A Literature Review of Alternative Substrate Options for Oyster Restoration

A summary of published literature on various substrates other than oyster shell that have been tested or used for oyster restoration in the Chesapeake Bay and other regions.

U.S. Army Corps of Engineers places rock mixture on restoration reefs in Harris Creek, Maryland. Photo: U.S. Army Corps of Engineers

Compiled by Taylor Goelz
NOAA Chesapeake Bay Office
2017 Policy Summer Intern

Table of Contents

Introduction

Oyster populations and oyster reef habitat have significantly decreased around the globe (Beck et al. 2011), prompting oyster restoration projects at many scales in the United States, especially along the Atlantic and Gulf Coasts (La Peyre et al. 2014, Schulte and Burke 2014), and around the world (Quan et al. 2017).

Oysters and the associated oyster reef habitat support commercial fisheries and many other ecosystem services, including shoreline protection and wave energy mitigation, nursery and foraging habitat for reef-associated species, and enhanced water filtration (Ulanowicz and Tuttle 1992, Piazza et al. 2005, Coen et al. 2007, Grabowski and Peterson 2007, Dunn et al. 2014, Walles et al. 2015, George et al. 2015).

Restoration projects to construct reefs and enhance oyster populations historically used oyster shell in many forms (recycled, fossilized, dredged) as the optimal hard substrate (Levine et al. 2016, Mann and Powell 2007, Waldbusser et al. 2011). But as oyster shell became less available and/or affordable, people have tried various alternative materials to build hard reef structure where oysters larvae can naturally settle or be planted. This report provides an inventory of these substrate materials and notes their characteristics and effectiveness based on published studies.

The Challenges of Natural Oyster Shell

Shell has been the preferable substrate for restoration due to its biological adequateness for oyster recruitment, settlement, and retention (Tamburri et al. 1992, 2007, 2008). In the Chesapeake Bay, up until the early to mid-2000s, oyster shell was the main substrate used for oyster restoration. However, issues with shell cost, availability, and allotment are growing around the world, including in the Chesapeake Bay region, which makes obtaining shell for restoration purposes more challenging (Stokes et al. 2012). Availability references the amount of oyster shell, whether “fresh” or “dredged,” that is available for use at any given time. This depends on the amount of shell recycled by restaurants, returned by shucking houses, and dredged from within the Chesapeake Bay. Allotment refers to the distribution of shell.

Oyster shell is used for oyster restoration projects by federal, state, and local governments and nonprofit groups for replenishment of public bars for the commercial fishery and for large- and small-scale oyster aquaculture endeavors. With high demand for oyster shell, determining how shell will be distributed among multiple interests is challenging. For example, in Virginia and Maryland, aquaculture is increasing. In 2015, 135.6 million single oysters and 46,500 bushels of spat-on-shell oysters were planted in Virginia (VIMS MAS 2016 Report). Aquaculturists in Maryland harvested just under 50,000 bushels in the same year from their leases, a huge expansion since aquaculture laws were streamlined in 2009 (SB 271). In addition to its work on restored oyster bars, the Oyster Recovery Partnership reported working with watermen to place approximately 200,812 bushels of oysters on public oyster ground in 2015 and 269,920 bushels in 2016 (ORP 2016 Report, J. Baxter, pers. comm.). An accounting of shell planted versus shell harvested in Maryland shows more shell leaving the water than going back. In 2015, roughly 383,000 bushels of oysters were harvested in Maryland waters, whereas only 200,000 bushels of shell were replanted (J. Baxter, pers. comm.).

The increase in demand for shell helps explain the expected, but rapid, increase in shell prices. Shucked shell in Maryland increased from $0.50 per bushel in 2006 to $2.00 in 2015; Virginia saw similar increases from $0.50 to $3.00 per bushel (MD DNR, ORP, VMRC). Despite potential difficulties with the future of shell availability, the Virginia Marine Resources Commission planted 450,000 bushels of dredged shell in 2017. The current shell-dredging permit—issued by the U.S. Army Corps of Engineers—is valid through October 2022. With costs and future limitations in mind, dredged shell may not be a reliable resource into the future.

These challenges and others have led managers, restoration practitioners, and industry to seek other options for producing oysters and restoring reefs.

Alternative Substrate Options

Restoration efforts and scientific research projects have tested and used a variety of alternative substrates for increasing the amount of hard substrate and the ecosystem services associated with oyster reefs.

Alternative substrate is an umbrella term that encompasses any substrate used for oyster reef restoration other than the area's native oyster shell (Brumbaugh and Coen 2009).

