates (Section C).

The laboratory analysis evaluated the performance of ten substrates for larval settlement and spat survival as well as metals leaching from the substrates. Fresh (reclaimed) Eastern Oyster (*Crassostrea virginica*) shell and nine alternative substrates were tested in the laboratory experiment in summer 2024: dredged (fossilized) Eastern Oyster shells, Pacific Oyster (*Crassostrea gigas*) shell, Atlantic Surf Clam shell, Whelk (aka Conch) shell, cleaned crushed concrete, limestone marl, granite (#57 chips), river rock, and Havre de Grace stone. Havre de Grace stone (#3 pieces) is a metagabbro and quartz diorite stone from a quarry in Havre de Grace, MD. It was formally known as amphibolite or granite in Maryland's restoration efforts.

A cost and emissions analysis evaluated these same ten substrates to determine the costs of the alternative substrates and the air pollution associated with their transportation.

Based on the results of the laboratory experiment, a field trial was conducted in summer 2025 to evaluate the performance of alternative substrates for receiving a natural spat set. Seven substrates were tested: fresh Eastern Oyster shell, dredged Eastern Oyster shell, Pacific Oyster shell, cleaned crushed concrete, granite (#57 chips), Havre de Grace stone, and a mixture of Atlantic Surf Clam, Whelk, and fresh Eastern Oyster shells.

A. Laboratory Evaluation

Authors

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Chapter 1: Evaluation of Alternative Substrates

Introduction

A six-week larval settlement laboratory experiment was conducted to provide initial screening information on ten substrates that have been used to enhance Eastern Oyster production in Maryland, Virginia, and other states along the Atlantic and Gulf coasts (see Chapter 3). We evaluated the performance of the substrates in terms of spat abundance and survival and investigated the environmental safety of these substrates by analyzing the concentrations of metals in water around the substrate for signs of leaching. Substrates selected for the study were chosen based on their permitted use in Maryland waters, on their successful use in other systems, and on discussions with state managers and commercial fishing and aquaculture representatives.

Highlights

- Oyster spat successfully settled and survived on all 10 substrates after six weeks in numbers that ranged from a mean of 0.13 spat/cm² (49 spat per container) for limestone to 0.41 spat/cm² (192 spat per container) for Pacific Oyster shell.
- Pacific Oyster shell, dredged Eastern Oyster shell, clean crushed concrete and Havre de Grace stone had the highest mean spat abundances after six weeks while limestone and granite had the lowest spat abundances.
- Substrates with the highest mean spat survival from week 3 to week 6 of the experiment were limestone (88%), Pacific Oyster shell (86%), fresh Eastern Oyster shell (84%), and dredged Eastern Oyster shell (80%). Those with lowest survival were Atlantic Surf Clam shell (54%), granite (51%), river rock (46%), and Havre de Grace stone (44%).
- Of the 10 substrates and 11 metals tested, aluminum was the only metal that was detected to be leaching from substrates into the water and this occurred only in the containers with clean crushed concrete and Whelk shell. Aluminum concentrations in the water of these containers remained lower than levels that could negatively impact marine life after six weeks.

Methods

Ten substrate types were evaluated in the laboratory experiment, including five shell-based materials—fresh and dredged Eastern Oyster shells, Pacific Oyster shells, Atlantic Surf Clam shells, and Whelk shells—and five non-shell materials: clean crushed concrete, limestone, granite, river rock, and Havre de Grace Stone (Figure 1A.1). Havre de Grace stone (#3 pieces) is a metagabbro and quartz diorite stone (formally known as amphibolite or granite in Maryland's restoration efforts).

The substrates were chosen based on their permitted use in Maryland waters, on reports by Maryland's Oyster Shell and Substrate Task Force and Aquaculture Coordinating Council's Alternate Materials Workgroup, and on discussions with staff of Maryland Department of Natural Resources and National Oceanic Atmospheric Administration, members of the Oyster Advisory Commission, Aquaculture Coordinating Council, Maryland's Oyster Shell and Substrate Task Force, Eastern Bay Oyster Coalition Workgroup, UMCES Oyster Team, and attendees of the Maryland Watermen's Association Commercial Fishing Expo, the Maryland Shellfish Aquaculture Conference, and the Symposium on Alternative Substrates for Oysters (Chapter 3).

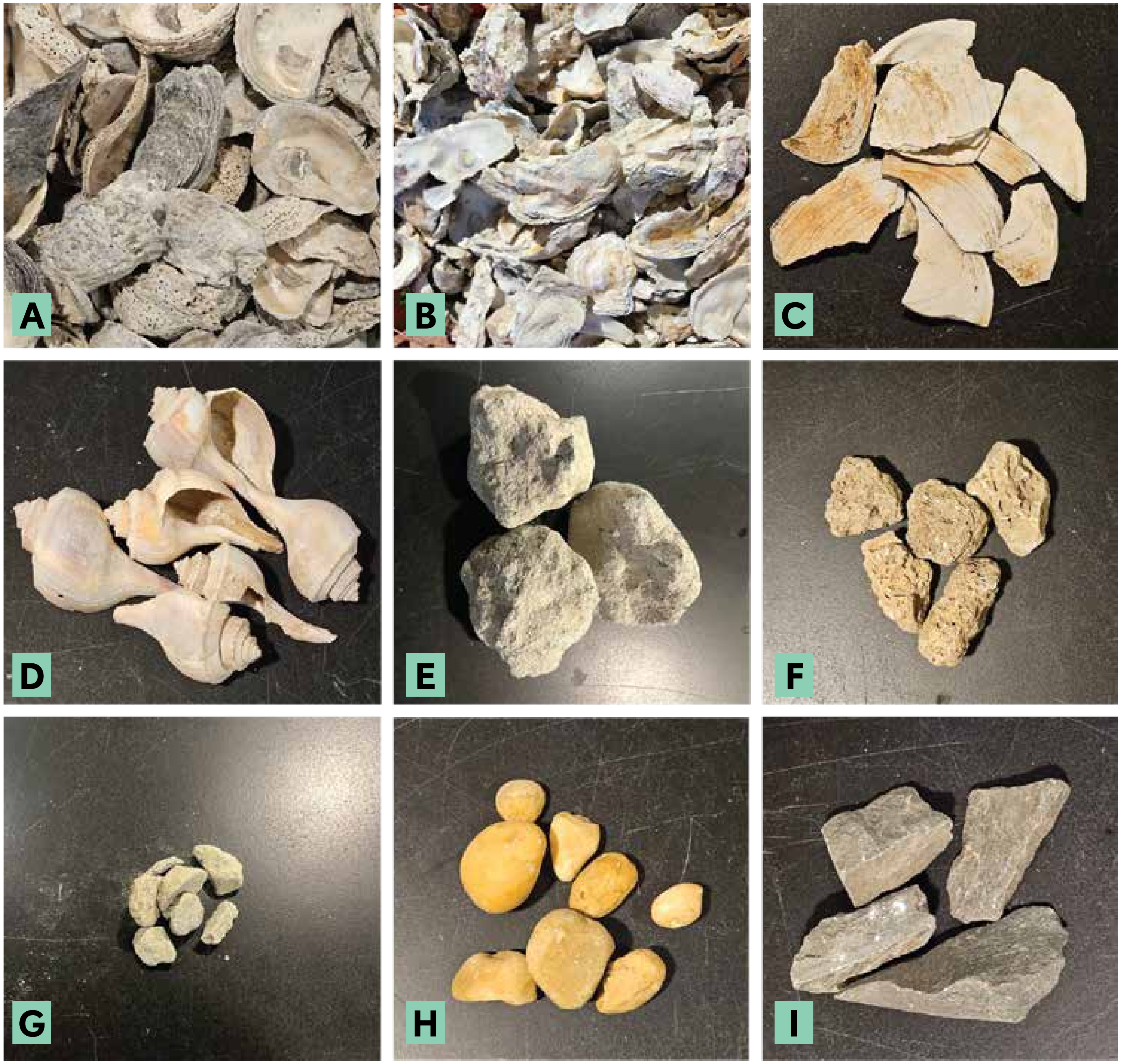

Figure 1A.1 *Alternative substrates used in the experiment: A) dredged Eastern Oyster shells; B) Pacific Oyster shells; C) Atlantic Surf Clam shells; D) Knobbed Whelk ("conch") shells; E) clean crushed concrete; F) limestone; G) granite (#57); H) river rocks; I) Havre de Grace stone (#3). Fresh Eastern Oyster shell also was evaluated. Photos by Monica Fabra.*

The experiment was conducted in June 2024 with a flow-through system that supplied ambient Choptank River water to 1-Liter containers, each containing a single type of substrate (Figures 1A.2 and 1A.3). We used fifty containers for the spat settlement and survival test (five containers per substrate for each of the ten substrates) and 30 containers for the water quality and chemical leaching test (three containers per substrate). Because the substrates varied widely in shape and density, the surface area of the substrates in each container was standardized (≈450 cm^2 per container) to ensure equal area for oyster larvae to settle upon. In addition, each piece of substrate was carefully wrapped with aluminum foil and then imageJ software was used to calculate the surface area of the foil after the experiment was completed to determine the actual surface area of the substrate that was in each container.

Figure 1A.2 *Experimental setup on a flow-through table that delivered Choptank River water to each of the 80 containers that were equipped with individual air lines. The same number of Eastern Oyster larvae were introduced to 50 of the containers on June 10, 2024. The remaining 30 containers were sampled periodically for water quality and metals leaching. Monica Fabra and Evan Merk are pictured setting up the system. Photo by Elizabeth North.*

To begin the experiment, we conditioned the substrates with flow-through river water for three days. After the conditioning period, all containers were emptied and refilled with filtered (1 µm) and aerated water from the Horn Point Oyster Hatchery (HPOH). Salinity was adjusted to 10 ppt in each container and Eastern Oyster larvae that were ready to settle were added to the containers. Oyster larvae were provided by the HPOH. The same number of larvae was added to each container (one larva per milliliter). The larvae were allowed to settle for two days with controlled aeration and algal feed, and then flow-through river water was restarted to provide food for the newly settled spat. Water quality was maintained in the containers due to the continuous flow of water from the river. Regular monitoring of temperature, salinity, pH, and dissolved oxygen occurred.

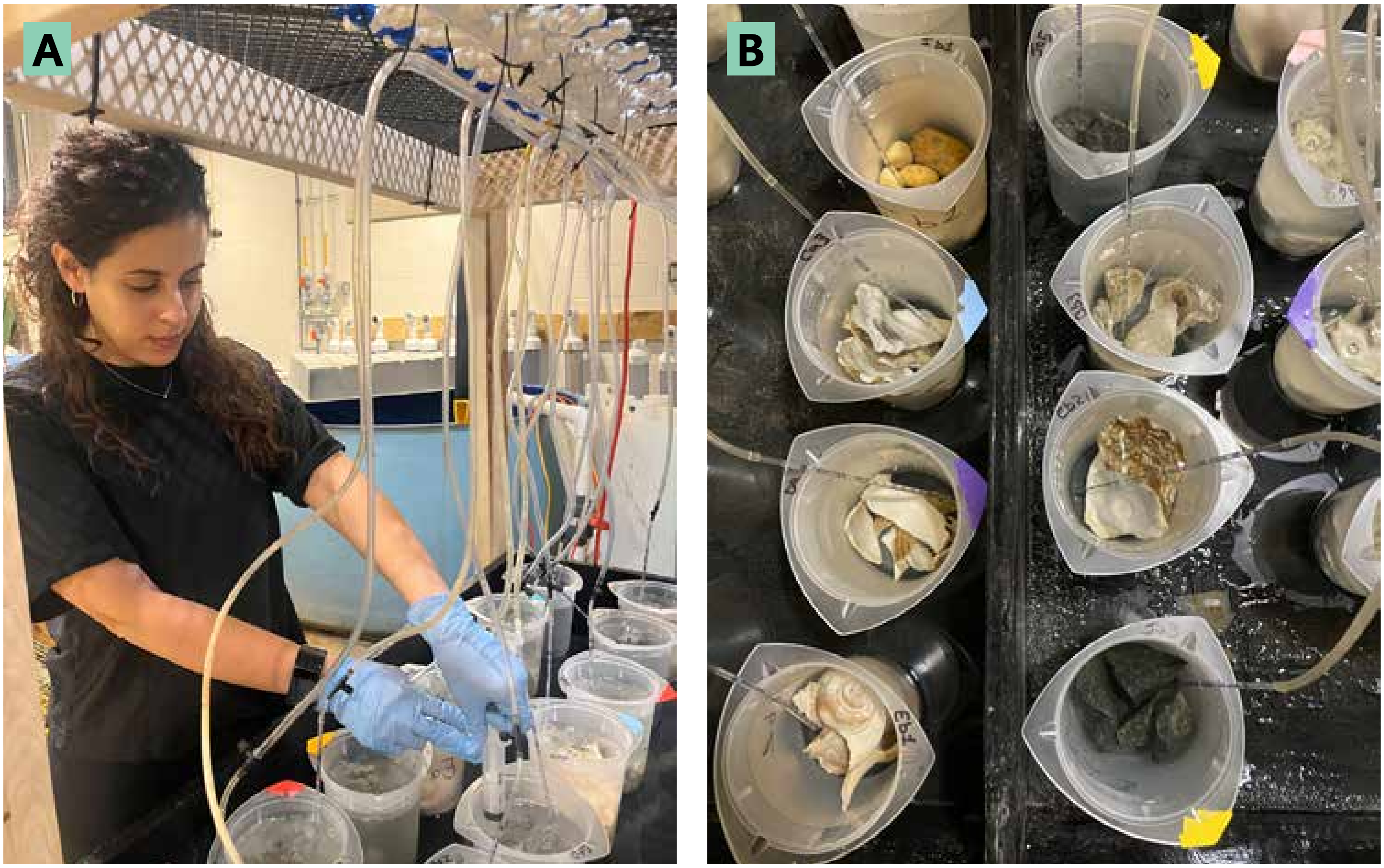

Figure 1A.3 *A) Monica Fabra taking water samples for metal leaching tests. B) Close up of containers with substrates at the beginning of the experiment. Photos by Elizabeth North.*

To determine the performance of the substrates for spat settlement and survival, HPOH technicians counted the number of spat on each piece of substrate at three and six weeks after settlement under a dissecting microscope. The number of spat was divided by the surface area of substrate in each container to calculate the abundance of spat per square centimeter (spat/cm^2). Percent survival from three to six weeks was calculated as 100 x (spat abundance at 6 weeks / spat abundance at 3 weeks). Statistical analyses (one-way ANOVA, pair-wise t-tests with Tukey adjustments for the number of comparisons, α = 0.05) were conducted to determine if there were statistically significant differences in spat abundance and survival between substrates.

To determine if metals leach from any of the substrates, water samples were collected from 30 containers just before larvae were added to the other 50 containers, and then on day 1, day 2, week 3, and week 6 after larvae were added. Samples for metals analysis were collected with 20 mL syringes (Figure 1A.3) and analyzed for 11 metals, including aluminum, arsenic, barium, beryllium, cadmium, chromium, copper, iron, lead, selenium, and zinc. Metal concentrations were measured with Inductively Coupled Plasma Optical Emission Spectroscopy.

Results

Oyster spat successfully settled and survived on all substrates, in numbers that ranged from a mean of 0.13 spat/cm² (49 spat per container) for limestone to 0.41 spat/cm² (192 spat per container) for Pacific Oyster shell after six weeks. Spat abundance, calculated as the number of spat per total surface area of substrate in each container, was statistically different between substrates (Figure 1A.4). While Pacific Oyster shell, dredged Eastern Oyster shell, clean crushed concrete and Havre de Grace stone had the highest mean spat abundances, they were not statistically significantly different from each other or Atlantic Surf Clam shell, Whelk shell, or river rock. Fresh Eastern Oyster shell, granite, and limestone had spat abundances that were statistically lower than dredged Eastern Oyster shell and Pacific Oyster shell.

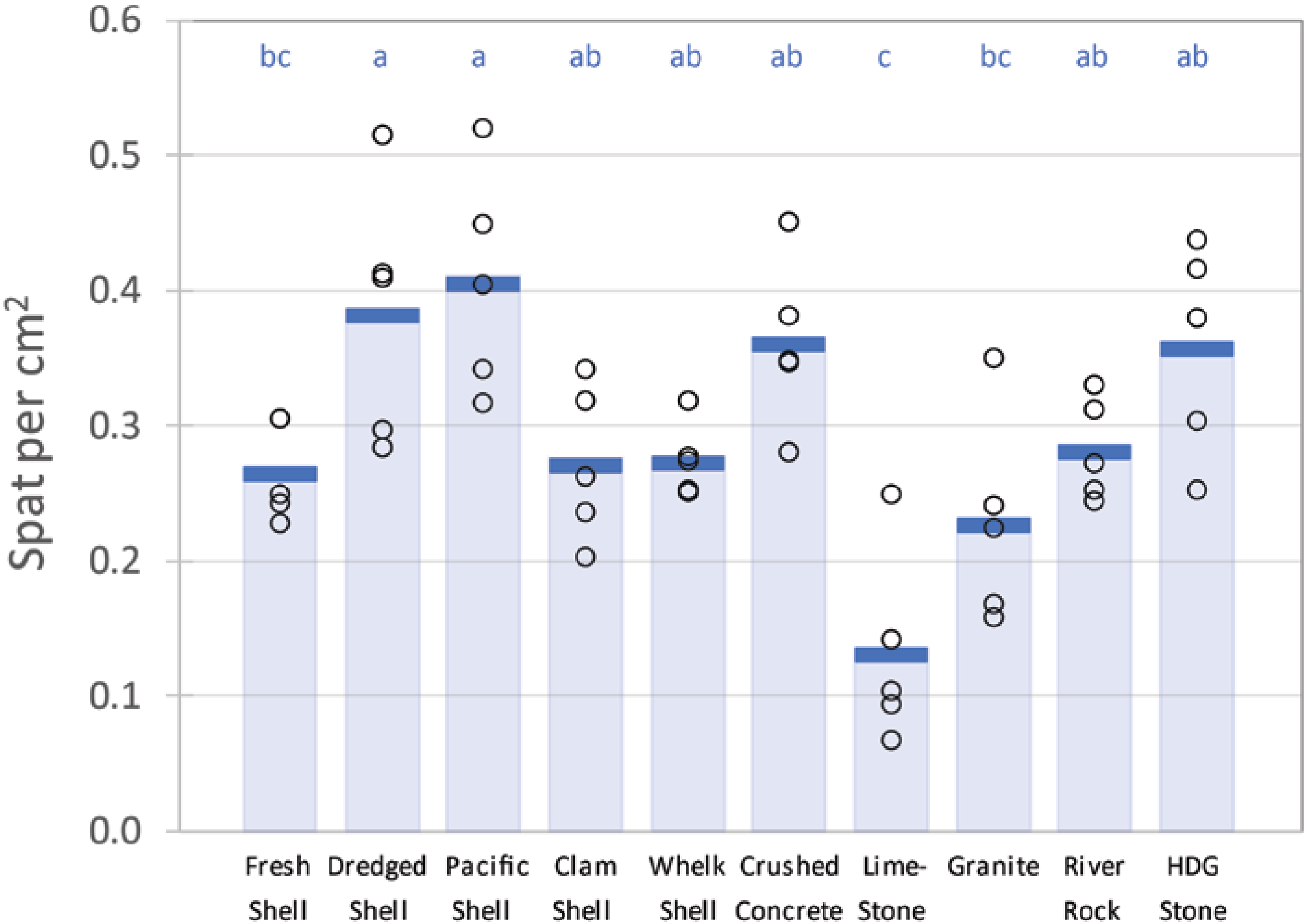

Figure 1A.4 *Spat abundance per surface area of substrate (spat per cm²) at week 6 of the experiment. Open circles are individual data points and the blue top of each bar is the mean. Means that do not share a letter at the top of the plot are significantly different (t-test with Tukey adjustment, $p < 0.05$).*

Percent survival of spat from week 3 to week 6 was statistically different between substrates (Fig. 1A.5). Substrates with the highest mean survival were limestone (88%), Pacific Oyster shell (86%), fresh Eastern Oyster shell (84%), and dredged Eastern Oyster shell (80%). Those with lowest survival were

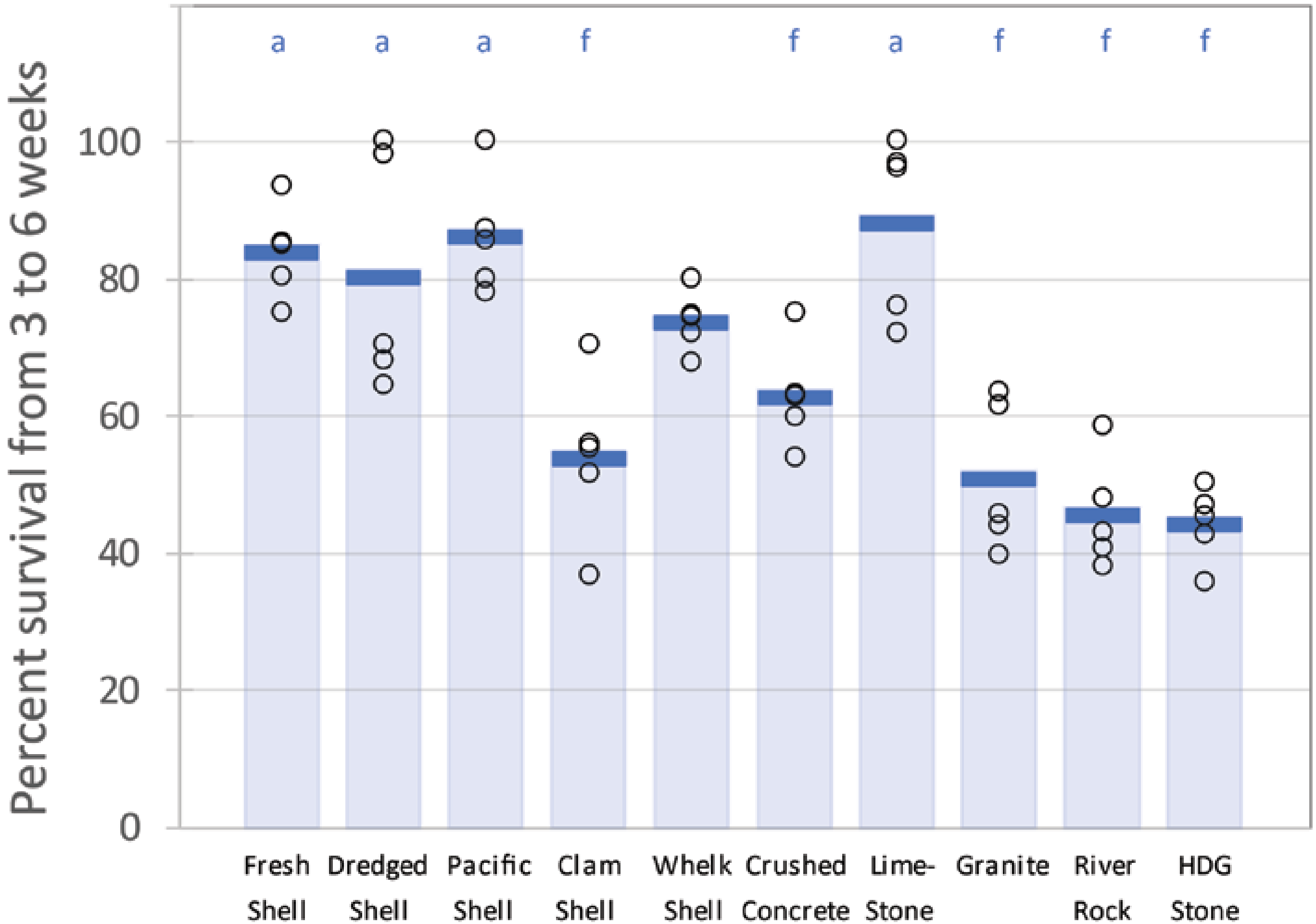

Figure 1A.5 *Percent survival of spat from week 3 to week 6 of the experiment. Open circles are individual data points and the top of each bar is the mean. Means that do not share a letter at the top of the plot are significantly different (t-test with Tukey adjustment, p > 0.05); only the substrates with the highest (letter a) and lowest (letter f) means are labeled.*

Atlantic Surf Clam shell (54%), granite (51%), river rock (46%), and Havre de Grace stone (44%). Although limestone had the lowest spat abundance at week 6, spat survival on limestone was the highest.

Water samples were analyzed to determine if metals could leach from the substrates into the water at levels that could harm spat or other marine life. Of the 1,650 metal concentrations that were measured over the experiment (10 substrates x 3 samples per substrate x 5 time points x 11 metals), the only significant increases in concentration over time, indicating potential metal leaching, occurred for aluminum concentrations in containers with Whelk shell (0.0428 to 0.0963 ppm) and clean crushed concrete (0.0708 to 0.1977 ppm). The rate of increase in aluminum in the water of the containers with clean crushed concrete was three times higher than that in the containers with Whelk shells. Although the increases in aluminum concentrations were significant in the water around both substrates, neither substrate resulted in aluminum concentrations above the maximum threshold for acute (1.2-2.4 ppm) and chronic (0.73-1.1 ppm) exposure for aquatic life over the course of the experiment.

Conclusions and Next Steps

This study demonstrated that all tested substrates were capable of supporting Eastern Oyster spat settlement and survival, but performance differed between substrates. Overall, Pacific Oyster shell and dredged Eastern Oyster shell had high performance in terms of both spat abundance and survival after six weeks. Limestone had the lowest spat abundance but the highest spat survival. Other substrates – Atlantic Surf Clam shell, Whelk shell, clean crushed concrete, granite, river rock, and Havre de Grace stone – had moderate performance. There was no evidence of metal leaching at harmful levels to marine life during this study. Longer term tests coupled with measurements of additional metals (like mercury) would provide valuable information.

While this laboratory evaluation allowed control over water quality and larval exposure, it was equally important to evaluate alternative substrates under natural field conditions to assess their performance with settlement and survival of wild oyster spat. Results of the field experiment are summarized in Section 1B.

Acknowledgments

We thank Jeff Alexander of the Horn Point Oyster Hatchery for his help constructing the aeration and water flow-though system for this experiment and Evan Merk for help running the experiment. We thank Jeff Alexander, Bob Carey, Mike Nossick, Shane Simms, Stacey Spicer, Evelyn Peyton, Maya Skirka and Katie Riggleman of the Horn Point Laboratory Oyster Hatchery for their expert help with counting oyster spat.

B. Field Evaluation

Authors

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Introduction

To evaluate the use of different substrates, including fresh shell, fossilized shell, combinations of shell, and alternative substrates that are most appropriate for use in oyster harvest areas, we conducted a field experiment that examined the ability of alternative substrates to catch juvenile wild oysters (spat) and support their growth under natural conditions. Oysters in Maryland reproduce in the summer and their offspring (larvae) are carried by the water for about two weeks, after which larvae must find and attach themselves to hard substrate in order to become spat.

To determine if wild oyster larvae would settle on (attach to) alternative substrates, we deployed 98 trays containing seven types of substrates in three Maryland rivers prior to the oyster spawning season and then collected them in the fall. Seven substrates were tested: fresh (reclaimed) Eastern Oyster shell, dredged (fossilized) Eastern Oyster shell, Pacific Oyster shell, cleaned crushed concrete, granite (#57 chips), Havre de Grace stone, and a mixture of Atlantic Surf Clam, Whelk, and fresh Eastern Oyster shells. After the trays were collected, oyster spat were counted on each substrate to determine spat settlement and survival. In addition, the amount of mud in each tray was assessed.

Highlights

- Wild spat were found on all substrates that were recovered from all three rivers (Nanticoke, St. Mary's and Tred Avon Rivers), with abundance levels differing between the river systems. Spat sets were high in the St. Mary's and Tred Avon Rivers.
- Within the St. Mary's and Tred Avon Rivers, there was no statistical difference between the abundance of spat on fresh Eastern Oyster shell and the alternative substrates. In other words, the alternative substrates and fresh Eastern Oyster shell performed equally well when spat sets were high.
- The amount of clean, exposed substrate with no mud had a significant, positive impact on how many live oyster spat were found – more spat were found in trays with less mud.
- Stone substrates weighed about twice as much as the shell substrates given the same surface area. This has implications for transportation and handing.
- The unusually high abundances of spat on all substrates in the St. Mary's and Tred Avon Rivers may have resulted, in part, because the clean substrates were deployed just before oyster spawning season. Planting clean Eastern Oyster shell just before the oyster spawning season is a technique used to increase spat set by commercial fishermen and aquaculturalists, and it appeared to be effective for alternative substrates as well.

Methods

Alternative substrates were deployed before the oyster spawning season in May 2025 in three Maryland river systems. Samples were sited on an oyster aquaculture lease held by Eric Wisner in the Nanticoke River, on an oyster aquaculture lease held by Victoria and Robert T. Brown in the St. Mary's River, and on the Cooperative Oxford Laboratory's oyster sanctuary in the Tred Avon River (see Figure 1B.1). The shell materials used in field trials were fresh (reclaimed) Eastern Oyster (*Crassostrea virginica*) shell, dredged (fossilized) Eastern Oyster shell, Pacific Oyster (*Crassostrea gigas*) shell, and a mixture of the shells of Knobbed Whelk or "conch" (*Busycon carica*), Atlantic Surf Clam (*Spisula solidissima*), and fresh Eastern Oyster. Stone materials used were clean, crushed concrete (#3 size pieces), granite (#57 chips), and "Havre de Grace stone" (#3 pieces) that is metagabbro and quartz diorite (formally known as amphibolite or granite in Maryland's restoration efforts). All materials were sourced locally (Table 1B.1) and have been used locally on oyster harvest areas, aquaculture leases, or oyster restoration projects.

Figure 1B.1 *Map of the study sites where trays of alternative substrates were deployed from May to September, 2025.*

Table 1B.1 *Sources, weights, volumes, and number of pieces of substrates used in field testing. Because all samples occupied similar surface areas in the deployment trays, the weights, volumes, and counts illustrate differences between substrates. The numbers below the mean are +/- one standard deviation. Standard deviation is an indicator of the amount of variability in the measurements.*

Materials	Source	Mean Weight per Tray (lbs)	Mean Volume per Tray (gal)	Mean Number of Pieces per Tray
Fresh Eastern Oyster Shell	Oyster Recovery Partnership Recycling Center	7.6 +/- 0.04	1.6 +/- 0.06	58 +/- 5
Dredged Eastern Oyster Shell	Norfolk, VA	6.9 +/- 0.05	1.6 +/- 0.05	99 +/- 10
Fresh Pacific Oyster Shell	Wittman Wharf Seafood - sourced from Pacific Seafood, Warrenton, Washington	6.4 +/- 0.10	1.9 +/- 0.07	75 +/- 19
Mixed Shell	Conch shell – SeaKing Processors, Atlantic VA Clam shell – SeaWatch Processors, Selbyville DE Oyster shell – Oyster Recovery Partnership Recycling Center	6.5 +/- 0.06	1.5 +/- 0.06	237 +/- 12
Crushed Concrete	Dagsboro Materials, Dagsboro, DE	16.1 +/- 0.04	1.9 +/- 0.06	60 +/- 15
Havre de Grace Stone	Vulcan Materials Company, Havre de Grace, MD Quarry	14.2 +/- 0.07	1.2 +/- 0.00	130 +/- 16
Granite	Dagsboro Materials, Dagsboro, DE	13.4 +/- 0.06	1.1 +/- 0.00	843 +/- 79

Figure 1B.2 *Example of alternative substrates and lines of trays before deployment. A) Trays with alternative substrates (bottom to top: clean crushed concrete, Havre de Grace stone, granite, and fresh Eastern oyster shell). B) Fully assembled line of trays. Lines had seven trays with each type of material in randomized order. Four or five lines of trays were deployed at each site. Photos by Elizabeth North.*

Before deployment, the bottoms of 15 plastic trays (18.5 X 12.5 in) were covered with each substrate (Figure 1B.2, Panel A) for a total of 105 trays and then the substrate in each tray was counted, weighed, and the volume was measured. Fifteen lines of seven trays were created and anchored on the ends with mushroom anchors (Figure 1B.2, Panel B). Because trays with shells weighed about half that of the trays with stones, bricks were added to the sides of the trays with shells so that the weight of all trays were similar.

University of Maryland Center for Environmental Science (UMCES) scientific divers deployed trays of substrates in May 2025 before the oyster spawning season (Figure 1B.3). Four (Nanticoke) or five (St. Mary's, Tred Avon) lines of seven trays were deployed at each site, spaced about 6 feet apart. Divers stretched out the lines of trays and added the substrates to the trays after the trays were on the bottom. The lines of trays were left in the rivers for at least three months to allow wild oyster larvae to settle on the substrates and grow.

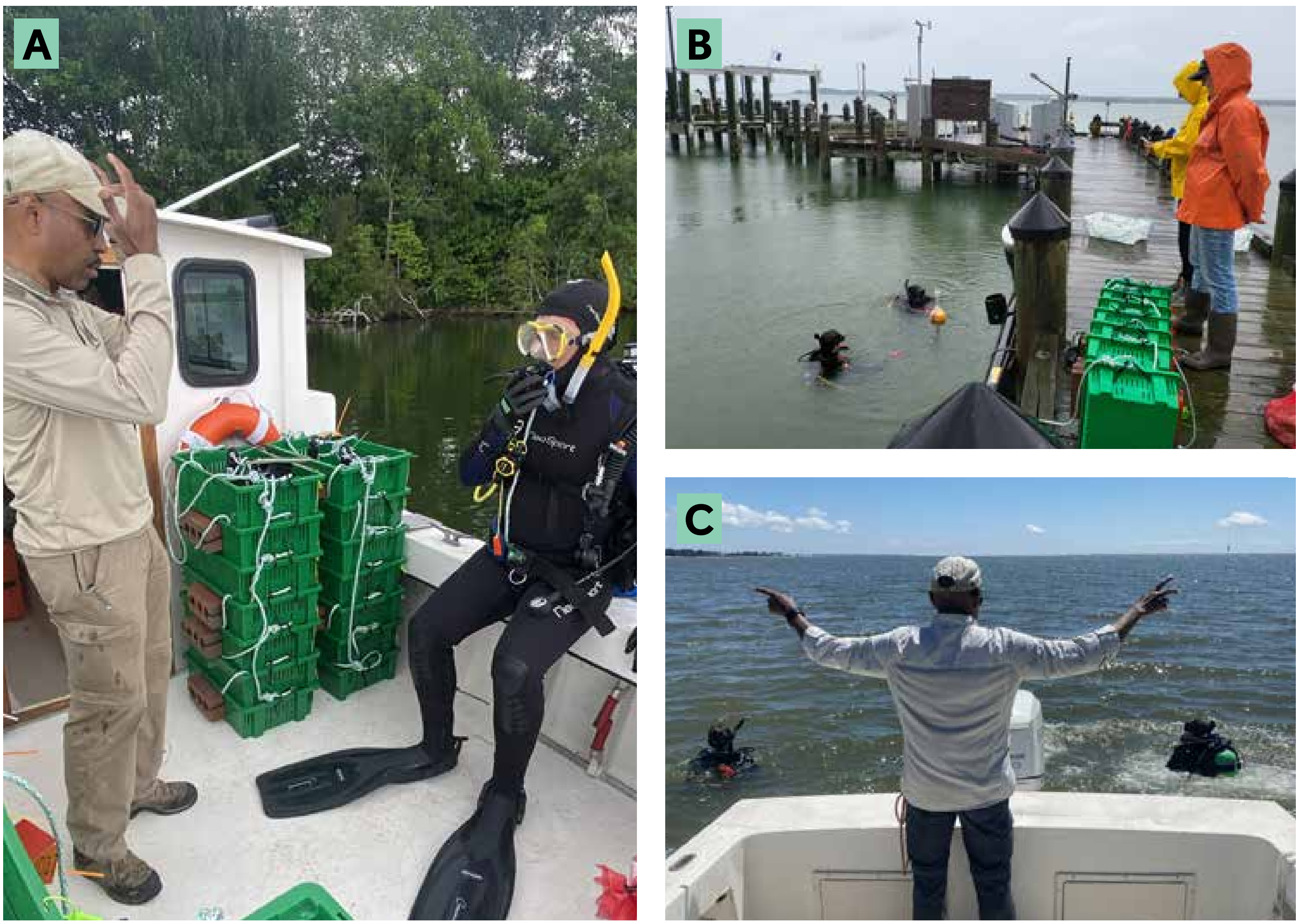

Figure 1B.3 *Images of substrate deployments in May 2025. Trays of substrates were deployed by divers before oyster spawning season in A) the St. Mary's River, B) the Cooperative Oxford Laboratory oyster sanctuary, and C) the Nanticoke River. Divers were Jake Shaner, Matt Gray, and Alan Williams. Topside science team included A.K. Williams and Jason Spires. Photos by Elizabeth North.*

In September 2025, UMCES divers recovered lines of trays from each site. Each tray was hoisted out of the water, photographed, rinsed, and then photographed again (Figure 1B.4). All 35 trays were recovered intact from the Tred Avon River; 27 of 35 were recovered intact from the St. Mary's River, and 14 of 28 trays were recovered intact from the Nanticoke River. All trays were returned to the UMCES Horn Point Laboratory Oyster Hatchery where spat were counted on a subsample of 20% of the substrate in each tray. The subsample included pieces of substrate from the top to the bottom of the tray to ensure that there was no bias in which pieces were selected. The subsample counts were divided by 20% of surface area of the tray to calculate spat abundance per bottom area (spat per m^2).

Trays had different amounts of mud in them when retrieved (Figure 1B.5). We assigned a "burial score" to each tray to characterize the amount of mud that was covering the substrates when the trays were retrieved. The scores ranged from 1 to 5 with lower numbers indicating a higher percentage of the tray was covered with mud (1 = 80-100% covered, 2 = 60-80%, 3 = 40-60%, 4 = 20-40%, 5 = 0-20%). Trays with burial scores of 1 or 2, indicating that at least 60% of the tray was covered with mud, were

Figure 1B.4 *Images of substrate retrieval in September 2025. A) Substrates were recovered by divers and hoisted in a lifting basket to the surface where trays were photographed and B) mud was rinsed from them. C) Divers entering the water. Divers were Jake Shaner and Matt Gray. Topside scientist is Emi McGeady. Photos were taken at the Cooperative Oxford Laboratory pier (A and B) and on the Nanticoke River (C) by Elizabeth North.*

excluded from the statistical analyses comparing substrate types.

We conducted analysis of variance (ANOVA) statistical analyses to determine if spat abundances differed between substrates in the trays from the St. Mary's and Tred Avon River. The burial score was included in the models to account for the effect of mud on spat settlement and survival. Although spat were found on the substrates from the Nanticoke River, 8 of 14 trays were mostly (>60%) covered with mud (e.g., Figure 1B.5C), so there was not enough good data to perform a statistical analysis with data from this river system. We also conducted an analysis of variance statistical analysis to determine if burial scores could have influenced the abundance of spat. River system was included in the model to account for potential differences in larval supply between systems.

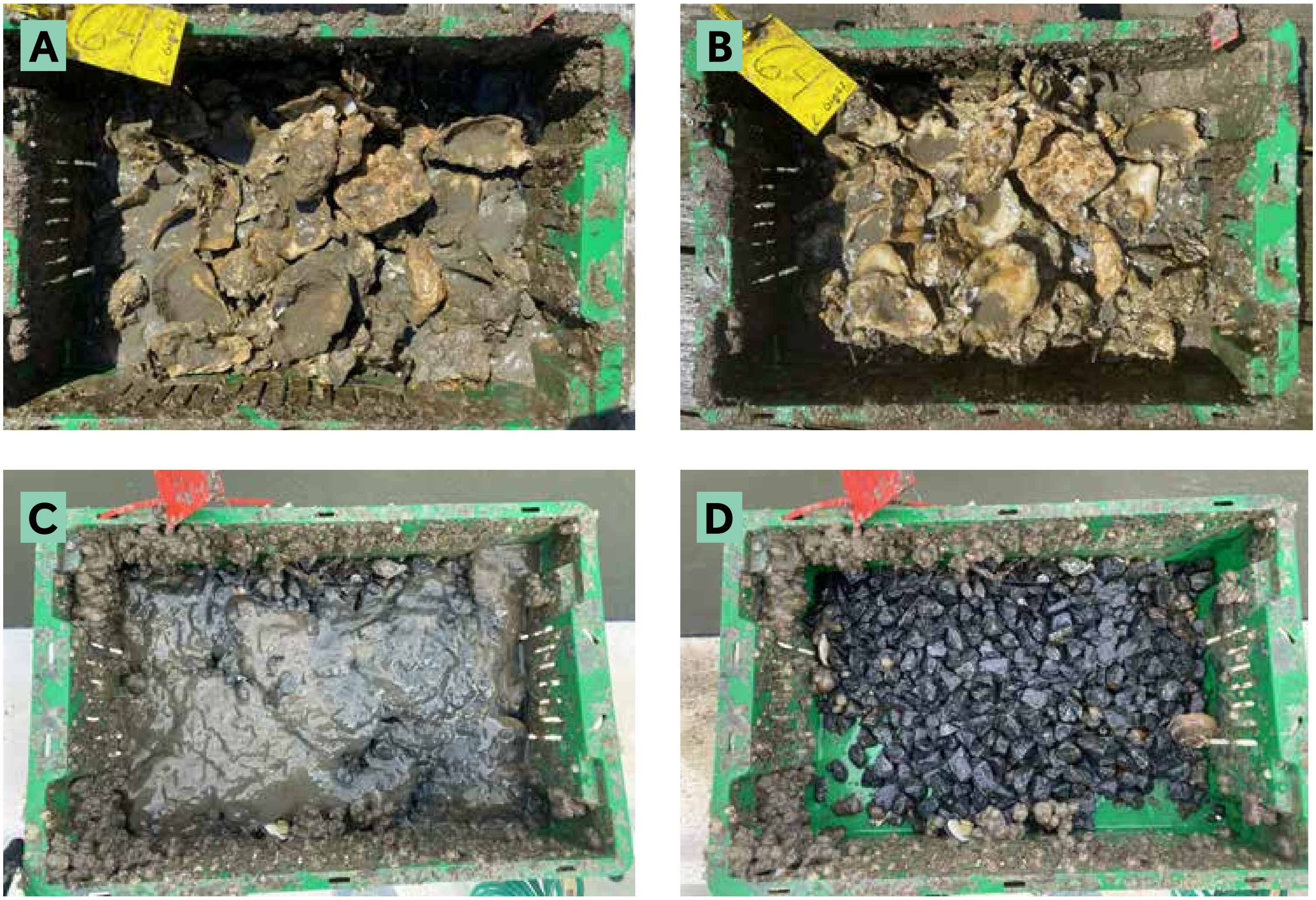

Figure 1B.5 *Photos of substrates in trays after a summer of deployment.*
Top panels: Pacific Oyster shell retrieved from the Tred Avon River A) before rinsing and B) after rinsing.
Bottom panels: Granite retrieved from the Nanticoke River C) before rinsing and D) after rinsing.
Substantially more sediment accumulated in the trays in the Nanticoke River.
Photos by Elizabeth North.

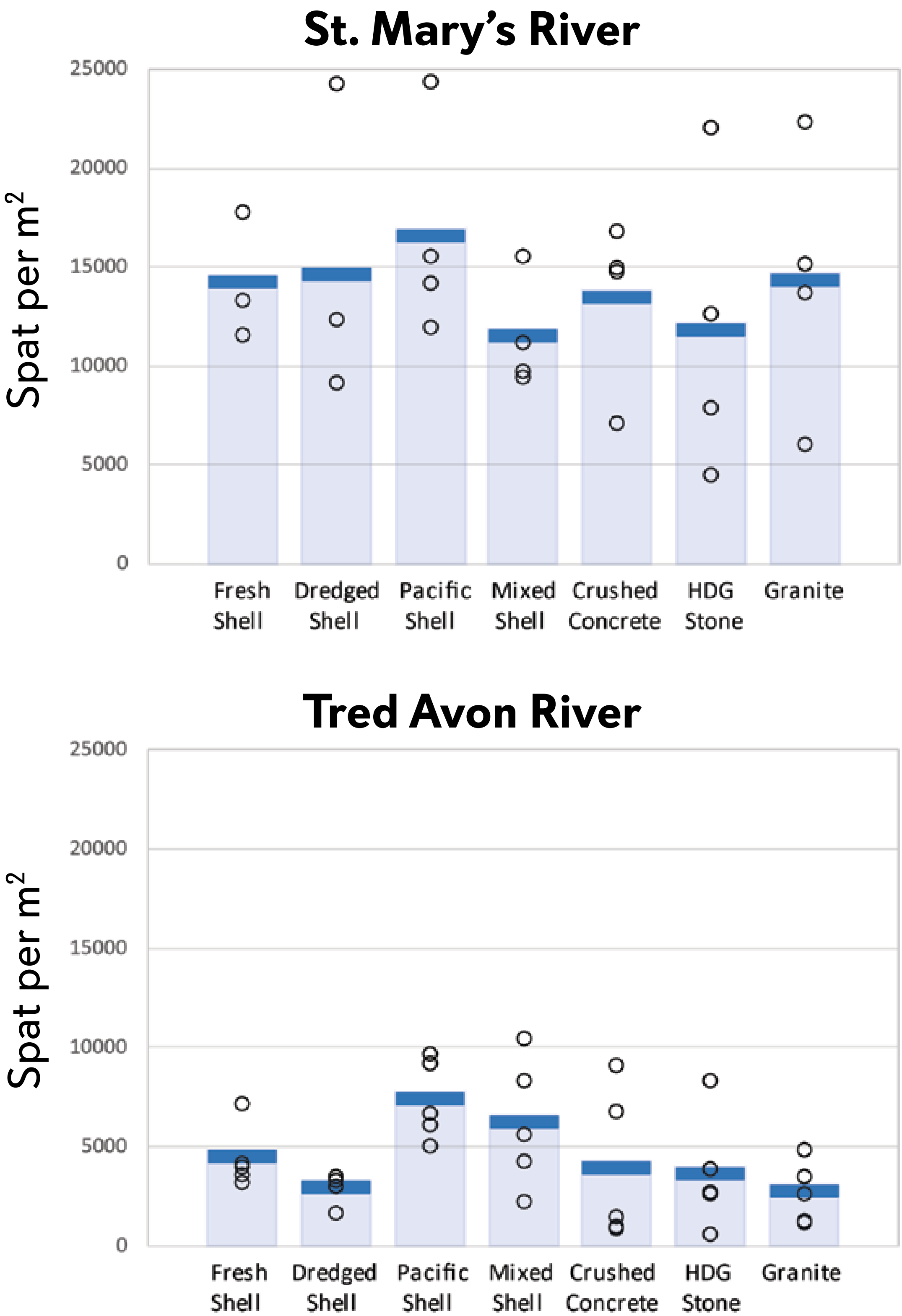

Figure 1B.6 *Mean abundance of spat (spat per m*^{2}*) on the different substrates that were retrieved in September 2025 from A) the St. Mary's River and B) the Tred Avon River. Open circles are individual data points and the top of each bar is the mean. Mean spat abundances were not statistically different between substrates for both river systems.*

Figure 1B.7 *Tray with fresh Eastern Oyster shell (left) from the St. Mary's River that was retrieved in September 2025 with a close-up view of the large numbers of wild spat (juvenile oysters) that settled on the shells. Note the spat attached to the sides of the tray. Photo by Elizabeth North.*

Results

Wild spat were found on all substrates that were recovered from all three river systems, with average abundance of spat differing between rivers. Spat abundances were extraordinary in the St. Mary's River, with average spat sets ranging from a low of 11,428 spat per m^2 on the mixed shell to a high of 16,480 spat per m^2 on the Pacific Oyster shell (Figure 1B.6, Panel A). In addition to the substrates, oysters also attached to the sampling equipment, such as anchors and trays (Figure 1B.7), suggesting that there was a large local supply of oyster larvae in the St. Mary's River. Statistical analysis indicated that there was no significant difference in the abundance of spat between the different substrate types – all substrates performed equally well in the St. Mary's River. The average amount of mud in the trays was about 20% of the trays' surface area.

Spat abundances on substrates in the Tred Avon River were about half of those in the St. Mary's River. In the Tred Avon, counts ranged from a low of 2,681 spat per m^2 on granite to a high of 7,313 spat per m^2 on the Pacific Oyster shell (Figure 1B.6, Panel B). Although lower than in the St. Mary's River, these numbers also represent a strong spat set. In addition, the range in sizes of spat attached to the substrate suggest that multiple spatfall events occurred (Figure 1B.8). Statistical analyses indicate that, like the St. Mary's River site, there was no significant difference between spat abundance on the different substrate types, with all substrates performing reasonably well. Only three of the 35 trays in the Tred Avon River were more than 60% buried. Overall, the average amount of mud covering the substrates was about 30% of the trays' surface area.

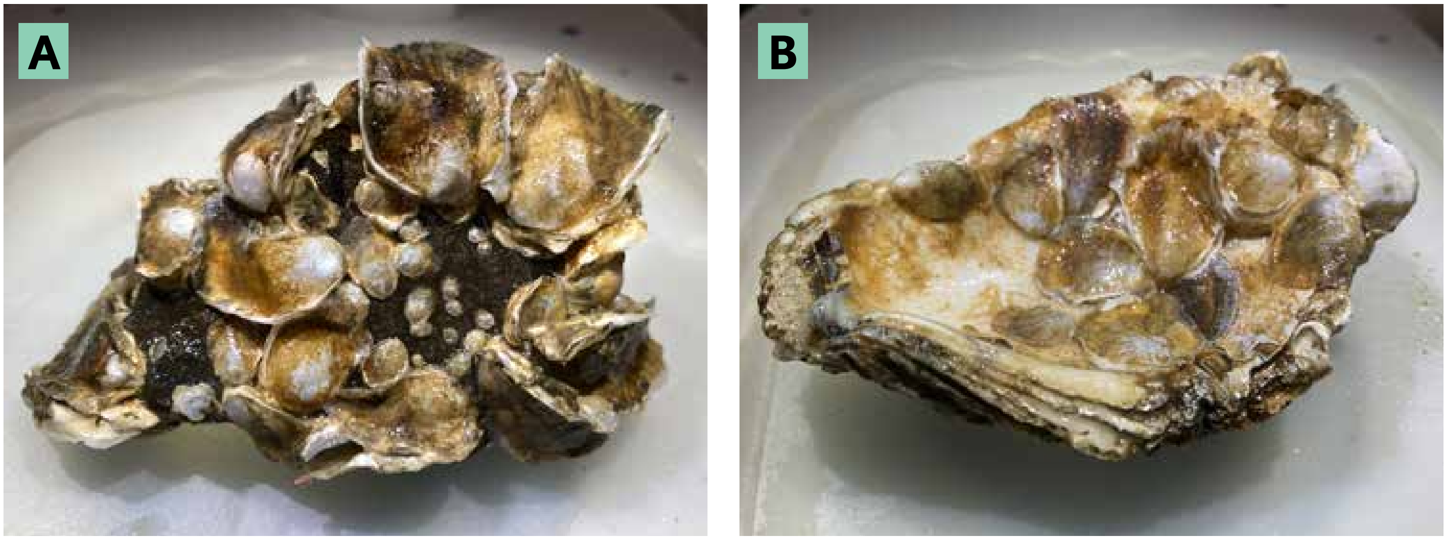

Figure 1B.8 *Spat (juvenile oysters) growing on individual pieces of substrate retrieved from the Tred Avon River: A) Havre de Grace stone, and B) fresh Eastern oyster shell. Note the multiple sizes of oysters on the stone, indicating multiple spatfall events. Photos by Elizabeth North.*

In the Nanticoke River, the average spatset was much lower than the other study sites, ranging from a low of 101 spat per m^2 on Havre de Grace stone to a high of 2,514 spat per m^2 on crushed concrete. Due to difficult diving conditions, only 14 of the 28 trays were recovered intact from the Nanticoke River. Of those 14 trays, 8 of 14 trays were mostly (>60%) covered with mud. Overall, the average amount of mud coverage was 60% of the trays' surface area. It is likely that the low abundance of spat observed at this site resulted from the large amount of mud that accumulated in the trays, although the amount of oyster larvae in the river also could have contributed.

In order to determine the impact of substrate burial on oyster spat abundance, the abundance of spat was statistically compared to the burial scores. The abundance of spat was significantly and positively related to the amount of clean, exposed substrate when data from all river systems were combined – the more clean substrate, the more spat (Figure 1B.9). About 55% of the trays with granite were buried with mud versus only about 20% of the trays with concrete. The strong negative effect of substrate burial on oyster spat abundance was likely due to mud preventing initial settlement of oyster larvae in the trays, or mud smothering and killing spat that had settled in the trays, or both.

Conclusions and next steps

Natural oyster spat settled, survived, and grew on all substrates tested and in all three Maryland river systems. Although spat settlement was successful in all river systems, the total abundance of spat differed greatly between rivers, likely due to differences in spawning and larval survival between the rivers and the differences in suspended sediment and bottom conditions at each site. Spat abundance in the St. Mary's River was exceptionally high and the lease had the hardest bottom with the lowest amounts of mud in the trays, allowing abundant oyster larvae to settle on clean substrates.

The unusually high abundances of spat on all substrates in the St. Mary's and Tred Avon Rivers may have resulted, in part, because the substrates were deployed in May, just before oyster spawning season. Planting clean Eastern Oyster shell just before the oyster spawning season is a technique used

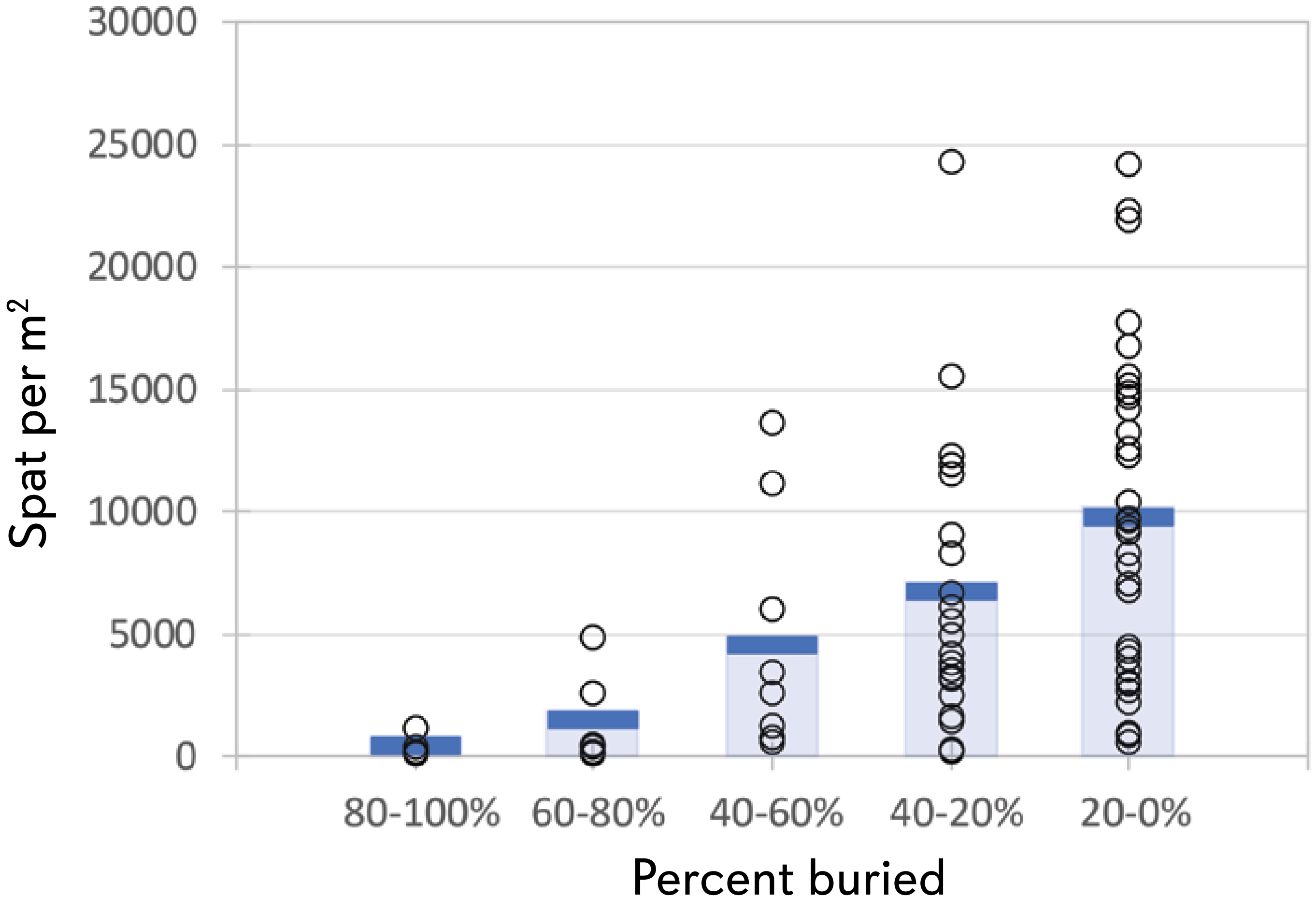

Figure 1B.9 *Abundance of oyster spat (spat per m^2) versus the percentage of the surface area of a tray that was buried by mud for all sites combined. Open circles are individual data points and the top of each bar is the mean.*

to increase spat set by commercial fishermen and aquaculturalists, and it appears to be effective for alternative substrates as well.

Results showed that burial of substrate by mud significantly affected the abundance of spat on all substrates – on average, more spat were found on cleaner substrates. Substrates with large surface areas and irregular shapes, such as Pacific Oyster shells, had higher profiles (more pieces were sticking up further off of the bottom of the tray), lower burial scores, and higher spat abundances, likely due to the availability of clean substrate for oyster larvae. Smaller, heavier materials with uniform shapes, such as granite, which was crushed to a specific size (#57 chips), had low profiles, high burial, and low spat abundances in the Tred Avon River where there was more mud in the trays than in the St. Mary's River. Even though stones weighed about twice that of shells in the trays, it is likely that the weight of the substrate did not influence burial as much as the profile of the substrate in the trays and the bottom type at the sites because bricks were attached to trays with shells, ensuring similar weights across the trays.

Large-scale, in-water evaluations would be the next step for determining which alternative substrates are most useful for the oyster industry of Maryland. This includes testing how the substrates behave when placed directly on the river bottom, how materials work with commercial harvesting methods, and identifying the cost and availability of materials. Some of the substrates in this test are currently used for other applications like road building and landscaping, so ensuring consistent supply as the commercial fishing and aquaculture industries grow is recommended.

Acknowledgments

We are grateful to oyster lease holders Victoria and Robert T. Brown and Eric Wisner for allowing us to deploy sampling gear on their active leases, as well as John Jacobs, Director of the NOAA Cooperative Oxford Lab, for providing space in the Oxford Oyster Sanctuary for our sampling gear.

We also are grateful to A.K. Williams, University of Maryland Dive Safety Officer, and NOAA Diver and scientist Jason Spires, for dive planning and topside safety assistance, Alan Williams and Emi McGeady for diving and topside support, Will Dorsey and Richie Long for boat operation, Alison Sanford for counting and weighing substrates, Stephanie and Jeff Alexander, Bob Carey, Mike Nossick, Shane Simms, Stacey Spicer, and Evelyn Peyton of the Horn Point Laboratory Oyster Hatchery for expert oyster counting assistance, and Olivia Caretti and Vyacheslav Lyubchich for valuable advice and guidance.

A special thanks to New Brick and Tile of Easton, MD for donating bricks, Nick Hargrove of Wittman Wharf Seafood for donating Pacific Oyster shell, SeaKing Inc and SeaWatch Inc for donations of Whelk and Clam shell, Ron Lambert of Vulcan Materials Company for donations of Havre de Grace stone, and Dagsboro Materials (H&K Group) for donations of crushed concrete and granite.

C. Cost and Emissions Analysis of Alternative Substrates

Authors

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Introduction

Cost of substrate, costs of transportation, and the environmental effects of transporting substrates are all important to consider when evaluating the use of alternative substrates for oysters. In addition to understanding the costs per unit of different substrates, source locations and means of transport differ widely between the substrates, which affect costs and influence purchasing decisions. In addition, air pollution from transportation can also be a factor in the decision-making process.

Air pollutants that are released during the transportation of materials like alternative substrates include nitrogen oxides (NO_x), particulate matter less than 2.5 micrometers in size ($PM_{2.5}$), and greenhouse gases like carbon dioxide (CO_2). Nitrogen oxides are released during the burning of fossil fuels, and are known to cause multiple respiratory problems. $PM_{2.5}$ comes from a variety of sources, including combustion of gasoline or diesel fuel, and brake and tire wear during the operation of vehicles. Exposure to $PM_{2.5}$ is associated with health impacts across multiple systems, particularly respiratory and cardiovascular systems. Outcomes include aggravation of asthma, heart attacks, and increases in overall mortality. Carbon dioxide, a gas that traps heat in the atmosphere, is associated with rising sea levels, more severe weather, saltwater intrusion in groundwater, and acidification of lakes, bays, and oceans.

The objective of this analysis was to calculate transportation costs, transportation distances, and air pollutant emissions for fresh Eastern Oyster shell (*Crassostrea virginica*), dredged Eastern Oyster shells, Pacific Oyster shell (*Crassostrea gigas*), Atlantic Surf Clam shell, Whelk (aka Conch) shell, cleaned crushed concrete, limestone, granite (#57 chips), river rock, and Havre de Grace stone (Figure 1A.1).

Highlights

- Barge transport costs were substantially lower than truck transport costs, even when comparing transport costs for a heavier material like Havre de Grace stone ($401/100 miles by barge) with a lightweight substrate like Whelk or Atlantic Surf Clam ($890/100 miles by truck).
- For substrates with total costs available, costs ranged from about $16,000 per acre of oyster bottom for fresh and dredged Maryland Eastern Oyster shell to $55,000 per acre of oyster bottom for granite.
- The most important factors determining air pollutant emissions were distance from the origin to the destination and the weight of the substrate. The per acre emissions are much lower for substrates that can be sourced close to the destination.
- Dredged Maryland Eastern Oyster shell had the lowest transport cost and lowest air pollution emissions during transport whereas granite and river rock had the highest transport costs and highest air pollution emissions.

Methods

The cost to transport each substrate by truck and/or barge was estimated. Costs for cargo transport by truck were based on many factors including fuel costs, operator wages and benefits, insurance premiums, vehicle purchase costs, and vehicle repair and maintenance. Mark Burton, an expert in transportation economics, used truck transport rates of $0.17 per ton-mile and barge rates of $0.01 per ton-mile in an analysis comparing the costs of different modes of cargo transport (Burton 2019). These values from 2019 were converted to 2024 dollars using the Producer Price Indexes for Truck and Water Transportation of Freight. We then applied these rates to estimate the costs to transport substrate sufficient for one acre of fishery restoration a common distance of 100 miles.

Per acre costs for substrate raw materials, loading and planting were also estimated for each alternative and transport mode. The Maryland Oyster Shell and Substrate Task Force (2024) estimated materials costs per bushel, and these values were multiplied by the estimated number of bushels needed for one acre of oyster bottom in the public fishery.

Data for the analysis came from a variety of sources. The Oyster Recovery Partnership (ORP) and researchers at UMCES provided information on bushel weights, origin point and mode of transport (i.e., dump truck, 18-wheeler or barge) for each alternative substrate. Additionally, ORP provided estimates of the volume (e.g., number of bushels) needed to restore one acre in the public fishery for each alternative (Table 1C.1). Heavier materials sink deeper into Bay sediments, so a greater volume of material is needed for heavier alternatives. Using information from ORP and published sources (FreightWaves 2020), we estimated the capacity by weight (lb) of each mode of truck transport. We used weight rather than volume because weight was the limiting factor in this context.

To compare substrates using distance traveled, we chose Horn Point Laboratory (HPL) as the destination point for all oyster substrate alternatives because it is an established location for receiving oyster shell and loading onto ships to transport material for final placement. For truck travel, we used Google Maps to estimate the number of miles from the origin to HPL. For barge travel, the distance from the Havre de Grace quarry and Man O' War Shoals to HPL was estimated in GIS using channel spatial data.

Table 1C.1 *Estimated number of bushels needed to restore one acre of oyster bottom in the public fishery. Shell includes fresh and dredged Eastern Oyster, Pacific Oyster, Whelk, and Atlantic Surf Clam shell.*

Substrate type	Substrate weight range (lb/bushel)	Estimated bushels per acre
Shell	39.4 - 67.0	2,000
Concrete	105.0	3,333
Stone	136.0 - 150.0	4,435*

*Due to uncertainty in the quantity of bushels of stone needed per acre of restoration, this value was estimated using the volume to weight ratio for shell versus concrete.

The methods used to estimate air emissions from transporting material for use in Chesapeake Bay oyster fishery restoration included several steps and calculations that varied by mode of transport. The first step was to identify material origin points and measure the distances to HPL, where material would be further processed and/or loaded onto barges for final water placement. For truck transport from origin to the destination, emissions were estimated based on the number of miles traveled. The second step was to estimate the number of trucks required to transport each alternative substrate. Different volumes of substrates are needed to restore one acre for oysters. Therefore, the weight by volume for each material type and the capacity of each transportation vehicle was used to estimate total volume and total truck trips. The third step was to multiply the number of trucks by the origin to destination distance in miles and by emissions per mile for each pollutant to yield the emissions per acre of public fishery restoration for each substrate alternative. Estimates of pollutant emissions per mile for heavy duty diesel trucks (i.e., dump trucks and 18-wheeler) came from the US Department of Transportation Bureau of Transportation Statistics (US DOT BTS 2025). Estimates of pollutant emissions per mile included NO_x from exhaust; $PM_{2.5}$ from exhaust, brake wear and tire wear; and CO_2 from exhaust.

For barge transport, CO_2 emissions estimates were based on the quantity of diesel fuel consumed. To estimate that value, we calculated the ton-miles of substrate transported and divided by the fuel efficiency of inland towing by barge in ton-miles per gallon. We then converted the quantity of diesel consumed to CO_2 emissions using a conversion factor of grams CO_2 per gallon of diesel and then to metric tons. Estimates of CO_2 emissions from barge transport were based on the fuel efficiency of inland towing (i.e., 675 ton-miles/gallon; Kruse et al. 2022), and estimates of CO_2 emissions from diesel consumption (i.e., 10,180 g CO_2/gallon diesel; US EPA 2025). Due to data availability, criteria pollutants (NO_x , $PM_{2.5}$) were only estimated for landside transportation. Because the concrete is recycled, we did not include air emissions from the concrete manufacturing.

Results: Transport and Materials Costs

Setting the transport distance to a common 100 miles allows us to directly compare substrate costs, transportation costs, and CO_2 emissions by alternative and transport mode (Figure 1C.1, Table 1C.2). The volumes transported vary because they represent the quantity necessary for one acre of oyster bottom. Transport by barge is considerably lower cost than transport by truck. Even though Havre de Grace stone is among the heaviest options, the costs of transport by barge are only a fraction of the estimated costs of trucking any alternative 100 miles (Figure 1C.1B). Barge transport costs are lower per ton-mile than trucking costs, and barge capacity is far greater. Specifically, barge capacity is around 2,000 tons (USACE 2023), while truck capacity is closer to 20 tons (Freightwaves 2020). Therefore, more than 16 dump trucks would be necessary to transport the quantity of granite or river rock for one acre of oyster bottom, while Havre de Grace stone for one acre would only partially fill a single barge.

Table 1C.2 *Transport costs, substrate costs, and CO_2 emissions per acre of oyster bottom by substrate and mode of transport with equal transport distance (100 miles) across all substrates. Substrates are in alphabetical order. MT = metric tons.*

Alternative Substrate	Mode	Weight (MT)	Transport cost/100 miles	Material cost per acre[a]	CO_2 emissions (MT) per 100 mile transport
Clean crushed concrete	Dump truck	158.8	$3,957	$20,065	1.24
Dredged Maryland Eastern Oyster shell	Barge	60.8	$89	$16,100	0.09
Fresh Maryland Eastern Oyster shell	18-Wheeler	60.8	$1,515	$16,100	0.43
Fresh Maryland Eastern Oyster shell	Dump truck	60.8	$1,515	$16,100	0.48
Fresh or dredged Virginia Eastern Oyster shell	Dump truck	60.8	$1,515	$18,100	0.48
Fresh Virginia Eastern Oyster shell	18-Wheeler	60.8	$1,515	$18,100	0.43
Granite	Dump truck	293.7	$7,320	$54,989	2.3
Havre de Grace stone	Barge	273.6	$401	$4,922[b]	0.41
Pacific Oyster shell	18-Wheeler	46.2	$1,151	$17,600	0.33
River rock	Dump truck	301.7	$7,521	$39,956	2.36
Whelk or Atlantic Surf Clam shell	Dump truck	35.7	$890	$10,360[b]	0.28

[a] Total costs per bushel (from MD Oyster Shell and Substrate Task Force 2024) multiplied by number of bushels per acre (Table 1C.1). Material costs include raw material, loading onto vessels and planting, except as noted (see b).
[b] Substrate material costs only. Does not include loading onto vessels or planting.

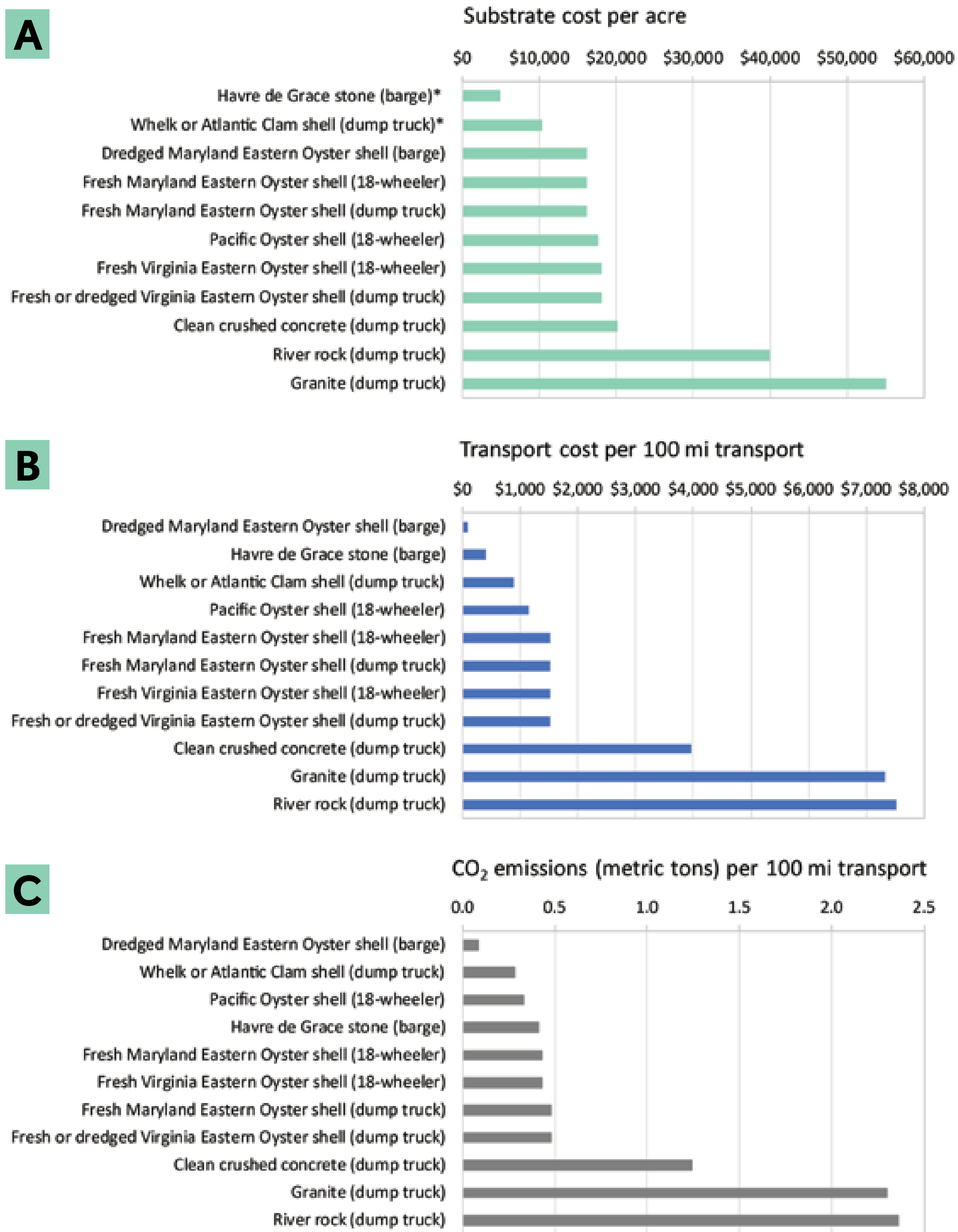

Figure 1C.1 *Costs and emissions analysis results for fresh Eastern Oyster shell and alternative substrates: A) substrate costs per acre of oyster bottom, B) transport costs per 100 miles of transport, and C) carbon dioxide (CO_2) emissions in metric tons per 100 miles of transport. Substrates in each panel are ordered from least to greatest; note that the order differs between the panels. Results in panel A were calculated as the total costs per bushel multiplied by number of bushels per acre, with substrate costs including raw material, loading onto vessels and planting, except as noted by * which indicates that the number is raw material costs only and does not include loading and/or planting costs.*

Results: Air Emissions

Dredged Maryland Eastern Oyster shell transported by barge has the lowest CO_2 emissions per 100 miles of transportation (Figure 1C.1C), although only a small fraction of the barge's capacity would be needed to transport substrate for one acre of restoration. The heaviest alternatives that must be transported by truck (i.e., granite and river rock) have the highest CO_2 emissions because substantially more dump trucks would be required to transport enough river rock or granite for one acre of oyster bottom than a lighter weight alternative like Whelk or Atlantic Surf Clam shell.

Because the quantity of air pollutant emissions is primarily a function of the transport distance, we calculated air emissions based on transport distance from the substrate source to HPL in Cambridge, Maryland (Table 1C.3). The per acre emissions are much lower for substrates that can be sourced close to HPL. When crushed concrete is sourced from nearby East New Market, MD (11 miles from HPL), it has the lowest emissions of any alternative. However, crushed concrete has also been sourced from as far away as 57 miles from HPL (i.e., Dagsboro, DE), and resulting emissions estimates are about 5 times as high.

Emissions associated with the transport of Pacific Oyster shell from the West Coast are nine times greater than the next closest alternative transported via truck (Table 1C.3). Local fresh Eastern Oyster shell has somewhat higher emissions than Atlantic Surf Clam and Whelk options, which have the lowest emissions among shell options. The relatively low emissions for local Eastern Oyster shell do not vary substantially by the two types of trucks reported to be used for transport. Dump trucks and 18-wheelers were estimated to have the same emissions per mile, but 18-wheelers have greater capacity, so their emissions per ton of cargo are slightly lower.

The use of heavy substrates that must be transported substantial distances will result in the emissions of more air pollutants. For example, the transportation of a heavy material like granite to HPL is estimated to emit about 1.3 MT of CO_2, about 3 kg NO_x and about 0.09 kg $PM_{2.5}$ per acre of oyster bottom (Table 1C.3). Atlantic Surf Clam and Whelk shell, by contrast, are lighter weight, and even with a greater transport distance (i.e., Whelk), emissions of CO_2 are much lower per acre (i.e., 0.23 MT for Whelk shell and 0.16 MT for Atlantic Surf Clam shell).

Transport of substrate alternatives by barge has lower CO_2 emissions than by truck (compare Dredged Maryland Eastern Oyster shell by barge (row 2) to Fresh Maryland Eastern Oyster shell by truck (row 3) in Table 1C.2). When taking into account distance, the quantity of dredged Virginia Eastern Oyster shell transported from Hampton Roads (Table 1C.3, row 10) and dredged Maryland Eastern Oyster shell from the Upper Chesapeake Bay (Table 1C.4, row 1) would be the same per acre of oyster bottom, but the shell would be barged only about a quarter as far as it would be trucked. Because of the higher distance and higher emissions from truck transport, the transport of dredged Virginia Eastern Oyster shell to HPL would emit 19 times more air pollutants than dredged Eastern Oyster shell barged from the Upper Chesapeake Bay.

Table 1C.3 *Summary of air pollutant emissions per acre of oyster bottom from each oyster substrate transported by truck from the source to Horn Point Laboratory in Cambridge, MD. Substrates are ordered from the least amount of emissions to the greatest.* CO_2 *= carbon dioxide,* NO_x *= nitrogen oxides,* $PM_{2.5}$ *= particulate matter 2.5 micrometers and smaller, kg = kilogram.*

Alternative substrate	Source location	Mode	Number of trucks	Distance (miles)	Total Distance (miles)	CO_2 emissions (metric tons)	NO_x (kg)	$PM_{2.5}$ (kg)
Clean crushed concrete[1]	East New Market, MD	Dump truck	8.7	11	96	0.14	0.31	0.009
Atlantic Surf Clam shell	Selbyville, DE	Dump truck	2	56	110	0.16	0.35	0.011
Whelk shell	Atlantic, VA	Dump truck	2	83	163	0.23	0.52	0.016
River rock	East New Market, MD	Dump truck	16.6	11	183	0.26	0.58	0.018
Fresh MD Eastern Oyster shell	Crisfield, MD	18-Wheeler	3	74	225	0.32	0.72	0.022
Fresh MD Eastern Oyster shell	Crisfield, MD	Dump truck	3.3	74	248	0.35	0.79	0.024
Clean crushed concrete[2]	Dagsboro, DE	Dump truck	8.7	57	499	0.71	1.59	0.049
Fresh VA Eastern Oyster shell	Kinsale, VA	18-Wheeler	3	175	533	0.76	1.7	0.052
Fresh VA Eastern Oyster shell	Kinsale, VA	Dump truck	3.3	175	586	0.83	1.87	0.057

Alternative substrate	Source location	Mode	Number of trucks	Distance (miles)	Total Distance (miles)	CO_2 emissions (metric tons)	NO_x (kg)	$PM_{2.5}$ (kg)
Dredged VA Eastern Oyster shell	Hampton Roads, VA	Dump truck	3.3	197	660	0.94	2.11	0.065
Granite	Dagsboro, DE	Dump truck	16.2	57	923	1.31	2.95	0.09
Pacific Oyster shell	South Bend, WA	18-Wheeler	2.3	2,900	6707	9.52	21.42	0.657

[1] Crushed recycled concrete is available from a variety of locations. The closest source, East New Market, is shown here.
[2] Crushed recycled concrete is available from a variety of locations. The source for our laboratory and field experiments, Dagsboro, DE, is shown here.

Table 1C.4 *Summary of CO_2 emissions per acre of oyster bottom from dredged Maryland Eastern Oyster shell and Havre de Grace stone transported by barge*[3].

Alternative substrate	Source location	Weight (tons)	Distance (miles)	Ton-miles	Diesel consumed (gallons)	CO_2 emissions (metric tons)
Dredged MD shell	Upper Chesapeake Bay[4]	59.8	53	3,170	4.7	0.05
Havre de Grace stone	Havre de Grace, MD	269.2	86	23,151	34.3	0.35

[3] Criteria air pollutants were only calculated for landside transportation
[4] Distance was measured from Man O' War Shoals to represent several alternative sites in the Upper Chesapeake Bay. Distance to Horn Point Laboratory would vary depending on location.

Conclusions

Barge transport costs were substantially lower than truck transport costs, even when comparing transport costs for a heavier material like Havre de Grace stone ($401/100 miles by barge) with a lightweight substrate like Whelk or Atlantic Surf Clam shell ($890/100 miles by truck). For substrates with total costs available, costs ranged from about $16,000 per acre (fresh and dredged Maryland Eastern Oyster shell) to $55,000 per acre (granite) of oyster bottom.

The most important factors determining air pollutant emissions were distance from the origin to the destination and the weight of the substrate. When distance was held to a common 100 miles, CO_2 emissions associated with the transport of substrate for one acre of oyster bottom ranged from 0.09 MT (dredged shell transported by barge) to 2.36 MT (river rock transported by dump truck).

Acknowledgments

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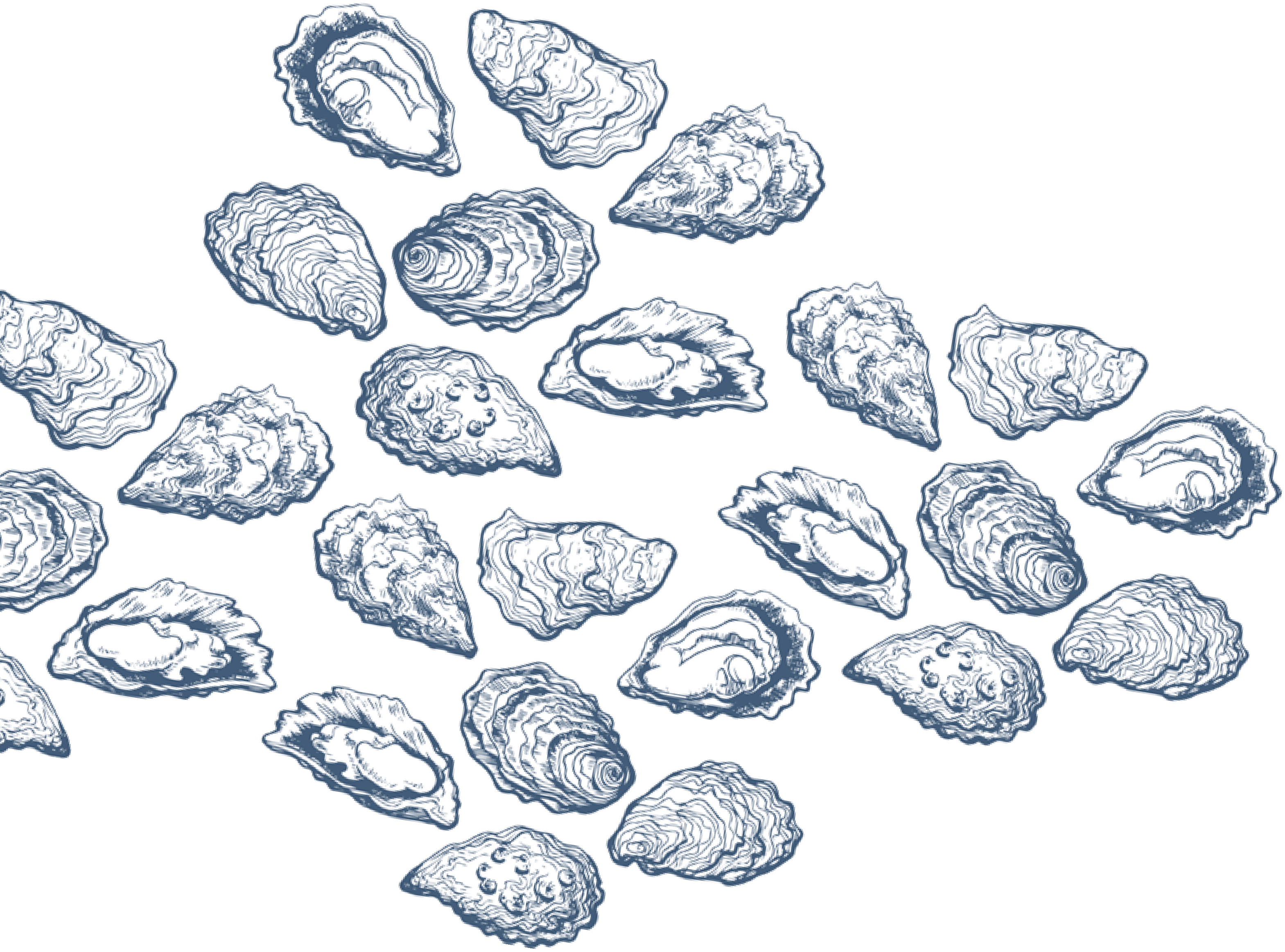
Chapter 2: Benefits of Stones in Restoration Areas



Chapter 2: Benefits of Stones in Restoration Areas

Authors

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Introduction

Three main efforts were conducted to assess the possible benefits, including habitat-related benefits, of the use of stones of various sizes in oyster restoration areas. While oyster reefs provide numerous benefits – supporting working waterfronts, enhancing water quality, strengthening the food webs that support commercial and recreational fishing – we focused on three habitat-related benefits that reefs made with stone could provide: oyster abundance, reef habitat structure, and biodiversity. Three tributaries were selected for this study – Harris Creek, Tred Avon River, and Little Choptank River – because stones were used at multiple sites in these restoration areas and because monitoring data for oyster abundance were available at the sites built with stones. Although oyster restoration efforts have used stones in other tributaries (e.g. St. Mary's and Manokin Rivers), monitoring data were not available at the time of this study.

Three reef types were compared in the restoration areas of the three tributaries in this study: spat-on-shell, stones with spat-on-shell, and natural reefs. Spat-on-shell sites were restored reefs that were constructed on areas with pre-existing, yet degraded, oyster habitat. Stone with spat-on-shell sites were primarily constructed on areas with firm bottom but little to no pre-existing shell or oysters. Natural reefs were either areas that qualified as suitable for spat-on-shell restoration but were left untreated to serve as reference reefs or areas that had pre-existing habitat and oyster abundances that did not require restoration. (See oyster restoration blueprints (Harris Creek, Little Choptank, and Tred Avon Rivers) and the Oyster Metrics Report for more information on restoration efforts and monitoring.)

We used a combination of field studies and analysis of oyster monitoring data to assess the performance of stone reefs for oyster abundance, reef structure, and biodiversity. Patent tong and diver monitoring data on live oyster abundances were compared between reef types (natural, spat-on-shell only, stone with spat-on-shell on top) to determine if oyster abundances differed between them. Acoustic measurements were made to compare reef structure between the reef types and sand bottom. In addition, water samples for environmental DNA (eDNA) were collected to assess biodiversity by identifying species associated with the different reef types. The influence of stone size was assessed in the Tred Avon River where stones of various sizes were used in restoration efforts.

Highlights

- Sonar measurements showed that reefs constructed with stones provide reef habitat structure. The reef structure metrics of cluster height and rugosity were highest on reefs constructed with stone in all tributaries.

- Mean oyster abundances at restoration sites created with stones were two to five times higher than the restoration target of 50 oysters/m². This demonstrates that stones can be used to rehabilitate areas with poor oyster habitat. In addition, in one of the three tributaries (Harris Creek), oyster abundances were significantly higher at sites created with stones than at natural and spat-on-shell reefs.
- Numerous (>24) species were identified from the DNA sequences in water over stone reefs in all three tributaries, suggesting that stone reefs support biodiversity.
- Stone size had variable influence on oyster restoration benefits in the Tred Avon River: smaller stones (2-4") supported higher oyster abundances than larger stones (3-6") but there was no clear difference in cluster height, rugosity, or biodiversity between stone sizes.

A. Statistical Analysis of Oyster Abundance

Introduction

The main intended benefits of reefs built with stone in oyster restoration areas are to support oysters along with the community of organisms that rely on them and to increase the area of bottom available for restoration beyond what is suitable for spat-on-shell restoration. Maryland is an international leader in large-scale oyster restoration, with more than 1,300 acres restored in five major tributaries from 2011 to the present. As part of this restoration process, oyster abundances are monitored three and six years after each site is completed to allow for adaptive management. This monitoring data provide a wealth of information that we used to compare oyster abundances between reef types (natural, spat-on-shell only, stone with spat-on-shell on top, defined above) to determine if oyster abundances differed between them.

Methods

This analysis was limited to oyster abundance data (number of live oysters per square meter) that were collected three years after restoration sites were completed because all restoration sites in Harris Creek, the Little Choptank River, and the Tred Avon River had three-year monitoring data and six-year monitoring data were not available for all sites. Data included oyster abundance, type of monitoring gear (patent tong or diver), and type of reef (natural, spat-on-shell, stone with spat-on-shell on top). Stone sizes were 3-6" in Harris Creek and the Little Choptank, and were either 3-6" or 2-4" in the Tred Avon River.

