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The Use of Non-Plastic Materials for Oyster Reef and Shoreline Restoration: Understanding What Is Needed and Where the Field Is Headed

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Abstract: Oyster and shoreline restoration is occurring around the globe to recover lost ecosystem services. In the state of Florida, USA, dozens of estuarine habitat restoration projects are underway. These projects have traditionally relied on both natural and man-made materials, including plastics. As the impacts of plastics on marine ecosystems are better understood, practitioners are increasingly focused on plastic-free restoration. To better understand this transition, we surveyed Florida restoration practitioners in April 2021 to capture current non-plastic restoration project trends and their status. Our descriptive survey goals were to understand: (1) what non-plastic materials have been tested, (2) trade-offs between plastic and non-plastic materials (e.g., cost, sourcing, volunteer engagement), and (3) the performance of non-plastic materials. Responses indicated that a variety of non-plastic materials are currently being used, including rock, cement-infused jute structures, cement Reef Balls™ (Reef Ball Foundation, USA), BESE-elements®, and metal gabions. Overall, these materials are more expensive and equally or more difficult to install than previously popular plastic-based materials. No "best" non-plastic material emerged from our survey in part because many novel materials have been deployed for under three years. Long-term performance under a variety of abiotic and biotic conditions is thus a future research priority.

Keywords: living shoreline; *Crassostrea virginica*; coastal restoration; Indian River Lagoon; Naples Bay; Cedar Key; gabions; BESE-elements®; oyster prism; Reef Ball™

1. Introduction

The degradation of marine habitats has resulted in the loss of biodiversity and associated ecosystem services (e.g., [1]). Estuarine habitats in particular have suffered extensive habitat losses, including shellfish reefs [2], salt marshes [3], mangrove wetlands [4], and seagrass beds [5]. These habitats provide critical ecological benefits such as refuge and foraging areas for many species, including recreationally and commercially important species [1,6], denitrification and nutrient cycling [7,8], water filtration [9], and carbon sequestration [10]. Coastal wetland habitats also attenuate waves and provide a natural buffer against erosive forces [11–13]. Loss of these areas can leave property and infrastructure susceptible to damage and erosion associated with wave energy and storm events. Estuarine habitat restoration efforts, including those focused on oyster reefs and shorelines, can help recover these lost ecosystem services [14–20].

In the southeastern USA, eastern oyster (*Crassostrea virginica*) populations have declined significantly due to diseases, freshwater diversions, harmful algal blooms, and other human impacts such as boat strikes and boat wakes or the installation of seawalls along shorelines (e.g., [2,21,22]). Oyster replenishment has been underway for over a century, especially in overharvested, subtidal areas such as Chesapeake Bay and Apalachicola Bay, FL (e.g., [23]). Restoration efforts have accelerated in the Gulf, Chesapeake, and Southeast USA over the past two decades [2,24]. Oyster cultch is very important in coastal restoration efforts, and it can be placed on the original reef footprint (restoration) or in new locations that exhibit favorable conditions (enhancement) in systems that historically supported oysters. Cultch serves as a foundation upon which oyster spat, either naturally recruiting or seeded onto the material, can settle and grow, eventually building reefs in subtidal or intertidal areas. Common historic cultch materials are recycled oyster shell, fossilized bivalve shell, or rock. Those basic materials have been used in small-scale, community-based restoration efforts (e.g., [25], or deployed from barges for large-scale restoration efforts [18,26,27]. In the Gulf of Mexico and Chesapeake regions where numerous large-scale restoration efforts have been implemented, shell material became limited and practitioners turned to concrete rubble, mixed rock material, pre-fabricated concrete structures (e.g., Oyster Castles®, Reef Balls™), or a combination of materials [24,28–30].

Along shorelines, hardened structures intended to control erosion (riprap, seawalls, bulkheads) have been shown to degrade habitat and ecological functions, and cannot adapt to changes in sea level or other coastal processes, leading to high societal costs [31]. Living shorelines or erosion control projects that incorporate natural elements, such as oyster shell and marsh vegetation, are an alternative to hardened structures and provide many environmental and societal benefits [32]. Oyster habitat enhancement is often a component of living shoreline designs, where materials are deployed as breakwaters to protect plants along the water's edge also become living reefs following natural oyster recruitment [33]. One common approach involves creating breakwater structures out of Naltex™ Duronet® aquaculture-grade polyethylene mesh netting and filling bags with 20–30 pounds of recycled oyster shell [34]. The bags are laid perpendicular to the shore so they do not roll or dislodge when met with wave energy. Groups of bags form reef modules that run parallel to shore; they can be arranged to fit the contours of the shoreline and stacked to meet target elevations. The mesh size allows free-floating oyster larvae to enter the bag and settle on the shells inside. Next, oysters grow out and around the bag as the resulting reef fills in over time. The stacked bags eventually provide a living wave break against erosive wind wave and boat wake energy [25,35]. This plastic mesh is inexpensive, easy to obtain, volunteer-friendly, and has no observed negative impacts on oyster recruitment or other biodiversity associated with oyster breakwaters (e.g., coastal birds, infaua, fishes, mobile and sessile invertebrates, mammals) (e.g., [36–39]).

1.1. The Problem with Plastic

The global issue of macro- and microplastic pollution is becoming more fully understood and embraced by both the public and the scientific community. Macroplastics are commonly referred to as marine debris while smaller pieces are referred to as microplastics [40]. Microplastics (plastic pieces <5 mm in length) have been documented in all coastal and oceanic areas examined, ranging from the ice sheets in Antarctica to deep-sea trenches in the Pacific Ocean [41,42]. There is an increasing body of evidence that microplastics are one of the most pervasive pollutants in the marine environment, and estuaries are frequently considered microplastic hotspots due to the long residence time of water. The most common types of microplastics are fibers, fragments, and beads; fibers are the dominant type found in many estuarine systems, including those in Florida's Indian River Lagoon (e.g., [43]). Microplastics have been found in most vertebrate and invertebrate species examined [44]. Of particular concern are the large numbers of plastics found in the tissues of filter-feeding species such as oysters (e.g., [45]) and top predators, such as raptors, that bioaccumulate plastics from the prey they consume [46]. Recent data has documented that some, but not all, plastic pieces are excreted by these animals (e.g., [47]), while the retention of other plastics in animal tissues can significantly reduce survival and reproductive success (e.g., [48,49]).

As we learn more about the detrimental impact of plastics on marine environments, previously praised and successful (in terms of oyster recruitment, sediment accretion, etc.) restoration projects have come under scrutiny for using plastic-based products, in particular the use of plastic oyster shell bags. While no direct links have been established between coastal restoration efforts and increased concentrations of microplastics, any additional plastic materials in the marine environment may contribute to the problem. The restoration community is pro-actively exploring whether alternative, non-plastic materials can achieve the structural and the functional habitat results that plastic materials have yielded. Florida has been the site of pilot testing for a variety of plastic-free alternatives for restoration materials, but there is no clear best replacement for plastics at this time, especially for materials that can encase oyster shell. Natural fibers such as jute, coconut coir, and hemp have been tested; and, in recent years, new variations that combine natural fibers with mineral hardeners such as Portland or calcium sulfoaluminate (CSA) cement have gained followings. Metal mesh in different thicknesses has also been tested as an alternative to plastic oyster shell bags. Thicker gauge mesh can be formed into boxy, rigid gabions that can be filled with oyster shell, while a thinner gauge mesh creates soft-sided gabions that act more like plastic mesh bags. In situations where sourcing oyster shell is not logistically feasible or cannot match the scale of material needed, native rock has been utilized. In Florida, limestone and coquina have been used as cultch on some subtidal, large-scale reef restoration projects; no plastic materials are required in this type of design.