The most commonly suggested alternative substrates for oyster reef restoration include:

- Biogenic: surfclam shell, dredged shell
- Geologic: sandstone, stone (including granite and amphibolite), and limestone marl
- Anthropogenic: porcelain, concrete (including crushed, Oyster Castles™, and Reef Balls™), and stabilized coal ash

Some considerations for choosing to use alternative substrates include the objectives of the reef construction (harvest or ecological restoration); reef size; spatial extent and height; the physical, chemical, and biological acceptability for oyster survival; recruitment and growth; likelihood of supporting associated reef species and ecosystem services; and potential effects on navigation, commercial fishing, and recreation (MD OAC, Oyster Summit, VA Blue Ribbon Panel, USACE Oyster Restoration Master Plan).

An overview of results from scientific studies (both peer-reviewed and white papers) on these alternative substrates are presented below.

Porcelain

Porcelain was an attention-grabbing alternative substrate used in Virginia tributaries in the early 2000s (*Bay Journal* 2004) and has been used more recently in the Gulf of Mexico (Dahle 2012, George et al. 2015, Graham et al. 2017) and in waters off New York City (Office of the Mayor 2016). Research has found that in terms of spat settlement over four months, porcelain performed no differently than limestone, concrete, river rock, or oyster shell reefs (George et al. 2015). Similar findings were reported by the Virginia Marine Resources Commission (VMRC), with spat numbers similar on porcelain reefs to natural oyster shell (*Bay*

Crushed porcelain before implementation in Jamaica Bay, New York City. Photo: New York City Department of Environmental Protection

Journal 2004). In addition to the biological suitability, an additional appeal of using porcelain is the idea of tapping into “waste” materials that would otherwise end up in landfills. Logistical problems, like transportation of materials and negative public perception of “potty-reefs,” would need to be addressed (Dahle 2012, *Bay Journal* 2004). In addition, further research is needed to determine whether porcelain is an ecological and economical sound choice for large-scale oyster restoration substrate.

Concrete

Concrete is one of the most commonly used alternative substrates for oyster restoration. This is in part due to its material characteristics like diversity in size and shape, ready availability of concrete, ease of manufacture, and material longevity (Haywood et al. 1999, Lipcius and Burke 2006, Dunn et al. 2014, Theuerkauf et al. 2015). Concrete can be obtained from construction project scraps (Clark et al. 2013) or as manufactured and engineered (Drexler et al. 2014, Theuerkauf et al. 2015).

Like coal ash and granite (discussed below), concrete has been found to be effective as an alternative substrate in terms of oyster productivity and other ecosystem services. In terms of oyster metrics, elements tested include oyster spat settlement, recruitment, growth, size of oysters, density and biomass of oysters, and health of oysters.

Concrete added to the Piankatank River. Photo: U.S. Army Corps of Engineers

Deploying reef balls in the Chesapeake Bay. Photo: CCA Maryland

Haywood et al. (1999), Greene and Grizzle (2005), Burke (2009), and George et al. (2015) among others demonstrated that concrete reefs performed equal or superior to oyster shell for oyster restoration in terms of oyster spat settlement, recruitment, and growth. Beyond initial oyster establishment on reefs, further studies found that size, biomass, and density of oysters was again equal or superior to oyster shell. Dunn et al. (2014) found in a field experiment after 12 months, concrete reefs had greater density of oysters than both limestone and granite reefs, attributing that to the higher levels of interstitial space (the size and number of gaps between substrate pieces) in concrete. The benefits of concrete include their persistence (like granite), allowing reefs to survive poor spat settlement years, and the ability to add vertical complexity. Theuerkauf et al. (2015) found that between an oyster shell and a concrete reef of identical surface area, the concrete reef provided better settlement surface and enhanced survival for oysters due to the vertical relief. Gregalis et al. (2008) found no significant differences for oyster abundance between concrete and limestone for alternative substrate; the key element was the vertical relief of reefs. Reefs that sit higher vertically in the water column are thought to perform better because more relief allows a greater percentage of substrate surface to remain above the sediment. This high relief helps remove settled oysters from hypoxia threats and limits the danger of siltation build up (Sonait et al. 2004, Theuerkauf et al. 2015).