Oyster abundance data were collected with patent tongs from natural and spat-on-shell reefs and with divers from stone reefs due to logistical considerations and gear limitations. Because diver collections are more efficient at collecting oysters from restored reefs than patent tongs, the patent tong data were adjusted using a correction factor to ensure that data collected with the two sampling methods were comparable. The correction factor was estimated with Harris Creek data by Wilberg et al. (2022) and was applied to patent tong data in all three tributaries.

A set of statistical analyses was conducted with the oyster restoration monitoring data. We modeled oyster abundances using a zero-adjusted gamma (ZAGA) distribution that was selected to accommodate the presence of zero values and skewed data. This model included tributary, reef type,

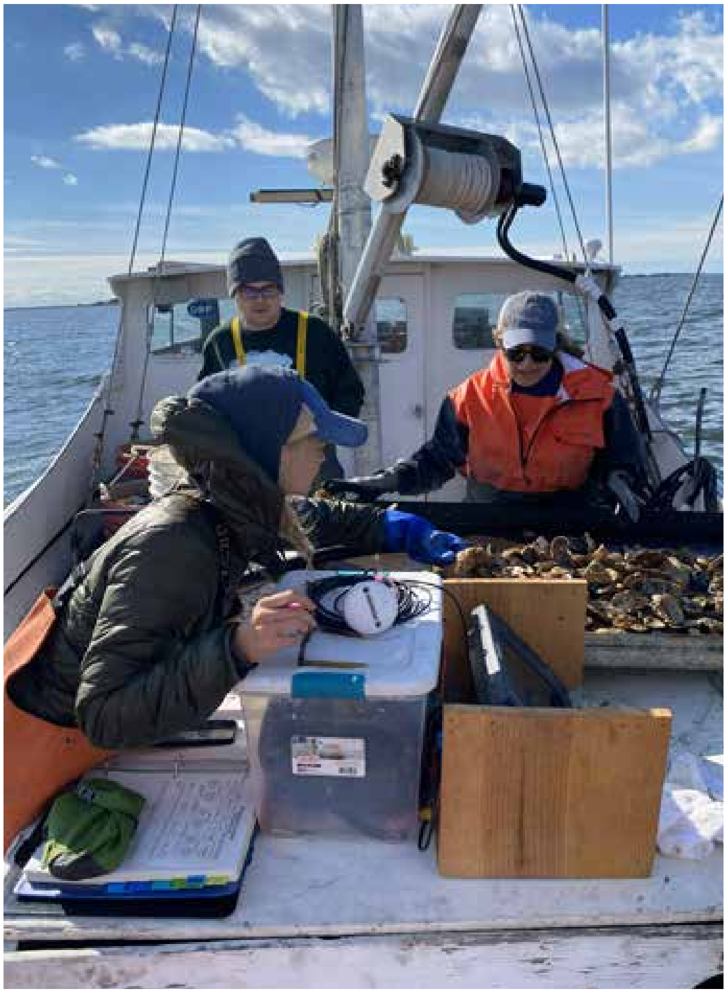


Figure 2.1 *An example of Oyster Recovery Partnership staff monitoring oyster abundance at an oyster restoration site. Photo by Elizabeth North.*

spatfall year (the year in which spat settlement occurred), and spatfall intensity (MD DNR Fall Survey) as predictors of oyster abundance. Spatfall year and spatfall intensity were included in the model to account for differences in environmental conditions and spat sets during the 10-year monitoring period (2015 to 2024). The final model structure was determined by minimizing the Bayesian information criterion (BIC) through a stepwise process.

The final statistical model for oyster abundance included all predictors (tributary, reef type, spatfall year, and spatfall intensity) for modeling both mean oyster abundance and its variability. The model for the mean also included combined effects of reef type and tributary. Model diagnostics indicated a good fit. Based on this model, we used pairwise comparisons of the means to assess differences between reef type within each tributary. The p-values were adjusted for multiple comparisons.

To assess the effect of stone size (2-4" vs. 3-6"), we performed a separate analysis on data from the Tred Avon River. For this subset, we fit a ZAGA model with stone size and spatfall year as predictors of oyster abundance. The variable selection in this model was also performed using BIC. Pairwise comparison of the estimated marginal means was used to statistically compare oyster abundances between the two stone sizes.

Results

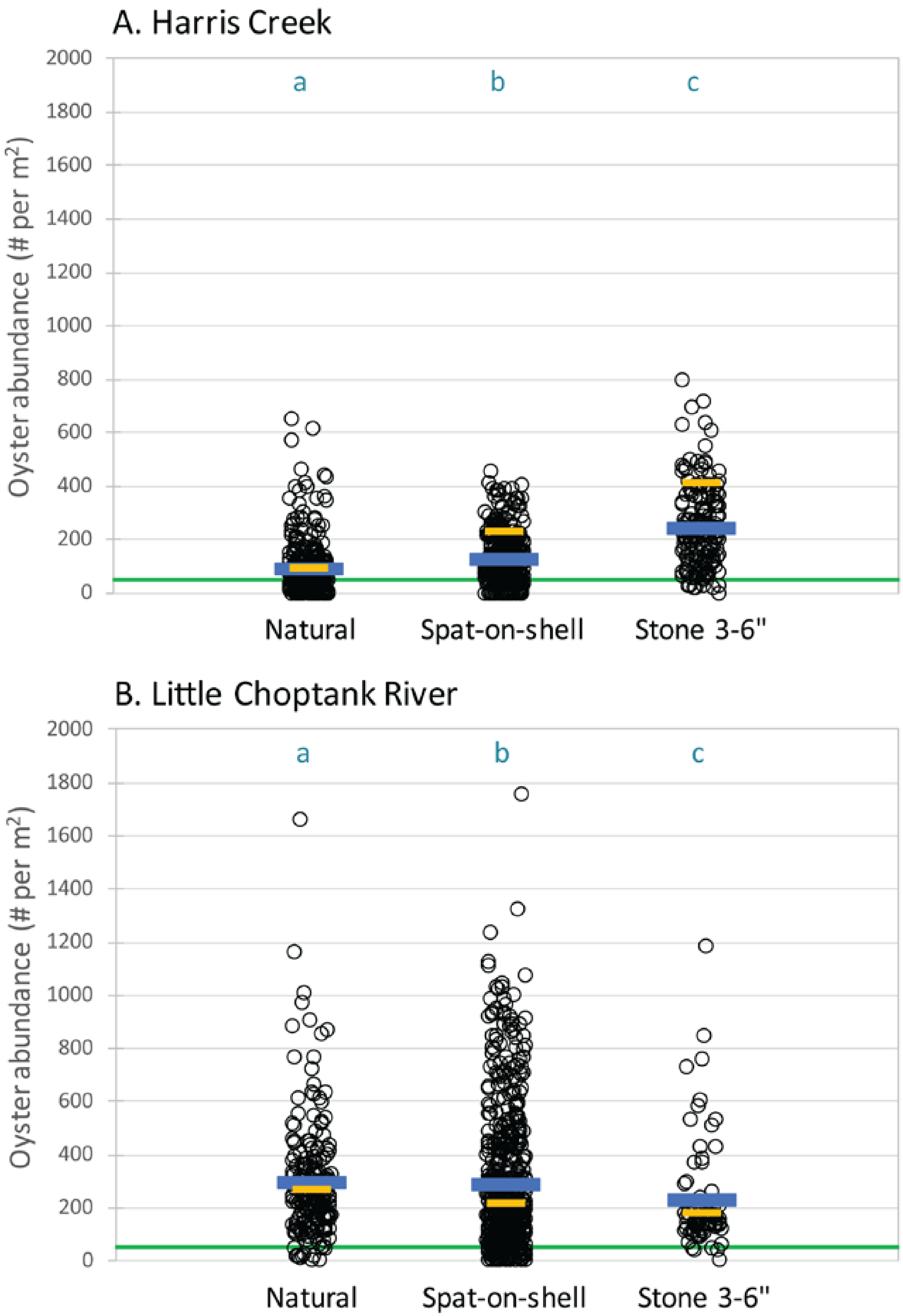
Mean oyster abundances at restoration sites created with stones were two to five times higher than the restoration target of 50 oysters/m² (Figure 2.2, Table 2.1). This demonstrates that stones can be used to rehabilitate areas that were previously poor oyster habitat. It also is interesting to note that mean oyster abundances in the Little Choptank River were about twice that of abundances in Harris Creek and the Tred Avon River, except for stone reefs in Harris Creek that had abundances similar to those in the Little Choptank River (Table 2.1).

The ZAGA statistical model revealed a significant interaction between tributary and reef type, indicating that the effect of reef type on oyster abundance depended on the specific tributary (Figure 2.2). In the Little Choptank and Tred Avon Rivers, mean oyster abundances on stone reefs were significantly lower than on spat-on-shell reefs. Conversely, in Harris Creek, stone reefs had significantly higher oyster abundances than natural and spat-on-shell reefs. Spatfall intensity was positively associated with both mean oyster abundance and its variability, indicating that higher spatfall led to higher, but more variable, abundances, as expected. Significant differences were also found among spatfall years, accounting for expected natural variations.

The statistical analysis of stone reefs within the Tred Avon River showed that smaller stones (2-4”) were associated with higher mean oyster abundances than those on sites created with larger stones (3-6”) (p-value = 0.037). Mean oyster abundances on 2-4” stone reefs was 111.2 +/- 68.0 oysters/m² (n = 70) while mean abundances on 3-6” stone reefs was 90.8 +/- 47.7 oysters/m² (n = 78). Although the model accounted for environmental variation, additional factors like location within the tributary were not included, so it is not clear whether the size of stone was the only factor contributing to the difference in oyster abundances between stone reefs of different sizes.

Table 2.1 *Mean oyster abundance three years after restoration by tributary and reef type, as well as the marginal means estimated by the statistical model. Marginal means take into account differences in spatfall and environmental conditions. +/- indicates one standard deviation.*

Tributary	Reef Material	Observed mean oyster abundance (#/m²)	Estimated marginal mean oyster abundance (#/m²)	Number of samples
Harris Creek	Natural	88.4 +/-105.8	92.8 +/- 18.5	307
	Spat-on-Shell	120.8 +/-103.1	230.4 +/- 25.2	536
	Stone 3-6”	240.6 +/-152.8	415.7 +/- 14.2	173
Little Choptank	Natural	288.5 +/-219.8	265.1 +/- 15.2	208
	Spat-on-Shell	280.6 +/-256.4	217.0 +/- 26.1	627
	Stone 3-6”	224.1 +/-206.3	174.2 +/- 9.3	75
Tred Avon	Natural	106.2 +/-104.2	114.4 +/- 16.1	208
	Spat-on-Shell	102.6 +/-120.4	100.5 +/- 16.5	215
	Stone 3-6”	100.8 +/-57.3	60.9 +/- 14.3	163


A. Harris Creek
Oyster abundance (# per m²)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
a
b
c
Natural
Spat-on-shell
Stone 3-6"
B. Little Choptank River
Oyster abundance (# per m²)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
a
b
c
Natural
Spat-on-shell
Stone 3-6"

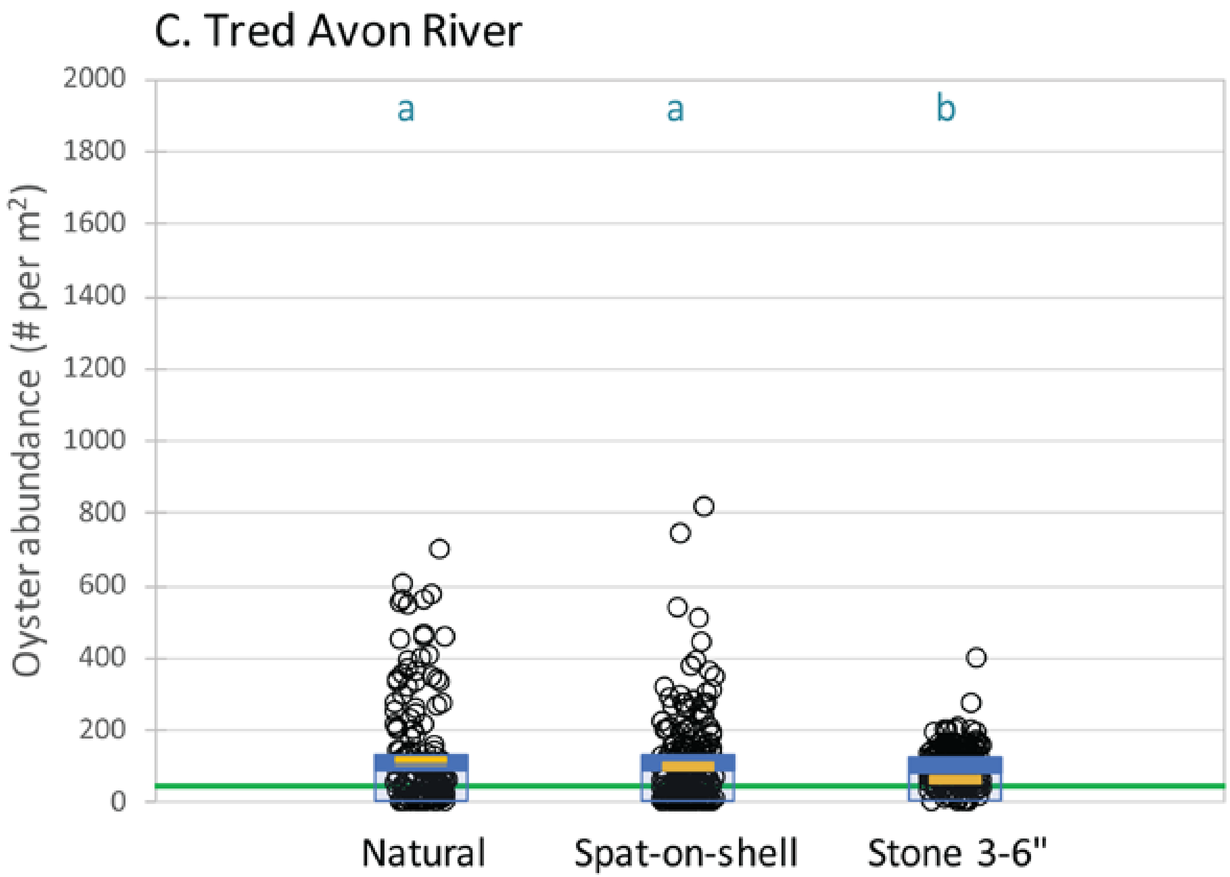


Figure 2.2 *Oyster abundance (number per m²) by reef type in A) Harris Creek, B) Little Choptank River, and C) Tred Avon River based on restoration monitoring three years after reef construction. Open circles are individual data points and the top of each blue bar is the mean. Orange lines indicate the back-transformed marginal means predicted by the statistical model – marginal means take into account differences in spatfall, environmental conditions, and tributaries. Individual points were jittered so more of the data can be seen. Means that do not share a letter at the top of the plot are significantly different based on a statistical model that accounted for tributary, spatfall year, and spatfall intensity (pairswise t-tests with Tukey correction for multiple testing, $p < 0.05$). The green line is the restoration target of 50 oysters per square meter.*

B. Reef Structure with Acoustics

Introduction

Reef structure provides habitat-related benefits to the numerous organisms that live on and near oyster reefs. Small spaces between oysters allow organisms to hide from predators, forming dense populations that would not be possible on a flat bottom. Because of the abundant life – from worms to crabs to fish – that the reef structure enables, oyster reefs are a focal point for the food web that underpins some commercially-, recreationally-, and ecologically-valuable fish and shellfish. The objective of this study was to determine if restoration sites built with stone reefs had reef structures that were similar to natural and spat-on-shell oyster reefs.

Methods

Reef structure measurements were made in Harris Creek, the Tred Avon River, and the Little Choptank River. Within each of these tributaries, two stations were sampled for each bottom type: sand, natural reef, spat-on-shell reef, and stone reef with spat-on-shell on top (Figure 2.3). Because two sizes of stones were used in the Tred Avon River, two additional stations were sampled over reefs made with 2-4" stones, in addition to 3-6" stones that also were sampled in the other tributaries. Stations were chosen over oyster restoration sites so that dates of construction, planting, and monitoring of the sites were similar, and so that there were more than 50 oysters/m² at the most recent monitoring survey to ensure oyster reefs were sampled. Stone sites were limited to only those with spat-on-shell planting on top. Stations with sand bottom types were selected using sonar-based bottom type maps provided by NOAA Chesapeake Bay Office.

We characterized reef structure using Adaptive Resolution Imaging Sonar (ARIS) images taken at each sampling location (Figure 2.3). An ARIS Explorer 3000 with a 1° concentrator lens was mounted on a pole and lowered approximately 1.6 ft below the surface, aimed vertically down so that the sonar beams intersected the reef at a 90° angle. Recordings were made at 3 MHz, providing sub-centimeter resolution. Example images are in Figure 2.4. Sonar surveys took place in Tred Avon River on 28 August 2025, Little Choptank River on 29 August 2025, and Harris Creek on 22 September 2025.

ARIS images were processed by measuring cluster height and rugosity, two potentially important metrics of reef structure. Each sonar video was reviewed in ARISFish software and a representative frame was selected for processing. Cluster height was defined as the vertical height of oysters (either individual or in a cluster) and attached sessile organisms (like mussels) above the surrounding substrate (sediment or stone). The vertical heights of up to five separate oyster clusters were measured and averaged. Rugosity was measured with the "chain" method within the ARISFish software and calculated so that a flat surface has a rugosity of 0 and a vertical surface has a rugosity of 1.

Statistical analyses were conducted to determine if cluster height and rugosity were statistically different between reef (natural, spat-on-shell, stone reefs) and bottom (sand) types. Beta regressions were used to analyze rugosity because the metric was bounded by 0 and 1. Cluster height was analyzed with a Generalized Linear Model (GLM) with a Poisson distribution, with original values rounded to the nearest whole number to fit the requirement for integer response values. The best model was selected using Akaike's Information Criterion (AIC) and p-values were adjusted for multiple comparisons. Model diagnostics indicated a good fit.

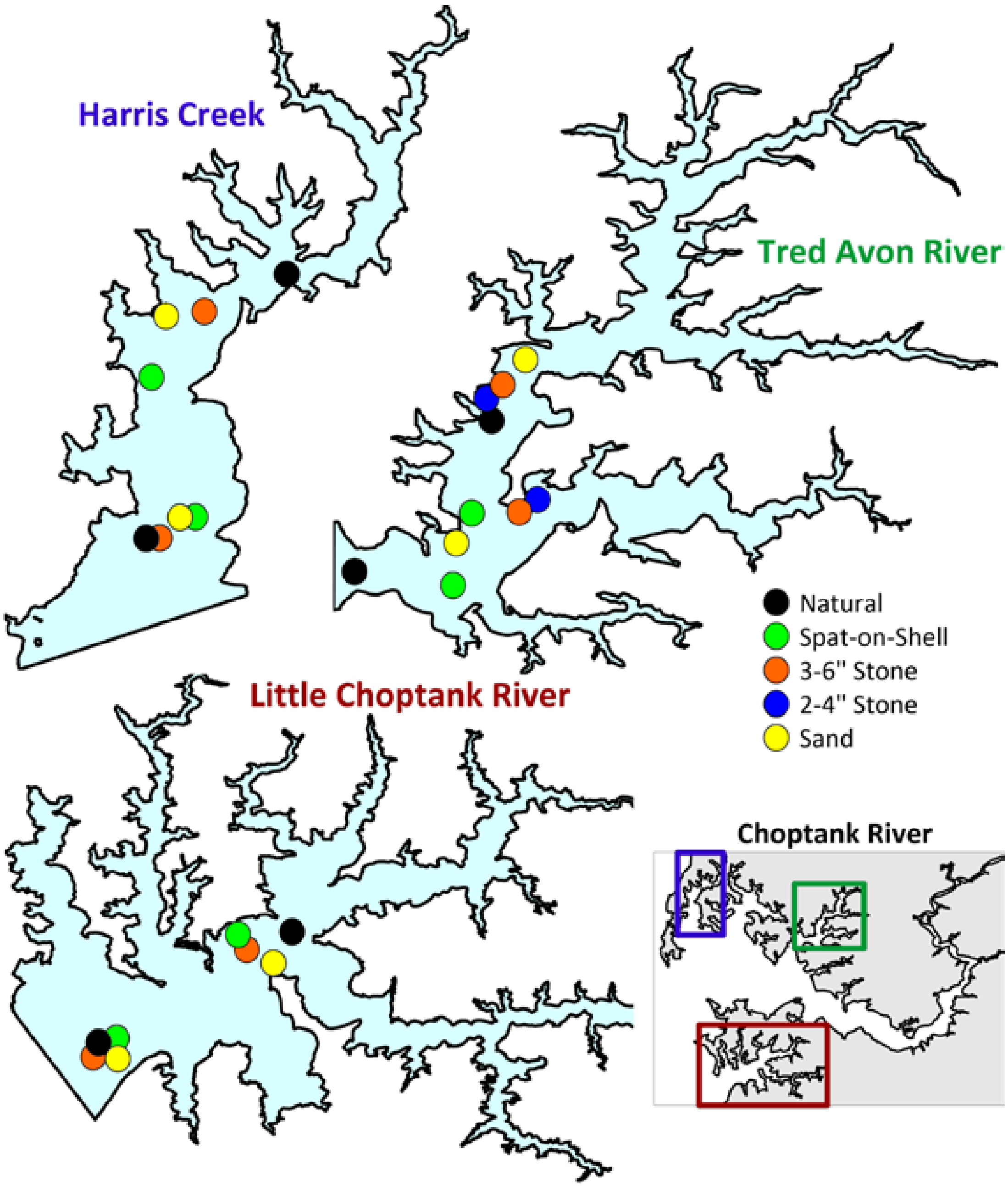


Figure 2.3 *Map of sampling stations for sonar-based reef structure and eDNA biodiversity samples in three tributaries where large-scale oyster restoration has occurred. The inset map on the lower right shows the location of the tributaries in relation to the Choptank River that is located on the Eastern Shore of Maryland. The colors of the boxes in the inset correspond with the colors of the tributary names, indicating their location. Sampling stations within each tributary are color-coded by bottom type (see legend on right). Three or four measurements of reef structure and three or four water samples for eDNA were made at each station.*

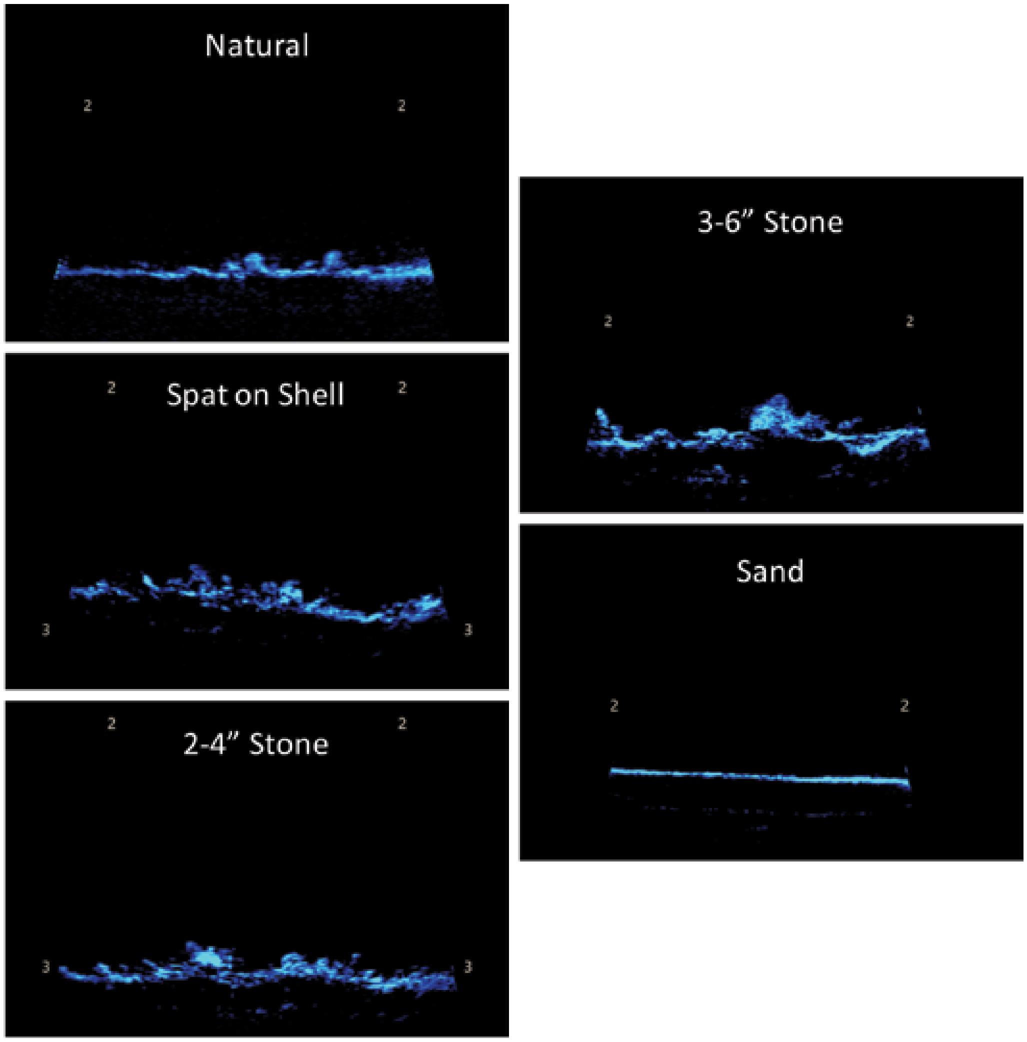


Figure 2.4 *Example sonar images collected with an Adaptive Resolution Imaging Sonar (ARIS) over a natural oyster reef, a reef created with spat-on-shell, a reef with 2-4" stone at its base, a reef with 3-6" stone at its base, and sandy bottom. Two measures of reef structure were calculated with these images: cluster height (the vertical height of oysters and other reef animals) and rugosity (the roughness of a surface).*

Results

Across all three tributaries, sand sites had significantly lower cluster heights compared to natural, spat-on-shell, and stone reefs. Stone reefs had significantly higher cluster heights than natural reefs and were not statistically different from spat-on-shell reefs (Figure 2.5A). Although there was no statistical difference in cluster height between natural, spat-on-shell, 2-4" stone, and 3-6" stone reefs in the Tred Avon River, all were significantly higher than sand (Figure 2.5B).

Sand sites in all three tributaries had significantly lower rugosity compared to natural, spat-on-shell, and stone reefs (Figure 2.6A). Stone reefs had significantly higher rugosity than natural reefs and were not statistically different from spat-on-shell reefs. In the Tred Avon, there were no significant differences in rugosity between habitat types, including no difference between 2-4" and 3-6" stone (Figure 2.6B).

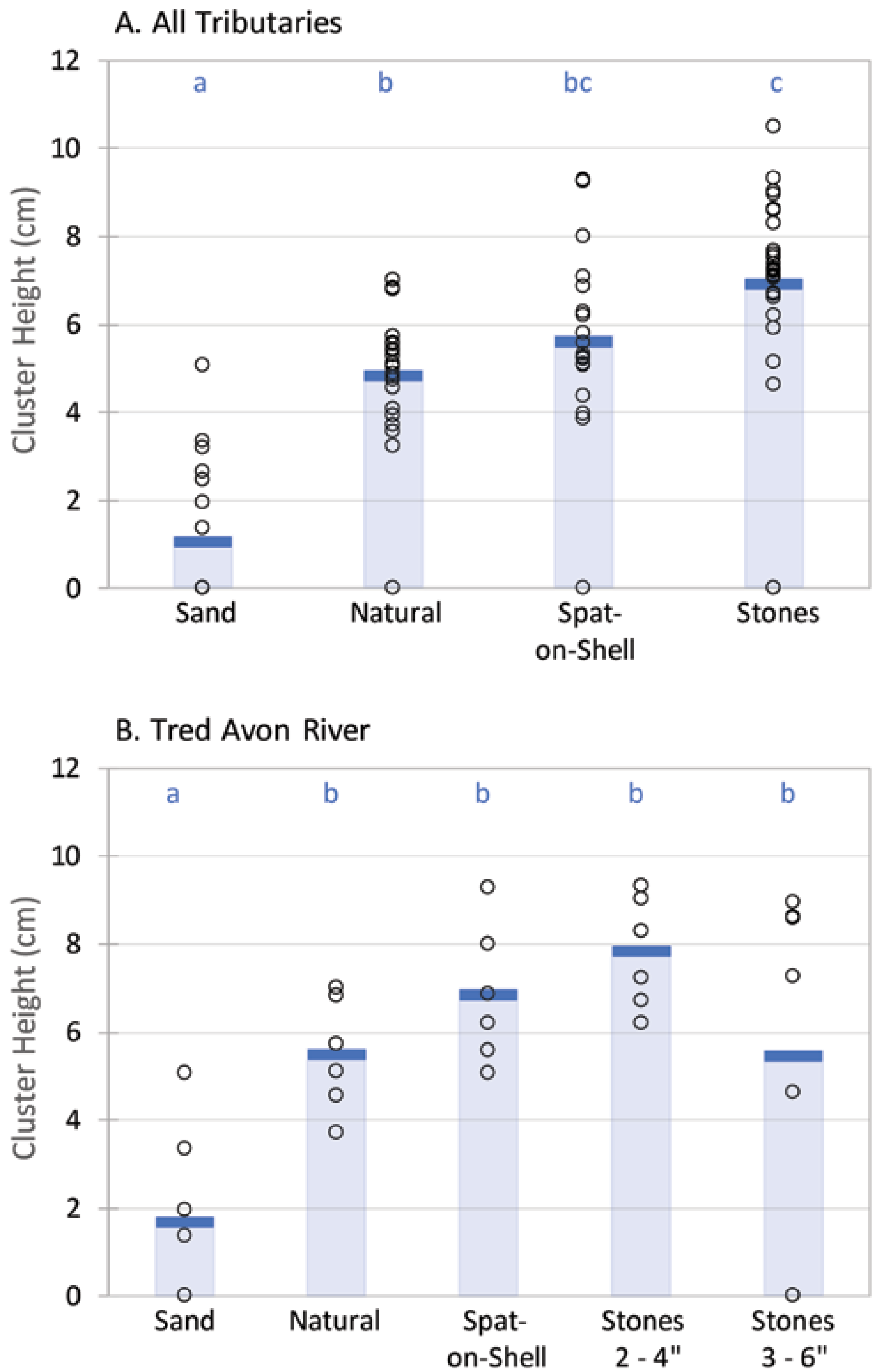
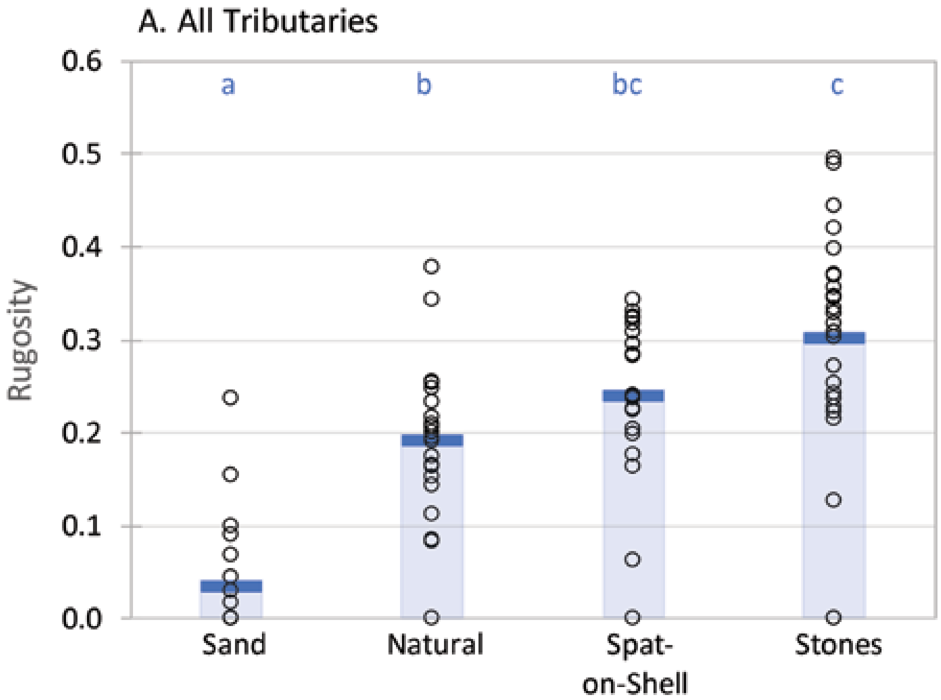


Figure 2.5 *Cluster height (cm) based on sonar measurements for A) all tributaries (Harris Creek, Little Choptank River, Tred Avon River) and for B) the Tred Avon River where two sizes of stones were used (2-4" and 3-6"). In Harris Creek and the Little Choptank River, 3-6" stones were used. Open circles are individual data points and the top of each bar is the mean. Means that do not share a letter at the top of the plot are significantly different.*



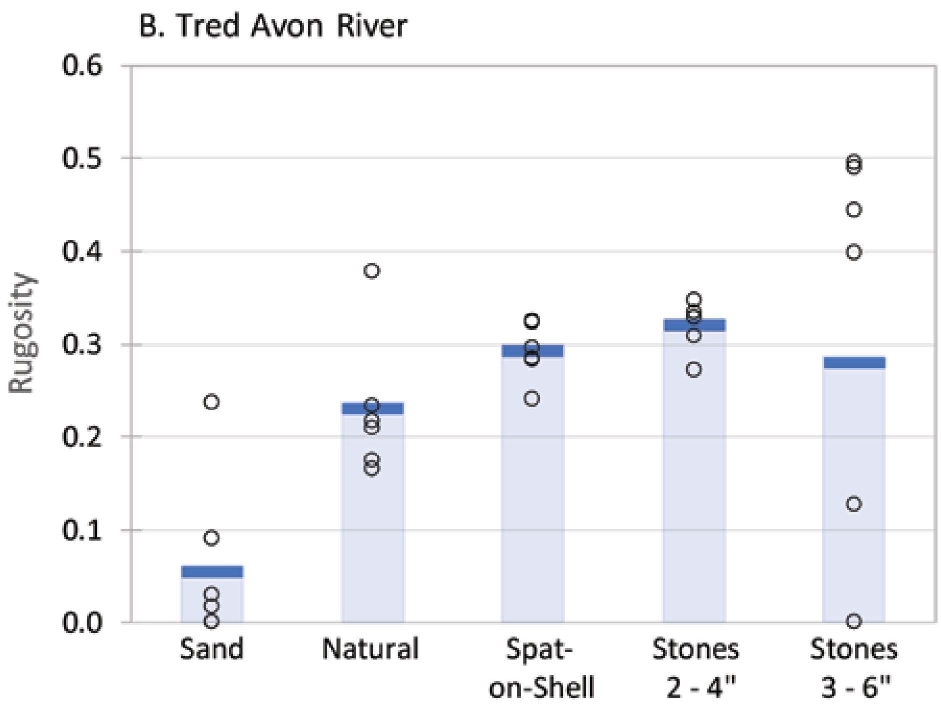


Figure 2.6 *Rugosity based on sonar measurements for A) all tributaries (Harris Creek, Little Choptank River, Tred Avon River) and for B) the Tred Avon River where two sizes of stones were used (2-4" and 3-6"). In Harris Creek and the Little Choptank River, 3-6" stones were used. Open circles are individual data points and the top of each bar is the mean. Means that do not share a letter at the top of the plot are significantly different. Rugosity was not statistically different between reef and bottom types in the Tred Avon River.*

C. Biodiversity with eDNA

Introduction

The goal of this eDNA research was to assess the habitat quality of stone restoration reefs by determining if biodiversity differed between oyster reefs created with stones topped with spat-on-shell, oyster reefs created with just spat-on-shell, natural oyster reefs, and sandy bottom. eDNA is a relatively new technique for identifying the presence of species using DNA that has been shed by organisms, such as mucus or excretions, into the water. DNA degrades rapidly (in less than 24 hrs) and gets dispersed quickly, so intact DNA within a sample that positively matches a known species likely indicates that the species was recently present at the sample location.

Methods

Water samples for eDNA were collected in July 2025 at the same sites as the sonar reef structure stations in Harris Creek, Tred Avon River, and Little Choptank River (Figure 2.3). Within each of these tributaries, two stations were sampled for each bottom type: sand, natural reef, spat-on-shell reef, and stone reef with 3-6” stones. Because two sizes of stones were used in the Tred Avon River, an additional two stations were sampled over reefs made with 2-4” stones. At each station, three or four

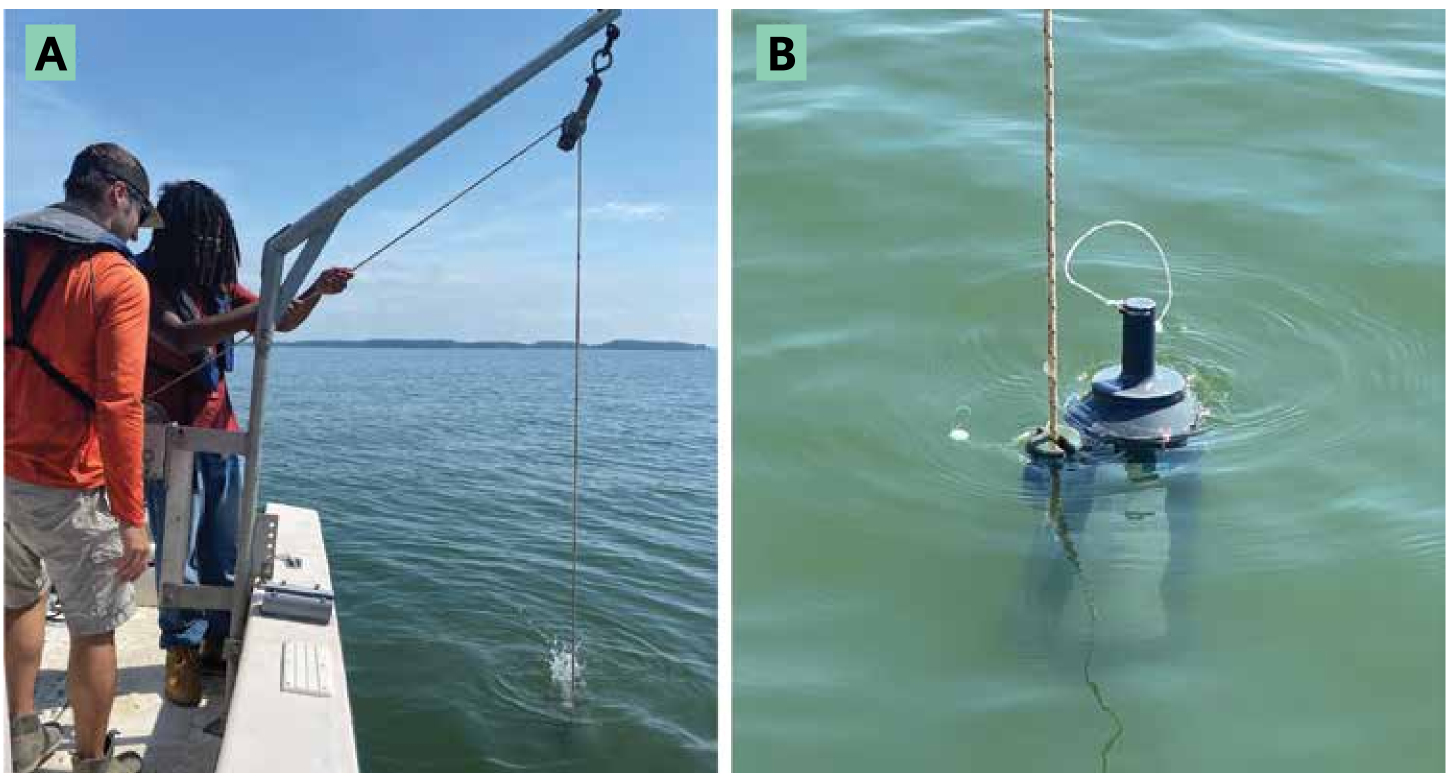


Figure 2.7 *Collecting water samples for biodiversity analysis with eDNA in Harris Creek, July 2025. A) Diego Pacheco rinsing the open Niskin bottle with surface water before submerging it to within 10 inches of the bottom where water was collected. Boat driver Jake Shaner watches while holding station. B) Close-up of a closed Niskin bottle filled with bottom water as it is pulled up to the surface. Photos by Elizabeth North.*

water samples were collected, for a total of 32 samples in Harris Creek, 24 in the Little Choptank River, and 30 in the Tred Avon River. Water samples were collected 10 inches from the bottom using a 5-L Niskin bottle (Figure 2.7) following the eDNA protocol of Smithsonian Environmental Research Center (SERC).

Sample processing followed the same protocol for all samples. All DNA samples were extracted from water filters, impurities were removed, and then stored frozen (-20°C) until sequencing. Extracted samples were submitted for library preparation and sequencing at Maryland Genomics (Institute for Genome Sciences, Baltimore, MD). The cytochrome c oxidase subunit 1 (CO1) gene was amplified and then sequenced on an Illumina NextSeq. Multiple steps were used to quality control the sequence data. Sequences were then matched to Chesapeake Bay species using SERC's Chesapeake Bay Barcode Initiative fish and invertebrate databases. This information was used to create lists of species present over each bottom type within each tributary.

Results

A total of 61 organisms were identified to species level from the DNA sequences in water samples: 49 in Harris Creek, 35 in the Little Choptank River, 42 in the Tred Avon River (Tables 2.2, 2.3, 2.4). Twenty-six of the 61 species (43%) were found in all tributaries. The percent match in species presence or absence between natural reefs and stone reefs was 78% in Harris Creek, 60% in the Little Choptank River, and 64% in the Tred Avon River, indicating that stone reefs had similar species profiles as natural oyster reefs.

Overall, the eDNA technique clearly shows that numerous species use the tributaries, many of which are closely associated with oyster reefs (Oyster Toadfish, Striped Blenny, Hooked Mussel, Dark False Mussel, Ribbed Mussel). It is likely that movement of water on and off oyster reefs by the tides would have spread the DNA of reef organisms throughout the tributary, resulting in similarity between species profiles on natural reefs and sandy bottom (66% - 79%).

In the Tred Avon River, 24 species were found over both 2-4" and 3-6" stone reefs (Table 2.4). There was a 62% match between natural reefs and stone reefs for both the 2-4" stone reefs and the 3-6" stone reefs.

Table 2.2 *Organisms present in Harris Creek by substrate type based on eDNA samples. ‡ indicates species only found in Harris Creek; • indicates species found in all three tributaries.*

Species	Common Name	Natural Reef	Spat on Shell Reef	Stone Reef	Sand Bottom
Fish and Rays					
Anchoa mitchilli •	Bay Anchovy	✓		✓	✓
Anguilla rostrata ‡	American Eel				✓
Apeltes quadracus‡	Fourspine Stickleback	✓			
Brevoortia tyrannus •	Atlantic Menhaden	✓	✓	✓	✓
Chasmodes bosquianus	Striped Blenny			✓	
Leiostomus xanthurus •	Spot	✓	✓		✓
Morone americana	White Perch		✓		
Morone saxatilis	Striped Bass				✓
Crabs					
Callinectes sapidus •	Atlantic Blue Crab		✓	✓	
Eurypanopeus depressus‡	Flatback Mud Crab	✓		✓	
Bivalves					
Ameritella mitchelli •	Cheating Macoma	✓	✓	✓	✓
Arcuatula papyria	Atlantic Paper Mussel		✓		✓
Crassostrea virginica •	Eastern Oyster	✓	✓	✓	✓
Gemma gemma	Amethyst Gem Clam			✓	✓
Ischadium recurvum •	Hooked Mussel	✓	✓	✓	✓
Limecola petalum •	Baltic Clam	✓	✓	✓	✓
Mulinia lateralis •	Dwarf Surf Clam, Coot Clam	✓	✓	✓	✓
Mytilopsis leucophaeata •	Dark False Mussel	✓	✓	✓	✓
Snails					
Boonea impressa	Impressed Odostome Snail	✓	✓		
Littoraria irrorata ‡	Marsh Periwinkle	✓		✓	✓
Littoridinops monroensis •	Cockscomb Hydrobe Snail	✓	✓	✓	✓
Melampus bidentatus •	Common Marsh Snail	✓	✓	✓	✓
Jellyfish					
Blackfordia virginica	Black Sea Jellyfish			✓	
Chrysaora chesapeakei •	Bay Nettle	✓	✓	✓	✓
Invertebrates					
Americamysis almyra	Mysid Shrimp		✓		✓
Americamysis bahia ‡	Mysid Shrimp	✓	✓	✓	
Amphibalanus eburneus •	Ivory Barnacle	✓	✓	✓	✓
Amphibalanus improvisus •	Bay Barnacle	✓	✓	✓	✓
Corambe obscura ‡	Obscure Sea Slug		✓		
Diadumene leucolena	Ghost Anemone		✓	✓	✓
Ercolania fuscata ‡	Dusky Sea Slug	✓			✓
Hargeria rapax ‡	Tanaidacean Crustacean		✓		
Leptocheirus plumulosus •	Amphipod			✓	✓
Melita nitida •	Elegant Amphipod	✓		✓	

Table continued on next page →

Table 2.2 *Organisms present in Harris Creek by substrate type based on eDNA samples. ‡ indicates species only found in Harris Creek; • indicates species found in all three tributaries. (Continued)*

Species	Common Name	Natural Reef	Spat on Shell Reef	Stone Reef	Sand Bottom
Bryozoan					
Amathia gracilis •	Creeping Bryozoan	✓	✓	✓	✓
Conopeum chesapeakensis ‡	Bryozoan	✓			
Membranipora tenuis •	White Crust	✓	✓	✓	
Victorella pavida	Trembling Sea Mat				✓
Worms					
Alitta succinea •	Pile Worm, Clam Worm	✓	✓	✓	✓
Eteone heteropoda •	Worm	✓	✓	✓	✓
Eteone longa ‡	Paddleworm	✓			
Glycinde multidens •	Worm	✓	✓	✓	✓
Heteromastus filiformis	Capitellid Thread Worm	✓	✓	✓	✓
Laeonereis culveri ‡	Nereid Worm	✓		✓	✓
Marenzelleria neglecta	Red-Gilled Mudworm	✓	✓	✓	✓
Polydora cornuta •	Whip Mudworm	✓	✓	✓	✓
Polydora websteri •	Oyster Mudworm	✓	✓	✓	✓
Streblospio benedicti •	Barred-Gilled Mudworm	✓	✓	✓	✓
Stylochus ellipticus •	Oyster Flatworm	✓	✓	✓	✓
TOTAL SPECIES = 49	**SPECIES COUNT =**	**35**	**33**	**35**	**35**

Table 2.3 *Organisms present in the Little Choptank River by substrate type based on eDNA samples. ‡ indicates species only found in the Little Choptank River; • indicates species found in all three tributaries.*

Species	Common Name	Natural Reef	Spat on Shell Reef	Stone Reef	Sand Bottom
Fish and Rays					
Anchoa mitchilli •	Bay Anchovy	✓			
Brevoortia tyrannus •	Atlantic Menhaden		✓	✓	✓
Chasmodes bosquianus	Striped Blenny			✓	
Leiostomus xanthurus •	Spot	✓		✓	✓
Micropogonias undulatus ‡	Atlantic Croaker	✓			✓
Rhinoptera bonasus ‡	Cownose Ray				✓
Crabs					
Callinectes sapidus •	Atlantic Blue Crab	✓			
Bivalves					
Ameritella mitchelli •	Cheating Macoma	✓	✓	✓	✓
Arcuatula papyria	Atlantic Paper Mussel			✓	
Crassostrea virginica •	Eastern Oyster	✓	✓	✓	✓
Gemma gemma	Amethyst Gem Clam			✓	✓

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Table 2.3 *Organisms present in the Little Choptank River by substrate type based on eDNA samples. ǂ indicates species only found in the Little Choptank River; • indicates species found in all three tributaries. (Continued)*

Species	Common Name	Natural Reef	Spat on Shell Reef	Stone Reef	Sand Bottom
Geukensia demissa ǂ	Ribbed Mussel	✓	✓		
Ischadium recurvum •	Hooked Mussel	✓	✓	✓	✓
Limecola petalum •	Baltic Clam	✓		✓	
Mulinia lateralis •	Dwarf Surf Clam, Coot Clam	✓	✓	✓	✓
Mytilopsis leucophaeata •	Dark False Mussel	✓		✓	✓
Snails					
Boonea impressa	Impressed Odostome Snail				✓
Haminoea solitaria ǂ	Solitary Glassy-Bubble Snail		✓	✓	✓
Littoridinops monroensis •	Cockscomb Hydrobe Snail	✓			✓
Melampus bidentatus •	Common Marsh Snail	✓	✓	✓	✓
Onobops jacksoni	Fine-Lined Hydrobe Snail	✓	✓		✓
Jellyfish					
Chrysaora chesapeakei •	Bay Nettle	✓	✓	✓	✓
Invertebrates					
Amphibalanus eburneus •	Ivory Barnacle	✓	✓	✓	✓
Amphibalanus improvisus •	Bay Barnacle	✓	✓	✓	✓
Leptocheirus plumulosus •	Amphipod	✓	✓	✓	
Melita nitida •	Elegant Amphipod	✓			
Bryozoans					
Amathia gracilis •	Creeping Bryozoan	✓		✓	✓
Membranipora tenuis •	White Crust	✓		✓	
Worms					
Alitta succinea •	Pile Worm, Clam Worm	✓	✓	✓	✓
Eteone heteropoda •	Worm	✓	✓		✓
Glycinde multidens •	Worm			✓	
Polydora cornuta •	Whip Mudworm	✓	✓	✓	✓
Polydora websteri •	Oyster Mudworm	✓	✓	✓	✓
Streblospio benedicti •	Barred-Gilled Mudworm	✓	✓	✓	✓
Stylochus ellipticus •	Oyster Flatworm	✓	✓	✓	✓
TOTAL SPECIES = 35	**SPECIES COUNT =**	**27**	**19**	**25**	**25**

Table 2.4 *Organisms present in the Tred Avon River by substrate type based on eDNA samples. Small Stone Reefs were constructed with 2-4" stones and Large Stone Reefs were constructed with 3-4" stones. ‡ indicates species only found in the Tred Avon River; • indicates species found in all three tributaries.*

Species	Common Name	Natural Reef	Spat on Shell Reef	Small Stone Reef	Large Stone Reef	Sand Bottom
Fish and Rays						
Anchoa mitchilli •	Bay Anchovy	✓	✓			✓
Brevoortia tyrannus •	Atlantic Menhaden	✓	✓	✓	✓	✓
Fundulus heteroclitus ‡	Mummichog			✓		
Leiostomus xanthurus •	Spot	✓			✓	✓
Morone americana	White Perch			✓	✓	
Morone saxatilis	Striped Bass	✓				✓
Opsanus tau ‡	Oyster Toadfish				✓	
Trinectes maculatus ‡	Hogchoker	✓				
Crabs						
Callinectes sapidus •	Atlantic Blue Crab		✓			
Bivalves						
Ameritella mitchelli •	Cheating Macoma	✓	✓	✓	✓	✓
Crassostrea virginica •	Eastern Oyster	✓	✓	✓	✓	✓
Ischadium recurvum •	Hooked Mussel	✓	✓	✓	✓	✓
Limecola petalum •	Baltic Clam				✓	
Mulinia lateralis •	Dwarf Surf Clam, Coot Clam	✓	✓	✓	✓	✓
Mytilopsis leucophaeata •	Dark False Mussel	✓	✓	✓	✓	✓
Snails						
Littoridinops monroensis •	Cockscomb Hydrobe Snail			✓		
Melampus bidentatus •	Common Marsh Snail				✓	
Onobops jacksoni	Fine-Lined Hydrobe Snail			✓		
Jellyfish						
Blackfordia virginica	Black Sea Jellyfish	✓				
Chrysaora chesapeakei •	Bay Nettle	✓	✓	✓	✓	✓
Invertebrates						
Americamysis almyra	Mysid Shrimp	✓				
Amphibalanus eburneus •	Ivory Barnacle	✓	✓		✓	✓
Amphibalanus improvisus •	Bay Barnacle	✓	✓	✓	✓	✓
Amphibalanus subalbidus ‡	Bay Barnacle		✓	✓	✓	
Apocorophium lacustre ‡	Scud Amphipod	✓		✓	✓	
Diadumene leucolena	Ghost Anemone	✓	✓			✓
Leptocheirus plumulosus •	Amphipod					✓
Melita nitida •	Elegant Amphipod	✓				
Probopyrus pandalicola ‡	Bopyrid Isopod		✓			
Bryozoans						
Amathia gracilis •	Creeping Bryozoan	✓	✓	✓	✓	✓
Membranipora tenuis •	White Crust	✓	✓	✓	✓	
Victorella pavida	Trembling Sea Mat	✓		✓		✓

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Table 2.4 *Organisms present in the Tred Avon River by substrate type based on eDNA samples. Small Stone Reefs were constructed with 2-4" stones and Large Stone Reefs were constructed with 3-4" stones. ‡ indicates species only found in the Tred Avon River; • indicates species found in all three tributaries. (Continued)*

Species	Common Name	Natural Reef	Spat on Shell Reef	Small Stone Reef	Large Stone Reef	Sand Bottom
Worms						
Alitta succinea •	Pile Worm, Clam Worm	✓	✓	✓	✓	✓
Ampharete americana ‡	Bristleworm			✓		
Eteone heteropoda •	Worm	✓	✓	✓		✓
Glycinde multidens •	Worm			✓	✓	✓
Heteromastus filiformis	Capitellid Thread Worm		✓			
Marenzelleria neglecta	Red-Gilled Mudworm				✓	
Polydora cornuta •	Whip Mudworm		✓			✓
Polydora websteri •	Oyster Mudworm	✓	✓	✓	✓	✓
Streblospio benedicti •	Barred-Gilled Mudworm	✓	✓	✓	✓	✓
Stylochus ellipticus •	Oyster Flatworm	✓	✓	✓	✓	✓
TOTAL SPECIES = 42	**SPECIES COUNT =**	**26**	**23**	**24**	**24**	**23**

Conclusions and Next Steps

In general, the use of stones in oyster restoration areas does appear to support reef structure, oyster abundance, and biodiversity.

Measures of reef structure had the clearest signal, showing that the use of stones can promote reef habitat. Across all three tributaries, reefs constructed with stone had higher cluster height and rugosity than natural reefs, and were not statistically different from spat-on-shell reefs, indicating that reefs constructed with stone can provide the benefit of reef structure habitat for reef organisms.

There also appeared to be a positive benefit of using stone reefs to support oyster abundance. Mean oyster abundances at restoration sites created with stones were two to five times higher than the restoration target of 50 oysters/m^2, indicating that stones topped with spat-on-shell can be used to rehabilitate areas of poor oyster habitat. Because stone reefs were built on sites with the poorest habitat, it is possible that the restoration targets would not have been met without the addition of a stone base. In Harris Creek, mean oyster abundances were two times higher on stone reefs than on natural and spat-on-shell reefs. In contrast, in the Little Choptank and Tred Avon Rivers, mean oyster abundances on stone reefs were lower than on natural and spat-on-shell reefs, but still higher than the restoration target. Perhaps a thicker stone base might be considered for future efforts to optimize oyster abundances on restoration areas with pre-existing conditions similar to those that were restored with stones in the Little Choptank and Tred Avon Rivers.

While numerous species were identified from the DNA sequences in water over stone reefs in all three tributaries, it was not possible to conclude that reefs made with stone were better or worse for biodiversity than natural, spat-on-shell reefs, or sand bottom. The fact that DNA of 24 to 35 species were found over stone reefs in each tributary suggests that stone reefs can support biodiversity. It is likely that the combination of different habitat types in each tributary overall supports more biodiversity than if fewer habitat types were present.

Stone size had variable influence on oyster restoration benefits. Our results show that reefs constructed with smaller (2-4") stone had higher oyster abundances than reefs built with larger stone at three years after construction. In contrast, we did not find an effect of stone size on cluster height or rugosity. For biodiversity, there was no difference in the number of species detected between 2-4" and 3-6" stone reefs, suggesting no difference in biodiversity related to stone size.

Acknowledgments

We thank Jason Spires of NOAA Cooperative Oxford Laboratory for sampling input and advice, Jennica Moffat of Oyster Recovery Partnership for providing access and insight to alternative substrate and live oyster density data, David Bruce of NOAA Chesapeake Bay Office for sharing shape files of sand habitat, Maryland Department of Natural Resources for providing additional information about the sizes of stones used in sanctuaries. We thank Smithsonian Environmental Research Center for the use of boats, vehicles, and the ARIS sonar and Rob Aguilar and Kim Richie for field support. In addition, we thank staff of UMCES Horn Point Laboratory: Greg Silsbe for use of equipment, Alison Sanford for sample processing assistance, and Jake Shaner, Emi McGeady, Diego Pacheco, Dylan Weber, and Nicholas Nishioka for field support. We thank the team at Maryland Genomics (University of Maryland School of Medicine, Institute for Genome Sciences) for sequencing services and bioinformatic analyses.

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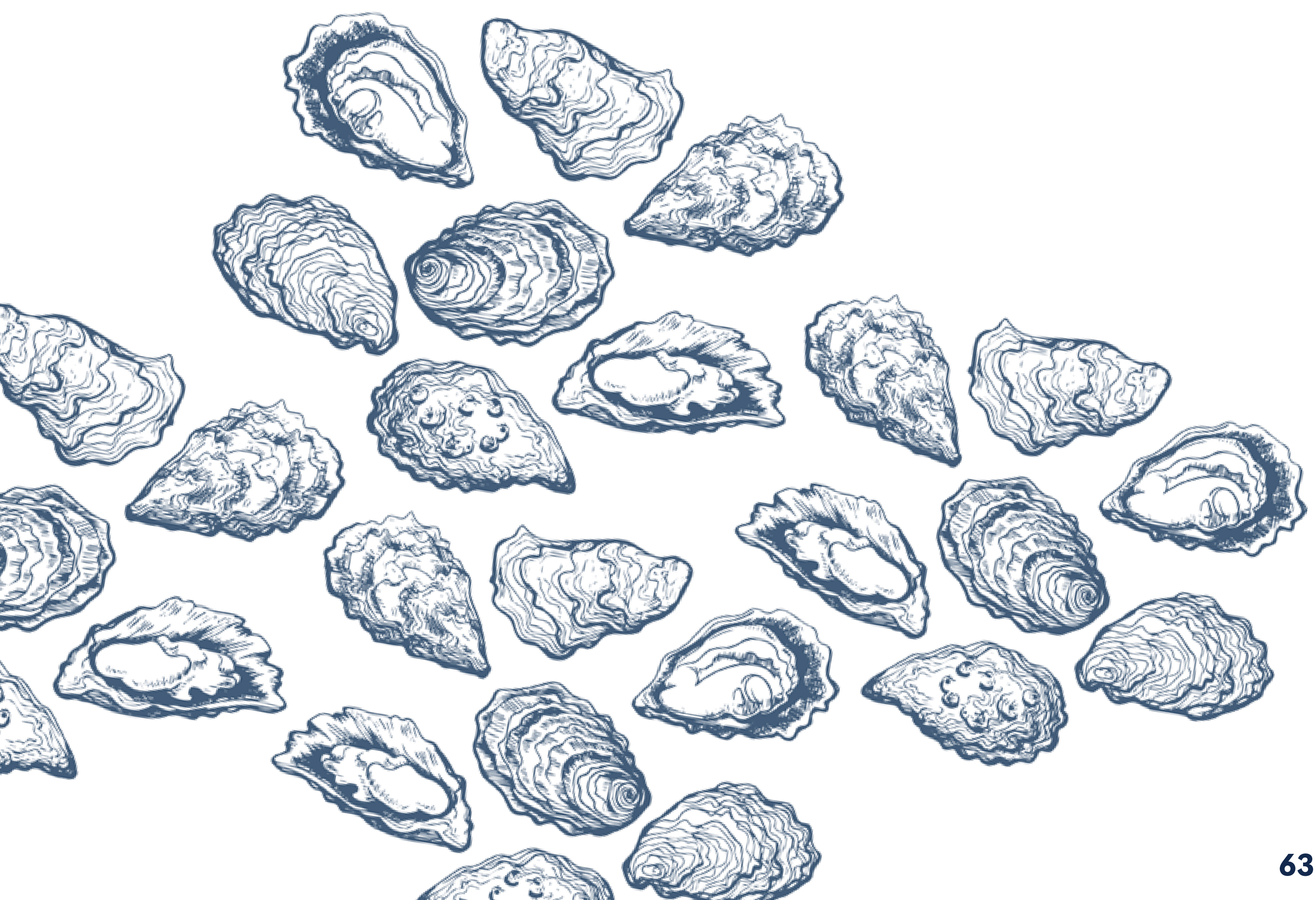
Chapter 3: Use of Alternative Substrate in Other Regions



Chapter 3: Use of Alternative Substrate in Other Regions

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University of Maryland Center for Environmental Science

Introduction

To better understand the use of alternative substrates for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates, UMCES hosted the virtual Symposium on Alternative Substrates for Oysters (SASSO) on February 26–28, 2024. The Symposium organizers are grateful to the speakers and attendants who made this event such a success.

Highlights

- There is a longstanding, widespread, and successful use of alternative substrates for enhancing oyster fishery production and restoration in large, subtidal areas along the U.S. Eastern seaboard and Gulf coasts.
- The size of the substrate is important for different applications. Small sizes of stones (< 1 to 2 inches) are regularly used in harvest areas, whereas larger stones are used in sanctuaries.

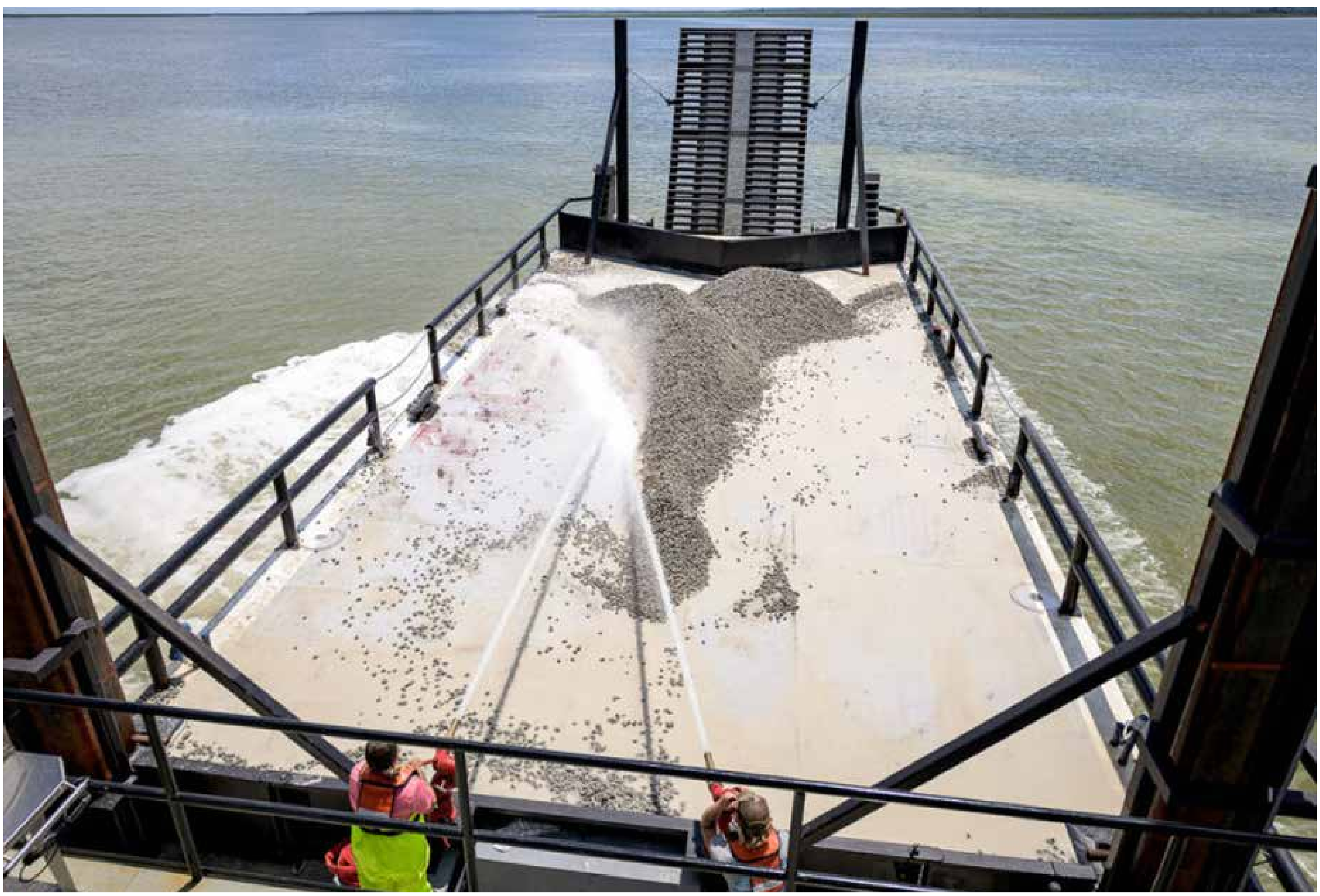


Figure 3.1 *Deployment of limestone marl in North Carolina. Photo courtesy of Doug Munroe.*

- In multiple states, stones are used in sanctuaries, and these sanctuaries are sited so that water currents carry oyster larvae out of the sanctuaries to harvest areas, thereby increasing production in the oyster industry.
- Suction dredge boats, an innovation in the aquaculture industry, can be used to reclaim and recycle oyster shells on leases.

Symposium description

The *Symposium on Alternative Substrates for Oysters* was held to better understand how alternative substrates are applied outside of Maryland for fishery, restoration, and aquaculture practices in large, subtidal areas and to learn about the successes and failures of these efforts (see full report in Appendix I). The symposium brought together shellfish managers, fishermen, aquaculturists, restoration specialists, and scientists who shared and discussed their experiences and innovations on the use of alternative substrates for oysters. Invited speakers were from the Bivalve Packing Company, Maryland Department of Natural Resources, NOAA Restoration Center, North Carolina Division of Marine Fisheries, Oyster Recovery Partnership, Virginia Institute of Marine Science, Virginia Marine Resource Commission, and Texas Parks and Wildlife Department.

On each of the three days of the virtual symposium, at least 125 people from across the nation, Europe, and Canada attended. With 21 speakers from nine states (see program booklet in Appendix II), their collective knowledge brought to light numerous commonalities and offered new ideas and practices that will inform the use of alternative substrates in Maryland and beyond. While this Executive Summary highlights commonalities, innovative ideas, and knowledge gaps, the report itself (Appendix I) offers a fuller account of each day's activities, with summaries of talks and discussions, tables of substrate types, and participants' input. Throughout this report, an alternative substrate is defined as anything other than fresh shells of the Eastern Oyster, *Crassostrea virginica*.

Results

Based on presentations at the symposium, it is clear that there is a longstanding, widespread, and successful use of alternative substrates for enhancing oyster fishery production and restoration in large, subtidal areas along the U.S. Eastern seaboard and Gulf coasts. In some states without access to fresh shells, alternative substrates are predominantly or exclusively used, such as limestone marl in North Carolina (Figure 3.1) and Texas, and river rock in Texas. In addition, crushed and cleaned (recycled) concrete has been used successfully in Florida, Maryland, Texas, and Virginia. In Virginia,

Figure 3.2 *Granite (#57 stone) that was planted on a harvest area in Virginia and shows natural oyster recruitment less than a year after planting. Photo courtesy of Andrew Button.*

granite chips (Figure 3.2) are used in oyster enhancement programs in addition to the rich supplies of both fresh and dredged oyster shells that are available in the state. Non-oyster shells, such as clam and whelk shells, are being successfully used as substrates in North Carolina and New Jersey.

The importance of the size of the substrate for different applications was a common theme at the symposium (Figure 3.3). Small sizes of stones (< 1 to 2 inches) are regularly used in harvest areas, whereas larger stones are used in sanctuaries. Smaller stones were found to be more appropriate for harvest areas because they do not damage juvenile oysters or fishing gear. In sanctuaries, larger stones provide habitat and raise the height of the bed above the bottom to promote oyster growth and survival.

Several innovative ideas and technologies were also brought forward, including shell recycling using suction dredge boats (Figure 3.4). These boats have a shallow draft and are specially designed to pull up the top 2 inches of shell and sediment from an aquaculture lease. This technique provides an efficient and cost-effective way to recycle shells within leases, ensure good spat catch, and – importantly – eliminate the need to purchase shells or other substrates. By suction dredging in the

Figure 3.3 *Different sizes of limestone marl used in Texas. Photos courtesy of Kathy Sweezey.*

wintertime, the shell has several months of drying time on land to remove fouling, which improves spat catch when the shell is deployed in early summer. Symposium co-chairs noted that dredging in wintertime may also help protect against the negative impacts of suspending sediments in regions where seagrass does not grow in winter.

Other innovative ideas focused on sanctuary siting and construction. In multiple states, sanctuaries are sited so that the spawning stock in a sanctuary is located so that water currents carry the spillover of oyster larvae out of the sanctuaries to harvest areas and thereby supplement the oyster industry. These large-scale coordinated programs for both sanctuaries and harvest areas are seen as a benefit that will ultimately enhance oyster populations and industry at the same time. In terms of sanctuary construction, innovative approaches for creating mounds tangential to currents (similar to maps of historic oyster reefs), using stone bases with shell tops, and using thousands of mini reef balls over large areas were notable innovative approaches that show great potential. The recognition that concrete structures with high relief perform better than low-relief shell plantings in polluted regions can inform urban sanctuary restoration efforts.

In addition to the suction dredge described above, innovations in aquaculture focused on new materials and structures that have been developed and show success in nearshore regions. These innovations combine new ingredients into concrete, making them more appropriate for oyster settlement and/or use new flexible materials that support oyster settlement and growth and create new shapes that have utility for nearshore and aquaculture implementations and have the potential for applications in large, subtitle areas.

Figure 3.4 *Suction dredge boat with a load of dredged shell in Delaware Bay. The head of the suction dredge is at the stern. Photo courtesy of Steve Fleetwood.*

Measuring the success of alternative substrates was another topic of discussion at the symposium. Participants agreed that the metrics that are used to determine the success of alternative substrates need to depend on the objectives of the use of alternative substrates, which can differ between fisheries, restoration, and aquaculture. While biological performance metrics (larval settlement, spat growth and survival, biodiversity) are the most commonly used to assess the suitability of substrates, structural (size, rugosity, complexity, durability) and economic metrics (costs, availability, logistics) are important to assess.

Knowledge gaps and next steps

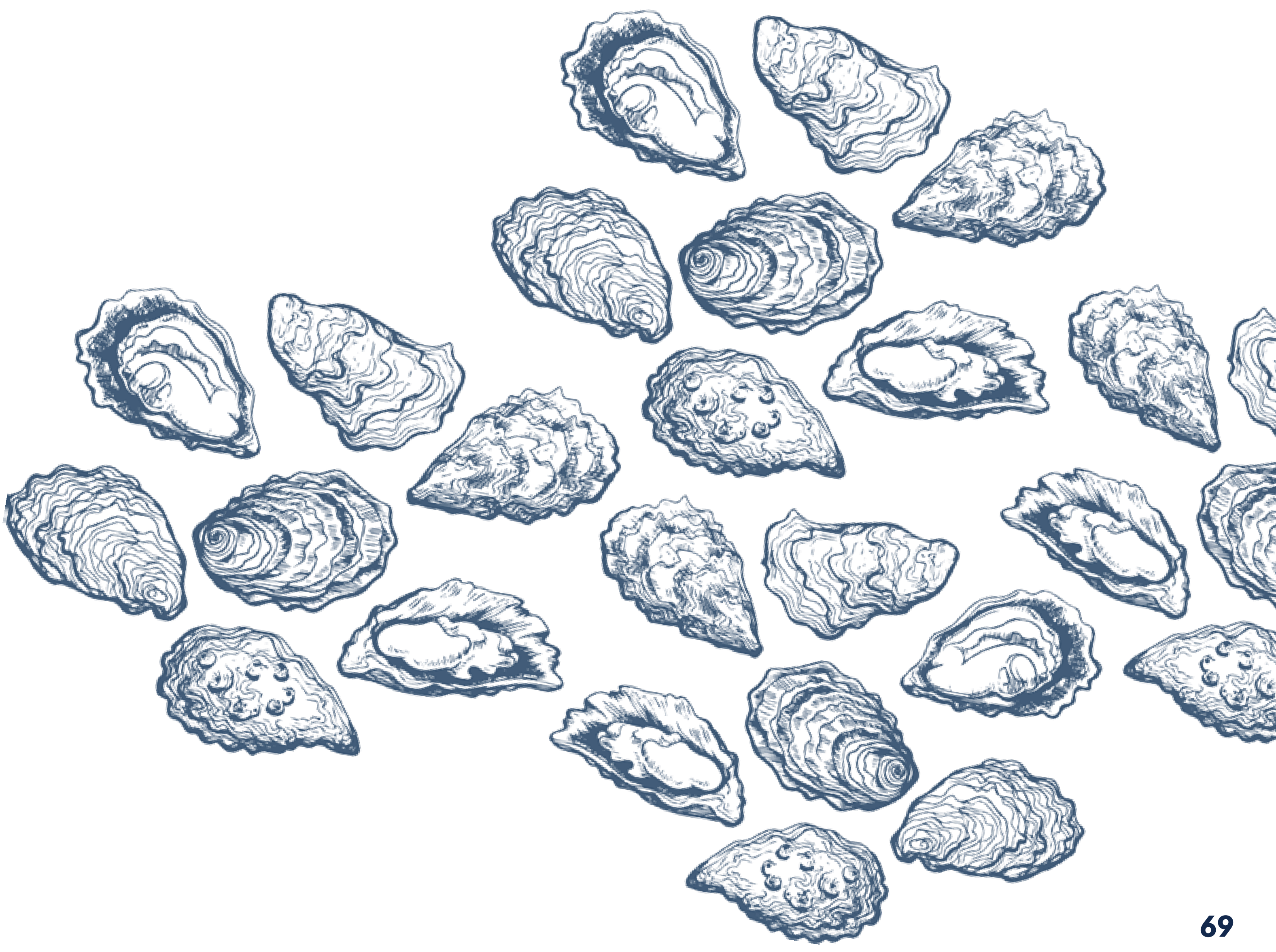
Symposium participants identified several important knowledge gaps that need to be filled to enhance the use of alternative substrates. Material properties, environmental footprint, and scalability were unanimously identified as important topics that require greater investigation in each of the three sectors. The long-term performance of alternative substrates is a key gap – how long they last in the marine environment, how long they remain productive for oysters, and the cost-benefit of the different materials over the long term. Gaps in knowledge also exist around the use of novel substrates, especially regarding environmental impacts (e.g., potential leaching of toxic chemicals and plastics), as well as how to scale up with them and transport them. Public perception and acceptability, the supply and availability of substrates, and regulations and permitting for alternative substrates were highlighted as issues that need to be addressed specifically in Maryland.

Looking forward, information from this symposium has many important uses, including offering new practices for enhancing fisheries production, restoration, and aquaculture in large subtidal areas as well as informing policy recommendations and guiding the design of laboratory and field evaluations of alternative substrates.

Acknowledgments

We are grateful to the symposium speakers and participants who made the symposium such a success, and are thankful for the IT help of Kurt Florez whose work behind the scenes made the symposium run smoothly.

Chapter 4: Retrofitting Existing Structures for Oysters



Chapter 4: Retrofitting Existing Structures for Oysters

Over 1,600 km of Chesapeake Bay shoreline are armored with bulkhead, riprap, or seawalls – structures that often degrade adjacent seagrass beds (Patrick et al. 2016) and limit ecological value. These same hardened shorelines represent a vast amount of potential hard-bottom habitat for oysters, that in turn could improve Chesapeake Bay health by enhancing water quality, biodiversity, and shoreline stability. Yet, there are challenges that need to be overcome to retrofit hard structures with oysters at a large scale, including permitting, material types, intertidal positioning, and larval supply.

To address these challenges, we held a symposium and conducted a field trial to better understand the potential for retrofitting existing structures, such as riprap revetments, to include oyster plantings. The international virtual symposium was held to survey the state of knowledge and current practices for including oysters in shoreline structures. Using the symposium findings, we evaluated nine techniques for retrofitting breakwaters and one method for retrofitting piers at UMCES Horn Point Laboratory.

A. Symposium on Strengthening Habitats with Oysters on Retrofitted & Engineered Structures (SHORES)

Authors

Matthew Gray, Monica Fabra, Conor Keitzer, Roshni Nair-Gonzalez, William Nardin, and Elizabeth North, University of Maryland Center for Environmental Science

Introduction

Maryland's growing need to protect shorelines while restoring oyster habitat prompted the creation of the **SHORES Symposium (Strengthening Habitats with Oysters on Retrofitted & Engineered Structures)** as a coordinated response to this dual challenge. Hosted by the University of Maryland Center for Environmental Science, the event brought together scientists, engineers, managers, and policymakers to explore how built coastlines can be adapted to support oysters and enhance resilience. The two keynote speakers were Rochelle Seitz of Virginia Institute of Marine Science and Kristen Orff of SCAPE.

Highlights

- Case studies demonstrated that retrofitting coastal structures such as riprap, seawalls, and pilings with habitat-forming materials for oysters can lead to oyster growth and survival, and produce measurable benefits for biodiversity, shoreline stability, and water quality.
- Success was demonstrated in small-scale (meters) to large-scale (kilometers) projects, showing that oysters can colonize even heavily modified environments when designs promote larval settlement.
- Joint design by engineers, ecologists, and planners coupled with performance monitoring are necessary to ensure both ecological success and structural reliability.
- Permitting is a current constraint. Streamlining this could be done by developing Maryland-specific guidelines that define performance metrics and creating a policy/regulatory framework that defines different types of oyster additions (like veneer on existing breakwater or expanding the toe of the breakwater).

- It is clear that there is a vibrant community eager to advance projects that link ecological uplift with shoreline restoration, and that Maryland is well-positioned to lead in this emerging field, given its scientific expertise, restoration infrastructure, and policy support.

Symposium Description

The Strengthening Habitats with Oysters on Retrofitted and Engineered Structures (SHORES) Symposium, held virtually on February 26–27, 2025, was convened to address Maryland Senate Bill 830's mandate to explore the potential for retrofitting existing structures, such as riprap revetments, to support oyster habitat (see full report in Appendix III). Hosted by the University of Maryland Center for Environmental Science, the event gathered +350 participants representing government agencies, academia, industry, and non-profit organizations. Over two days, 20 invited speakers and poster presenters from across the U.S. and Europe shared research, case studies, and engineering innovations for integrating oysters into shoreline protection and restoration designs (see full speakers list in program booklet in Appendix IV). Discussions emphasized balancing ecological function with engineering performance and identifying design standards, permitting pathways, and monitoring frameworks for scalable implementation. The symposium provided a foundation for cross-sector collaboration and informed Maryland's emerging strategy to unite habitat restoration with resilient coastal infrastructure.

Results

The **SHORES Symposium** provided a comprehensive overview of emerging science and design innovations focused on enhancing oyster habitat within existing and engineered coastal structures. Case studies demonstrated that retrofitting structures such as riprap, seawalls, and pilings with habitat-forming materials can produce measurable benefits for biodiversity, shoreline stability, and water quality, while complementing ongoing oyster restoration efforts in the coastal systems (e.g. Figure 4A.1), including Chesapeake Bay. Across talks, several consistent themes emerged: the ecological value

Figure 4A.1 *Oyster monitoring along the Living Breakwater project in Staten Island, New York. Photos courtesy of Carolyn Khoury.*

of microhabitats such as crevices for oyster survival; the potential for oysters to enhance the longevity and adaptive capacity of grey infrastructure; the promise of lightweight, modular structures for scalable deployment; and the importance of pairing physical engineering with biological monitoring.

A key outcome of the symposium was recognition that interdisciplinary design frameworks are essential to advance habitat-enhancing infrastructure. Engineers, ecologists, and planners stressed that joint design and performance monitoring are necessary to ensure both ecological success and structural reliability. Modeling studies presented by researchers from the University of Florida and Virginia Institute of Marine Science showed that oyster-integrated systems can dissipate wave energy, enhance sediment retention, and provide adaptive protection that grows with sea-level rise.

Participants emphasized that retrofit potential is substantial but is highly dependent on the specific site. Success depends on matching substrate type, surface texture, and intertidal elevation to local hydrodynamics and oyster recruitment potential. The scale of projects presented varied considerably, indicating that there is an opportunity to match oyster integration efforts with the amount of resources (natural, financial, labor, etc.) that may be available at any given time. There was also a diverse array of products and approaches, and strategies used—from biodegradable oyster "cuffs" for pilings (Figure 4A.2) to modular reef units for urban harbors (Figure 4A.3) and offshore wind installations. These examples illustrated that oysters can colonize even heavily modified environments when designs promote larval settlement.

The symposium also revealed the importance of standardization and policy coordination. Participants identified a lack of consistent design and monitoring criteria as a barrier to scaling oyster retrofits statewide. Discussions called for developing Maryland-specific guidelines that define performance metrics. The concept of integrating oysters into existing grey infrastructure or incorporating them into living shoreline projects is novel, creating new design and permitting issues. Classifying oyster integration efforts by how they affect the underlying infrastructure geometry might help smooth

Figure 4A.2 *Oyster Catcher™ piling cuff installed in Bogue Sound, Morehead City, NC in February 2024, and photographed a year later. Photos courtesy of Niels Lindquist.*

permitting. For example, differentiating oyster additions that add a veneer of oyster habitat would not be expected to have the same regulatory hurdles as oyster-based structures that expand the footprint of a structure or impact the navigability of the surrounding water. Developing a policy/regulatory framework that teases out these strategies could help streamline permitting. Several speakers noted that these standards should be co-developed through collaboration between state agencies, academic institutions, and private partners.

Innovation and scalability were recurring themes throughout both the talks and poster sessions. Presenters introduced a range of new materials and fabrication approaches, including 3D-printed substrates, jute-reinforced concrete, and tunably biodegradable clay units. These technologies promise to reduce cost, carbon footprint, and permitting complexity while enabling rapid, large-scale production of oyster-friendly infrastructure. Industry partners underscored that scaling up adoption will require sustained investment in research, demonstration projects, and local workforce development.

Finally, the symposium underscored a strong momentum for collaboration and implementation. Polling results and breakout discussions reflected a community eager to advance pilot projects that link ecological uplift with shoreline protection. Attendees widely agreed that Maryland is well-positioned to lead in this emerging field, given its scientific expertise, restoration infrastructure, and policy support. The SHORES Symposium, therefore, not only fulfilled its legislative mandate but also laid the groundwork for a coordinated, science-driven approach to building resilient coasts that work with nature rather than against it.

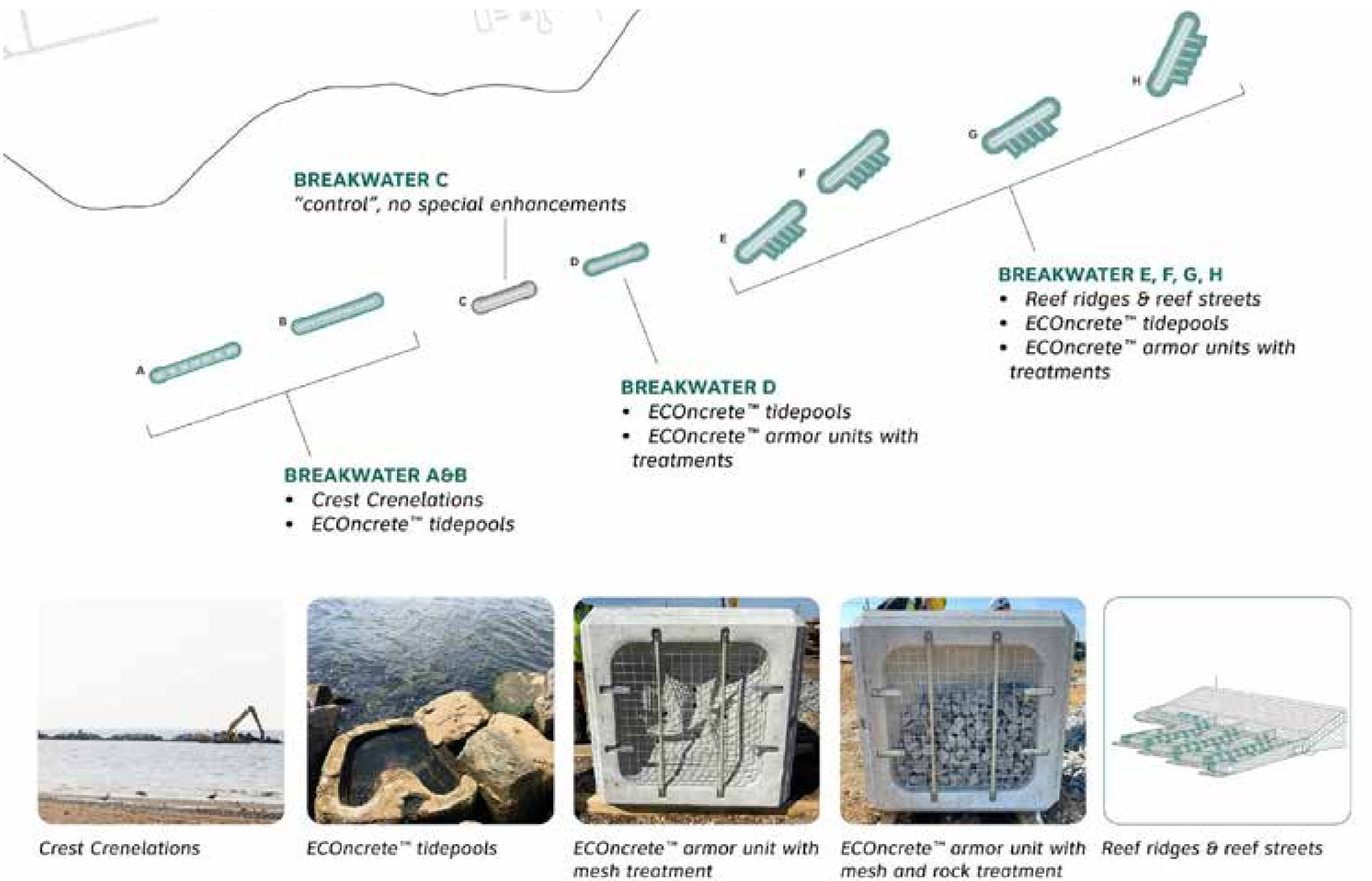


Figure 4A.3 *Diagram of the Living Breakwaters project in Staten Island, New York, demarcating the various types of units used to retrofit the breakwaters. Diagram and photos courtesy of Kate Orff.*

Knowledge Gaps and Next Steps

The SHORES symposium revealed that one of the greatest challenges to integrating oysters into coastal infrastructure is identifying the "sweet spot" between the engineering requirements for shoreline stabilization and the biological requirements that oysters need to thrive. In Maryland, this balance is particularly delicate because oysters placed too high in the intertidal zone face lethal winter freezing (Gray, unpublished data), while those too low provide limited shoreline protection. Determining how to design, place, and shape structures so that oysters can survive while still attenuating waves represents the next frontier of building with nature. Participants noted that understanding long-term material performance, recruitment dynamics, and the hydrodynamic effects of surface complexity will be essential to achieving this balance. These data are currently limited, and without them it is difficult to develop standard design guidance or quantify the physical and ecological tradeoffs of hybrid systems.

Looking ahead, advancing oyster-based infrastructure in Maryland will require a tighter integration of engineering and ecology. Future efforts should focus on developing and testing designs that couple structural durability with environmental suitability, supported by long-term field trials across different salinity and exposure gradients. Streamlined permitting processes and standardized performance metrics are also needed to accelerate innovation and evaluate success consistently. By addressing these gaps, Maryland can transform aging grey infrastructure into living systems that strengthen shorelines, enhance biodiversity, and exemplify how coastal protection and habitat restoration can work together under a changing climate.