1.2. The Need for a Statewide Assessment of Progress

With so many materials being tested, it is important to share both methods and results for the most effective alternatives to date. The primary focus of our assessment is the state of Florida, USA due to the wide range of active restoration partners across the state, dominance of intertidal oyster reefs, small-scale nature of most reef and shoreline restoration projects (i.e., <5 acres), and historic heavy reliance on bagged oyster shell. There is increasing interest from state and federal funding partners to support projects that do not use plastic as well as a growing use of customized non-plastic materials best suited for local conditions. We also chose this geographic scope to ensure that the projects represented were designed for similar threats/conditions, had access to the same funding sources, and were held to comparable permitting requirements.

Practitioners in Florida are well-connected through working groups and teams, many of which have been established over the past decade. There are efforts at the county level (e.g., Brevard Shellfish and Living Shoreline Working Group), the regional level (e.g., East Coast Shellfish Technical Advisory Committee, the Northeast Estuarine Restoration Team [NERT] and other regional estuarine restoration groups in East Central Florida [ECERT], the Panhandle [PERT], and Southwest Florida [SWERT]), and the state level (e.g., Oyster Integrated Mapping and Monitoring Program, Florida Oyster Recovery Science Working Group, Plastic-free Restoration of Oyster Shorelines—Community of Practice). Each of these working groups and teams maintains a listserv of its members. Through ongoing discussions and collaborations, transitioning away from plastic materials for oyster and shoreline restoration has become an emerging theme. However, no summary of statewide efforts exists. As a restoration community, we lack a comprehensive understanding of the extent of non-plastic projects across the state, the types of materials being applied, the spatial scale at which new materials are being utilized, and which types of organizations are engaged (e.g., state, non-profit, university). Additional questions include: How are professionals evaluating the trade-offs of plastic vs. non-plastic materials? Are current non-plastic restoration efforts transferable to other locations and systems? Are restoration practitioners interested in continuing the use of non-plastic cultch materials into the future?

To address this gap, we developed a descriptive survey, and we distributed it widely to coastal restoration practitioners in Florida. These results provide the first statewide, systematic effort to capture the experiences of practitioners regarding non-plastic materials in oyster and shoreline habitat restoration. Due to the recent timeline of most reported projects and thus a lack of long-term performance data, the results are unable to provide an assessment of the various materials themselves. Instead, we can provide a snapshot of progress within the statewide restoration community. In addition to our comprehensive survey results, we share four case studies from the survey responses to highlight different applications of non-plastic materials. Insights from our survey and case studies can help to improve techniques and practices in the field of aquatic habitat restoration in all similar habitats. Understanding restoration results will support further development of sustainable, practical methods and products.

2. Methods

We conducted a non-hypothesis driven, descriptive survey focused on the experiences of coastal restoration practitioners in Florida regarding the use of non-plastic materials for oyster restoration and shoreline stabilization efforts. This type of non-biased survey is commonly used when scientists do not have a starting hypothesis. Survey questions explored what non-plastic materials were used, overall performance of materials, and whether a methodological shift is occurring within the restoration community toward the use of non-plastic materials. The questions were also designed to determine whether certain types or scales of habitat restoration are employing non-plastic materials more than others and what aspects of material use are most important when implementing a project.

Our goal for survey distribution was to reach as many practitioners as possible who have worked or are currently working with non-plastic materials for oyster restoration in Florida. A link to the survey was sent via email through five well-established coastal restoration listserv channels (NERT, ECERT, PERT, SWERT, and a living shoreline listserv managed by US Fish and Wildlife Service staff) on 1 April 2021 with a response deadline of 23 April 2021. The 5 listservs contained a combined 835 members, although some overlap between lists was expected. A snowball sampling technique was used to help distribute the survey; in the solicitation, we asked recipients to share the survey link broadly with others who might have input. Thus, the actual reach of the survey is unknown. The survey was administered by FL Fish and Wildlife Conservation Commission employees using SurveyMonkey™, a product of Momentive Inc., San Mateo, CA, USA.

The online survey consisted of 29 questions with an estimated 10–15 min completion time. Respondents were asked to share details about their project(s), including scope and scale, any non-plastic materials used, and experience with those materials in terms of production/sourcing, permitting, installation, and material performance. The questionnaire included both open-ended and closed-ended questions (Appendix A). To our knowledge, this was the first survey exploring these specific concepts, thus there were no previously tested instruments in the literature to apply in this circumstance. Additionally, we did not use scales or multiple items to measure any single constructs so we did not have concerns about reliability or reliability testing. To ensure content validity, the instrument was created and reviewed by a team of social scientists, biologists, and coastal managers with expertise in this area. The survey was pre-tested on five restoration projects and amended as needed for clarity prior to a larger roll-out.

The 23-day response window yielded 54 responses, including three from out of state but within similar systems in the Gulf of Mexico region, so they were included in the analysis. We removed duplicate or incomplete entries, and the results and the discussion were derived from the remaining 49 responses. Our four case studies were selected from the responses to highlight the variation in efforts happening throughout Florida. The four case studies were selected from projects using different materials, and individuals were asked to provide more detailed project information via email based on a template. The case studies represent different organizations, different locations around the state, and different tested materials.

3. Results

3.1. Survey Outcomes

Survey respondents were located in 19 Florida counties (Figure 1) and 3 additional states (Texas, Mississippi, Alabama). The oldest submitted project began in 2000 and utilized concrete structures for the purpose of shoreline stabilization. Two survey submissions were in the planning stage, with deployment scheduled for 2022. The remaining projects began between 2010 and 2021, and 65% of projects were started within the last 3 years (2019–2021; 32 projects). Nearly half of all respondents classified their projects as either pilot scale (9 projects) or small scale (20–100 m^2; 14 projects). Forty respondents cited no permitting challenges for their projects; those with permitting challenges stated the causes were primarily related to size, location, or design issues. No respondents had permitting issues at the state or the federal levels associated with deploying novel, non-plastic materials. Thirty-one respondents said non-plastic materials were not prioritized by funding agencies, compared to 18 respondents who said non-plastics had been prioritized in writing by their funding or regulatory agencies.

Non-plastic materials used by survey respondents included natural fibers, such as jute or burlap, either alone or combined with a mineral hardener (Portland or CSA cement); "bioplastics" such as BESE-elements®; cement-only structures (e.g., Reef Balls™); organic materials (e.g., wood, coir); recycled or fossilized oyster shell; metal for cage structures (i.e., gabions); rocks; and plants (Figure 2). Projects using non-plastic materials were evenly divided between living shoreline stabilization (25 projects) and oyster reef restoration (24 projects, Figure 2). The most frequently used materials in living shoreline stabilization were cement structures, recycled oyster shell, and natural fiber with a hardener. In oyster restoration, the most commonly used material was recycled shell, with rock being the second most-used material. Metal gabions and bioplastics were each utilized in five projects. Only one restoration project in Florida reported using oyster shell with no modular or perimeter containment.