In addition to oyster benefits, Brown et al. (2013) and Graham et al. (2017) evaluated concrete alternative substrate reefs in terms of other ecosystem services. Brown and colleagues found no structural difference between natural shell and rock reefs and that older rock reefs supported more benthic macroinvertebrates than did shell reefs. Graham et al. (2017) found that concrete and oyster shell reefs supported the highest densities of associated motile fauna and both returned the higher benefit/cost ratio for motile fauna. This example of involving economic analysis into evaluation of oyster restoration beyond the oyster fishery has been used in some studies (Louisiana Fish and Wildlife 2004, Grizzle et al. 2006) and is promoted as a necessary metric to include in future oyster restoration analysis (Bushek et al. 2015, Graham et al. 2017).

New reef ball (L) and reef ball after 7 months in the water (R). Photo: CCA Maryland

Like other alternative substrates, there is some negative public perception concerning the use of concrete for substrate use. Concerns focus on the potential leaching of chemicals from concrete when placed in the water. However, Clark et al. (2013) conducted a study looking at water-quality effects from concrete materials on oyster aquaculture within the Chesapeake Bay; their study found no adverse effects on oyster spat growth or survival of the surrounding environment with the use of this concrete material. Wide reporting of these results could help address negative stakeholder concerns with use of concrete for alternative substrate within the Chesapeake Bay.

Stabilized Coal Ash

In the late 1990s and early 2000s, coal ash, a byproduct from the combustion of coal to produce electricity, was tested as a possible alternative to oyster shell for oyster restoration (PR Newswire 1996, Andrews et al. 1997, Coen and Luckenbach 2000). Before recycling methods were discovered, coal ash was almost exclusively disposed in landfills, filling space and no longer useful (PR Newswire 1996). Coal ash, or coal fly-ash, is produced by combining coal ash with small amounts of cement and water (Leard et al. 1999). The resulting pellets can then be shaped in whatever form or size scientists or managers prefer. In a large field study off Fisherman Island on the Eastern Shore of Virginia, Coen and Luckenbach (2000) collected the greatest number of species per reef and displayed the highest diversity at the coal ash reefs. However, despite the diversity benefit, fine material released from coal ash pellets reduced the amount of interstitial space between larger pellets. Despite the fine material, oysters from the reef were deemed safe for human consumption, elements of concern being well below U.S. Food and Drug Administration (USDA) requirements (Hafner 2017).

Although coal ash pellets were determined to be environmentally suitable substrate for oyster settlement and growth and no threat to human health, competing interests for use of coal ash prevented its widespread use for oyster restoration (Homziak et al. 1993, Alden et al. 1996, EPA 2017, Hafner 2017). Virginia Power, now Dominion Energy, found other ways to dispose of the coal ash, including to builders as construction material (Hafner 2017). Due to the loss of interest from energy providers, stabilized coal ash has not been used for restoration since the early 2000s. Mark Luckenbach, one of the lead researchers of the study, reflected that the halting of coal ash for reef restoration was probably for the best; the cost of mixing cement with ash in a safe way was incredibly expensive (Hafner 2017). Also considering the long term, former head of conservation and replenishment at Virginia Marine Resources Commission (VMRC) Jim Wesson, articulated that coal ash would not be a viable long-term solution due to the phasing out of coal plants (Hafner 2017).

Sandstone

The only report of sandstone being used as alternative substrate for oysters is a field experiment by Sonait and Burton (2005) in Louisiana. Sandstone was thought to have potential as a viable alternative substrate due to its ready availability, chemical composition (quarzitic), and similar rough texture to the siliceous limestone also used in this experiment. Despite these predictions, Sonait and Burton (2005) found oyster spat significantly preferred limestone over sandstone at both high and low salinity and high and low larval abundance. The conclusion of the Sonait and Burton (2005) paper is that sandstone does not appear to be biologically acceptable for oyster restoration processes. No other studies that were analyzed used sandstone as a substrate for testing. It may be premature to draw conclusions on sandstone based on a single study for total avoidance of use in large-scale oyster restoration.

Stone (Including Granite)

“Granite” is commonly used to refer to nonlimestone stones with a variety of mineral composition that have low or no calcium. Sometimes the substrate used is granite; other times, like in the Choptank River Complex oyster restoration, materials such as amphibolite are used (2016 Oyster Reef Monitoring Report). Therefore, the more appropriate term for this group of alternative substrates is “stone.” The discussion below will use “stone” if the type of stone was not specified in the scientific paper or report and will use the specific type of stone (i.e., granite) when it was named.