Acknowledgments

We are grateful to the symposium speakers and participants who made the symposium such a success, and are thankful for the IT help of Kurt Florez whose work behind the scenes made the symposium run smoothly.

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B. Field Evaluation of Breakwater and Piling Retrofits

Authors

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Introduction

In the Chesapeake Bay, shoreline armoring using rock (riprap) and concrete (seawalls) has become widespread, yet these hard structures provide limited ecological function and are increasingly vulnerable to climate-driven deterioration and failure due to sea level rise (Temmerman et al. 2013). Retrofitting these existing "grey" shorelines with biologically active elements —particularly oysters— offers a promising strategy to enhance habitat value and structural resilience simultaneously. Oysters naturally build reef structures that stabilize sediment, attenuate waves, and grow vertically at rates that can keep pace with sea level rise, aligning ecological benefits with coastal protection goals (Reidenbach et al. 2025).

Maryland Senate Bill 830 directed UMCES to evaluate "the potential for retrofitting existing structures, such as riprap revetments, that are unrelated to oyster restoration but that use materials similar to artificial reefs, to include oyster plantings". This study addressed that mandate by testing practical, scalable retrofits within or next to the existing riprap and around pier pilings at UMCES Horn Point Laboratory (HPL) in Cambridge, MD.

Three approaches for retrofitting shoreline structures were examined: 1) **Integrated** materials that were put on existing riprap; 2) **Supplemental** materials that were put at the base (toe) of the riprap; 3) **Piling wraps** attached to the pilings on a pier near the riprap shoreline. The retrofit materials were placed in a setting tank on the Horn Point Oyster Hatchery (HPOH) pier where oyster larvae were added and given time to attach (Figure 4B.1). The retrofits then were deployed on or near the riprap and around pilings at a nearby pier. We evaluated ease of deployment as well as durability and abundance of spat (juvenile oysters) after three months.

Highlights

- All retrofits tested—supplemental, integrated, and piling wraps—attracted oyster larvae and supported spat growth, demonstrating that a wide range of materials can enhance habitat value along armored shorelines. The retrofits were deployable by one or two people and lasted for at least three months in a high-energy environment subject to wind and storm waves.
- Among the supplemental materials, spat counts were highest on the Tables, followed by Shoreline Habitat Units (SHU), Oyster Castles and finally Reef Arches that had the lowest spat numbers. Among the integrated materials, Tufts supported the highest spat abundances, followed by Tridents, HPL riprap stone, Havre de Grace stone, and Inserts with the lowest spat numbers in the group.
- Durability varied across designs: the Table units and Tufts degraded the fastest, whereas several other materials —including SHU units, Oyster Castles, HPL riprap stone, Havre de Grace stone, and Tridents— maintained high structural integrity during the 3-month evaluation period.

- Across all approaches, Oyster Castles, HPL riprap stones, Tridents, SHU units, and Havre de Grace stones had the highest total performance scores, suggesting that both integrated and supplemental approaches provide viable, high performing options for oyster habitat that are durable and straightforward to deploy.

Methods

The study was carried out along the HPL shoreline on the Choptank River, targeting low-intertidal zones to minimize risk of winter oyster mortality. A suite of retrofit materials were tested that were specifically selected for being lightweight, cost-effective, and deployable by hand. These included existing stones from the HPL riprap, Havre de Grace stones (metagabbro and quartz diorite stone from a quarry in Havre de Grace, MD), Oystercatcher™ Tufts and Tables (Sandbar Oyster Company), Reef Arch inserts and small Reef Arches, Native Shoreline's Tridents, Shoreline Habitat Units (SHU), and Oyster Castles (Table 4B.1). All materials except for the stones used a form of concrete without or with additions (e.g., jute fiber core in Tufts and Tables or oyster shell in Tridents).

Retrofits were organized into three categories:

- **Integrated** approaches, where materials were incorporated into existing riprap structures without altering the riprap footprint or stability (i.e., placed on the riprap);
- **Supplemental** approaches, where units were placed at the base of riprap in adjacent shallow, subtidal waters to expand habitat and resilience (i.e., placed at the toe of the riprap); and
- **Piling wraps**, where units were secured to the pilings of a pier

Figure 4B.1 *Photos of the retrofit materials in the oyster setting tank at Horn Point Laboratory A) before flooding the tank with river water and adding oyster larvae, and B) after oyster larvae were added and given 10 days to attach to the materials. Photographs by Jake Shaner and Elizabeth North.*

Six units of each retrofit type were placed in a single tank on the Horn Point Oyster Hatchery setting pier in July of 2025 (Figure 4B.1) and two million Eastern Oyster (*Crassostrea virginica*) larvae were added. After 10 days in the tank, each retrofit unit was deployed to the field site (Figure 4B.2).

To determine if wild oysters also set on the retrofit materials, six strings of Eastern Oyster shells were attached to the Horn Point Laboratory pier and left submerged from July to October, 2025. The strings were built to the specifications of the Virginia Institute of Marine Science manual for monitoring natural oyster reproduction (Southworth 2017) and were composed of 12 fresh Eastern Oyster shells attached in a vertical line using stainless steel wire. Because a total of three spat were found on the 72 shells, we decided that no corrections of retrofit count data were necessary because natural oyster reproduction in the area was negligible.

In October of 2025, each retrofit unit was retrieved and moved to the shoreline and photographed to assess oyster abundance and survival. Retrofit units were evaluated for spat abundance by repetitively subsampling each unit with multiple photographs of a 10 cm x 10 cm quadrat, counting the number of spat in each quadrat, and then calculating the mean number of spat in all quadrats for each unit. More than 20% of all available surface area from each replicate retrofit was photographed during the subsampling process.

We evaluated and scored each candidate retrofit material based on ease of deployment as well as durability and spat abundance after three months. We focused on these metrics with both contractors in mind (the people who likely would be installing retrofits) and the need to assess how materials performed in the field environment.

Ease of Deployment
Ease of deployment was assessed based on the number of people required to safely and efficiently install a single retrofit unit. Scores reflected the practical effort needed retrofit riprap or pilings:

- **High (3)**: A single person can deploy a unit easily.
- **Moderate (2)**: Two people are required, but deployment is still straightforward.
- **Low (1)**: Two to three (or more) people are needed to deploy one unit, indicating substantial logistical effort.

This criterion captures real-world constraints that contractors would face when installing retrofits that would impact scalability for restoration or shoreline protection applications.

Durability
Durability of retrofit units and materials was heavily weighted because structural integrity is essential for retrofit function and because any noticeable degradation within a three-month window would be concerning. We assessed durability after retrieval using a graded scale:

- **High (10)**: No visible signs of degradation.
- **Moderate–High (9–7)**: Slight degradation or minor superficial damage.
- **Moderate (6–4)**: Limited but clear signs of degradation extending beyond superficial wear.
- **Low (3–1)**: Obvious structural degradation, compromised integrity
- **Loss (0)**: Complete loss of unit (removal or total disintegration)

Spat Abundance

Spat abundance (spat counts per 100 cm²) measured the material's ability to attract settlement of oyster larvae in the hatchery tank and support spat survival during the field deployment period. To assess spat abundance on the larger retrofits, we counted the number of spat in multiple quadrats and calculated the mean number of spat in all quadrats taken for each unit. For smaller retrofits like stones and Tufts, we counted all spat and accounted for surface area to estimate the abundance per 100 cm².

For the ten materials evaluated, we computed the 20th, 40th, 60th, and 80th percentiles of mean spat abundance. Each material was then assigned to a performance category based on its position within this distribution. Because percentiles were defined by percentage thresholds rather than equal group sizes, categories might contain different numbers of materials, reflecting real differences in spat settlement.

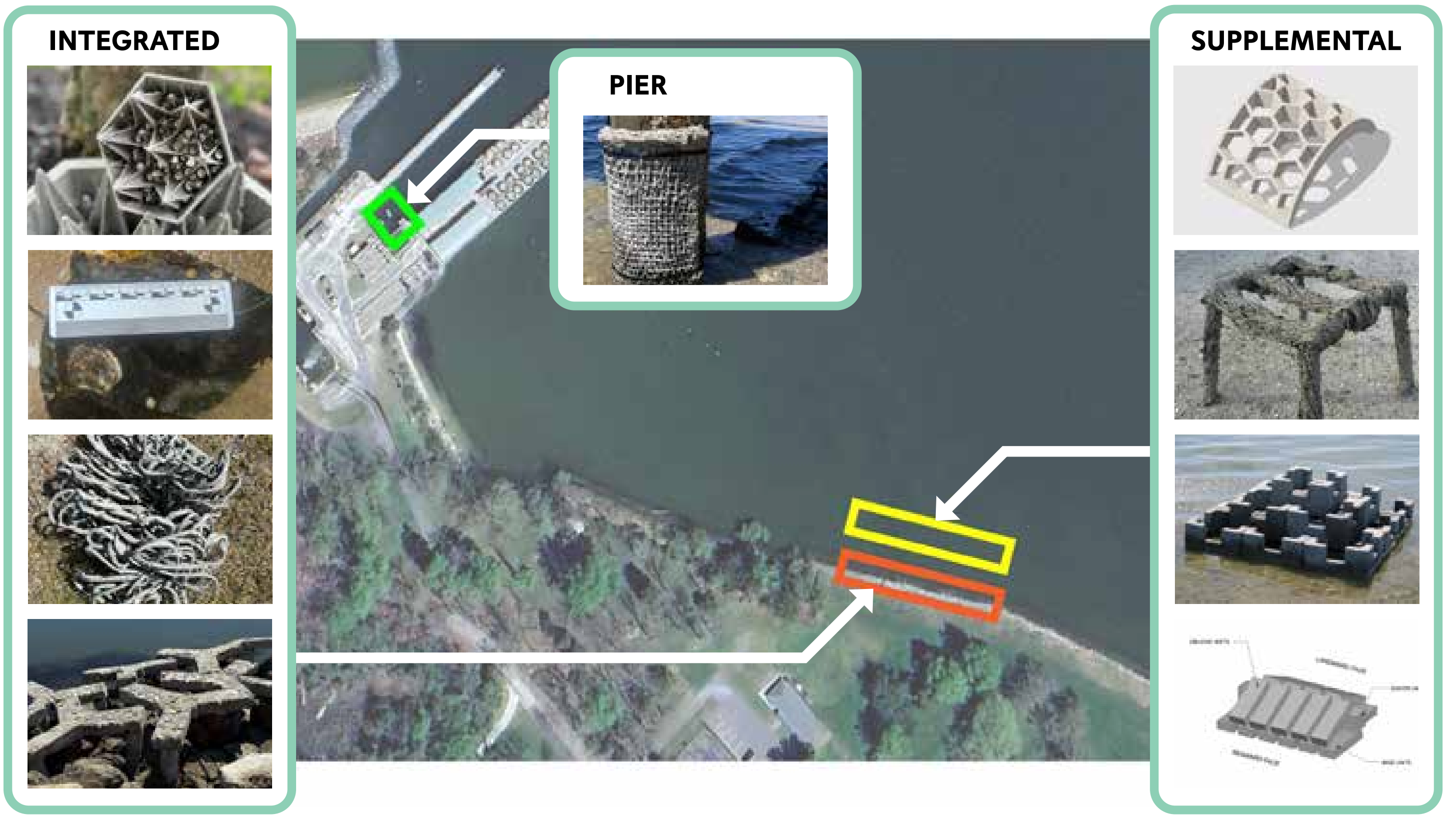

Figure 4B.2 *Deployment locations of retrofits in the high-energy field site at Horn Point Laboratory (HPL). All materials were pre-seeded in an oyster larvae setting tank at HPL. Orange outlines and the left panel photos indicate integrated approaches that were placed directly in and on the riprap along the HPL shoreline. Integrated approaches included (top to bottom) Reef Inserts, Havre de Grace stones, Tufts, and Trident structures. Yellow outlines and the right panel photos and diagrams indicate supplemental approaches that were placed on the river bottom directly in front of the riprap. Supplemental approaches (top to bottom) included Reef Arches, Tables, Oyster Castles, and Shoreline Habitat Units (SHU). The top middle panel shows a piling wrap made of coated jute fiber. These piling wraps were strapped directly to the wooden pilings of the HPL pier. The field site areas outlined in this figure are not drawn to scale.*

Spat Count Score (1–5):

5: 80th-100th percentile (highest-performing materials)

4: 60–80th percentile

3: 40–60th percentile

2: 20–40th percentile

1: 0-20th percentile (lowest-performing materials)

This percentile-based classification provided a scale that was both statistically defensible and biologically meaningful, allowing materials to be compared on a relative performance spectrum without distortion from extreme outliers.

Combining Scores into a Total Performance Score
Scores for ease of deployment, durability, and spat abundance were added together to create a Total Performance Score for each retrofit. This combined score gave a simple overall picture of how each material performed. Because there were different approaches to retrofitting—Integrated, Supplemental, and Piling Wrap— that exposed retrofits to different deployment conditions, the Total Performance Score should be viewed as a general comparison rather than a strict ranking. While differences in deployment conditions matter, the scoring system offers insight into which retrofits may be most effective or practical for high-energy shorelines.

Data Analysis
To compare spat abundance between retrofit units, we used a one-way analysis of variance statistical test (ANOVA) to evaluate differences in mean spat counts per 100 cm^2 among retrofit types within the integrated and supplemental approaches. All assumptions of data (e.g., normality) were tested and met prior to performing the ANOVA test. When ANOVA results indicated significant differences among retrofit types, we conducted Tukey's Honestly Significant Difference (HSD) post-hoc tests to identify which types differed from one another.

Results

Oysters settled and grew on all four supplemental retrofits that were deployed along the Horn Point shoreline: Tables, SHU units, Oyster Castles, and Reef Arches. These materials were installed in shallow subtidal waters next to existing riprap to evaluate their potential to expand habitat and enhance shoreline resilience.

Ease of deployment and durability differed between supplemental retrofit options (Table 4B.1), with SHU units being the most difficult to deploy, Oyster Castles being the easiest, and the remaining options receiving a moderate ease of deployment score. Oyster Castles and SHU units had highest durability scores with no visible signs of degradation. Reef Arches had moderate-to-high durability while Tables scored Low, with obvious structural degradation due to the high energy environment, material breakdown, and handling.

Clear differences emerged among the supplemental retrofits in terms of spat performance (Figure 4B.3). Table units supported the highest mean spat counts (Figure 4B.3) and were significantly greater than the other supplemental retrofits tested except for SHU units. While Reef Arches, SHU units and Oyster Castles did not differ significantly from one another, Reef Arches had the lowest mean spat counts overall.

Total performance score for supplemental approaches (Table 4B.1) – that integrated ease of deployment, durability, and spat performance – resulted in the following ranking: Oyster Castle > SHU unit > Reef Arch > Tables. Although Oyster Castles did not have the highest spat performance score (2 of 5), its ease of deployment and durability were high. Overall, results show that supplementing existing riprap with appropriately designed materials can increase oyster habitat, and that the choice of retrofits strongly affects the magnitude of that benefit.

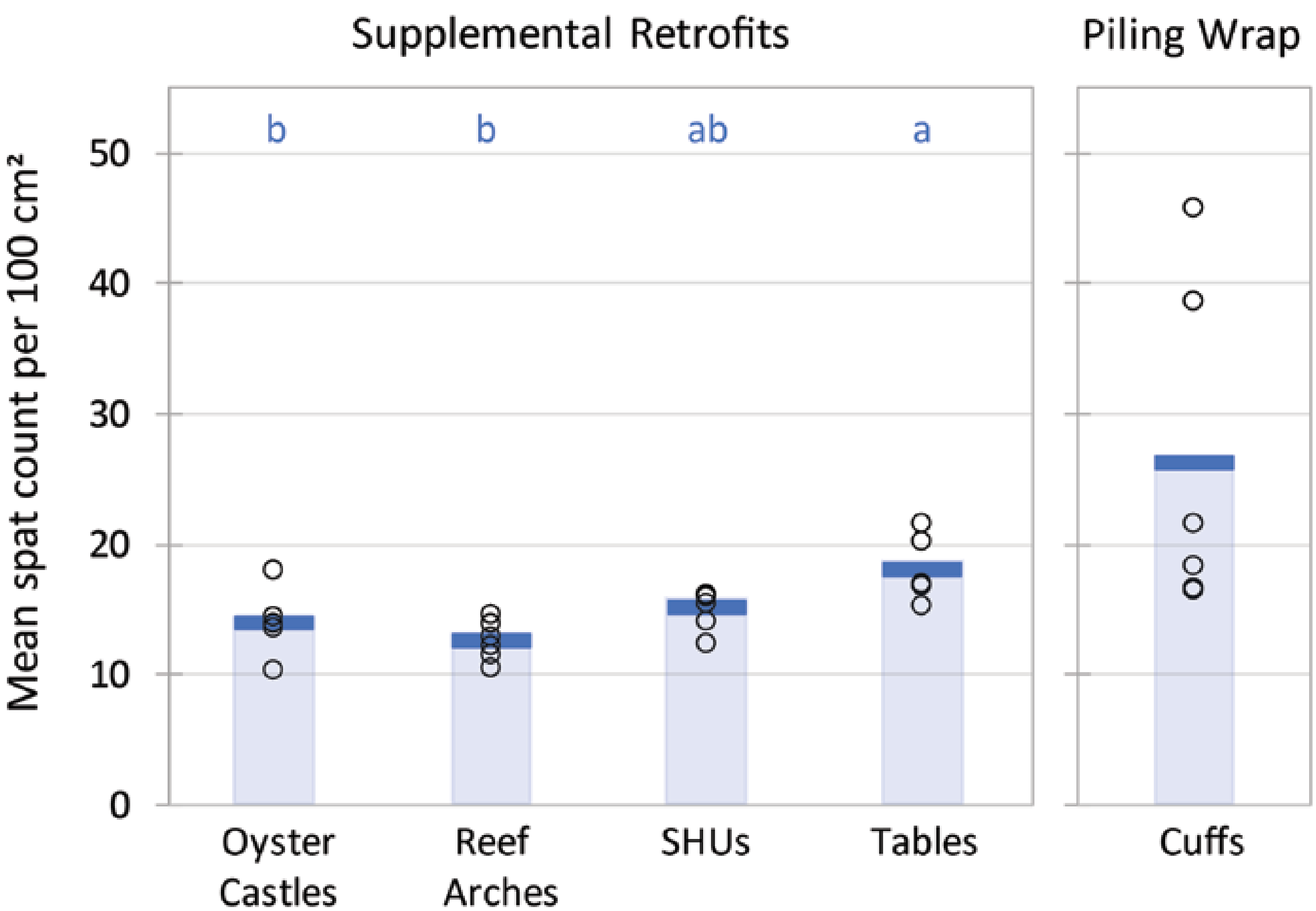

Figure 4B.3 *Mean spat count per 100 cm² on supplemental retrofits (left) deployed in the subtidal zone near riprap along the Horn Point Laboratory shoreline, and piling wraps (right) deployed on a nearby pier. Open circles are individual data points and the top of each bar is the mean. Means that do not share a letter at the top of the plot are significantly different.*

Oysters settled and survived on all of the integrated retrofits that were placed directly within the riprap along the Horn Point Laboratory shoreline. These materials—HPL riprap stones, Havre de Grace stones, Tufts, Reef Arch inserts, and Tridents—were evaluated to understand how different materials perform when incorporated into a high-energy riprap shoreline.

Ease of deployment and durability differed between supplemental retrofit options (Table 4B.1), with Tridents having lowest ease of deployment (1 of 3) and the other materials having high ease of deployment (3 of 3). In contrast, Tridents and stones (HPL riprap and Havre de Grace) had highest durability (10 of 10) while Reef Arch Inserts and Tufts scored moderate to low durability, respectively.

In terms of spat counts, Tufts supported the highest numbers of live oysters (Figure 4B.4). Spat counts on Tufts were significantly greater than all other tested materials. Havre de Grace stone, Inserts, and Tridents formed a group with comparatively lower oyster counts, and differences among these three materials were not statistically significant.

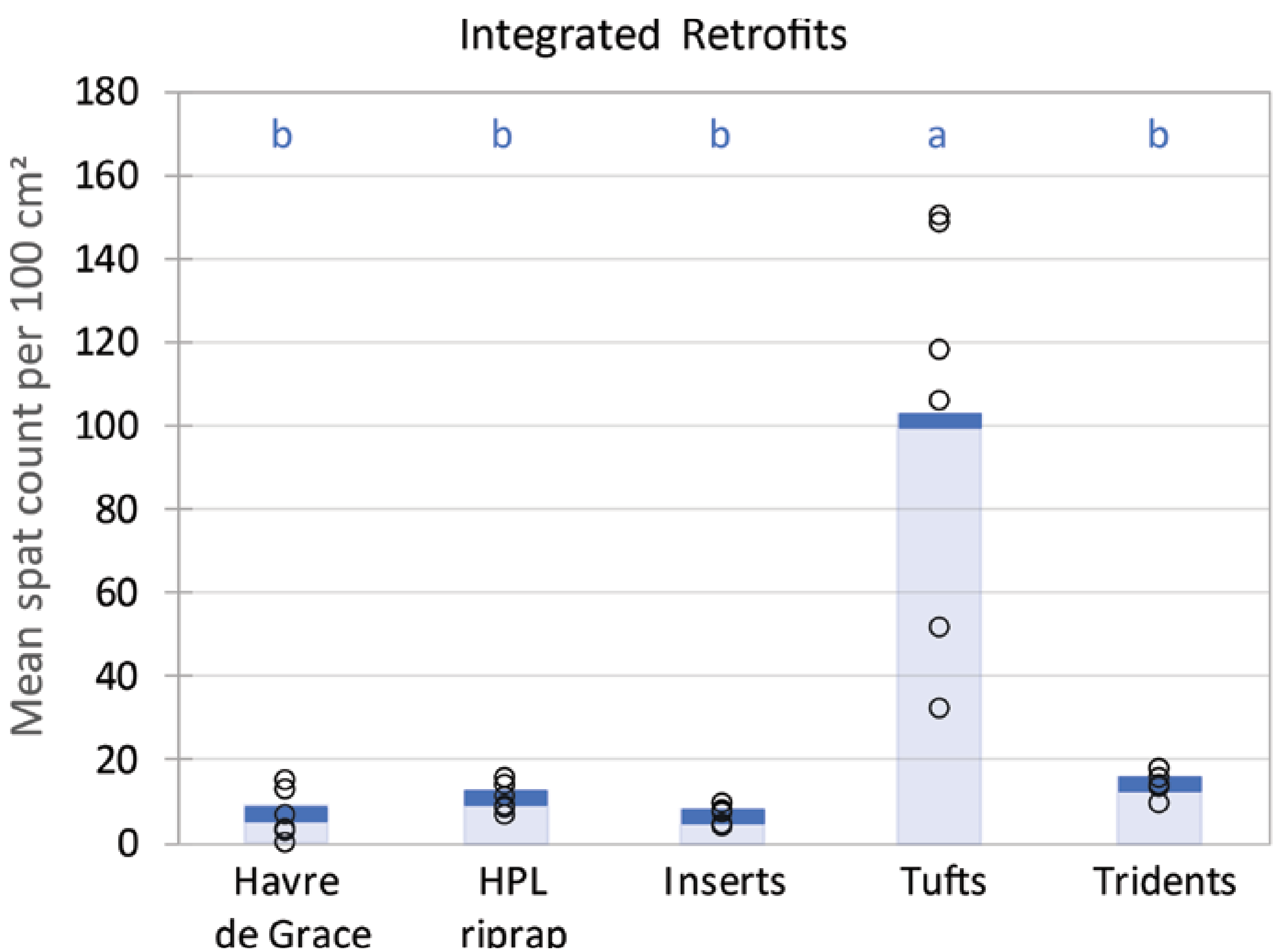

Figure 4B.4 *Mean spat count per 100 cm² on integrated retrofits incorporated within the riprap along the shoreline at Horn Point Laboratory. Open circles are individual data points and the top of each bar is the mean. Means that do not share a letter at the top of the plot are significantly different.*

Total performance scores for integrated retrofits (Table 4B.1) after the three month deployment resulted in the following ranking: HPL riprap stones > Havre de Grace stones and Tridents > Tufts > Inserts. The best performers (stones) scored well for ease of deployment and durability but relatively low for spat count (1 or 2 out of 5). While low spat count scores in comparison to the other retrofits, the total number of spat on the stones ranged from 30 to 50 individuals on average. Tufts had the highest spat count score (5 of 5) but lowest durability (2 of 10) in the high wave energy conditions.

To understand how pilings on piers, bulkheads, and other structures could be retrofitted with oysters, we evaluated the performance of Cuffs. Cuffs had a relatively high spat count score (4 of 5) but a moderate durability (5 of 10) and ease of deployment score (2 of 3) (Table 4B.1). When considered alongside the broader patterns observed in both the supplemental and integrated retrofit approaches, Cuffs appear to perform within an intermediate range in terms of total performance score.

Total performance scores allow comparison across retrofit approaches (Supplemental, Integrated, and Piling Wrap) (Figure 4B.6). Across approaches, Oyster Castles, HPL riprap stones, Havre de Grace stones, Tridents and SHU units had the highest total scores, suggesting that both integrated and supplemental approaches provide viable, high performing options. Despite differences in deployment conditions and unit shape, all three approaches and all retrofits tested supported measurable spat settlement, were deployable by one or two people, and lasted for at least three months in a high-energy environment.

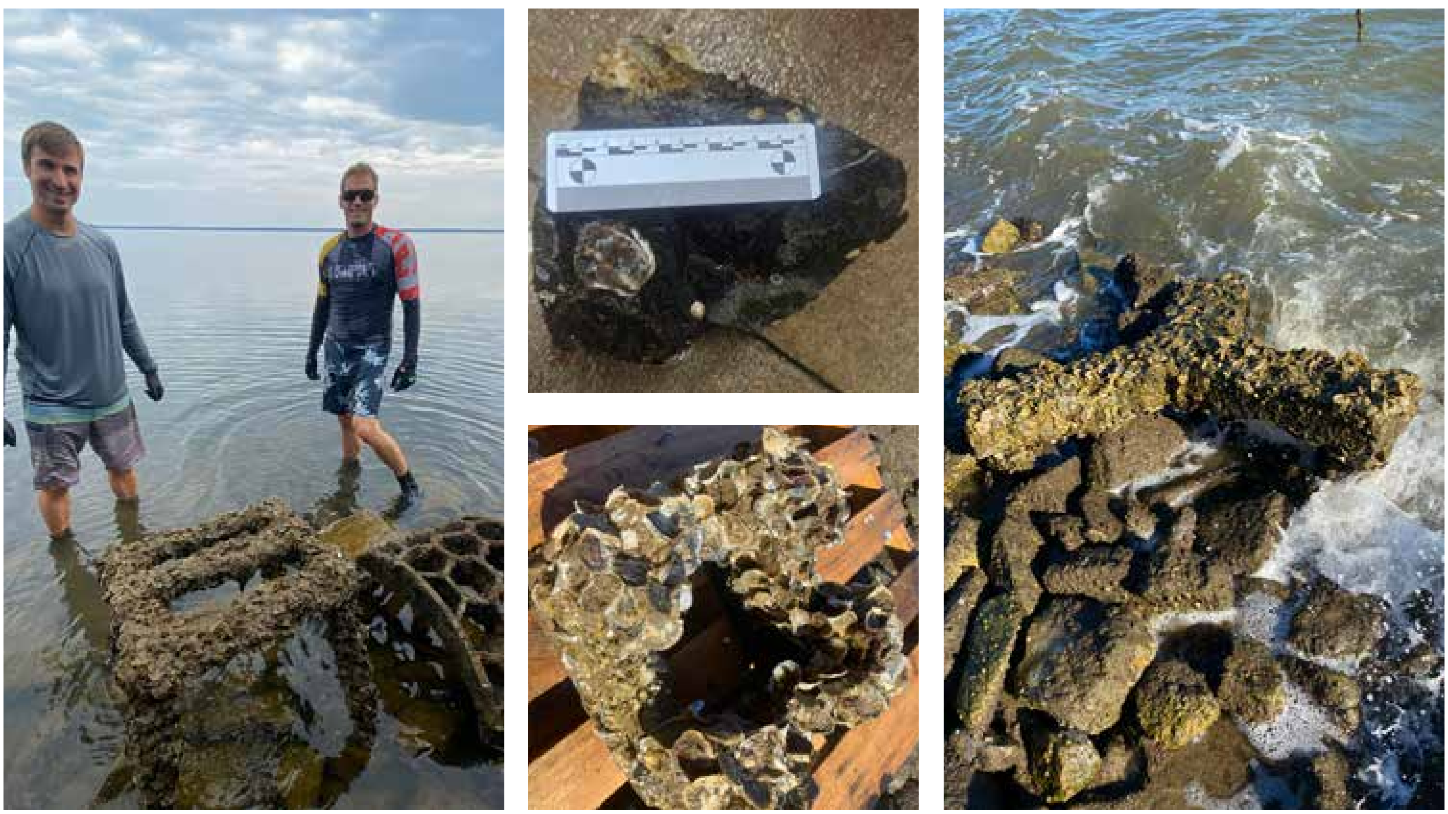

Figure 4B.5 *Photograph of Tables and Reef Arches (Left), Havre de Grace stone and Oyster Castles (Center), and Tridents (right) on retrieval three months after development. Researchers Jake Shaner and Matthew W. Gray shown in the left panel. The ruler in the top center panel is 10 centimeters long. Photos by Elizabeth North and Jake Shaner.*

Table 4B.1 *Retrofits deployed in field study. Unit descriptions including dimensions and composition can be found at the company websites using hyperlinks embedded in the product name. Scoring criteria justification can be found in the method section above. Minimum and maximum scores are: 1-3 for ease of deployment, 1-10 for durability, 1-5 for spat count, and 3-18 for total performance. Total performance score was the sum of the ease of deployment, durability and spat count scores. N/A = not applicable because HPL riprap stones were taken from the riprap (not purchased).*

Approach	Product	Cost ($ per piece)	Mean spat count per 100 cm²	Ease of deployment score	Durability after three months score	Spat count score	Total performance score
Integrated (On-riprap)	HPL Riprap stones	N/A	10.5	3	10	2	**15**
	Havre de Grace stones	$0.73	6.6	3	10	1	**14**
	Tufts from the Oystercatcher™ product line (Sandbar Oyster Company)	$35	100.8	3	2	5	**10**
	Inserts (Reef Arch)	$50	5.9	3	5	1	**9**
	Tridents (Native Shoreline)	$100	13.6	1	10	3	**14**

Table continued on next page →

Approach	Product	Cost ($ per piece)	Mean spat count per 100 cm²	Ease of deployment score	Durability after three months score	Spat count score	Total performance score
Supplemental (Toe of riprap)	Oyster Castles (Allied Concrete; Subsidiary of Chaney)	$9	13.9	3	10	5	**16**
	Small Reef Arches (Reef Arches)	$300	12.5	2	7	2	**11**
	Shoreline Habitat Units (Native Shorelines)	$80	15.0	1	10	4	**15**
	Tables from the Oystercatcher™ product line (Sandbar Oyster Company)	$95	17.9	2	3	4	**9**
Piling Wrap	Cuffs from the Oystercatcher™ product line (Sandbar Oyster Company)	$50	26.2	2	5	5	**12**

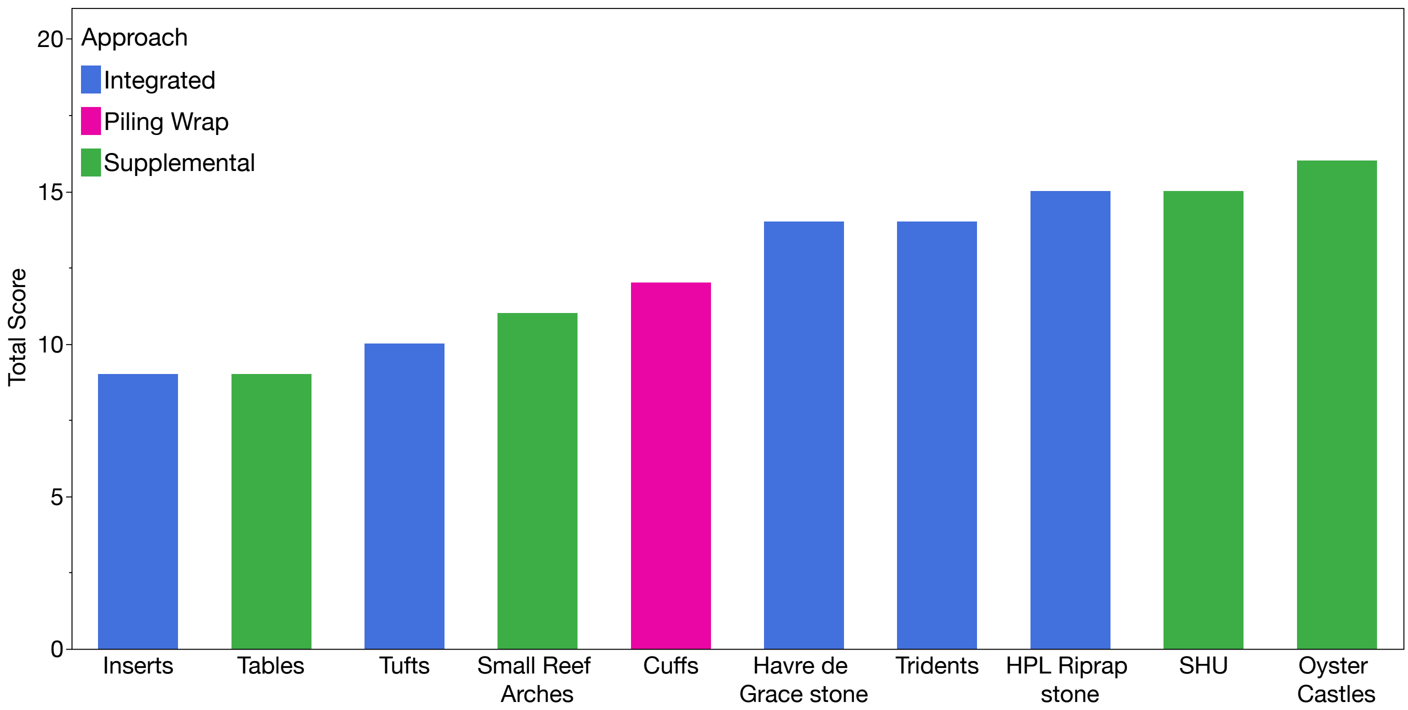

Table 4B.6 *Total performance scores for retrofit types across three implementation approaches. Retrofits are ordered from lowest to highest total performance score that integrates three evaluation criteria: ease of deployment, durability after three months in the field, and a spat count score. Bars are color-coded by retrofit approach (Integrated, Supplemental, and Piling Wrap). Higher total performance scores identify materials that combine robust field durability with practical deployability and support for oyster settlement and survival in our field study.*

Conclusions and Next Steps

This study demonstrated that a wide range of retrofit materials — supplemental, integrated, and piling wraps — can successfully support settlement of oyster larvae and growth of spat. All materials tested attracted oysters, confirming that multiple retrofit strategies have potential to enhance habitat value along armored shorelines. Differences in oyster abundance, durability, and ease of deployment reveal important considerations for designing scalable shoreline solutions.

Among the supplemental retrofits, Table units supported the highest spat abundances, reflecting strong biological appeal. However, they did not hold up well over the three-month deployment. Importantly, this outcome should be viewed in context: the study site was a particularly high-energy environment, and these units were not originally designed with such conditions in mind. Tables are typically deployed in groups with interlocking units that likely add to their stability. SHU units and Oyster Castles showed moderate spat counts after three months and remained more structurally stable. These results highlight how both retrofit geometry and environmental forces can shape performance and suggest that relative performance may differ in other deployment conditions.

Among the integrated retrofits, Tufts produced the highest oyster abundances but, like Tables, showed noticeable degradation after three months in a high energy environment. Again, this likely reflects the challenging hydrodynamic setting rather than a general material failure. Indeed, spat count data indicated that oyster larvae preferentially settled on Tables, Tufts, and Cuffs compared to other materials. Stones from the HPL riprap performed consistently well, supporting relatively high spat densities while retaining their integrity throughout deployment. Havre de Grace Stones, Oyster Castles, and Tridents supported lower but steady spat numbers and showed excellent durability, reinforcing the tradeoff between biological attraction and structural robustness under energetic conditions.

It is important to note that low spat count scores do not necessarily indicate poor performance in relation to spat settlement and survival - just that the spat counts were lower than other materials. For example, spat on Havre de Grace stone, that had a spat count score of 1, was based on a mean of 33 individuals per stone after three months. This is a high number of spat on a single stone that can be carried in one hand, and puts into perspective the very high spat abundances that were achieved by using hatchery-reared larvae to pre-seed the retrofits in this study. In addition, densely packed spat will be overcrowded and die as they grow, so it is not clear how different the oyster abundances will be between the retrofit types after multiple years; longer-duration evaluations are needed.

The Piling Wrap (Cuff) retrofits offered a valuable solution. Cuffs supported moderate spat abundances, suggesting they can perform well under certain conditions. Their ease of installation and compatibility with existing pier infrastructure make them a promising option for retrofitting vertical structures, with long-term durability warranting further study.

Total performance scores allowed comparison across approaches. Both supplemental and integrated approaches were represented in the top 50% of total performance, with Cuffs falling near the middle of the range. Notably, all three approaches—supplementing, integrating, and piling wraps—showed substantial overlap, reinforcing that no single method universally outperformed others; instead, site-specific constraints and project goals should guide material selection.

Ease of deployment emerged as a major determinant of scalability. With the exception of SHUs and Tridents, nearly all integrated retrofits were easy for one person to carry and place within or near riprap. In terms of supplemental approaches, SHUs required two people due to the heavy base, while Reef Arches and Cuffs were especially manageable from a small skiff. Because much of Maryland's shoreline is accessible only by small craft, materials that can be deployed without specialized equipment are particularly suitable for wide-scale application.

Collectively, these results help address the knowledge gaps outlined at the SHORES Symposium by providing comparative data on performance, durability, and ease of deployment in a realistic, high-energy field setting.

Next steps include (1) refining engineering specifications for retrofit materials; (2) conducting longer-term durability and spat abundance assessments across a range of energy environments; (3) testing hybrid or modified designs that balance settlement potential with structural resilience; and (4) expanding multi-season field demonstrations to evaluate longer-term survival and habitat development; (5) conducting direct-setting studies and evaluating other efficient methods for accelerating oyster recruitment onto retrofit materials, particularly in locations with limited natural larval supply. On-site setting approaches may also reduce reliance on remote setting facilities and lower transportation and labor costs, making retrofit strategies more scalable and cost-effective. Together, these next steps will build the foundation needed to advance oyster-enhancing retrofits from experimental trials to reliable, widely deployable shoreline management tools.

Acknowledgments

We are grateful to Alan Williams, Emi McGeady, Chelsea Fowler, and Bill Dennison for deployment assistance and Stephanie Alexander, Jeff Alexander, Bob Carey, Mike Nossick, Shane Simms, Stacey Spicer, and Evelyn Peyton of the Horn Point Laboratory Oyster Hatchery for expert oyster counting assistance and for raising the larvae used in this experiment. We also wish to thank the Retrofit Experimental Design Team members William Nardin, Olivia Caretti, William Ryall, and Stephanie Alexander for valuable input during the planning stage of this study.

Special thanks to Jeff Miley and the Horn Point Laboratory Maintenance Staff for assistance with the transport of the numerous heavy retrofit materials, and to Vulcan Materials Company for generous donations of gabion-sized stones from their Havre de Grace quarry.

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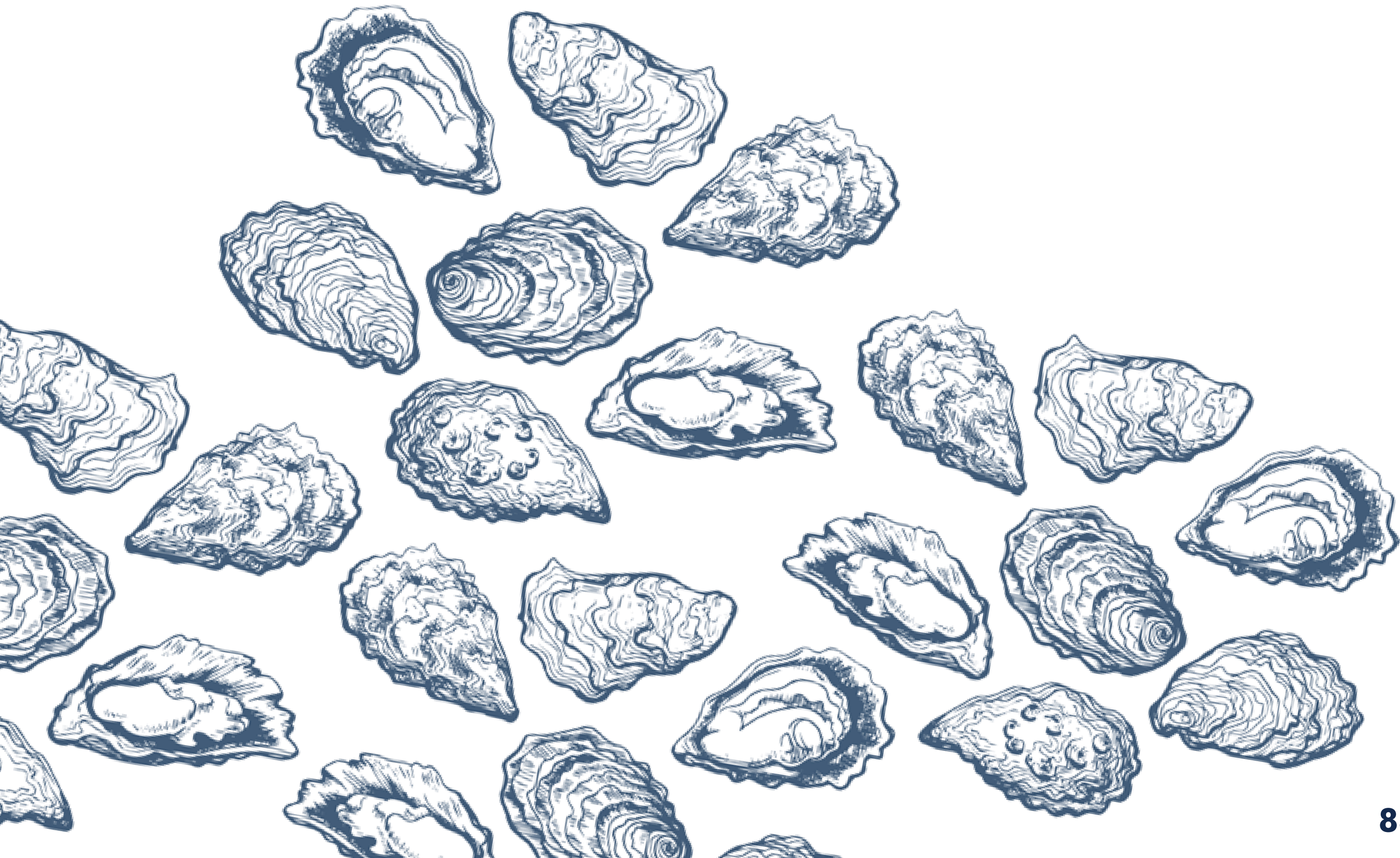
Chapter 5: The Effect of Hatchery Spat Size on Abundance



Chapter 5: The Effect of Hatchery Spat Size on Abundance

Authors

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Introduction

We conducted a large-scale experiment to evaluate the effect of the age of Eastern Oyster spat (juvenile oysters) on deployment on spat production. This research took place at the University of Maryland Center for Environmental Science (UMCES) Horn Point Oyster Hatchery (HPOH) and the NOAA Cooperative Oxford Laboratory (COL) in collaboration with the Oyster Recovery Partnership (ORP).

Since its inception in 1974, the HPOH has produced a total of 18.5 billion spat that have been planted on oyster sanctuaries, commercial fishing areas, and aquaculture leases in Chesapeake Bay. Currently, the facility includes fifty 3,000 gallon (11,400 L) oyster setting tanks that can be filled with eight cages of fresh oyster shells (Figure 5.1). River water is pumped into each tank before oyster larvae from the hatchery are added. The larvae are left in static, aerated water for 48 hours to allow their settlement.

Figure 5.1. *A) Oyster Setting Pier at the University of Maryland Center for Environmental Science Horn Point Laboratory. B) Hatchery technician Maya Skirka introducing oyster larvae into a setting tank. C) Cages of oyster shells in a setting tank. Photos by Monica Fabra and Stephanie Alexander.*

Chapter 5: The Effect of Hatchery Spat Size on Abundance

After larvae settle on the shells, the water is turned back on and the newly settled spat-on-shell are held in the tanks before being planted in Chesapeake Bay. Spat-on-shell are loaded onto commercial planting vessels from the HPOH setting pier, transported to a pre-determined restoration location, and planted on the Bay bottom using a low-pressure hose to gently wash spat off the deck of the vessel. Spat-on-shell are planted in a relatively even layer across the restoration site at standard abundances determined by Maryland Department of Natural Resources.

The amount of time that spat-on-shell are held in the setting tanks – the "holding time" – can influence their survival in the wild after planting as well as the total amount of spat that the hatchery can produce each year. Potentially, longer holding times could allow spat to grow to larger, more robust sizes, that could better withstand the rigors of transportation and planting and their predators in the wild. Shorter holding times allow the hatchery to produce more batches in a given year, increasing the total amount of spat planted in Chesapeake Bay. Which produces more surviving spat – shorter or longer holding times? To answer this question, we set out to determine the optimal holding time that would produce the highest numbers of surviving spat after planting, and to assess the effect of transportation, deployment, and predation on spat survival. Spat survival was assessed two days, one month, and eight months after planting.

Highlights

- Initially, longer holding times resulted in higher spat survival. Two days after planting, the abundance of spat produced with the 11-day holding time was 23% higher than those with 5-day or 17-day holding times. One month after planting, the abundance of spat produced with the 17-day holding time was 26% higher than those with 5-day or 11-day holding times. After eight months, there was no difference in spat survival based on holding time.
- Over a whole hatchery production year, the 5-day holding time was projected to result in twice the amount of surviving spat than the 11- or 17-day holding time because at least twice the number of batches of spat-on-shell could be produced with the 5-day holding time.
- The 5-day holding time appears to be the optimal holding time because more spat could be produced in a given year. The marginal gains in spat survival at longer holding times did not outweigh the volume of spat that could be produced with the shorter holding time.

Methods

We used hatchery data from 2023, a record high production year, and statistical analyses to determine what holding times to test and how many shells to count when doing our sampling. Hatchery data from 600+ tanks were used to determine that most holding times at the HPOH were 5 days (24.7%) with as few as 3 days to as many as 11 days. Based on this, we decided to test holding times of 5, 11, and 17 days to ensure we tested the most common (5 days), longest observed (11 days), and the longest observed plus an additional 6 days (17 days). A statistical power analysis with the HPOH data showed that spat on 25 shells from each cage would need to be counted during the experiment to be able to confidently distinguish differences in spat abundance between holding times.

Oyster larvae were spawned and reared in the HPOH in June 2024 and the holding time experiment was conducted starting in July 2024. To start the holding time experiment, each of six setting tanks on the HPOH setting pier was filled with eight cages of oyster shells, then river water was pumped into each tank. After one day conditioning the shells in flow-through river water, the water was turned off so the tank remained full without flushing water out. Five to six million larvae from a single broodstock spawn were added to each tank. After two days, river water was turned back on to flush through the tank and provide natural food for the newly settled spat-on-shell. Two or three cages were removed from each tank after 5, 11, and 17 days (Figure 5.2), and the spat-on-shell were deployed by ORP in the Tred Avon River at the COL using the industry standard planting procedures.

Figure 5.2 *Schematic of experimental design with 6 tanks (blue). Gray shapes represent cages filled with spat-on-shell, 16 of which were randomly selected to be removed and planted on days 5, 11, and 17 until the tanks were empty.*

Samples of spat-on-shell were collected before and after each cage was deployed in the Tred Avon River at the COL. After a cage of spat-on-shell was removed from the tanks and before it was conveyed onto the planting boat, a total of 25 shells were collected from the top, middle and bottom of the cage (Figure 5.3) and returned to the HPOH microscope lab where the number of spat on each shell was counted. The remaining spat-on-shell from each tank were placed in separate piles on the planting boat, then deployed around specific pilings of the COL pier (Figure 5.4). Two days after each deployment, divers collected 50 or 75 individual shells from around each of these pilings (Figure 5.5A). The sampled spat-on-shell were returned to the HPOH microscope lab where spat were counted (Figure 5.5B,C).

Figure 5.3. *A) Oyster Recovery Partnership's crane lifting a cage of spat-on-shell out of a setting tank. B) Fork lift putting spat-on-shell onto a conveyor belt to load them onto the planting vessel Poppa Francis. Dr. Monica Fabra takes samples of spat-on-shell for counting before deployment. C) The Poppa Francis taking spat-on-shell to the Cooperative Oxford Laboratory planting site. Photos by Monica Fabra and Matthew Gray.*

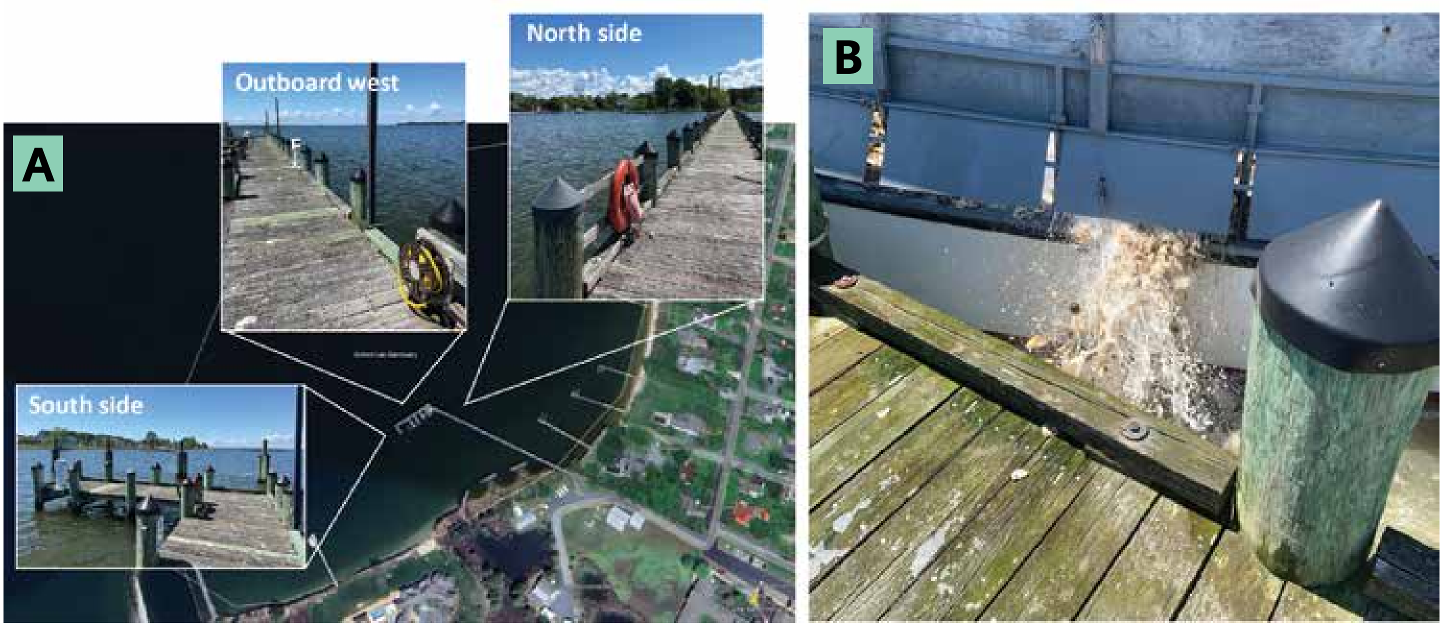

Figure 5.4 *A) Aerial view of NOAA Cooperative Oxford Laboratory pier with inset photos showing the pilings around which the spat-on-shell were deployed. B) Photo of spat-on-shell being deployed near a piling. Aerial photograph from Google Earth. Photos by Jason Spires and Monica Fabra.*

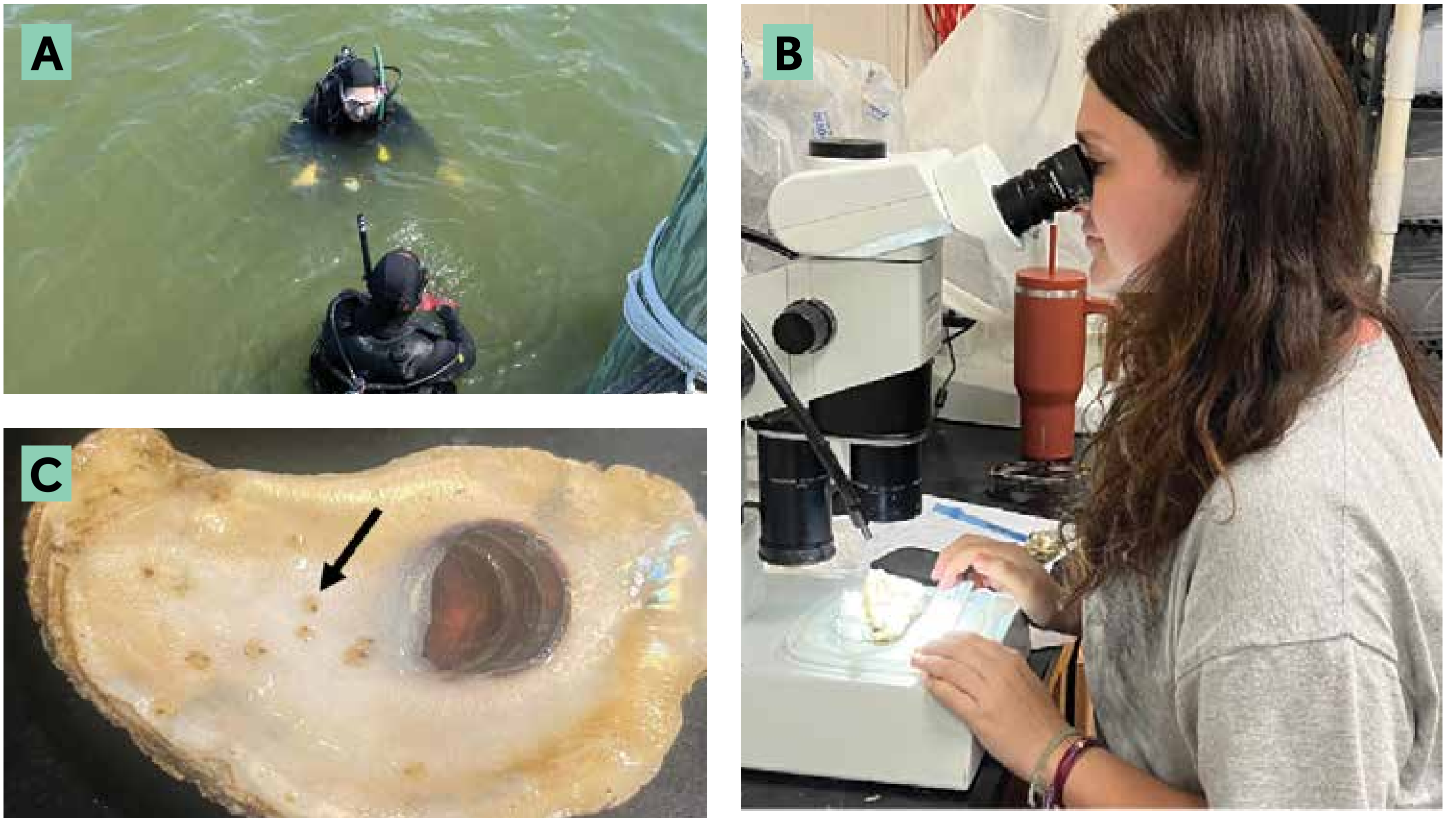

Figure 5.5 *A) Divers collecting spat-on-shell at the NOAA Cooperative Oxford Laboratory pier. B) Hatchery technician Maya Skirka counting the spat on each shell. C) Seven-day-old spat (small dark dots) on an oyster shell. Black arrow points to one of the spat. Photos by Monica Fabra.*

One and eight months after the initial planting in July 2024, divers collected samples from around every piling to collect spat-on-shell from all tanks and holding times. The spat-on-shell (e.g., Figure 5.6) were returned to the HPOH microscope lab and spat were counted. A total of 7,214 shells were counted for oyster spat over the course of the experiment.

We conducted statistical analyses to determine if spat abundance was significantly different between holding times and before and after planting. Generalized Additive Models for Location, Scale and Shape (GAMLSS) were used to test whether holding time, tank, and planting depth described a significant amount of variability in the number of spat per shell. A separate model was fit to data collected before planting, two days after planting, one month after planting, and eight months after planting. An additional model was used to compare spat abundances before and two days after planting to assess the impact of planting, predation, and handling on spat survival. Model fit tests indicated that the residual diagnostics were satisfactory, the selected distributions were adequate, and all of the models described the data sufficiently well. Mean and standard deviations were calculated for each deployment and holding time.

The mean numbers of spat-on-shell that survived after one month and eight months after planting were used to calculate the theoretical production of the HPOH over a whole season using different holding times. Assumptions for this analysis were that the season length was 191 days, all 50 tanks at the HPOH were continuously in use, that there were an estimated 88.6K shells per tank, and that all holding times could be uniform. The number of shells per tank varies annually depending on the shell source; this estimate is based on shell counts by HPOH and ORP staff in 2024. In reality, spawning and logistics create differences in holding times within each season. Despite the simplifications, these calculations allow us to compare the effect of holding time and spat survival on potential hatchery production.

Results

There was no significant difference in spat per shell between the three holding times for the spat-on-shell that were collected before planting (Figure 5.7). As expected, there was high variability in the spat-on-shell counts – this is a known characteristic of spat settlement: some shells have zero spat and others can have more than 50. Two days after planting, the number of spat per shell was significantly higher for the 11-day holding time. The abundance of spat produced with the 11-day holding time was 23% higher than those with 5- or 17-day holding times.

Figure 5.6 *Spat-on-shell eight months after planting. The ruler indicates millimeters. Photo by Monica Fabra.*

When spat-on-shell were collected and counted one month after planting, the number of spat per shell was significantly higher for the 17-day holding time (Figure 5.7). The spat-on-shell that had been held for 17 days had, on average, 1.1 more spat per shell (5.3 +/- 5.7 standard deviation) than those that had been held for 5 days (4.2 +/- 3.7) and 11 days (4.2 +/- 4.8). The number of spat per shell held for 17 days was 26% higher than those at 5- or 11-day holding times.

Eight months after planting, there was no significant difference in the number of spat per shell between the three holding times (Figure 5.7).

The mean number of spat per shell decreased from before planting (8.4 to 9.3 spat per shell) to two days after planting (4.0 to 4.9 spat per shell) for all holding times. This statistically significant decrease by roughly 50% in the number of spat per shell was due to a combination of factors that affect spat survival including transportation, deployment, predation, diver collection, and handling. It is notable that the mean number of spat per shell did not decrease markedly after the first two days, showing the highest mortality when spat are smallest and most vulnerable, as expected.

Tank and depth of planting were significant factors in most statistical models indicating that some tanks had higher spat sets than others, and that spat abundance was influenced by the depth of planting around the COL pier, with higher abundances at deeper depths, although the depth effect diminished with time. These factors were accounted for in the statistical models, thus allowing for a better comparison of the effect of holding times.

When using mean spat-on-shell data from one month after planting (Table 1A), the projected effect of holding time on the total spat produced per year showed that the 5-day holding time produced 1.9

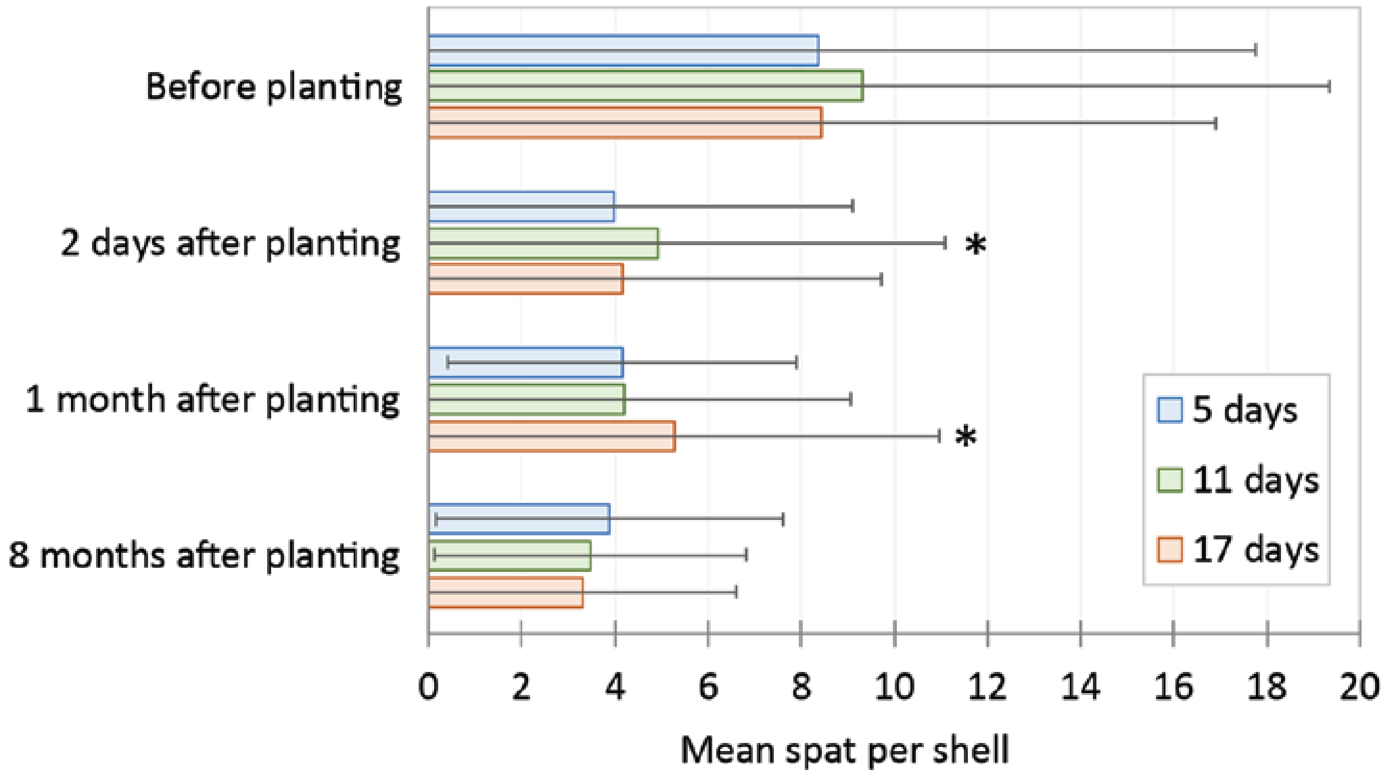

Figure 5.7 *Mean spat per shell before planting, two days after planting, one month after planting, and eight months after planting for each holding time (5, 11, and 17 days). Stars indicate a statistically significant result that the holding time is higher than the other holding times within its group. Error bars represent one standard deviation. The number of shells counted for each bar ranged from 376 to 400.*

times more spat than the 11-day holding time and 2.1 times more spat than the 17-day holding time. With a 5-day holding time, 497.5M spat were projected to be produced compared to 260.9M for the 11-day holding time and 233.2M for the 17-day holding time – despite the fact that the number of spat produced with 17-day holding time was 26% higher than the shorter holding times.

When using mean spat-on-shell data from eight months after planting (Table 1B), the projected effect of holding time on the total spat produced per year showed that the 5-day holding time produced 1.8 times more spat than the 11-day holding time and 2.3 times more spat than the 17-day holding time.

In both the one-month and eight-month analysis, the 5-day holding time produced roughly twice the total number of surviving spat in a year than the longer holding times (Figure 5.8). This result is due to the fact that many more batches of spat-on-shell can be produced with the shorter holding time. Ultimately, the gain in survival with a longer holding time does not outweigh the increased hatchery production enabled by the 5-day holding time.

It is also useful to note that the longer holding times, especially the 17-day holding time, resulted in substantially more fouling within the tanks and greater labor to clean the tanks before they could be used again. In addition, mortality due to predation in tanks varies between years and could be more significant with a longer holding time in some years.

Table 5.1 *Projection of the effect of holding time on the total number of spat produced per year using mean spat per shell data for each holding time: A) one month after planting and B) eight months after planting. Calculations are based on a season length of 191 days (i.e. the number of days that the hatchery is in production) and the estimate of 88.6K shells per tank. M = Million.*

A) Using mean spat abundance one month after planting

Holding time	Days in the season	Batches per season per tank	Tanks	Batches per season	Shells per season	Spat per shell (one month after planting)	Total spat per season
5 days	191	27	50	1350	119.6 M	4.16	497.5 M
11 days	191	14	50	700	62.0 M	4.21	260.9 M
17 days	191	10	50	500	44.3 M	5.27	233.2 M

B) Using mean spat abundance eight months after planting

Holding time	Days in the season	Batches per season per tank	Tanks	Batches per season	Shells per season	Spat per shell (one month after planting)	Total spat per season
5 days	191	27	50	1350	119.6 M	3.30	394.6 M
11 days	191	14	50	700	62.0 M	3.46	214.5 M
17 days	191	10	50	500	44.3 M	3.88	171.7 M

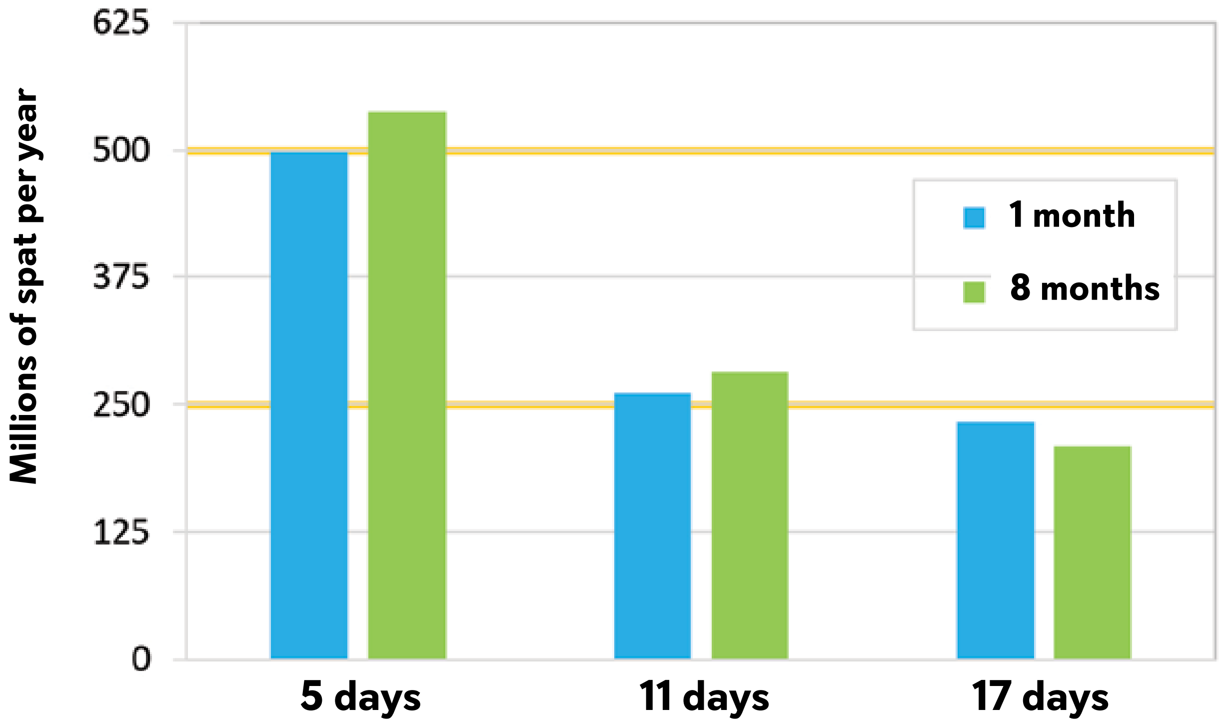

Figure 5.8 *Projected hatchery production with 5-day, 11-day, and 17-holding times using data from this experiment collected one month after planting and eight months after planting. Orange lines highlight the values of 250M spat and 500M spat per year, showing a doubling in annual production using the 5-day holding time compared to the other holding times. Calculations are in Table 1.*

Conclusions and Next Steps

The 5-day holding time was identified as the optimal holding time because more spat could be produced in a given year. The marginal gains in spat survival at longer holding times did not outweigh the volume of spat that could be produced with the shorter holding times.

It is worth noting that 2024 was an unusually low-salinity year, and this could have influenced our experiment's outcomes and projections. The low salinity conditions may have affected larval and spat survival, as well as other factors, such as predator presence in the setting tanks and the river.

This study was valuable for increasing the efficiency of the HPOH, allowing operations to target 5-day holding times to maximize annual production and the total number of oysters that can be planted and survive in Chesapeake Bay. While every hatchery and planting strategy is different and the 5-day holding time may not be optimal for other hatcheries, these findings do provide guidance that holding times can be adjusted to maximize oyster hatchery efficiency and production.

Acknowledgments

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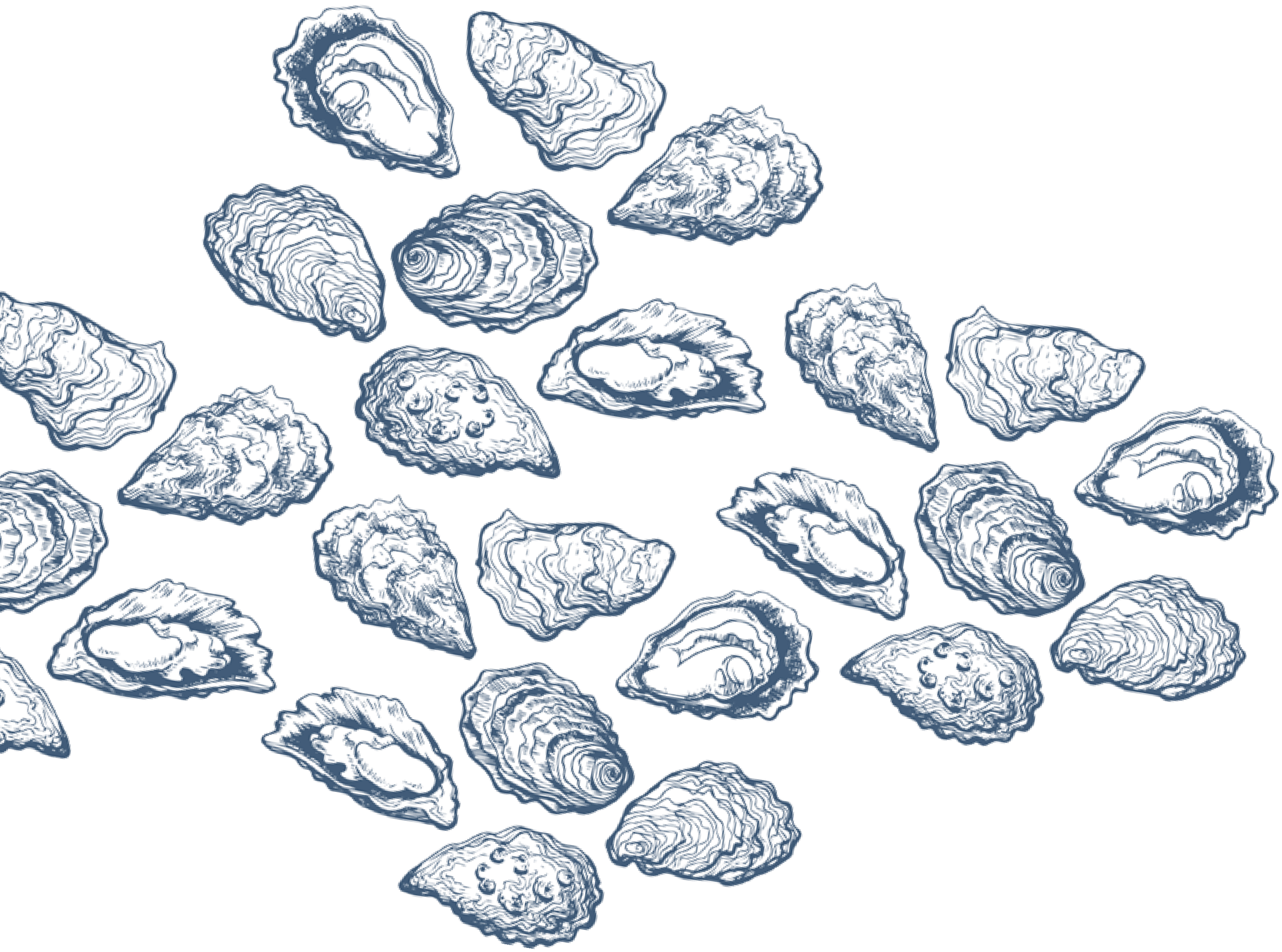
Appendices for the SB830 Report



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Symposium on Alternative Substrate for Oysters

Report on the Virtual Symposium

Feb 26-28, 2024

About the Symposium

Symposium and Report Sponsors and Organizers

This symposium and report were sponsored by the State of Maryland and convened and produced by University of Maryland Center for Environmental Science (UMCES). Lead organizers were Dr. Elizabeth North and Dr. Matthew Gray of UMCES Horn Point Laboratory. The symposium team also included David Nemazie, Conor Keitzer, Roshni Nair-Gonzalez, Monica Fabra, and Kurt Florez. Graphic design and logistical support were provided by the UMCES Integration and Application Network (IAN).

For questions regarding this symposium and report please contact Elizabeth North at **enorth@umces.edu** or Matthew Gray at **mgray@umces.edu.** For more information, please see the symposium webpage: **https://www.umces.edu/alternative-substrate-for-oysters**

Please cite this symposium report as:

North, Elizabeth W., Monica Fabra, Conor Keitzer, Roshni Nair-Gonzalez, and Matthew Gray. 2025. Symposium on Alternative Substrate for Oysters: Report on the Virtual Symposium Feb 26–28, 2024. University of Maryland Center for Environmental Science, Horn Point Laboratory. Cambridge, MD. 53 pp. *https://www.umces.edu/sites/default/files/SASSO-Report-2025.pdf*

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Acknowledgments

We thank speakers and audience members for their valuable contributions and Kurt Florez for assistance with IT during the symposium.

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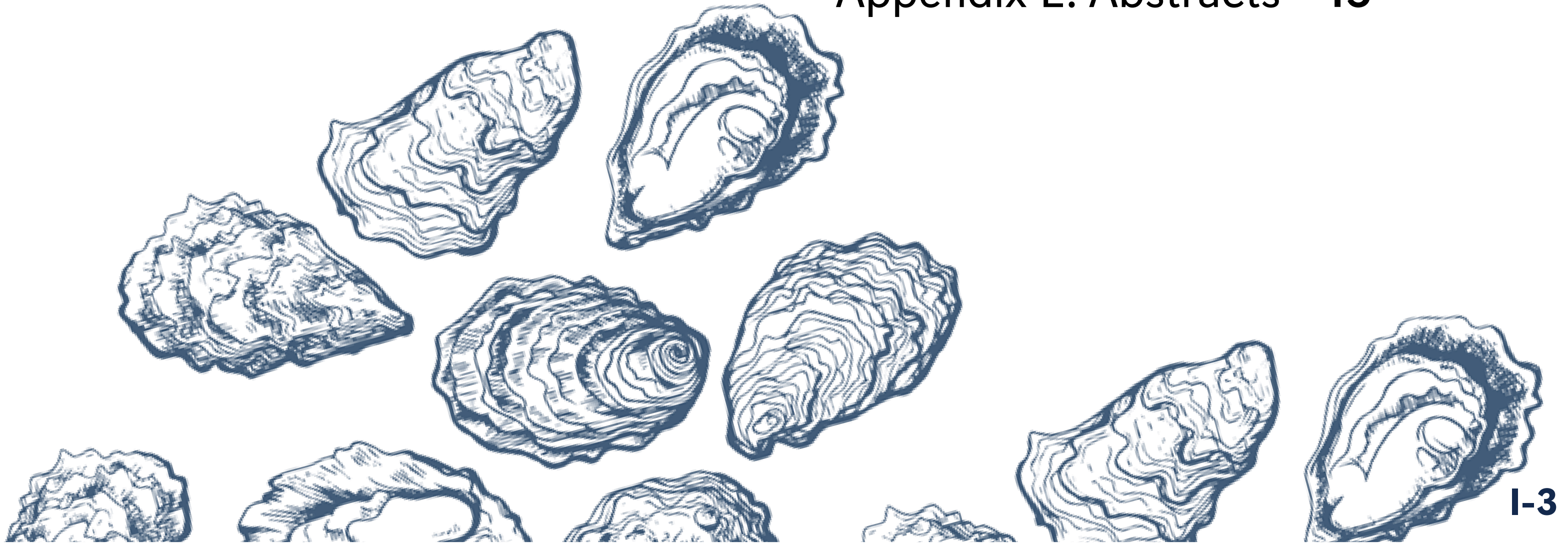


Executive Summary

The Symposium on Alternative Substrates for Oysters brought together shellfish managers, fishermen, aquaculturists, restoration specialists, and scientists who shared and discussed their experiences and innovations on the use of alternative substrates for oysters. On each of the three days of the virtual symposium, at least 125 people from across the nation, Europe, and Canada attended. With 21 speakers from nine states, their collective knowledge brought to light numerous commonalities and offered new ideas and practices that will inform the use of alternative substrates in Maryland and beyond. While this Executive Summary highlights commonalities, innovative ideas, and knowledge gaps, the report itself offers a fuller account of each day's activities, with summaries of talks and discussions, tables of substrate types, and participant's input. Throughout this report, alternative substrate is defined as anything other than fresh shells of the Eastern oyster, *Crassostrea virginica*.

This symposium was part of a larger effort to inform the use of alternative substrates for oysters in Maryland. The demand for fresh shell of the Eastern oyster in Maryland by the fishery, restoration, and aquaculture sectors is substantial—recently totaling greater than 200,000 bushels per year—and the fresh shell resource is limited. While there are ongoing efforts to keep shells in the state of Maryland, alternative materials are being used or considered for use, including shells (*e.g.*, clam, whelk, dredged or weathered oyster shell) and stones (*e.g.*, limestone, river rock, granite). This symposium was held to better understand how alternative substrates are applied outside of Maryland for fishery, restoration, and aquaculture practices in large, subtidal areas and to learn about the success and failures of these efforts. The Symposium organizers are grateful to the speakers and attendees who made this event such a success.

Based on presentations at the symposium, it is clear that there is longstanding, widespread, and successful use of alternative substrates for enhancing oyster fishery production and restoration in large, subtidal areas along the U.S. Eastern seaboard and Gulf coasts. In some states without access to fresh shells, alternative substrates are predominantly or exclusively used, such as **limestone marl** in North Carolina and Texas, and **river rock** in Texas. In addition, **crushed and cleaned (recycled) concrete** has been used successfully in Florida, Maryland, Texas, and Virginia. In Virginia, **granite chips** are used in oyster enhancement programs in addition to the rich supplies of both fresh and **dredged oyster shells** that are available in the state. Non-oyster shells, such as **clam** and **whelk** shells, are being successfully used as substrates in New Jersey.

The importance of the size of the substrate for different applications was a common theme at the symposium. Small sizes of stones (< 1 to 2 inches) are regularly used in harvest areas whereas larger stones are used in sanctuaries. Smaller stones were found to be more appropriate for harvest areas because they do not damage juvenile oysters or fishing gear. In sanctuaries, larger stones provide habitat and raise the height of the bed above the bottom to promote oyster growth and survival.

Several innovative ideas and technologies also were brought forward, including shell recycling using suction dredge boats. These boats have a shallow draft and are specially designed to pull up the top 2 inches of shell and sediment from an aquaculture lease. This technique provides an efficient and cost-effective way to recycle shells within leases, ensure good spat catch, and—importantly—eliminate the need to purchase shells or other substrates. By suction dredging in the wintertime, the shell has several months of drying time on land to remove fouling, which improves spat catch when the shell is deployed in early summer. Symposium co-chairs noted that dredging in wintertime may also help protect against the negative impacts of sediment on seagrass in regions where seagrass does not grow in winter.

Other innovative ideas focused on sanctuary siting and construction. In multiple states, sanctuaries are sited so that the spawning stock in a sanctuary is located so that water currents carry the spillover of oyster larvae out of the sanctuaries to harvest areas and thereby supplement the oyster industry. These large-scale coordinated programs for both sanctuaries and harvest areas are seen as a benefit that will ultimately enhance oyster populations and industry at the same time. In terms of sanctuary construction, innovative approaches for creating mounds tangential to currents (similar to maps of historic oyster reefs), using stone bases with shell tops, and using thousands of mini reef balls over large areas were also notable innovative approaches that show great potential. The recognition that concrete structures with high relief perform better than low-relief shell plantings in polluted regions can inform urban sanctuary restoration efforts.

In addition to the suction dredge described above, innovations in aquaculture focused on new materials and structures that have been developed and show success in nearshore regions. These innovations combine new ingredients into concrete making them more appropriate for oyster settlement and/or use new flexible materials that support oyster settlement and growth and create new shapes that have utility for nearshore and aquaculture implementations.

Measuring the success of alternative substrates was another topic of discussion at the symposium. Participants agreed that the metrics that are used to determine the success of alternative substrates need to depend on the objectives of the use of alternative substrates, which can differ between fisheries, restoration, and aquaculture. While **biological** performance metrics (larval settlement, spat growth and survival, biodiversity) are the most commonly used to assess the suitability of substrates, **structural** (size, rugosity, complexity, durability) and **economic** metrics (costs, availability, logistics) are important to assess.

Symposium participants identified several important knowledge gaps that need to be filled to enhance the use of alternative substrates. Material properties and scalability were unanimously identified in panel discussions as important topics that require greater investigation in each of the three sectors. The long-term performance of alternative substrates is a key gap—how long they last in the marine environment, how long they remain productive for oysters, and the cost-benefit of the different materials over the long term. Gaps in knowledge also exist around the use of novel substrates, especially regarding environmental impacts (*e.g.*, potential leaching of toxic chemicals and plastics) as well as how to scale up with them and transport them.

Issues that hinder the use of alternative substrates in Maryland also were identified. Public perception and acceptability, the supply and availability of substrates, and regulations and permitting for alternative substrates were highlighted. In addition, participants recognized the need in Maryland for equitable access and distribution of materials, more cost-effective deployment methods, and performance testing of alternative substrates including persistence in the natural environment.

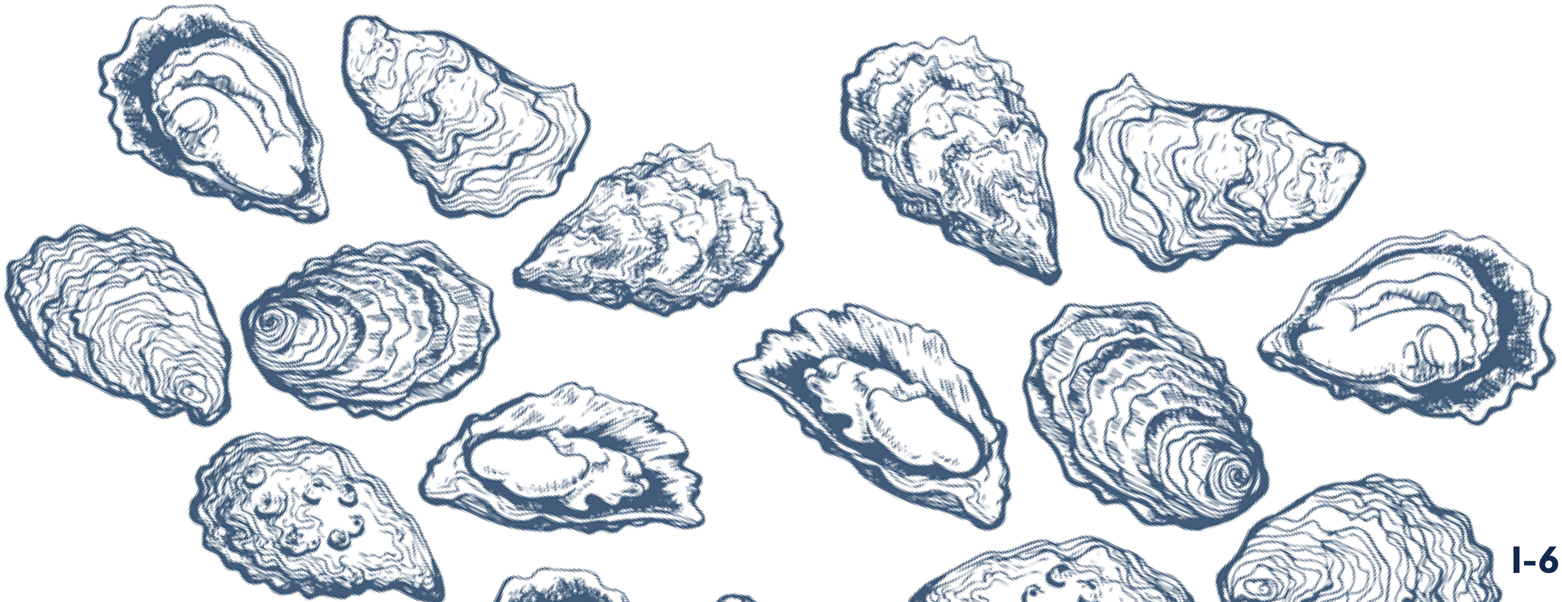
Looking forward, information from this symposium has many important uses, including offering new practices for enhancing fisheries production, restoration, and aquaculture in large subtidal areas as well as informing policy recommendations and guiding design of laboratory and field evaluations of alternative substrates.