The majority of respondents said non-plastic materials were relatively easy to produce or source (61%; 30 projects). Respondents also considered materials to be appropriate for able-bodied volunteers to assist with both preparation (65%; 32 responses) and installation (69%; 34 responses). The need for safety precautions when preparing materials was reported in 45% cases (22 responses). There was no relationship between the need for safety precautions and type of material or with perception of appropriateness for volunteers in general. Non-plastic materials were considered not appropriate for school-aged children (kindergarten through 12th grade, ages 5–18) to assist with preparation (75%, 37 responses) or with installation (80%, 39 responses). A total of 47% (23 responses) ranked overall installation difficulty as moderate. Most projects (69%; 34 responses) utilized standard equipment for transport and installation, such as small to medium-sized trucks, boats, and trailers, as compared to 31% (15 responses) needing larger or more specialized equipment. Greater costs and time commitments for non-plastics were cited by 23 respondents (47%) and 21 respondents (43%), respectively, as compared to plastic materials.

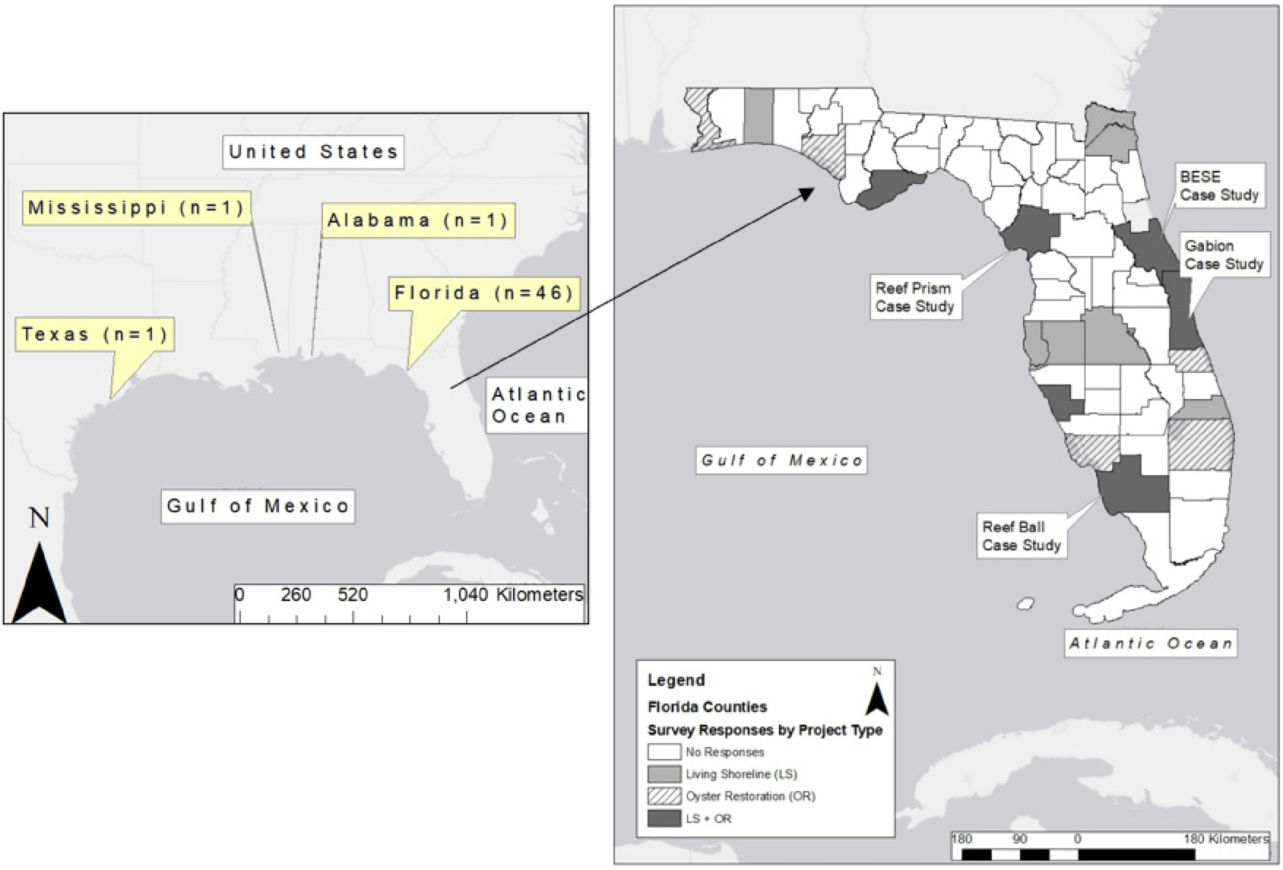

Figure 1. Study areas associated with survey results. The map on the left of the southeastern United States shows locations of survey responses (*n* = number of survey responses received from each state). The map on the right shows, by county, Florida restoration. The locations of living shoreline projects are shown in light grey, oyster restoration projects are shown in diagonal stripes, and dark grey had both living shoreline and oyster restoration projects. Note that this map does not reflect all restoration projects in Florida but only those who responded to our survey.

Restoration practitioners considered non-plastics to be successful based on their experiences, with 42 respondents (86%) indicating a willingness to use non-plastics in future projects and to recommend to other colleagues, either with modifications (12 responses) or without (30 responses). All respondents reported monitoring was part of the project plan, with most projects conducting annual (29%; 14 responses) or quarterly (27%; 13 responses) evaluations. Monitoring plans commonly included post-restoration evaluations for 2 years (27%; 13 responses) or longer (49%; 24 responses). Over half of respondents stated the integrity of the material was better than expected (27 responses), and 49% (24 responses) observed oyster recruitment to non-plastic materials at levels similar or greater than nearby intact, productive oyster reefs. The ability for structures to attenuate wave energy was less known, with 55% (27 responses) stating they were not able to evaluate. Of those evaluating wave attenuation, 16 responses indicated wave attenuation and shoreline protection exceeded their expectations.

Evaluation of the long-term overall performance of individual materials via standard metrics was difficult given the high number of recent (<3 years old) projects and the consequent lack of monitoring data across the intended life span of each product. However, the case studies outlined below provide specific information regarding four different non-plastic materials, including decisions about project design, installation, and performance in each particular application.