Oysters set on stone pieces. Photos captured from video on Oyster Recovery Partnership’s Instagram page. Photos: Jay Fleming

Stone has become a frequently used alternative substrate material for oyster restoration because of its ready availability in many regions from nearby quarries, relatively reasonable price compared to oyster shell, and durability. Stone is a non-calcium carbonate structure, thus lacking the chemical composition that has been suggested to promote oyster recruitment and settlement (O’Beirn et al. 2000, Sonait and Burton 2005, Levine et al. 2016). Despite its chemical composition, stone has shown to be a successful alternative substrate type all along the East Coast of the United States in terms of oyster settlement, recruitment, growth, and ecosystem services (i.e., other fisheries, water quality).

Oysters dredged up along with small granite stones that they attached to and grew on. Photo: Virginia Marine Resource Commission

Signed stone pieces to be added to Piankatank River. Photo: U.S. Army Corps of Engineers

Burke (2009) found in a Virginia tributary, granite reefs showed the highest oyster recruitment and long-term abundance compared to other alternative substrates and were filled with high biomass and density of healthy oysters. On the Eastern Shore of Virginia, Tamburri et al. (2008) found no significant difference of oyster settlement between oyster shell and granite. Both studies emphasize the importance of the persistence of granite reefs. Stone reefs, because of their hardiness, are less vulnerable to a poor shell budget year or large sediment loads and excessive siltation because these reefs will not disappear (Burke 2009, Tamburri et al. 2008). Stone reefs and other sturdy alternative substrates allow managers and oyster restoration groups to “buy time” between poor oyster recruitment and growth years, a sentiment echoed by other scientists (M. Luckenbach, per. comm.). Even in poor oyster recruitment years, alternative oyster reefs can still provide valuable habitat to other species or other ecosystem services. Assessing benefits of alternative reefs beyond value to the oyster fishery is a suggested additional metric that could be applied to all restoration projects (Baggett et al. 2015, Kennedy et al. 2011, La Peyre et al. 2014).

In a North Carolina laboratory study, Dunn (2013) found calcium carbonate substrates (like oyster shells and limestone marl) supported the highest oyster settlement compared to non-calcium carbonate substrates like granite and concrete. However, the next year in a field experiment, Dunn et al. (2014) found that oyster growth rate and valve length were similar across all substrates. Also, granite was found to be more effective as a substrate in terms of oyster recruitment (Dunn et al. 2014). This study does highlight the importance of interstitial space for oyster metric success (also discussed in Bartol and Mann 1999, Kuykendall et al. 2015). Interstitial space can vary based on type of substrate as well as size of substrate. For example, granite pieces could be selected to maximize the interstitial space to help promote oyster larval recruitment for oyster restoration goals.

Further north in New Hampshire, crushed granite has been used in oyster restoration (Grizzle et al. 2006). This study specifically compared crushed granite reefs to natural oyster reefs and found that granite reefs had substantially and significantly higher spat sets and oyster densities than natural reefs. The authors postulate that these results likely come from the addition of hard substrate provided by the granite in an area that was perhaps habitat-limited. This highlights the importance of information on the hydromorphological conditions in an area of oyster restoration to allow best reef placement considering biotic and abiotic factors like locations of hard bottom (Walles et al. 2015).

In a recent evaluation of Harris Creek, one of the Maryland tributaries undergoing oyster reef restoration under the Chesapeake Bay Program’s goal to restore oysters in 10 tributaries by 2025, results showed that the highest average oyster densities were found on stone-based reefs (2016 Oyster

Reef Monitoring Report). Oyster densities on stone reefs were found to be four times higher than on shell reefs; however, this was based on a small sample size in one tributary. Further work as these reefs mature will continue to test the viability of stone substrate. Oysters found on the stone reefs were also all from natural spat, as hatchery-based spat was only placed on the shell reefs. This suggests that stone can act as a suitable settlement substrate for juvenile oysters and could encourage the further use of stone substrate for oyster reef restoration within the Chesapeake Bay.

For the oyster restoration that has occurred in the Maryland portion of the Chesapeake Bay, amphibolite is the non-calcium stone used for reef rebuilding or reef supplementation purposes (Reynolds Westby pers. comm., Reynolds Westby 2013, 2014, 2015, 2016, USACE 2012). As stated before, “granite” has been used as a catchall term for any stone that is not limestone (Reynolds Westby pers. comm.). Due to this generalization throughout many restoration projects, it is not possible to evaluate any potential differences between non-limestone stone substrates that have been used. Despite this, non-limestone stone alternative substrates as a group have been shown to be suitable for large-scale oyster restoration projects in providing hard substrate and habitat for oysters and associated species.