Background

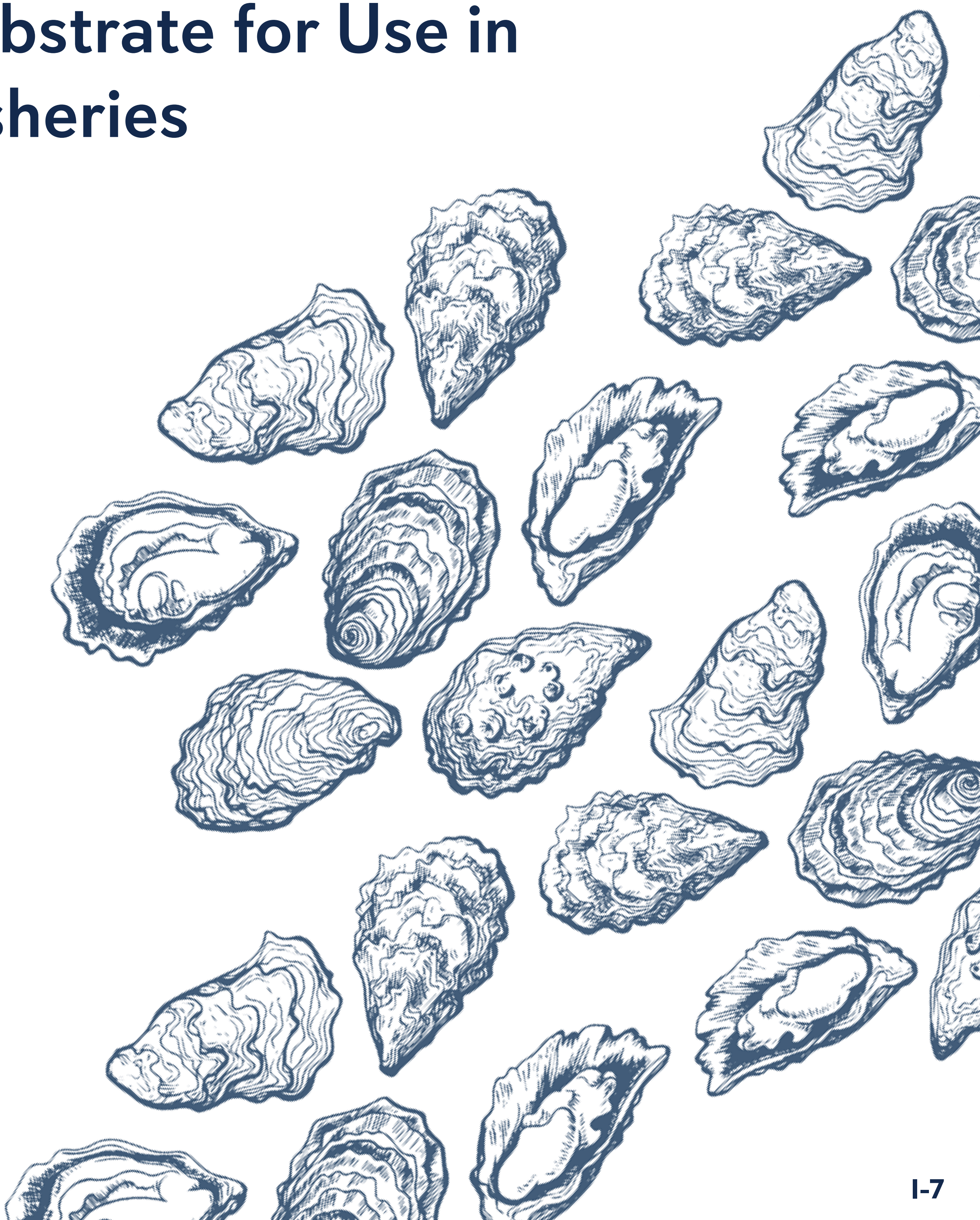
The Symposium on Alternative Substrate for Oysters (SASSO)
was part of an effort to fill key knowledge gaps in support of Maryland's oyster resource and oyster industries. Chesapeake Bay is home to thriving commercial fishing and aquaculture industries and one of the largest oyster restoration efforts in North America. The lack of fresh shell substrate has become a major impediment to all of these activities and alternatives are being considered for large-scale use in restoration and industry efforts. To address this challenge, the Maryland General Assembly mandated a program (SB830 2023) that will evaluate:

1. Types of substrate, including fresh shell, fossilized shell, combinations of shell and alternative substrates that are most appropriate for use in oyster harvest areas.
2. Benefits, including habitat-related benefits, of using stones of various sizes in oyster restoration areas.
3. Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates.
4. Potential for retrofitting existing structures, such as riprap revetments that are unrelated to oyster restoration, but use materials similar to artificial reefs including oyster plantings.
5. Effect of spat size upon deployment on oyster abundance.

This symposium directly addressed Chapter 3: to evaluate alternative substrates used for oyster restoration, or repletion, in other regions. The focus the SASSO symposium was on large areas and/or subtidal efforts with alternative substrates (*i.e.*, anything other than fresh oyster shell).



Day 1: Alternative Substrate for Use in Fisheries

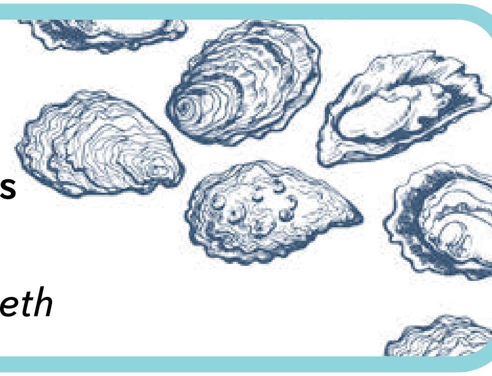


Day 1: Talk Highlights

Day 1 of the symposium featured speakers from state agencies, academia, and non-governmental organizations who discussed using alternative substrates for oyster fisheries in large, subtidal areas. Maryland State Senator, Sarah Elfreth, who sponsored the legislation supporting the symposium, gave opening remarks. Senator Elfreth encouraged everyone to stay solution-oriented around the goal of restoring Maryland's oyster population and reminded us all that we are stewards of this important resource.

"....We all share a very similar goal, which is to restore the oyster population in Maryland and... ensure that the future generations of Marylanders can still rely on this keystone species."

- Maryland Senator Sarah Elfreth



Dr. Elizabeth North welcomed speakers and thanked them for sharing their valuable knowledge with symposium participants and the people in Maryland working to increase oysters.

Chris Judy
Director, Shellfish Division, Maryland Department of Natural Resources

Chris Judy gave a thorough overview of the different shell (dredged, surf clam) and non-shell (stone, concrete, slag) alternative substrates tested in Maryland to support local fisheries. Currently, the Maryland oyster fishery uses approximately 200,000 bushels of fresh shells per year but the need is easily for a million bushels per year. DNR used to manage a large-scale oyster shell dredging program that recovered 2 to 5 million bushels per year (1960–2006). The performance of dredged shells was quite good, with 2 to 50 times greater spat set on clean dredged shells than on natural oyster bars. Surf clam shells also were tested but were found to be brittle and too densely packed on the bottom. Recently, tests have been done with clam dredging boats that demonstrated that 1,000 bushels of shallow-buried oyster shells can be recovered per day and moved to nearby harvest sites. In past tests, spat were found to set on stone, concrete, and slag but the suitability of the material for fisheries is highly dependent on size, which needs to be small enough to be compatible with harvest gears. Also presented was the concept of man-made sources of alternate materials such as large-scale manufacturing of artificial shells similar in shape to actual shells. Any formula developed for man-made substrates would have to be thoroughly analyzed and deemed safe. Additional questions for man-made substrates include sourcing, weight, location of manufacturing, and policy issues of putting large amounts of man-made materials in the Chesapeake Bay.

Andrew Button
Virginia Marine Resource Commission

Andrew Button spoke about Virginia's approach to using alternative substrates to support fisheries in their waters that have consistent spat sets. Although they have found that oysters can set on any hard substrate, their program primarily uses dredged shells (500,000 to 700,000 bushels/year) and crushed stone (#57 stone chips, 1" or smaller). The stones need to be planted on a bit firmer bottom than shells to prevent sinking. He outlined their successful replenishment approach, which includes monitoring shell volumes and targeting 5 liters of substrate (fresh shell, dredged shell, or crushed stone) per m^2

Day 1: Talk Highlights

as a minimum and 10 liters of substrate per m² as a goal to ensure reliable spat sets. A target 2-inch reef height works well and 250 tons per acre of crushed #57 stone will deliver this height at a new site that has a decent bottom. Less substrate is applied at sites that already have substrate. They use 2- to 4-inch size rocks in sanctuaries, which can be deployed using a high-pressure water cannon, but these sizes are too large for harvest areas because the interaction with the fishing gear can damage oysters.

Doug Munroe and Bennett Paradis
North Carolina Division of Marine Fisheries

Doug Munroe and Bennett Paradis discussed North Carolina's rehabilitation strategy, which includes a detailed site selection process, the deployment of artificial reefs, and a thorough monitoring program in both planting sites and oyster sanctuaries. Today they plant about 300,000 bushels of substrate per year. Although freshly recycled oyster shells are the preferred substrate, limestone marl has been used since 1981 and is now the primary substrate used in this program. It is local, relatively inexpensive, and the supply is reliable. In their decision-making process for site selection, they use a detailed GIS-based habitat suitability index, include fisherman/stakeholder input through annual surveys, and take into account the location of sanctuaries in an effort to create a network of reefs through the Sounds. Their monitoring program includes mapping clutch areas, assessing spat sets at sites < 3 years old, and tracking adult abundance on mechanical harvest areas to guide the opening and closing of harvest areas.

William Rodney
Texas Parks and Wildlife Department

Bill Rodney described several projects conducted in Texas using crushed recycled concrete, river rock, and limestone in a variety of reef configurations. Since 2007, over 600 acres of oyster reef have been restored in Galveston Bay using alternative substrates because they do not have a source of clean shells. Larger stones and concrete rubble (2–6") are used in no-harvest areas whereas smaller pieces (1–2") are used in harvest areas because the latter does not accumulate in dredges. Notably, fresh river rock placed near a natural oyster reef caught substantially more spat than the natural reef, indicating the preference of oyster larvae for clean substrate. While they have seen successful spat sets on all of the substrates, darker gray limestone is preferred by oyster leaseholders over white, chalky limestone which does not seem to last as long. Other novel substrates of opportunity (*e.g.*, granite countertop scraps, porcelain) need to be carefully examined for toxic effects (like leaching from plastics in countertops). Another issue is the cost of planting substrate at scale—it is too expensive to restore at the scale that needs to be achieved. Either cultch cost needs to come down or more funding needs to be obtained.

Sandra Brooke
Florida State University, Coastal Marine Lab

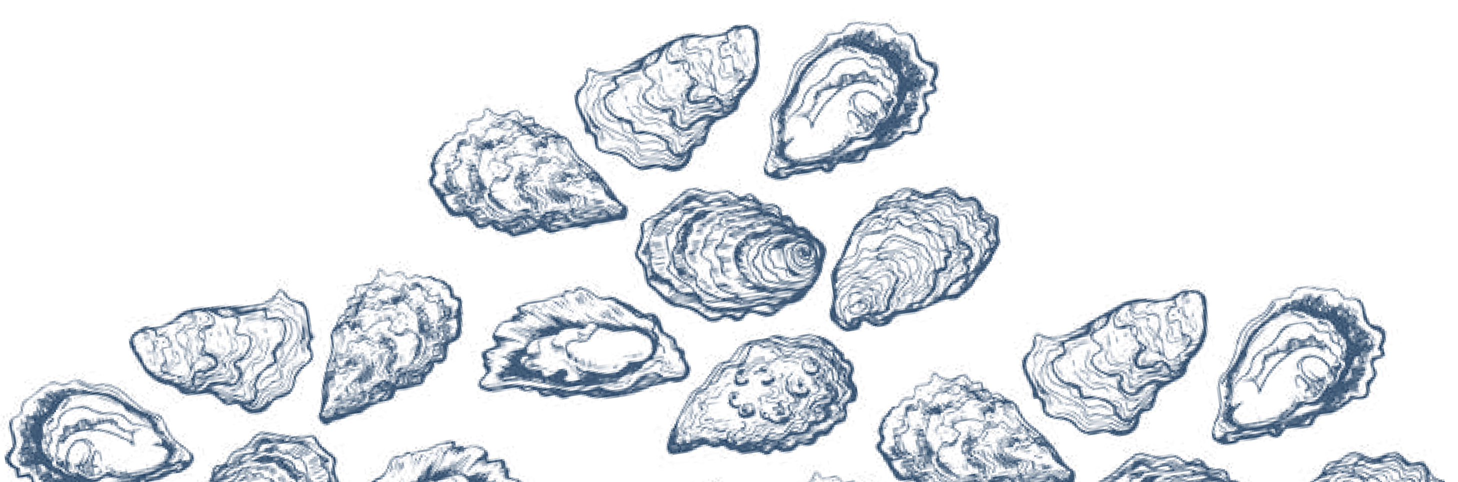
Sandra Brooke discussed restoration efforts in Apalachicola Bay (FL) following the loss of oysters and oyster reef habitat that culminated in a fishery closure in 2020. Recently, substrates of different sizes and types were compared in two restoration experiments. The first experiment showed that, while spat initially settled similarly on shell and limestone after 1.5 years, more market-sized oysters were found on large limestone rocks (5–7") than on small limestone rocks (2") or shell. The shell was dispersed by currents and did not form a lasting habitat in the shallow Bay. Although the large limestone rocks provide the most vertical relief and structural complexity, fishermen prefer smaller stones for better compatibility with the hand tong harvest gear (although hand tonging can be done over the larger limestone rocks). Data from the second experiment showed that after 6 months, there was no difference in abundance of spat, seed, or market-sized oysters between treatments with limestone rocks (5–7”), crushed concrete (4–6”), limestone rocks (5–7”) plus shell on top, or crushed concrete (4–6”) plus shell on top, but oysters were significantly smaller in the limestone rock only treatment. Monitoring is ongoing and an additional study is underway.

Kathy Sweezey
The Nature Conservancy in Texas

Kathy Sweezey talked about large-scale subtidal restoration efforts conducted by The Nature Conservancy (TNC), totaling over 150 acres across the Texas coast. In recent projects, limestone rocks were deployed to build artificial reefs in both sanctuaries and harvestable areas, with different sizes of stones in harvest areas (small rocks 0.5–4”) compared to those in sanctuaries (rip-rap ranging in weight from 60–1500 lbs). Despite the initial rapid success, they encountered challenges, such as costs, substrate availability, and lack of multiple competitive bids. In terms of emerging alternative materials for use in large subtidal areas, they tried to work with contractors specializing in alternative materials, such as those that demolish bridges or use 3D printed materials but were hindered by cost (three times higher than limestone) and a mismatch in the timing for construction and when the products would be available. A recent TNC report on oysters in the Gulf of Mexico calls for managing oyster populations based on the multiple benefits of oysters so that both ecological benefits and the human economic benefit of harvest are realized. In addition, it cites the need to enhance collaboration to reach project goals within limited budgets and to think creatively to increase the scale and pace of projects.

Matt Pluta
ShoreRivers in Maryland

Matt Pluta described a field experiment performed in the Choptank River (MD) that compared oyster shells to seven different alternative substrates with different orientations (*e.g.*, cup side up or down). They created platforms that contained 12 1-foot squares that held the different substrate types. Three platforms were deployed at each of the three locations in the Choptank River for five months in 2021. All but one platform were recovered. After recovery, each of the 12 squares from each platform was photographed and spat were counted. Squares with oyster shells—either cup-side up or cup-side down—had the highest spat settlement (mean spat per tile was at least 2x higher on shell than on all other substrates). Spat were found in lower numbers on clam shell, cobblestone, granite rock, and the back side of cement pavers. The substrates that caught little to no spat were marble tiles, ceramic tiles, brick, and the topside of cement pavers. It was notable that spat were found on the underside of the plastic platforms that were deployed in the river, but larvae did not set on the substrates or platforms that were held in the lab.



Day 1: Panel Discussion and Participants' Input

Key Points:

Knowledge gaps

During the panel discussion, speakers were invited to discuss key knowledge gaps for using alternative substrates in large areas and subtidal regions. Multiple speakers agreed that the long-term performance of alternative substrates is a key gap: how long they last in the marine environment, how long they remain productive for oysters, and the cost-benefit of the different materials over the long term. Gaps in knowledge also exist around the use of novel substrates (*e.g.*, granite countertops, toilets), especially regarding environmental impacts (*e.g.*, potential leaching of toxic chemicals) as well as how to scale up with them and transport them. Because biofilm formation has been found to be important for larval settlement, a better understanding of biofilm formation and community structure on alternative substrates is warranted.

Public perception and regulatory hurdles

According to panelists, the most effective way to overcome public perception challenges and regulatory hurdles is through careful site selection and communication to increase public awareness. Site selection includes avoiding high-use areas as well as depths that have any chance of being, or perceived as being, a navigation hazard. Employing habitat suitability analysis, as well as accurate tests to ensure the safety of materials, can enhance site selection and public perception. Increasing local public awareness and stakeholder engagement also was identified as valuable and essential, including being proactive about notifying the public, especially fishing communities about changes to navigation maps. In addition, the use of interactive online maps can increase understanding of where sites have been placed and are proposed.

Key metrics

The following metrics were identified by the panelists as key for measuring the performance of alternative substrates and their suitability for harvest areas: oyster abundance by size class, spat recruitment, substrate volume, and durability, the ratio of black shells to brown shells as an indicator of cultch depletion on the reef's surface, and, the costs of the substrate, its transportation, and deployment. In addition, revisiting sites with a side scan sonar can help determine if hard substrate is still available. Another metric to track is the amount of substrate deployed compared to the amount of oysters produced. For example, in productive regions in Virginia, approximately two times the amount of substrate is needed to produce a given amount of oysters.

Overcoming barriers

In order to overcome barriers related to the introduction of new substrates, the panelists suggested that site selection is critical: it should be in a new place—not at a site that already has oysters—so that if the experimental site works, it would add to oyster populations. In the process of site selection, it is important to consider all the different possible conflicts (*e.g.*, interference with boat traffic, fishing gear) and create a plan that is tailored to achieve the specific goals of the effort (*e.g.*, harvesting, reef restoration). In addition, strong outreach is important through step-by-step communication and the inclusion of different stakeholders.

Environmental concerns and biosecurity issues

The need for strict and consistent monitoring of alternative materials, particularly recycled materials, was highlighted by the panelists as important in order to avoid the introduction of pests, diseases, or unwanted toxic materials that could compromise the success of the programs. In addition, anything

Day 1: Panel Discussion and Participants' Input

that will be applied at scale needs to be considered from many angles and checked thoroughly. Recycled materials like crushed concrete may not work well at scale because of the variability between loads and hence the need to check every load.

Other questions and ideas

Through the discussion, questions and ideas for improving oyster management emerged. On the reef scale, a better understanding of the acoustic signature of reefs might help with larval recruitment and assessing ecosystem services. On the landscape scale, it would be helpful to know how close in proximity a sanctuary should be to nearby harvest reefs to have a positive impact on harvest through larval transport. To take advantage of larval transport that can enhance oyster populations, it would be useful to promote public understanding that having large-scale programs for both oyster restoration in sanctuaries and replenishment in harvest areas is ideal. Another open question is the minimum acreage necessary to re-establish self-sustaining oyster populations in both sanctuaries and harvest areas.

Participants' Input: Day 1

Symposium participants were asked to fill out an online anonymous poll. The poll respondents on Day 1 of the symposium worked in the following sectors: Restoration (86%), Aquaculture (40%), Fisheries (30%).

The shell substrates most commonly used by the poll's participants were clam shells (36%), Whelk shells (28%), *C. virginica* fossil shells (27%), and *C. virginica* dredged shells (21%), while limestone marl (24%), crushed concrete (24%) and granite (22%) were the most popular alternative substrates. Numerous poll respondents never used alternative substrates (26%) or used others (22% concrete complex structures like reef balls and castles, scallops, bamboo, tomato stakes, crab pots, pallets).

Larval preference (65%), availability (47%), and costs (44%) were selected by the symposium's participants as the top 3 priority features of alternative substrates. According to the poll's respondents, alternative materials should also support biodiversity and should not have harmful effects on water quality (42%). Other additional characteristics of alternative substrates were highlighted as important: integration into seascape, ecological/habitat function and development of functioning ecosystems, substrate complexity, permitting.

Scalability (68%), material properties (62%), and environmental footprint (62%) were selected by the symposium's participants as the main knowledge gaps surrounding the use of alternative substrates. The following features were also identified as important aspects requiring greater attention: long-term environmental impact, hydrological effects, impact on other species, ecosystem services, food safety, permitting, and development of objective methods to measure the suitability of new substrates.

When the poll's respondents were asked to name any issues with alternative substrates that should be addressed specifically in Maryland, public perception, equitable access and distribution of materials, and lack of cost-effective deployment methods were selected as the main problems.

Please see Appendix B for poll graphics and more information.

Different sizes of limestone marl used in Texas. Photos courtesy of Kathy Sweezey.

Granite (#57 stone) that was planted on a harvest area in Virginia and shows natural oyster recruitment less than a year after planting. Photo courtesy of Andrew Button.

Day 1: Table of Alternative Substrate in Fisheries

Speaker	State	Sector	Substrate	Used Since	Metrics	Summary
Chris Judy	Maryland	Fishery	Dredged Shells	1960	Spat recruitment, shell budget	Successful
			Surf Clam Shells	1995	Larval settlement, durability	Unsuccessful
			Slag	1935-1978	Spat recruitment	Successful; but potential toxins not measured
			Concrete	2022 (Experiment)	Spat recruitment	Successful
			Stones			Successful
Andrew Button	Virginia	Fishery	Dredged shells	1935	Spat recruitment, shell volume	Successful
			Granite stone chips (#57, 1" or smaller)	2014	Spat recruitment, compatibility with harvesting gear	Successful
Doug Monroe/ Bennett Paradis	North Carolina	Fishery	Limestone marl (rock)	1980	Spat recruitment, shell volume, local availability, compatibility with harvesting gear	Successful
Bill Rodney	Texas	Fishery	Crushed concrete (1–6 in)	2009	Oyster density, total area of restored reef	Successful
			River rock (0.75–6 in)	2009	Oyster density, total area of restored reef	Successful
			Limestone rock (1–2 in)	2020	Oyster density, total area of restored reef	Successful
Sandra Brooke	Florida	Experiment	Fresh oyster shell	2015	Spat recruitment, oyster growth and survival	Unsuccessful because shells dispersed
			Limestone rocks (2 in, 5–7 in)	2017	Spat recruitment, structural complexity, oyster growth and survival, compatibility with hand tongs (esp. 2-in rocks)	Successful
			Crushed concrete (4–6 in)	2023	Spat recruitment, oyster growth, and survival	Successful

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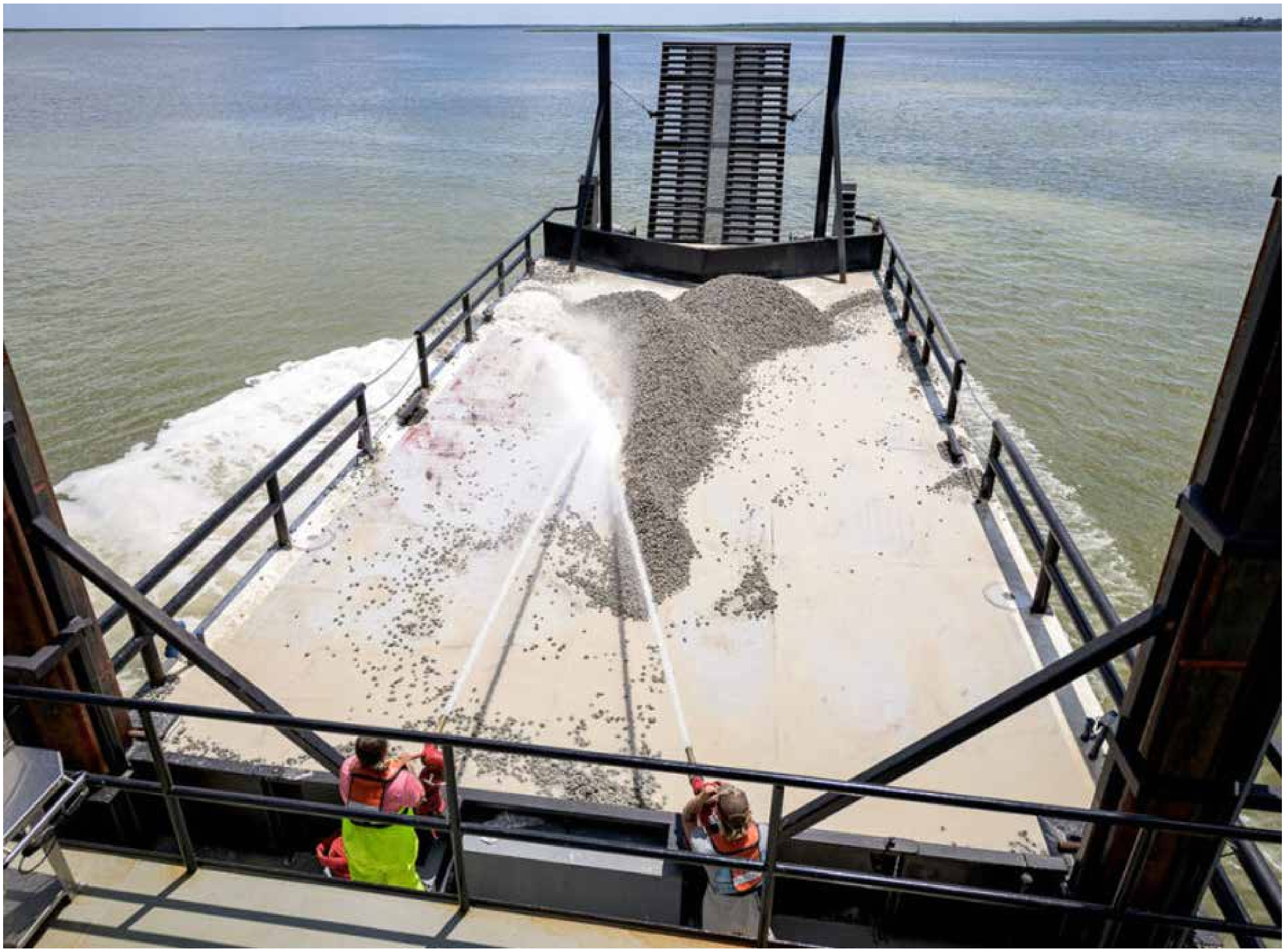
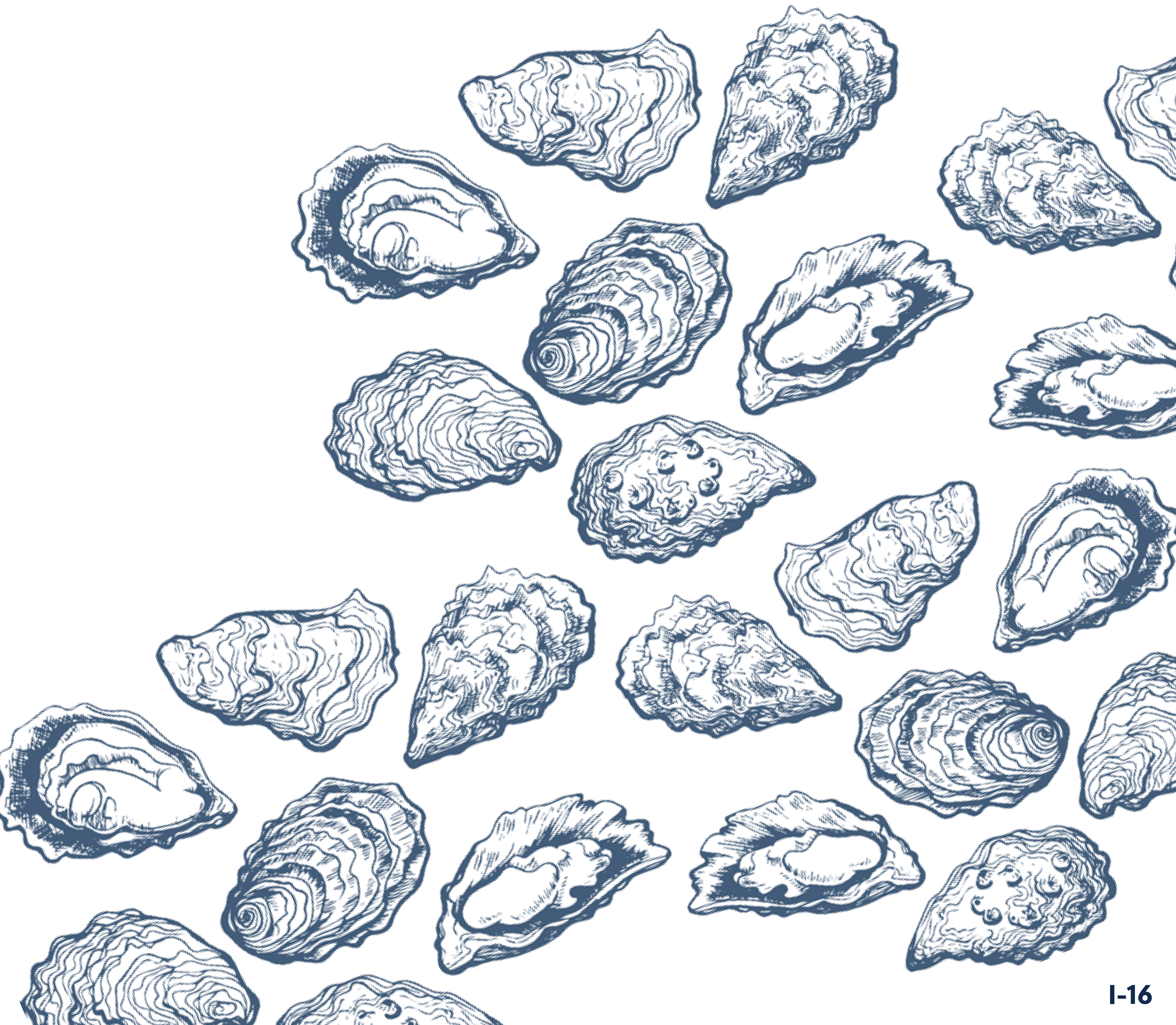
Day 1: Table of Alternative Substrate in Fisheries

Speaker	State	Sector	Substrate	Used Since	Metrics	Summary
Kathy Sweezey	Texas	Restoration, Fishery	Limestone marl (harvest mounds: 0.5–4"; sanctuary rows: 60–1500 lb. pieces)	2014	Spat recruitment, survival	Successful; but issues with cost and supply
Matt Pluta	Maryland	Experiment	Fresh oyster shells	2021	Spat recruitment	Successful
			Clam shells			Successful
			Cement			Successful
			Cobble			Successful
			Granite			Successful
			Ceramic			Unsuccessful
			Marble			Unsuccessful
			Brick			Unsuccessful



Deployment of limestone marl in North Carolina. Photo courtesy of Doug Munroe.

Day 2: Alternative Substrate for Use in Restoration

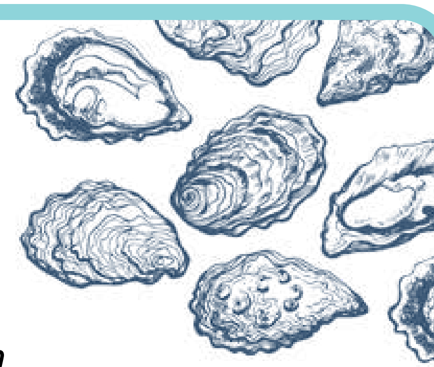


Day 2: Talk Highlights

Day Two was centered around using alternative substrates for oyster restoration and featured speakers from state and federal agencies, academia, and non-governmental organizations. Dr. Bill Dennison, interim president of the University of Maryland Center for Environmental Science (UMCES) and Vice President for Science Application, gave opening remarks. Beginning with the Native Americans that first lived in the Chesapeake Bay region, Dr. Dennison highlighted the importance of oysters to the people that lived there. Oysters continue to be a vital part of the social, economic, and ecological fabric of life in this region.

"...this conference is an exciting opportunity to share results, discuss ideas, and work collaboratively to enhance our understanding of nature, and employ science to create a better stewardship of our precious coastal resources."

- UMCES President Dr. Bill Dennison



Dr. Gray welcomed speakers and thanked them for sharing their valuable knowledge with symposium participants and the people in Maryland working to increase oysters.

Stephanie Reynolds Westby
NOAA Restoration Center

Stephanie Reynolds Westby opened the second day with an overview of the "Ten Tributaries" large-scale and multi-partners restoration initiative, based on the 2014 Chesapeake Bay Agreement, which has the goal to restore oysters and ensure their protection in 10 Chesapeake tributaries by 2025. To date, over 1,400 acres have been restored, with efforts completed in 9 of 11 tributaries. Alternative substrates, primarily stone of different sizes but also, in some cases, modular structures such as prefabricated cast concrete structures, were used in areas where there was no extant oyster reef (*i.e.*, where the reef needed to be created). For example, 1"–4" stones were used in the Manokin River on 31% of the 441 acres slated for restoration. In the Piankatank River, 2–4" stone plus VDOT A1 rip rap (approx. American football-size stones) were used on the 288 acres that needed amendment. Many projects involved multi-million dollar contracts for large barges of substrate that were deployed either by cranes or sprayed onto the riverbed with water cannons. The major barriers to the large-scale use of alternative substrates in oyster restoration in Maryland were public acceptance of the material, stakeholder use conflicts, cost of the materials, and the availability of materials.

Bennett Paradis
North Carolina Division of Marine Fisheries

Bennett Paradis presented their oyster sanctuary program in Pamlico Sound (NC) that started in 1996. Currently, the 15 large-scale oyster sanctuaries total 566 acres and range in size from 5 to 80 acres. They were established near oyster harvest areas to take advantage of larval spillover and provide a 'larval insurance policy' for the fishery. A range of materials have been used to build these sites, including marl limestone, granite, various forms of recycled concrete, reef balls, various shell types, and basalt, totaling over 240,000 tons of aggregate materials. After the initial sanctuaries were built in the late 90s, research suggested the importance of building up because relief on

Day 2: Talk Highlights

oyster reefs provides refuge from low dissolved oxygen events and creates better flow and food availability for oysters. Since 2003, NC oyster sanctuaries have been designed and constructed to be 4–6 ft high. Around 2017, managers began placing greater emphasis on building an interconnected and self-sustaining network of sanctuaries using a Habitat Suitability Model to guide site placement. The most recent projects (2017–current) have seen the construction of high-relief reefs created in ridges parallel to the bathymetry. Ongoing monitoring efforts via SCUBA surveys have resulted in a high-resolution, 6-year dataset quantifying oyster metrics on various alternative materials across Pamlico Sound. Results suggest that both total and adult oyster densities were significantly higher on granite and crushed concrete than on basalt, consolidated concrete, limestone marl, or reef balls. Additionally, there is a significant interaction between material type and material age, as oyster density declined at older sanctuaries (>25 years old).

Romuald Lipcius
Virginia Institute of Marine Science

Romuald Lipcius gave an overview of the lessons learned from subtidal oyster reef restoration in Virginia. In the Rappahannock River, large concrete structures had thousands of oysters per square meter of river bottom. In the Piankatank River (VA), a Habitat Suitability Model was used to guide restoration that resulted in many hundreds of oysters per square meter on reefs constructed with granite and shells. To build the Habitat Suitability Model, high-resolution side-scan sonar data was used to identify hard bottom areas. Next, a hydrodynamic and larval transport model was used to estimate larval dispersal and connectivity between sites to identify potential broodstock sites (that provide subsidies of larvae to the other reefs in the Piankatank), recipient sites (in a location to receive larvae but not contribute larvae to other reefs), and self-replenishment sites (that both release and receive larvae). Reefs were constructed in parallel ridges tangential to current flow as seen in historic oyster reef structures. Using precise habitat maps was important for avoiding bias in monitoring programs. The precision of abundance estimates can be improved by using a combination of both video camera footage and a subset of diver-collected samples.

Jay Lazar
NOAA Chesapeake Bay Office

Jay Lazar talked about a video-based assessment of habitat quality at restoration sites in Harris Creek (MD). The camera system allowed rapid assessment of 20 sites per hour with a three-person crew, resulting in 484 usable camera drops in eight sampling days. Results showed that reefs built with stone (6 to 12 inches in size) or with a base of stone had the highest mean habitat score followed by reefs constructed of mixed shell (oyster and clam or Whelk shell) and then by seed-only (spat on oyster shell) reefs. Reefs with stone and mixed shells cost approximately the same and had high and consistent habitat scores whereas seed-only reefs were less expensive but resulted in more variable habitat scores. Overall, the camera system demonstrated that the alternative substrates worked extremely well and that the camera system was a useful tool for assessing habitat quality. It was noted that each sector (fishery, habitat restoration, aquaculture) likely has a different size of substrate that best suits their needs, with larger stone more beneficial for restoration efforts. Because larger stones can pose a challenge for traditional monitoring gears (*e.g.*, patent tongs), a camera-based system is useful for monitoring habitat quality at restoration sites.

Day 2: Talk Highlights

Jennifer Zhu
Billion Oyster Project

Jennifer Zhu talked about the alternative materials and substrates used in New York Harbor through the Billion Oyster Project (BOP), which was established in 2014. BOP aims to restore 1 billion oysters to the Harbor and engage 1 million New Yorkers by 2035. New York Harbor is substrate-limited and larvae-limited, challenging oyster restoration efforts. To address the lack of suitable substrate, BOP established a shell recycling program, which now works with over 75 restaurants in New York City, to collect, cure, and reuse shells (primarily oysters, hard clams, and scallop shells). To contain shells and create bagged shell reefs or facilitate setting in its remote setting facility, BOP used coir bags (easy to use but not sturdy), biodegradable mesh bags (easy to use but may release microplastics), burlap bags (easy to use but degrades rapidly), or super trays (large capacity and easy to use but made of plastic). BOP considers oyster shells to be an ideal substrate for oyster larval settlement and incorporates recycled shells in project designs wherever possible: to create shell mounds, to serve as a setting substrate (spat-on-shell), or as aggregate in larger reef structures (such as reef balls). Some structures tested by BOP, such as piling wraps, proved more effective for enhancing habitat along shoreline infrastructure rather than restoring self-sustaining and functional oyster populations. Larger reef structures, such as reef balls, and eco-friendly concrete disks or blocks, demonstrate high larval setting rates and support high oyster density, but drawbacks related to accessibility, carbon footprint, biodegradability, scalability, and permitting require consideration.

David Schulte
US Army Corps of Engineers

David Schulte described results from a large-scale restoration project using reef balls in the Lynnhaven River in Virginia. The USACE, in partnership with the City of Virginia Beach, placed 28,045 1.5-ft-wide reef balls spaced 2.6 ft apart over an 8-acre footprint in subtidal waters. Mean oyster density on the reef ball network was found to be much higher than those noted on very successfully restored shell reefs in the Great Wicomico and Lynnhaven Rivers. Despite the reefs being less than three years old and holding only three-year classes, many adults exceeded 100 mm shell height, with the largest specimens being over 140 mm (5.5") long. Mean oyster biomass was 1,138 g dry weight per square meter of the bottom area covered by the reef ball network and exceeded the USACE goal by 3.5 fold and the Goal Implementation Team (GIT) goal by almost 23 fold. Gill net surveys indicate that the restoration site was an important foraging area and nursery to other species (*e.g.*, black sea bass, spot, seatrout), supporting benthic and pelagic biodiversity. A direct comparison between the reef balls and shell reefs in the Lynnhaven shows that the reef balls significantly outperformed shell reefs, suggesting that alternative reef structures should be seriously considered when planning large-scale oyster restoration efforts.

Russell Burke
Christopher Newport University

Russell Burke closed the second day of presentations with a description of a large-scale restoration project in the Elizabeth River (VA). They created five restoration sites, each with multiple types of substrate (shell beds, granite beds (6 to 12 inches in size), 2-ft-high pyramids, 2-ft-high reef balls, and 1.5-ft-high tables). Five years later, oysters were doing well at all sites but oyster abundances were not as high as those in the Lynn Haven River, likely because of poor water quality in the southern branch of the Elizabeth River. Mean oyster density exceeded restoration goals at all sites over all 5 years of monitoring, but mean oyster biomass was below restoration targets in all five years at 3 of the 4 sites with granite beds and 2 of the 4 sites with shell beds. All sites with pyramid and reef ball

Day 2: Panel Discussion and Participants' Input

concrete structures exceeded mean oyster biomass thresholds in all years, potentially because they provided more height in the polluted waters. Notably, a side-by-side comparison of live oyster shell volume at four sites over five years showed that alternative substrate outperformed shell in 17 out of 20 comparisons. In polluted systems, alternative substrates enabled restoration goals to be met. Shell reefs were successful when built in areas with good water quality.

Key Points:

Knowledge gaps

A key aspect of the panel discussion on knowledge gaps for using alternative substrates in sanctuaries focused on identifying ecosystem services at both the reef and tributary levels with the recognition that these services can differ between regions and that some services are difficult to measure (*e.g.*, larval spillover and use by transient species). Another key knowledge gap was how to build sanctuaries spatially to take advantage of the combination of connectivity and habitat suitability, and, at the same time, be efficient and cost-effective (in terms of both material and transportation costs). Panelists pointed to the need to build sanctuaries to support the fishery and to get the most ecological "bang for the buck" with the limited funding and materials in hand. The ability to monitor sites where the substrate cannot be brought to the surface was also identified, as was the potential solution of using a camera and computer-assisted identification software. The question of how to marry restoration efforts in shallow water with shoreline protection efforts to best enhance coastal and climate resilience was identified as an important area in need of future work.

Public perception and regulatory hurdles

Persistence has helped with public perception and regulatory hurdles, and working with, and communicating with, affected communities. Listening and really taking into account what is being said in local communities is important—in other words, being sure to honor local public perception and trying to adapt. Some examples of responding to local communities include leaving wide buffers around navigational channels, not building in high-use places, trying alternative materials, and capping stone sites with shell or minimizing the use of alternative materials if shell is preferred. It is important to note that what sits well in the scientific community has not proven particularly compelling to those in the harvest community, so scientific measurements may not always be the right tool to inform public perceptions.

Key metrics

The following metrics were identified by the panelists as key to measuring/tracking the performance of alternative substrates and their suitability for use in restoration sites: oyster density (spat recruitment and survival), biodiversity and water filtration (ecosystem services), substrate volume, structural complexity and durability (*i.e.*, persistence over time), and indicators of reef health like biodiversity and the presence of species that do reef husbandry (*e.g.*, shrimp and mud crabs). Also, measuring the system's response to determine if a restoration effort creates conditions at a scale that allows the system to respond.

Overcoming barriers

According to the panelists, barriers to the large-scale use of alternative substrates for oyster restoration include costs, public perception, and "NIMBY" (Not In My Back Yard) resistance. There can be different amounts of resistance to restoration in some areas more than other areas. It's important to meet with local communities and politicians, demonstrate that you're listening to them, and give them a voice in project designs.

Day 2: Panel Discussion and Participants' Input

Environmental concerns and biosecurity issues

The need for thorough research on sources and compositions of alternative substrates was highlighted as crucial to avoid/reduce environmental concerns, especially when recycled materials are selected to be used in restoration programs (*e.g.*, avoid any concrete pipe that's been used in sewage systems). Other issues include being aware of the potential leaching of chemicals from recycled materials and the potential input of microplastics from biodegradable materials.

Other questions and ideas

In a system with poor larval supply, "sentinel reefs" (a network of smaller-scale reefs) could be used to test if the reefs are in locations that perform well before investing funds for large-scale projects. It also is important to take into account the observation that egg fertilization declines exponentially with distance away from spawners so highly concentrated broodstock on a small area may be more effective in producing larvae than the same amount of broodstock spread out over a larger area. Another important question in areas with low larval supply (*e.g.*, tributaries in upper Chesapeake Bay) is if large-scale efforts must be self-sustaining over the long term or do we need to recognize, and quantify, benefits that justify some maintenance costs (*e.g.*, overplanting spat-on-shell every 5 or 10 years) as worthwhile ongoing public investments.

Participants' Input: Day 2

Symposium participants were asked to fill out an online anonymous poll. The poll respondents on Day 2 of the symposium worked in the following sectors: Restoration (91%), Aquaculture (30%), Fisheries (16%).

The shell **substrates** most commonly used by the poll's participants were clam shells (46%) and *C. virginica* fossil shells (48%), while limestone marl (40%) and crushed concrete (34%) were the most popular non-shell alternative substrates. Numerous respondents used alternative substrates that were not listed in this question (42% river rocks, concrete complex structures (reef balls, castles, etc.), recycled concrete, other shells (scallops, flat oysters, mussels, cockles), bricks, tiles, bamboo, tomato stakes, crab pots, pallets, basalt, slate).

Larval preference (59%), support of biodiversity (53%), availability of materials (34%), and costs (32%) were selected by the poll respondents as alternative substrates' top **priority features**. According to the poll's participants, alternative materials should also promote high vertical relief, increasing the height of oysters above sediments (32%). The following additional characteristics of alternative substrates were highlighted as important: scalability and substrate complexity.

The **knowledge gaps** on the use of alternative substrates selected by the symposium's participants were the same as on the first day: scalability (80%), material properties (54%), and environmental footprint (63%). Ecosystem services, persistence of materials, and larval preferences also were identified as important aspects requiring greater attention.

When respondents were asked to name any issues with alternative substrates that should be addressed specifically **in Maryland**, the following barriers were mentioned: interaction/interference with SAV, use of recycled materials, permitting, public perception, lack of performance testing for alternative materials, lack of information on persistence of materials in the natural environment.

Please see Appendix C for poll graphics and more information.

C-dome deployed for oyster reef restoration in Virginia. Photo courtesy of Rom Lipcius.

Monitoring efforts include counting and measuring thousands of oysters at restoration sites in North Carolina. Photo courtesy of Bennett Paradis.

Day 2: Table of Alternative Substrate in Restoration

Speaker	State	Sector	Substrate	Used Since	Metrics	Summary
Stephanie Reynolds Westby	Maryland, Virginia	Restoration	Stones (small: 1–4”, large: 10–11”)	2011	Spat recruitment, biodiversity, structural complexity	Successful
			Prefabricated cast concrete structures	~2000	Spat recruitment, biodiversity, structural complexity	Successful
Bennett Paradis	North Carolina	Restoration	Mixed substrates: limestone, granite, shells, concrete, reef balls, basalt	1996	Spat recruitment, oyster growth, structural complexity	Successful (best performance: granite and concrete)
Romuald Lipcius	Virginia	Restoration	Concrete	NA	Spat recruitment	Successful
			Granite riprap (size: A1 class)	NA	Spat recruitment oyster growth	Successful
Jay Lazar	Maryland	Restoration	Stones (6–10 in) and crushed shells (Whelk + clam)	2012	Spat recruitment, structural complexity	Successful
Jennifer Zhu	New York	Restoration	Coir bags	2020	Biodegradability, logistics, larval settlement	Unsuccessful
			Biodegradable mesh bags	2021	Biodegradability, logistics, larval settlement	Unsuccessful
			Burlap bags	2021	Biodegradability, logistics, larval settlement	Unsuccessful
			Piling wraps	2021	Spat recruitment, oyster growth, durability	Successful (enhancement technique)
			Reef Ball	2021	Spat recruitment, durability, carbon footprint	Successful
			ECOncrete disk	2018	Spat recruitment, logistics, carbon footprint	Successful

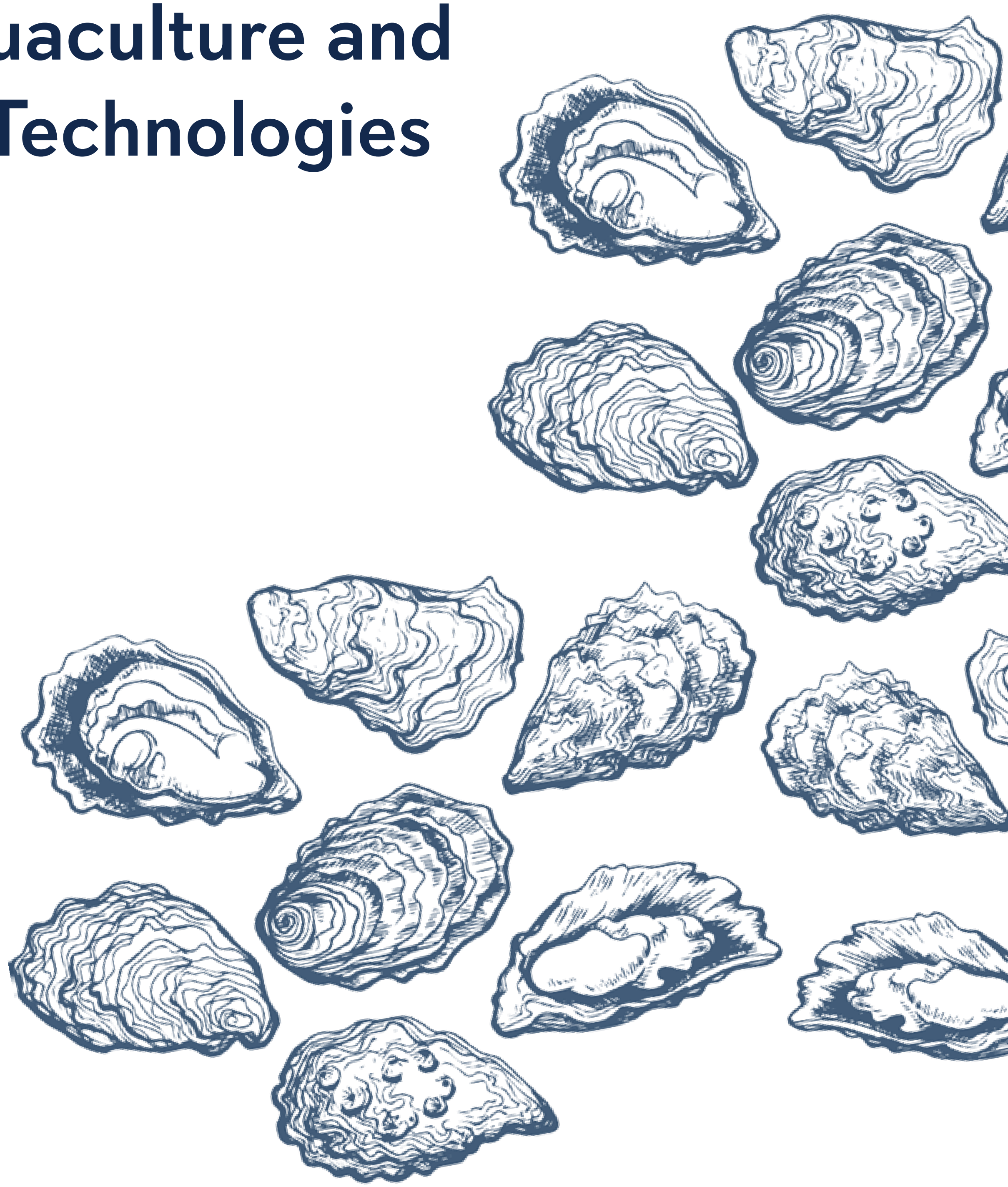
Table continued on next page →

Day 2: Table of Alternative Substrate in Restoration

Speaker	State	Sector	Substrate	Used Since	Metrics	Summary
David Schulte	Virginia	Restoration	Concrete (reef balls)	2020	Spat recruitment, oyster performance (survival and growth)	Successful
Russell Burke	Virginia	Restoration	Shells + alternative substrates: granite stones (6–12 in), concrete (reef balls, table tops, pyramids)	2015	Spat recruitment, oyster performance (survival, growth, condition index), structural complexity (reef biomass and volume)	Successful

Pre-fabricated oyster reef installed in Baines Creek, Virginia. Photo courtesy of Russell Burke.

Day 3: Alternative Substrate for Use in Aquaculture and New Technologies

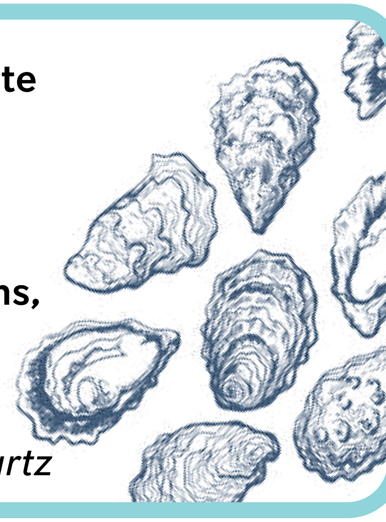


Day 3: Talk Highlights

Day three featured speakers from aquaculture, academia, and private businesses to discuss the use of alternative substrates in oyster aquaculture. Josh Kurtz, Secretary of the Maryland Department of Natural Resources, gave opening remarks. Secretary Kurtz emphasized Governor Moore's commitment to supporting the oyster industry and oyster restoration through the development of innovative solutions like alternative substrates.

"We know that we don't have enough shell and substrate or hard bottom in the Bay to support the industry, to support the sanctuaries, the restoration, as well as aquaculture....the work that you're doing to develop innovative solutions, and frankly, cost effective solutions, is going to be critical to us being able to expand aquaculture and restoration effort across the Bay."

- Secretary Josh Kurtz



Dr. North welcomed speakers and thanked them for sharing their valuable knowledge with symposium participants and the people in Maryland working to increase oysters.

Ward Slacum
Oyster Recovery Partnership

Ward Slacum began Day 3 with an overview of the findings of the Alternate Materials Workgroup of the Maryland Department of Natural Resources Aquaculture Coordinating Council. Workgroup members aimed to identify alternatives to shells that could be used in the remote setting process that involves setting hatchery-reared oyster larvae on shells, and then deploying the spat-on-shell at remote sites. He reiterated that oyster shell is an increasingly limited resource; it is in high demand and there is a national shortage. The workgroup decided that key metrics for evaluating alternative substrates for use in remote settings include suitability for oyster settlement and growth, cost and logistics, feasibility for use in large-scale efforts, where and how the material is currently being used, and regulations for use. The workgroup highlighted the current regulatory environment and the stakeholders' perception as major challenges for the use of alternative substrates. Key recommendations of the workgroup were to work with stakeholders from all oyster production sectors to communicate the benefits of alternative substrates; improve the regulatory environment for the use of alternative substrates, and determine and publish a list of approved alternative substrate materials and then test them for suitability in the remote setting process.

Steve Fleetwood
Bivalve Packing Company

Steve Fleetwood described the custom-built suction dredge boats that the Bivalve Packing Company uses to recycle oyster shells on their aquaculture leases in Connecticut and New Jersey. Their suction dredge boats were designed to be able to reach their leases and piers when fully loaded. Two boats are 105 ft long and 35 ft wide and the third is 90 ft long and 30 ft wide. The suction dredges only suck up what is loose on the bottom; it does not create holes on the bottom. With the smaller boat, 3,000 bushels of shell per day can be retrieved from the top 1 inch of the lease. The larger boats can recover

Day 3: Talk Highlights

4,000 to 5,000 bushels per day. The shell can be unloaded in ~1.5 hrs with a skid steer loader or less than that if an excavator with clamshell bucket is used. Recovering shell is done in the wintertime, with the goal of being finished by the end of February in order to give the shell plenty of drying time on land so that fouling doesn't prevent spat catching when the shell is deployed in early summer. They use sophisticated electronics and dredge sampling to suction dredge with accuracy and caution to ensure what they do is compatible with the bottom type of each lease. Overall, suction dredging is an efficient and cost-effective way to recycle shells within leases, ensure good spat catch, and eliminate the need to purchase shell or other substrate.

Niels Lindquist
Sandbar Oyster Company Inc

Niels Lindquist presented a new plastic-free material for oyster habitat creation called the Oyster CatcherTM substrate (OCS)—a patented/patent-pending composite of cement-infused plant fiber cloths. OCS is now being used in North Carolina, Virginia, Georgia, Florida, and California. A variety of modular OCS shapes (*e.g.*, tables, pillows, mats, panels, patties) can be fabricated and combined in many different ways to create reef frameworks tailored to specific environments that facilitate oyster recruitment and reef growth, act as wave breaks and/or promote sediment capture. The relatively low OCS costs and ease of installation make it cost-effective for larger-scale habitat restoration and living shoreline projects in low- to high-energy environments and across hard to soft bottom types. Multiple projects now demonstrate OCS efficacy, for example, Lindquist and co-inventor/SANDBAR co-founder David Cessna, an NC commercial oysterman, are transforming intertidal sand flats into self-sustaining and rapidly expanding oyster reef-salt marsh mosaics. Another Oyster Catcher™ product, Tufts, are SANDBAR's pretzel-shaped oyster shell substitute. Tufts are ideal for achieving high set density in nature and remote setting, facile rearing of juvenile oysters, and ease of relay. Further, Tufts readily shed single spat as seed for aquaculture. Oyster Catcher™ substrates offer multiple means to create oyster-based habitats that provide diverse ecosystem services including shoreline protection, habitat provisioning, water-quality improvement, carbon sequestration and food.

Christine Thompson
Stockton University

Christine Thompson presented the results of two studies conducted in Southern Barnegat Bay (NJ), investigating the suitability of non-oyster shells as alternate substrates for remote settings. The first study involved two treatments: Whelk shells set with oysters and transplanted oysters from a different river system. While oysters from both treatments thrived, the remote-set Whelk shells had higher growth and less disease mortality than the transplanted oysters. An additional experiment was conducted in remote setting tanks to compare the preference of oyster larvae for oyster, Whelk, and clam shell. Although there was variability between tanks and depths within tanks, the overall trend was the number of spat per shell was greatest for clam > oyster > Whelk shell. After planting the shells in June 2019, the team conducted follow-up monitoring after 4 months to assess growth rates among the oysters on different shell types. Shell height was significantly greater on clam and oyster shell compared to Whelk shell, but those that were on the Whelk shell had higher survival. Overall, the remote setting process was highly variable and influenced by factors ranging from the larval batch, number of larvae, and environmental conditions in the setting tanks. Although there are tradeoffs in terms of which type of shell promotes the best oyster settlement or provides the best reef habitat, currently the choice of shell type is limited by what is available and cost-effective.

Day 3: Talk Highlights

Mark Clark
University of Florida

Mark Clark described his group's development of Jute-Reinforced Calcium Sulfoaluminate (JR-CSA) for creating structures that promote oyster settlement and aid in coastal erosion protection and habitat restoration in low- to moderate-energy environments. CSA is primarily used for rapid infrastructure repair (runway, tunnel) where rapid set time and early strength development are required. Often called "green cement," CSA is a cement accelerator that has lower carbon dioxide emissions than ordinary portland cement. Oyster larvae were found to settle and grow on ceramic tiles coated with CSA in similar numbers compared to portland cement. When combined with jute, JR-CSA structures are plastic-free and can be constructed from readily available materials and deployed by volunteers with no specialized equipment. Currently, semi-pervious Jute Erosion Control Mats are used for structure instead of tight weave burlap because the loose weave reduces wave refraction by allowing wave energy to move into the structure and be absorbed. Numerous shapes can be created such as mounds ("reef turtles"), ribs, panels, and prisms. Empty prisms and panels weigh ~45 lbs and shell-filled prisms weigh ~120 lbs. JR-CSA materials have been deployed and are undergoing testing at 14 sites in Florida and one in South Carolina. While it is known that CSA mix composition and Jute quality are critical aspects of JR-CSA performance, material longevity, quality control mechanisms and optimal deployment configuration of reef panels and reef prisms are the leading knowledge gaps at this time.

Christopher Karwacki
C.J. Karwacki Consulting, LLC

Christopher Karwacki is focused on understanding the chemistry behind the oyster shells and using this knowledge to create alternative materials for oyster settlement. The main chemical components in the growth of an oyster shell are carbonic acid (CO_2 dissolved in water) and calcium hydroxide, which interact at the inside surface of an oyster shell to form an amorphous calcium carbonate phase. This phase eventually crystallizes, forming calcium carbonate crystals. Further strengthening occurs with the oyster's synthesis of acyl-acetylated chitosan (chitin), an organic binder that integrates with the crystalline structure, making it more resilient by adding stability through covalent and ionic bonding. This bonding sequence creates layers that repeat within the shell, forming a fortified, sequential structure that enhances durability. Materials like chitin are complex to synthesize, so they are using cellulose which can be effective and cost-efficient. They are developing layered structures using calcium carbonate encapsulated in cellulose or chitin, with the goal of building shell-like structures. These engineered materials could be used to form either small shell shapes or larger structures for reef environments. Controlled trials with the materials are ongoing.

Hunter Mathews
University of North Florida

Hunter Mathews is using Pervious Oyster Shell Habitat (POSH) for oyster reef habitat restoration along high-energy shorelines in northeast Florida. POSH structures are made with oyster shells and portland cement, providing structurally complex habitat. They use about half the cement of a comparable oyster ball and require a similar curing period on land of about a month before deployment. In one study, POSH-coated shells had higher oyster settlement than uncoated oyster shells. In a different study, when compared with oyster balls deployed in the same locations, POSH structures had higher oyster recruitment, better use by oysters of the surface area, and a more natural reef appearance after one year. Both types of structures had similar heights, sediment accretion on landward sides and scour on seaward sides, some gain in height from oysters, and similar shifting of the structures. POSH structures attracted higher densities of benthic organisms like mud crabs.

Day 3: Panel Discussion and Participants' Input

After two years, POSH structures continued to maintain greater oyster densities and use by benthic organisms, showing promise for restoration efforts in high-energy near-shore environments. A construction manual for creating POSH structures is available from University of North Florida.

Key Points:

Knowledge gaps

Panelists were invited to discuss key knowledge gaps for using alternative substrates for aquaculture in large areas and subtidal regions. Performance and handling of alternative substrates, in both remote setting and in-water applications, were identified as important knowledge gaps, as were the effect of substrates on harvest methods. Additional key gaps were related to the longevity and appearance of the substrate which, if fragmented, could end up as small pieces attached to oysters. Panelists questioned how small pieces of concrete would look on oysters intended for the half shell market and whether this would detract from the product or, if the concrete was colored, help with product tracing and enforcement.

Public perception and regulatory hurdles

One of the public perception challenges named by the panelists was concern over the safety of alternative materials. It was noted that subtidal practices were highlighted as more publicly accepted, compared to intertidal ones, because of their distance from the shoreline which makes them more invisible to local communities. For suction dredging, the large width of the suction dredge (6 feet) makes it look potentially damaging to the bottom, but actually the operators are quite careful; it only removes the upper 2 inches and creates no more disturbance than a half-foot dredge on the bottom. It was noted that public perception with shell piles on land can be negative if the smell and bird droppings (from birds attracted to the pile) are close to residential or commercial sites. These perception issues could be addressed through a collaborative approach between different stakeholders and better communication with the public.

Key metrics

Panelists identified several key metrics for alternative substrate, including setting efficiency, oyster growth, substrate durability of the material (how long it lasts), ease of harvesting, and knowledge of the spawning stock biomass in the system. Additional important metrics include weight of the material, return on investment, and the carbon footprint of the material and its transportation.

Overcoming barriers

Panelists discussed key barriers for use of alternative substrate including cost of the substrate and the fact that the regulatory environment is not conducive for using anything other than oyster shell. Additional logistical and timing issues related to substrate deployment were highlighted, as is the need for a labor force that could produce some alternative materials.

Environmental concerns and biosecurity issues

In terms of aquaculture, panelists discussed that alternative substrates need to be non-toxic and that biosecurity issues should be assessed for biological materials that come from out of the region.

Day 3: Panel Discussion and Participants' Input

Other questions and ideas

The idea of recycling shell with shallow-draft suction dredges on leases was discussed with interest, noting that there is a tremendous amount of shell already available in and on the Chesapeake Bay bottom that would not require deep dredging. It was also noted that suction dredges can be used to move large volumes of seed oysters and the process of removing fouling from the shell using suction is beneficial because even productive areas can end up with too much sediment in some years.

Participants' Input: Day 3

Symposium participants were asked to fill out an online anonymous poll. The poll respondents on Day 3 of the symposium worked in the following sectors: Restoration (90%), Aquaculture (42%), Fisheries (29%).

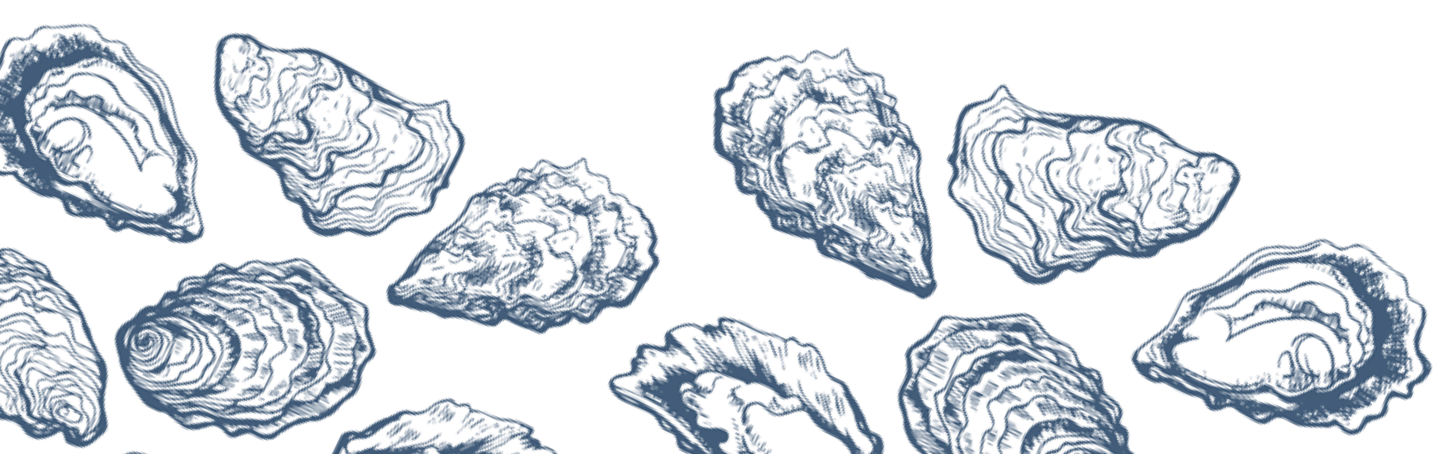
The shell **substrates** most commonly used by the poll's participants were clam shells (45%), Whelk shells (35%), *C. virginica* fossil shells (42%), and *C. virginica* dredged shells (32%), while limestone marl (38%) and granite (32%) were the most popular stone alternative substrates. Poll's respondents also used alternative substrates that were not listed in this question: recycled concrete, cement-coated jute, and foam glass.

Larval preference (54%), support of biodiversity (45%), availability of materials (45%), costs (42%), and durability (42%) were selected by the poll's participants as alternative substrates' top **priority features**. According to the poll's respondents, the weight of alternative materials is also important because it needs to be light enough to be easily deployed, but also heavy enough to endure wave energy.

Scalability (73%), material properties (66%), and environmental footprint (56%) were selected by the symposium's participants as the main **knowledge gaps** surrounding the use of alternative substrates. The ability to adapt to rising seawater levels was also highlighted as an important aspect requiring greater attention.

When the poll's respondents were asked to name any issues with alternative substrates that should be addressed specifically **in Maryland**, public perception, stakeholder engagement, lack of performance testing for alternative materials, and lack of information on the persistence of materials in the natural environment were identified as major barriers.

Please see Appendix D for poll graphics and more information.



Suction dredge boat with a load of dredged shell in Delaware Bay. The head of the suction dredge is at the stern. Photo courtesy of Steve Fleetwood.

Oyster Catcher™ Tuffs used to catch wild oyster spat set in the intertidal and relay to aquaculture sites. Photos courtesy of Niels Lindquist.

Day 3: Table of Alternative Substrate in Aquaculture

Speaker	State	Sector	Substrate	Used Since	Metrics	Summary
Ward Slacum	Maryland, New Jersey, N. Carolina, S. Carolina	Restoration (sanctuaries), Aquaculture (remote setting)	Limestone marl	N/A	Larval settlement, spat growth, costs, logistics	Successful
	Maryland, New Jersey, N. Carolina, S. Carolina		Concrete	N/A		Successful
	New Jersey		Non-oyster shells (Whelk, clams)	N/A		Successful
Niels Lindquist	North Carolina	Restoration, Aquaculture	Oyster Catcher™ (Cement: plant fiber)	2014	Larval settlement, spat recruitment and growth, cost, logistics, availability	Successful
Christine Thompson	New Jersey	Restoration (remote setting)	Whelk Shells	2016	Spat recruitment, survival and growth	Successful
			Clam Shells	2019	Spat recruitment, survival and growth	Successful
Mark Clark	Florida	Restoration, Aquaculture	JR-CSA (Jute-Reinforced Calcium Sulfoaluminate)	N/A	Spat recruitment, biodiversity, costs, availability, logistics, environmental footprint	Successful
Hunter Mathews	Florida	Restoration, Aquaculture	POSH (cement + oyster shells)	2019	Logistics, costs, carbon footprint	Successful
				2022 (experiment)	Larval settlement, spat recruitment and growth	Successful
				2022 (experiment)	Biodiversity: fish and crustaceans	Successful

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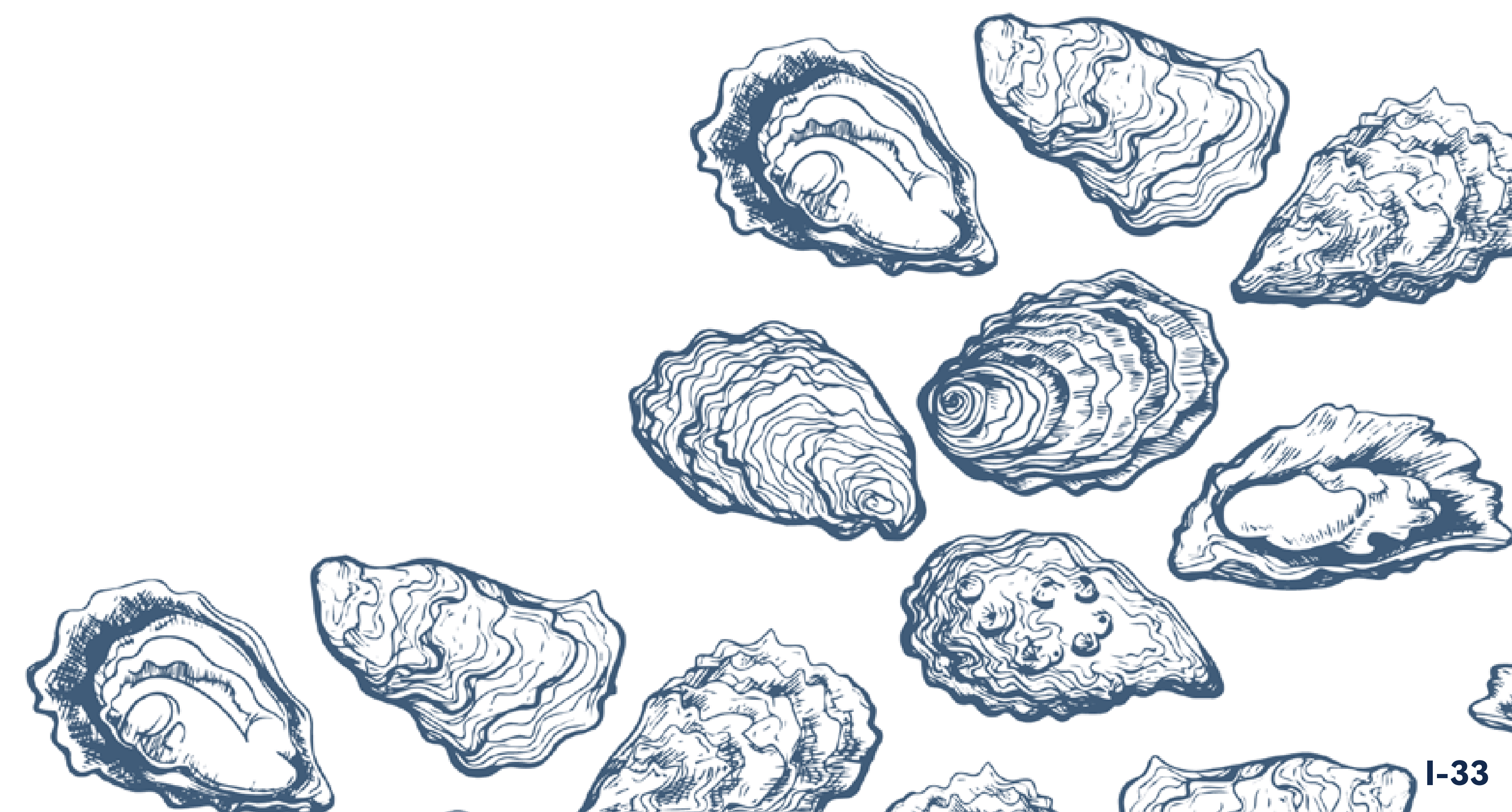


Appendix A: Schedule of Events and Logistics

Monday, Feb 26: Alternative Substrate for Use in Fisheries

10:00	Introduction
10:05	Sarah Elfreth, Maryland State Senator
10:15	Chris Judy, Maryland Department of Natural Resources
10:30	Andrew Button, Virginia Marine Resource Commission
10:45	Doug Munroe, North Carolina's Division of Marine Fisheries
11:00	William Rodney, Texas Parks and Wildlife
11:15	Sandra Brooke, Florida State University Coastal and Marine Lab
11:30	Kathy Sweezey, The Nature Conservancy
11:45	Matt Pluta, ShoreRivers
12:00	Speaker Q&A
12:30	Chat n' Chew Breakouts
01:00	Plenary Discussion
02:00	Adjourn

Tuesday, Feb 27: Alternative Substrate in Large-Scale Restoration

10:00	Introduction
10:05	Dr. Bill Dennison, UMCES Interim President
10:15	Stephanie Reynolds Westby, NOAA Restoration Center
10:30	Bennett Paradis, North Carolina Division of Marine Fisheries
10:45	Romuald Lipcius, Virginia Institute of Marine Science
11:00	Jay Lazar, NOAA Chesapeake Bay Office
11:15	Jennifer Zhu, Billion Oyster Project
11:30	David Schulte, US Army Corps of Engineers
11:45	Russell Burke, Christopher Newport University
12:00	Speaker Q&A
12:30	Chat n' Chew Breakouts
01:00	Plenary Discussion
02:00	Adjourn

Appendix A: Schedule of Events and Logistics

Wednesday, Feb 28: Alternative Substrate in Aquaculture & New Technologies

10:00	Introduction
10:05	Josh Kurtz, Secretary, Maryland Department of Natural Resources
10:15	H. Ward Slacum, Oyster Recovery Partnership
10:30	Steve Fleetwood, Bivalve Packing Company
10:45	Niels Lindquist, Sandbar Oyster Company Inc.
11:00	Christine Thompson, Stockton University
11:15	Mark Clark, University of Florida
11:30	Christopher J. Karwacki, C.J. Karwacki Consulting, LLC.
11:45	Hunter Mathews, University of North Florida
12:00	Speaker Q&A
12:30	Chat n' Chew Breakouts
01:00	Plenary Discussion
02:00	Adjourn

Symposium Logistics

To join the symposium: Follow this Zoom link
http://tinyurl.com/5h44vwjf
Passcode: 104153

To ask the speakers a question: Type your question in the Zoom chat. Only the speakers will be able to see your questions.

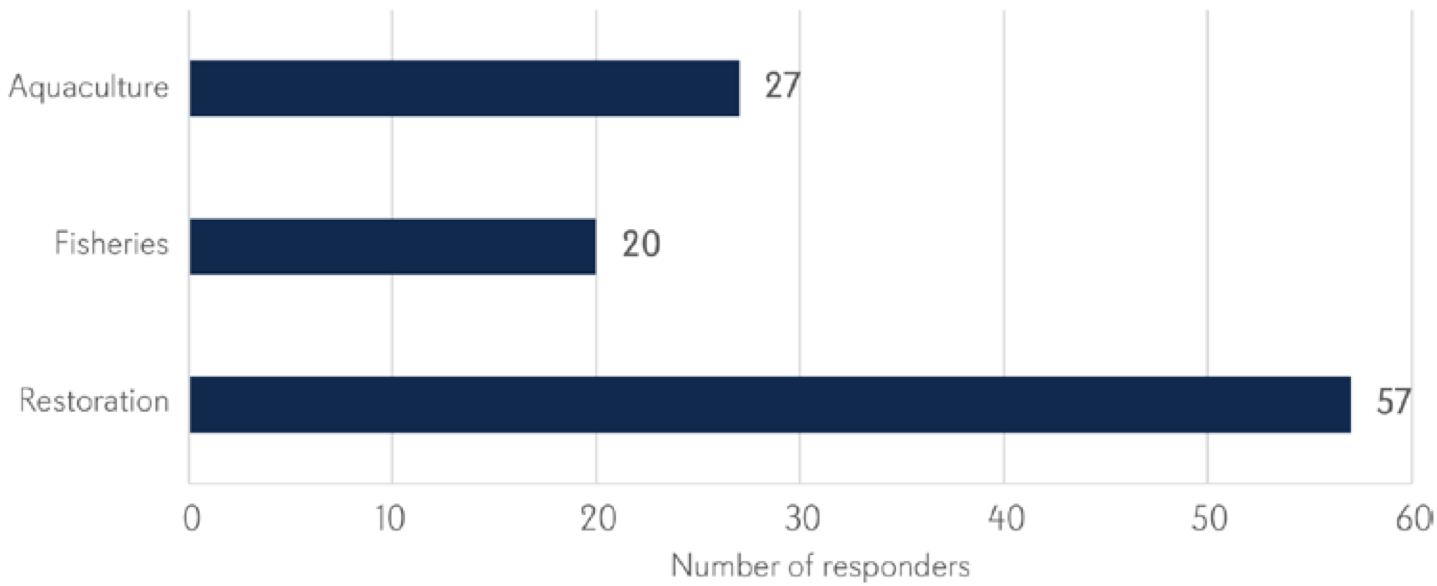
To join a Chat n' Chew: Follow the link provided in the Zoom chat at lunchtime.

To ask a question or make a comment during plenary: Type your question or comment in the Zoom chat. The moderators will be able to see your questions and comments and will relay them to the panelists.

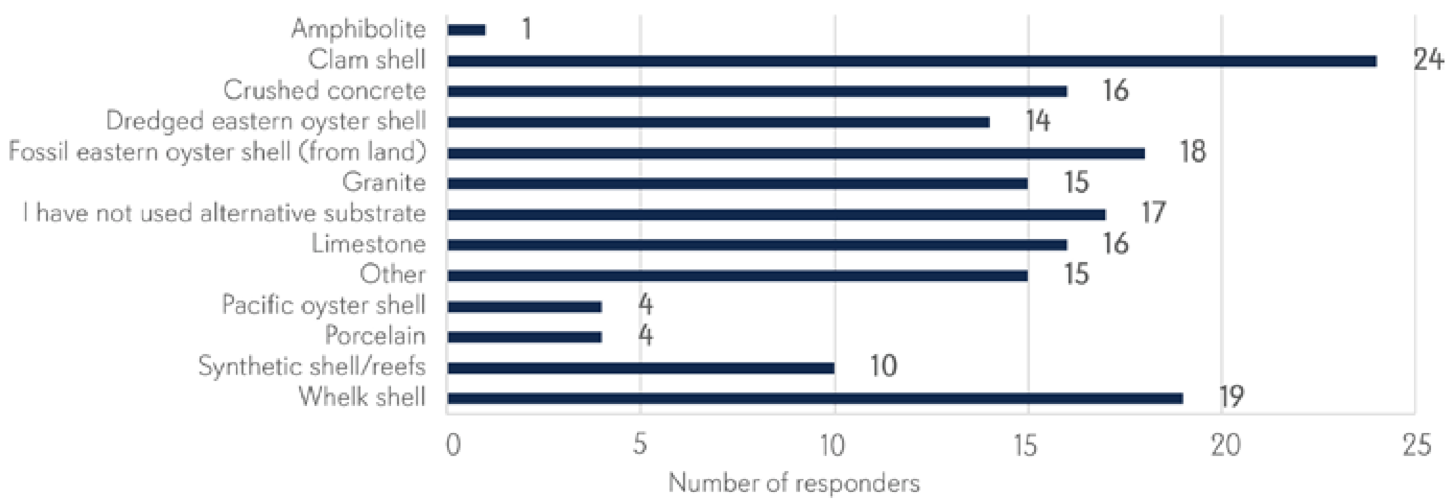
To receive a copy of the symposium report: All registrants will be sent the report.

Appendix B: Poll Results on Day 1

I work in the following sector(s):



What types of alternative substrates have you used? (check all that apply)

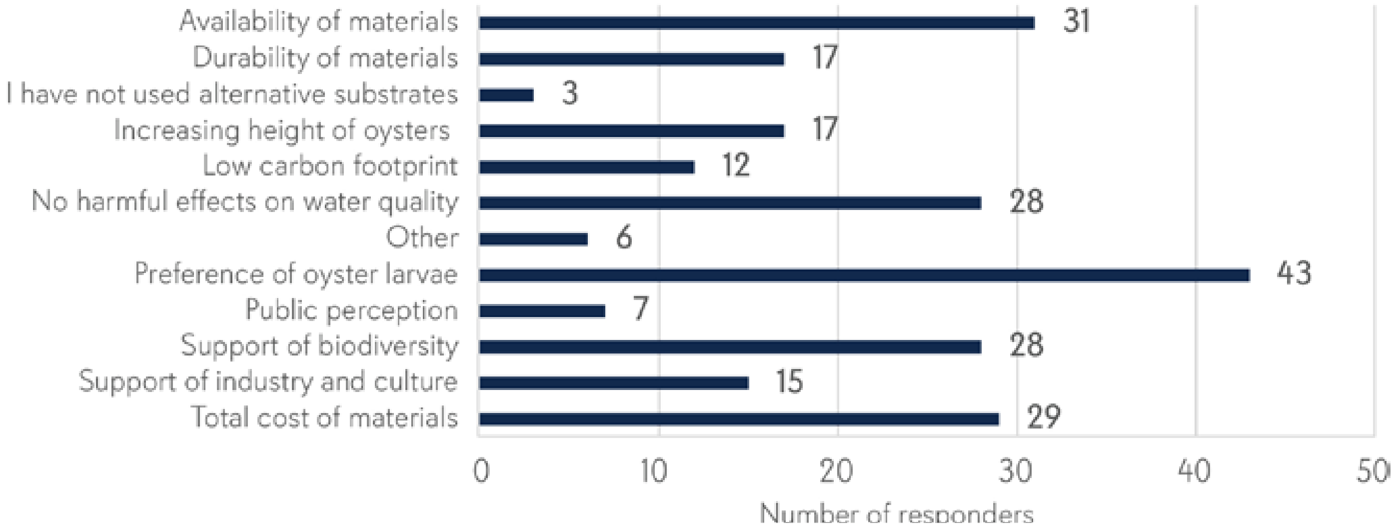


In the Other category, the following were listed:

- Reef balls
- Stone
- River rock
- Portland cement
- Quickreef crumbles
- Crab pots
- Manufactured wire reefs
- Bamboo
- Tomato stakes
- Oyster castles
- Sandbar oyster catcher
- Recycled shell
- Concrete made with shell powder
- Natural river gravel (quartzite)
- Scallop balls and blocks

Appendix B: Poll Results on Day 1

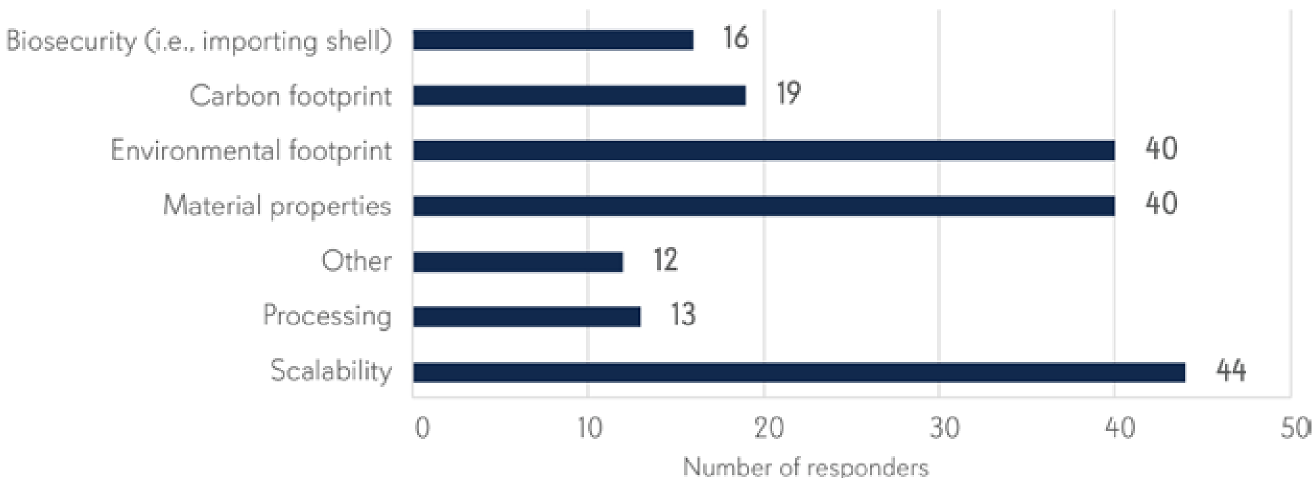
What benefits of alternative substrates are most important to you:



In the Other category, the following were listed:

- Permitting agency
- Integration into the seascape
- Ecological/habitat function
- Use of recycled concrete for living shorelines
- Use in living shoreline efforts
- Development of functioning ecosystem, rather than just fisheries
- Substrate complexity, not just surface rugosity

What aspects of alternative substrate require greater investigation? (choose your top 3)



In the Other category, the following were listed:

- Long term effects of alternative substrates
- Plastic alternative shellbags
- Constraints and creative opportunities of alternative substrates (beneficial use of dredge materials, shell "contaminants" of an offshore borrow area for beach nourishment projects)
- Preference of oyster larvae
- Food safety thresholds for potential contaminants in non-natural substrates
- Cost efficiency: delivered cost per ton/spat recruitment or market oyster yield
- Ecological function
- Fisheries impact on other species
- Contribution to ecological and ecosystem services
- Permitting pathways enter recruitment relative to cured shell
- Suitability for fishery use

Appendix B: Poll Results on Day 1

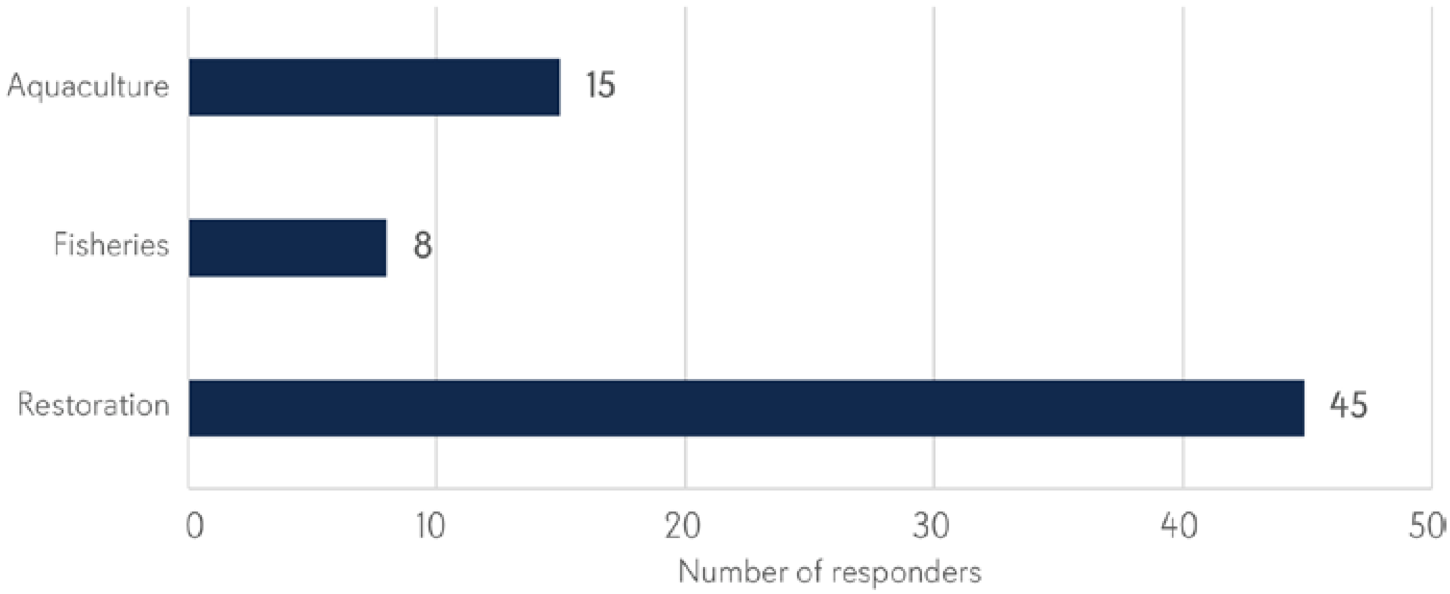
Are there issues with alternative substrate in Maryland that you think need to be addressed?