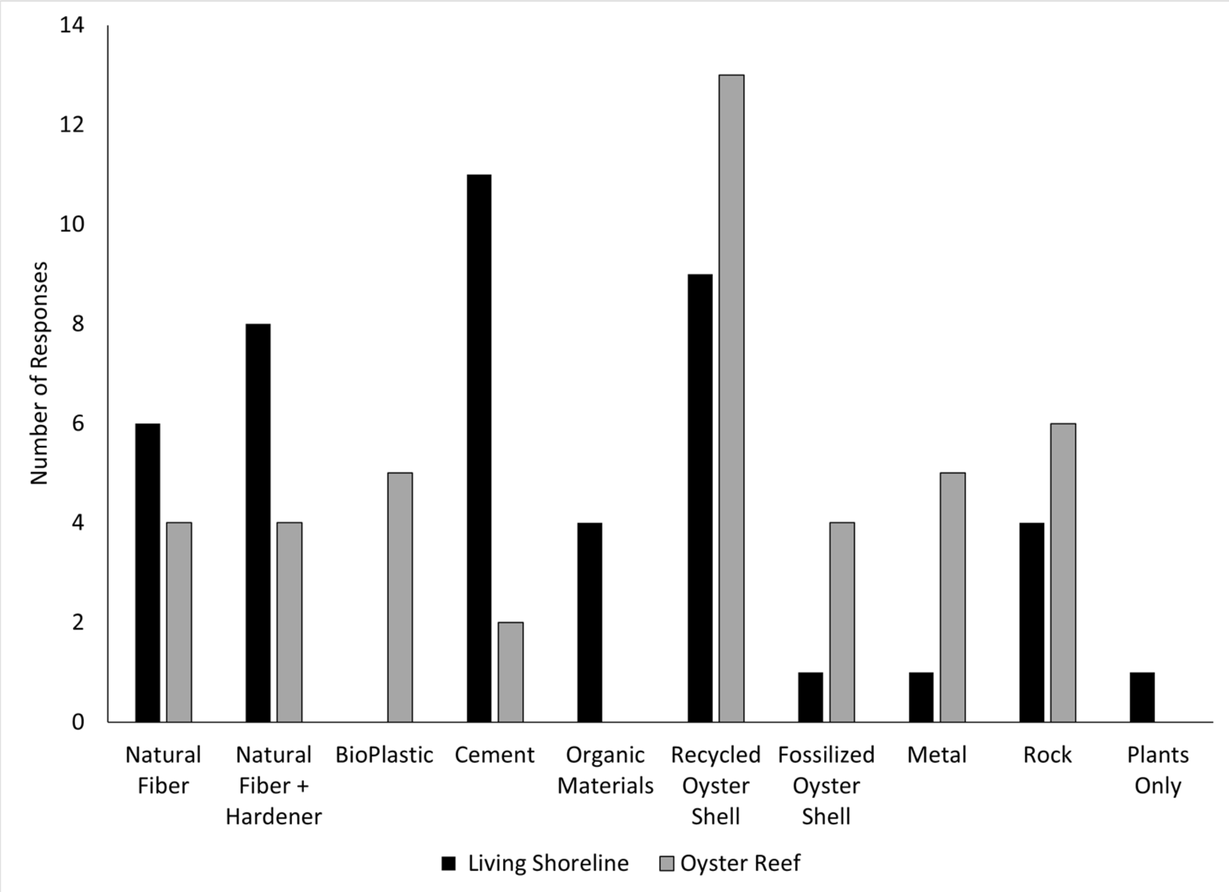

Figure 2. Non-plastic materials that were utilized in living shoreline (black) and oyster reef (grey) projects throughout Florida from 2000–2021 as reported in our survey. Some projects incorporated multiple materials.

3.2. Case Studies

3.2.1. BESE-Elements® Oyster Restoration Mats by University Group

Mosquito Lagoon, along the east coast of Central Florida and the northernmost section of the Indian River Lagoon system, lost over 40% of oyster acreage between 1943 and 2009 [50]. Walters et al. [22] determined that recreational boat wakes dislodged oyster clusters and pushed them above the intertidal zone; this was the primary source of oyster mortality in the shallow, microtidal, subtropical estuary [51]. Oyster densities and natural recruitment remained high in areas away from boating channels, so the restoration goal was stabilizing substrate for recruitment in boating channels. Walters and team [22] developed and tested oyster restoration mats beginning in 2004 to provide low-profile, oyster cultch in a modular design that mimicked the reef canopy for patch reefs in Mosquito Lagoon. Oyster restoration mats (0.25 m^2) were constructed of industrial aquaculture mesh (Vexar® extruded polyethylene) with 36 recycled oyster shells attached via plastic cable ties through a hole drilled near the umbo of each shell. The mats were laid out in a quilt-like pattern on the historic footprint at the appropriate intertidal elevation. Mats were connected to each other and held in place with cement rings and cable ties. Within 3–8 years, restored reefs averaged 1000 live oysters/m^2; these values met or exceeded oyster densities on natural, intact local reefs [22].

Although successful, this method introduced a layer of plastic into the estuarine environment. The team's goal became to retain the oyster restoration mat design but eliminate the plastic mesh and cable ties. Biodegradable EcoSystem Engineering Elements, or BESE-elements®, was chosen to replace the plastic mesh and stainless-steel wire would replace the cable ties (Figure 3). BESE-elements® are a biodegradable potato starch lattice and have been deployed at 7+ sites in Florida in a variety of applications [52–54]. BESE-elements® is 98% organic matter with an atomic C:N:P ratio of 16,000:5:1 [52].

Figure 3. (**Left**) BESE-elements® oyster restoration mats with recycled oyster shell attached on day of deployment in Mosquito Lagoon, FL, USA, with a row of metal soft-sided gabions for added protection against wind and boat wakes along the outer edge of reef (bottom of photograph). (**Right**) Significant oyster growth on BESE-elements® oyster restoration mat after 12 months. Each mat has a footprint of 0.25 m^2. Note that the BESE-elements® remain intact after 1 year of intertidal conditions in this FL estuary.

A secondary restoration goal was to keep the same dimensions as previous Vexar® mats to facilitate monitoring and to continue engaging volunteers through the assembly process (Figure 3). Standard-sized sheets of BESE-elements® were cut in half, and the two resulting squares were layered on top of one another and snapped together (surface area: 0.25 m^2; height: 0.02 m). A single layer of BESE-elements® could not withstand the weight of the shells, so this design provided sufficient structural integrity while maintaining a low profile. Shells with holes drilled near the umbo were attached to the BESE-elements® using 18-gauge stainless wire or stainless steel cable ties. BESE-elements® proved to be much more fragile than the plastic mesh, thus stacking and handling had to be minimized. Storage, transport, and deployment of the BESE-elements® mats required much more care and planning than their plastic counterparts. On the reefs, mats were carefully deployed and weighed down by cement rings and additional wire or stainless steel cable ties. To minimize any potential loss of mats from wakes on reef edges, soft-sided gabions were deployed around the perimeter of each patch reef (Figure 3).

The initial reefs in Mosquito Lagoon made from BESE-elements® were constructed from 100–130 mats. Monitoring of success occurred in three ways. First, recruitment of the oyster *C. virginica* on BESE-elements® was compared to Vexar® mesh mats by counting densities of live oysters on attached shell. There was no difference in recruitment densities after 1 [52] or 2 years. By the end of year 2, BESE-elements® in Mosquito Lagoon averaged 676.4 live oysters/m^2. Second, damage to individual BESE-elements® on reefs was minimal at the end of year 2; 8 total mats out of 500 (1.6%) were damaged due to wave energy contacting mats where shell bags were not placed seaward of mat edges, while 1 mat on a separate reef was broken into pieces from a presumed boat strike. Third, sediment biogeochemistry directly under the deployed mats was examined; BESE-elements® released dissolved organic carbon, soluble reactive phosphorus, and nitrate into the surrounding water, but this did not translate into measurable changes in the reef sediment pools under field conditions [52]. BESE-elements® lost 7–12% mass in year 1, suggesting a half-life of 4.4–6.7 years [52]. Overall, the monitoring indicated that this non-plastic material recruited oysters as well as plastic materials, sustained minimal damage in situ, would last through multiple years of oyster recruitment and growth, and did not measurably change the sediment chemistry below the reef. The trade-off is that BESE-elements® are more expensive and fragile than their plastic counterparts, substantially increasing the project budget and the logistics required to install an equivalent area of plastic-based reef. Researchers working with BESE-elements® are continuing to explore the use of this material for small-scale reef and shoreline restoration.

3.2.2. GAW Rigid Gabions for Oyster Restoration by Conservation Non-Profit

The Indian River Lagoon (IRL), a shallow estuary along Florida's east coast, has suffered significant losses of oyster habitat over the last century, especially within Brevard County, USA [55,56]. After intense, recurring algal blooms and water quality issues, Brevard County developed a recovery plan through the Save Our Indian River Lagoon (SOIRL) Plan, that incorporates rehabilitation of oyster populations [57]. The oyster rehabilitation design was based off three pilot oyster projects deployed in 2014–2015 [58]. Since 2014, 58 subtidal oyster sites have been constructed in Brevard County, totaling 1.12 acres. The majority of the projects feature a standard two-layer design of stacked Naltex™ plastic oyster shell bags. Success has varied by location based on variable natural oyster recruitment, sedimentation and subsidence. Most of these projects support oyster densities ranging from 100–1000 oysters/m^2.

Brevard Zoo, a non-profit zoo facility with a focus on conservation, has been actively restoring oyster reefs and stabilizing shorelines in Brevard County prior to establishment of the SOIRL Plan, and they continue their work toward ecological improvement of the IRL through habitat restoration. With funding from the County and access to recycled oyster shell, Brevard Zoo tested steel wire mesh boxes or "rigid gabions" filled with oyster shell for shallow, subtidal reefs and wavebreaks (Figure 4). Similar rigid gabion designs have been used to restore oyster reefs in St. Augustine, Florida, the Gulf of Mexico, and the Netherlands [59–61]. The Zoo constructed their gabions from 14-gauge galvanized-after-welding (GAW) steel wire mesh, galvanized steel hog rings, and recycled oyster shell. Rigid gabions were designed with dimensions similar to plastic oyster bags at 61.0 × 30.5 × 15.3 cm (Figure 4). These dimensions also suited the readily available 61 cm wide rolls of GAW wire mesh, minimizing waste. Gabion projects typically consist of a base layer with three rows of gabions and a top layer of two rows of gabions, as opposed to the two-row base with a single top row design commonly used in plastic oyster shell bag projects. This design adjustment maintained the same overall width of bag and gabion projects (2 m). Large, 9-gauge hog rings replaced plastic cable ties to secure gabions to one another on the lagoon bottom.

Construction of rigid gabions was more costly and time consuming than plastic oyster shell bags. Raw material cost, excluding donated shell, for a two-layer oyster bag project was $4.09 per square meter, compared to $44.56 per square meter for a two-layer oyster gabion project. The overall shell requirement for a rigid gabion is approximately 1.5–2 times greater than a plastic oyster shell bag project, with greater labor related to assembling gabions. Traditionally, a group of 30 volunteers could produce 1000–1400 oyster bags in a 4-h time frame. Over the same period of time, rigid gabion production has been approximately 10–20% of bag production. The need for electric tools to construct gabions is an additional safety consideration when engaging volunteers.

Pilot rigid gabion projects were deployed in 2020 and 2021. To compare materials side-by-side, 46 linear meters of reef was constructed with oyster gabion modules and 52 linear meters with plastic oyster bag modules. Average oyster density in rigid gabions has been significantly greater (ANOVA: $p < 0.05$) than bags, when density was corrected for differences in shell volume. After 1 year, there were approximately 1099 oysters/m^2 in gabions versus 440 oysters/m^2 in plastic oyster shell bags (Figure 4). In addition to greater shell volume, higher oyster recruitment in rigid gabions may be related to their position higher in the water column as these modules were approximately 40 cm tall and individual bags only 25 cm tall. Sedimentation and subsidence of gabions was minimal with only a few centimeters of sediment observed in the rigid gabion base layer.

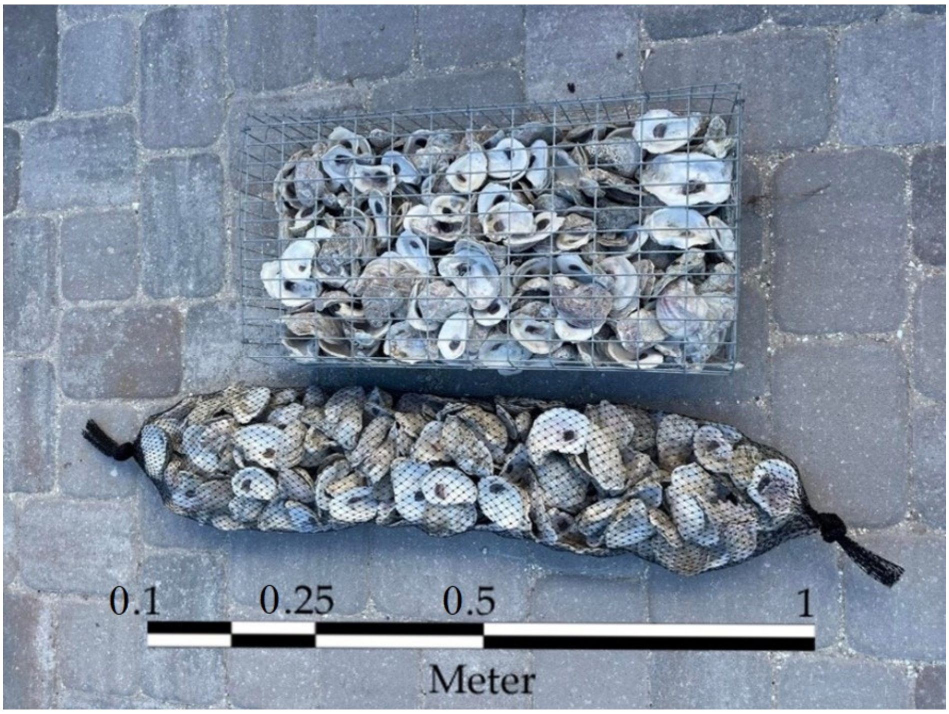

Figure 4. Size comparison of 14-gauge galvanized-after-welding (GAW) steel mesh rigid gabion and a Naltex™ plastic mesh oyster shell bag. Both contain recycled oyster shell, and are they typically stacked and arranged to create a living breakwater for shoreline stabilization. Gabion dimensions are 61.0 × 30.5 × 15.3 cm, and they contain 1.5–2 times the volume of shell compared to a plastic mesh oyster shell bag.

3.2.3. Reef Prisms, University Group, including Sea Grant Extension Office

A team at the University of Florida spearheaded the creation of "reef prisms" in response to a desire for a modular, plastic-free alternative to plastic oyster shell bags that could be built and deployed with the help of volunteers using affordable and readily available materials (Figure 5). Reef prisms (and other shape varieties) are made from a combination of jute fiber erosion control netting and CSA cement, both of which can be ordered in bulk from online vendors. This material combination is referred to as jute reinforced-calcium sulfoaluminate (JR-CSA). A standard reef prism unit is an equilateral or isosceles prism that is 30 cm tall and 120 cm long with 35–40 cm sides and a 35–45 cm bottom. A standard prism unit covers approximately 0.42–0.54 m^2 of bottom area, and it has an outward facing surface area of 0.94–1.08 m^2. Each unit weighs 20–22 kg, and it can be filled with shell or other materials to increase the total weight to 55–60 kg. Reef prisms absorb, rather than simply deflect, waves due to their shape and semi-porous construction. Their triangular dimensions can be adjusted based on site conditions, modules can be easily stacked, and placement tailored to a wide variety of reef and shoreline designs.