- Public perception for harvest areas for the use of rocks
- Scalability, availability and cost
- Planning for equitable access/distribution of material sourced from public domain
- Reef height necessary for effective spat recruitment
- Objective methods are needed to verify material suitability in a formal document
- Ability to take advantage of natural systems in support of harvest and non-harvest areas
- Permanence of material and practice
- Public policy analysis
- Suitability of widespread terraforming of the bay bottom

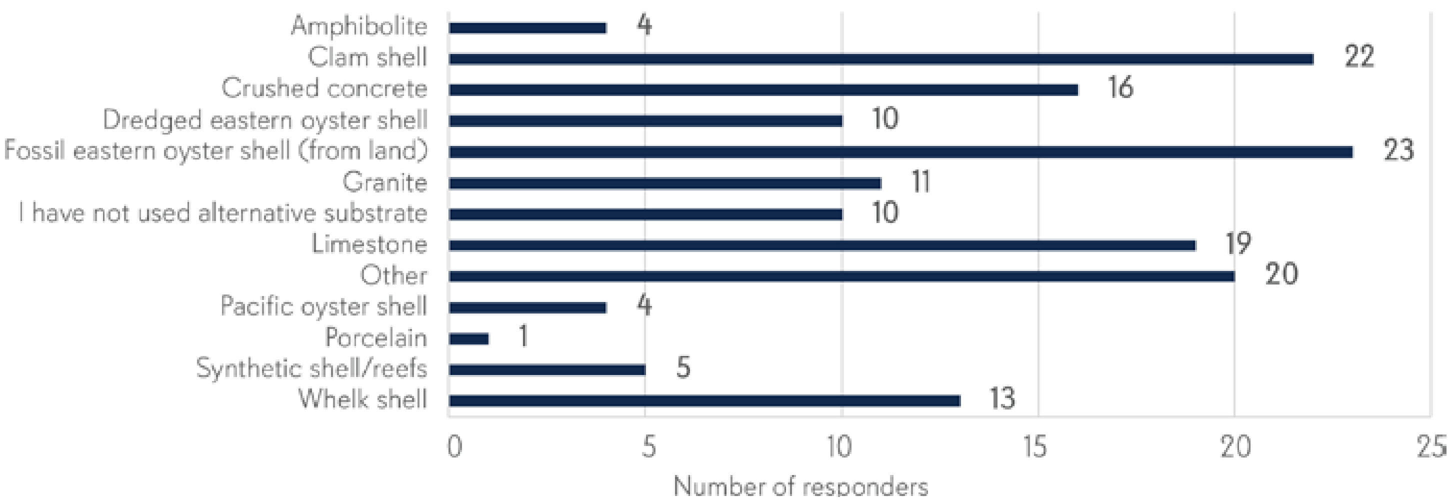
Local oystermen deploying alternative substrates experiments in Apalachicola Bay, Florida. Photo courtesy of Sandra Brooke.

Appendix C: Poll Results on Day 2

I work in the following sector(s):



What types of alternative substrates have you used? (check all that apply)

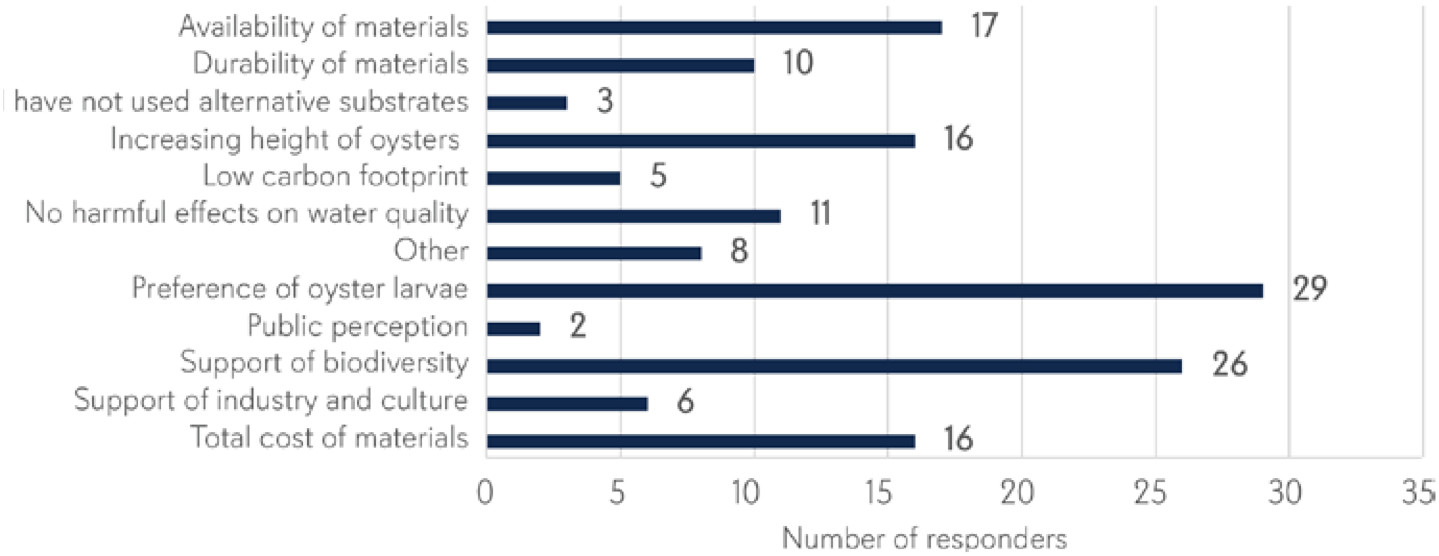


In the Other category, the following were listed:

- 3D structures made of concrete
- Reef balls
- Blue muscle shell
- Scallop shell
- Cockle shell
- Clay bricks
- Cement coated jute
- Oyster castle
- Bamboo/ wooden stakes
- Repurposed crab pots
- Tiles
- Wire mesh
- Palettes
- Porous alpha
- Slate
- River rocks

Appendix C: Poll Results on Day 2

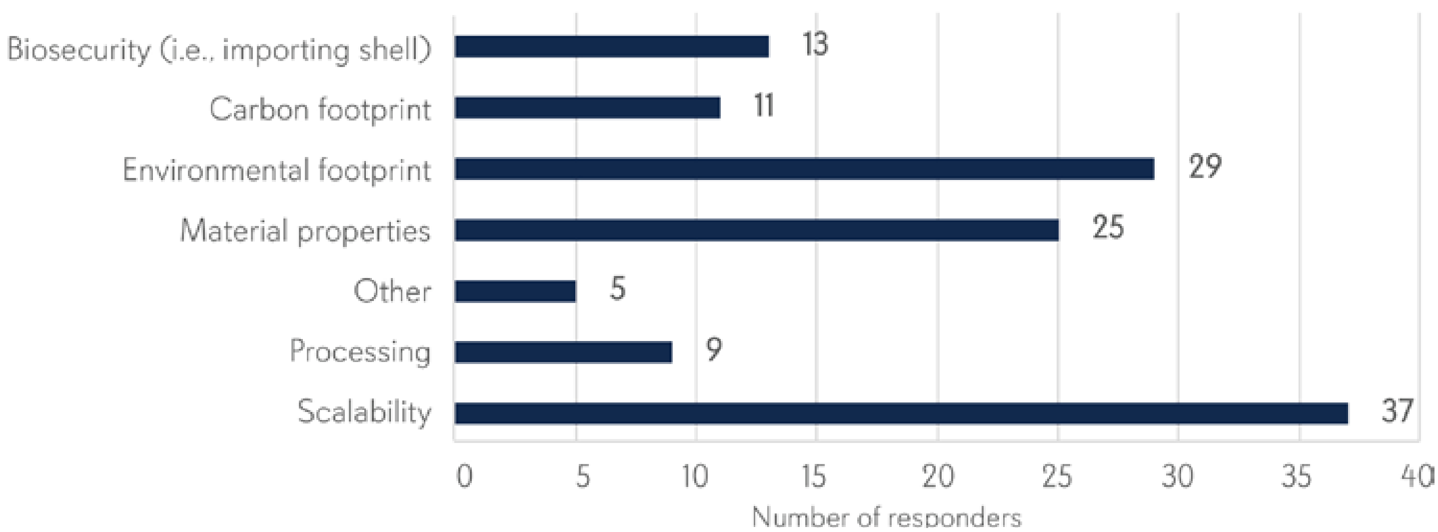
What benefits of alternative substrates are most important to you:



In the Other category, the following were listed:

- Suitability of materials
- Support of biodiversity
- Materials that promote long-term reef persistence
- A balance of all the above and scalability
- Structural complexity, not just height
- Integrate the different solutions into a cohesive package that can be clearly presented to wide audiences to justify large scale funding outside the traditional geography's

What aspects of alternative substrate require greater investigation? (choose your top 3)



In the Other category, the following were listed:

- Recruitment potential
- Integrity of installed structures
- Durability
- Sustainability
- Simulated oyster shells with porous alpha and bentonite clay
- Ecosystem goods and services

Appendix C: Poll Results on Day 2

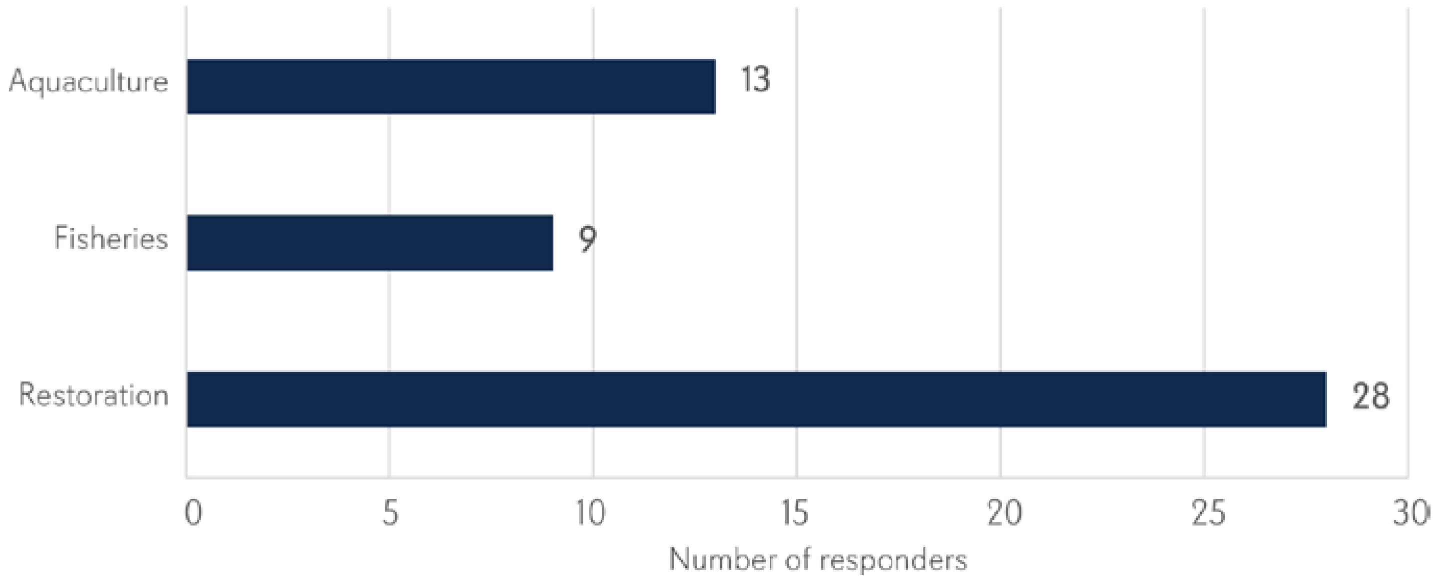
Are there issues with alternative substrate in Maryland that you think need to be addressed?

- SAV interactions
- Use of recycled concrete to reduce cost and carbon footprint
- The future of oyster gabions for restoration projects
- Public perception and acceptability
- Analysis of material performance specifically in production of spat-on-substrate
- Avoid use of plastic in oyster reef construction
- Persistence in the environment
- Need to streamline the permitting and authorization process to develop standard implementations

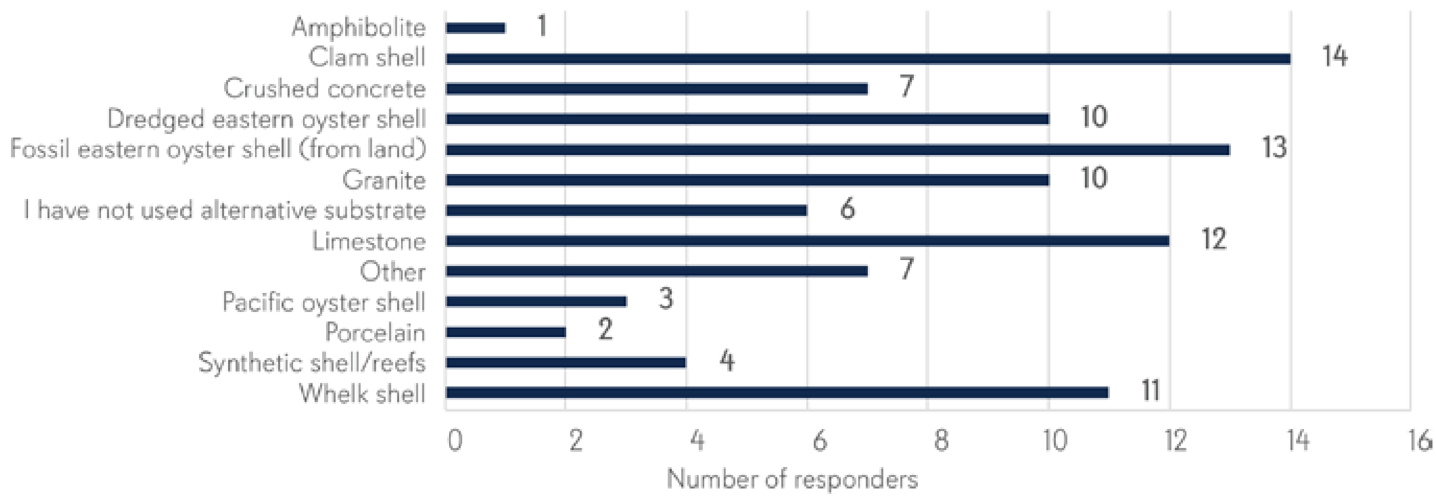
3 ft tall X-Reefs being deployed in Fort Norfolk. Photos courtesy of Russell Burke.

Appendix D: Poll Results on Day 3

I work in the following sector(s):



What types of alternative substrates have you used? (check all that apply)

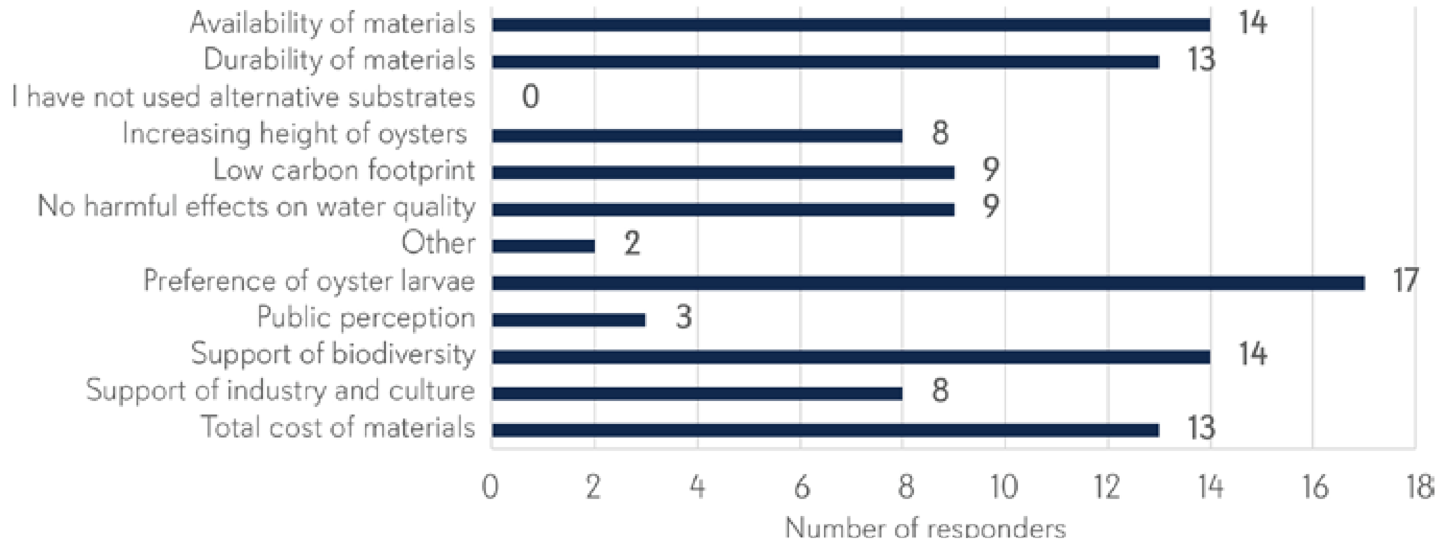


In the Other category, the following were listed:

- Reef balls
- Oyster catcher
- Cement coated jute
- Recycled concrete
- JR-CSA
- Concrete block and balls
- Foam glass tested at VIMS for settlement with success

Appendix D: Poll Results on Day 3

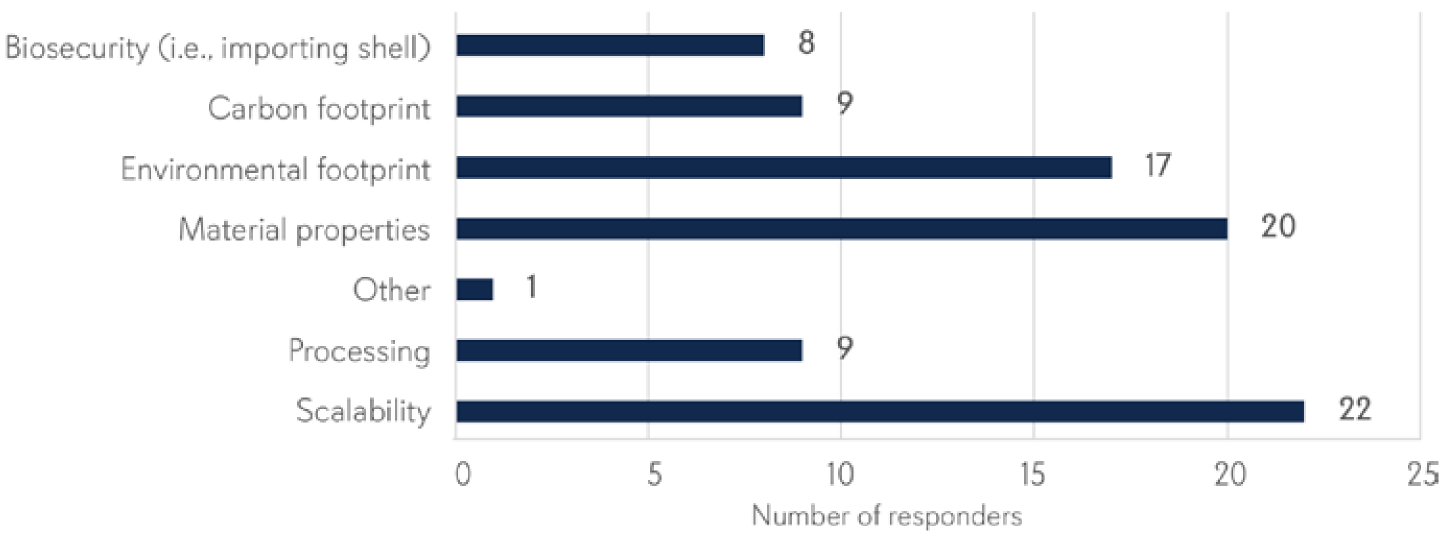
What benefits of alternative substrates are most important to you:



In the Other category, the following were listed:

- Light enough to deploy in shallow water and stable enough to endure wave energy

What aspects of alternative substrate require greater investigation? (choose your top 3)



In the Other category, the following were listed:

- Ability to adapt with rising sea level
- Simulated oyster shell
- Next step in product design and oyster farm development and cost analysis

Appendix D: Poll Results on Day 3

Are there issues with alternative substrate in Maryland that you think need to be addressed?

- Resilience of material
- Cost comparison
- Retrofitting remote setting tanks to create spat-on alternative substrate
- Maryland has collected bottle glass that can be transformed into a sustainable, non-toxic material that can help bridge the gap as increase shell collection and old shell recovery can catch up.
- The Japanese have a technology that makes toxicity of glass into the chemistry of sand. This can be added to a clay structure to keep costs low to make a shell shape or any shape you want.
- Public and all stakeholders for acceptance
- Best substrates for success in getting spat set at a reasonable cost

Jute Reinforced Calcium Sulfoaluminate (JR-CSA) in the shape of reef turtles (top), reef prisms (middle), and reef panels (bottom) upon deployment (left) and 6 months (middle) and 18 months (right) post-deployment. Photos courtesy of Mark Clark.

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Sandra Brooke

Florida State University, Coastal and Marine Lab

Evaluation of materials for sub-tidal oyster reef restoration in Apalachicola Bay, Florida

In 2013 the Apalachicola Bay oyster fishery was declared a Federal Fishery Disaster, and several restoration projects were initiated to facilitate oyster population recovery. These projects maximized the restoration area by placing a thin layer of fossil shell or small (~5 cm) limestone rocks on the natural substrate. The construction goals of the projects were met, but oyster populations continued to decline. A few years after deployment, the fossil shell restoration material had deteriorated significantly and the only sub-tidal habitats that supported oysters were those restored with limestone. The Apalachicola Bay System Initiative (ABSI) is a five-year (2019–2024) multi-disciplinary project that includes research into restoration approaches for Apalachicola Bay oyster habitats, which are so degraded that the reefs have been reduced to compacted shell hash. Oysters recruiting to unstable substrate may be swept away, buried, or exposed to hypoxia, and without the structural complexity that provides refuge, oyster juveniles are exposed to predation. The ABSI conducted a series of experiments to evaluate different materials for stability and oyster population development. The first experiment tested shell, small limestone (~5cm), and larger limestone (~15 cm), which was intended to create habitat niches for predator refuge and reef community development. The reefs were constructed with ~0.5m relief and were surveyed twice annually using hand tongs. The larger limestone performed better than the other materials, so a second experiment compared limestone with cleaned, crushed construction concrete of similar size. Half of the reefs for each material had a layer of natural shell (~8 cm deep) to assess the cost-benefit of this approach. Preliminary results indicate similar performance among all treatments. Our presentation will discuss the positive and negative aspects of these approaches for large scale oyster restoration.

Russell Burke

Christopher Newport University

Large-scale implementation of shallow subtidal alternative substrate reefs as part of a comprehensive oyster reef mitigation strategy in the Elizabeth River, VA, Chesapeake Bay

The Eastern Oyster (*Crassostrea virginica*) fulfills numerous essential ecological roles in marine ecosystems, including prevention of shoreline erosion, water filtration, and provision of habitat for many marine organisms. In response to ecological functions and services that might be lost resulting from the Craney Island Eastward Expansion (CIEE) Project in Southeast Virginia, the US Army Corps of Engineers, in support of the Virginia Port Authority's (VPA) port expansion project, was tasked with supervising construction and placement of oyster reefs (2013–14) as part of a comprehensive mitigation strategy. Seven oyster reefs (16.5 acres), composed of shell, granite and prefabricated concrete structures, were placed at five sites: the Lafayette River, the Elizabeth River's Western and Southern Branches, and the Lower James River (Hoffler Creek). As part of the Project Compensation Plan, the Virginia Department of Environmental Quality (VDEQ) mandated that each of these reefs be monitored and assessed for a period of five consecutive years (2015–2020). Christopher Newport University (CNU) has overseen this program in collaboration with the Virginia Institute of Marine Science; CNU has continued monitoring the project since its implementation of an adaptive management strategy that included a number of alternative substrate reefs composed of concrete

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with oyster shell embedded in all outward-facing reef surfaces. By 2019, oyster density (50 oysters per m^2) and biomass targets (50 g AFDM per m^2) were exceeded across alternative substrates at all sites. In addition, CNU surveyed ~5 acres of granite breakwaters and revetments along the perimeter of Craney Island in 2022 which ultimately resulted in formal inclusion of this reef acreage within the official oyster reef compensation package. Most recently (January 2024), the CIEE project team received confirmation from the VDEQ that the oyster mitigation requirements for the associated permit had been fulfilled—a true testament to innovative project design, effective adaptive management, and inter-agency collaboration.

Mark Clark

University of Florida

Jute Reinforced Calcium Sulfoaluminate (JR-CSA)

Jute Reinforced Calcium Sulfoaluminate (JR-CSA) was developed in 2017 at the University of Florida and first deployed along Florida's central west coast in 2018. Initially developed as a plastic-free alternative to mesh shell bags and used as a low intertidal sill and wave break element of living shorelines, configuration now includes application as a high surface area substrate for oyster recruitment and habitat restoration on declining natural reefs. The material is a combination of readily available Jute erosion control mat and Calcium Sulfoaluminate (CSA) as either premixed Cement-All® (CTS Rapid Set®) or a tailored mix of CSA, sand, and water reducing additive. The CSA coated jute is then placed on a form for curing. Although the material can be arranged in almost any shape, the two principal shapes utilized are triangular prisms 30 cm x 120 cm and referred to as a "reef prism", or a corrugated panel 5 cm x 120 cm x 120 cm and referred to as a "reef panel". CSA was chosen over ordinary portland cement due to its rapid set times (20–30min), early curing strength and reduced carbon footprint. These characteristics facilitate a more efficient use of forms during production and the potential for rapid deployment. Another design objective of JR-CSA was a material where volunteers or a stakeholder labor force could readily participate in the construction process and deployment did not require specialized equipment. Since inception, the material has been deployed at over 15 sites throughout Florida and South Carolina. When compared to other substrates, JR-CSA performs very well for oyster spat colonization and growth. Depending on the CSA mix and deployment site water quality, JR-CSA can last between 18 months and at least 5 years with the original deployment site still seeing little or no degradation of the material.

Chris Karawacki

C.J. Karwacki Consulting, LLC

Biomimetic nacre-like material for recruitment and growth of oyster spat

Watermen and scientists have observed for many years the strong dependence of shell mass on oyster recruitment rate and abundance across several destabilizing factors, such as disease, natural mortality, and fishing. Today there is an urgent need for suitable alternative nacre like materials that can offset the decreasing supply of natural oyster shell used for the recruitment and growth of oyster larvae in the Chesapeake Bay and surrounding estuaries. Here we discuss an approach to develop a material that mimics the natural oyster shell's chemical composition, structure and cueing properties for the setting and growth of oyster larvae with the aim to maximize the recruitment and growth of oyster larvae throughout their life cycle. Natural oyster shell is formed by a biological-driven process involving sequencing of water-borne calcium and magnesium ions, carbonic acid, amino acids, and

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chitin to form a layered assembly of fortified crystalline calcium carbonate. During the transitional assembly of calcium hydroxide to amorphous calcium carbonate, calcium ions bind at oxygen centers on amino acids such as aspartic and glutamic acids to form ionic/covalent bonds that significantly strengthen the bulk structure compared to calcium carbonate alone. Amino acids in combination with magnesium ions influence the formation of specific forms of crystalline calcium carbonate (node), such as aragonite while retarding formation of calcite. Finally, chitin is synthesized *in situ* and systematically excreted to form an encapsulated organic sheath (linker) across layers of crystalline calcium carbonate. Chemical binding with oxygen centers on the chitin to calcium ions further increases the strength of the bulk shell while providing a protective barrier.

Jay Lazar

National Oceanographic and Atmospheric Administration

Applying a novel oyster reef habitat quality monitoring methodology in Harris Creek, MD

2021 marked the end of formal monitoring for the Harris Creek large-scale oyster restoration project, the first of five in MD. Challenges with comparing results across treatment types arose from using two sampling gears, patent tong and diver. A novel video based approach to score habitat quality with one gear type was created by the Smithsonian and applied across all reefs in Harris Creek during summer 2022. The study used a video based rapid assessment protocol to assess the impact of different restoration treatments on oyster reef habitat quality in Harris Creek. Sites included seed-only, mixed shell and variations of stone substrates within the sanctuary and harvest areas outside the sanctuary. We conducted field sampling to collect underwater GoPro photos at each site. We then assigned each site a qualitative habitat score from 0–3 based on oyster shell coverage and reef height (oysters growing vertically), with 3 indicating the highest quality habitat.

Of the 574 sites sampled over 8 days, 84% (484) were usable with an average of 20 samples collected an hour. Sites restored with stone treatments had the highest proportion of 3 scores (93%), followed by mixed shell (71%), seed only (62%), unrestored sanctuary sites (14%), and unrestored harvest sites (5%). These results suggest that there may be benefit to stone treatments for future oyster reef restoration efforts, as stone treatments may provide more surface area for larval recruitment and the interstices act as a sink to sediment, providing longevity to the available recruitment surface. Additionally, the rapid assessment protocol proved to be a viable alternative monitoring tool to understand sedimentation, observe and catalog reef evolution and potentially do so in a more efficient manner. Together, our study provides a clearer image of Harris Creek post-restoration and a method to compare the future condition of the restored tributary.

Niels Lindquist

Sandbar Oyster Company Inc

Use of Oyster Catcher™ substrates for facile setting of oyster larvae and relaying of juvenile oysters

The long-term success of oyster habitat restoration efforts is dependent upon reliable stocking via natural recruitment and/or seeding. With global climate change accelerating sea-level rise, salinity levels of many estuaries are increasing and thereby shifting areas conducive to sustainable subtidal reef development farther up estuaries (Tice-Lewis *et al.* 2022, *Ecol. Appl.*). While potentially opening vast areas previously devoid of reefs to reef development, these up-estuary shifts may incur

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recruitment limitation if estuarine waters replete with larvae aren't reliably transported to the sites. Additionally, these areas may be at high risk for prolonged freshets that could periodically cause mass oyster mortality and create the need to seed reefs located where levels of natural recruitment are low. For millennia, recruitment limitation has been overcome by seeding cultch and transporting spat-coated materials from areas of high oyster recruitment to areas of low recruitment. Oyster shell and stone materials have long been used for seeding and relay, but various features of these materials may limit their utility, including weight, relatively low surface area/volume ratios, bulk and handling logistics. Sandbar Oyster Company (hereafter SANDBAR) is pioneering the use of cement-infused plant cloth substrates having features and benefits ideal for facile seeding and relay of vast numbers of juvenile oysters. These proprietary, patent-pending substrates are trade named Oyster Catcher™. The "Tuft" form of Oyster Catcher™, which is shaped like a three-dimensional pretzel, is light-weight, has a very high surface area/volume ratio, is easily handled and degradable. The latter feature allows spat-covered Tufts to break apart and detached oysters to disperse thereby lowering mortality associated with tightly clustered oysters. This presentation introduces SANDBAR's use of Tufts seeded with wild spat to source juvenile oysters into oyster restoration projects (*e.g.* New River Estuary Oyster Highway) and aquaculture. Tufts have also been successfully seeded in a hatchery setting.

Rom Lipcius

Virginia Institute of Marine Science

Ecosystem-based planning, implementation and success of subtidal, granite oyster reefs in the Piankatank River, VA, Chesapeake Bay

Although oyster restoration practitioners have adopted alternative reef substrates for projects in subtidal waters, a comprehensive strategy for this approach has not been fully developed. As part of the Chesapeake Bay Native Oyster Recovery Project, the USACE constructed a large subtidal granite reef in the Piankatank River (PR) of lower Chesapeake Bay. We describe a restoration strategy implemented in the PR, which included (i) hydrodynamic modeling of metapopulation connectivity, (ii) field validation of connectivity, (iii) habitat suitability modeling, (iv) high-resolution benthic habitat mapping, (v) historical data on oyster distribution, (vi) reef geometry proven to be successful, and (vii) surveys of oyster and mussel abundance on the reefs to examine restoration reef performance. Based on the hydrodynamic model, mid- to down-river reaches could support a source metapopulation that self-sustains and exports larvae to sink habitats farther downriver and outside the mouth. Upriver segments would not receive larvae despite availability of suitable habitat, which was validated by field surveys. Two years after construction, the reef network harbored a dense population of age-0 juveniles and age-1 adults. Adult oyster density averaged 219.3 per square meter and biomass 75.3 g dry weight per square meter. Mean live mussel density was also high at 194.5 per square meter. Mean live oyster volume was 3.2 L per square meter and consistent with a positive shell budget, even though it was an underestimate because it did not include the volume of underlying reef base of oxic dead shell normally aggregated with live oyster shell volume. ROV video corroborated high species diversity from lab samples, which included shrimp, fish, crabs, clams, snails, mussels and sponges. Several predatory fish species were on the reef, while crustaceans, including blue crabs, mud crabs and shrimp, were walking and feeding on the reef surface, indicating a successfully restored oyster reef community.

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Hunter Mathews

University of North Florida

Early performance of the Pervious Oyster Shell Habitat (POSH) in restoring intertidal habitat for oysters and associated nekton along energetic shorelines in northeast Florida

The "Pervious Oyster Shell Habitat" (POSH) is a novel artificial reef structure designed to minimize pollution and provide quality oyster habitat in high-energy systems. The POSH is composed of oyster shell bound by a thin layer of portland cement, into a dome. POSH modules were compared *in situ* to the industry standard "Oyster Ball" model Reef Ball™ for oyster recruitment and utilization by fish and crustaceans. The study took place from June 2021 to June 2023, along two energetic shorelines in northeast Florida: Kingsley Plantation along the Fort George River (Duval County) and Wrights Landing along the Tolomato River (St. Johns County). Oyster demographics and densities were assessed on the structures throughout the first year of deployment. Nekton densities and communities were assessed throughout the second year, using $2m^2$ bottomless lift nets. Artificial reefs were compared to an adjacent oyster reef at Kingsley Plantation. Oyster recruitment was significantly greater on the POSH compared to the Oyster Balls at both Kingsley Plantation ($p < 0.000$) and Wrights Landing ($p < 0.01$). Fish densities did not differ among treatments at either site ($p > 0.05$). At Kingsley Plantation, crustacean densities were significantly greater on the natural oyster reef than both artificial reef structures ($p < 0.01$), excluding with the Oyster Ball in winter ($p = 0.263$). Densities were significantly greater on the POSH than the Oyster Ball during summer ($p < 0.001$), fall ($p < 0.001$), and spring ($p < 0.0001$), and greater on the Oyster Ball in winter ($p < 0.05$). At Wrights Landing, crustacean densities were greater on the POSH in summer ($p < 0.0001$) and spring ($p < 0.05$). Fish and crustacean diversity metrics were similar among treatments at both sites. Early findings for the POSH indicate that it can be a viable method for rapidly restoring oyster reef communities in high-energy systems.

Doug Munroe

North Carolina Division of Marine Fisheries

North Carolina's use of alternative substrate for cultch planting in support of oyster rehabilitation strategy

North Carolina has been utilizing various materials to construct low-relief (< 1') oyster cultch reefs since 1915. These efforts are designed to support the state's oyster restoration program. Cultch sites provide a suitable substrate for larval oysters to settle and develop on in North Carolina's estuarine waters. Due to limited availability of oyster shell, the Cultch Planting Program has adapted the use of alternative material types. Shell only accounts for 10–20% of total materials deployed on cultch sites constructed since 2018, while materials such as limestone marl and crushed concrete, which are more readily available, have taken the place of oyster shell in the construction of cultch reefs. North Carolina constructs 40–50 acres of cultch reefs annually, which are opened to commercial harvest, once the oysters on the reefs have grown to harvestable size. Cultch sites support valuable biological and ecological functions, are designed to help reduce overall fishing pressure on natural oyster reefs and create additional opportunities for commercial fishermen to harvest oysters.

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Bennett Paradis

North Carolina Division of Marine Fisheries

North Carolina's oyster sanctuary program: restoring Pamlico Sound's subtidal oysters with artificial reefs

Beginning in 1996, North Carolina's Division of Marine Fisheries has been investing in the construction and monitoring of no-take oyster sanctuaries with the intention of subsidizing larval availability in Pamlico Sound. In total, 17 large scale artificial reefs covering 566 acres of protected habitat have been built by deploying 223,640 tons of various materials. While most of these sanctuaries were built with marl limestone rip-rap, other materials have also been used including reef balls, granite, basalt, crushed concrete, recycled concrete pipe, and a variety of recycled shells. Annual monitoring of the sanctuaries provides high resolution data into the performance of each site in terms of oyster density and population structure. The long-term dataset has given managers and biologists valuable insight for comparing materials, salinity regimes, and reef design across time, guiding future large scale oyster restoration projects.

Matt Pluta

ShoreRivers

Natural recruitment to alternative substrates in the Tred Avon River: a pilot study

Oyster shell represents a critical resource for restoration, aquaculture, and fisheries in the Chesapeake Bay. The exploration of alternative substrates, as substitutes for natural oyster shells, to capture spat and facilitate recruitment is gaining significant attention. While numerous potential alternative substrates exist, only a limited number have undergone testing in field conditions during natural spat fall events. In our study, we deployed replicate platforms, each hosting 12 different substrates, including oyster shell, clam shell, and various building materials such as brick, granite slabs, ceramic tile, etc., that have been suggested for potential large-scale use. These platforms were strategically placed in three distinct sites within Tred Avon River during the summer of 2021, coinciding with a notably favorable year for oyster recruitment in the Maryland portion of the Bay. At the end of the study, eight of nine platforms were retrieved, gently cleaned, and photographs of each substrate were meticulously taken. Utilizing image analysis, we recorded oyster recruits across the different substrates. Oyster spat exhibited a higher affinity for oyster shells, with clam shells following closely. Conversely, the remaining tested materials did perform nearly as well in attracting oyster spat. The study demonstrated a preference for shell but we also noted many oysters recruited to the underside of the plastic platform supporting the tested materials on the surface. These and other study details will be discussed.

William Rodney

Texas Parks and Wildlife Department

A summary of TPWD oyster restoration activities utilizing alternative cultch materials

Since 2007, Texas Parks and Wildlife Department's (TPWD) Coastal Fisheries Division has been actively working to restore oyster reefs for the purpose of enhancing the oyster fishery as well as the ecosystem services that these critical habitats provide. These efforts began in 2007 when TPWD received an appropriation from Congress in response to impacts from hurricanes Katrina and Rita. As of 2023, $16

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million has been spent and more than 600 acres of oyster habitat has been restored through cultch planting. About 95% of TPWD's restoration efforts were completed in commercially harvestable waters and thus directly benefited the commercial oyster industry. The remaining 5% was placed in waters that are closed to commercial harvest, and thus provided enhanced ecosystem services. Over the years, a variety of substrate types and design approaches have been successfully employed. Substrates have included river rock, recycled crushed concrete, and crushed limestone of various sizes. Designs have featured flat layers with low vertical relief and mounds with moderate vertical relief. Decisions on cultch types and design approaches were informed by restoration goals. Several projects utilizing different cultch types and designs are discussed.

David Schulte

US Army Corps of Engineers

Lynnhaven River, VA results of large-scale reef ball-based oyster restoration

In 2021, a large network of reef balls (28,500), each 0.4572 m (1.5 ft) wide and 0.3048 m (1.0 ft) tall covering 8.0 acres of subtidal, sand/clay/silt mix bottom in the polyhaline waters of the Lynnhaven River, VA, the most southeastern tributary river of Chesapeake Bay. The site selected was determined by both historical documentation as well as modern-day hydrodynamic modeling to be a good site for reef construction. Monitoring results have demonstrated the reef ball system, despite its young age, already is well in exceedance of Chesapeake Bay Program goals for oyster density and biomass, and exceeds the more ambitious goals of the Lynnhaven River Ecosystem Restoration Plan written by the USACE. At present, the three-dimensional reefs have a mean of 1137.6 ± 94.99 SE g/m^2 DM oyster tissue, 4,275.1 live oysters/m^2/river bottom area, consisting of 2,884.3 ± 240.23 SE spat and 1390.8 ± 104.85 SE adults. Live shell volume was also exceptionally high at 40.1 ± 2.80 SE l/m^2/river bottom area. The largest oysters observed on the reef balls were over 150 mm in shell height. These results suggest that oyster restoration using alternative materials in subtidal, polyhaline waters of Chesapeake Bay can produce exceptionally good results, and suggests that such alternative material based efforts can greatly assist in oyster restoration efforts in Chesapeake Bay.

H. Ward Slacum Jr.

Oyster Recovery Partnership

Advancing alternatives to shell for oyster production

Natural oyster reefs depend on shell accretion for long-term growth and survival, and their restoration is dependent on the availability of oyster shell as substrate for successful recruitment. In most coastal environments, shell loss has been accelerated by fishing activities and increased sediment deposition. To account for this, management agencies encourage initiatives to expand oyster production through aquaculture, public fishery management activities, and oyster restoration. This three-pronged management approach has increased the demand for shell, and availability is insufficient to meet demand. There are several ongoing initiates underway in Maryland to identify alternatives and alleviate the demand for native shell resources.

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Kathy Sweezey

The Nature Conservancy

A discussion on the challenges of using alternative substrate: a project manager's perspective

Despite the many benefits they provide, oyster reefs are one of the most imperiled marine habitats on earth. Globally, over 85% of oyster reefs have disappeared. Oyster populations in Texas are at a historic low, emphasizing the need for oyster reef restoration and protection efforts.

Restoration practitioners face many challenges including the increasing cost of commonly used "traditional" substrate like shell or limestone, limited availability of traditional substrate near project locations, and increased emissions to transport and deploy substrate for the project. Alternative substrate provides an opportunity to address each of these challenges and potentially leads to additional benefits and a more effective way to reach project goals.

Beezley Reef is a 40-acre subtidal oyster reef restored by The Nature Conservancy in Galveston Bay, Texas. This reef has a unique design as a hybrid part harvestable, part sanctuary reef complex. During the second phase of this project which focused on expanding the sanctuary reef by two acres, project managers emphasized the desired preference for alternative substrate with the engineer and in bid documents. However, the low number of bids returned, the cost of the alternative substrate bid obtained, and the limitation of alternative substrate that could be used on a subtidal reef all led to the decision to restore the reef using traditional substrate, limestone. Project managers met with multiple alternative substrate providers during the design phase to discuss Beezley Reef, assess feasibility, and gauge interest. Unfortunately, the providers met with were either unable to support a subtidal oyster reef or did not bid on this project.

For discussion, project managers ask: How do other practitioners seek alternative substrate providers? What alternative substrates are available for subtidal oyster reef restoration? How can restoration practitioners and alternative substrate providers enhance collaboration to best reach the project goals within limited budgets?

Christine Thompson

Stockton University

Optimizing remote setting on different cultch types for oyster restoration in Barnegat Bay, NJ

Restoration efforts for the eastern oyster, *Crassostrea virginica*, are often limited by sources and availability of cultch for remote setting. In Southern New Jersey, a shell recycling program has been created to provide shell for restoration purposes, but the types and availability of shell can vary. Additionally, the growth of oysters on these shell types once planted may affect restoration success if set ratios are too high or low. This study evaluated the average settlement of eyed oyster larvae in circular setting tanks with mixtures of three shell types: eastern oyster (*C. virginica*), surf clam (*Spisula solidissima*) and Knobbed Whelk shell (*Busycon carica*). Spat settlement was assessed prior to deployment on the subtidal reef site and again four months post-planting. Initial settlement numbers (no. oysters per shell) significantly differed between each shell type and were highest for surf clam shell and lowest for Whelk shell ($p<0.001$). During post-planting monitoring, oysters and surf clam

shell had the largest oysters but also had the highest mortality. This study is important for optimizing aquaculture techniques for both large and small-scale remote setting that can be restricted by both the availability of shell types and permitting requirements prohibiting certain substrates in shallow-water bays.

Jennifer Zhu

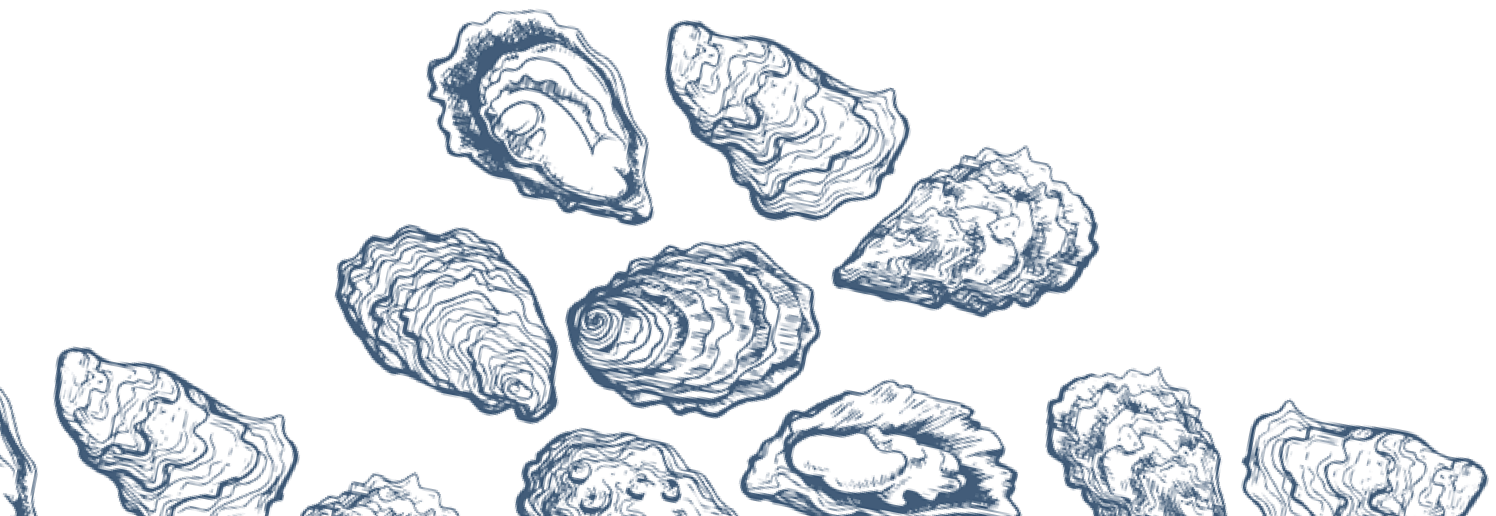
Billion Oyster Project

Innovative approaches in oyster restoration: exploring alternative materials and substrates in the New York Harbor

With a growing focus on microplastics and individual and collective carbon footprints, many restoration practitioners and innovative suppliers are actively exploring alternative materials for application in marine restoration projects. Billion Oyster Project is enthusiastic about ongoing research and collaboration with industry professionals to understand how these materials can enhance oyster restoration efforts throughout New York Harbor. This presentation highlights the alternative materials and substrates that have been applied to oyster restoration projects since 2016.

Materials such as coir, burlap, and biodegradable mesh offer an eco-friendly alternative to the conventional plastic mesh bags used in bagged shell reef oyster restoration. However, their biodegradability often occurs at a pace that exceeds the time required for an oyster reef to develop. Burlap bags have degraded before oysters could cement to each other and form reefs. Some biodegradable meshes may also still leach microplastic material faster than traditional nylon bags. Further research is needed to understand how long biodegradable bags take to break down in marine environments and provide insight into their applicability across restoration projects and community engagement and education programs.

Alternative substrates seeded with oysters, such as reef balls and ECOncrete® disks are widely applicable restoration techniques with longer lifespans to sufficiently support the establishment of oyster populations at restoration sites. Cement is a primary ingredient in these concrete structures, which extends the lifetime of the structure but is more carbon-heavy. This can be offset through the addition of aggregates, such as rocks or shells, to the mixture. Structures such as piling wraps to attract wild oysters to settle on bulkheads have shown short-term success in the harbor, but are challenging to install and maintain. In New York Harbor, these types of applications are better suited for habitat enhancement than habitat creation. Hard substrate such as reef balls provide more surface area on which oysters can grow, and are easier to monitor, making them more optimal for use in oyster restoration projects.



Symposium on Alternative Substrate for Oysters

Program Booklet

Virtual Symposium

Feb 26-28, 2024

Background

This **Symposium on Alternative Substrate for Oysters (SASSO)** is part of an effort to fill key knowledge gaps in support of Maryland's oyster resource and oyster industries. Chesapeake Bay is home to thriving commercial fishing and aquaculture industries and one of the largest oyster restoration efforts in North America. The lack of fresh shell substrate has become a major impediment to all of these activities and alternatives are being considered for large-scale use in restoration and industry efforts. To address this challenge, the Maryland General Assembly mandated a program (SB830 2023) that will evaluate:

1. Types of substrate, including fresh shell, fossilized shell, combinations of shell and alternative substrates that are most appropriate for use in oyster harvest areas.
2. Benefits, including habitat-related benefits, of using stones of various sizes in oyster restoration areas.
3. Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates.
4. Potential for retrofitting existing structures, such as riprap revetments that are unrelated to oyster restoration, but use materials similar to artificial reefs including oyster plantings.
5. Effect of spat size upon deployment on oyster abundance.

This symposium directly addresses Topic 3: to evaluate alternative substrates used for oyster restoration, or repletion, in other regions. The focus of this year's symposium is on large areas and/or subtidal efforts with alternative substrates (i.e., anything other than fresh oyster shell). Next year, we will host a symposium on the use of alternative substrates in the near shore and the inclusion of oysters on existing grey infrastructure.

Symposium Sponsors

This symposium is sponsored by the State of Maryland and convened by University of Maryland Center for Environmental Science (UMCES). Lead organizers are Dr. Elizabeth North and Dr. Matthew Gray of UMCES Horn Point Laboratory. The symposium team also includes David Nemazie, Conor Keitzer, Roshni Nair, Monica Fabra, and Kurt Florez. Graphic design and logistical support are from UMCES Integration and Application Network (IAN).

For questions regarding this symposium please contact Elizabeth North at **enorth@umces.edu** or Matthew Gray at **mgray@umces.edu.** For more information, please see the symposium webpage: **https://www.umces.edu/alternative-substrate-for-oysters**

University of Maryland
CENTER FOR ENVIRONMENTAL SCIENCE

Scan here to access the symposium website

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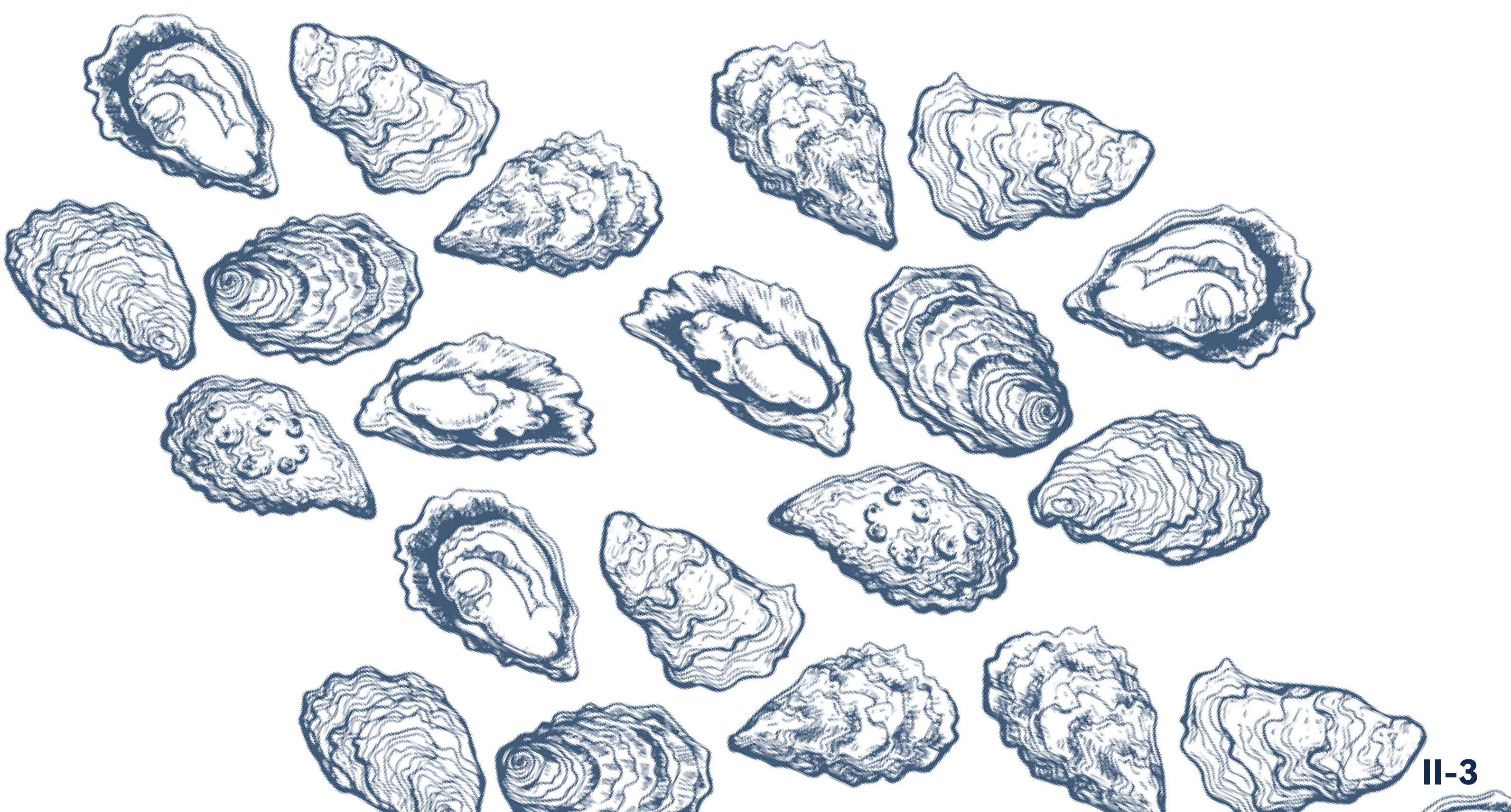


Schedule of Events and Logistics

Monday, Feb 26: Alternative Substrate for Use in Fisheries

10:00	Introduction
10:05	Sarah Elfreth, Maryland State Senator
10:15	Chris Judy, Maryland Department of Natural Resources
10:30	Andrew Button, Virginia Marine Resource Commission
10:45	Doug Munroe, North Carolina's Division of Marine Fisheries
11:00	William Rodney, Texas Parks and Wildlife
11:15	Sandra Brooke, Florida State University Coastal and Marine Lab
11:30	Kathy Sweezey, The Nature Conservancy
11:45	Matt Pluta, ShoreRivers
12:00	Speaker Q&A
12:30	Chat n' Chew Breakouts
01:00	Plenary Discussion
02:00	Adjourn

Tuesday, Feb 27: Alternative Substrate in Large-Scale Restoration

10:00	Introduction
10:05	Dr. Bill Dennison, UMCES Interim President
10:15	Stephanie Reynolds Westby, NOAA Restoration Center
10:30	Bennett Paradis, North Carolina Division of Marine Fisheries
10:45	Romuald Lipcius, Virginia Institute of Marine Science
11:00	Jay Lazar, NOAA Chesapeake Bay Office
11:15	Jennifer Zhu, Billion Oyster Project
11:30	David Schulte, US Army Corps of Engineers
11:45	Russell Burke, Christopher Newport University
12:00	Speaker Q&A
12:30	Chat n' Chew Breakouts
01:00	Plenary Discussion
02:00	Adjourn

Schedule of Events and Logistics

Wednesday, Feb 28: Alternative Substrate- Aquaculture & New Technologies

10:00	Introduction
10:05	Josh Kurtz, Maryland Secretary of Natural Resources
10:15	H. Ward Slacum, Oyster Recovery Partnership
10:30	Steve Fleetwood, Bivalve Packing Company
10:45	Niels Lindquist, Sandbar Oyster Company Inc.
11:00	Christine Thompson, Stockton University
11:15	Mark Clark, University of Florida
11:30	Christopher J. Karwacki, C.J. Karwacki Consulting, LLC.
11:45	Hunter Mathews, University of North Florida
12:00	Speaker Q&A
12:30	Chat n' Chew Breakouts
01:00	Plenary Discussion
02:00	Adjourn

Symposium Logistics

To join the symposium: Follow this Zoom link
http://tinyurl.com/5h44vwjf
Passcode: 104153

To ask the speakers a question: Type your question in the Zoom chat. Only the speakers will be able to see your questions.

To join a Chat n' Chew: Follow the link provided in the Zoom chat at lunchtime.

To ask a question or make a comment during plenary: Type your question or comment in the Zoom chat. The moderators will be able to see your questions and comments and will relay them to the panelists.

To receive a copy of the symposium report: All registrants will be sent the report this spring.

Welcome Speakers

Senator Sarah Elfreth
Maryland State Senate

Sarah Elfreth is the youngest woman elected to the State Senate in Maryland history. Over the course of her first five years in office, she passed 84 bills into law on issues that actually impact Maryland families – protecting the Chesapeake Bay, strengthening the economy, expanding prenatal care, and helping veterans with PTSD. At the beginning of her second term, Sarah was appointed to an important leadership position in the Senate's budget committee, overseeing tens of billions of dollars of taxpayer investments in transportation, environmental, and public safety programs. As a member of the tri-state Chesapeake Bay Commission, she helps coordinate State and federal efforts to clean up the Bay. Sarah represents parts of the Broadneck Peninsula, the City of Annapolis, and southern Anne Arundel County.

Bill Dennison
University of Maryland Center for Environmental Sciences (UMCES)

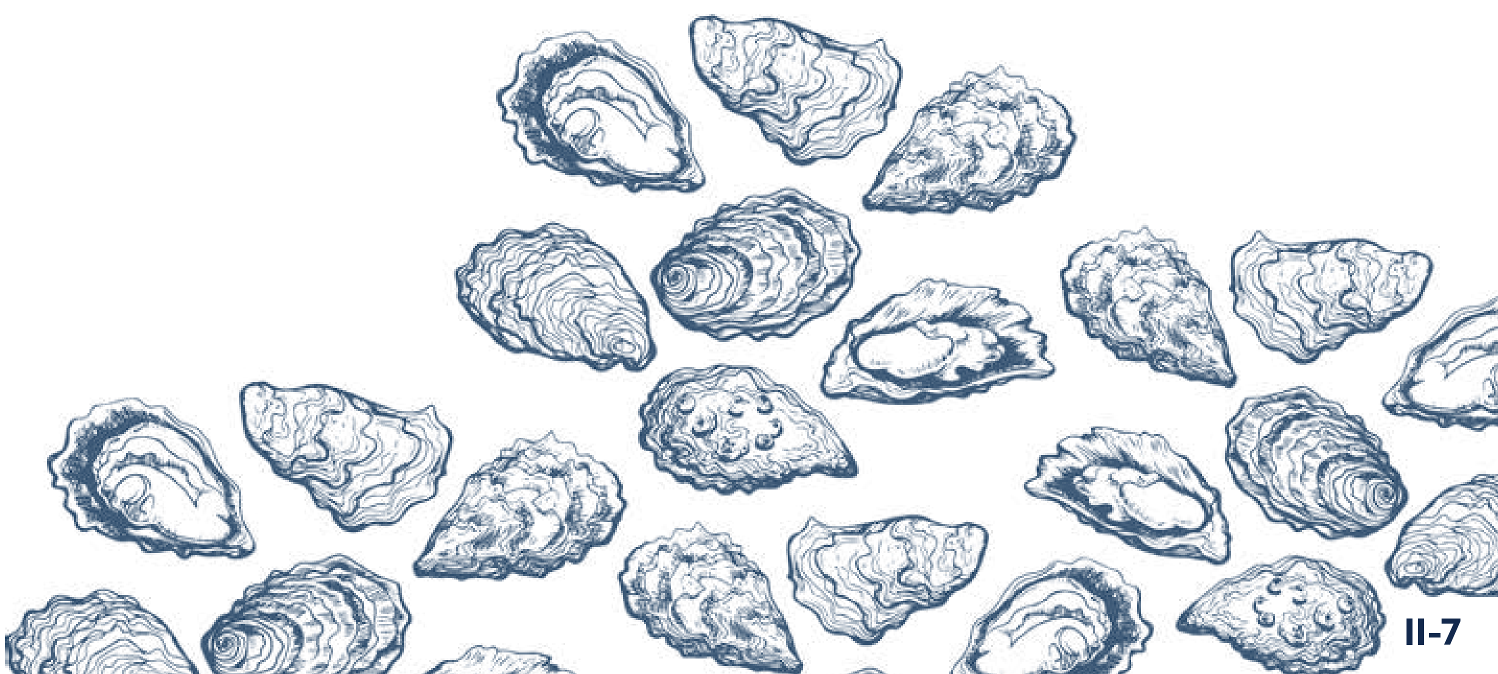
Bill Dennison is a Professor of Marine Science and Interim President for the University of Maryland Center for Environmental Science. Since 2003, he has served as Vice President for Science Application and led the Integration and Application Network (IAN), charged to inspire, manage and produce timely syntheses and assessments on key environmental issues with a special emphasis on Chesapeake Bay and its waters. He has published hundreds of papers and books on coastal ecosystem ecology and has presented at international, national, and regional meetings, and at various universities, research institutions, and government agencies.

Welcome Speakers

Josh Kurtz
Maryland Department of Natural Resources

Under the Moore/Miller administration, Secretary Kurtz leads teams across the state, working to improve water quality and bay resilience, restore and conserve forested land, expand access to our state parks, monitor and slow the spread of invasive species, and ensure the state maintains sustainable fisheries.

Kurtz previously served as the Maryland executive director of the Chesapeake Bay Foundation, and has also served as policy and government relations director for The Nature Conservancy in Maryland where he created and led advocacy campaigns leveraging strong relationships with partners and industry leaders to build support for policies regarding conservation and climate change in both the Maryland General Assembly and the DC City Council.



Invited Speakers: Day 1

Chris Judy
Director, Shellfish Division, Maryland Department of Natural Resources

Chris Judy is currently the Shellfish Division Director for MD DNR and has held this position for over 10 years. His experience includes oyster enhancement projects and management programs in both fishery and sanctuary areas. He helps coordinate many diverse groups that often have competing interests.

Andrew Button
Virginia Marine Resource Commission

Andrew Button is currently the Deputy Chief of the Shellfish Management Division and Head of the Conservation and Replenishment Department (CRD). He has been with VMRC since 2014. The CRD has been in the business of large-scale oyster restoration and replenishment since its inception in 1929. The Division maintains and monitors both harvest and sanctuary areas on more than 240,000 acres of public oyster ground in the waters of the Commonwealth, manages a leasing and aquaculture permitting program on more than 130,000 acres of private ground, develops harvest regulations on both public and private oyster grounds, and coordinates with or is directly involved in a multitude of oyster and shellfish focused activities with multiple governmental and non-governmental groups.

Invited Speakers: Day 1

Doug Munroe
North Carolina Division of Marine Fisheries

Doug received his AS in Aquaculture from Carteret Community College and a BS in Biology from East Carolina University. He has worked at the NC Division of Marine Fisheries for two years, currently filling the Cultch Planting Biologist role in the Habitat and Enhancement section of DMF. Doug also enjoys wildlife photography and kayaking.

William Rodney
Texas Parks and Wildlife Department

Bill has a MS from the University of Maryland College Park in ecology as well as a BS in biology from University of Maryland College Park and a BS in journalism from West Virginia University. He has over 25 years of experience in marine science and natural resources management focused on ecological restoration and habitat assessment. In his 16 years at TPWD, Bill has been involved in several large-scale oyster restoration projects in Galveston Bay and Sabine Lake. He is currently the oyster habitat restoration specialist on the new Restoration and Artificial Reef Team (RART).

Invited Speakers: Day 2

Stephanie Reynolds Westby
NOAA Restoration Center

Stephanie Reynolds Westby directs NOAA's Chesapeake Bay oyster restoration program. She has also worked as a lobbyist and fisheries scientist for a regional nonprofit, and earlier as the captain of several educational vessels, both power and sail. She holds a master's degree in environmental science and policy from John Hopkins University, and a 100-ton master's license ('captain's license'). When not on the water, she paints and plays the ukulele (though not simultaneously).

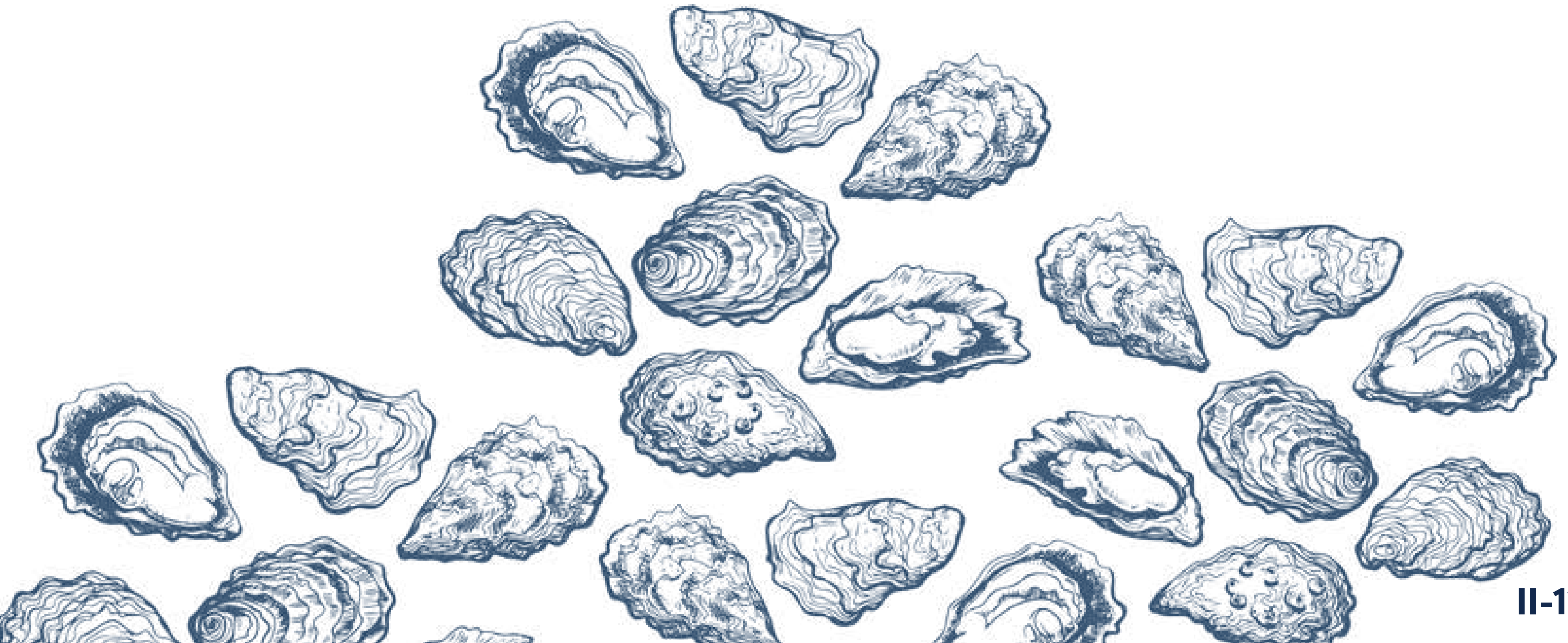
Bennett Paradis
North Carolina Division of Marine Fisheries

Bennett has worked as North Carolina's Oyster Sanctuary Biologist for two years. He received his Bachelors in Biology at Boston University, and his Masters in Biology from Auburn University where he studied coral physiology. During COVID he worked as a Fisheries Observer in Alaska and briefly lived in Colorado before accepting his current position.

Invited Speakers: Day 2

Romuald Lipcius
Virginia Institute of Marine Science

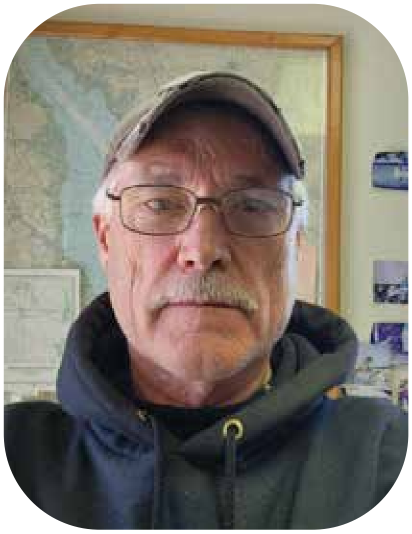
Rom Lipcius is a Professor of Maine Science at VIMS, William & Mary. Lipcius joined the VIMS/W&M faculty in 1986 after postdoctoral fellowships at the Smithsonian Institution and U.S. National Research Council and a Ph.D. degree from Florida State University. Scientific expertise includes Ecology, Conservation and Restoration of Crustaceans and Molluscs (blue crab, native oyster, spiny lobster, queen conch), Fisheries Management, Mathematical Biology, and Ecological Statistics, with emphasis on globally relevant solutions for major threats to marine ecosystems.



Invited Speakers: Day 3

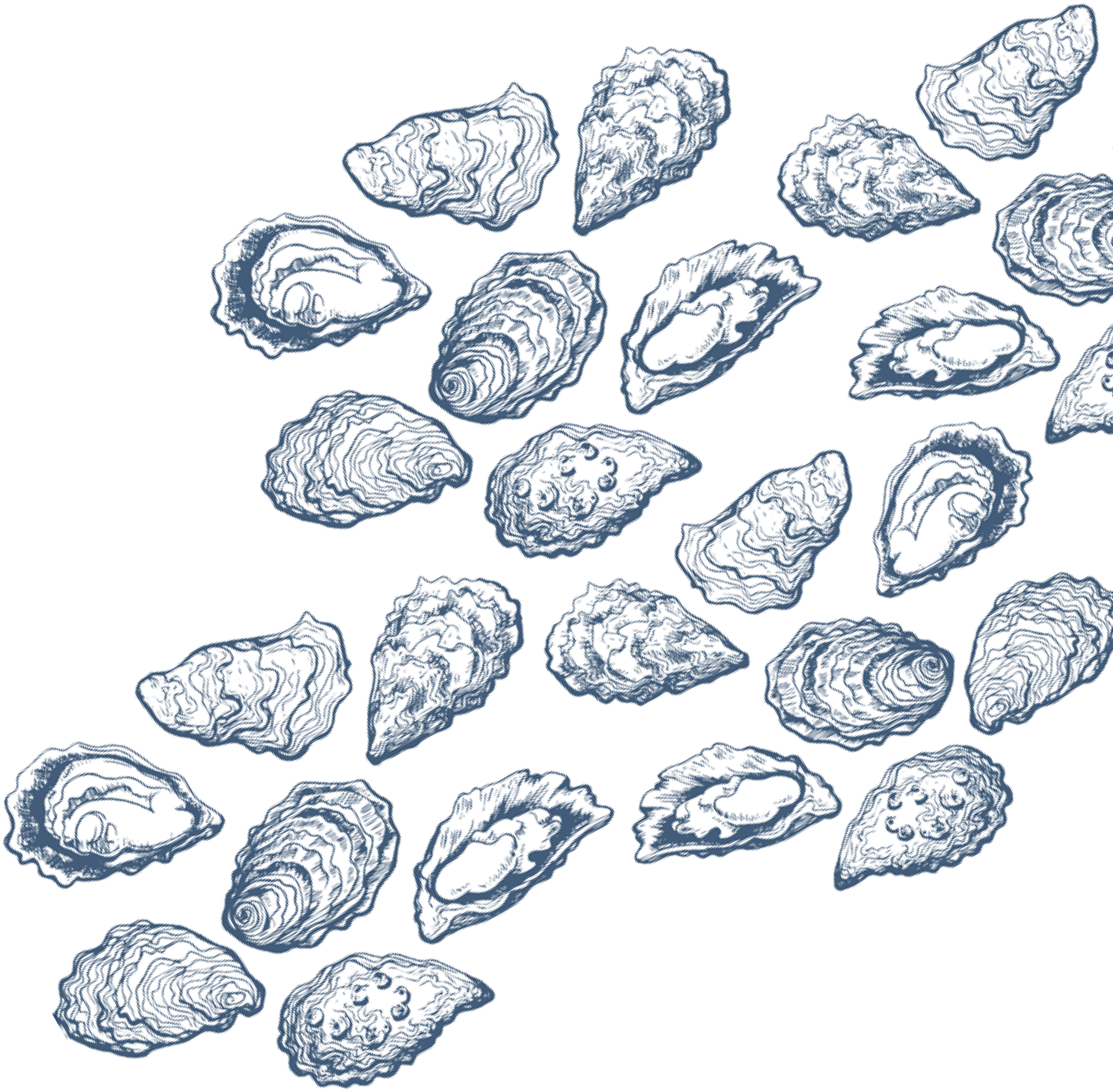
H. Ward Slacum
Oyster Recovery Partnership

Ward Slacum leads ORP's strategic growth initiatives to strengthen our region's blue economy and coastal communities through oyster restoration and sustainable fisheries initiatives. Ward has a proven record of producing results through stakeholder engagement, research, and innovation.



Steve Fleetwood
Bivalve Packing Company

Steve Fleetwood is the co-owner of Bivalve Packing Company. He is a grower, harvester, and shipper of Delaware Bay and Atlantic coast oysters and clams, both aquaculture and traditional fishery.



Abstracts

Sandra Brooke

Florida State University, Coastal and Marine Lab

Evaluation of materials for sub-tidal oyster reef restoration in Apalachicola Bay, Florida

In 2013 the Apalachicola Bay oyster fishery was declared a Federal Fishery Disaster, and several restoration projects were initiated to facilitate oyster population recovery. These projects maximized the restoration area by placing a thin layer of fossil shell or small (~5 cm) limestone rocks on the natural substrate. The construction goals of the projects were met, but oyster populations continued to decline. A few years after deployment, the fossil shell restoration material had deteriorated significantly and the only sub-tidal habitats that supported oysters were those restored with limestone. The Apalachicola Bay System Initiative (ABSI) is a five-year (2019-2024) multi-disciplinary project that includes research into restoration approaches for Apalachicola Bay oyster habitats, which are so degraded that the reefs have been reduced to compacted shell hash. Oysters recruiting to unstable substrate may be swept away, buried, or exposed to hypoxia, and without the structural complexity that provides refuge, oyster juveniles are exposed to predation. The ABSI conducted a series of experiments to evaluate different materials for stability and oyster population development. The first experiment tested shell, small limestone (~ 5cm), and larger limestone (~15 cm), which was intended to create habitat niches for predator refuge and reef community development. The reefs were constructed with ~0.5m relief and were surveyed twice annually using hand tongs. The larger limestone performed better than the other materials, so a second experiment compared limestone with cleaned, crushed construction concrete of similar size. Half of the reefs for each material had a layer of natural shell (~ 8 cm deep) to assess the cost-benefit of this approach. Preliminary results indicate similar performance among all treatments. Our presentation will discuss the positive and negative aspects of these approaches for large scale oyster restoration.

Russell Burke

Christopher Newport University

Large-Scale Implementation of Shallow Subtidal Alternative Substrate Reefs as Part of a Comprehensive Oyster Reef Mitigation Strategy in the Elizabeth River, VA, Chesapeake Bay

The Eastern Oyster (*Crassostrea virginica*) fulfills numerous essential ecological roles in marine ecosystems, including prevention of shoreline erosion, water filtration, and provision of habitat for many marine organisms. In response to ecological functions and services that might be lost resulting from the Craney Island Eastward Expansion (CIEE) Project in Southeast Virginia, the US Army Corps of Engineers, in support of the Virginia Port Authority's (VPA) port expansion project, was tasked with supervising construction and placement of oyster reefs (2013-14) as part of a comprehensive mitigation strategy. Seven oyster reefs (16.5 acres), composed of shell, granite and prefabricated concrete structures, were placed at five sites: the Lafayette River, the Elizabeth River's Western and Southern Branches, and the Lower James River (Hoffler Creek). As part of the Project Compensation Plan, the Virginia Department of Environmental Quality (VDEQ) mandated that each of these reefs be monitored and assessed for a period of five consecutive years (2015-2020) – Christopher Newport University (CNU) has overseen this program in collaboration with the Virginia Institute of Marine Science; CNU has continued monitoring the project since its implementation of an adaptive management strategy that included a number of alternative substrate reefs composed of concrete with oyster shell embedded in all outward-facing reef surfaces. By 2019, oyster density (50 oysters m^2) and

biomass targets (50 g AFDM m^2) were exceeded across alternative substrates at all sites. In addition, CNU surveyed ~5 acres of granite breakwaters and revetments along the perimeter of Craney Island in 2022 which ultimately resulted in formal inclusion of this reef acreage within the official oyster reef compensation package. Most recently (January 2024), the CIEE project team received confirmation from the VDEQ that the oyster mitigation requirements for the associated permit had been fulfilled – a true testament to innovative project design, effective adaptive management, and inter-agency collaboration.

Mark Clark

University of Florida

Jute Reinforced Calcium Sulfoaluminate (JR-CSA)

Jute Reinforced Calcium Sulfoaluminate (JR-CSA) was developed in 2017 at the University of Florida and first deployed along Florida's central west coast in 2018. Initially developed as a plastic-free alternative to mesh shell bags and used as a low intertidal sill and wave break element of living shorelines, configuration now includes application as a high surface area substrate for oyster recruitment and habitat restoration on declining natural reefs. The material is a combination of readily available Jute erosion control mat and Calcium Sulfoaluminate (CSA) as either premixed Cement-All® (CTS Rapid Set®) or a tailored mix of CSA, sand, and water reducing additive. The CSA coated jute is then placed on a form for curing. Although the material can be arranged in almost any shape, the two principal shapes utilized are triangular prisms 30 cm x 120 cm and referred to as a "reef prism", or a corrugated panel 5 cm x 120 cm x 120 cm and referred to as a "reef panel". CSA was chosen over ordinary portland cement due to its rapid set times (20-30min), early curing strength and reduced carbon footprint. These characteristics facilitate a more efficient use of forms during production and the potential for rapid deployment. Another design objective of JR-CSA was a material where volunteers or a stakeholder labor force could readily participate in the construction process and deployment did not require specialized equipment. Since inception, the material has been deployed at over 15 sites throughout Florida and South Carolina. When compared to other substrates, JR-CSA performs very well for oyster spat colonization and growth. Depending on the CSA mix and deployment site water quality, JR-CSA can last between 18 months and at least 5 years with the original deployment site still seeing little or no degradation of the material.

Chris Karawacki

C.J. Karwacki Consulting, LLC

Biomimetic Nacre-Like Material For Recruitment And Growth Of Oyster Spat

Watermen and scientists have observed for many years the strong dependence of shell mass on oyster recruitment rate and abundance across several destabilizing factors, such as disease, natural mortality, and fishing. Today there is an urgent need for suitable alternative nacre like materials that can offset the decreasing supply of natural oyster shell used for the recruitment and growth of oyster larvae in the Chesapeake Bay and surrounding estuaries. Here we discuss an approach to develop a material that mimics the natural oyster shell's chemical composition, structure and cueing properties for the setting and growth of oyster larvae with the aim to maximize the recruitment and growth of oyster larvae throughout their life cycle. Natural oyster shell is formed by a biological-driven process involving sequencing of water-borne calcium and magnesium ions, carbonic acid, amino acids, and

Abstracts

chitin to form a layered assembly of fortified crystalline calcium carbonate. During the transitional assembly of calcium hydroxide to amorphous calcium carbonate, calcium ions bind at oxygen centers on amino acids such as aspartic and glutamic acids to form ionic/covalent bonds that significantly strengthen the bulk structure compared to calcium carbonate alone. Amino acids in combination with magnesium ions influence the formation of specific forms of crystalline calcium carbonate (node), such as aragonite while retarding formation of calcite. Finally, chitin is synthesized in-situ and systematically excreted to form an encapsulated organic sheath (linker) across layers of crystalline calcium carbonate. Chemical binding with oxygen centers on the chitin to calcium ions further increases the strength of the bulk shell while providing a protective barrier.

Jay Lazar

National Oceanographic and Atmospheric Administration

Applying a Novel Oyster Reef Habitat Quality Monitoring Methodology in Harris Creek, MD

2021 marked the end of formal monitoring for the Harris Creek large-scale oyster restoration project, the first of five in MD. Challenges with comparing results across treatment types arose from using two sampling gears, patent tong and diver. A novel video based approach to score habitat quality with one gear type was created by the Smithsonian and applied across all reefs in Harris Creek during summer 2022. The study used a video based rapid assessment protocol to assess the impact of different restoration treatments on oyster reef habitat quality in Harris Creek. Sites included seed-only, mixed shell and variations of stone substrates within the sanctuary and harvest areas outside the sanctuary. We conducted field sampling to collect underwater GoPro photos at each site. We then assigned each site a qualitative habitat score from 0-3 based on oyster shell coverage and reef height (oysters growing vertically), with 3 indicating the highest quality habitat.

Of the 574 sites sampled over 8 days, 84% (484) were usable with an average of 20 samples collected an hour. Sites restored with stone treatments had the highest proportion of 3 scores (93%), followed by mixed shell (71%), seed only (62%), unrestored sanctuary sites (14%), and unrestored harvest sites (5%). These results suggest that there may be benefit to stone treatments for future oyster reef restoration efforts, as stone treatments may provide more surface area for larval recruitment and the interstices act as a sink to sediment, providing longevity to the available recruitment surface. Additionally, the rapid assessment protocol proved to be a viable alternative monitoring tool to understand sedimentation, observe and catalog reef evolution and potentially do so in a more efficient manner. Together, our study provides a clearer image of Harris Creek post-restoration and a method to compare the future condition of the restored tributary.

Niels Lindquist

Sandbar Oyster Company Inc

Use of Oyster Catcher™ Substrates for Facile Setting of Oyster Larvae and Relaying of Juvenile Oysters

The long-term success of oyster habitat restoration efforts is dependent upon reliable stocking via natural recruitment and/or seeding. With global climate change accelerating sea-level rise, salinity levels of many estuaries are increasing and thereby shifting areas conducive to sustainable subtidal reef development farther up estuaries (Tice-Lewis et al. 2022, Ecol Appl). While potentially opening vast areas previously devoid of reefs to reef development, these up-estuary shifts may incur recruitment limitation if estuarine waters replete with larvae aren't reliably transported to the sites. Additionally, these areas may be at high risk for prolonged freshets that could periodically cause mass oyster mortality and create the need to seed reefs located where levels of natural recruitment are low. For millennia, recruitment limitation has been overcome by seeding cultch and transporting spat-coated materials from areas of high oyster recruitment to areas of low recruitment. Oyster shell and stone materials have long been used for seeding and relay, but various features of these materials may limit their utility, including weight, relatively low surface area/volume ratios, bulk and handling logistics. Sandbar Oyster Company (hereafter SANDBAR) is pioneering the use of cement-infused plant cloth substrates having features and benefits ideal for facile seeding and relay of vast numbers of juvenile oysters. These proprietary, patent-pending substrates are trade named Oyster Catcher™. The "Tuft" form of Oyster Catcher™, which is shaped like a three-dimensional pretzel, is light-weight, has a very high surface area/volume ratio, is easily handled and degradable. The latter feature allows spat-covered Tufts to break apart and detached oysters to disperse thereby lowering mortality associated with tightly clustered oysters. This presentation introduces SANDBAR's use of Tufts seeded with wild spat to source juvenile oysters into oyster restoration projects (e.g. New River Estuary Oyster Highway) and aquaculture. Tufts have also been successfully seeded in a hatchery setting.

Rom Lipcius

Virginia Institute of Marine Science

Ecosystem-based planning, implementation and success of subtidal, granite oyster reefs in the Piankatank River, VA, Chesapeake Bay

Although oyster restoration practitioners have adopted alternative reef substrates for projects in subtidal waters, a comprehensive strategy for this approach has not been fully developed. As part of the Chesapeake Bay Native Oyster Recovery Project, the USACE constructed a large subtidal granite reef in the Piankatank River (PR) of lower Chesapeake Bay. We describe a restoration strategy implemented in the PR, which included (i) hydrodynamic modeling of metapopulation connectivity, (ii) field validation of connectivity, (iii) habitat suitability modeling, (iv) high-resolution benthic habitat mapping, (v) historical data on oyster distribution, (vi) reef geometry proven to be successful, and (vii) surveys of oyster and mussel abundance on the reefs to examine restoration reef performance. Based on the hydrodynamic model, mid- to down-river reaches could support a source metapopulation that self-sustains and exports larvae to sink habitats farther downriver and outside the mouth. Upriver segments would not receive larvae despite availability of suitable habitat, which was validated by field surveys. Two years after construction, the reef network harbored a dense population of age-0 juveniles and age-1 adults. Adult oyster density averaged 219.3 per square meter and biomass 75.3 g dry weight per square meter. Mean live mussel density was also high at 194.5 per square meter. Mean live oyster volume was 3.2 L per square meter and consistent with a positive shell budget, even though it was an underestimate because it did not include the volume of underlying reef base of oxic dead shell normally aggregated with live oyster shell volume. ROV video corroborated high species diversity from lab samples, which included shrimp, fish, crabs, clams, snails, mussels and sponges. Several predatory fish species were on the reef, while crustaceans, including blue crabs, mud crabs and shrimp, were walking and feeding on the reef surface, indicating a successfully restored oyster reef community.

Abstracts

Hunter Mathews

University of North Florida

Early performance of the Pervious Oyster Shell Habitat (POSH) in restoring intertidal habitat for oysters and associated nekton along energetic shorelines in northeast Florida

The “Pervious Oyster Shell Habitat” (POSH) is a novel artificial reef structure designed to minimize pollution and provide quality oyster habitat in high-energy systems. The POSH is composed of oyster shell bound by a thin layer of Portland cement, into a dome. POSH modules were compared in-situ to the industry standard “Oyster Ball” model Reef Ball™ for oyster recruitment and utilization by fish and crustaceans. The study took place from June 2021 to June 2023, along two energetic shorelines in northeast Florida: Kingsley Plantation along the Fort George River (Duval County) and Wrights Landing along the Tolomato River (St. Johns County). Oyster demographics and densities were assessed on the structures throughout the first year of deployment. Nekton densities and communities were assessed throughout the second year, using $2m^2$ bottomless lift nets. Artificial reefs were compared to an adjacent oyster reef at Kingsley Plantation. Oyster recruitment was significantly greater on the POSH compared to the Oyster Balls at both Kingsley Plantation ($p < 0.000$) and Wrights Landing ($p < 0.01$). Fish densities did not differ among treatments at either site ($p > 0.05$). At Kingsley Plantation, crustacean densities were significantly greater on the natural oyster reef than both artificial reef structures ($p < 0.01$), excluding with the Oyster Ball in winter ($p = 0.263$). Densities were significantly greater on the POSH than the Oyster Ball during summer ($p < 0.001$), fall ($p < 0.001$), and spring ($p < 0.0001$), and greater on the Oyster Ball in winter ($p < 0.05$). At Wrights Landing, crustacean densities were greater on the POSH in summer ($p < 0.0001$) and spring ($p < 0.05$). Fish and crustacean diversity metrics were similar among treatments at both sites. Early findings for the POSH indicate that it can be a viable method for rapidly restoring oyster reef communities in high-energy systems.

Doug Munroe

North Carolina Division of Marine Fisheries

North Carolina’s Use of Alternative Substrate for Cultch Planting in Support of Oyster Rehabilitation Strategy

North Carolina has been utilizing various materials to construct low-relief (< 1’) oyster cultch reefs since 1915. These efforts are designed to support the state’s oyster restoration program. Cultch sites provide a suitable substrate for larval oysters to settle and develop on in North Carolina’s estuarine waters. Due to limited availability of oyster shell, the Cultch Planting Program has adapted the use of alternative material types. Shell only accounts for 10-20% of total materials deployed on cultch sites constructed since 2018, while materials such as limestone marl and crushed concrete, which are more readily available, have taken the place of oyster shell in the construction of cultch reefs. North Carolina constructs 40-50 acres of cultch reefs annually, which are opened to commercial harvest, once the oysters on the reefs have grown to harvestable size. Cultch sites support valuable biological and ecological functions, are designed to help reduce overall fishing pressure on natural oyster reefs and create additional opportunities for commercial fishermen to harvest oysters.

Bennett Paradis

North Carolina Division of Marine Fisheries

North Carolina's Oyster Sanctuary Program: Restoring Pamlico Sound's Subtidal Oysters with Artificial Reefs

Beginning in 1996, North Carolina's Division of Marine Fisheries has been investing in the construction and monitoring of no-take oyster sanctuaries with the intention of subsidizing larval availability in Pamlico Sound. In total, 17 large scale artificial reefs covering 566 acres of protected habitat have been built by deploying 223,640 tons of various materials. While most of these sanctuaries were built with marl limestone rip-rap, other materials have also been used including reef balls, granite, basalt, crushed concrete, recycled concrete pipe, and a variety of recycled shells. Annual monitoring of the sanctuaries provides high resolution data into the performance of each site in terms of oyster density and population structure. The long-term dataset has given managers and biologists valuable insight for comparing materials, salinity regimes, and reef design across time, guiding future large scale oyster restoration projects.

Matt Pluta

ShoreRivers

Natural recruitment to alternative substrates in the Tred Avon River: a pilot study

Oyster shell represents a critical resource for restoration, aquaculture, and fisheries in the Chesapeake Bay. The exploration of alternative substrates, as substitutes for natural oyster shells, to capture spat and facilitate recruitment is gaining significant attention. While numerous potential alternative substrates exist, only a limited number have undergone testing in field conditions during natural spat fall events. In our study, we deployed replicate platforms, each hosting 12 different substrates, including oyster shell, clam shell, and various building materials such as brick, granite slabs, ceramic tile, etc., that have been suggested for potential large-scale use. These platforms were strategically placed in three distinct sites within Tred Avon River during the summer of 2021, coinciding with a notably favorable year for oyster recruitment in the Maryland portion of the Bay. At the end of the study, eight of nine platforms were retrieved, gently cleaned, and photographs of each substrate were meticulously taken. Utilizing image analysis, we recorded oyster recruits across the different substrates. Oyster spat exhibited a higher affinity for oyster shells, with clam shells following closely. Conversely, the remaining tested materials did perform nearly as well in attracting oyster spat. The study demonstrated a preference for shell but we also noted many oysters recruited to the underside of the plastic platform supporting the tested materials on the surface. These and other study details will be discussed.

William Rodney

Texas Parks and Wildlife Department

A Summary of TPWD Oyster Restoration Activities Utilizing Alternative Cultch Materials

Since 2007, Texas Parks and Wildlife Department's (TPWD) Coastal Fisheries Division has been actively working to restore oyster reefs for the purpose of enhancing the oyster fishery as well as the ecosystem services that these critical habitats provide. These efforts began in 2007 when TPWD received an appropriation from Congress in response to impacts from hurricanes Katrina and Rita. As of 2023, $16 million has been spent and more than 600 acres of oyster habitat has been restored through cultch

Abstracts

planting. About 95% of TPWD's restoration efforts were completed in commercially harvestable waters and thus directly benefited the commercial oyster industry. The remaining 5% was placed in waters that are closed to commercial harvest, and thus provided enhanced ecosystem services. Over the years, a variety of substrate types and design approaches have been successfully employed. Substrates have included river rock, recycled crushed concrete, and crushed limestone of various sizes. Designs have featured flat layers with low vertical relief and mounds with moderate vertical relief. Decisions on cultch types and design approaches were informed by restoration goals. Several projects utilizing different cultch types and designs are discussed.

David Schulte

US Army Corps of Engineers

Lynnhaven River, VA results of large-scale reef ball-based oyster restoration

In 2021, a large network of reef balls (28,500), each 0.4572 m (1.5 ft) wide and 0.3048 m (1.0 ft) tall covering 8.0 acres of subtidal, sand/clay/silt mix bottom in the polyhaline waters of the Lynnhaven River, VA, the most southeastern tributary river of Chesapeake Bay. The site selected was determined by both historical documentation as well as modern-day hydrodynamic modeling to be a good site for reef construction. Monitoring results have demonstrated the reef ball system, despite its young age, already is well in exceedance of Chesapeake Bay Program goals for oyster density and biomass, and exceeds the more ambitious goals of the Lynnhaven River Ecosystem Restoration Plan written by the USACE. At present, the three-dimensional reefs have a mean of 1137.6 ± 94.99 SE g/m^2 DM oyster tissue, 4,275.1 live oysters/m^2/river bottom area, consisting of 2,884.3 ± 240.23 SE spat and 1390.8 ± 104.85 SE adults. Live shell volume was also exceptionally high at 40.1 ± 2.80 SE l/m^2/river bottom area. The largest oysters observed on the reef balls were over 150 mm in shell height. These results suggest that oyster restoration using alternative materials in subtidal, polyhaline waters of Chesapeake Bay can produce exceptionally good results, and suggests that such alternative material based efforts can greatly assist in oyster restoration efforts in Chesapeake Bay.

H. Ward Slacum Jr.

Oyster Recovery Partnership

Advancing alternatives to shell for oyster production

Natural oyster reefs depend on shell accretion for long-term growth and survival, and their restoration is dependent on the availability of oyster shell as substrate for successful recruitment. In most coastal environments, shell loss has been accelerated by fishing activities and increased sediment deposition. To account for this, management agencies encourage initiatives to expand oyster production through aquaculture, public fishery management activities, and oyster restoration. This three-pronged management approach has increased the demand for shell, and availability is insufficient to meet demand. There are several ongoing initiates underway in Maryland to identify alternatives and alleviate the demand for native shell resources.

Kathy Sweezey

The Nature Conservancy

A Discussion on the Challenges of using Alternative Substrate: A Project Manager's Perspective

Despite the many benefits they provide, oyster reefs are one of the most imperiled marine habitats on earth. Globally, over 85% of oyster reefs have disappeared. Oyster populations in Texas are at a historic low, emphasizing the need for oyster reef restoration and protection efforts.

Restoration practitioners face many challenges including the increasing cost of commonly used "traditional" substrate like shell or limestone, limited availability of traditional substrate near project locations, and increased emissions to transport and deploy substrate for the project. Alternative substrate provides an opportunity to address each of these challenges and potentially leads to additional benefits and a more effective way to reach project goals.

Beezley Reef is a 40-acre subtidal oyster reef restored by The Nature Conservancy in Galveston Bay, Texas. This reef has a unique design as a hybrid part harvestable, part sanctuary reef complex. During the second phase of this project which focused on expanding the sanctuary reef by two acres, project managers emphasized the desired preference for alternative substrate with the engineer and in bid documents. However, the low number of bids returned, the cost of the alternative substrate bid obtained, and the limitation of alternative substrate that could be used on a subtidal reef all led to the decision to restore the reef using traditional substrate, limestone. Project managers met with multiple alternative substrate providers during the design phase to discuss Beezley Reef, assess feasibility, and gauge interest. Unfortunately, the providers met with were either unable to support a subtidal oyster reef or did not bid on this project.

For discussion, project managers ask: How do other practitioners seek alternative substrate providers? What alternative substrates are available for subtidal oyster reef restoration? How can restoration practitioners and alternative substrate providers enhance collaboration to best reach the project goals within limited budgets?

Christine Thompson

Stockton University

Optimizing remote setting on different cultch types for oyster restoration in Barnegat Bay, NJ

Restoration efforts for the eastern oyster, *Crassostrea virginica*, are often limited by sources and availability of cultch for remote setting. In Southern New Jersey, a shell recycling program has been created to provide shell for restoration purposes, but the types and availability of shell can vary. Additionally, the growth of oysters on these shell types once planted may affect restoration success if set ratios are too high or low. This study evaluated the average settlement of eyed oyster larvae in circular setting tanks with mixtures of three shell types: eastern oyster (*C. virginica*), surf clam (*Spisula solidissima*) and knobbed whelk shell (*Busycon carica*). Spat settlement was assessed prior to deployment on the subtidal reef site and again four months post-planting. Initial settlement numbers (no. oysters per shell) significantly differed between each shell type and were highest for surf clam shell and lowest for whelk shell ($p<0.001$). During post-planting monitoring, oysters and surf clam shell had the largest oysters but also had the highest mortality. This study is important for optimizing aquaculture techniques for both large and small-scale remote setting that can be restricted by both the availability of shell types and permitting requirements prohibiting certain substrates in shallow-water bays.

Jennifer Zhu

Billion Oyster Project

Innovative Approaches in Oyster Restoration: Exploring Alternative Materials and Substrates in the New York Harbor

With a growing focus on microplastics and individual and collective carbon footprints, many restoration practitioners and innovative suppliers are actively exploring alternative materials for application in marine restoration projects. Billion Oyster Project is enthusiastic about ongoing research and collaboration with industry professionals to understand how these materials can enhance oyster restoration efforts throughout New York Harbor. This presentation highlights the alternative materials and substrates that have been applied to oyster restoration projects since 2016.

Materials such as coir, burlap, and biodegradable mesh offer an eco-friendly alternative to the conventional plastic mesh bags used in bagged shell reef oyster restoration. However, their biodegradability often occurs at a pace that exceeds the time required for an oyster reef to develop. Burlap bags have degraded before oysters could cement to each other and form reefs. Some biodegradable meshes may also still leach microplastic material faster than traditional nylon bags. Further research is needed to understand how long biodegradable bags take to break down in marine environments and provide insight into their applicability across restoration projects and community engagement and education programs.

Alternative substrates seeded with oysters, such as reef balls and ECOncrete® disks are widely applicable restoration techniques with longer lifespans to sufficiently support the establishment of oyster populations at restoration sites. Cement is a primary ingredient in these concrete structures, which extends the lifetime of the structure but is more carbon-heavy. This can be offset through the addition of aggregates, such as rocks or shells, to the mixture. Structures such as piling wraps to attract wild oysters to settle on bulkheads have shown short-term success in the harbor, but are challenging to install and maintain. In New York Harbor, these types of applications are better suited for habitat enhancement than habitat creation. Hard substrate such as reef balls provide more surface area on which oysters can grow, and are easier to monitor, making them more optimal for use in oyster restoration projects.

Appendix II: SASSO Program

Strengthening Habitats with Oysters on Retrofitted & Engineered Structures

Report on the Virtual Symposium

Feb 26-27, 2025

Background

This symposium on **Strengthening Habitats with Oysters on Retrofitted & Engineered Structures (SHORES)** is part of an effort to fill key knowledge gaps in support of Maryland's oyster resource and oyster industries. Chesapeake Bay is home to thriving commercial fishing and aquaculture industries and one of the largest oyster restoration efforts in North America. The lack of fresh shell substrate has become a major impediment to all of these activities and alternatives are being considered for large-scale use in restoration and industry efforts. To address this challenge, the Maryland General Assembly mandated a program (SB830 2023) that will evaluate:

1. Types of substrate, including fresh shell, fossilized shell, combinations of shell and alternative substrates that are most appropriate for use in oyster harvest areas.
2. Benefits, including habitat-related benefits, of using stones of various sizes in oyster restoration areas.
3. Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates.
4. Potential for retrofitting existing structures, such as riprap revetments that are unrelated to oyster restoration, but use materials similar to artificial reefs including oyster plantings.
5. Effect of spat size upon deployment on oyster abundance.

This symposium directly addresses topic 4: Potential for retrofitting existing structures, such as riprap revetments, that are unrelated to oyster restoration but that use materials similar to artificial reefs, to include oyster plantings.

In 2024, the Symposium for Alternative Substrates for Oysters (SASSO) addressed topic 3: Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates. If you are interested in learning more about SASSO, see the symposium webpage: **https://www.umces.edu/alternative-substrate-for-oysters**

Symposium Sponsors

This symposium was sponsored by University of Maryland Center for Environmental Science (UMCES). Lead organizers were Dr. Matthew Gray, Dr. Elizabeth North, and Dr. William Nardin of UMCES Horn Point Laboratory. The symposium team also included Monica Fabra, Kurt Florez, Conor Keitzer, Roshni Nair-Gonzalez, and David Nemazie. Graphic design and logistical support are from UMCES Integration and Application Network (IAN). Funding support was provided by the State of Maryland.

For questions regarding this symposium please contact Matthew Gray at **mgray@umces.edu** or see the symposium webpage: **https://www.umces.edu/shores-symposium**

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Executive Summary

The **Symposium on Strengthening Habitats with Oysters on Retrofitted and Engineered Structures (SHORES)** brought together more than 150 participants to explore how the Chesapeake Bay's extensive armored shoreline and growing use of living shorelines can be adapted to support Eastern Oyster (*Crassostrea virginica*) populations. Over 1,600 km of Chesapeake Bay shoreline are armored with bulkhead, riprap, or seawalls, structures that often degrade adjacent submerged aquatic vegetation (SAV) and limit ecological value.

These same hardened shorelines represent a vast amount of potential hard-bottom habitat for oysters if strategies can be developed to overcome limitations of material properties, intertidal positioning, and larval supply. Living shorelines are gaining traction across Maryland as a preferred stabilization method, but questions remain about how to incorporate oysters into their design and siting. The SHORES symposium directly addressed these challenges, advancing Topic 4 of Maryland Senate Bill 830 (2023), which called for evaluation of retrofits and engineered coastal infrastructure for oyster habitat creation.

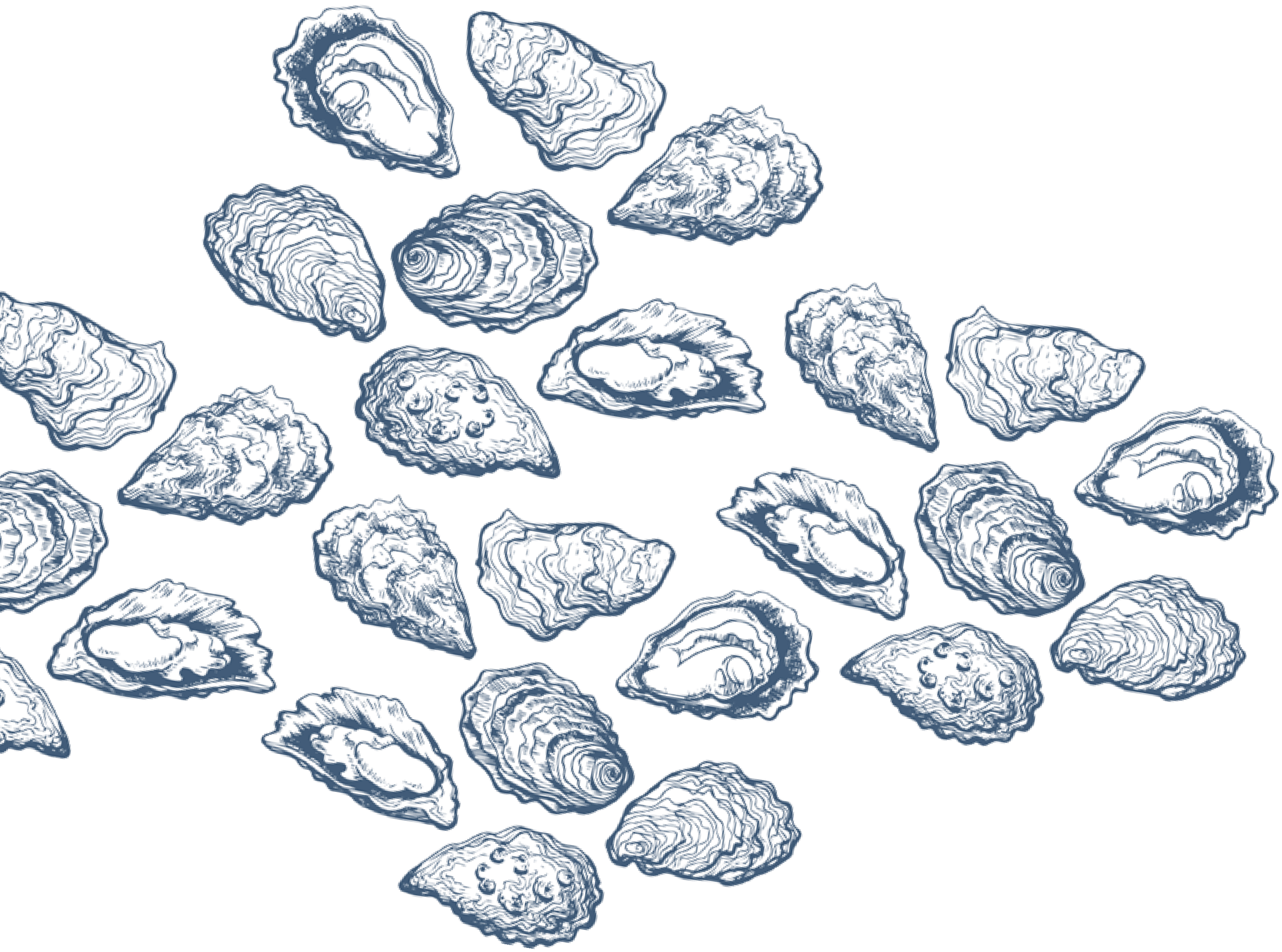
Over two days, fourteen invited speakers presented case studies spanning the Atlantic seaboard, Gulf of Mexico, and North Sea. Participants shared experimental approaches using alternative materials, structural modifications, and hybrid systems that integrate oysters into seawalls, docks, bulkheads, breakwaters, offshore wind turbines, and living shorelines. Across talks, several consistent themes emerged: the ecological value of microhabitats such as crevices for oyster survival; the potential for oysters to enhance the longevity and adaptive capacity of grey infrastructure; the promise of lightweight, modular structures for scalable deployment; and the importance of pairing physical engineering with biological monitoring.

Numerous key findings were highlighted in the symposium. The success of oyster recruitment on engineered seawall tiles with protective crevices was notable, as were trials of oyster-seeded tetrapods and sediment cubes at offshore wind turbines. Community-supported oyster gardening with biodegradable and natural materials showed promise, while hybrid breakwaters in Maryland's Choptank River improved wave attenuation by 20% when oysters were present. New commercial products are available, that combine engineering reliability with habitat uplift. Equally important were lessons from failures, such as the poor durability of some biodegradable plastics or the limited survival of oysters on pilings treated with toxic compounds. These case studies underscored the need to carefully match design and materials to local ecological and physical conditions.

Symposium discussions and participant polling emphasized both opportunities and barriers. Habitat creation (54% of participants), oyster recruitment (40%), and durability (26%) were consistently ranked as the most valued benefits of oyster-infrastructure integration. However, permitting complexity was identified as the single greatest barrier, with 42–60% of participants citing regulatory hurdles as a limiting factor. Other gaps included the need for standardized metrics to evaluate hybrid systems, long-term durability data for new materials, and better understanding of how oysters on hardened structures influence adjacent SAV and biodiversity.

Overall, SHORES demonstrated that integrating oysters into retrofitted and engineered coastal infrastructure can transform necessary shoreline protection into multi-functional systems that provide ecological, social, and climate resilience benefits. Lessons shared at the symposium provide immediate guidance for Maryland's restoration and permitting community, while also contributing to global innovation on how to "green the grey" with oysters.

Day 1: Retrofitting Existing Infrastructure

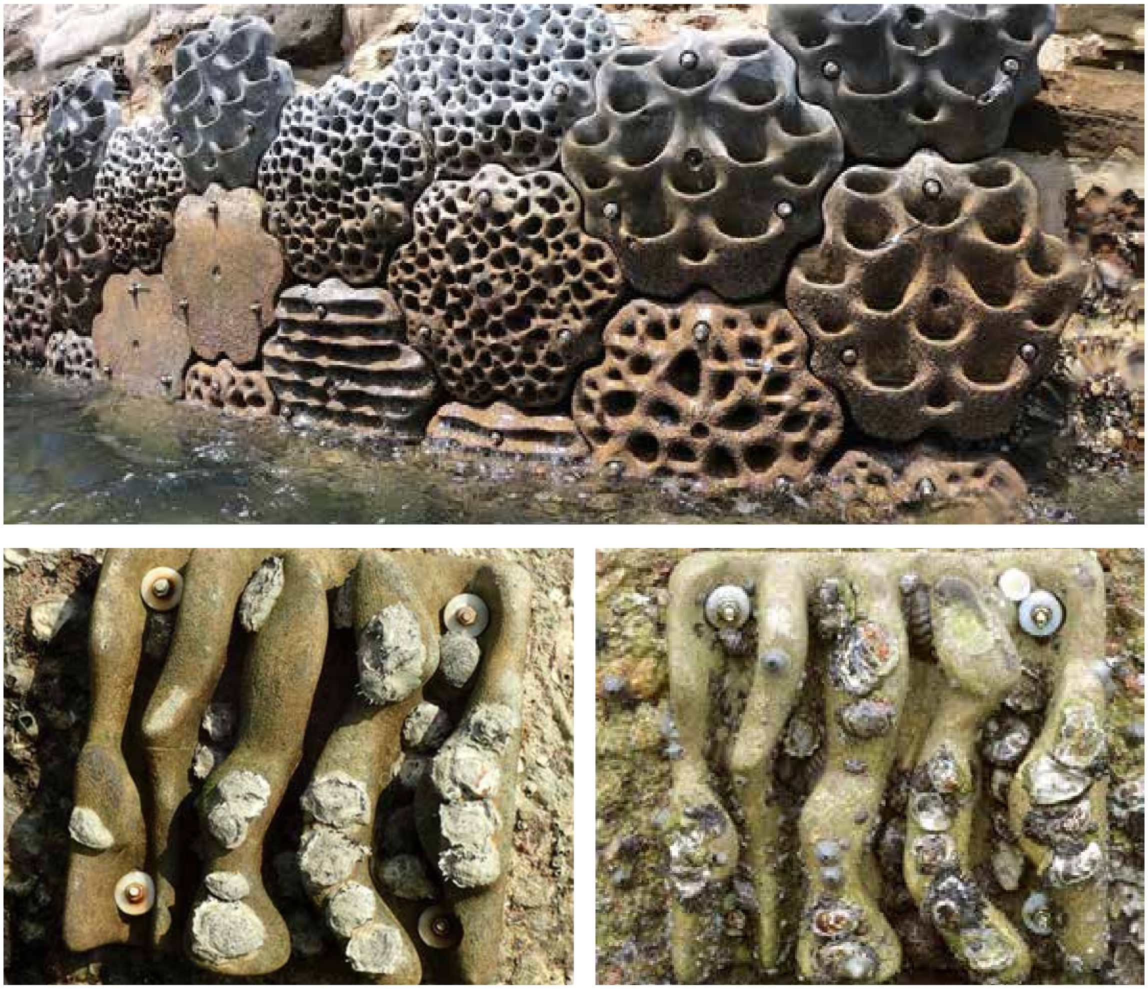


Day 1 Talk Highlights

Rochelle Seitz

Virginia Institute of Marine Science

Rochelle Seitz presented research on retrofitted seawall structures designed to support oyster settlement and survival. Her team used concrete tiles manufactured by Reef Design Lab with ridges and crevices of varying dimensions to create microhabitats. Juvenile oysters, approximately 23–25 mm shell length, were seeded onto the structures using non-toxic epoxy. The design was particularly effective because crevices protected from desiccation and predation, two major stressors for intertidal oysters. Seitz stated that she would recommend crevice-based structures for retrofitting seawalls, because they enhance oyster survival and habitat value. While her group did not measure the effects of oysters or added structures on seawall performance directly, she referenced other studies showing that "green" modifications can improve seawall longevity. Oyster survival data from her experiments are not yet published, though a manuscript is in preparation. An important social dimension of the work was highlighted: homeowners at the test sites were enthusiastic partners and expressed consistent interest in the project. This response suggests strong public acceptance of oyster-based shoreline interventions. Overall, Seitz's findings underscore how modest design modifications to grey infrastructure can substantially increase ecological value while maintaining shoreline protection.



Seawalls with built in groves that produce a micro-habitat for settlement of bivalves and increase diversity of sessile and mobile invertebrates. Photos courtesy of Rochelle Sietz.

Day 1 Talk Highlights

Anthony Dvarskas
Ørsted

Anthony Dvarskas discussed efforts to integrate oysters into offshore wind lease areas. As part of Ørsted's 2030 biodiversity ambition, the company seeks to deliver a net positive biodiversity impact across all projects commissioned after 2030. One strategy being piloted is to use offshore wind infrastructure to restore the European flat oyster, which was once widespread in the North Sea but is now nearly nonexistent near the Netherlands. At the Borssele 1 & 2 wind farms off the Dutch coast, his team deployed lightweight, easily handled oyster structures in 2024. Two types were used: tetrapod concrete units and sediment-based cubes with binders, both seeded with flat oysters and designed for manual deployment from small crew transport vessels. The structures were placed on existing scour protection layers around turbines, which already provide some hard substrate but lack sufficient complexity for oyster recovery. In total, 70 tetrapods and 10 sediment cubes were deployed, with careful site selection to maximize larval spread and avoid cables. Deployment was straightforward, though sediment cubes crumbled during handling, highlighting durability challenges. Monitoring is being conducted with remotely operated vehicles (ROVs), with follow-up scheduled at 1, 3, and 5 years post-deployment. This work examines how engineered offshore energy infrastructure can be retrofitted with oyster habitat, effectively creating multi-use platforms for energy and biodiversity. If successful, the approach could be expanded across Ørsted's global lease areas. While results on oyster survival are not yet available, the project demonstrates a promising, scalable, low-cost, and lightweight deployment method for integrating oysters into large-scale grey infrastructure.

Pier piles retrofitted with textured pile to encourage habitat for oysters in the Hudson River. Photo courtesy of Hudson River Park Trust.

Day 1 Talk Highlights

Siddhartha Hayes
Hudson River Park Trust

Siddhartha Hayes described efforts to enhance habitat along heavily urbanized waterfronts. The Park encompasses four miles of Manhattan's shoreline, much of which is dominated by hard bulkheads, piers, and mudflats. Historically, Eastern Oysters were abundant in this estuary, but today the system is larval-limited and lacks suitable substrate. Hayes and collaborators first tested whether oysters could survive in suspended pile wraps, and found that they grew and even reproduced despite harsh winter conditions. Dive surveys also revealed oysters and other organisms already using pier piles and shaded habitats, suggesting vertical structures hold promise. Building on this, the Park launched large-scale enhancement projects. In Tribeca, nearly 200 structures were deployed, including reef balls, gabions filled with shell, pile wraps, and textured concrete piles. Monitoring has shown that oysters survived, grew, reproduced, and recruited new spat on these structures, while also supporting diverse fish and invertebrate communities. A second project at Gansevoort created a more compact artificial reef of about 300 structures adjacent to a salt marsh restoration site, requiring novel monitoring methods like sonar and underwater video because the units could not be lifted easily. Early results showed healthy oysters, strong plant growth, and expanding biodiversity. Hayes emphasized that these projects were designed not just to restore oysters, but to enhance the broader ecosystem and reconnect urban residents with their estuary. The work demonstrated that even in a stressed, turbid system like the Hudson, oysters can be successfully integrated into existing infrastructure and paired with marsh restoration.

Adrian Sakr
University of Florida

Adrian, a PhD student at the University of Florida, presented research on improving oyster gardening techniques for restoration and community engagement. Oyster gardens are small modular structures hung from docks or seawalls to provide habitat, improve water quality, and engage the public in restoration. While widely used, current oyster gardens often rely on unsustainable materials like PVC or plastic mesh, and there is little standardization on which designs perform best. Sakr's project tested several alternative garden structures, including biodegradable potato-starch mesh, jute fiber cylinders coated in cement, reef discs, and drilled oyster shells strung on wire. The gardens were deployed in residential canals on Sanibel Island, Florida, in collaboration with local homeowners. Within months, oyster recruitment began, but in September 2022, Hurricane Ian struck, killing most oysters due to poor post-storm water quality. After 15 months, the biodegradable plastics had disintegrated without supporting oysters, while the jute-cement cylinders, reef discs, and shell-on-wire structures remained intact and supported dense oyster and mussel communities. These surviving gardens also demonstrated strong biofiltration capacity, reducing chlorophyll a and turbidity in controlled tests. Sakr emphasized that water quality was a critical factor, because gardens in poor-quality sites performed poorly regardless of structure type. Cost and durability analyses showed tradeoffs: natural-material gardens were inexpensive and effective, while prefabricated units like reef discs were more costly but easier to handle. The study demonstrated that simple, low-cost structures can be both ecologically effective and community-friendly, especially when paired with strong homeowner engagement. The work highlights how oyster gardening can retrofit private docks and seawalls into functional habitat, while also creating grassroots support for oyster restoration.

Day 1 Talk Highlights

Niels Lindquist
SANDBAR Oyster Company Inc.

Niels discussed the development of Oyster Catcher™, a cement-infused jute cloth designed to enhance oyster settlement on hardened structures. His work was motivated by the observation that oysters thrive on concrete pilings but are largely absent from chemically treated wood pilings that dominate docks along the coast. Oyster Catcher™ can be manufactured into cuffs or wraps that are strapped around pilings, creating textured, cemented surfaces suitable for oyster colonization. Early trials in North Carolina's Bogue Sound showed high oyster settlement during the first summer, suggesting the material was effective at attracting spat. However, after one year, oyster growth slowed and degradation of the material began, raising questions about long-term durability. Lindquist pointed to possible factors such as the toxicity of treated wood pilings, predation from fish and crabs, and stormwater runoff affecting water quality. He suggested several improvements, including making the cuffs more cement-rich, timing deployment just before spawning season, strapping them tightly to pilings to reduce predator access, or adding liners to buffer wood toxicity. Despite these challenges, the material has proven to be versatile, easy to manufacture, and effective in creating settlement surfaces in otherwise inhospitable zones. Oyster Catcher™ represents a promising retrofit technology that could transform underutilized pilings and docks into productive oyster habitat. The project highlights both the ecological potential and the engineering challenges of adapting living substrates to grey infrastructure in high-energy, human-dominated shorelines.

Oyster Catcher™ piling cuff installed in Bogue Sound, Morehead City, NC in February 2024, and photographed a year later. Photo courtesy of Niels Lindquist.

Day 1 Talk Highlights

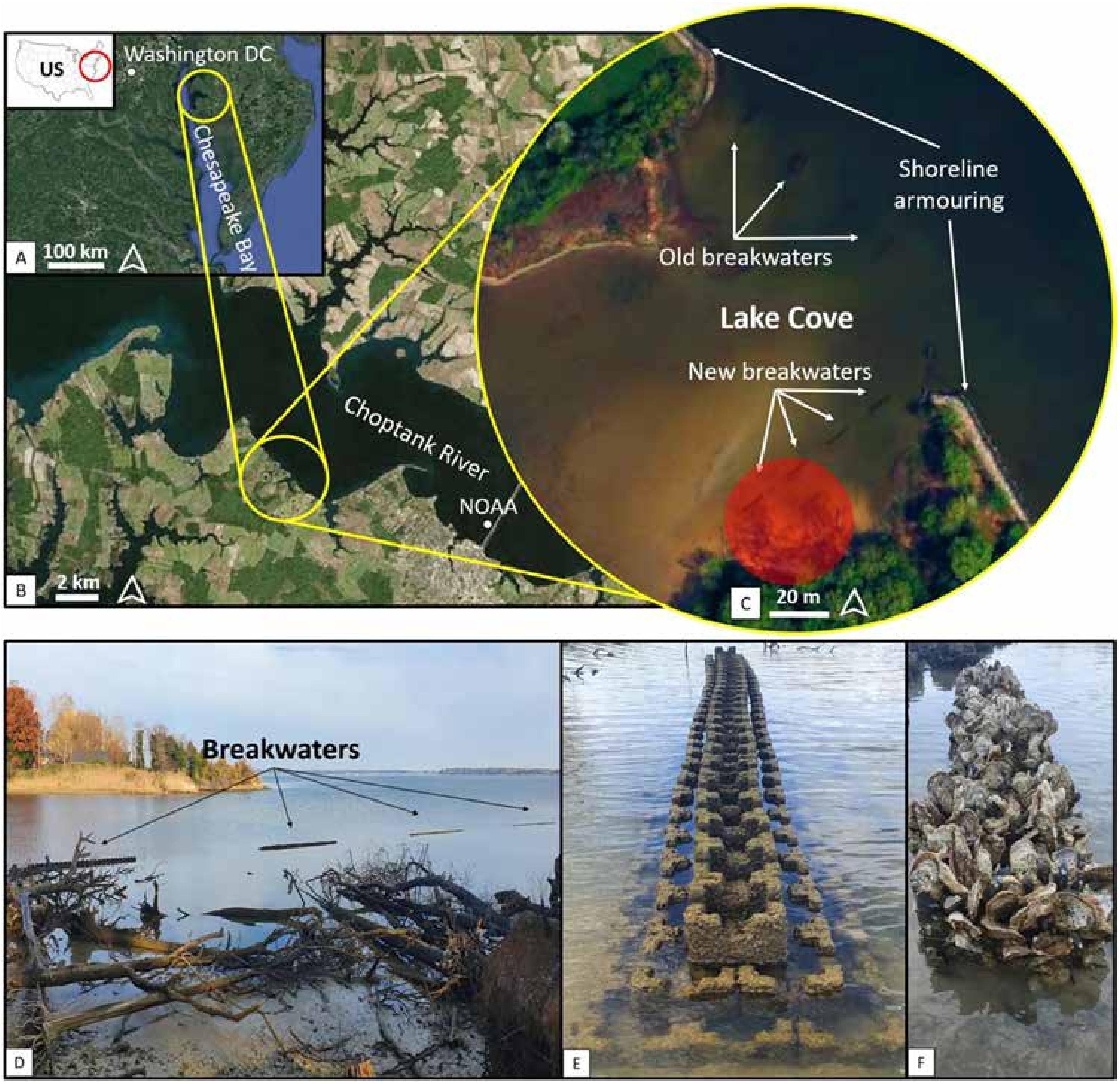
Jason Spires
National Oceanic and Atmospheric Administration

Jason Spires described experiments exploring new ways to colonize hardened shorelines with oysters. His work focused on regions of Chesapeake Bay with poor larval supply, where natural recruitment onto seawalls and riprap is unlikely. One strategy tested was using natural-derived materials such as coconut fiber mats and basalt fibers, which could be pre-seeded with oyster larvae in hatcheries and then wrapped around pilings or stones. In settlement trials, oysters attached readily to coated basalt but performed poorly on coconut fiber, which degraded quickly. Larger mats of coated basalt retained oysters for over a year in high-energy conditions, showing promise as a veneer for pilings. Spires also tested whether bubble curtain diffusers—commonly used for oil rigs, canals, and algal control—could retain oyster larvae around hardened structures to encourage settlement. Initial trials showed larvae escaped the curtains, but he plans to refine pore size and flow rates to improve retention. This concept could allow direct *in situ* colonization of bulkheads and piers without needing to transplant seeded material. His experiments underscore the importance of finding materials that both support initial settlement and withstand predation, wave action, and fouling. The work demonstrates creative methods to retrofit existing grey infrastructure with oysters, even in larval-limited systems. By testing biodegradable substrates and scalable diffuser technologies, the project provides potential tools to expand oyster-based habitat enhancement in challenging urban and estuarine settings.

Iacopo Vona
UMCES, presently at University of Central Florida

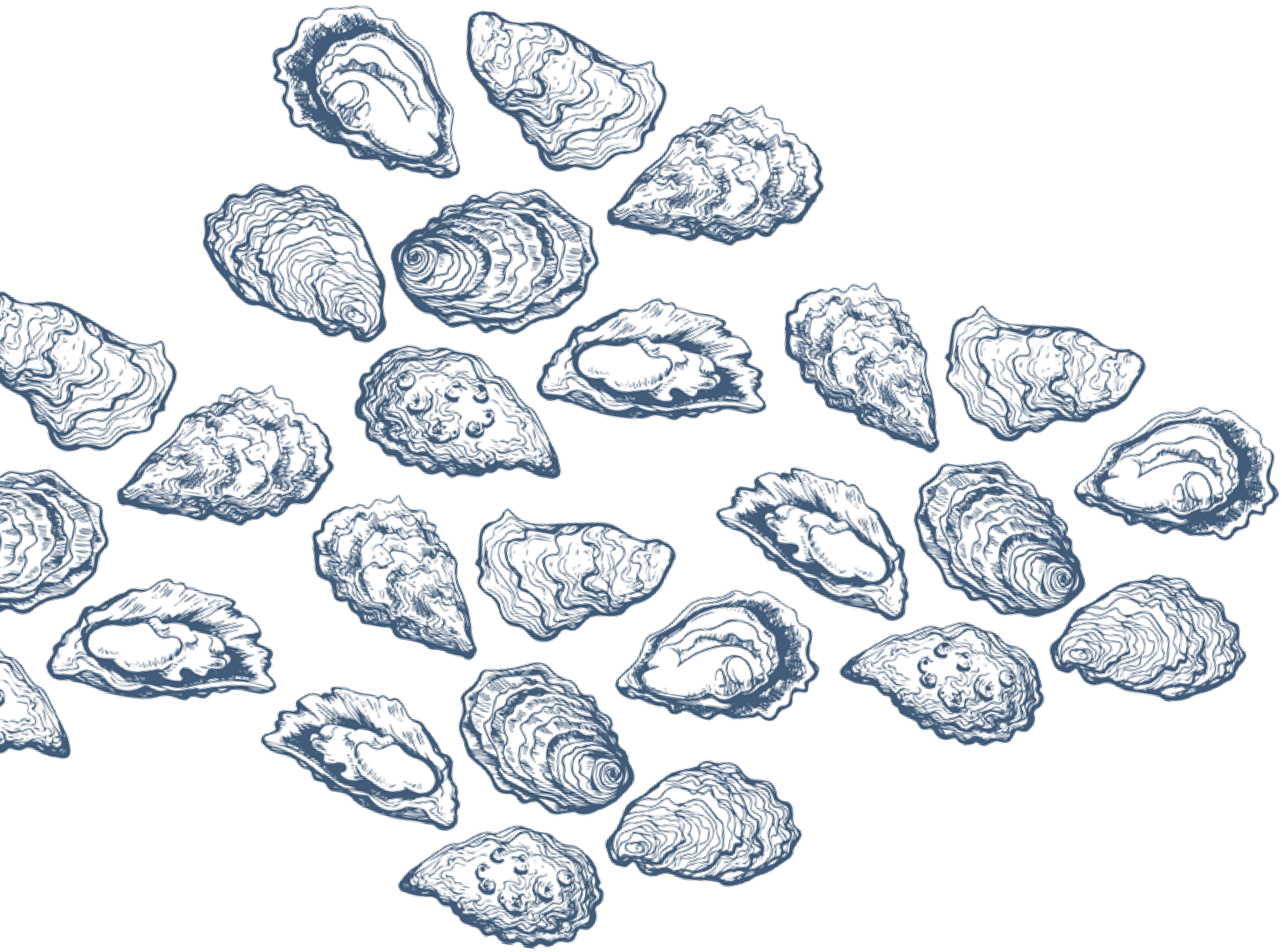
Iacopo Vona presented his PhD research on combining submerged breakwaters with oysters as a nature-based solution for shoreline protection. Traditional grey structures, such as breakwaters and seawalls, lose effectiveness over time with sea level rise and provide no ecological services. By contrast, oysters form three-dimensional reefs that can attenuate waves, self-repair, and grow vertically with rising seas, while also delivering ecosystem benefits. Vona's work tested this integration in the Choptank River, Maryland, where four breakwaters were built in 2019 using oyster castles. Monitoring revealed that adding oysters improved wave attenuation by about 20% compared to grey breakwaters alone. Field data on bed-level changes and sediment deposition were used to calibrate a numerical model simulating future sea level rise scenarios. Modeling showed that while grey breakwaters alone lose functionality under higher sea levels, oysters sustain sediment retention and wave attenuation into the future. Importantly, the research emphasized the engineering–ecology tradeoff: taller structures attenuate more waves but reduce oyster survival, while lower structures favor oysters but attenuate less. The team also experimented with retrofitting old, degraded breakwaters by adding oyster castles, effectively "reviving" them through oyster colonization. In discussion, Vona noted that oyster castles naturally recruit oysters but can also be hatchery-seeded, and he flagged cold winters as a survival risk for intertidal oysters. Overall, his results demonstrate that integrating oysters into coastal defense structures provides adaptive protection that strengthens with time.

Day 1 Talk Highlights



(A) Study area frame on the eastern shore of the US, within the Choptank River in Chesapeake Bay.
(B) Zoom on the Choptank River.
(C) Zoom on the Lake Cove. The red circle indicates the area impacted by fallen trees.
(D) Breakwaters view from the shoreline side, with details of fallen trees into the water.
(E) Detail of one breakwater within the Lake Cove.
(F) Detail of 2 year old oyster castles colonized by oysters.
Photos courtesy of Iacopo Vona.

Day 2: Building Engineered Living Shorelines



Day 2 Talk Highlights

Kate Orff
SCAPE

Kate Orff opened Day 2 with reflections on the Living Breakwaters project in Staten Island, New York. She described its origins in early design concepts like "Oyster-tecture," which envisioned oyster reefs as ecological and cultural infrastructure. After Superstorm Sandy, these ideas gained urgency, leading to a decade-long effort combining science, design, and community engagement to build engineered breakwaters seeded with oysters. The project consists of eight rubble mound structures enhanced with ecological concrete, reef ridges, reef streets, and tide pools to foster oyster colonization and fish habitat. Orff emphasized that the breakwaters serve multiple purposes: reducing coastal risk, restoring habitat, and strengthening community resilience. She highlighted the long permitting, modeling, and engineering process, which included wave tank testing and iterative design to ensure both structural stability and ecological value. The project also integrated extensive educational and outreach components through the Billion Oyster Project, embedding oyster restoration into school curricula and citizen science. Orff stressed that oysters were both a functional engineering partner and a cultural connector, helping engage residents in coastal resilience. She concluded that the Living Breakwaters represent a new model for large-scale, nature-based infrastructure, balancing grey engineering with oyster-driven ecosystem services.

Carolyn Khoury
Billion Oyster Project

Carolyn Khoury described the Living Breakwaters project on Staten Island as a model of climate-adaptive, nature-based infrastructure. The $111 million effort constructs 2,400 linear feet of nearshore breakwaters made of stone and ecologically enhanced concrete to reduce wave energy, slow erosion, and create habitat for oysters and finfish. Developed after Superstorm Sandy through the HUD "Rebuild by Design" competition, the breakwaters aim to both reduce physical risk and reverse shoreline loss. Billion Oyster Project (BOP) is leading the biological component, adding seeded substrate beginning in 2025 to accelerate oyster colonization. The design includes "reef ridges" and "reef streets" that create diverse habitat niches and are intended to support self-sustaining oyster populations. Beyond ecological goals, Khoury emphasized the project's social dimension: partnering with local schools to create curriculum and hands-on education linked to oyster restoration. The breakwaters are expected to enhance community resilience by blending physical protection with environmental stewardship. This layered approach—physical, ecological, and social—demonstrates how engineered shoreline systems can be strengthened by oysters. Khoury positioned the project as both a large-scale experiment and a transferable model for other coastal communities seeking to integrate oysters into shoreline protection.

Tyler Oretego
Natrx

Tyler Ortego presented Natrx's approach to integrating engineered structures with oyster habitat to create resilient shorelines. His company has developed a proprietary Dry Forming™ manufacturing process that produces cement-based units with customizable voids and naturalistic surfaces. These

Day 2 Talk Highlights

structures are designed to optimize oyster recruitment, enhance biodiversity, and deliver wave attenuation while still functioning as protective shoreline infrastructure. Ortego emphasized that digital design tools allow tailoring the units to site-specific conditions, ensuring both ecological performance and structural stability. He showcased a case study from Hog Island, Virginia, where Natrx ExoForms™ were deployed in both high-energy and low-energy environments. In exposed sites, large stacked ExoForms provided marsh protection, while in calmer areas, lower crested oyster reefs were installed to maximize oyster colonization. The project created habitat capacity for millions of oysters, with the potential to filter vast amounts of water and prevent tens of thousands of tons of sediment from entering the Chesapeake Bay. Importantly, monitoring showed resilience to storm events, suggesting the units balance engineering needs with natural processes like overwash and sediment deposition. Ortego concluded that combining advanced manufacturing with ecological design offers scalable, adaptive solutions for shoreline protection that integrate seamlessly with existing grey and hybrid systems.

Amanda Poskaitis & Camille Calure

Underwood & Associates

Amanda Poskaitis and Camille Calure discussed work on dynamic living shorelines that use vegetated headland–bay systems to restore natural coastal processes while incorporating oysters. Their designs rely on native stone, sand, and woody materials to create variable habitats that accrete sediment and promote marsh growth. At the Assateague State Park boat ramp project, these techniques were tested in partnership with the Maryland Coastal Bays Program. Natural oyster recruitment was found on the boat ramp infrastructure after construction. Surveys since 2021 showed oysters were settling but typically survived only one to two years, likely due to disease, predation, and water quality stressors. Despite these challenges, the ironstone headlands used in the shoreline design proved to be suitable substrates for oyster attachment. Poskaitis noted that the project demonstrates how oysters can be a co-benefit of properly designed living shorelines, even in regions without self-sustaining populations. She also described experiments suspending oysters in cages and testing different placements around headlands, which provided insights into survival limits and site-specific suitability. The team is extending these methods to other Chesapeake and Coastal Bays projects, with interest in pairing oyster restoration with marsh stabilization. Poskaitis concluded that integrating oysters into dynamic shoreline designs requires careful site assessment but can substantially increase the ecological value of protection projects.

Oysters growing on grey infrastructure. Photo courtesy of the Maryland Coastal Bays Program and Amanda Poskaitis.

Day 2 Talk Highlights

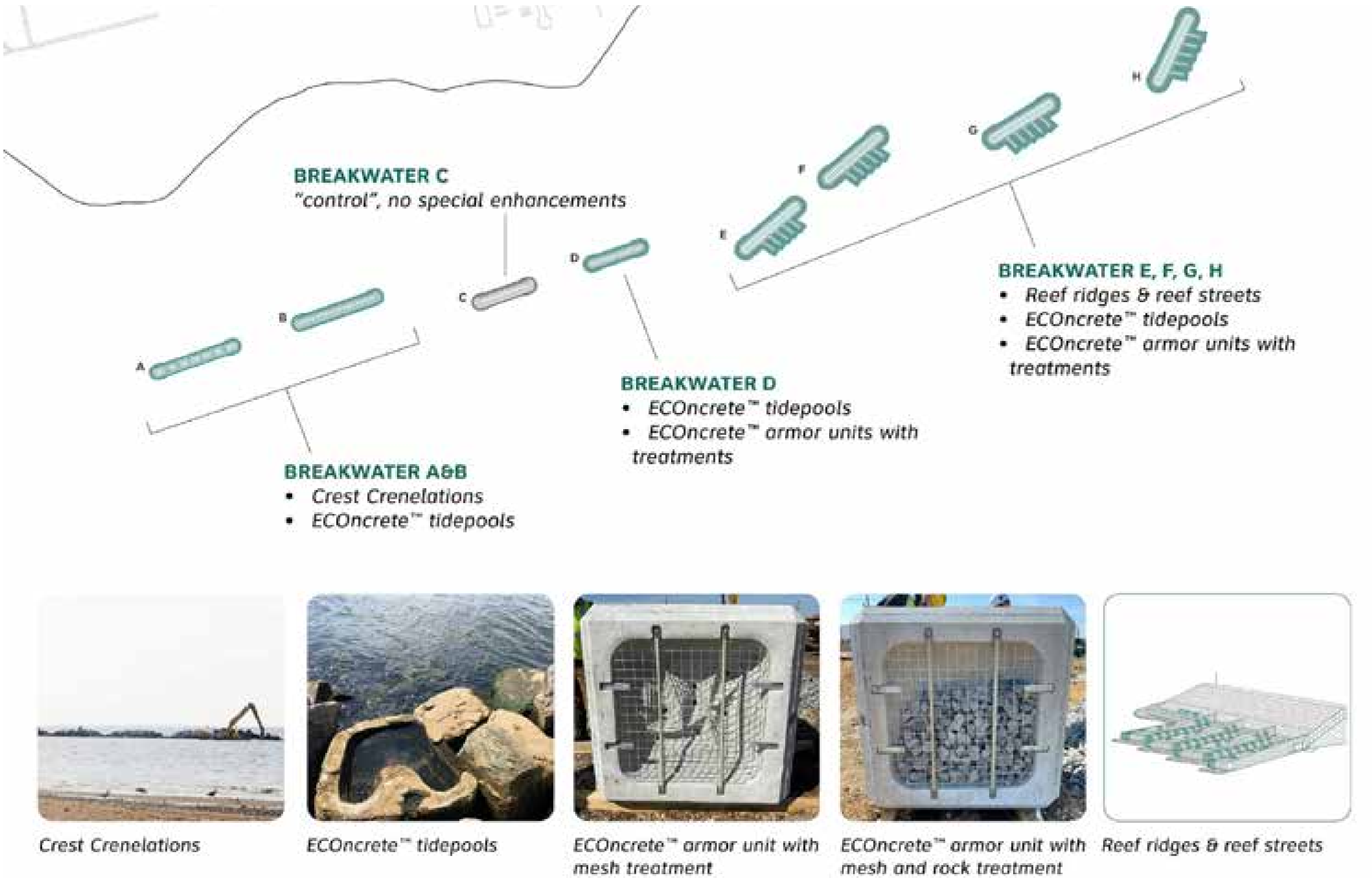
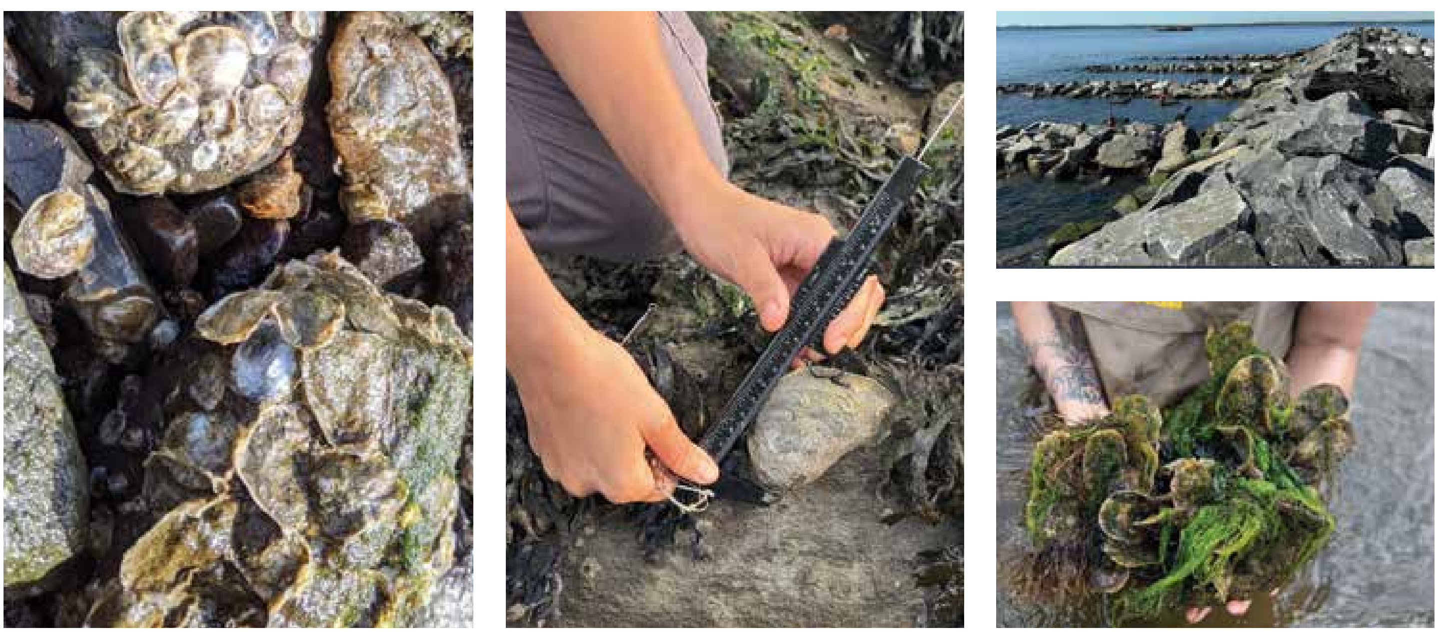


Diagram of the Living Breakwaters project in Staten Island, New York, demarcating the various types of units used to retrofit the breakwaters. Diagram and photos courtesy of Kate Orff.



Oysters self-sustaining growth documented around .the Living Breakwaters project in Staten Island, New York. Photo courtesy of Carolyn Khoury.

Day 2 Talk Highlights

Mary-Margaret McKinney
Native Shorelines, A Davey company

McKinney described Native Shorelines' QuickReef® technology, an oyster-centric living shoreline system designed as an alternative to traditional rubble mound structures. QuickReef® units are made from native coastal materials such as limestone, marl, sand, and recycled oyster shell bound with cement, and are engineered to provide immediate wave attenuation and habitat for oysters. More than five miles of QuickReef® have already been deployed in North Carolina and Virginia, where qualitative observations showed strong oyster recruitment and reduced shoreline retreat. To validate these outcomes, the company partnered with Southern Shores Engineering and the University of South Alabama to conduct quantitative wave flume studies. Testing measured wave attenuation, structural stability, and current velocities, and results indicated that QuickReef® attenuated waves at levels comparable to rubble mound sills while remaining highly stable. Importantly, the structures are designed to improve further over time as oysters colonize, cementing the units together and enhancing roughness. McKinney emphasized that scaling these systems requires engineering data that regulators and contractors trust, which is why quantitative validation is critical. She also highlighted the versatility of QuickReef®, which can be manufactured in units small enough for hand placement or in panels weighing several thousand pounds for large-scale projects. Ultimately, QuickReef® aims to combine the engineering reliability of traditional armoring with the ecological uplift of oyster reefs, offering a cost-effective and habitat-positive shoreline solution.

Adrian Sakr
University of Florida

Adrian Sakr discussed the environmental tradeoffs of materials commonly used in living shorelines and coastal restoration. He emphasized that while concrete, metal, and plastic are widely used because of cost and predictability, their full life-cycle impacts—production, transportation, installation, and degradation—carry significant environmental costs. His review of the literature showed that despite heavy reliance on these conventional materials, reduced-impact alternatives like biodegradable plastics, natural fibers, and recycled aggregates are rarely used at scale. Sakr presented a comparative framework that indexed both dollar cost and carbon footprint, revealing that natural and biodegradable options can often outperform conventional materials when full environmental costs are considered. He highlighted case studies showing how local sourcing, recycled shell, or plant-based binders can reduce impacts and support sustainable shoreline construction. Importantly, he argued that not all projects require long-lasting, durable materials—shorter-lived substrates may be appropriate where oysters or vegetation quickly establish and provide structural resilience. Sakr urged the development of standardized specifications for materials to help practitioners, regulators, and contractors evaluate performance and select low-impact alternatives with confidence. He also noted that policy shifts, such as Florida's encouragement of plastic-free restoration, are already pushing the field in this direction. His conclusion was that material choice is a central but often overlooked factor in scaling sustainable oyster-based shoreline projects, and a life-cycle lens can improve both ecological and economic outcomes.

Panel Discussion and Participant Input

Knowledge Gaps:

Panelists identified key knowledge gaps around how oysters interact with engineered shorelines, particularly regarding long-term resilience, recruitment in larval-limited systems, and ecological uplift beyond the footprint of structures. There is still uncertainty about the relative performance of different substrates (e.g., rock types, concrete formulations, biodegradable materials) and their durability in diverse environments. Participants also noted the need for standardized specifications and datasets to compare materials and methods across projects. Understanding how oyster reefs recover after storms and self-repair over time was highlighted as areas needing more systematic study.

Permitting & Policy:

A recurring theme was the difficulty of navigating permitting for living shorelines that integrate oysters, with barriers ranging from “fill” classifications to limited regulator familiarity with novel substrates. Practitioners stressed the importance of early and consistent engagement with permitting agencies and building trust through pilot projects. Policy frameworks were seen as lagging behind restoration innovations, especially regarding material approval and hybrid approaches. In urban settings like New York, additional hurdles exist where aquaculture regulations intersect with restoration goals, creating tension around risk to harvestable waters.

Metrics:

Participants recommended expanding success metrics beyond simple oyster presence or absence to include wave attenuation, sediment retention, and broader ecological uplift. Tracking genetic diversity and larval contributions of restored populations could clarify long-term sustainability. Several panelists emphasized measuring resilience—how well oyster structures recover from disturbance—as a critical indicator. There was consensus that monitoring programs should integrate engineering and ecological measures to fully capture project outcomes.

Overcoming Barriers:

Contractor involvement, cost, and logistics were cited as major barriers to scaling oyster-based living shorelines. Speakers noted that designs must not only be ecologically sound but also deployable by marine contractors under real-world conditions. Education and public outreach remain important, since many landowners still default to bulkheads or riprap out of habit. Participants stressed the value of hybrid solutions, partnerships across disciplines, and demonstration projects to build confidence and reduce risk perceptions.

Poll Results Summary

Poll Results:

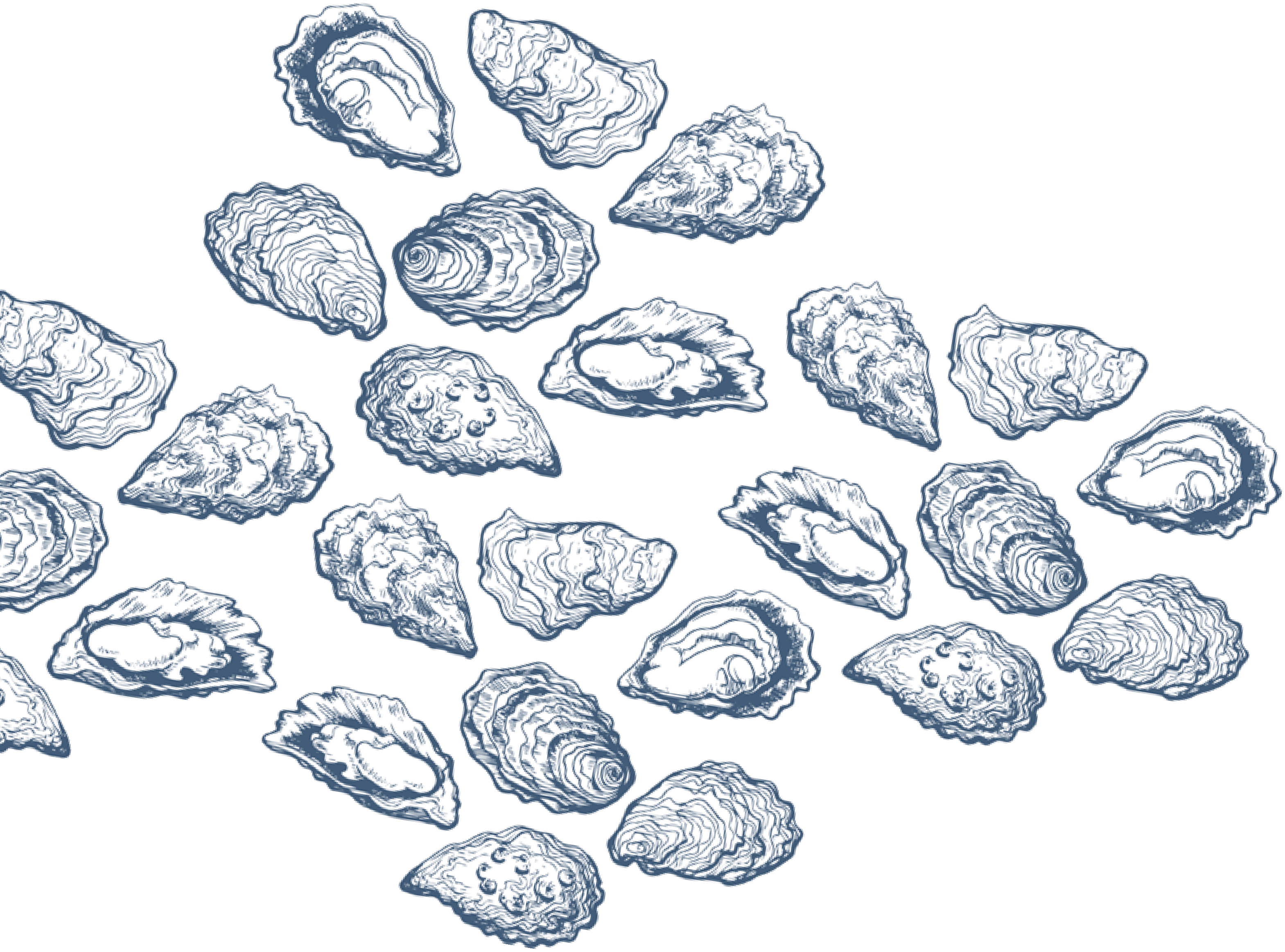
Polling during the symposium revealed strong support for oysters as a habitat-building tool.

On Day 1, when asked about the benefits of retrofitting existing infrastructure, 83 respondents (63%) ranked habitat creation as most important, followed by 46 (35%) for oyster spat recruitment and 31 (24%) for biodiversity enhancement. Durability (28%), cost-effectiveness (23%), and public perception (15%) were also noted but less frequently prioritized. On Day 2, the most valued benefits of oyster-inclusive living shorelines were again habitat creation (54%), oyster spat recruitment (40%), and durability of structures (26%). Participation data indicated that most attendees had practical experience: 71% reported involvement in living shoreline projects, and of those, nearly 90% included oysters. Oyster castles, reef balls, and shell bags were the most frequently used substrates, though participants also reported experimenting with newer options like biodegradable mats and manufactured wire reefs.

Across both days, permitting and regulations were identified as the top barrier (42–60% of respondents), followed by biological suitability (39%) and logistical constraints (33%). Maryland-specific concerns highlighted in the poll included the availability of suitable substrate, managing shallow-water habitat alongside SAV, and ensuring oyster survival in fresher and colder waters.

Oyster growing on rocks and on oyster shell at the Assateague State Park boat ramp in Maryland. Photo courtesy of the Maryland Coastal Bays Program and Amanda Poskaitis.

Appendices



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Appendix A: Schedule of Events and Logistics

Wednesday, Feb 26: Retrofitting Existing Infrastructure

10:00 Introduction

10:15 **Rochelle D. Seitz**, Virginia Institute of Marine Science, Batten School of Coastal and Marine Sciences

10:30 **Iacopo Vona**, University of Central Florida, Department of Civil, Environmental, and Construction Engineering

10:45 **Anthony Dvarskas**, Ørsted

11:00 **Jason Spires**, NOAA Cooperative Oxford Laboratory

11:15 **Niels Lindquist**, SANDBAR Oyster Company Inc.

11:30 **Siddhartha Hayes**, Hudson River Park Trust

11:45 **Adrian Sakr**, University of Florida

12:00 Poster session & Chat n' Chew breakouts

01:00 Plenary discussion

02:00 Adjourn

Thursday, Feb 27: Building Engineered Living Shorelines

10:00 Introduction

10:15 **Kate Orff**, SCAPE

10:30 **Carolyn Khoury**, Billion Oyster Project

10:45 **Tyler Ortego**, Natrx

11:00 **Amanda Poskaitis**, Underwood & Associates

11:15 **Mary-Margaret McKinney**, Native Shorelines, a Davey company

11:30 **Adrian Sakr**, University of Florida

11:45 **Alberto Canestrelli**, University of Florida

12:00 Poster session & Chat n' Chew breakouts

01:00 Plenary discussion

02:00 Adjourn

Appendix A: Schedule of Events and Logistics

Poster Session Presenters on both symposium days:

Savanna Barry, University of Florida

George Birch, Oyster Heaven (Day 1 only)

George Thatos, Coastal Technologies

Niels Lindquist, SANDBAR Oyster Company

Nicholas Muzia, Sea & Shoreline

Symposium Logistics

To join the symposium:
https://tinyurl.com/SHORES-Virtual-Symposium

To ask the speakers a question: Type your question in the Zoom chat. Only the speakers and moderators will be able to see your questions.

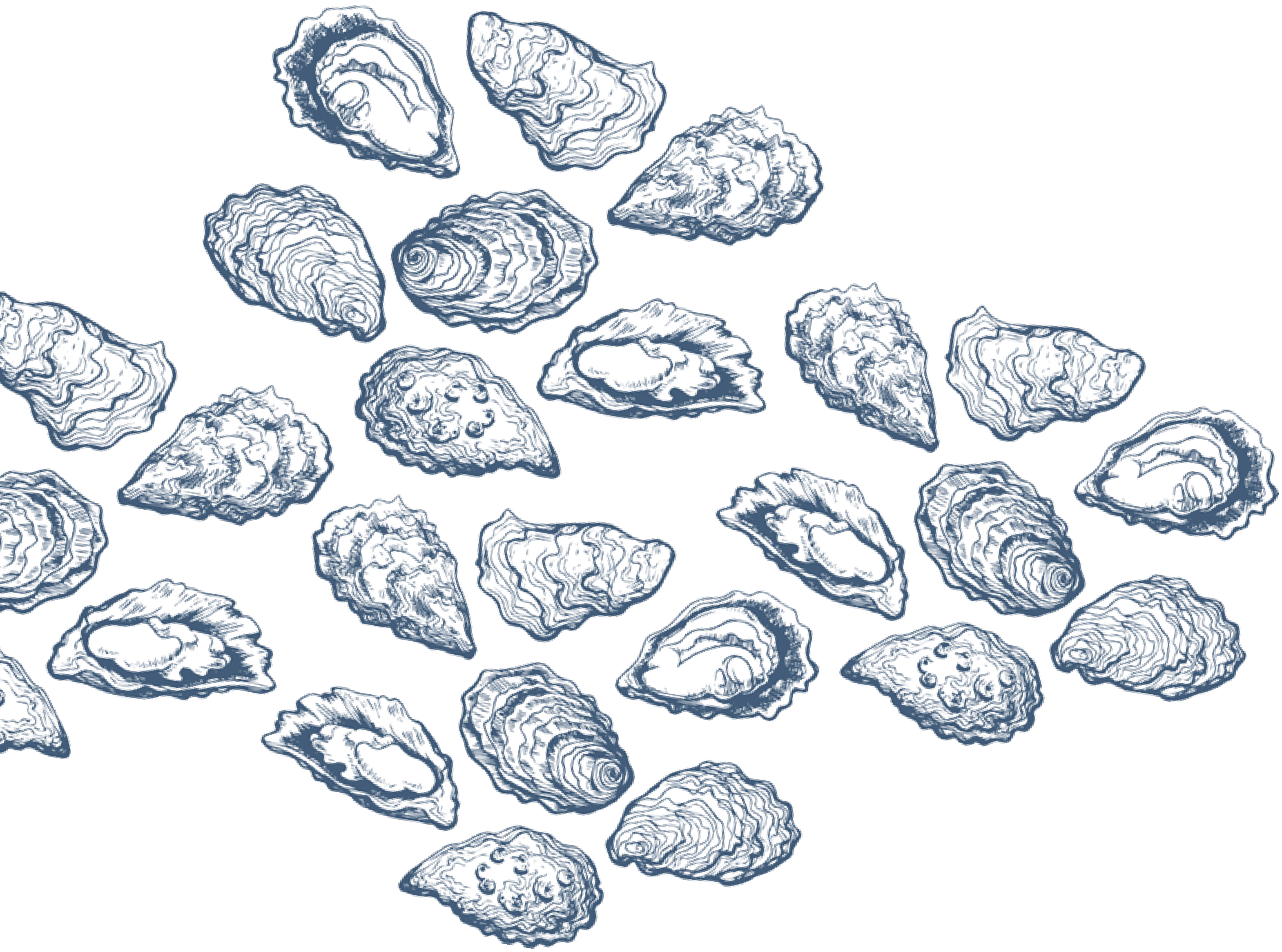
To join the Poster session & Chat n' Chew:
https://tinyurl.com/Posters-and-Chat-n-Chew

To ask a question or make a comment during plenary: Type your question or comment in the Zoom chat. The moderators will be able to see your questions and comments and will relay them to the panelists.

To receive a copy of the symposium report: All registrants will be sent the report this spring.

Day 1: Retrofitting Existing Infrastructure

Talk Abstracts



Day 1 Invited Speaker: Retrofitting Existing Infrastructure

Rochelle D. Seitz

Professor at Virginia Institute of Marine Science, Batten School of Coastal and Marine Sciences

Rochelle Seitz is a Benthic Ecologist and Professor at the Virginia Institute of Marine Science in Gloucester Point, VA. Her research expertise encompasses three primary areas of focus, including (i) effects of environmental stress, such as shoreline development and hypoxia, upon benthic invertebrate diversity, (ii) predator-prey dynamics and top-down versus bottom-up control of benthic systems, and (iii) restoration ecology.

Her current research projects include the impacts of habitat degradation on faunal communities, restoration of bivalves in the Chesapeake Bay, quantifying nursery habitat quality for the blue crab, and examining benthic predator-prey relationships and food-web dynamics. Additional interests include experimental and theoretical population and community ecology of marine benthic and epibenthic organisms focused on a quantitative understanding of processes operating in estuaries and the coastal ocean.

Kate Orff

Landscape Architect, Founding Principal of SCAPE, and Professor at Columbia University

Kate Orff, FASLA is the founder of SCAPE, a landscape architecture and urban design practice with offices in New York, New Orleans and San Francisco. SCAPE's Oyster-tecture and Living Breakwaters (constructed 2024) projects have been celebrated for interweaving social and ecological goals together with climate risk reduction. She is also a Professor at Columbia University with a joint appointment in the School of Architecture and the Climate School.

Kate's talk will focus on the trajectory of oyster restoration in New York Harbor, and how Living Breakwaters evolved into a funded and implemented project in the post-Super storm Sandy recovery process. She will show how the Living Breakwaters project developed, including its engineering and approvals process, and will feature the work of SCAPE's many collaborators, including the Billion Oyster Project.

Appendix B: Day 1 Talk Abstracts

Anthony Dvarskas
Ørsted

Integrating oysters into offshore wind lease areas: droppable oyster structure deployment at Borssele 1&2

Authors: Anthony Dvarskas, Karin Bilo, Tommy Kristoffersen

In 2021, Ørsted announced its ambition to have a net-positive impact on biodiversity for all renewable energy projects commissioned by 2030 or later. As a part of meeting this ambition, Ørsted is investigating the potential for nature-inclusive design at its offshore lease areas, including the addition of structured habitat and hard surfaces to benefit critical keystone species like cod and oysters. European flat oysters are a particular concern in the North Sea, given the substantial decline in their numbers and the absence of these reef-builders from areas where they had historically been present.

To address this, Ørsted recently collaborated with Van Oord to install droppable oyster structures at the scour protection for Ørsted's Borssele 1&2 wind lease area in the North Sea. Adult oysters were attached to these structures and, if successful, will generate larvae to colonize the areas adjacent to the installation, providing benefits to biodiversity and local water quality. Video footage will be collected at multiple time points following installation to monitor the structures. These structures are innovative for their lightweight design and their potential to be integrated into scour protection during routine maintenance activities. Some of the droppable structures were also composed of reused materials. This presentation will describe the characteristics of the droppable oyster structures, the installation approach, and the planned monitoring activities to evaluate the success of the deployment.

Siddhartha Hayes
Hudson River Park Trust

Enhancing infrastructure and nearshore habitat in an urban estuary, Hudson River Park, NYC

Authors: Siddhartha Hayes, Carrie Roble, Michaela Mincone

Located on Manhattan's west side between Chambers and W59th Street, Hudson River Park's 400-acre Estuarine Sanctuary waters are predominantly characterized by a homogeneous, fine silt/mud bottom. In a concerted effort to enhance both these mud flats and existing relict marine infrastructure with greater habitat variety, the Park installed over 200 enhancement structures between Piers 26 and 34 from 2021 to 2023. These structures include pile wraps, biohuts, textured concrete pile encasements, reef balls, and gabions. The Park designed the on-bottom reef balls and gabions in clusters to function as a contiguous corridor for nekton seeking shelter in Park piers and piling fields. The pile wraps, biohuts and textured pile encasements were designed to test vertical and off-bottom habitat opportunities that utilize Park pilings. Collectively, these enhancements aim to simultaneously introduce Eastern oysters (*Crassostrea virginica*), to supplement low-but-present annual wild recruitment, and to provide increased and varied benthic and demersal habitat for fishes, crustaceans, other nekton, and non-oyster epibionts. The enhancement structures are being monitored over a five-year period to assess oyster health, estuarine community utilization, water quality, and structure performance. This enhancement project was supplemented in 2022 by another installation of ~300 reef

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balls and gabions further north along Gansevoort Peninsula, as well as a ~100m cordgrass (*Spartina spp.*) salt marsh that has an associated four-year monitoring program. The Park is currently planning an additional enhancement project for an area north of 14th street that will continue to explore adapting marine infrastructure for improved habitat value.

Niels Lindquist
SANDBAR Oyster Company Inc.

Use of Oyster Catcher™ substrates as oyster-enhancing amendments for hardened structures

Authors: SANDBAR Oyster Company Inc.

Hardened structures, such as rock revetments, seawalls, and bulkheads, have long been used for shoreline erosion control and to protect built infrastructure. While certain types of hard armoring, as well as dock and pier pilings, can support the growth of oyster reef communities, their general lack of complex structure and rough surface texturing can limit the extent of oyster community development.

In recent years, structural amendments have been designed to integrate with existing hard structures, aiming to create habitats that foster more robust oyster communities. SANDBAR Oyster Company is currently developing Oyster Catcher™—cement-infused cloth hardscapes—as "cuffs" for pier and dock pilings to enhance oyster community growth in estuarine waters. These cuffs consist of Oyster Catcher™ panels shaped to encircle about half the circumference of a piling and are strapped in place at the optimal intertidal zone for oyster growth (Ridge et al. 2015, Scientific Reports 5; doi:10.1038/srep14785). The cuffs have either a flat or corrugated design. Oyster Catcher™ products are engineered to degrade over time at variable rates, allowing the developing oyster communities to naturally detach and settle on the surrounding seabed. Replacing degraded cuffs can help accelerate oyster accumulation at the base of pilings.

In initial tests, cuffs were installed on dock pilings adjacent to a major navigation channel, where they were exposed to boat wakes and large wind-generated waves. Oysters successfully recruited to the cuffs; however, community development was limited by the use of cuffs designed to degrade relatively quickly. Additionally, the complex habitat created by the cuffs served as a refuge for stone crabs (*Menippe mercenaria*), which preyed on oyster spat and accelerated cuff degradation. Future testing of Oyster Catcher™ cuffs for enhancing oyster communities on hardened structures will involve longer-lasting cuffs and designs that minimize spaces where crabs can shelter.

Adrian Sakr
University of Florida

Changing of the garden: evaluating the performance and ecosystem functionality of novel oyster garden structures

Authors: Adrian Sakr, Logan Mazor, Joseph P. Morton, Andrew Altieri

Oyster gardening, in which modular oyster reefs are suspended from docks, has become an increasingly common and accessible technique for coastal communities to enhance oyster

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populations for water filtration and biodiversity enhancement. However, little research has been done to evaluate materials and methods for oyster gardens regarding durability and ecosystem benefits, making it difficult to scale up efforts and maximize project success. We conducted a field experiment in a residential canal system of Sanibel Island, Florida where we deployed a variety of oyster garden structures to evaluate performance in oyster recruitment, durability, water filtration rate, and biodiversity. Additionally, the occurrence of Hurricane Ian during the deployment provided an opportunity to evaluate how these structures resisted severe storm events. We tested five structures: (1) a conventional design made of drilled oyster shell on steel wire; and four alternatives (2) GROW concrete discs; (3) jute fiber coated with calcium sulfoaluminate cement; (4) BESE biodegradable plastic matrix panels; and (5) BESE biodegradable plastic mesh bags filled with oyster cultch. All structures survived Hurricane Ian; however, both BESE structures ultimately disintegrated without recruiting oysters. Disc, jute, and shell wire structures demonstrated similar levels of durability, oyster recruitment and growth, and biofiltration rates. Thus, we conclude that material selection considerations may come down to the availability of materials and labor as well as the extent to which cost and biodegradability are prioritized. Our results provide important information for optimizing oyster garden performance while minimizing environmental impacts.

Rochelle Seitz

Virginia Institute of Marine Science

Retrofitting seawalls with artificial substrates promotes oyster recruitment and macrofaunal communities

Authors: Rochelle D. Seitz, Kathleen E. Knick, Alison Smith, Michael S. Seebo, Gabrielle G. Saluta

With the urbanization of coastal cities, natural shorelines have been extensively modified. Shoreline development has increased the presence of vertical seawalls, which can negatively impact benthic macrofaunal communities. Green engineering techniques can be used to enhance inhospitable seawall structures by creating micro-habitats on the structures and using materials that increase the settlement of bivalves. Oysters enhance benthic communities by creating complexity and heterogeneity, providing microhabitats for other macrofauna, which protects them from predation and physical stressors. At two field sites in the Chesapeake Bay, we retrofitted seawalls with artificial substrates with varying habitat complexity and oyster seeding density and investigated the effects on oyster densities and macrofaunal communities. The substrates included 3D printed tiles (0.25 × 0.25 m) with three levels of complexity (flat, 2.5 cm ridges, and 5 cm ridges) plus control tiles of the existing seawall, at three seeding densities (0, 36, and 56 oysters per tile). Tiles were monitored every three months for oyster survival, oyster growth, and primary cover. After a year, tiles were destructively sampled for oyster survival, oyster recruitment, and the macrofaunal assemblage. Both increased tile complexity and higher seeded oyster density increased seeded oyster survival and recruitment of oyster spat. The high-complexity, high-seeded tiles had 10x more recruits than flat, unseeded tiles and 70x more recruits than the controls of the existing seawall. Macrofaunal abundance and biomass also increased as habitat complexity of the tiles increased, providing habitat for larger organisms, such as mussels and mud crabs. Using retrofitted structures on seawalls increased habitat complexity, leading to higher seeded oyster survival, oyster recruitment, macrofaunal abundance, biomass, and species richness in coastal ecosystems.

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Jason Spires

National Oceanic and Atmospheric Administration

Nature based oyster settlement substrate investigations

Authors: Jason Spires

Oysters occupy a unique space in coastal ecosystems and communities. These bivalves provide a range of ecosystem services and direct (wild and farmed fisheries) and indirect (habitat for other fauna, recreational fisheries) economic benefits. Additionally, oysters are increasingly considered as a tool for mitigating effects of climate change and promoting coastal resilience. Current oyster restoration practitioners frequently desire to place oysters along hardened shorelines but are hampered by inefficient or costly methods. In regions of high natural recruitment, oysters settle naturally on a variety of hardened surfaces, however, in regions of low natural recruitment this type of greening gray infrastructure is more challenging. Our work investigates novel population replenishment techniques by using biodegradable oyster setting materials (basalt, coconut fiber) and mechanical behavioral manipulation (bubble curtains) to create oyster communities on hardened structures. Our objectives are to develop a cost-effective material/technique that can be used to create oyster populations on hardened surfaces. Initial oyster settlement rates are similar among tested materials, however, retention is poor on the most pliable materials. Additionally, larval behavior was not controlled by bubble curtains and modifications to the experimental design are required.

Iacopo Vona

University of Central Florida

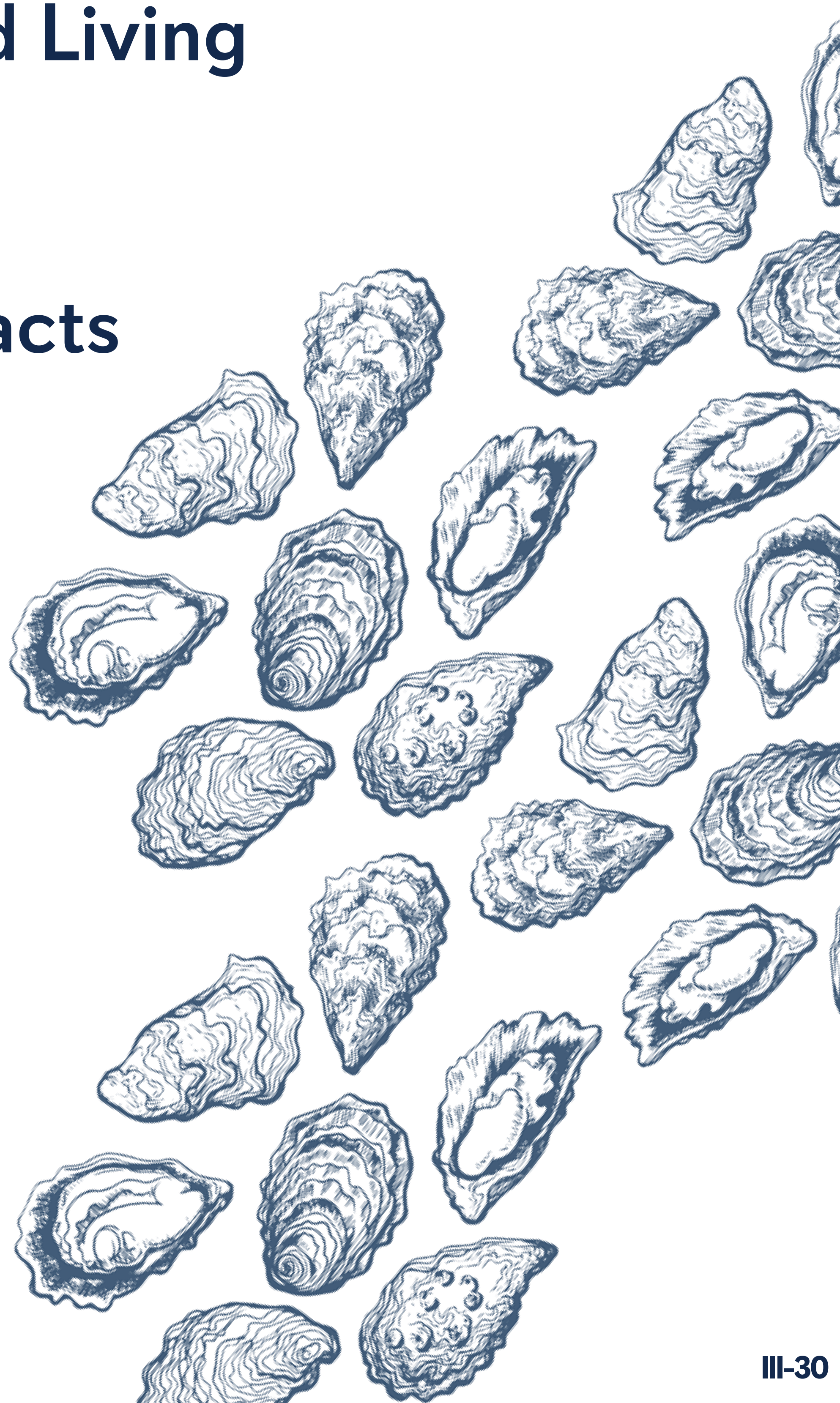
Integration on submerged breakwaters offers new adaptive shoreline protection in low-energy environments in the face of sea level rise

Authors: Iacopo Vona and William Nardin

Sea level rise (SLR) and increasing storm frequency threaten coastal environments. To naturally protect our coasts, living organisms such as oysters can be used. They provide a multitude of benefits for the surrounding environment, including coastal protection. Unlike any common gray structure used for coastal defense, such as breakwaters, oysters can grow with SLR and self-repair from damage following extreme events. In this study, we analyzed the coupling between breakwaters and oysters through a numerical model, Delft3D-SWAN, validated with field data. The research aimed to evaluate the performance of this hybrid solution under future scenarios of climate change and SLR. The study results showed that the coastline was more preserved and protected over time when oysters were included in the simulation, thanks to their capability to self-adapt over a changing climate. Incoming wave heights and sediment export from the shore were reduced compared with the use of gray breakwaters alone, resulting in a resilient and healthier coast. The coupling between oysters and breakwaters may represent a valuable and effective methodology to protect our coast over a changing climate and a rising sea, where optimal conditions for oyster survivability occur and are maintained over time.

Day 2: Building Engineered Living Shorelines

Talk Abstracts



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Alberto Canestrelli
University of Florida

Integrating physical and numerical models to assess wave dissipation and sediment accumulation at restored oyster reefs

Authors: Alberto Canestrelli, William Nardin, Rafael O. Tinoco, Jacopo Composta, Salman Fahad Alkhidhr, Kamil Czaplinski, Luca Martinelli, Savanna Barry, Anthony Priestas, Duncan Bryant

Oyster reef ecosystems are increasingly recognized for their resilience and ability to provide sustainable, nature-based alternatives to traditional "gray" infrastructure. These reefs offer critical benefits, such as mitigating shoreline erosion, promoting sediment deposition, and supporting adjacent habitats like salt marshes. Despite their potential, there is a limited understanding of the physical processes driving sediment transport around oyster reefs under varying wave and tidal conditions, reef geometries, and locations. Bridging this gap is vital for optimizing sediment retention and supporting shoreline progradation.

This study aims to quantify the mechanisms through which oyster reefs stabilize sediments. Using a combination of physical and numerical modeling, researchers are investigating the influence of tidal and wave dynamics, longshore currents, reef geometries, and distances from the coast. Initial experiments employ 1:7 scaled 3D-printed oyster reefs in a wave flume at the Ven Te Chow Hydrosystems Lab, University of Illinois Urbana-Champaign. Concurrently, numerical simulations with OpenFOAM on the HiPerGator high-performance cluster analyze wave-reef interactions under varying conditions.

Findings from these efforts will guide large-scale experiments at the Large-scale Sediment Transport Facility (LSTF) in Vicksburg, MI, conducted at a 1:2 scale. These tests will include regular and irregular waves (i.e., wave spectra in both frequency and direction), wind-driven and tidal longshore currents, and tidal variations in water level. Four distinct reef geometries will be tested under these hydrodynamic conditions. The collected data will calibrate a numerical model, enabling predictions of reef-induced sediment aggradation beyond experimental conditions and identifying optimal reef designs.

The outcomes of this research include a robust dataset on sediment dynamics, calibrated models, and actionable guidelines for oyster reef restoration. These results will inform sustainable coastal management strategies, enhancing shoreline protection and promoting the use of oyster reefs as effective, nature-based solutions for long-term resilience in coastal environments.

Carolyn Khoury
Billion Oyster Project

Living breakwaters: engineering with nature and restoring oyster reef habitat

Authors: Pippa Brashear, Carolyn Khoury

Widely considered a model for climate-adaptive nature-based infrastructure, Living Breakwaters is a $111 million project with a layered approach to risk reduction—enhancing physical, ecological, and social resilience along the South Shore of Staten Island.

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The project consists primarily of 2,400 linear feet of near-shore breakwaters—partially submerged structures built of stone and ecologically-enhanced concrete units—that break waves, reduce erosion of the beach along Staten Island's Tottenville shoreline, and provide a range of habitat spaces for oysters, fin fish and other marine species. The Living Breakwaters concept was developed by a large, multi-disciplinary team led by SCAPE as part of a winning proposal for Rebuild By Design, the design competition launched by the U.S. Department of Housing and Urban Development (HUD) after Superstorm Sandy.

The breakwaters are designed to reduce the impact of climate-intensified weather events on the low-lying coastal community of Tottenville, which experienced some of the most damaging waves in the region and tragic loss of life during Superstorm Sandy. Informed by extensive hydrodynamic modeling, the breakwaters are also designed to slow and, eventually, reverse decades of beach erosion along the Tottenville shoreline. The breakwaters are constructed with "reef ridges" and "reef streets" that provide diverse habitat space. Billion Oyster Project (BOP), a non-profit organization based in New York City whose mission is to restore functional, self-sustaining oyster reefs to New York Harbor, will introduce additional substrate seeded with juvenile oysters to the breakwaters beginning in 2025.

Beyond the physical breakwaters and habitat restoration, the project also aims to build social resilience in Tottenville through educational programs and the implementation of an open-access curriculum for local schools for local schools in partnership with BOP and local community committees and action groups.

Mary-Margaret McKinney
Native Shorelines, A Davey company

Quantitative evaluation of an alternative oyster-centric living shoreline system

Authors: Mary-Margaret McKinney, Worth Creech, Whitney Thompson, Chris Paul, John Darnall, and Bret Webb.

Coastal erosion and shoreline retreat, resulting from both from extreme weather events and sea level rise, pose great challenges to coastal management across U.S. coastal areas. To address this challenge, many State, Local, and Federal stakeholders have deployed living shorelines as a cost-effective method of reducing shoreline retreat rates and providing ecological benefits such as marine habitat, fish spawning areas, and shellfish and oyster habitat.

As such, the deployment of these structures has gained increasing popularity, and many new technologies and variations of living shorelines have been developed in recent years. However, coastal engineering metrics such as wave attenuation, structural stability, and changes to current velocities are rarely validated prior to deployment. Native Shorelines' QuickReef® technology is one of the new types of living shorelines and has been deployed along over 5 miles of shorelines in North Carolina and Virginia. Qualitative observations from deployment sites appeared to show significant oyster spat recruitment and a reduction in shoreline retreat rates. In early 2024, QuickReef® designs were evaluated via physical and numerical modeling to determine the effectiveness and stability of the structures.