The chemical formulation of CSA, when compared to ordinary Portland cement, allows for rapid development of strength (CSA achieves the same strength within 24 h, whereas Portland cement takes 28 days), a significantly faster set time (20–30 min depending on ambient temperature), a more neutral pH during and after curing, reduced cracking, greater durability, resistance to sulfate attack due to a smaller pore size, and 35–50% lower CO_2 emissions. The rapid set time allows quick cycling of casting forms, optimal use of secondary materials, and overall space efficiency during construction. The reef prism process and material are fully open-source and available for any organization to adopt and to apply for free after training (no royalties or license fees).

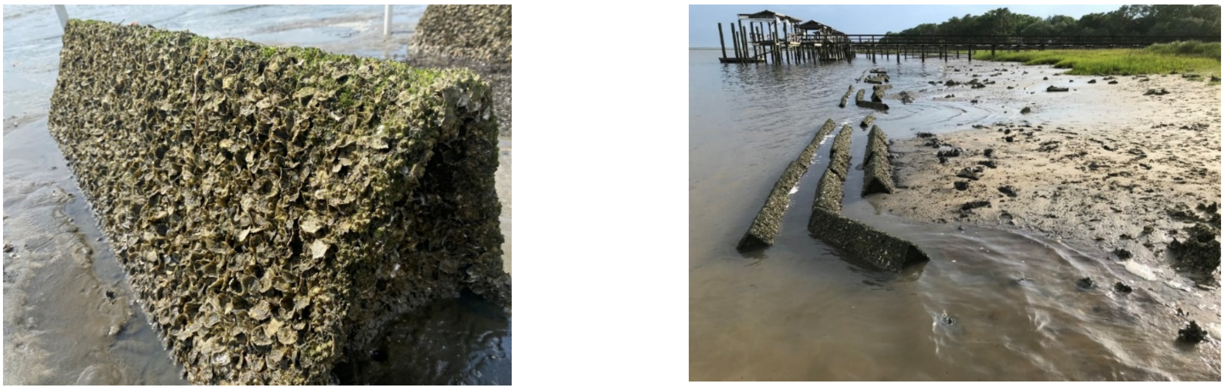

Figure 5. (**Left**) Reef prism in Cedar Key, FL, USA at approximately 6 weeks after deployment in 2021. Prism dimensions are 30 cm tall, 120 cm long, with 35–40 cm sides. (**Right**) Sediment accumulation behind reef prism reefs deployed September 2020 at Goffinsville Park, Nassau County, FL, USA. Photograph taken on 10 June 2021.

While costs for raw materials can vary, the average cost for raw materials to produce a standard 30 cm tall × 120 cm long equilateral prism using donated shell and volunteer labor is roughly $15 (2.5 m of jute fiber, 7 kg CSA, 7 kg masonry sand, and water). This is significantly higher than the average cost of roughly $1 per shell bag unit (91 cm Naltex® plastic mesh plus 2 stainless hog ring clamps). However, shell bags units are smaller and 3–4 shell bags are required to match the volume of one reef prism, somewhat decreasing the cost differential between the two materials when considering the total amount needed to build a reef of similar size. Oyster shell can be added to the inner area of reef prisms but is not required for their construction, providing a non-plastic alternative for high-energy areas where shell may be a limited resource.

The materials that make up reef prisms will eventually break down. However, recruitment of oysters onto the substrate or burial by sediment significantly decrease the rate of decay of the material. The first deployment of this material was in June 2018 in Cedar Key, FL, USA. The modules were 100% coated with oysters within months. After F14 months, units were retrieved and weighed. The deployment weight of these units was 13.6 kg, and the average weight after 30 months was 29.1 ± 2.46 kg (n = 11), representing a 113% average increase in mass. As of January 2022, those units remained intact and have not structurally degraded. Obtaining further information about mass changes related to the 2018 deployment would be counter-productive as the units are now fully cemented together by oyster growth.

Anecdotally, this team has observed similar levels of stability in prisms that become covered in oysters. Conversely, they have observed structural degradation of prisms related to physical strikes by boats and storm debris, bottom chafing of prisms not weighed down with shell, and vandalism at public sites by walking on top or damaging the side of the structure. At this point, there is limited information about the durability of reef prisms that fail to recruit oysters; however, even with limited oyster recruitment, prisms formed into breakwater reefs have shown significant sediment accretion landward of the structures (Goffinsville Park, Nassauville, FL, USA; Marine Resources Council Lagoon House, Palm Bay, FL, USA) and increased sediment stability and protection of planted vegetation when prisms were used as a sill (G Street, Cedar Key, FL, USA) (Figure 5).

3.2.4. Loose Shell, Limestone Rocks, and Reef Balls, City/County

Naples Bay is a shallow, narrow estuarine system within the City of Naples, Collier County, FL. Since the 1950s, Naples Bay has lost approximately 70% of its mangrove wetlands, 80% of oyster beds, and 90% of its seagrass beds due to urbanization and dredging for navigation [62]. In an effort to restore a portion of the oyster reef community and improve water quality, the City of Naples, Natural Resources Division, permitted three oyster restoration sites within the Naples Bay system with the largest site located in the southern portion of the bay adjacent to a mangrove fringe. This site is 3.4 acres, and the original design was comprised of plastic bagged shell stacked into approximately 1.2 m × 1.2 m units with a maximum height of 1.5 m, spaced at a minimum of 4.9 m apart. Three chevron-shaped 46 m × 4 m cement Reef Ball™ wave attenuation structures were to be placed seaward of the bags as this area receives significant wave energy from boat wakes. Upon evaluating the initial design, it was realized just how much plastic would be required to create the shell-filled Naltex® mesh oyster shell bags, in addition to the labor and quantity of shell (2700 tons) needed. A re-design of the project occurred with the goal of eliminating the use of plastic for creating the oyster reefs. The use of chevron Reef Ball™ structures remained unchanged. However, in lieu of the plastic oyster shell bags, loose fossilized shell was placed within a perimeter of large limestone rocks for the reefs closest to the Reef Ball™ structures. The reefs closest to the mangrove shoreline and furthest from the influence of the boat wakes did not have the addition of limestone rocks. The project included a total of 23 reefs, and it was completed in June 2019 (Figure 6).

Figure 6. (**Left-Top**) Aerial view of the restoration site in Naples Bay, FL, USA that includes three chevron-shaped reefs constructed of Reef Balls™ (bottom of photograph), reefs constructed of loose, fossilized shell surrounded by a perimeter of large limestone rocks (closest to the Reef Ball™ structures), and reefs constructed of loose, fossilized shell with no rock perimeter (closest to mangrove shoreline). (**Right-Top**) Oyster recruitment on limestone rock after 12 months. (**Bottom**) Profile view of Reef Balls™ and limestone/loose shell reefs.

Overall, the Reef Balls™ are effective for wave abatement and remain intact on the outer portion of the restoration footprint. Some sculpting by wave action was apparent at a few of the constructed reefs located near gaps between the Reef Ball™ structures, and this waterward erosion progressed the following year. Further, approximately 70% of the reefs, including those with no visual signs of erosion, had a lower mean elevation by 0.2 m in comparison with their initially surveyed height. This was likely due to settling or subsidence. The remaining 30% of the reef elevations remained unchanged.