A desktop study evaluating field conditions at representative sites was performed to inform critical

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design forcings for flume study purposes, which was then conducted at the University of South Alabama Center for Applied Coastal Engineering and Science. Wave attenuation, stability, and current velocities were measured during physical modeling. Results from the wave flume study were utilized to calibrate FLOW-3D models. This presentation will discuss findings from the physical and numerical modeling studies as well as demonstrate the overall effectiveness of living shoreline designs using quantitative methods.

Kate Orff
SCAPE

Living Breakwaters

Designed by SCAPE, COWI, Arcadis, SeArc Ecological Marine Consulting, WSP, MFS Engineers, Prudent Engineering. Engagement by Billion Oyster Project. Construction by Weeks Marine, Ramboll, Baird. Environmental Review & Permitting by AKRF.

Kate's talk will focus on the trajectory of oyster restoration in the New York Harbor, and how Living Breakwaters evolved into a funded and implemented project in the post-Super storm Sandy recovery process. She will show how the Living Breakwaters project developed, including its engineering and approvals process, and will feature the work of SCAPE's many collaborators, including the Billion Oyster Project.

Tyler Oretego
Natrx

Integrating engineered structures and oyster habitat for resilient shorelines

Authors: Drew Keeley, Tyler Ortego

The integration of oyster and marine habitat with engineered structures offers a transformative approach to enhancing shoreline resilience and ecological health. Traditional materials and construction methods often lack adequate capability to balance coastal protection with optimal habitat formation. New technologies are emerging that provide new capabilities for coastal resilience and habitat restoration practitioners.

Natrx has pioneered the Dry Forming™ advanced manufacturing technique, which enables development of tailored, habitat-positive structures that address site-specific needs while promoting oyster colonization and ecosystem restoration. Natrx reef structures feature customizable void spaces and biomimetic surfaces to optimize conditions for oyster recruitment, habitat formation, and ecological uplift. These structures support shoreline stabilization and also deliver ecosystem services such as water filtration and biodiversity enhancement. By leveraging digital tools, advanced manufacturing, and material science innovations, Natrx can efficiently produce scalable, site-specific solutions that enhance the longevity of coastal infrastructure and integrate seamlessly with existing gray and hybrid systems.

Case Study: Hog Island, VA - A nature-based wetland protection and habitat restoration solution using Natrx ExoForms™ along Hog Island in Gloucester County, Virginia. The goals of this project was to

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protect the residential and commercial properties along Monday Creek and the York River, reduce erosion and sedimentation into the Chesapeake Bay, and a focus on enhancing maritime habitat for shorebirds, oysters, and other marine life. Designed customized interlocking ExoForms for highwave energy areas exposed to Mobjack Bay and low crested oyster reef ExoForms for low energy areas. Placed 972 linear feet of large stacked units and 122 linear feet of low crested oyster reefs. Added available surface area for 14 million oysters that will filter water and provide foundational habitat and prevent 40,000 tons of eroding sediment from entering the bay system and contributing to suspended sediment and nutrient loading.

Amanda Poskaitis & Camille Calure
Underwood & Associates

Oyster recruitment on dynamic living shorelines

Authors: Underwood & Associates, Maryland Coastal Bays Program

Underwood & Associates, a design/build stream and living shoreline contractor, developed the dynamic living shoreline, which can be adapted to various site conditions to create critical shallow water wildlife habitat and solve erosion issues for communities and property owners. Underwood uses all native stone material in our vegetated headland designs and we have been working to incorporate oysters into our living shorelines to achieve even greater habitat co-benefits on our project sites. An example of oysters thriving on one of our projects is at the Assateague State Park Living Shoreline – a partnership between Assateague State Park, Maryland Coastal Bays Program, and Underwood & Associates.

Oyster surveys have been conducted at the Assateague Living Shoreline site since 2021 by the Maryland Coastal Bays Program. The surveys started after noticing an abundance of oysters along the vegetated headlands. Years of surveying has shown that although this site experiences oyster recruitment, the oysters tend to not live past 1-2 years due to disease or other environmental factors. This is typical in the Maryland Coastal Bays watershed, which has not had a self-sustaining wild oyster population in over 50 years. In addition to the research conducted on oysters at the Assateague Living Shoreline, we are working on many other living shoreline projects throughout the Chesapeake and Coastal Bays that have potential for incorporation of oysters. We will be presenting on our work and exploring how to incorporate oysters into living shoreline designs effectively. We will share multiple projects, research, and lessons learned.

Adrian Sakr
University of Florida, Department of Environmental Engineering Sciences

Living in a material world: support for the use of natural and alternative materials in coastal restoration and living shorelines

Authors: Adrian Sakr, Andrew Altieri

The size and expense of coastal restoration efforts are increasing exponentially to mitigate anthropogenic environmental impacts and achieve international conservation goals. As part of these efforts, a variety of conventional materials including plastic, metal, and concrete are used in

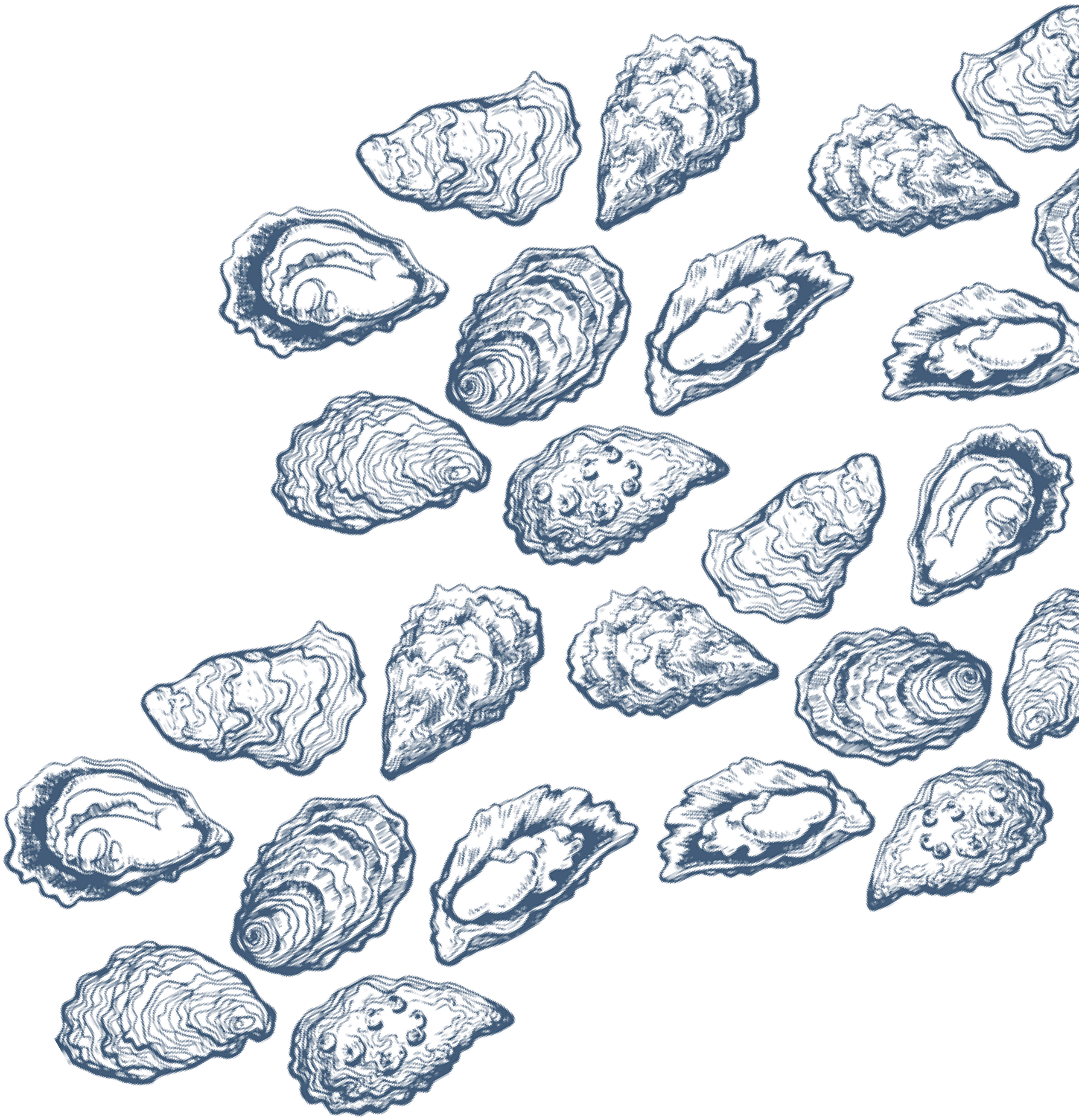
Appendix C: Day 2 Talk Abstracts

breakwater, settling substrate, vegetation stabilization, and sediment retention structures because of their availability, inexpensive purchase price, and predictable properties. However, questions regarding sustainability arise given the adverse environmental impacts of the life cycle processes for each material.

Life cycle impacts from production, transportation, installation, and degradation should be key considerations in material selection, with criteria that allow decision makers an opportunity to evaluate less impactful alternative materials. Natural and reduced-impact alternative materials include natural elements such as plant fibers and rock as well as reduced-impact materials such as bio-based and biodegradable plastics. These items may have comparable availability and functionality and exhibit reduced carbon, chemical, and particulate emission impacts. However, they are often not selected for full-scale restoration applications due to uncertainties regarding their financial cost and ability to replace conventional materials. Here, we compare conventional and reduced-impact alternative materials for use in coastal restoration applications. The function, engineering performance, and life cycle environmental impacts are reported for each material followed by a presentation of case studies that illustrate the value of appropriate material selection. We then compare the impacts of material sourcing and product lifespan to develop a material selection framework enhancing the selection process of reduced-impact alternatives.

This study reveals a need for more detailed and standardized life cycle information about the materials used in the coastal environment. The proposed framework allows more emphasis on material life-cycle implications in the design process, which could lead to enhanced use of alternative over conventional materials and improved project value and outcomes.

Poster Abstracts



Appendix D: Poster Abstracts

Savanna Barry
University of Florida

Performance assessment of living shoreline retrofits on Florida's Gulf of Mexico coast

Authors: Savanna C. Barry, Elix M. Hernandez, and Mark W. Clark. University of Florida, Florida Sea Grant.

A community-driven effort in Cedar Key, Florida, USA, resulted in the construction of three living shoreline retrofits intended to bolster failing coastal infrastructure and restore habitat functions in Daughtry Bayou. A multi-year monitoring program tracked changes in elevation and vegetation communities across the entire shoreline profile from lower-intertidal to upland/transitional zones and measured wave attenuation during typical and extreme (hurricane) conditions. Overall, these living shoreline retrofits served to soften more than 30% of the bayou's shoreline, dramatically reducing the extent of armored shoreline in direct contact with tidal influence. The extent of vegetated habitat area has increased at all three sites, despite sediment export from higher elevation zones driven largely by repeated impacts from hurricanes and tropical storms. These living shorelines reduced wave energy by 33 to 79% in typical conditions and by up to 28% in hurricane conditions, consistently outperforming armored shorelines, even during an extreme event (Hurricane Idalia). The living shoreline retrofit projects assessed here have persisted through and shown signs of recovery after multiple tropical storms and hurricanes, while providing important energy reduction services. Thus, living shoreline retrofits continue to be a cost-effective shoreline management strategy in the short term for this area. However, our analyses suggest that persistence of these shorelines could be threatened by the combination of sea-level rise (by 2040), upland armoring, and an increasing risk of more intense tropical systems. Therefore, future interventions should more carefully consider these threats in conjunction with habitat enhancement goals.

George Birch
Oyster Heaven

The Mother Reef: A scalable clay based biodegradable substrate for oysters

Authors: George Birch, Ronald Lewrissa, Jochem van der Beek and Natacha Juste-Poinapen

The "Mother Reef," developed and patented by Oyster Heaven, is a step change in the scalability, predictability and permissibility for building oyster focused engineered living shorelines. The low fired clay structures are tunably biodegradable (depending on firing temperatures), they are an effective oyster settlement substrate and can be produced at generic brick manufacturers around the world. An average factory can be brought online in a matter of months and can produce enough substrate for 100 acres of reef per day for the same price as household bricks.

Constructed from locally sourced clay, Mother Reefs are designed to facilitate oyster settlement, growth, nutrient flowthrough, reproduction, and protection from predators. Their trapezoidal shape and sine wave patterned ribs maximize settlement surface area while minimizing contact area, reducing spat loss during transport.

The Mother Reef's innovative design and use of natural materials are key to its scalability and permissibility. As a biodegradable structure, it seamlessly integrates into the marine environment,

Appendix D: Poster Abstracts

generating natural reef development without long-term ecological disruption. The scaffolding eventually melts away into the background sediment, chemically and physically indistinguishable from the sediment already there. This approach aligns with current policy trends that favor nature-based solutions for coastal protection, making it more likely to secure necessary permits for large-scale deployment.

The Mother Reef's adaptability to local conditions further enhances its scalability and permissibility. Its composition and structural arrangement can be tailored to optimize specific ecosystem services, such as biodiversity enhancement or coastal erosion mitigation, based on the needs of the local environment.

By providing a scalable, permissible, and biodegradable solution for oyster reef restoration, Oyster Heaven will play a pivotal role in building resilient and sustainable living shorelines. Its innovative design and alignment with policy objectives position it as a leading technology for large-scale coastal protection and marine habitat regeneration.

George Thatos

Coastal Technologies

Coastal Technologies Corp's Oyster Reef Building Technology

Authors: George Thatos, and Raphael de Perlinghi

Coastal Technologies Corp (CTC) introduces a revolutionary patented solution to address the global need for oyster reef restoration—a critical factor in coastal resilience, pollution remediation, and ecosystem recovery. Standard reef-building methods are slow, labor-intensive, and suffer from failure rates as high as 85%. CTC's innovative, nature-inspired technology overcomes these limitations, enabling near-instant reef creation while preserving coastal ecosystems.

Our Oyster Reef Building system uses stainless steel corkscrew armatures installed into sediments using simple tools. These armatures support stone plates, providing elevated, predator-resistant habitats for oysters. By raising reefs off the seafloor, our system avoids issues like siltation, hypoxia, and subsidence—common causes of failure in traditional methods. The vertical structure enhances resilience to climate change and allows for adjustments to rising sea levels. Easy installation, minimal disruption to coastal mudflats, and high surface area make this system efficient, scalable, and adaptable.

CTC's technology serves vulnerable coastal communities worldwide, particularly those threatened by storm surges, erosion, and sea-level rise. Oysters act as "ecosystem engineers," filtering water, preventing harmful algae blooms, and supporting diverse marine life. For communities like the Biloxi-Chitimacha-Choctaw Indians in Louisiana, our system offers food security, cultural preservation, and coastal protection.

Field-tested prototypes have demonstrated the technology's effectiveness, with further validation planned through partnerships with academic institutions, NGOs, and coastal restoration groups. CTC's team combines technical expertise with a passion for environmental and social justice, ensuring community involvement in every stage of implementation.

Appendix D: Poster Abstracts

By dramatically increasing the capacity to build resilient oyster reefs at scale, CTC provides a practical, cost-effective tool to protect coastal populations, restore ecosystems, and mitigate climate impacts. With support from SHORES, we aim to advance this technology to market, navigate regulatory pathways, and foster partnerships that bring life-saving solutions to the communities that need them most.

Niels Lindquist
SANDBAR Oyster Company Inc.

A decade of development, refinement and scaling of Oyster Catcher™ hardscapes for oyster habitat creation, living shorelines and oyster culturing

Authors: Niels Lindquist and David Cessna

At the 18th International Conference on Shellfish Restoration in Charleston, SC in 2016, Niels Lindquist and the late David Cessna (co-inventors), made the first public presentation on an innovative, composite hardscape for oyster habitat creation/restoration and oyster culturing. Our degradable hardscape, trade named Oyster Catcher™, is a composite of plant-fiber cloths infused with cements (any and all mineral-based binders/hardeners claimed) made by soaking and manipulating the cloth in cement slurries to work the cement into the threads of the cloth.

Prior to cement hardening, we form the cement-infused cloth pieces into different modular shapes, some of which we use to build robust reef frameworks and others to trap sediments and thereby promote salt marsh development. The surface of Oyster Catcher™ is highly textured and exceptionally attractive to oyster larvae and protective of juvenile oysters. In addition to reef building, a 3-dimensional, pretzel-shaped Oyster Catcher™ derivative is proving to offer a facile path for capturing and manipulating wild and hatchery settled spat for culturing for food and oyster restoration products. In addition to Sandbar Oyster Company's direct development efforts with Oyster Catcher™, independent, third-party testing is showing Oyster Catcher™ to be an exceptionally valuable technology in the living shoreline/shoreline protection toolbox.

Oyster Catcher™ is now being used in multiple, large-scale living shoreline and oyster habitat creation projects in North Carolina, Virginia, Georgia and California. Our cement-infused hardscape technology is owned by UNC Chapel Hill and now patented in Australia, Canada and New Zealand and is under examination in the US and EU. Sandbar Oyster Company Inc. has an exclusive license from UNC to commercialize this technology. This presentation offers an overview of our work developing and testing Oyster Catcher™ and views of projects showing the range of applications of Oyster Catcher™ products.

Appendix D: Poster Abstracts

Nicholas Muzia
Sea & Shoreline, LLC.

The Oyster Ark: A new role for oyster farming in ecosystem restoration

Authors: Nicolette Mariano, Nicholas Muzia P.E., Nicholas Bourdon

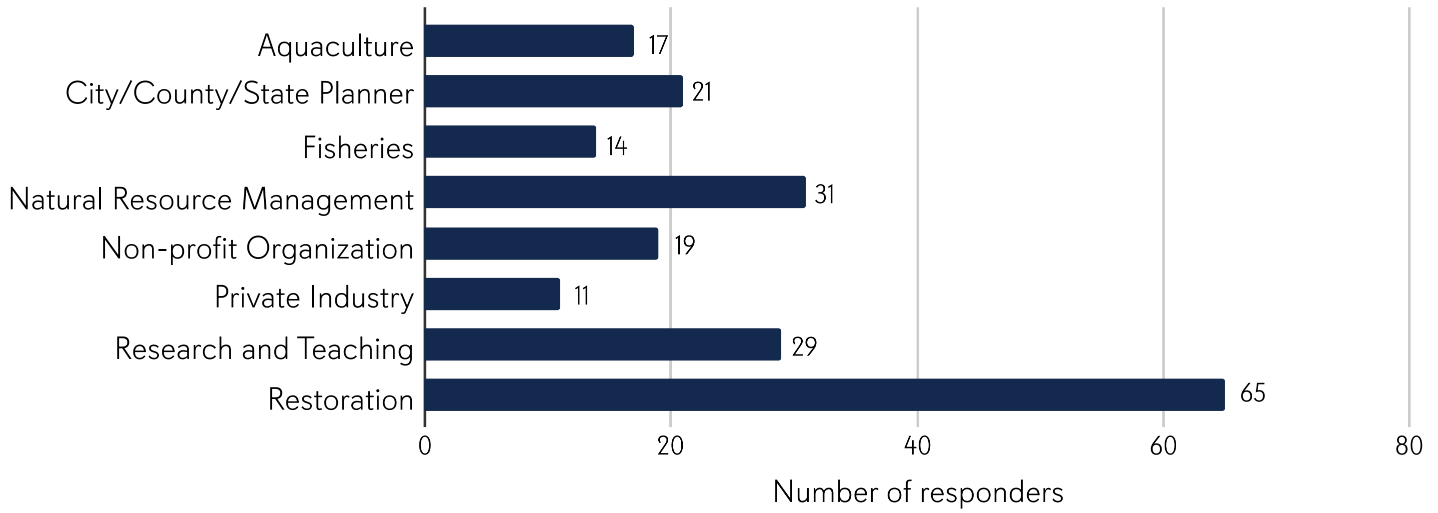
Oyster aquaculture offers a unique opportunity to enhance environmental restoration while supporting local economies. This presentation highlights a pilot project conducted in Florida's Indian River Lagoon by Treasure Coast Shellfish, which aimed to integrate oyster farming with ecosystem restoration efforts. The project evaluated a novel technique, the "Oyster Ark," designed to capture microorganisms from healthy sites and transplant them to less productive or restoration sites. By introducing live oysters and their associated microorganism communities, the Oyster Ark approach appears to accelerate the growth and success of restoration sites.

In addition to its restoration potential, the project documented the broader biological life supported by responsible oyster aquaculture, showcasing its role as an environmental asset. The initiative also explored the potential for oyster farmers to generate supplemental revenue through restoration activities, creating a symbiotic relationship between sustainable aquaculture and ecosystem health.

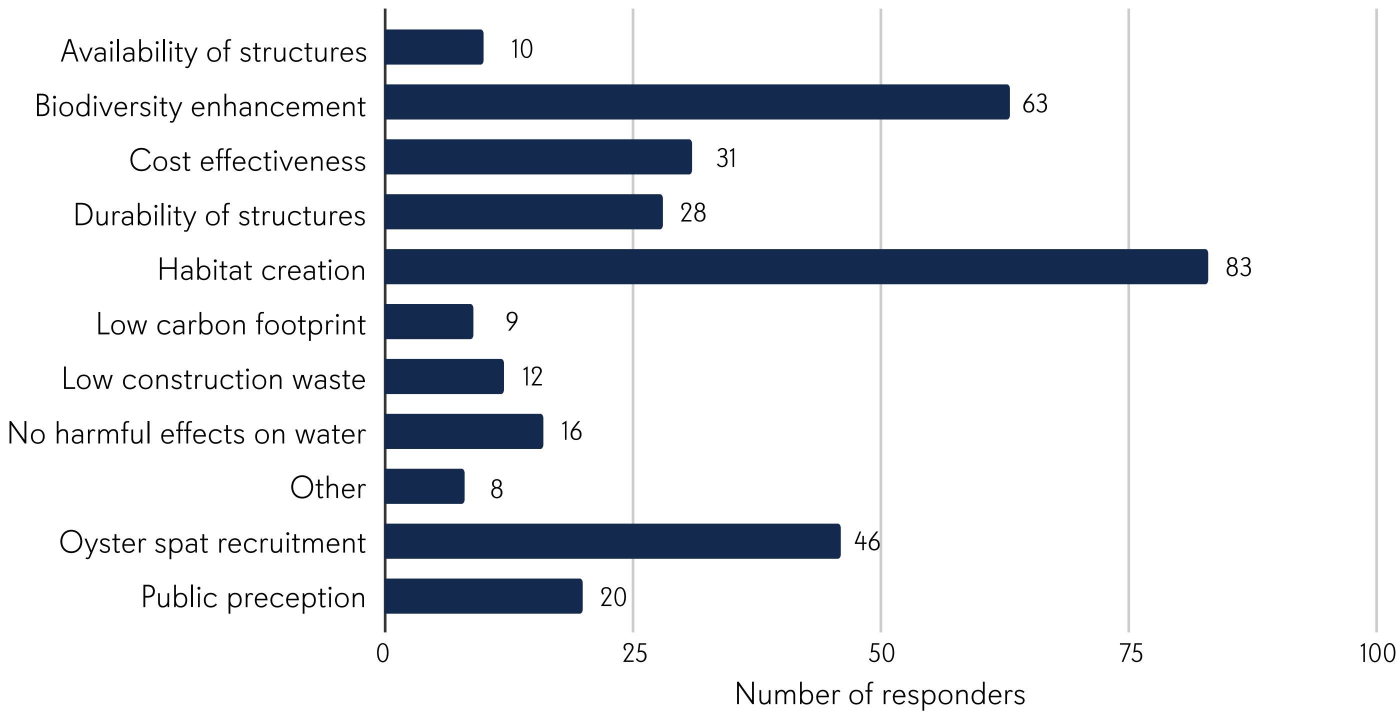
This presentation will discuss the outcomes of the pilot project, including its ecological and economic impacts, and seek feedback on how this approach could be refined and scaled to support both environmental restoration and the viability of local shellfish farms.

Appendix E: Poll Results Day 1

I work in the following sector(s):



What benefits of retrofitting existing infrastructure for oysters is most important to you? (Choose 3)

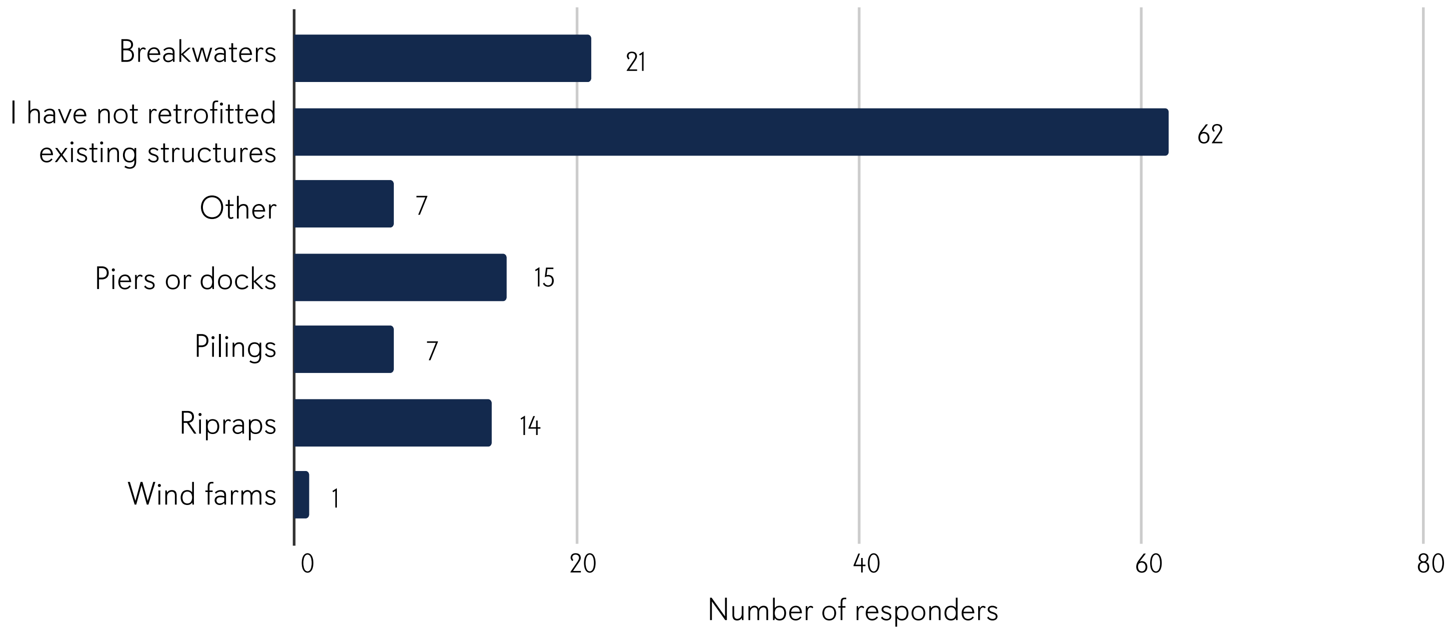


In the Other category, the following were listed:

- No negative impacts (structural, negative species composition changes, etc.)
- Boat wake attenuation
- Potential wave dissipation
- Positive benefits for waterways and water quality
- Water filtration
- Coastal resilience
- Wild harvest
- Erosion control

Appendix E: Poll Results Day 1

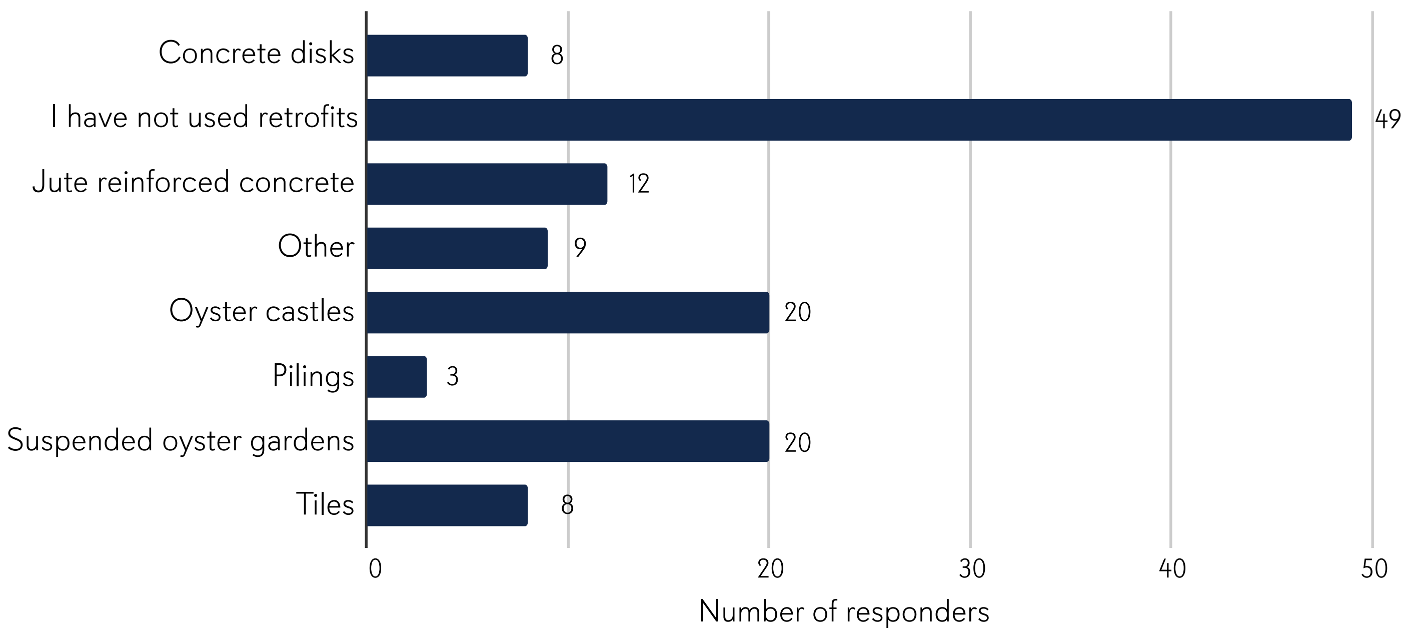
What types of structures have you retrofitted with oysters?



In the Other category, the following were listed:

- Bulkheads
- Levees
- Earthen berms
- Living shorelines
- Seawalls
- Marine Pontoons
- Estuaries around the world

What types of retrofits for oysters have you used?

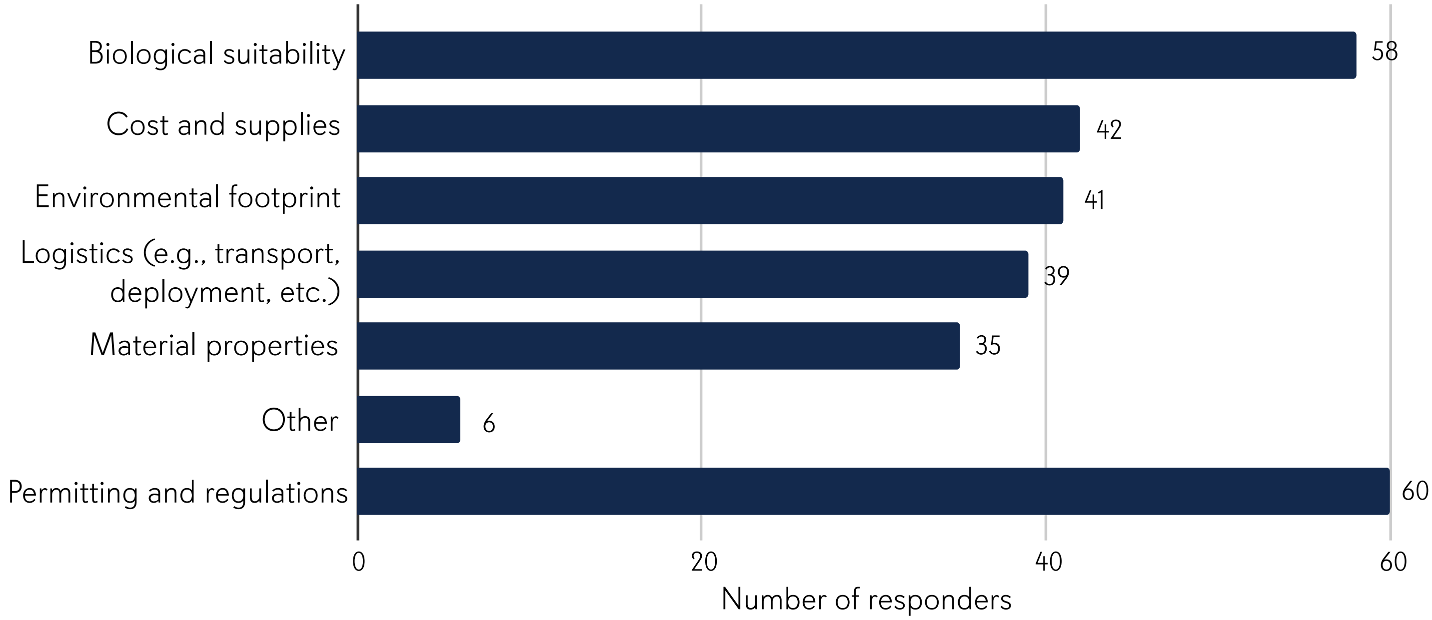


Appendix E: Poll Results Day 1

In the Other category, the following were listed:

- Reef balls
- Wrap, net, overlaid coating
- Natrx ExoForms
- Bioconcrete made from waste shells and natural binders that were 3D printed/cast into artificial reefs
- Plastic mesh bags
- BESE biodegradable plastic
- Drilled shell on steel wire
- Oyster shell bags
- Econcrete

What aspects of retrofitting existing infrastructure for oysters require greater investigation?



In the Other category, the following were listed:

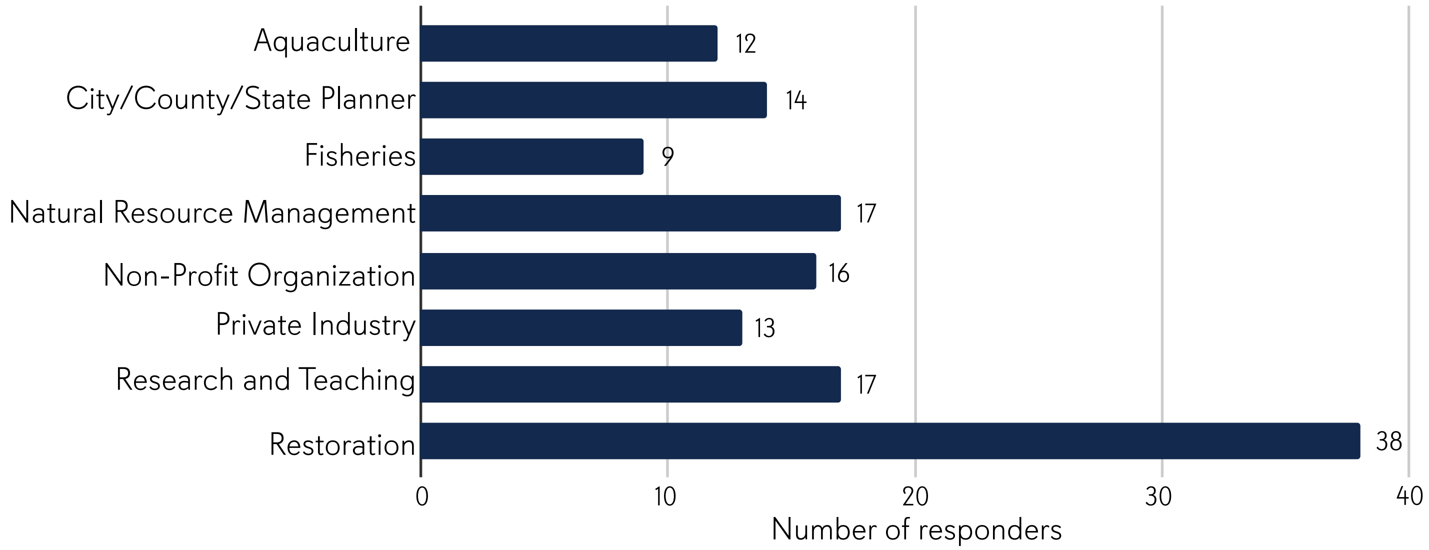
- Risk assessment of greener structures compared to traditional infrastructure
- Biogeochemical interfaces/gradients
- Scalability
- Biologically significant impact
- Resilience and adaptation to a changing marine environment

Are there other Maryland-specific issues that need addressing?

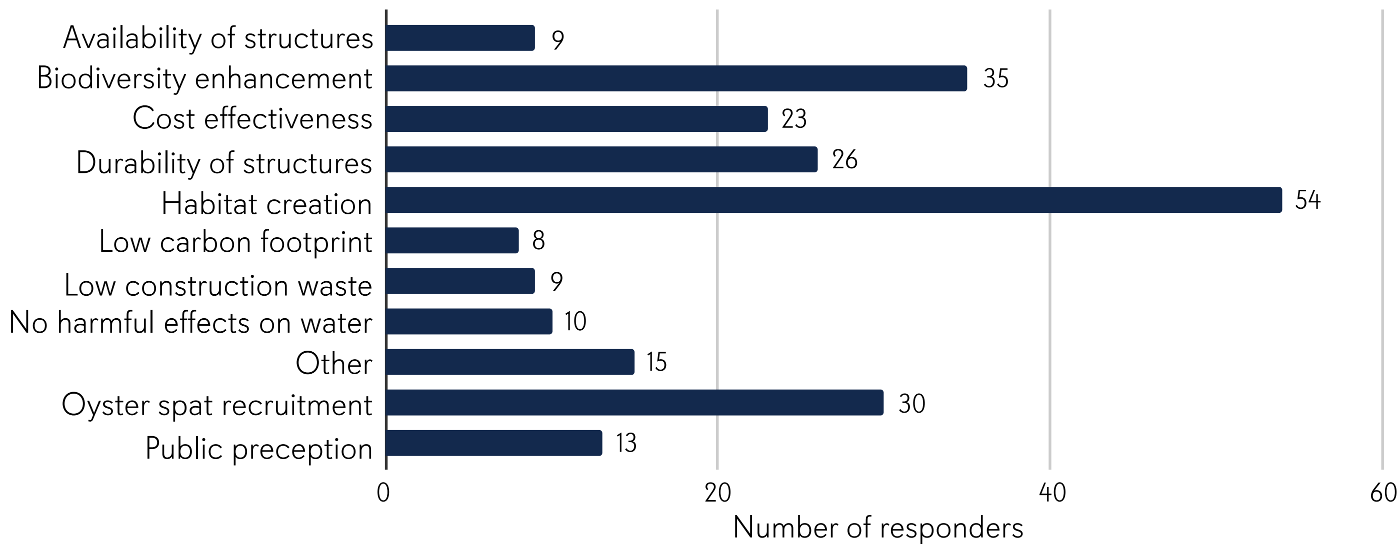
- Funding and other support for research (deployment procedures, costs, and integration with shoreline protection)
- MDE permitting
- Increasing oyster harvesting regulations RE methods of collecting and number of sanctuaries
- Making living shorelines and other nature based features more cost-effective and attractive to the general public
- Public engagement and support and being honest and communicative about pros/cons
- Shallow water habitat management in the context of changing baselines
- Increase shell collection efforts and using this abundant resource for restoration projects

Appendix F: Poll Results Day 2

I work in the following sector(s):



What benefits of creating living shorelines with oysters are most important to you? (Choose 3)

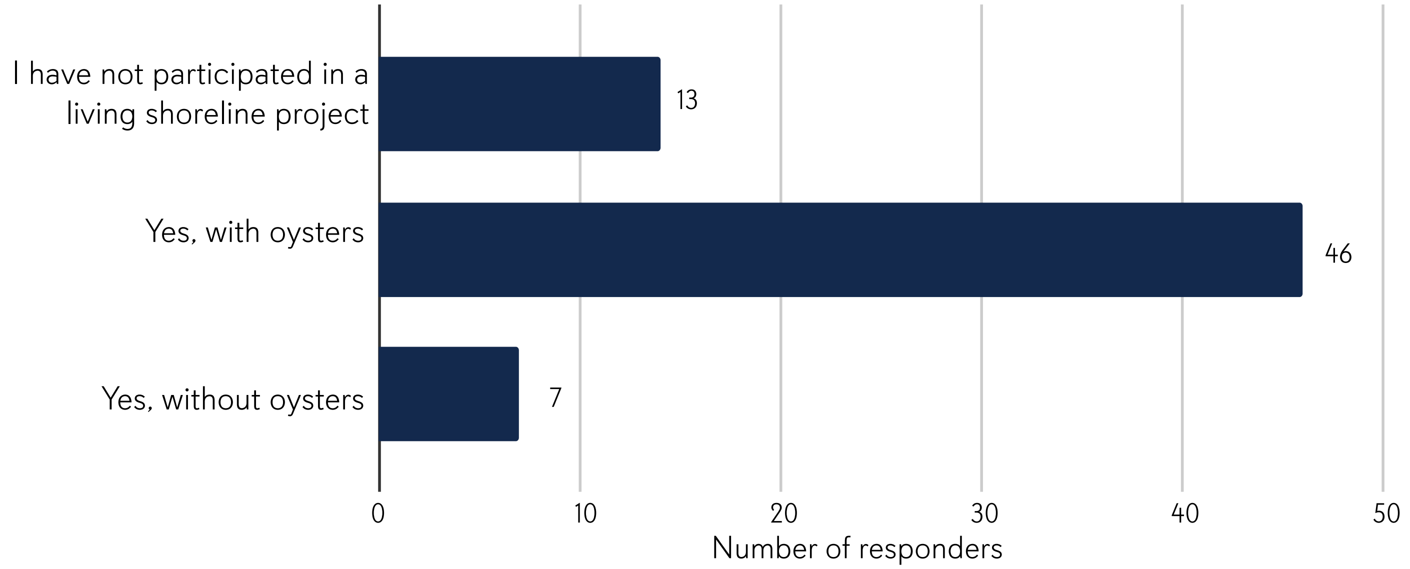


In the Other category, the following were listed:

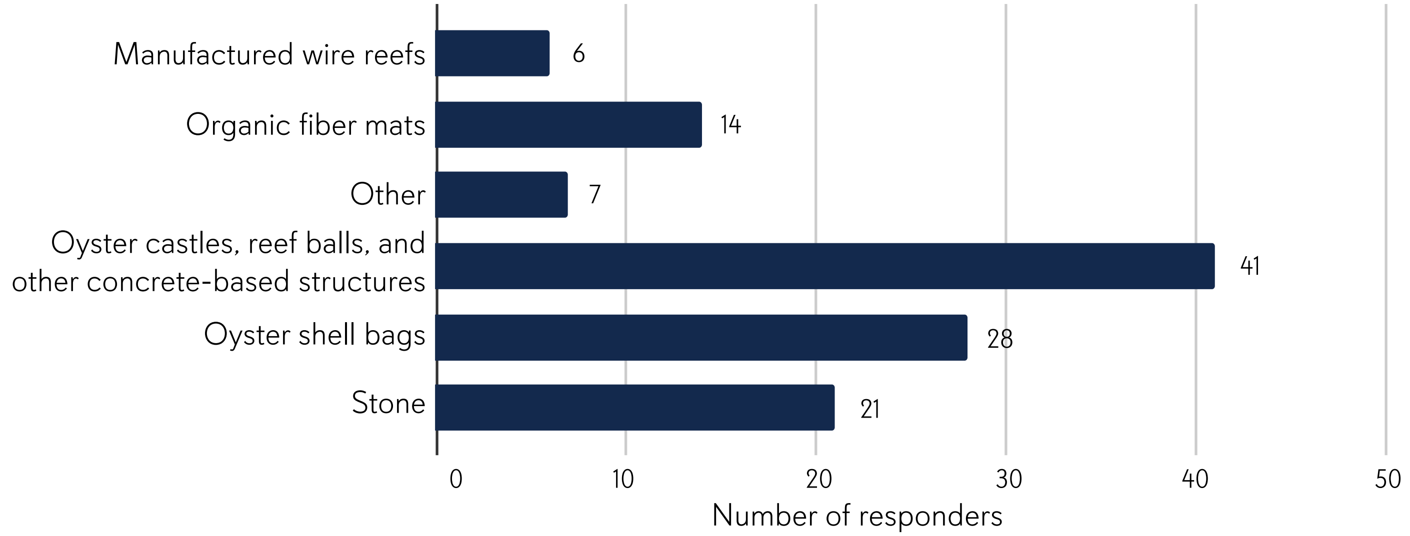
- Improved wave attenuation
- Habitat continuity
- Climate and coastal resilience
- Sediment capture
- Ensuring that structures allow for coastal access by other wildlife
- Shoreline stabilization and protection
- Facilitation of salt marsh communities
- Ecosystem services
- Increased living shorelines with oysters results in decreased riprap and bulkheads
- Adaptive solution

Appendix F: Poll Results Day 2

Have you ever participated in a living shoreline project, and if so, have you included oysters in the living shoreline?



If you have participated in a living shoreline project with oysters, what types of oyster focused substrates have you used?

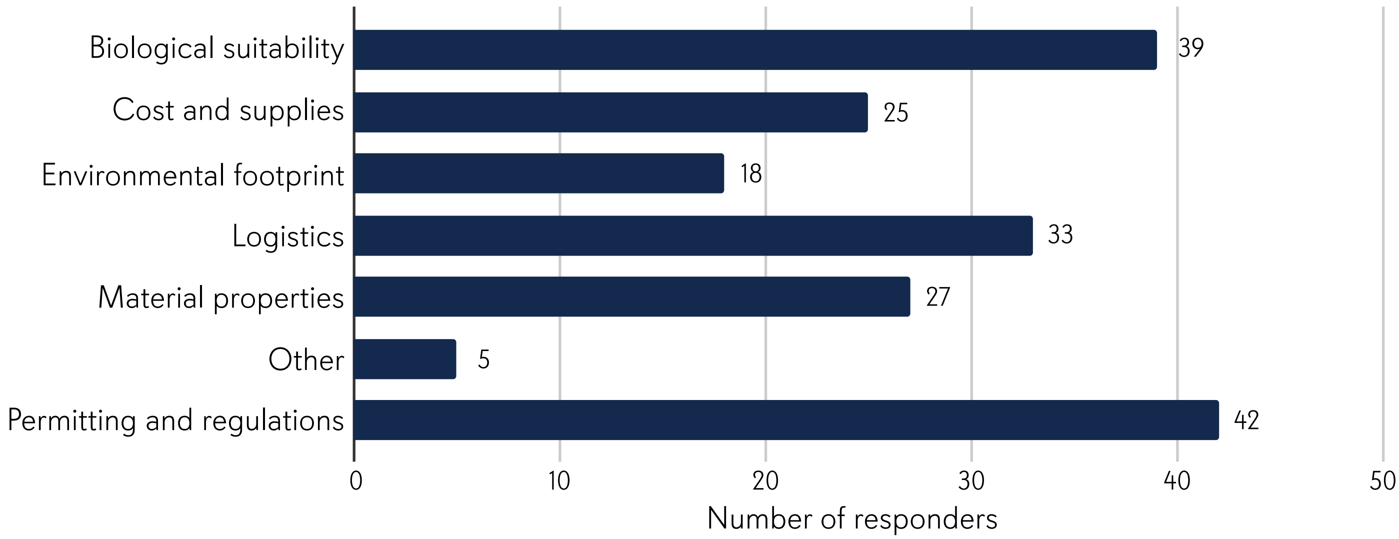


In the Other category, the following were listed:

- Oyster gardens
- Loose oyster shells
- Oyster catcher substrate from Sandbar Oyster Company
- QuickReef®
- Wave Attenuation Devices (WADs)
- Previous oyster shell habitats
- Bamboo (Non-native, cut, and coated with concrete)
- Oyster ‘volcanoes’ made of jute and cement

Appendix F: Poll Results Day 2

What aspects of retrofitting existing infrastructure for oysters require greater investigation?



In the Other category, the following were listed:

- Resilience of the shoreline over time
- Habitat suitability studies
- Potential effect of larval transport on retrofit reefs in close proximity to the bottom/column leases
- The economic impacts on aquaculture
- The engineering analysis and design process
- Ecological trajectories and limitations
- True ecological uplift

Are there other Maryland-specific issues that need addressing?

- Hydrodynamics of oyster larvae
- Carbon sequestration
- Management of shallow water habitat acknowledging changing baseline for shallow water zones
- The mandated stone to vegetation ratio pushes project footprint channelward, impacting aquatic resources like SAV
- Riparian property owners should be expected to grade banks and align structures landward to minimize impacts to aquatic environments
- MDE and USACOE permitting
- Designed reef crest elevation to begin reefs
- Economic analysis to comprehensively and holistically analyze the cost/benefits including opportunity costs, without diminishing the benefits of oyster reef structures
- Addressing the native oyster species survival rates in cold/freezing temperatures and their struggle in low salinity waters
- Assessing the dangers and benefits of introducing species from other places that may overtake native species but can result in improvement of water quality

SHORES Appendix A: Schedule of Events and Logistics

Wednesday, Feb 26: Retrofitting Existing Infrastructure

10:00 Introduction

10:15 **Rochelle D. Seitz**, Virginia Institute of Marine Science, Batten School of Coastal and Marine Sciences

10:30 **Iacopo Vona**, University of Central Florida, Department of Civil, Environmental, and Construction Engineering

10:45 **Anthony Dvarskas**, Ørsted

11:00 **Jason Spires**, NOAA Cooperative Oxford Laboratory

11:15 **Niels Lindquist**, SANDBAR Oyster Company Inc.

11:30 **Siddhartha Hayes**, Hudson River Park Trust

11:45 **Adrian Sakr**, University of Florida

12:00 Poster session & Chat n' Chew breakouts

01:00 Plenary discussion

02:00 Adjourn

Thursday, Feb 27: Building Engineered Living Shorelines

10:00 Introduction

10:15 **Kate Orff**, SCAPE

10:30 **Carolyn Khoury**, Billion Oyster Project

10:45 **Tyler Ortego**, Natrx

11:00 **Amanda Poskaitis**, Underwood & Associates

11:15 **Mary-Margaret McKinney**, Native Shorelines, a Davey company

11:30 **Adrian Sakr**, University of Florida

11:45 **Alberto Canestrelli**, University of Florida

12:00 Poster session & Chat n' Chew breakouts

01:00 Plenary discussion

02:00 Adjourn

SHORES Appendix A: Schedule of Events and Logistics

Poster Session Presenters on both symposium days:

Savanna Barry, University of Florida

George Birch, Oyster Heaven (Day 1 only)

George Thatos, Coastal Technologies

Niels Lindquist, SANDBAR Oyster Company

Nicholas Muzia, Sea & Shoreline

Symposium Logistics

To join the symposium:
https://tinyurl.com/SHORES-Virtual-Symposium

To ask the speakers a question: Type your question in the Zoom chat. Only the speakers and moderators will be able to see your questions.

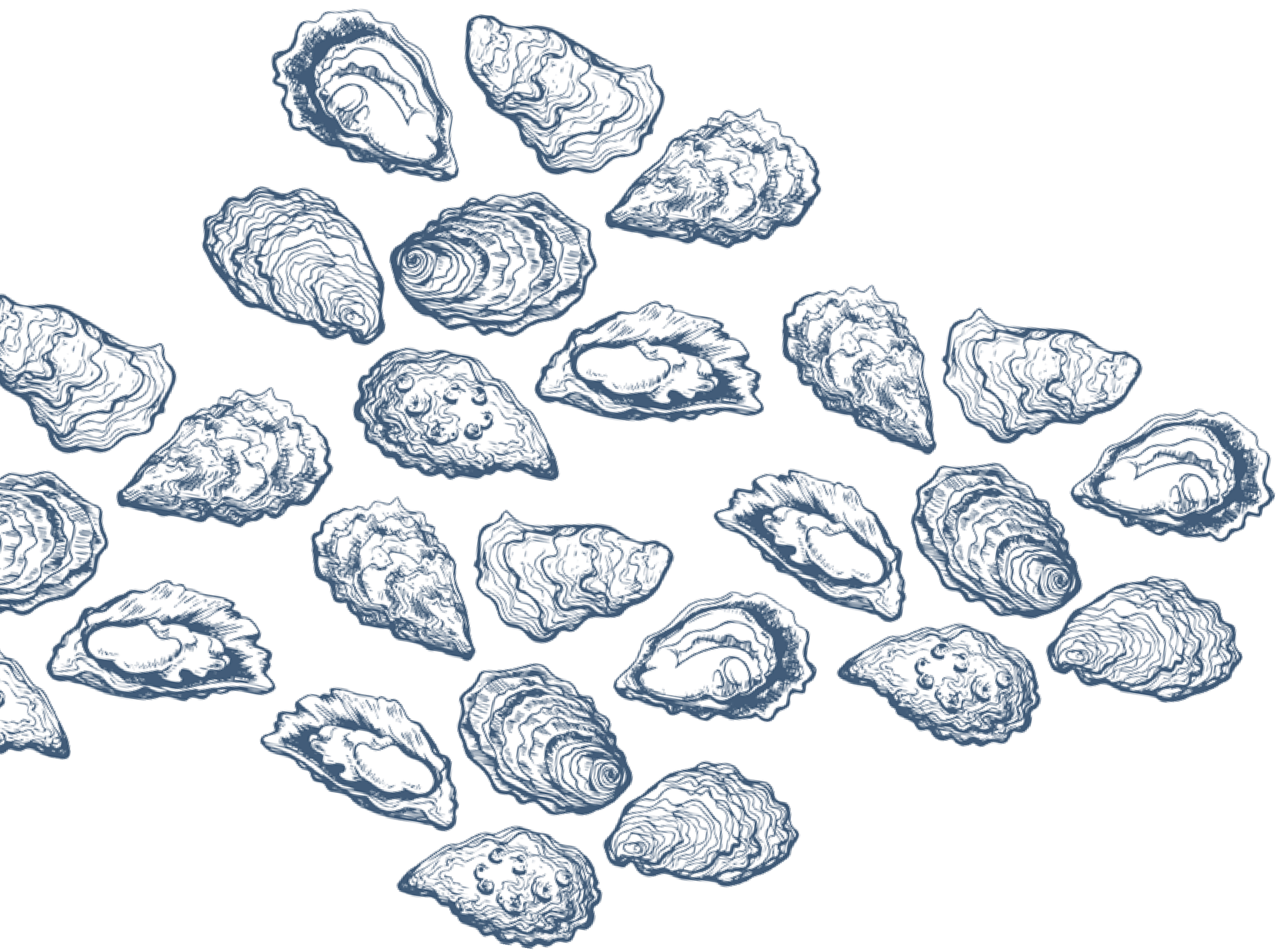
To join the Poster session & Chat n' Chew:
https://tinyurl.com/Posters-and-Chat-n-Chew

To ask a question or make a comment during plenary: Type your question or comment in the Zoom chat. The moderators will be able to see your questions and comments and will relay them to the panelists.

To receive a copy of the symposium report: All registrants will be sent the report this spring.

Day 1: Retrofitting Existing Infrastructure

Talk Abstracts



Appendix B: Day 1 Talk Abstracts

Anthony Dvarskas
Ørsted

Integrating oysters into offshore wind lease areas: droppable oyster structure deployment at Borssele 1&2

Authors: Anthony Dvarskas, Karin Bilo, Tommy Kristoffersen

In 2021, Ørsted announced its ambition to have a net-positive impact on biodiversity for all renewable energy projects commissioned by 2030 or later. As a part of meeting this ambition, Ørsted is investigating the potential for nature-inclusive design at its offshore lease areas, including the addition of structured habitat and hard surfaces to benefit critical keystone species like cod and oysters. European flat oysters are a particular concern in the North Sea, given the substantial decline in their numbers and the absence of these reef-builders from areas where they had historically been present.

To address this, Ørsted recently collaborated with Van Oord to install droppable oyster structures at the scour protection for Ørsted's Borssele 1&2 wind lease area in the North Sea. Adult oysters were attached to these structures and, if successful, will generate larvae to colonize the areas adjacent to the installation, providing benefits to biodiversity and local water quality. Video footage will be collected at multiple time points following installation to monitor the structures. These structures are innovative for their lightweight design and their potential to be integrated into scour protection during routine maintenance activities. Some of the droppable structures were also composed of reused materials. This presentation will describe the characteristics of the droppable oyster structures, the installation approach, and the planned monitoring activities to evaluate the success of the deployment.

Siddhartha Hayes
Hudson River Park Trust

Enhancing infrastructure and nearshore habitat in an urban estuary, Hudson River Park, NYC

Authors: Siddhartha Hayes, Carrie Roble, Michaela Mincone

Located on Manhattan's west side between Chambers and W59th Street, Hudson River Park's 400-acre Estuarine Sanctuary waters are predominantly characterized by a homogeneous, fine silt/mud bottom. In a concerted effort to enhance both these mud flats and existing relict marine infrastructure with greater habitat variety, the Park installed over 200 enhancement structures between Piers 26 and 34 from 2021 to 2023. These structures include pile wraps, biohuts, textured concrete pile encasements, reef balls, and gabions. The Park designed the on-bottom reef balls and gabions in clusters to function as a contiguous corridor for nekton seeking shelter in Park piers and piling fields. The pile wraps, biohuts and textured pile encasements were designed to test vertical and off-bottom habitat opportunities that utilize Park pilings. Collectively, these enhancements aim to simultaneously introduce Eastern oysters (*Crassostrea virginica*), to supplement low-but-present annual wild recruitment, and to provide increased and varied benthic and demersal habitat for fishes, crustaceans, other nekton, and non-oyster epibionts. The enhancement structures are being monitored over a five-year period to assess oyster health, estuarine community utilization, water quality, and structure performance. This enhancement project was supplemented in 2022 by another installation of ~300 reef

Appendix B: Day 1 Talk Abstracts

balls and gabions further north along Gansevoort Peninsula, as well as a ~100m cordgrass (*Spartina spp.*) salt marsh that has an associated four-year monitoring program. The Park is currently planning an additional enhancement project for an area north of 14th street that will continue to explore adapting marine infrastructure for improved habitat value.

Niels Lindquist
SANDBAR Oyster Company Inc.

Use of Oyster Catcher™ substrates as oyster-enhancing amendments for hardened structures

Authors: SANDBAR Oyster Company Inc.

Hardened structures, such as rock revetments, seawalls, and bulkheads, have long been used for shoreline erosion control and to protect built infrastructure. While certain types of hard armoring, as well as dock and pier pilings, can support the growth of oyster reef communities, their general lack of complex structure and rough surface texturing can limit the extent of oyster community development.

In recent years, structural amendments have been designed to integrate with existing hard structures, aiming to create habitats that foster more robust oyster communities. SANDBAR Oyster Company is currently developing Oyster Catcher™—cement-infused cloth hardscapes—as "cuffs" for pier and dock pilings to enhance oyster community growth in estuarine waters. These cuffs consist of Oyster Catcher™ panels shaped to encircle about half the circumference of a piling and are strapped in place at the optimal intertidal zone for oyster growth (Ridge et al. 2015, Scientific Reports 5; doi:10.1038/srep14785). The cuffs have either a flat or corrugated design. Oyster Catcher™ products are engineered to degrade over time at variable rates, allowing the developing oyster communities to naturally detach and settle on the surrounding seabed. Replacing degraded cuffs can help accelerate oyster accumulation at the base of pilings.

In initial tests, cuffs were installed on dock pilings adjacent to a major navigation channel, where they were exposed to boat wakes and large wind-generated waves. Oysters successfully recruited to the cuffs; however, community development was limited by the use of cuffs designed to degrade relatively quickly. Additionally, the complex habitat created by the cuffs served as a refuge for stone crabs (*Menippe mercenaria*), which preyed on oyster spat and accelerated cuff degradation. Future testing of Oyster Catcher™ cuffs for enhancing oyster communities on hardened structures will involve longer-lasting cuffs and designs that minimize spaces where crabs can shelter.

Adrian Sakr
University of Florida

Changing of the garden: evaluating the performance and ecosystem functionality of novel oyster garden structures

Authors: Adrian Sakr, Logan Mazor, Joseph P. Morton, Andrew Altieri

Oyster gardening, in which modular oyster reefs are suspended from docks, has become an increasingly common and accessible technique for coastal communities to enhance oyster

Appendix B: Day 1 Talk Abstracts

populations for water filtration and biodiversity enhancement. However, little research has been done to evaluate materials and methods for oyster gardens regarding durability and ecosystem benefits, making it difficult to scale up efforts and maximize project success. We conducted a field experiment in a residential canal system of Sanibel Island, Florida where we deployed a variety of oyster garden structures to evaluate performance in oyster recruitment, durability, water filtration rate, and biodiversity. Additionally, the occurrence of Hurricane Ian during the deployment provided an opportunity to evaluate how these structures resisted severe storm events. We tested five structures: (1) a conventional design made of drilled oyster shell on steel wire; and four alternatives (2) GROW concrete discs; (3) jute fiber coated with calcium sulfoaluminate cement; (4) BESE biodegradable plastic matrix panels; and (5) BESE biodegradable plastic mesh bags filled with oyster cultch. All structures survived Hurricane Ian; however, both BESE structures ultimately disintegrated without recruiting oysters. Disc, jute, and shell wire structures demonstrated similar levels of durability, oyster recruitment and growth, and biofiltration rates. Thus, we conclude that material selection considerations may come down to the availability of materials and labor as well as the extent to which cost and biodegradability are prioritized. Our results provide important information for optimizing oyster garden performance while minimizing environmental impacts.

Rochelle Seitz

Virginia Institute of Marine Science

Retrofitting seawalls with artificial substrates promotes oyster recruitment and macrofaunal communities

Authors: Rochelle D. Seitz, Kathleen E. Knick, Alison Smith, Michael S. Seebo, Gabrielle G. Saluta

With the urbanization of coastal cities, natural shorelines have been extensively modified. Shoreline development has increased the presence of vertical seawalls, which can negatively impact benthic macrofaunal communities. Green engineering techniques can be used to enhance inhospitable seawall structures by creating micro-habitats on the structures and using materials that increase the settlement of bivalves. Oysters enhance benthic communities by creating complexity and heterogeneity, providing microhabitats for other macrofauna, which protects them from predation and physical stressors. At two field sites in the Chesapeake Bay, we retrofitted seawalls with artificial substrates with varying habitat complexity and oyster seeding density and investigated the effects on oyster densities and macrofaunal communities. The substrates included 3D printed tiles (0.25 × 0.25 m) with three levels of complexity (flat, 2.5 cm ridges, and 5 cm ridges) plus control tiles of the existing seawall, at three seeding densities (0, 36, and 56 oysters per tile). Tiles were monitored every three months for oyster survival, oyster growth, and primary cover. After a year, tiles were destructively sampled for oyster survival, oyster recruitment, and the macrofaunal assemblage. Both increased tile complexity and higher seeded oyster density increased seeded oyster survival and recruitment of oyster spat. The high-complexity, high-seeded tiles had 10x more recruits than flat, unseeded tiles and 70x more recruits than the controls of the existing seawall. Macrofaunal abundance and biomass also increased as habitat complexity of the tiles increased, providing habitat for larger organisms, such as mussels and mud crabs. Using retrofitted structures on seawalls increased habitat complexity, leading to higher seeded oyster survival, oyster recruitment, macrofaunal abundance, biomass, and species richness in coastal ecosystems.

Appendix B: Day 1 Talk Abstracts

Jason Spires

National Oceanic and Atmospheric Administration

Nature based oyster settlement substrate investigations

Authors: Jason Spires

Oysters occupy a unique space in coastal ecosystems and communities. These bivalves provide a range of ecosystem services and direct (wild and farmed fisheries) and indirect (habitat for other fauna, recreational fisheries) economic benefits. Additionally, oysters are increasingly considered as a tool for mitigating effects of climate change and promoting coastal resilience. Current oyster restoration practitioners frequently desire to place oysters along hardened shorelines but are hampered by inefficient or costly methods. In regions of high natural recruitment, oysters settle naturally on a variety of hardened surfaces, however, in regions of low natural recruitment this type of greening gray infrastructure is more challenging. Our work investigates novel population replenishment techniques by using biodegradable oyster setting materials (basalt, coconut fiber) and mechanical behavioral manipulation (bubble curtains) to create oyster communities on hardened structures. Our objectives are to develop a cost-effective material/technique that can be used to create oyster populations on hardened surfaces. Initial oyster settlement rates are similar among tested materials, however, retention is poor on the most pliable materials. Additionally, larval behavior was not controlled by bubble curtains and modifications to the experimental design are required.

Iacopo Vona

University of Central Florida

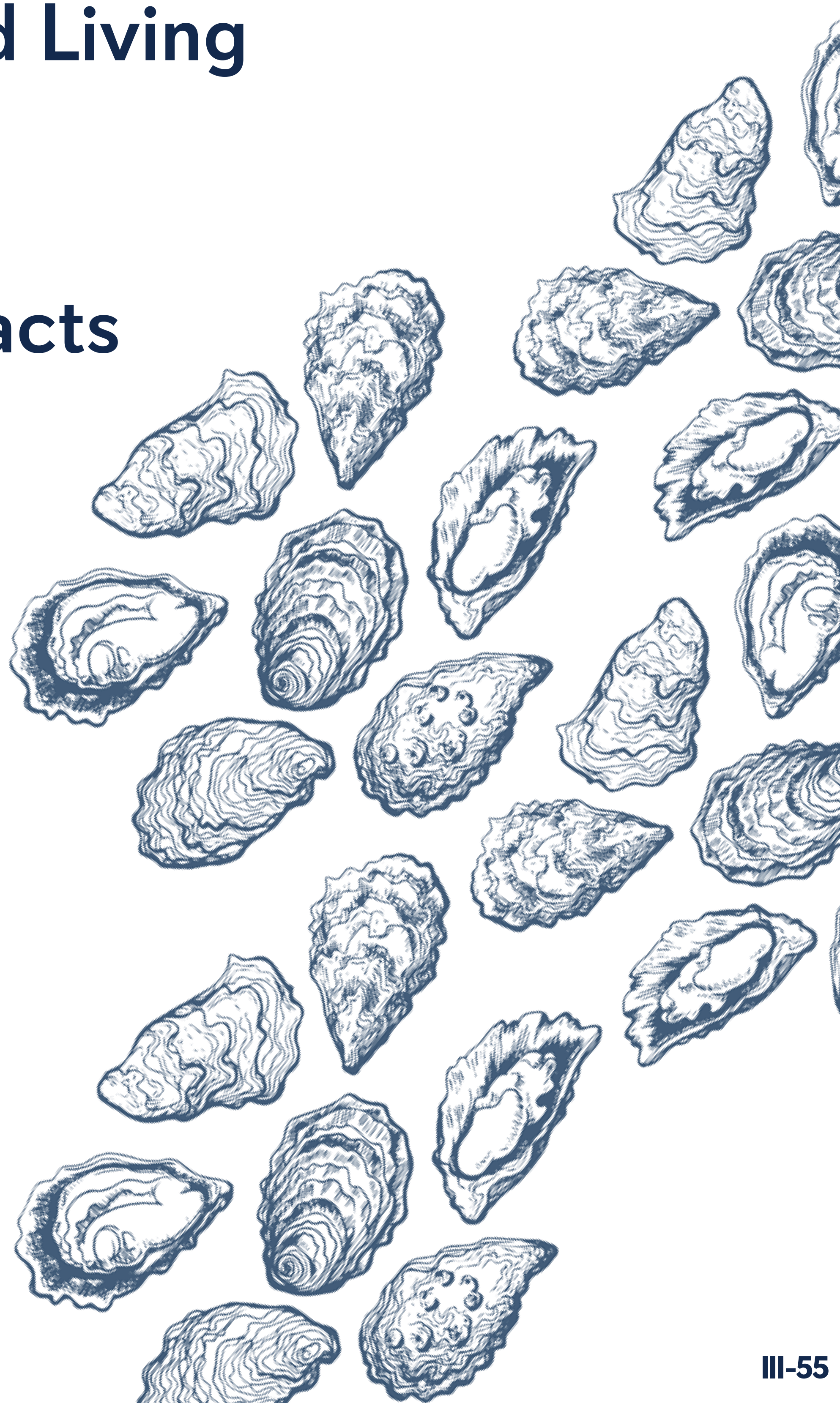
Integration on submerged breakwaters offers new adaptive shoreline protection in low-energy environments in the face of sea level rise

Authors: Iacopo Vona and William Nardin

Sea level rise (SLR) and increasing storm frequency threaten coastal environments. To naturally protect our coasts, living organisms such as oysters can be used. They provide a multitude of benefits for the surrounding environment, including coastal protection. Unlike any common gray structure used for coastal defense, such as breakwaters, oysters can grow with SLR and self-repair from damage following extreme events. In this study, we analyzed the coupling between breakwaters and oysters through a numerical model, Delft3D-SWAN, validated with field data. The research aimed to evaluate the performance of this hybrid solution under future scenarios of climate change and SLR. The study results showed that the coastline was more preserved and protected over time when oysters were included in the simulation, thanks to their capability to self-adapt over a changing climate. Incoming wave heights and sediment export from the shore were reduced compared with the use of gray breakwaters alone, resulting in a resilient and healthier coast. The coupling between oysters and breakwaters may represent a valuable and effective methodology to protect our coast over a changing climate and a rising sea, where optimal conditions for oyster survivability occur and are maintained over time.

Day 2: Building Engineered Living Shorelines

Talk Abstracts



Appendix C: Day 2 Talk Abstracts

Alberto Canestrelli
University of Florida

Integrating physical and numerical models to assess wave dissipation and sediment accumulation at restored oyster reefs

Authors: Alberto Canestrelli, William Nardin, Rafael O. Tinoco, Jacopo Composta, Salman Fahad Alkhidhr, Kamil Czaplinski, Luca Martinelli, Savanna Barry, Anthony Priestas, Duncan Bryant

Oyster reef ecosystems are increasingly recognized for their resilience and ability to provide sustainable, nature-based alternatives to traditional "gray" infrastructure. These reefs offer critical benefits, such as mitigating shoreline erosion, promoting sediment deposition, and supporting adjacent habitats like salt marshes. Despite their potential, there is a limited understanding of the physical processes driving sediment transport around oyster reefs under varying wave and tidal conditions, reef geometries, and locations. Bridging this gap is vital for optimizing sediment retention and supporting shoreline progradation.

This study aims to quantify the mechanisms through which oyster reefs stabilize sediments. Using a combination of physical and numerical modeling, researchers are investigating the influence of tidal and wave dynamics, longshore currents, reef geometries, and distances from the coast. Initial experiments employ 1:7 scaled 3D-printed oyster reefs in a wave flume at the Ven Te Chow Hydrosystems Lab, University of Illinois Urbana-Champaign. Concurrently, numerical simulations with OpenFOAM on the HiPerGator
high-performance cluster analyze wave-reef interactions under varying conditions.

Findings from these efforts will guide large-scale experiments at the Large-scale Sediment Transport Facility (LSTF) in Vicksburg, MI, conducted at a 1:2 scale. These tests will include regular and irregular waves (i.e., wave spectra in both frequency and direction), wind-driven and tidal longshore currents, and tidal variations in water level. Four distinct reef geometries will be tested under these hydrodynamic conditions. The collected data will calibrate a numerical model, enabling predictions of reef-induced sediment aggradation beyond experimental conditions and identifying optimal reef designs.

The outcomes of this research include a robust dataset on sediment dynamics, calibrated models, and actionable guidelines for oyster reef restoration. These results will inform sustainable coastal management strategies, enhancing shoreline protection and promoting the use of oyster reefs as effective, nature-based solutions for long-term resilience in coastal environments.

Carolyn Khoury
Billion Oyster Project

Living breakwaters: engineering with nature and restoring oyster reef habitat

Authors: Pippa Brashear, Carolyn Khoury

Widely considered a model for climate-adaptive nature-based infrastructure, Living Breakwaters is a $111 million project with a layered approach to risk reduction—enhancing physical, ecological, and social resilience along the South Shore of Staten Island.

Appendix C: Day 2 Talk Abstracts

The project consists primarily of 2,400 linear feet of near-shore breakwaters—partially submerged structures built of stone and ecologically-enhanced concrete units—that break waves, reduce erosion of the beach along Staten Island's Tottenville shoreline, and provide a range of habitat spaces for oysters, fin fish and other marine species. The Living Breakwaters concept was developed by a large, multi-disciplinary team led by SCAPE as part of a winning proposal for Rebuild By Design, the design competition launched by the U.S. Department of Housing and Urban Development (HUD) after Superstorm Sandy.

The breakwaters are designed to reduce the impact of climate-intensified weather events on the low-lying coastal community of Tottenville, which experienced some of the most damaging waves in the region and tragic loss of life during Superstorm Sandy. Informed by extensive hydrodynamic modeling, the breakwaters are also designed to slow and, eventually, reverse decades of beach erosion along the Tottenville shoreline. The breakwaters are constructed with "reef ridges" and "reef streets" that provide diverse habitat space. Billion Oyster Project (BOP), a non-profit organization based in New York City whose mission is to restore functional, self-sustaining oyster reefs to New York Harbor, will introduce additional substrate seeded with juvenile oysters to the breakwaters beginning in 2025.

Beyond the physical breakwaters and habitat restoration, the project also aims to build social resilience in Tottenville through educational programs and the implementation of an open-access curriculum for local schools for local schools in partnership with BOP and local community committees and action groups.

Mary-Margaret McKinney
Native Shorelines, A Davey company

Quantitative evaluation of an alternative oyster-centric living shoreline system

Authors: Mary-Margaret McKinney, Worth Creech, Whitney Thompson, Chris Paul, John Darnall, and Bret Webb.

Coastal erosion and shoreline retreat, resulting from both from extreme weather events and sea level rise, pose great challenges to coastal management across U.S. coastal areas. To address this challenge, many State, Local, and Federal stakeholders have deployed living shorelines as a cost-effective method of reducing shoreline retreat rates and providing ecological benefits such as marine habitat, fish spawning areas, and shellfish and oyster habitat.

As such, the deployment of these structures has gained increasing popularity, and many new technologies and variations of living shorelines have been developed in recent years. However, coastal engineering metrics such as wave attenuation, structural stability, and changes to current velocities are rarely validated prior to deployment. Native Shorelines' QuickReef® technology is one of the new types of living shorelines and has been deployed along over 5 miles of shorelines in North Carolina and Virginia. Qualitative observations from deployment sites appeared to show significant oyster spat recruitment and a reduction in shoreline retreat rates. In early 2024, QuickReef® designs were evaluated via physical and numerical modeling to determine the effectiveness and stability of the structures.

A desktop study evaluating field conditions at representative sites was performed to inform critical

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design forcings for flume study purposes, which was then conducted at the University of South Alabama Center for Applied Coastal Engineering and Science. Wave attenuation, stability, and current velocities were measured during physical modeling. Results from the wave flume study were utilized to calibrate FLOW-3D models. This presentation will discuss findings from the physical and numerical modeling studies as well as demonstrate the overall effectiveness of living shoreline designs using quantitative methods.

Kate Orff
SCAPE

Living Breakwaters

Designed by SCAPE, COWI, Arcadis, SeArc Ecological Marine Consulting, WSP, MFS Engineers, Prudent Engineering. Engagement by Billion Oyster Project. Construction by Weeks Marine, Ramboll, Baird. Environmental Review & Permitting by AKRF.

Kate's talk will focus on the trajectory of oyster restoration in the New York Harbor, and how Living Breakwaters evolved into a funded and implemented project in the post-Super storm Sandy recovery process. She will show how the Living Breakwaters project developed, including its engineering and approvals process, and will feature the work of SCAPE's many collaborators, including the Billion Oyster Project.

Tyler Oretego
Natrx

Integrating engineered structures and oyster habitat for resilient shorelines

Authors: Drew Keeley, Tyler Ortego

The integration of oyster and marine habitat with engineered structures offers a transformative approach to enhancing shoreline resilience and ecological health. Traditional materials and construction methods often lack adequate capability to balance coastal protection with optimal habitat formation. New technologies are emerging that provide new capabilities for coastal resilience and habitat restoration practitioners.

Natrx has pioneered the Dry Forming™ advanced manufacturing technique, which enables development of tailored, habitat-positive structures that address site-specific needs while promoting oyster colonization and ecosystem restoration. Natrx reef structures feature customizable void spaces and biomimetic surfaces to optimize conditions for oyster recruitment, habitat formation, and ecological uplift. These structures support shoreline stabilization and also deliver ecosystem services such as water filtration and biodiversity enhancement. By leveraging digital tools, advanced manufacturing, and material science innovations, Natrx can efficiently produce scalable, site-specific solutions that enhance the longevity of coastal infrastructure and integrate seamlessly with existing gray and hybrid systems.

Case Study: Hog Island, VA - A nature-based wetland protection and habitat restoration solution using Natrx ExoForms™ along Hog Island in Gloucester County, Virginia. The goals of this project was to

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protect the residential and commercial properties along Monday Creek and the York River, reduce erosion and sedimentation into the Chesapeake Bay, and a focus on enhancing maritime habitat for shorebirds, oysters, and other marine life. Designed customized interlocking ExoForms for highwave energy areas exposed to Mobjack Bay and low crested oyster reef ExoForms for low energy areas. Placed 972 linear feet of large stacked units and 122 linear feet of low crested oyster reefs. Added available surface area for 14 million oysters that will filter water and provide foundational habitat and prevent 40,000 tons of eroding sediment from entering the bay system and contributing to suspended sediment and nutrient loading.

Amanda Poskaitis
Underwood & Associates

Oyster recruitment on dynamic living shorelines

Authors: Underwood & Associates, Maryland Coastal Bays Program

Underwood & Associates, a design/build stream and living shoreline contractor, developed the dynamic living shoreline, which can be adapted to various site conditions to create critical shallow water wildlife habitat and solve erosion issues for communities and property owners. Underwood uses all native stone material in our vegetated headland designs and we have been working to incorporate oysters into our living shorelines to achieve even greater habitat co-benefits on our project sites. An example of oysters thriving on one of our projects is at the Assateague State Park Living Shoreline – a partnership between Assateague State Park, Maryland Coastal Bays Program, and Underwood & Associates.

Oyster surveys have been conducted at the Assateague Living Shoreline site since 2021 by the Maryland Coastal Bays Program. The surveys started after noticing an abundance of oysters along the vegetated headlands. Years of surveying has shown that although this site experiences oyster recruitment, the oysters tend to not live past 1-2 years due to disease or other environmental factors. This is typical in the Maryland Coastal Bays watershed, which has not had a self-sustaining wild oyster population in over 50 years. In addition to the research conducted on oysters at the Assateague Living Shoreline, we are working on many other living shoreline projects throughout the Chesapeake and Coastal Bays that have potential for incorporation of oysters. We will be presenting on our work and exploring how to incorporate oysters into living shoreline designs effectively. We will share multiple projects, research, and lessons learned.

Adrian Sakr
University of Florida, Department of Environmental Engineering Sciences

Living in a material world: support for the use of natural and alternative materials in coastal restoration and living shorelines

Authors: Adrian Sakr, Andrew Altieri

The size and expense of coastal restoration efforts are increasing exponentially to mitigate anthropogenic environmental impacts and achieve international conservation goals. As part of these efforts, a variety of conventional materials including plastic, metal, and concrete are used in

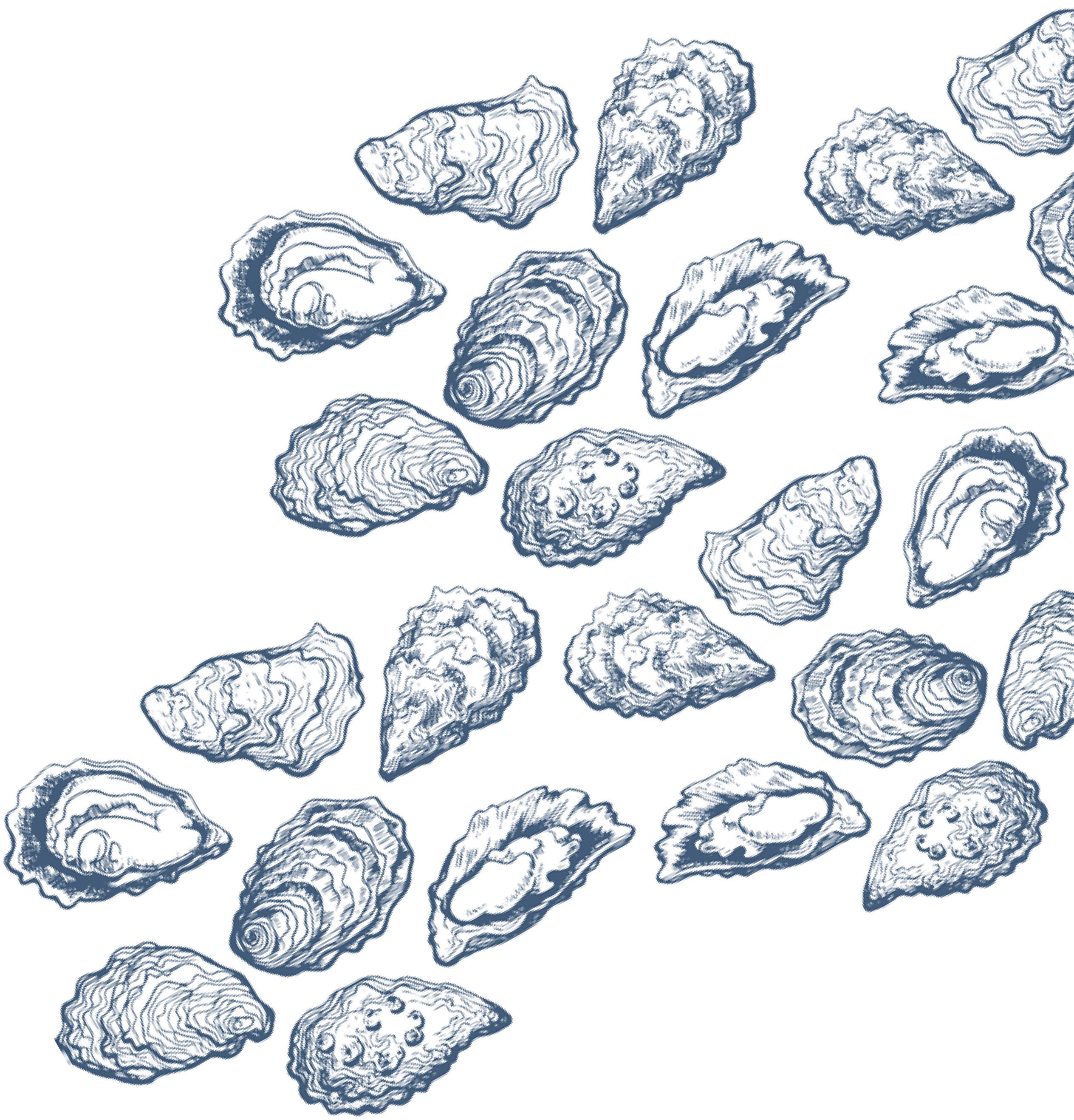
Appendix C: Day 2 Talk Abstracts

breakwater, settling substrate, vegetation stabilization, and sediment retention structures because of their availability, inexpensive purchase price, and predictable properties. However, questions regarding sustainability arise given the adverse environmental impacts of the life cycle processes for each material.

Life cycle impacts from production, transportation, installation, and degradation should be key considerations in material selection, with criteria that allow decision makers an opportunity to evaluate less impactful alternative materials. Natural and reduced-impact alternative materials include natural elements such as plant fibers and rock as well as reduced-impact materials such as bio-based and biodegradable plastics. These items may have comparable availability and functionality and exhibit reduced carbon, chemical, and particulate emission impacts. However, they are often not selected for full-scale restoration applications due to uncertainties regarding their financial cost and ability to replace conventional materials. Here, we compare conventional and reduced-impact alternative materials for use in coastal restoration applications. The function, engineering performance, and life cycle environmental impacts are reported for each material followed by a presentation of case studies that illustrate the value of appropriate material selection. We then compare the impacts of material sourcing and product lifespan to develop a material selection framework enhancing the selection process of reduced-impact alternatives.

This study reveals a need for more detailed and standardized life cycle information about the materials used in the coastal environment. The proposed framework allows more emphasis on material life-cycle implications in the design process, which could lead to enhanced use of alternative over conventional materials and improved project value and outcomes.

Poster Abstracts



Appendix D: Poster Abstracts

Savanna Barry
University of Florida

Performance assessment of living shoreline retrofits on Florida's Gulf of Mexico coast

Authors: Savanna C. Barry, Elix M. Hernandez, and Mark W. Clark. University of Florida, Florida Sea Grant.

A community-driven effort in Cedar Key, Florida, USA, resulted in the construction of three living shoreline retrofits intended to bolster failing coastal infrastructure and restore habitat functions in Daughtry Bayou. A multi-year monitoring program tracked changes in elevation and vegetation communities across the entire shoreline profile from lower-intertidal to upland/transitional zones and measured wave attenuation during typical and extreme (hurricane) conditions. Overall, these living shoreline retrofits served to soften more than 30% of the bayou's shoreline, dramatically reducing the extent of armored shoreline in direct contact with tidal influence. The extent of vegetated habitat area has increased at all three sites, despite sediment export from higher elevation zones driven largely by repeated impacts from hurricanes and tropical storms. These living shorelines reduced wave energy by 33 to 79% in typical conditions and by up to 28% in hurricane conditions, consistently outperforming armored shorelines, even during an extreme event (Hurricane Idalia). The living shoreline retrofit projects assessed here have persisted through and shown signs of recovery after multiple tropical storms and hurricanes, while providing important energy reduction services. Thus, living shoreline retrofits continue to be a cost-effective shoreline management strategy in the short term for this area. However, our analyses suggest that persistence of these shorelines could be threatened by the combination of sea-level rise (by 2040), upland armoring, and an increasing risk of more intense tropical systems. Therefore, future interventions should more carefully consider these threats in conjunction with habitat enhancement goals.

George Birch
Oyster Heaven

The Mother Reef: A scalable clay based biodegradable substrate for oysters

Authors: George Birch, Ronald Lewrissa, Jochem van der Beek and Natacha Juste-Poinapen

The "Mother Reef," developed and patented by Oyster Heaven, is a step change in the scalability, predictability and permissibility for building oyster focused engineered living shorelines. The low fired clay structures are tunably biodegradable (depending on firing temperatures), they are an effective oyster settlement substrate and can be produced at generic brick manufacturers around the world. An average factory can be brought online in a matter of months and can produce enough substrate for 100 acres of reef per day for the same price as household bricks.

Constructed from locally sourced clay, Mother Reefs are designed to facilitate oyster settlement, growth, nutrient flowthrough, reproduction, and protection from predators. Their trapezoidal shape and sine wave patterned ribs maximize settlement surface area while minimizing contact area, reducing spat loss during transport.

The Mother Reef's innovative design and use of natural materials are key to its scalability and permissibility. As a biodegradable structure, it seamlessly integrates into the marine environment,

Appendix D: Poster Abstracts

generating natural reef development without long-term ecological disruption. The scaffolding eventually melts away into the background sediment, chemically and physically indistinguishable from the sediment already there. This approach aligns with current policy trends that favor nature-based solutions for coastal protection, making it more likely to secure necessary permits for large-scale deployment.

The Mother Reef's adaptability to local conditions further enhances its scalability and permissibility. Its composition and structural arrangement can be tailored to optimize specific ecosystem services, such as biodiversity enhancement or coastal erosion mitigation, based on the needs of the local environment.

By providing a scalable, permissible, and biodegradable solution for oyster reef restoration, Oyster Heaven will play a pivotal role in building resilient and sustainable living shorelines. Its innovative design and alignment with policy objectives position it as a leading technology for large-scale coastal protection and marine habitat regeneration.

George Thatos
Coastal Technologies

Coastal Technologies Corp's Oyster Reef Building Technology

Authors: George Thatos, and Raphael de Perlinghi

Coastal Technologies Corp (CTC) introduces a revolutionary patented solution to address the global need for oyster reef restoration—a critical factor in coastal resilience, pollution remediation, and ecosystem recovery. Standard reef-building methods are slow, labor-intensive, and suffer from failure rates as high as 85%. CTC's innovative, nature-inspired technology overcomes these limitations, enabling near-instant reef creation while preserving coastal ecosystems.