As of May 2021 (year 2 sampling), constructed reefs were supporting 1366 oysters/m^2. Density was higher on constructed reefs in year 2 than on reference reefs (706 oysters/m^2), but it was slightly less than the highest density of oysters observed on constructed reefs (1516 oysters/m^2 in May 2020). Oyster size distribution on constructed reefs in May 2021 was similar to that on reference reefs. Constructed reefs also had larger and more numerous oysters than unrestored control sites, indicating that restoration has been successful in creating an oyster habitat with a stable population size and a mature demographic structure.

4. Discussion

Our non-hypothesis driven, descriptive survey found that Florida restoration practitioners are testing a diverse array of non-plastic materials for oyster reef and shoreline projects throughout the state, and are pleased with initial results. Florida has long been considered a "hotbed" of restoration with year-round activity on both sides of the peninsula plus long recruitment and growing seasons for oysters (April–December annually) [63]. As evidenced in the survey responses, practitioners in Florida are actively creating/modifying materials for restoration and making modifications based on site conditions (e.g., water depth, accessibility, tidal amplitude, wake energy, etc.). Over half of the project leads (27 responses) modified their non-plastic material designs to meet specific, local habitat needs. Cost increases associated with a switch to non-plastic materials has not deterred respondents, and practitioners recognize that it eliminates the potential need for costly clean-up efforts that could occur when using plastic-based materials. Table 1 provides a cost comparison of plastic versus biodegradable materials described in our case studies. For example, the cost to make a single oyster restoration mat with Vexar® and cable ties was $2.43 (excluding donated recycled shells). A single mat produced using BESE-elements® costs $9.18, a 377.8% increase (Table 1) [52]. Two additional types of restoration units were included in Table 1 as they were mentioned by multiple respondents; soft-sided gabions are similar to rigid gabions with the exception of using lighter-weight metal mesh to make the resulting structure more flexible in shape, and Oyster CORE (Community Oyster Reef Enhancement) modules that incorporate natural fibers, wood chips, cement, and oyster shells into low-profile blocks. Additional non-plastic material designs published in the peer-reviewed literature include cement Oyster Castles® (e.g., [30]), Portland cement-infused jute structures called Oyster Catchers™ (e.g., [64]), and Pervious Oyster Shell Habitat (POSH) that combines cement and oyster shell [65].

Table 1. Cost per unit is based on living shoreline or oyster restoration projects completed in Florida, USA in recent years. The costs shown here may not reflect economic fluctuations in material pricing or transportation/shipping costs to the site.

Material	Footprint/Unit	Cost/Unit	Cost/m^2
VEXAR® plastic oyster mat	0.25 m^2	$2.43	$9.72
BESE-elements® oyster mat	0.25 m^2	$9.18	$36.72
Naltex® plastic oyster shell bag	0.3 m^2	$1.00	$3.33
GAW metal gabion	0.185 m^2	$8.28	$44.56
Reef Prism	0.5 m^2	$15.00	$30.00
Soft-sided metal gabion	0.3 m^2	$6.00	$20.00
Oyster CORE module	0.1 m^2	$3.00	$30.00

Non-plastic materials are being tested at every project scale in Florida, and scale was shown to be an important factor in determining the approach for reducing or eliminating plastic in oyster and living shoreline restoration. Some alternative materials are designed to replace existing plastics in a direct one-for-one approach, especially for medium or small-scale projects. One example is swapping metal gabions for the Naltex® plastic mesh bagging material. With the soft-sided metal gabions (Figure 3), the size and the volume of oyster shell contained was similar to a plastic shell bag, so project design and permitting, construction of units, and logistics for transport and installation remained similar to previous shell bag projects. This approach allows for a more controlled transition away from plastic if an organization already has existing momentum with shell bag restoration, volunteer engagement, and monitoring. Direct replacement is also occurring in areas where low-profile, Vexar® plastic oyster mats have been successful, such as Mosquito Lagoon, FL, USA. The oyster reef restoration approach remains the same but the restoration units are now produced from biodegradable BESE-elements® (Figure 3) instead of plastic mats. For larger-scale restoration (>500 m^2), project considerations and materials were different than small- or medium-scale projects as reported in our survey. All projects that involved the use of rock were reported as large-scale with the exception of one. Rock was used both as cultch on its own (1 response) but more often as containment material for loose recycled or fossilized shell (7 responses). The large-scale projects that employed cement (4 responses) relied on pre-fabricated units such as Reef Balls™ or Wave Attenuation Devices (WADs®) [25], rather than specialty cement-based units that can be modified such as reef prisms or Oyster Catchers™. Half of projects that involved natural fiber were classified as large-scale, with coir logs or coir-based mesh used as shell containment. No large-scale projects reported using either metal or bio-plastics. Large-scale projects are typically less reliant on volunteer engagement to create and to install cultch materials, allowing for an approach that differs from one-to-one "plastic replacement". For large-scale projects reported in our survey, rather than a swap of plastic material (e.g., metal mesh for plastic bagging mesh), projects either replaced an entire restoration unit with a non-plastic material with similar characteristics (e.g., rock or Reef Ball™) or never included plastic materials in the initial project design.

Survey responses largely indicated that the durability of non-plastic materials exceeded expectations (27 responses), yet most projects (32 responses) were less than three years old. Hence, long-term durability of most non-plastic materials in Florida's subtropical waters remains unknown. The predicted lifespan of non-plastics is important when considering the goals of a project and individual site conditions. Non-plastic restoration materials are expected to either degrade over time or become bound within the reef matrix. Hence, long-term monitoring of material durability is needed. Significant material breakdown that leads to premature collapse could require costly cleanup and deployment of replacement materials. This would depend on the reason for restoration. If the result of a single event, such as a hurricane, then the restoration material only needs to remain in place long enough for new oyster recruitment or plants deployed landward of the materials to become established. In areas with chronic problems, such as boat wakes, materials such as jute-cement structures and BESE-elements® that are designed to break down over time need to be monitored over years or even decades to evaluate the potential need for repeated restoration.

In addition to tracking durability of materials, it is important to monitor oyster and associated ecosystem metrics. Universal metrics for monitoring oyster reef restoration success have been in place and commonly used for over a decade [66], and they include live oyster density, shell heights, and reef canopy heights. Positive and negative control areas are similarly monitored for comparison. With all the sizes and the shapes of the novel non-plastic materials described here, monitoring may become more complicated. Projects that were traditionally monitored in 2D may find themselves needing to consider a 3D perspective. As the community of practitioners continues testing new materials, standardized metrics for evaluating these materials may be helpful in providing comparisons and determining the optimal material for a given set of conditions. Likewise, some plastic oyster shell bag restoration projects traditionally removed all shell from bags to quantify recruitment; this many not be possible with gabions that are linked together with hog clamps (e.g., [58]). One large unknown is what happens to the non-plastic materials as the components break down in the field. When looking at the sediment biogeochemistry directly under the BESE-elements® oyster restoration mats, Nitsch et al. [52] found that this material released dissolved organic carbon, soluble reactive phosphorus, and nitrate into the surrounding water, but this did not translate into measurable changes in the reef sediment pools under field conditions. It is imperative that similar biogeochemical research be conducted on all novel materials. We do not want to remove plastics from our coastal waters only to find out later that the replacement materials were even more damaging to the environment.

Volunteer engagement is an important part of many restoration projects in Florida and beyond (e.g., [22]). Plastic-based shell bagging events are very popular for community groups and friendly for volunteers of all ages. While oyster shells can have sharp edges, the weight of the materials and the tools employed were accessible to all. Likewise, making oyster restoration mats with plastic bases was a common service activity for scouts, school groups, and clubs. As restoration practitioners transition away from plastic-based restoration activities, many still want all ages and abilities to have the opportunity to participate in oyster and shoreline restoration activities. Fragile materials and mixing cement with high levels of dust and a low pH require adequate supervision and additional safety protocols, and they may not be appropriate for some of our youngest volunteers. Finding safe and age-appropriate activities to maintain engagement in the restoration process is important, as volunteer participation is often fundamental to project implementation and community buy-in, especially for small- and medium-scale efforts.

Although permitting is often considered a challenge when utilizing novel or modified materials in the environment, 80% of survey respondents reported no issues during the permitting process regardless of project scale at the state or federal level. At the state level, our survey results show that 30% (15 respondents) of reported projects qualified for a verification of exemption, while 56% (28 respondents) obtained an Environmental Resource Permit (ERP). The remaining 14% did not specify which state permit was received. Florida streamlined the permitting process for small-scale shoreline stabilization in 2013. If projects are expected to have minimal negative impacts and meet the size criteria, applicants can be considered "exempt" from the otherwise required ERP (F.A.C. 62-330.051; Florida Statutes, 2021). State permitting agencies must still review project plans and verify that each project meets the exemption criteria, which include breakwaters being constructed of non-degradable materials (Florida Statutes, 2021). Approvals of biodegradable materials do occur on a case-by-case basis, and the results of our survey indicate that permits for non-plastic cultch were obtained with few issues. The exemption criteria provide a streamlined process, allowing small-scale projects or pilot tests that will have minimal negative impacts to proceed more rapidly through the permitting system. For larger-scale shoreline stabilization projects or oyster reef restoration, the ERP is needed from the FL Department of Environmental Protection (F.A.C. 62-330.051; Florida Statutes, 2021). At the federal level, permitting occurs through the US Army Corps of Engineers, with the most common permits issued for shoreline stabilization or oyster reef restoration being the Nationwide Permit (NWP) #54 for small-scale living shorelines or NWP #27 for general aquatic habitat restoration. Nationwide Permits cover a set list of activities and materials, and they serve to streamline the federal permitting process for common, acceptable techniques to conduct those activities. Of the 49 projects submitted in response to this survey, 66% obtained an NWP. Federal permit requirements do not specify the types of materials for use in breakwaters or oyster restoration beyond requiring oyster shell be contained in mesh bags or attached to stable substrate. Additional permitting requirements can differ by region in Florida and by land management structure. Local permits include approvals from municipalities or management agencies when projects are in designated reserves, including national and state parks, aquatic preserves, and wildlife refuges. Resource managers from national parks, state parks, and aquatic preserves along the east coast of Florida have advocated for the use of biodegradable materials in restoration for years, and several permitting or permit review agencies strongly recommend the use of non-plastic cultch material, when possible.

Our survey results suggest that plastic is being phased out of coastal restoration, as nearly 90% of respondents indicated an intention to continue using non-plastic materials. Moving forward, we must ensure that the materials used in place of plastics are also not a threat to coastal waters, flora, or fauna. Monitoring of oyster and shoreline restoration projects using non-plastics should include metrics for both water quality, structural stability, and biodiversity. While the impacts of plastic pollution in our waterways are often direct and apparent, it is critical to include discussion about the potential environmental impacts of non-plastic materials that may be more indirect, such as release of heavy metals, nutrients, or other pollutants, as they biodegrade. Materials that are made of, or incorporate, Portland or CSA cement may result in high carbon emissions through manufacturing and transport. Rocks are usually mined from a quarry, and they require heavy machinery for transport and placement at a site. The comparison of carbon footprint from assembly, transport, and installation of various oyster cultch materials is beyond the scope of this paper, but a worthwhile consideration as we accelerate the scale and the pace of non-plastic oyster reef restoration.

5. Conclusions

A non-hypothesis driven, descriptive study was conducted to determine if and how a transition to non-plastic materials is occurring in the coastal habitat restoration community in Florida. While plastic materials remain in use for oyster restoration and shoreline stabilization, the application of non-plastics has accelerated in recent years. Natural (e.g., rock) and numerous plastic-free materials (e.g., cement Reef Balls™, jute-infused cement structures, BESE-elements® produced from potato starch, metal gabions) are all being tested around the state under a range of biotic and abiotic conditions. The 49 responses to our survey found no "best" product for all or specific conditions in part because many of the restoration deployments occurred less than three years ago. However, long-term performance testing of listed non-plastic materials will continue with regional sharing of field successes and concerns to colleagues.

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Appendix A

Table A1. Online survey questions, response categories, and number of respondents related to experiences and attitudes of restoration practitioners.

Survey Question	Response Categories	Number of Respondents
What was the first year of deployment?	2000	1
	2010–2014	3
	2015–2018	11
	2019–2021	32
	N/A (Design Phase)	2
What is the approximate size of the project?	Pilot (1–few units)	9
	Small scale (20–100 m^2)	14
	Medium scale (101–500 m^2)	7
	Large scale (>500 m^2)	17
	N/A	2
Did you experience any permitting challenges related to this project?	Yes	9
	No	40
If yes, what were the permitting challenges related to? Check all that apply.	Non-plastic material	0
	Other material used in project	0
	Project size	5
	Project location	5
	Project layout	4
Does your funding prioritize biodegradables?	Yes	18
	No	31
Ease of production/sourcing?	Easy	30
	Moderate	10
	Difficult	9
Material is appropriate for able-bodied volunteers to assist with material preparation?	Yes	32
	No	17
Material is suitable for able-bodied volunteers to assist with installation?	Yes	34
	No	15
Safety precautions must be taken during production of these materials?	Yes	22
	No	27
Material is appropriate for K-12 students to assist with material preparation?	Yes	12
	No	37
Material is suitable for K-12 students to assist with installation?	Yes	10
	No	39
Ease of Installation?	Easy	16
	Moderate	23
	Difficult	9
	N/A	1
Can be transported using basic equipment (e.g., truck, small trailer, small boats)?	Yes	34
	No	15
Financial cost as compared to plastic materials?	Less	8
	About the Same	2
	More	23
	Unknown/Unsure	16

Table A1. *Cont.*

Survey Question	Response Categories	Number of Respondents
Time commitment required as compared to plastic materials?	Less	8
	About the Same	11
	More	21
	Unknown/Unsure	9
Would you use again?	No	1
	Yes	30
	Yes, w/Modifications	12
	Unknown/Unsure	6
Monitoring Frequency?	Monthly	10
	Quarter	13
	Annual	14
	2 Times per Year	8
	Other	4
Duration of monitoring plan?	6 months	1
	1 year	6
	2 years	13
	>2 years	24
	Other	5
How did the non-plastic materials in your project perform regarding structural integrity?	Lower than Expected	0
	As Expected	13
	Better than Expected	27
	Unknown/Unsure	9
How did the non-plastic materials in your project perform regarding oyster recruitment?	Minimal Recruitment	3
	Moderate Recruitment	7
	High Recruitment	24
	Unknown/Unsure	15
How did the non-plastic materials in your project perform regarding wave attenuation and shoreline protection?	Lower than Expected	3
	As Expected	3
	Better than Expected	16
	Unknown/Unsure	27

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