Our Oyster Reef Building system uses stainless steel corkscrew armatures installed into sediments using simple tools. These armatures support stone plates, providing elevated, predator-resistant habitats for oysters. By raising reefs off the seafloor, our system avoids issues like siltation, hypoxia, and subsidence—common causes of failure in traditional methods. The vertical structure enhances resilience to climate change and allows for adjustments to rising sea levels. Easy installation, minimal disruption to coastal mudflats, and high surface area make this system efficient, scalable, and adaptable.

CTC's technology serves vulnerable coastal communities worldwide, particularly those threatened by storm surges, erosion, and sea-level rise. Oysters act as "ecosystem engineers," filtering water, preventing harmful algae blooms, and supporting diverse marine life. For communities like the Biloxi-Chitimacha-Choctaw Indians in Louisiana, our system offers food security, cultural preservation, and coastal protection.

Field-tested prototypes have demonstrated the technology's effectiveness, with further validation planned through partnerships with academic institutions, NGOs, and coastal restoration groups. CTC's team combines technical expertise with a passion for environmental and social justice, ensuring community involvement in every stage of implementation.

Appendix D: Poster Abstracts

By dramatically increasing the capacity to build resilient oyster reefs at scale, CTC provides a practical, cost-effective tool to protect coastal populations, restore ecosystems, and mitigate climate impacts. With support from SHORES, we aim to advance this technology to market, navigate regulatory pathways, and foster partnerships that bring life-saving solutions to the communities that need them most.

Niels Lindquist
SANDBAR Oyster Company Inc.

A decade of development, refinement and scaling of Oyster Catcher™ hardscapes for oyster habitat creation, living shorelines and oyster culturing

Authors: Niels Lindquist and David Cessna

At the 18th International Conference on Shellfish Restoration in Charleston, SC in 2016, Niels Lindquist and the late David Cessna (co-inventors), made the first public presentation on an innovative, composite hardscape for oyster habitat creation/restoration and oyster culturing. Our degradable hardscape, trade named Oyster Catcher™, is a composite of plant-fiber cloths infused with cements (any and all mineral-based binders/hardeners claimed) made by soaking and manipulating the cloth in cement slurries to work the cement into the threads of the cloth.

Prior to cement hardening, we form the cement-infused cloth pieces into different modular shapes, some of which we use to build robust reef frameworks and others to trap sediments and thereby promote salt marsh development. The surface of Oyster Catcher™ is highly textured and exceptionally attractive to oyster larvae and protective of juvenile oysters. In addition to reef building, a 3-dimensional, pretzel-shaped Oyster Catcher™ derivative is proving to offer a facile path for capturing and manipulating wild and hatchery settled spat for culturing for food and oyster restoration products. In addition to Sandbar Oyster Company's direct development efforts with Oyster Catcher™, independent, third-party testing is showing Oyster Catcher™ to be an exceptionally valuable technology in the living shoreline/shoreline protection toolbox.

Oyster Catcher™ is now being used in multiple, large-scale living shoreline and oyster habitat creation projects in North Carolina, Virginia, Georgia and California. Our cement-infused hardscape technology is owned by UNC Chapel Hill and now patented in Australia, Canada and New Zealand and is under examination in the US and EU. Sandbar Oyster Company Inc. has an exclusive license from UNC to commercialize this technology. This presentation offers an overview of our work developing and testing Oyster Catcher™ and views of projects showing the range of applications of Oyster Catcher™ products.

Appendix D: Poster Abstracts

Nicholas Muzia
Sea & Shoreline, LLC.

The Oyster Ark: A new role for oyster farming in ecosystem restoration

Authors: Nicolette Mariano, Nicholas Muzia P.E., Nicholas Bourdon

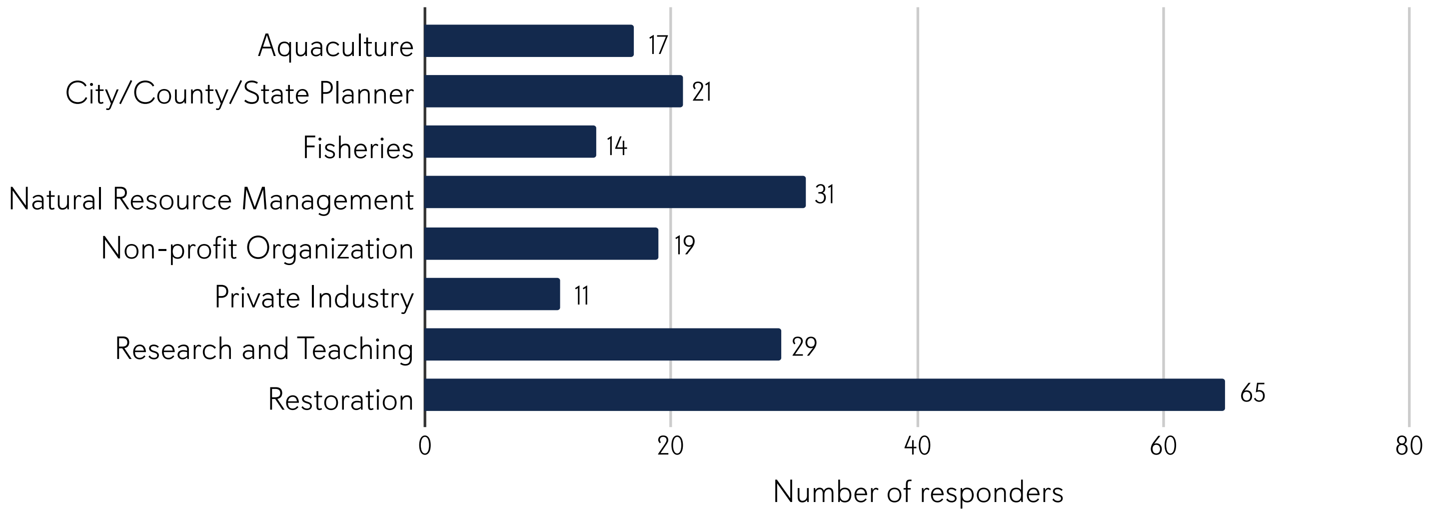
Oyster aquaculture offers a unique opportunity to enhance environmental restoration while supporting local economies. This presentation highlights a pilot project conducted in Florida's Indian River Lagoon by Treasure Coast Shellfish, which aimed to integrate oyster farming with ecosystem restoration efforts. The project evaluated a novel technique, the "Oyster Ark," designed to capture microorganisms from healthy sites and transplant them to less productive or restoration sites. By introducing live oysters and their associated microorganism communities, the Oyster Ark approach appears to accelerate the growth and success of restoration sites.

In addition to its restoration potential, the project documented the broader biological life supported by responsible oyster aquaculture, showcasing its role as an environmental asset. The initiative also explored the potential for oyster farmers to generate supplemental revenue through restoration activities, creating a symbiotic relationship between sustainable aquaculture and ecosystem health.

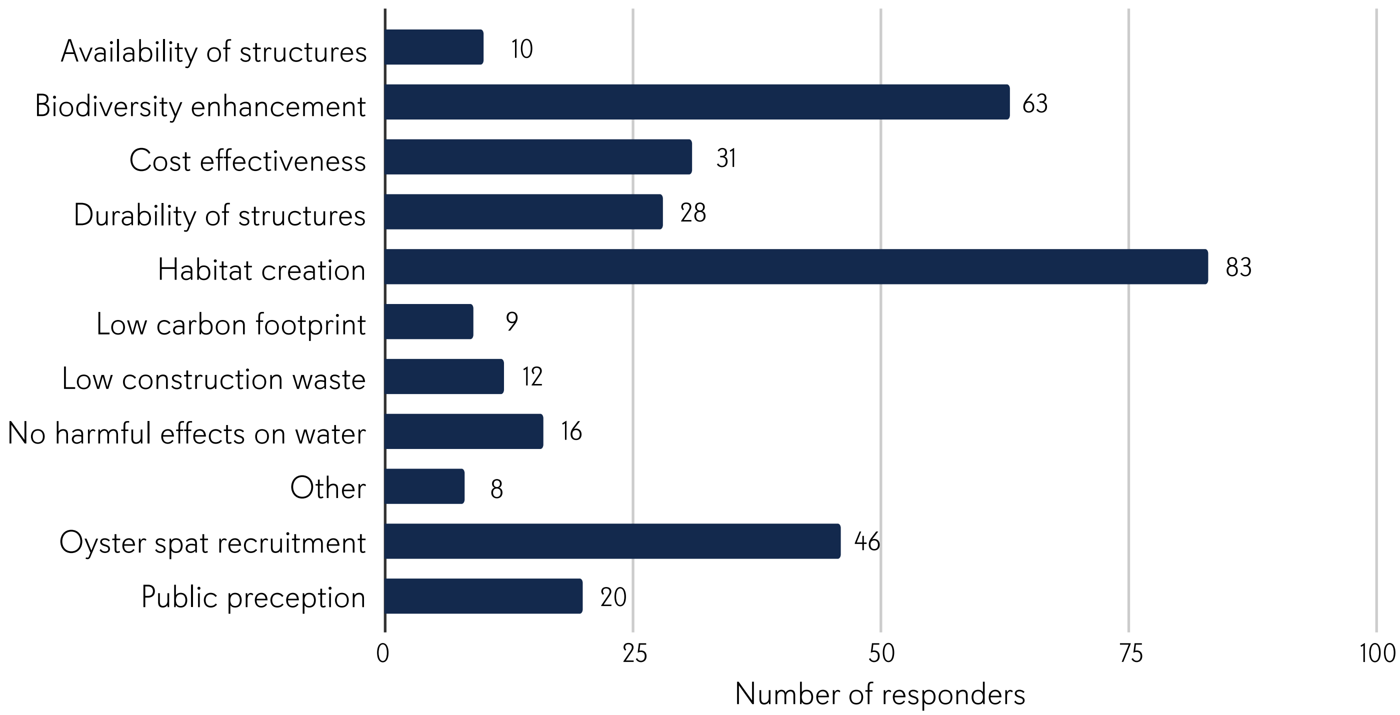
This presentation will discuss the outcomes of the pilot project, including its ecological and economic impacts, and seek feedback on how this approach could be refined and scaled to support both environmental restoration and the viability of local shellfish farms.

Appendix E: Poll Results Day 1

I work in the following sector(s):



What benefits of retrofitting existing infrastructure for oysters is most important to you? (Choose 3)

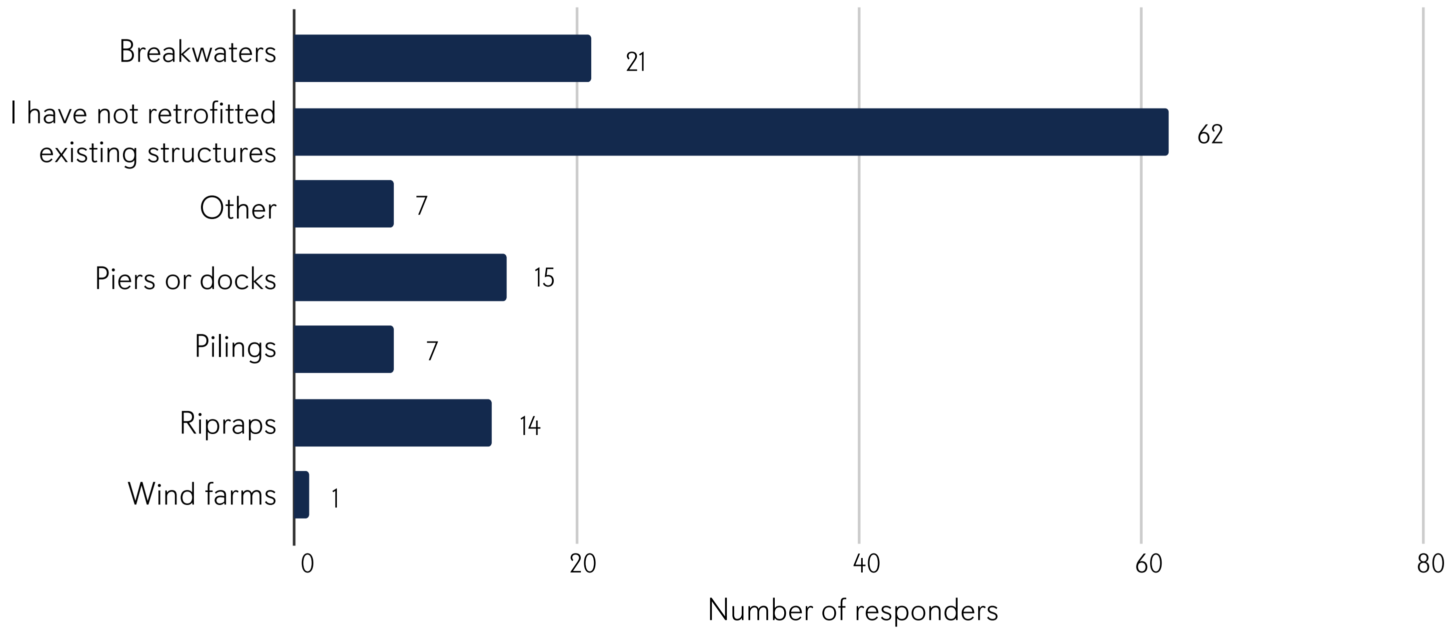


In the Other category, the following were listed:

- No negative impacts (structural, negative species composition changes, etc.)
- Boat wake attenuation
- Potential wave dissipation
- Positive benefits for waterways and water quality
- Water filtration
- Coastal resilience
- Wild harvest
- Erosion control

Appendix E: Poll Results Day 1

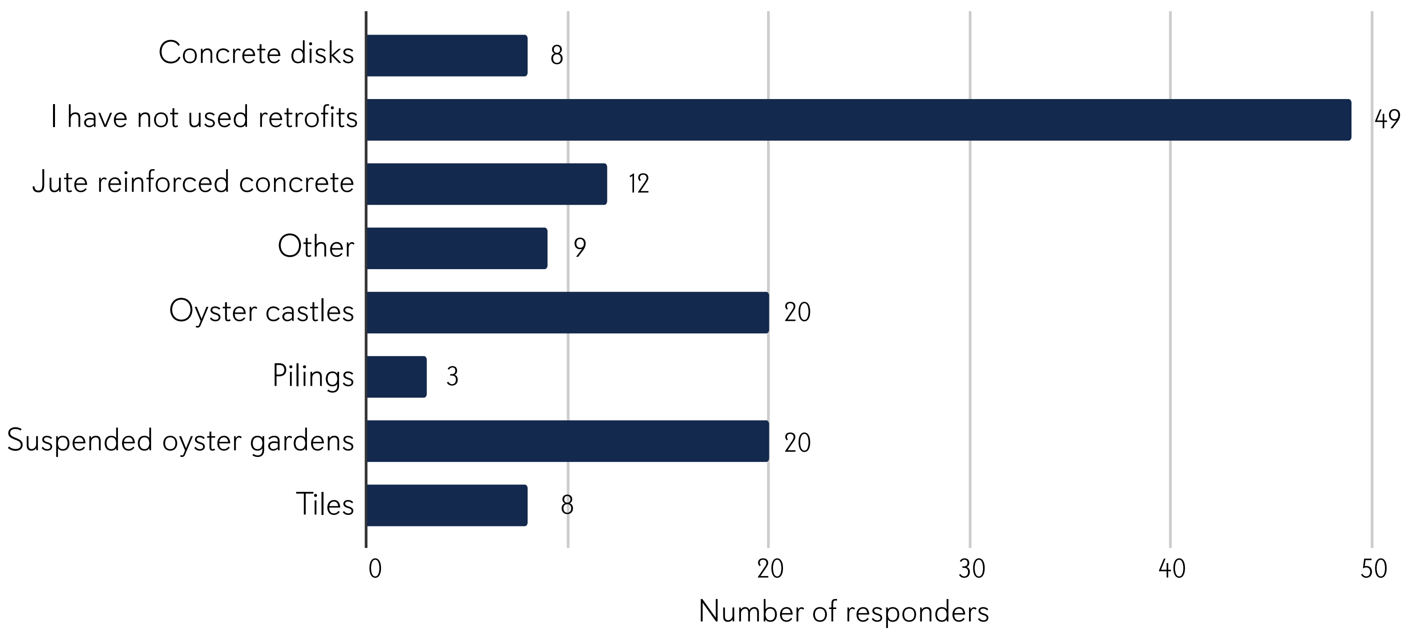
What types of structures have you retrofitted with oysters?



In the Other category, the following were listed:

- Bulkheads
- Levees
- Earthen berms
- Living shorelines
- Seawalls
- Marine Pontoons
- Estuaries around the world

What types of retrofits for oysters have you used?

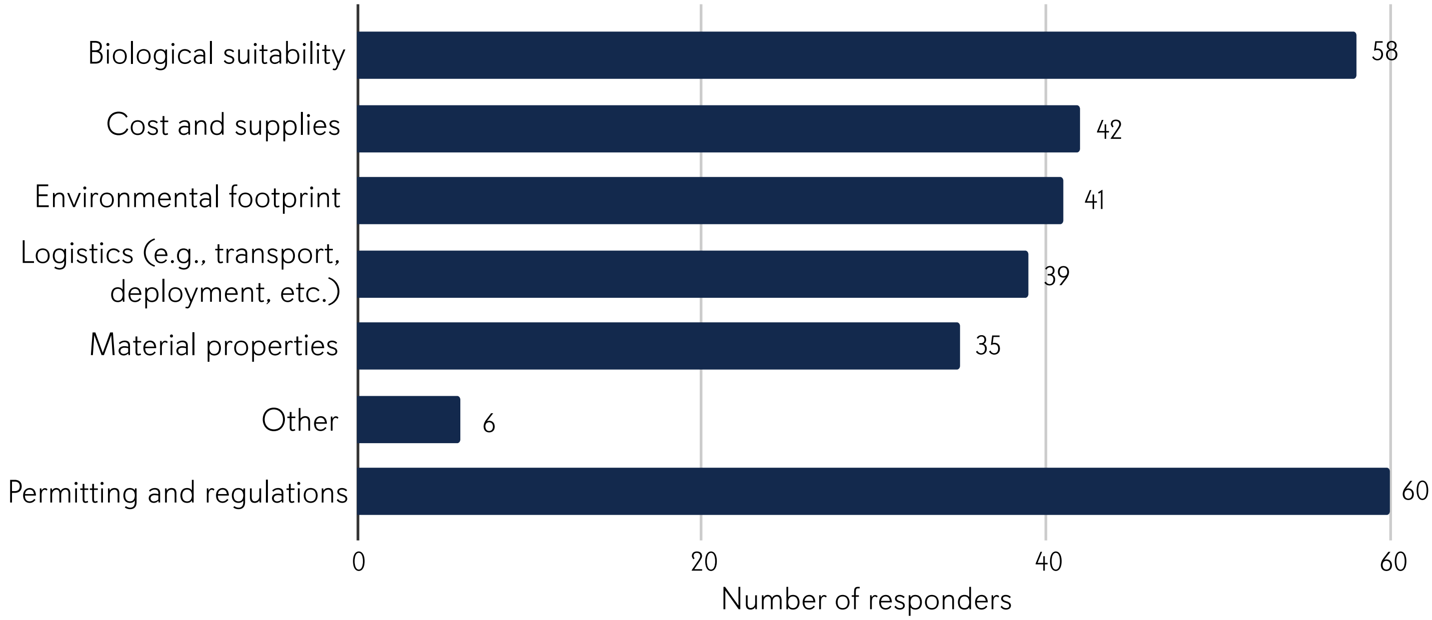


Appendix E: Poll Results Day 1

In the Other category, the following were listed:

- Reef balls
- Wrap, net, overlaid coating
- Natrx ExoForms
- Bioconcrete made from waste shells and natural binders that were 3D printed/cast into artificial reefs
- Plastic mesh bags
- BESE biodegradable plastic
- Drilled shell on steel wire
- Oyster shell bags
- Econcrete

What aspects of retrofitting existing infrastructure for oysters require greater investigation?



In the Other category, the following were listed:

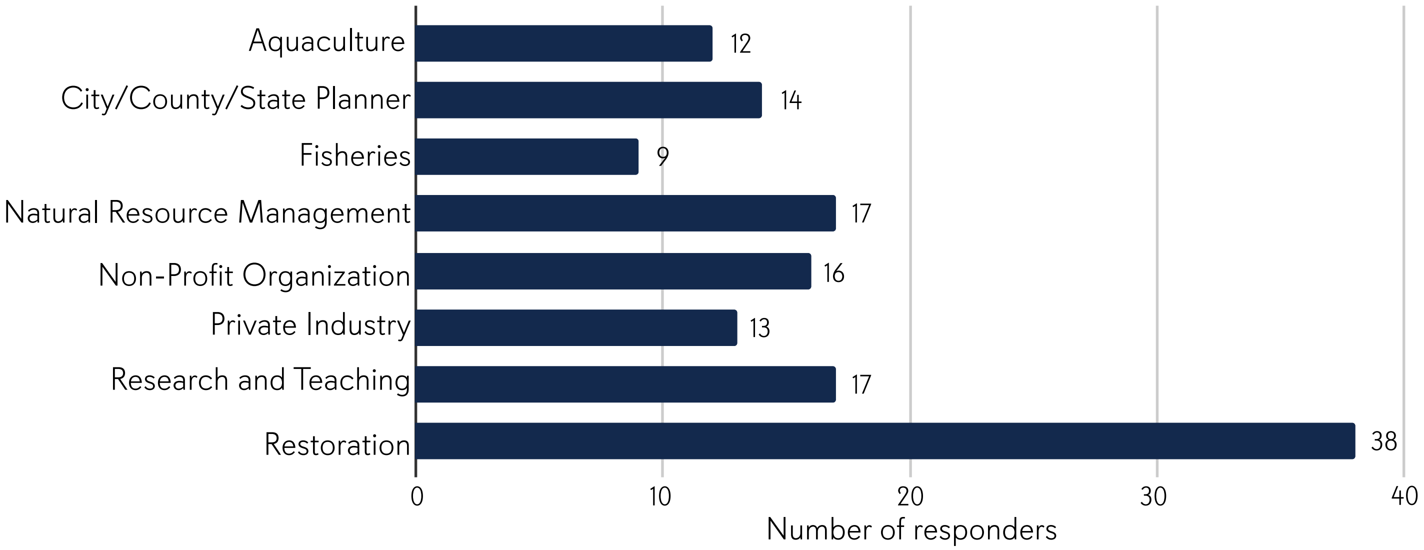
- Risk assessment of greener structures compared to traditional infrastructure
- Biogeochemical interfaces/gradients
- Scalability
- Biologically significant impact
- Resilience and adaptation to a changing marine environment

Are there other Maryland-specific issues that need addressing?

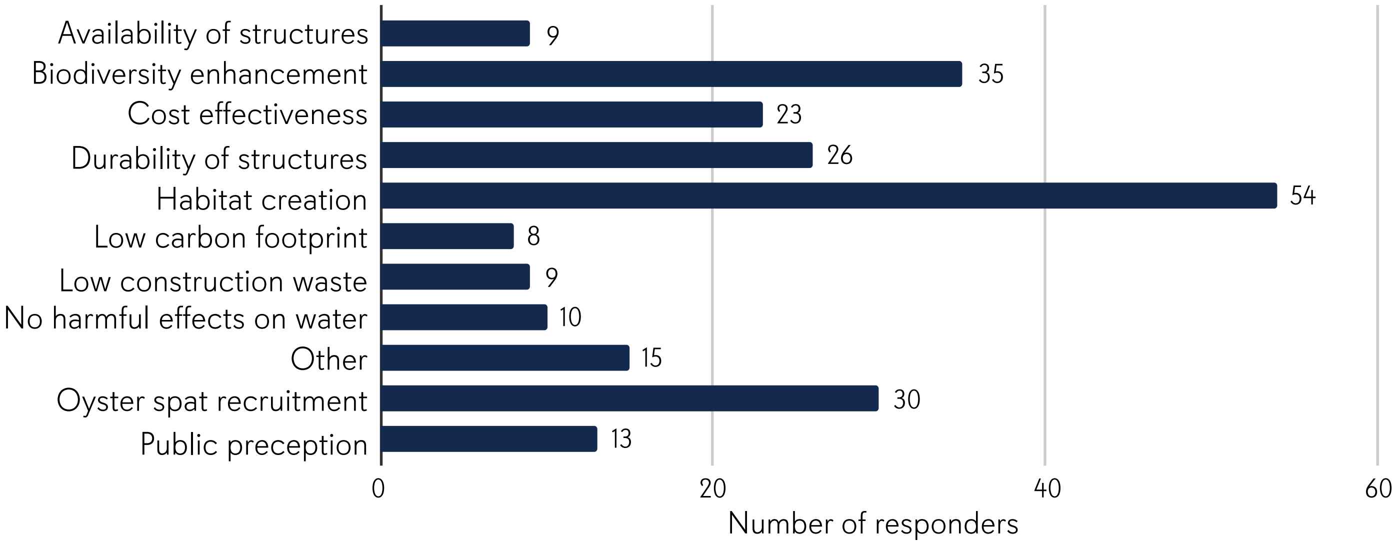
- Funding and other support for research (deployment procedures, costs, and integration with shoreline protection)
- MDE permitting
- Increasing oyster harvesting regulations regarding methods of collecting and number of sanctuaries
- Making living shorelines and other nature based features more cost-effective and attractive to the general public
- Public engagement and support and being honest and communicative about pros/cons
- Shallow water habitat management in the context of changing baselines
- Increase shell collection efforts and using this abundant resource for restoration projects

Appendix F: Poll Results Day 2

I work in the following sector(s):



What benefits of creating living shorelines with oysters are most important to you? (Choose 3)

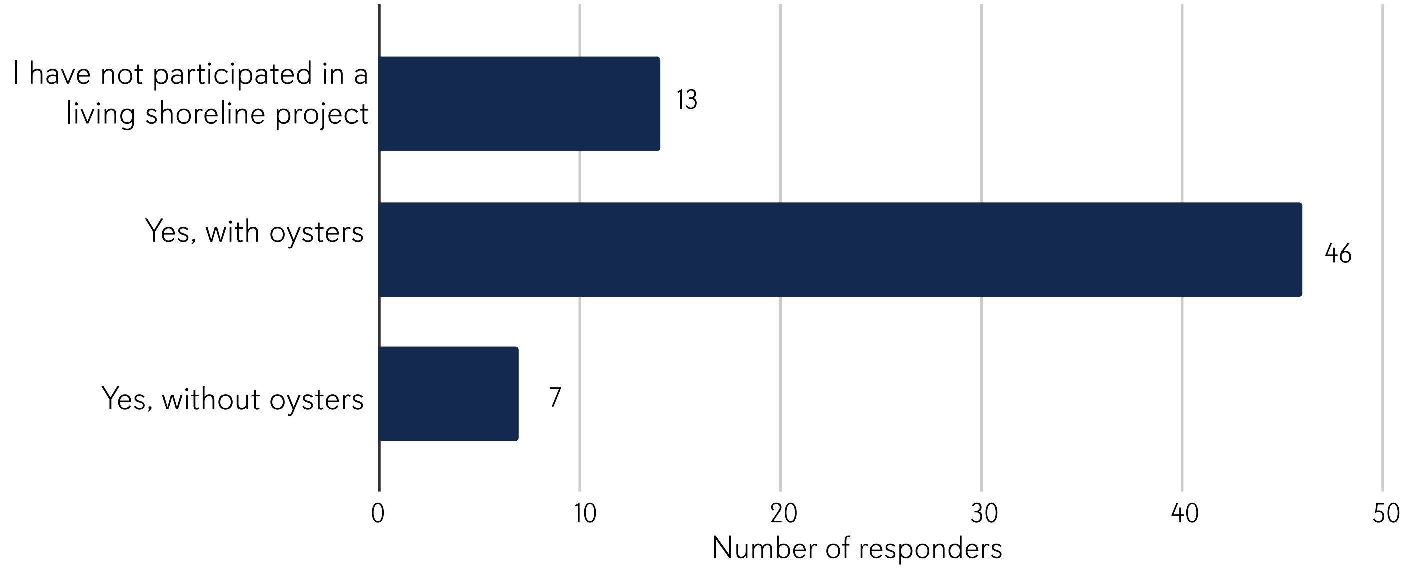


In the Other category, the following were listed:

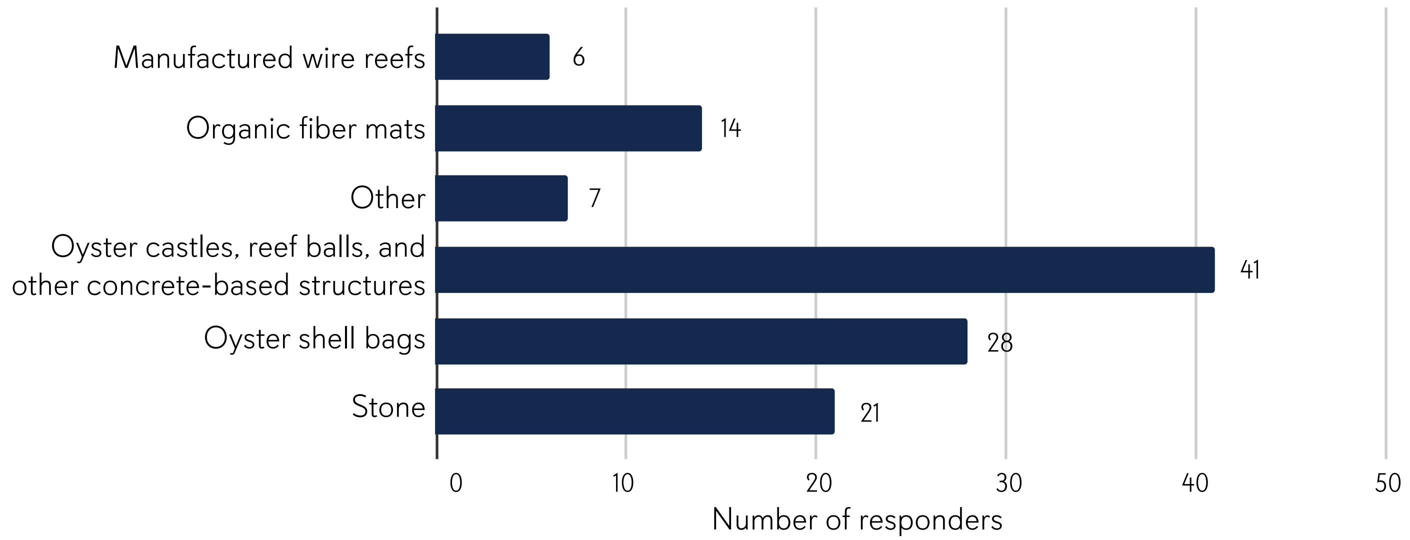
- Improved wave attenuation
- Habitat continuity
- Climate and coastal resilience
- Sediment capture
- Ensuring that structures allow for coastal access by other wildlife
- Shoreline stabilization and protection
- Facilitation of salt marsh communities
- Ecosystem services
- Increased living shorelines with oysters results in decreased riprap and bulkheads
- Adaptive solution

Appendix F: Poll Results Day 2

Have you ever participated in a living shoreline project, and if so, have you included oysters in the living shoreline?



If you have participated in a living shoreline project with oysters, what types of oyster focused substrates have you used?

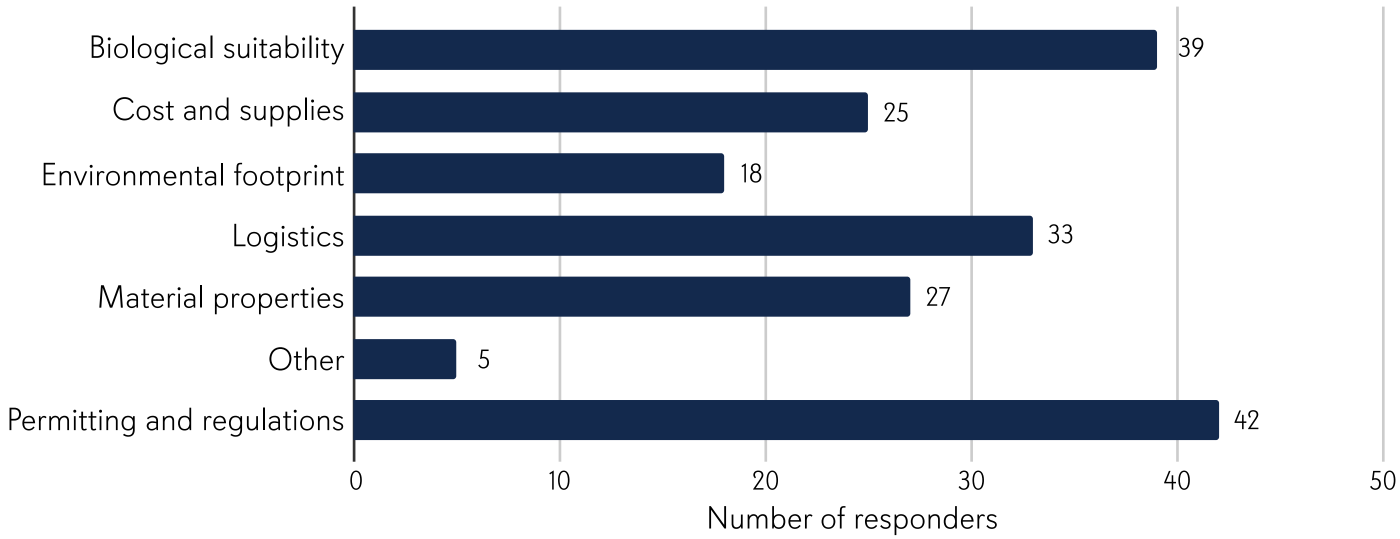


In the Other category, the following were listed:

- Oyster gardens
- Loose oyster shells
- Oyster catcher substrate from Sandbar Oyster Company
- QuickReef
- Wave Attenuation Devices (WADs)
- Previous oyster shell habitats
- Bamboo (Non-native, cut, and coated with concrete)
- Oyster ‘volcanoes’ made of jute and cement

Appendix F: Poll Results Day 2

What aspects of retrofitting existing infrastructure for oysters require greater investigation?



In the Other category, the following were listed:

- Resilience of the shoreline over time
- Habitat suitability studies
- Potential effect of larval transport on retrofit reefs in close proximity to the bottom/ column leases
- The economic impacts on aquaculture
- The engineering analysis and design process
- Ecological trajectories and limitations
- True ecological uplift

Are there other Maryland-specific issues that need addressing?

- Hydrodynamics of oyster larvae
- Carbon sequestration
- Management of shallow water habitat acknowledging changing baseline for shallow water zones
- The mandated stone to vegetation ratio pushes project footprint channelward, impacting aquatic resources like SAV
- Riparian property owners should be expected to grade banks and align structures landward to minimize impacts to aquatic environments
- MDE and USACOE permitting
- Designed reef crest elevation to begin reefs
- Economic analysis to comprehensively and holistically analyze the cost/benefits including opportunity costs, without diminishing the benefits of oyster reef structures
- Addressing the native oyster species survival rates in cold/freezing temperatures and their struggle in low salinity waters
- Assessing the dangers and benefits of introducing species from other places that may overtake native species but can result in improvement of water quality

Strengthening Habitats with Oysters on Retrofitted & Engineered Structures

Program Booklet

Virtual Symposium

Feb 26-27, 2025

Background

This symposium on **Strengthening Habitats with Oysters on Retrofitted & Engineered Structures (SHORES)** is part of an effort to fill key knowledge gaps in support of Maryland's oyster resource and oyster industries. Chesapeake Bay is home to thriving commercial fishing and aquaculture industries and one of the largest oyster restoration efforts in North America. The lack of fresh shell substrate has become a major impediment to all of these activities and alternatives are being considered for large-scale use in restoration and industry efforts. To address this challenge, the Maryland General Assembly mandated a program (SB830 2023) that will evaluate:

1. Types of substrate, including fresh shell, fossilized shell, combinations of shell and alternative substrates that are most appropriate for use in oyster harvest areas.
2. Benefits, including habitat-related benefits, of using stones of various sizes in oyster restoration areas.
3. Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates.
4. Potential for retrofitting existing structures, such as riprap revetments that are unrelated to oyster restoration, but use materials similar to artificial reefs including oyster plantings.
5. Effect of spat size upon deployment on oyster abundance.

This symposium directly addresses topic #4: Potential for retrofitting existing structures, such as riprap revetments, that are unrelated to oyster restoration but that use materials similar to artificial reefs, to include oyster plantings.

In 2024, the Symposium for Alternative Substrates for Oysters (SASSO) addressed topic #3: Alternative substrates used for oyster restoration or repletion in other regions, including the success of efforts to use alternative substrates. If you are interested in learning more about SASSO, see the symposium webpage: **https://www.umces.edu/alternative-substrate-for-oysters**

Symposium Sponsors

This symposium is sponsored by University of Maryland Center for Environmental Science (UMCES). Lead organizers are Dr. Matthew Gray, Dr. Elizabeth North, and Dr. William Nardin of UMCES Horn Point Laboratory. The symposium team also includes Monica Fabra, Kurt Florez, Conor Keitzer, Roshni Nair, and David Nemazie. Graphic design and logistical support are from UMCES Integration and Application Network (IAN).

For questions regarding this symposium please contact Matthew Gray at **mgray@umces.edu** or see the symposium webpage: **https://www.umces.edu/shores-symposium**

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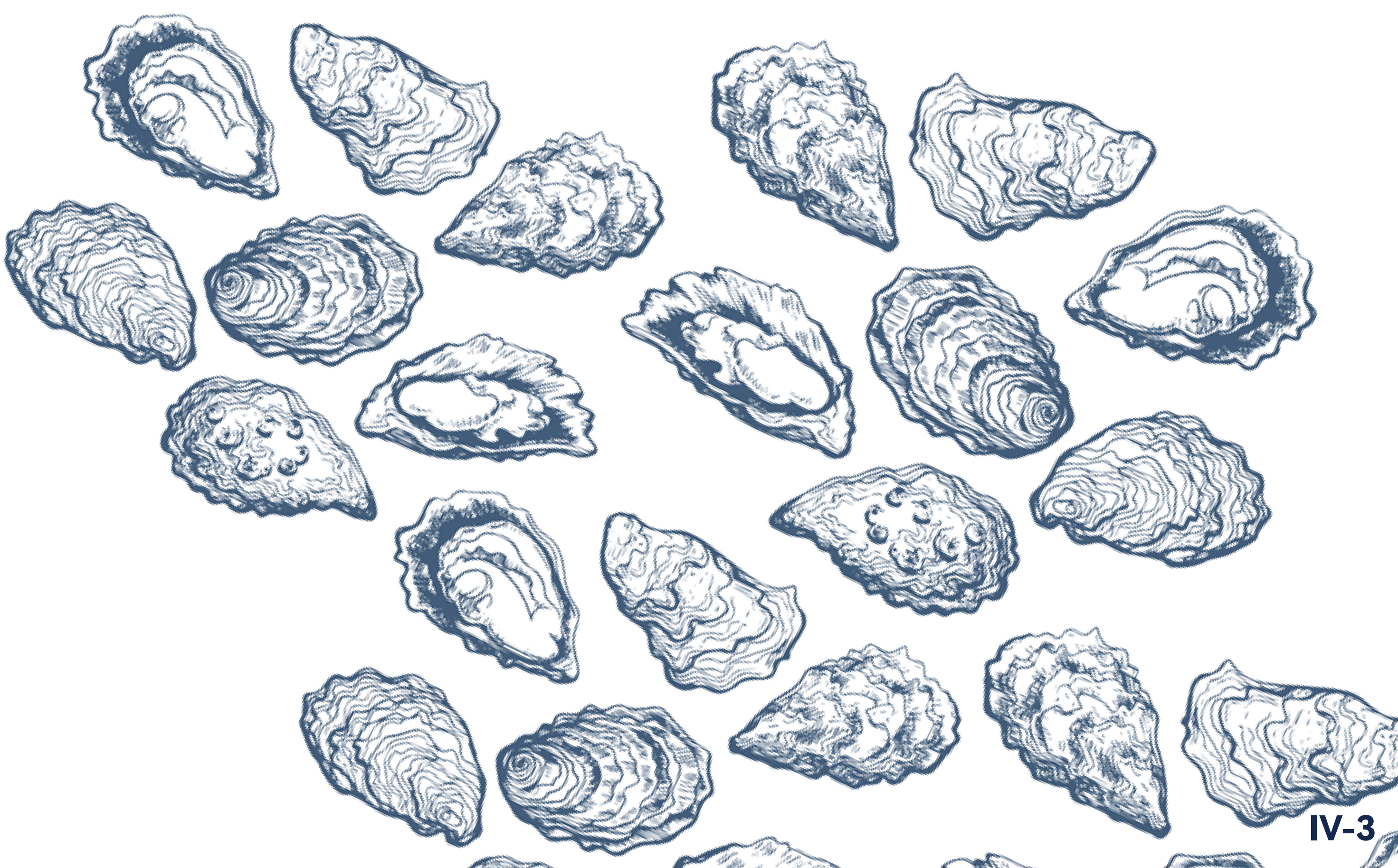


Schedule of Events and Logistics

Wednesday, Feb 26: Retrofitting Existing Infrastructure

10:00 Introduction

10:15 **Rochelle D. Seitz**, Virginia Institute of Marine Science, Batten School of Coastal and Marine Sciences

10:30 **Iacopo Vona**, University of Central Florida, Department of Civil, Environmental, and Construction Engineering

10:45 **Anthony Dvarskas**, Ørsted

11:00 **Jason Spires**, NOAA Cooperative Oxford Laboratory

11:15 **Niels Lindquist**, SANDBAR Oyster Company Inc.

11:30 **Siddhartha Hayes**, Hudson River Park Trust

11:45 **Adrian Sakr**, University of Florida

12:00 Poster session & Chat n' Chew breakouts

01:00 Plenary discussion

02:00 Adjourn

Thursday, Feb 27: Building Engineered Living Shorelines

10:00 Introduction

10:15 **Kate Orff**, SCAPE

10:30 **Carolyn Khoury**, Billion Oyster Project

10:45 **Tyler Ortego**, Natrx

11:00 **Amanda Poskaitis**, Underwood & Associates

11:15 **Mary-Margaret McKinney**, Native Shorelines, a Davey company

11:30 **Adrian Sakr**, University of Florida

11:45 **Alberto Canestrelli**, University of Florida

12:00 Poster session & Chat n' Chew breakouts

01:00 Plenary discussion

02:00 Adjourn

Schedule of Events and Logistics

Poster Session Presenters on both symposium days:

Savanna Barry, University of Florida

George Birch, Oyster Heaven (Day 1 only)

George Thatos, Coastal Technologies

Niels Lindquist, SANDBAR Oyster Company

Nicholas Muzia, Sea & Shoreline

Symposium Logistics

To join the symposium:
https://tinyurl.com/SHORES-Virtual-Symposium

To ask the speakers a question: Type your question in the Zoom chat. Only the speakers and moderators will be able to see your questions.

To join the Poster session & Chat n' Chew:
https://tinyurl.com/Posters-and-Chat-n-Chew

To ask a question or make a comment during plenary: Type your question or comment in the Zoom chat. The moderators will be able to see your questions and comments and will relay them to the panelists.

To receive a copy of the symposium report: All registrants will be sent the report this spring.

Day 1 Invited Speaker: Retrofitting Existing Infrastructure

Rochelle D. Seitz

Professor at Virginia Institute of Marine Science, Batten School of Coastal and Marine Sciences

Rochelle Seitz is a Benthic Ecologist and Professor at the Virginia Institute of Marine Science in Gloucester Point, VA. Her research expertise encompasses three primary areas of focus, including (i) effects of environmental stress, such as shoreline development and hypoxia, upon benthic invertebrate diversity, (ii) predator-prey dynamics and top-down versus bottom-up control of benthic systems, and (iii) restoration ecology.

Her current research projects include the impacts of habitat degradation on faunal communities, restoration of bivalves in the Chesapeake Bay, quantifying nursery habitat quality for the blue crab, and examining benthic predator-prey relationships and food-web dynamics. Additional interests include experimental and theoretical population and community ecology of marine benthic and epibenthic organisms focused on a quantitative understanding of processes operating in estuaries and the coastal ocean.

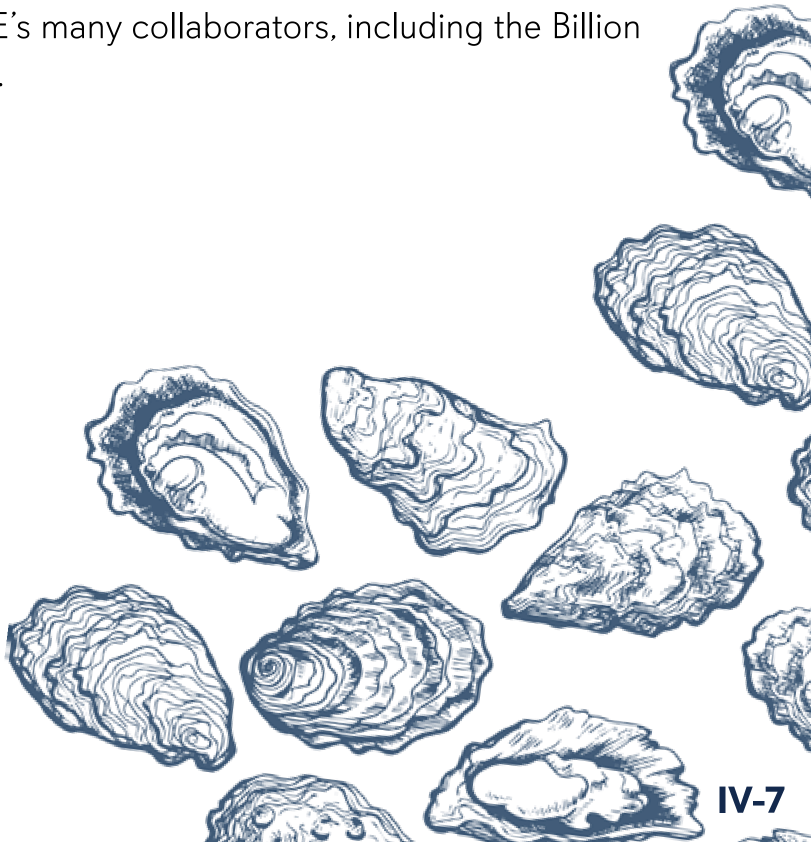
Day 2 Invited Speaker: Building Engineered Living Shorelines

Kate Orff

Landscape Architect, Founding Principal of SCAPE, and Professor at Columbia University

Kate Orff, FASLA is the founder of SCAPE, a landscape architecture and urban design practice with offices in New York, New Orleans and San Francisco. SCAPE's Oyster-tecture and Living Breakwaters (constructed 2024) projects have been celebrated for interweaving social and ecological goals together with climate risk reduction. She is also a Professor at Columbia University with a joint appointment in the School of Architecture and the Climate School.

Kate's talk will focus on the trajectory of oyster restoration in New York Harbor, and how Living Breakwaters evolved into a funded and implemented project in the post-Super storm Sandy recovery process. She will show how the Living Breakwaters project developed, including its engineering and approvals process, and will feature the work of SCAPE's many collaborators, including the Billion Oyster Project.



Day 1: Retrofitting Existing Infrastructure

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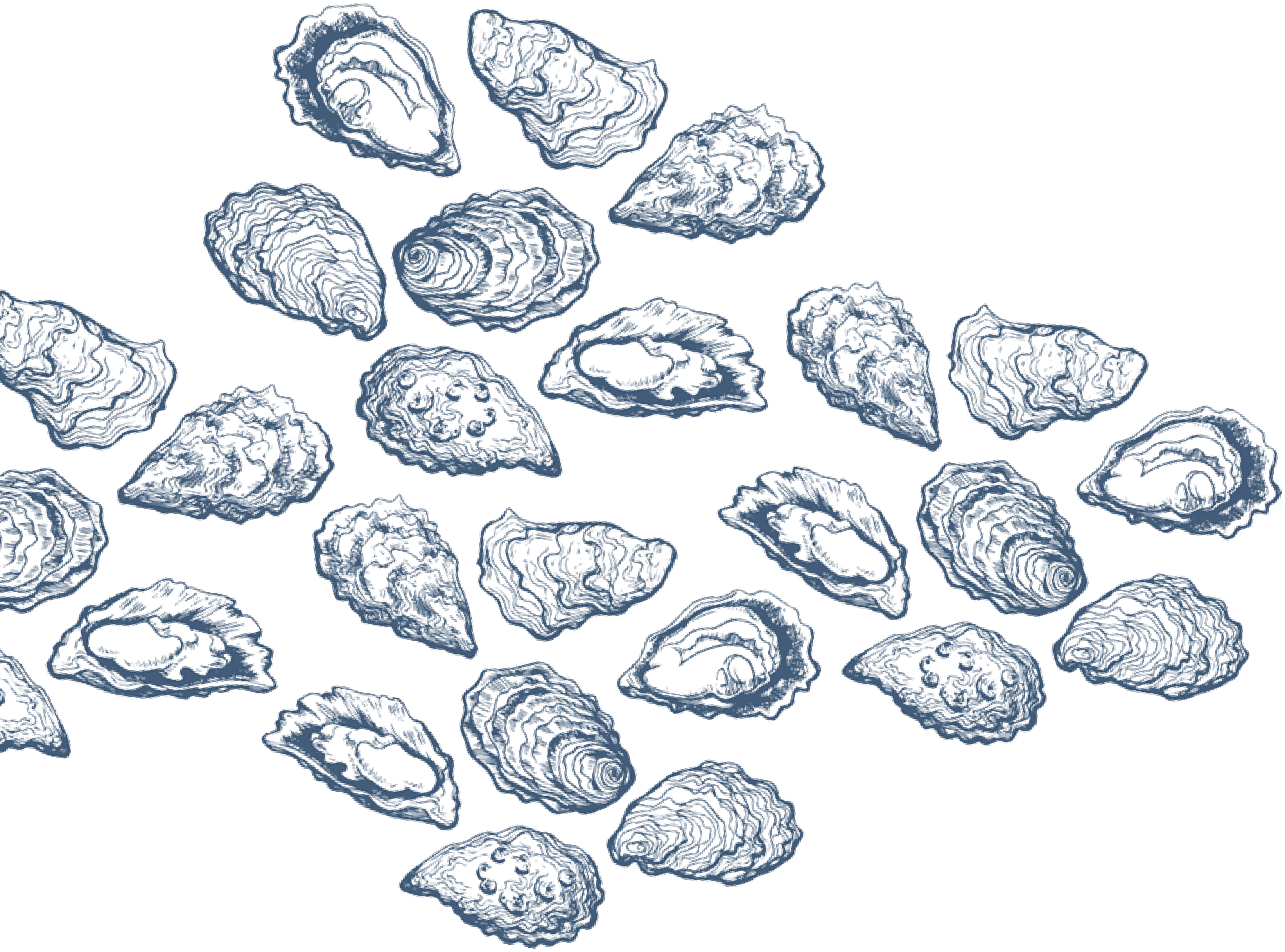

Day 1 Talk Abstracts

Anthony Dvarskas
Ørsted

Integrating oysters into offshore wind lease areas: droppable oyster structure deployment at Borssele 1&2

Authors: Anthony Dvarskas, Karin Bilo, Tommy Kristoffersen

In 2021, Ørsted announced its ambition to have a net-positive impact on biodiversity for all renewable energy projects commissioned by 2030 or later. As a part of meeting this ambition, Ørsted is investigating the potential for nature-inclusive design at its offshore lease areas, including the addition of structured habitat and hard surfaces to benefit critical keystone species like cod and oysters. European flat oysters are a particular concern in the North Sea, given the substantial decline in their numbers and the absence of these reef-builders from areas where they had historically been present.

To address this, Ørsted recently collaborated with Van Oord to install droppable oyster structures at the scour protection for Ørsted's Borssele 1&2 wind lease area in the North Sea. Adult oysters were attached to these structures and, if successful, will generate larvae to colonize the areas adjacent to the installation, providing benefits to biodiversity and local water quality. Video footage will be collected at multiple time points following installation to monitor the structures. These structures are innovative for their lightweight design and their potential to be integrated into scour protection during routine maintenance activities. Some of the droppable structures were also composed of reused materials. This presentation will describe the characteristics of the droppable oyster structures, the installation approach, and the planned monitoring activities to evaluate the success of the deployment.

Siddhartha Hayes
Hudson River Park Trust

Enhancing infrastructure and nearshore habitat in an urban estuary, Hudson River Park, NYC

Authors: Siddhartha Hayes, Carrie Roble, Michaela Mincone

Located on Manhattan's west side between Chambers and W59th Street, Hudson River Park's 400-acre Estuarine Sanctuary waters are predominantly characterized by a homogeneous, fine silt/mud bottom. In a concerted effort to enhance both these mud flats and existing relict marine infrastructure with greater habitat variety, the Park installed over 200 enhancement structures between Piers 26 and 34 from 2021 to 2023. These structures include pile wraps, biohuts, textured concrete pile encasements, reef balls, and gabions. The Park designed the on-bottom reef balls and gabions in clusters to function as a contiguous corridor for nekton seeking shelter in Park piers and piling fields. The pile wraps, biohuts and textured pile encasements were designed to test vertical and off-bottom habitat opportunities that utilize Park pilings. Collectively, these enhancements aim to simultaneously introduce Eastern oysters (*Crassostrea virginica*), to supplement low-but-present annual wild recruitment, and to provide increased and varied benthic and demersal habitat for fishes, crustaceans, other nekton, and non-oyster epibionts. The enhancement structures are being monitored over a five-year period to assess oyster health, estuarine community utilization, water quality, and structure performance. This enhancement project was supplemented in 2022 by another installation of ~300 reef

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balls and gabions further north along Gansevoort Peninsula, as well as a ~100m cordgrass (*Spartina spp.*) salt marsh that has an associated four-year monitoring program. The Park is currently planning an additional enhancement project for an area north of 14th street that will continue to explore adapting marine infrastructure for improved habitat value.

Niels Lindquist
SANDBAR Oyster Company Inc.

Use of Oyster Catcher™ substrates as oyster-enhancing amendments for hardened structures

Authors: SANDBAR Oyster Company Inc.

Hardened structures, such as rock revetments, seawalls, and bulkheads, have long been used for shoreline erosion control and to protect built infrastructure. While certain types of hard armoring, as well as dock and pier pilings, can support the growth of oyster reef communities, their general lack of complex structure and rough surface texturing can limit the extent of oyster community development.

In recent years, structural amendments have been designed to integrate with existing hard structures, aiming to create habitats that foster more robust oyster communities. SANDBAR Oyster Company is currently developing Oyster Catcher™—cement-infused cloth hardscapes—as "cuffs" for pier and dock pilings to enhance oyster community growth in estuarine waters. These cuffs consist of Oyster Catcher™ panels shaped to encircle about half the circumference of a piling and are strapped in place at the optimal intertidal zone for oyster growth (Ridge et al. 2015, Scientific Reports 5; doi:10.1038/srep14785). The cuffs have either a flat or corrugated design. Oyster Catcher™ products are engineered to degrade over time at variable rates, allowing the developing oyster communities to naturally detach and settle on the surrounding seabed. Replacing degraded cuffs can help accelerate oyster accumulation at the base of pilings.

In initial tests, cuffs were installed on dock pilings adjacent to a major navigation channel, where they were exposed to boat wakes and large wind-generated waves. Oysters successfully recruited to the cuffs; however, community development was limited by the use of cuffs designed to degrade relatively quickly. Additionally, the complex habitat created by the cuffs served as a refuge for stone crabs (Menippe mercenaria), which preyed on oyster spat and accelerated cuff degradation. Future testing of Oyster Catcher™ cuffs for enhancing oyster communities on hardened structures will involve longer-lasting cuffs and designs that minimize spaces where crabs can shelter.

Adrian Sakr
University of Florida

Changing of the garden: evaluating the performance and ecosystem functionality of novel oyster garden structures

Authors: Adrian Sakr, Logan Mazor, Joseph P. Morton, Andrew Altieri

Oyster gardening, in which modular oyster reefs are suspended from docks, has become an increasingly common and accessible technique for coastal communities to enhance oyster

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populations for water filtration and biodiversity enhancement. However, little research has been done to evaluate materials and methods for oyster gardens regarding durability and ecosystem benefits, making it difficult to scale up efforts and maximize project success. We conducted a field experiment in a residential canal system of Sanibel Island, Florida where we deployed a variety of oyster garden structures to evaluate performance in oyster recruitment, durability, water filtration rate, and biodiversity. Additionally, the occurrence of Hurricane Ian during the deployment provided an opportunity to evaluate how these structures resisted severe storm events. We tested five structures: (1) a conventional design made of drilled oyster shell on steel wire; and four alternatives (2) GROW concrete discs; (3) jute fiber coated with calcium sulfoaluminate cement; (4) BESE biodegradable plastic matrix panels; and (5) BESE biodegradable plastic mesh bags filled with oyster cultch. All structures survived Hurricane Ian; however, both BESE structures ultimately disintegrated without recruiting oysters. Disc, jute, and shell wire structures demonstrated similar levels of durability, oyster recruitment and growth, and biofiltration rates. Thus, we conclude that material selection considerations may come down to the availability of materials and labor as well as the extent to which cost and biodegradability are prioritized. Our results provide important information for optimizing oyster garden performance while minimizing environmental impacts.

Rochelle Seitz

Virginia Institute of Marine Science

Retrofitting seawalls with artificial substrates promotes oyster recruitment and macrofaunal communities

Authors: Rochelle D. Seitz, Kathleen E. Knick, Alison Smith, Michael S. Seebo, Gabrielle G. Saluta

With the urbanization of coastal cities, natural shorelines have been extensively modified. Shoreline development has increased the presence of vertical seawalls, which can negatively impact benthic macrofaunal communities. Green engineering techniques can be used to enhance inhospitable seawall structures by creating micro-habitats on the structures and using materials that increase the settlement of bivalves. Oysters enhance benthic communities by creating complexity and heterogeneity, providing microhabitats for other macrofauna, which protects them from predation and physical stressors. At two field sites in the Chesapeake Bay, we retrofitted seawalls with artificial substrates with varying habitat complexity and oyster seeding density and investigated the effects on oyster densities and macrofaunal communities. The substrates included 3D printed tiles (0.25 × 0.25 m) with three levels of complexity (flat, 2.5 cm ridges, and 5 cm ridges) plus control tiles of the existing seawall, at three seeding densities (0, 36, and 56 oysters per tile). Tiles were monitored every three months for oyster survival, oyster growth, and primary cover. After a year, tiles were destructively sampled for oyster survival, oyster recruitment, and the macrofaunal assemblage. Both increased tile complexity and higher seeded oyster density increased seeded oyster survival and recruitment of oyster spat. The high-complexity, high-seeded tiles had 10x more recruits than flat, unseeded tiles and 70x more recruits than the controls of the existing seawall. Macrofaunal abundance and biomass also increased as habitat complexity of the tiles increased, providing habitat for larger organisms, such as mussels and mud crabs. Using retrofitted structures on seawalls increased habitat complexity, leading to higher seeded oyster survival, oyster recruitment, macrofaunal abundance, biomass, and species richness in coastal ecosystems.

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Jason Spires

National Oceanic and Atmospheric Administration

Nature based oyster settlement substrate investigations

Authors: Jason Spires

Oysters occupy a unique space in coastal ecosystems and communities. These bivalves provide a range of ecosystem services and direct (wild and farmed fisheries) and indirect (habitat for other fauna, recreational fisheries) economic benefits. Additionally, oysters are increasingly considered as a tool for mitigating effects of climate change and promoting coastal resilience. Current oyster restoration practitioners frequently desire to place oysters along hardened shorelines but are hampered by inefficient or costly methods. In regions of high natural recruitment, oysters settle naturally on a variety of hardened surfaces, however, in regions of low natural recruitment this type of greening gray infrastructure is more challenging. Our work investigates novel population replenishment techniques by using biodegradable oyster setting materials (basalt, coconut fiber) and mechanical behavioral manipulation (bubble curtains) to create oyster communities on hardened structures. Our objectives are to develop a cost-effective material/technique that can be used to create oyster populations on hardened surfaces. Initial oyster settlement rates are similar among tested materials, however, retention is poor on the most pliable materials. Additionally, larval behavior was not controlled by bubble curtains and modifications to the experimental design are required.

Iacopo Vona

University of Central Florida

Integration on submerged breakwaters offers new adaptive shoreline protection in low-energy environments in the face of sea level rise

Authors: Iacopo Vona and William Nardin

Sea level rise (SLR) and increasing storm frequency threaten coastal environments. To naturally protect our coasts, living organisms such as oysters can be used. They provide a multitude of benefits for the surrounding environment, including coastal protection. Unlike any common gray structure used for coastal defense, such as breakwaters, oysters can grow with SLR and self-repair from damage following extreme events. In this study, we analyzed the coupling between breakwaters and oysters through a numerical model, Delft3D-SWAN, validated with field data. The research aimed to evaluate the performance of this hybrid solution under future scenarios of climate change and SLR. The study results showed that the coastline was more preserved and protected over time when oysters were included in the simulation, thanks to their capability to self-adapt over a changing climate. Incoming wave heights and sediment export from the shore were reduced compared with the use of gray breakwaters alone, resulting in a resilient and healthier coast. The coupling between oysters and breakwaters may represent a valuable and effective methodology to protect our coast over a changing climate and a rising sea, where optimal conditions for oyster survivability occur and are maintained over time.

Day 2: Building Engineered Living Shorelines

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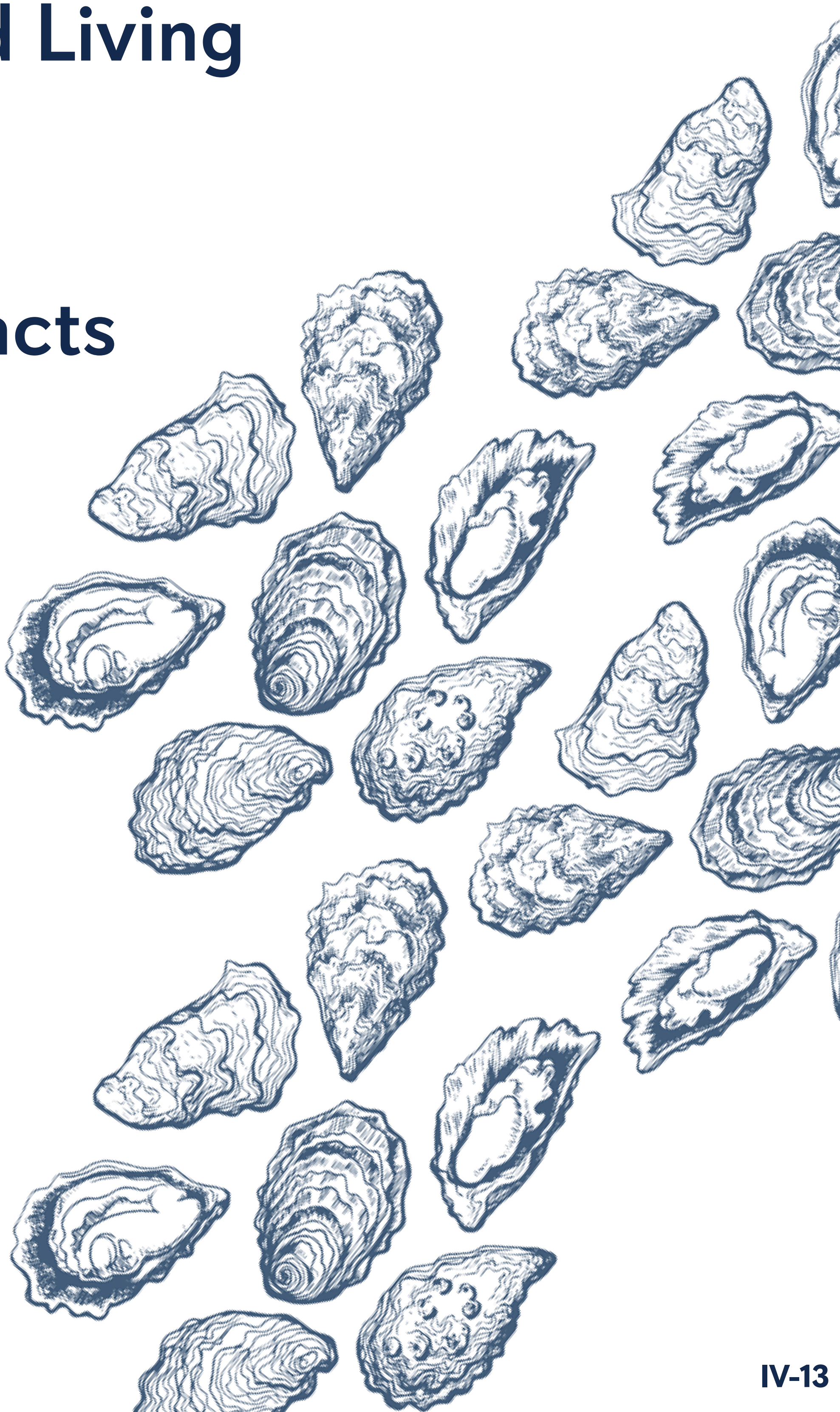

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Alberto Canestrelli
University of Florida

Integrating physical and numerical models to assess wave dissipation and sediment accumulation at restored oyster reefs

Authors: Alberto Canestrelli, William Nardin, Rafael O. Tinoco, Jacopo Composta, Salman Fahad Alkhidhr, Kamil Czaplinski, Luca Martinelli, Savanna Barry, Anthony Priestas, Duncan Bryant

Oyster reef ecosystems are increasingly recognized for their resilience and ability to provide sustainable, nature-based alternatives to traditional "gray" infrastructure. These reefs offer critical benefits, such as mitigating shoreline erosion, promoting sediment deposition, and supporting adjacent habitats like salt marshes. Despite their potential, there is a limited understanding of the physical processes driving sediment transport around oyster reefs under varying wave and tidal conditions, reef geometries, and locations. Bridging this gap is vital for optimizing sediment retention and supporting shoreline progradation.

This study aims to quantify the mechanisms through which oyster reefs stabilize sediments. Using a combination of physical and numerical modeling, researchers are investigating the influence of tidal and wave dynamics, longshore currents, reef geometries, and distances from the coast. Initial experiments employ 1:7 scaled 3D-printed oyster reefs in a wave flume at the Ven Te Chow Hydrosystems Lab, University of Illinois Urbana-Champaign. Concurrently, numerical simulations with OpenFOAM on the HiPerGator
high-performance cluster analyze wave-reef interactions under varying conditions.

Findings from these efforts will guide large-scale experiments at the Large-scale Sediment Transport Facility (LSTF) in Vicksburg, MI, conducted at a 1:2 scale. These tests will include regular and irregular waves (i.e., wave spectra in both frequency and direction), wind-driven and tidal longshore currents, and tidal variations in water level. Four distinct reef geometries will be tested under these hydrodynamic conditions. The collected data will calibrate a numerical model, enabling predictions of reef-induced sediment aggradation beyond experimental conditions and identifying optimal reef designs.

The outcomes of this research include a robust dataset on sediment dynamics, calibrated models, and actionable guidelines for oyster reef restoration. These results will inform sustainable coastal management strategies, enhancing shoreline protection and promoting the use of oyster reefs as effective, nature-based solutions for long-term resilience in coastal environments.

Carolyn Khoury
Billion Oyster Project

Living breakwaters: engineering with nature and restoring oyster reef habitat

Authors: Pippa Brashear, Carolyn Khoury

Widely considered a model for climate-adaptive nature-based infrastructure, Living Breakwaters is a $111 million project with a layered approach to risk reduction—enhancing physical, ecological, and social resilience along the South Shore of Staten Island.

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The project consists primarily of 2,400 linear feet of near-shore breakwaters—partially submerged structures built of stone and ecologically-enhanced concrete units—that break waves, reduce erosion of the beach along Staten Island's Tottenville shoreline, and provide a range of habitat spaces for oysters, fin fish and other marine species. The Living Breakwaters concept was developed by a large, multi-disciplinary team led by SCAPE as part of a winning proposal for Rebuild By Design, the design competition launched by the U.S. Department of Housing and Urban Development (HUD) after Superstorm Sandy.

The breakwaters are designed to reduce the impact of climate-intensified weather events on the low-lying coastal community of Tottenville, which experienced some of the most damaging waves in the region and tragic loss of life during Superstorm Sandy. Informed by extensive hydrodynamic modeling, the breakwaters are also designed to slow and, eventually, reverse decades of beach erosion along the Tottenville shoreline. The breakwaters are constructed with "reef ridges" and "reef streets" that provide diverse habitat space. Billion Oyster Project (BOP), a non-profit organization based in New York City whose mission is to restore functional, self-sustaining oyster reefs to New York Harbor, will introduce additional substrate seeded with juvenile oysters to the breakwaters beginning in 2025.

Beyond the physical breakwaters and habitat restoration, the project also aims to build social resilience in Tottenville through educational programs and the implementation of an open-access curriculum for local schools for local schools in partnership with BOP and local community committees and action groups.

Mary-Margaret McKinney
Native Shorelines, A Davey company

Quantitative evaluation of an alternative oyster-centric living shoreline system

Authors: Mary-Margaret McKinney, Worth Creech, Whitney Thompson, Chris Paul, John Darnall, and Bret Webb.

Coastal erosion and shoreline retreat, resulting from both from extreme weather events and sea level rise, pose great challenges to coastal management across U.S. coastal areas. To address this challenge, many State, Local, and Federal stakeholders have deployed living shorelines as a cost-effective method of reducing shoreline retreat rates and providing ecological benefits such as marine habitat, fish spawning areas, and shellfish and oyster habitat.

As such, the deployment of these structures has gained increasing popularity, and many new technologies and variations of living shorelines have been developed in recent years. However, coastal engineering metrics such as wave attenuation, structural stability, and changes to current velocities are rarely validated prior to deployment. Native Shorelines' QuickReef® technology is one of the new types of living shorelines and has been deployed along over 5 miles of shorelines in North Carolina and Virginia. Qualitative observations from deployment sites appeared to show significant oyster spat recruitment and a reduction in shoreline retreat rates. In early 2024, QuickReef® designs were evaluated via physical and numerical modeling to determine the effectiveness and stability of the structures.

A desktop study evaluating field conditions at representative sites was performed to inform critical

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design forcings for flume study purposes, which was then conducted at the University of South Alabama Center for Applied Coastal Engineering and Science. Wave attenuation, stability, and current velocities were measured during physical modeling. Results from the wave flume study were utilized to calibrate FLOW-3D models. This presentation will discuss findings from the physical and numerical modeling studies as well as demonstrate the overall effectiveness of living shoreline designs using quantitative methods.

Kate Orff
SCAPE

Living Breakwaters

Designed by SCAPE, COWI, Arcadis, SeArc Ecological Marine Consulting, WSP, MFS Engineers, Prudent Engineering. Engagement by Billion Oyster Project. Construction by Weeks Marine, Ramboll, Baird. Environmental Review & Permitting by AKRF.

Kate's talk will focus on the trajectory of oyster restoration in the New York Harbor, and how Living Breakwaters evolved into a funded and implemented project in the post-Super storm Sandy recovery process. She will show how the Living Breakwaters project developed, including its engineering and approvals process, and will feature the work of SCAPE's many collaborators, including the Billion Oyster Project.

Tyler Oretego
Natrx

Integrating engineered structures and oyster habitat for resilient shorelines

Authors: Drew Keeley, Tyler Ortego

The integration of oyster and marine habitat with engineered structures offers a transformative approach to enhancing shoreline resilience and ecological health. Traditional materials and construction methods often lack adequate capability to balance coastal protection with optimal habitat formation. New technologies are emerging that provide new capabilities for coastal resilience and habitat restoration practitioners.

Natrx has pioneered the Dry Forming™ advanced manufacturing technique, which enables development of tailored, habitat-positive structures that address site-specific needs while promoting oyster colonization and ecosystem restoration. Natrx reef structures feature customizable void spaces and biomimetic surfaces to optimize conditions for oyster recruitment, habitat formation, and ecological uplift. These structures support shoreline stabilization and also deliver ecosystem services such as water filtration and biodiversity enhancement. By leveraging digital tools, advanced manufacturing, and material science innovations, Natrx can efficiently produce scalable, site-specific solutions that enhance the longevity of coastal infrastructure and integrate seamlessly with existing gray and hybrid systems.

Case Study: Hog Island, VA - A nature-based wetland protection and habitat restoration solution using Natrx ExoFormsTM along Hog Island in Gloucester County, Virginia. The goals of this project was to

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protect the residential and commercial properties along Monday Creek and the York River, reduce erosion and sedimentation into the Chesapeake Bay, and a focus on enhancing maritime habitat for shorebirds, oysters, and other marine life. Designed customized interlocking ExoForms for highwave energy areas exposed to Mobjack Bay and low crested oyster reef ExoForms for low energy areas. Placed 972 linear feet of large stacked units and 122 linear feet of low crested oyster reefs. Added available surface area for 14 million oysters that will filter water and provide foundational habitat and prevent 40,000 tons of eroding sediment from entering the bay system and contributing to suspended sediment and nutrient loading.

Amanda Poskaitis
Underwood & Associates

Oyster recruitment on dynamic living shorelines

Authors: Underwood & Associates, Maryland Coastal Bays Program

Underwood & Associates, a design/build stream and living shoreline contractor, developed the dynamic living shoreline, which can be adapted to various site conditions to create critical shallow water wildlife habitat and solve erosion issues for communities and property owners. Underwood uses all native stone material in our vegetated headland designs and we have been working to incorporate oysters into our living shorelines to achieve even greater habitat co-benefits on our project sites. An example of oysters thriving on one of our projects is at the Assateague State Park Living Shoreline – a partnership between Assateague State Park, Maryland Coastal Bays Program, and Underwood & Associates.

Oyster surveys have been conducted at the Assateague Living Shoreline site since 2021 by the Maryland Coastal Bays Program. The surveys started after noticing an abundance of oysters along the vegetated headlands. Years of surveying has shown that although this site experiences oyster recruitment, the oysters tend to not live past 1-2 years due to disease or other environmental factors. This is typical in the Maryland Coastal Bays watershed, which has not had a self-sustaining wild oyster population in over 50 years. In addition to the research conducted on oysters at the Assateague Living Shoreline, we are working on many other living shoreline projects throughout the Chesapeake and Coastal Bays that have potential for incorporation of oysters. We will be presenting on our work and exploring how to incorporate oysters into living shoreline designs effectively. We will share multiple projects, research, and lessons learned.

Adrian Sakr
University of Florida, Department of Environmental Engineering Sciences

Living in a material world: support for the use of natural and alternative materials in coastal restoration and living shorelines

Authors: Adrian Sakr, Andrew Altieri

The size and expense of coastal restoration efforts are increasing exponentially to mitigate anthropogenic environmental impacts and achieve international conservation goals. As part of these efforts, a variety of conventional materials including plastic, metal, and concrete are used in

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breakwater, settling substrate, vegetation stabilization, and sediment retention structures because of their availability, inexpensive purchase price, and predictable properties. However, questions regarding sustainability arise given the adverse environmental impacts of the life cycle processes for each material.

Life cycle impacts from production, transportation, installation, and degradation should be key considerations in material selection, with criteria that allow decision makers an opportunity to evaluate less impactful alternative materials. Natural and reduced-impact alternative materials include natural elements such as plant fibers and rock as well as reduced-impact materials such as bio-based and biodegradable plastics. These items may have comparable availability and functionality and exhibit reduced carbon, chemical, and particulate emission impacts. However, they are often not selected for full-scale restoration applications due to uncertainties regarding their financial cost and ability to replace conventional materials. Here, we compare conventional and reduced-impact alternative materials for use in coastal restoration applications. The function, engineering performance, and life cycle environmental impacts are reported for each material followed by a presentation of case studies that illustrate the value of appropriate material selection. We then compare the impacts of material sourcing and product lifespan to develop a material selection framework enhancing the selection process of reduced-impact alternatives.

This study reveals a need for more detailed and standardized life cycle information about the materials used in the coastal environment. The proposed framework allows more emphasis on material life-cycle implications in the design process, which could lead to enhanced use of alternative over conventional materials and improved project value and outcomes.

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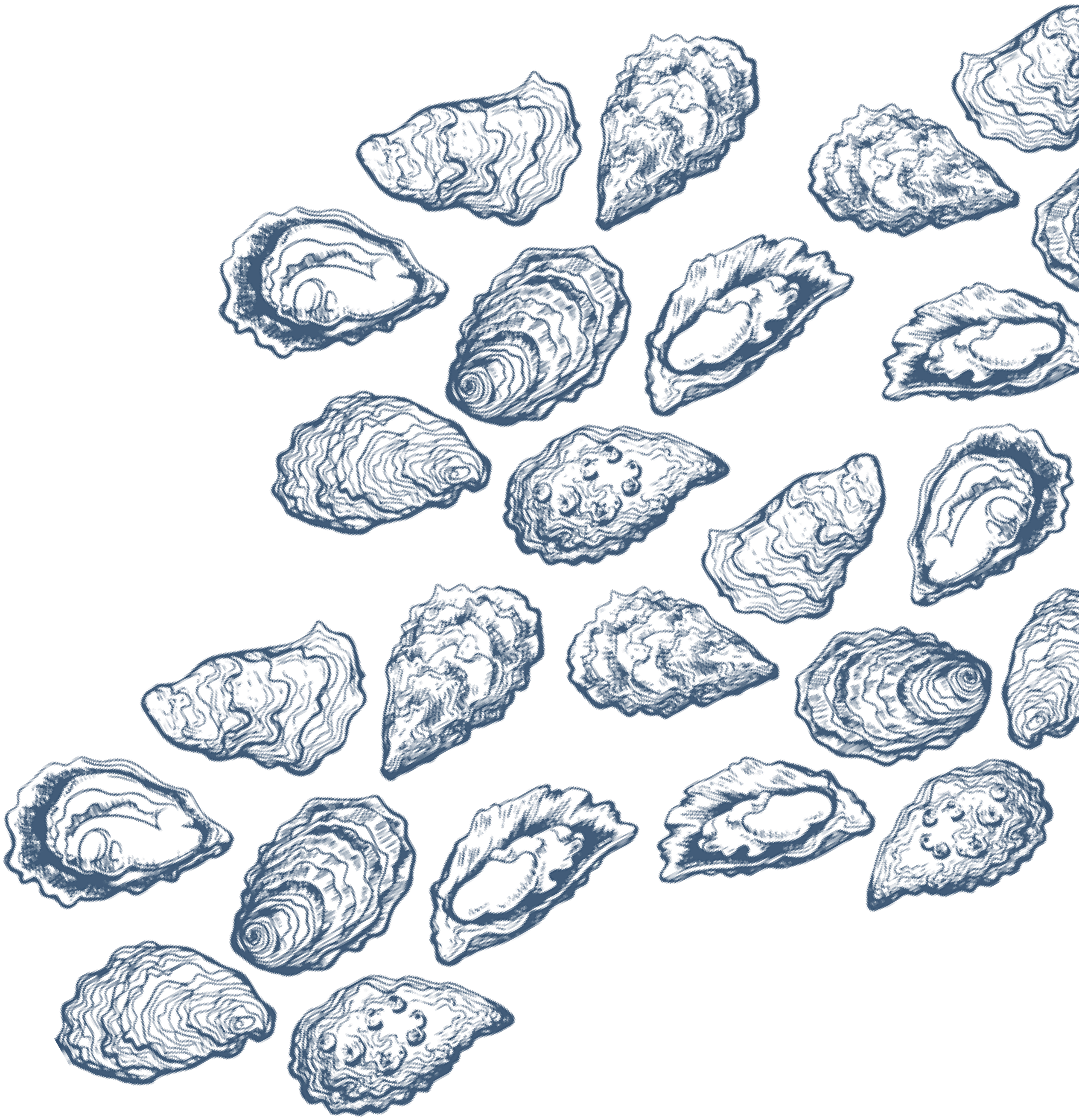

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Savanna Barry
University of Florida

Performance assessment of living shoreline retrofits on Florida's Gulf of Mexico coast

Authors: Savanna C. Barry, Elix M. Hernandez, and Mark W. Clark. University of Florida, Florida Sea Grant.

A community-driven effort in Cedar Key, Florida, USA, resulted in the construction of three living shoreline retrofits intended to bolster failing coastal infrastructure and restore habitat functions in Daughtry Bayou. A multi-year monitoring program tracked changes in elevation and vegetation communities across the entire shoreline profile from lower-intertidal to upland/transitional zones and measured wave attenuation during typical and extreme (hurricane) conditions. Overall, these living shoreline retrofits served to soften more than 30% of the bayou's shoreline, dramatically reducing the extent of armored shoreline in direct contact with tidal influence. The extent of vegetated habitat area has increased at all three sites, despite sediment export from higher elevation zones driven largely by repeated impacts from hurricanes and tropical storms. These living shorelines reduced wave energy by 33 to 79% in typical conditions and by up to 28% in hurricane conditions, consistently outperforming armored shorelines, even during an extreme event (Hurricane Idalia). The living shoreline retrofit projects assessed here have persisted through and shown signs of recovery after multiple tropical storms and hurricanes, while providing important energy reduction services. Thus, living shoreline retrofits continue to be a cost-effective shoreline management strategy in the short term for this area. However, our analyses suggest that persistence of these shorelines could be threatened by the combination of sea-level rise (by 2040), upland armoring, and an increasing risk of more intense tropical systems. Therefore, future interventions should more carefully consider these threats in conjunction with habitat enhancement goals.

George Birch
Oyster Heaven

The Mother Reef: A scalable clay based biodegradable substrate for oysters

Authors: George Birch, Ronald Lewrissa, Jochem van der Beek and Natacha Juste-Poinapen

The "Mother Reef," developed and patented by Oyster Heaven, is a step change in the scalability, predictability and permissibility for building oyster focused engineered living shorelines. The low fired clay structures are tunably biodegradable (depending on firing temperatures), they are an effective oyster settlement substrate and can be produced at generic brick manufacturers around the world. An average factory can be brought online in a matter of months and can produce enough substrate for 100 acres of reef per day for the same price as household bricks.

Constructed from locally sourced clay, Mother Reefs are designed to facilitate oyster settlement, growth, nutrient flowthrough, reproduction, and protection from predators. Their trapezoidal shape and sine wave patterned ribs maximize settlement surface area while minimizing contact area, reducing spat loss during transport.

The Mother Reef's innovative design and use of natural materials are key to its scalability and permissibility. As a biodegradable structure, it seamlessly integrates into the marine environment,

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generating natural reef development without long-term ecological disruption. The scaffolding eventually melts away into the background sediment, chemically and physically indistinguishable from the sediment already there. This approach aligns with current policy trends that favor nature-based solutions for coastal protection, making it more likely to secure necessary permits for large-scale deployment.

The Mother Reef's adaptability to local conditions further enhances its scalability and permissibility. Its composition and structural arrangement can be tailored to optimize specific ecosystem services, such as biodiversity enhancement or coastal erosion mitigation, based on the needs of the local environment.

By providing a scalable, permissible, and biodegradable solution for oyster reef restoration, Oyster Heaven will play a pivotal role in building resilient and sustainable living shorelines. Its innovative design and alignment with policy objectives position it as a leading technology for large-scale coastal protection and marine habitat regeneration.

George Thatos
Coastal Technologies

Coastal Technologies Corp's Oyster Reef Building Technology

Authors: George Thatos, and Raphael de Perlinghi

Coastal Technologies Corp (CTC) introduces a revolutionary patented solution to address the global need for oyster reef restoration—a critical factor in coastal resilience, pollution remediation, and ecosystem recovery. Standard reef-building methods are slow, labor-intensive, and suffer from failure rates as high as 85%. CTC's innovative, nature-inspired technology overcomes these limitations, enabling near-instant reef creation while preserving coastal ecosystems.

Our Oyster Reef Building system uses stainless steel corkscrew armatures installed into sediments using simple tools. These armatures support stone plates, providing elevated, predator-resistant habitats for oysters. By raising reefs off the seafloor, our system avoids issues like siltation, hypoxia, and subsidence—common causes of failure in traditional methods. The vertical structure enhances resilience to climate change and allows for adjustments to rising sea levels. Easy installation, minimal disruption to coastal mudflats, and high surface area make this system efficient, scalable, and adaptable.

CTC's technology serves vulnerable coastal communities worldwide, particularly those threatened by storm surges, erosion, and sea-level rise. Oysters act as "ecosystem engineers," filtering water, preventing harmful algae blooms, and supporting diverse marine life. For communities like the Biloxi-Chitimacha-Choctaw Indians in Louisiana, our system offers food security, cultural preservation, and coastal protection.

Field-tested prototypes have demonstrated the technology's effectiveness, with further validation planned through partnerships with academic institutions, NGOs, and coastal restoration groups. CTC's team combines technical expertise with a passion for environmental and social justice, ensuring community involvement in every stage of implementation.

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By dramatically increasing the capacity to build resilient oyster reefs at scale, CTC provides a practical, cost-effective tool to protect coastal populations, restore ecosystems, and mitigate climate impacts. With support from SHORES, we aim to advance this technology to market, navigate regulatory pathways, and foster partnerships that bring life-saving solutions to the communities that need them most.

Niels Lindquist
SANDBAR Oyster Company Inc.

A decade of development, refinement and scaling of Oyster Catcher™ hardscapes for oyster habitat creation, living shorelines and oyster culturing

Authors: Niels Lindquist and David Cessna

At the 18th International Conference on Shellfish Restoration in Charleston, SC in 2016, Niels Lindquist and the late David Cessna (co-inventors), made the first public presentation on an innovative, composite hardscape for oyster habitat creation/restoration and oyster culturing. Our degradable hardscape, trade named Oyster Catcher™, is a composite of plant-fiber cloths infused with cements (any and all mineral-based binders/hardeners claimed) made by soaking and manipulating the cloth in cement slurries to work the cement into the threads of the cloth.

Prior to cement hardening, we form the cement-infused cloth pieces into different modular shapes, some of which we use to build robust reef frameworks and others to trap sediments and thereby promote salt marsh development. The surface of Oyster Catcher™ is highly textured and exceptionally attractive to oyster larvae and protective of juvenile oysters. In addition to reef building, a 3-dimensional, pretzel-shaped Oyster Catcher™ derivative is proving to offer a facile path for capturing and manipulating wild and hatchery settled spat for culturing for food and oyster restoration products. In addition to Sandbar Oyster Company's direct development efforts with Oyster Catcher™, independent, third-party testing is showing Oyster Catcher™ to be an exceptionally valuable technology in the living shoreline/shoreline protection toolbox.

Oyster Catcher™ is now being used in multiple, large-scale living shoreline and oyster habitat creation projects in North Carolina, Virginia, Georgia and California. Our cement-infused hardscape technology is owned by UNC Chapel Hill and now patented in Australia, Canada and New Zealand and is under examination in the US and EU. Sandbar Oyster Company Inc. has an exclusive license from UNC to commercialize this technology. This presentation offers an overview of our work developing and testing Oyster Catcher™ and views of projects showing the range of applications of Oyster Catcher™ products.

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Nicholas Muzia
Sea & Shoreline, LLC.

The Oyster Ark: A new role for oyster farming in ecosystem restoration

Authors: Nicolette Mariano, Nicholas Muzia P.E., Nicholas Bourdon

Oyster aquaculture offers a unique opportunity to enhance environmental restoration while supporting local economies. This presentation highlights a pilot project conducted in Florida's Indian River Lagoon by Treasure Coast Shellfish, which aimed to integrate oyster farming with ecosystem restoration efforts. The project evaluated a novel technique, the "Oyster Ark," designed to capture microorganisms from healthy sites and transplant them to less productive or restoration sites. By introducing live oysters and their associated microorganism communities, the Oyster Ark approach appears to accelerate the growth and success of restoration sites.

In addition to its restoration potential, the project documented the broader biological life supported by responsible oyster aquaculture, showcasing its role as an environmental asset. The initiative also explored the potential for oyster farmers to generate supplemental revenue through restoration activities, creating a symbiotic relationship between sustainable aquaculture and ecosystem health.

This presentation will discuss the outcomes of the pilot project, including its ecological and economic impacts, and seek feedback on how this approach could be refined and scaled to support both environmental restoration and the viability of local shellfish farms.