Limestone Marl

Like granite and concrete, limestone marl has become popular because of its diversity in size and shape, its ready availability, its relative affordability compared to shell, and its ability to persist in the system (Kuykendall et al. 2015). One benefit limestone substrates have over concrete or granite is their calcium carbonate composition. The chemical composition of calcium carbonate (or just calcium) may enhance a substrate’s attractiveness to settling larvae or induce them to settle (Hidu et al. 1975, Tamburri et al. 1992, Sonait and Burton 2005). The calcium carbonate composition of limestone in its various forms (including the Florida shell used in the Chesapeake Bay, discussed below) has been used as a reason to select limestone for alternative substrate reef projects.

Like the other alternative substrates, there are conflicting results from studies, but most are positive. Chatry et al. (1986) found that two times as many larvae settled on limestone as did on clamshell reefs. Sonait et al (1991) also found that oyster settlement on limestone was significantly greater than on clamshell. Many studies since then have also found that limestone performs equal to other alternative substrates—and, at times, oyster shell—in terms of oyster settlement, recruitment, growth, abundance, and density (Brumbaugh 2000, Gregalis et al. 20008, Powers et al. 2009, La Peyre et al. 2014, George et al. 2015, Kuykendall et al. 2015, Quan et al. 2017). Limestone has been found to perform no different from concrete in terms of overall number of oysters. The differences between the performance of limestone and concrete and other alternative substrates and oyster shell in terms of these metrics were statistically significant (Furlong 2012, Graham et al. 2017). Kuykendall et al. (2015) found that economically, limestone performed similarly to shell when purchased by volume

Florida shell at the Port of Baltimore en route to Harris Creek. Photo: Maryland Department of Natural Resources

because of the variety of sizes of limestone pieces. The demonstrated performance of limestone compared to other substrates and its similarity in performance to oyster shell economically suggests the continued use of limestone for oyster restoration projects. Again, this economic aspect of evaluating alternative substrates provides a new lens through which to compare different options.

For large-scale Maryland Chesapeake Bay projects, "Florida shell" has been used for reef building and supplementing. The Florida shell is oyster shell cemented into a fossilized limestone, making it another possible variation of limestone. This fossilized shell is a true fossil, mined from 30-40 feet under dry land after being deposited in the late Pliocene epoch 3 million years ago, as opposed to the Chesapeake Bay dredged shell discussed below (Little Choptank FAQ). After the end of the shell-dredging program in 2006, Maryland partnered with a quarry in Florida (hence the name "Florida shell") and CSX (a railroad company) to transport enough substrate from Florida to "cover 80 football fields a foot deep with oyster shell" (Mother Nature Network 2014). Use of the Florida shell, however, was halted due to concerns from watermen concerning the quality of the material (Wheeler 2015, 2017). Maryland Department of Natural Resources (DNR) undertook extensive precautions to ensure that the Florida shell did not negatively affect the Bay's ecosystem. These precautions included quality tests by independent contractors before shipping and Maryland DNR review of the fossil quarry, train loading, barge sites, and restoration areas to ensure viability before and after the contract was signed (Little Choptank FAQ, Reecy and Jordan 2013).

Reefs built with Florida shell will be part of the annual three-year check-in monitoring done in 2017, so more information (report expected early summer 2018) on the performance of this substrate material will be available (J. Baxter, pers. comm). If the Florida shell performs similarly to other experiments of limestone discussed above, it could constitute a viable alternative substrate for use within the Chesapeake Bay for oyster restoration.

Surfclam Shell

The suggested chemical importance of calcium carbonate for oyster larvae settlement (Hidu et al. 1975, Sonait and Burton 2005) led to the use of surfclam shell as an oyster restoration alternative substrate. Surfclam was tested in the early 2000s in Virginia (O'Beirn et al. 2000, Coen and Luckenbach 2000, Nestlerode et al. 2007) and was found to not be the most suitable substrate for oyster restoration. Coen and Luckenbach (2000) noted that surfclam shells fractured easily during handling, which limited critical interstitial space. Interstitial space has been found to be determinant in oyster larvae recruitment (Bartol and Mann 1999). O'Beirn et al. (2000) and Nestlerode et al. (2007) both found that oyster larvae settlement was similar across substrates (coal ash pellets, surfclam shell, and oyster shell), but post-settlement mortality was significantly higher on surfclam shells. The limited growth potential post recruitment and

Oyster spat on clam shell in the Lamprey River, Great Bay, Newmarket, NH. Photo: Krystin Ward, University of New Hampshire

Spat set on surf clam shells Photo: Ray Grizzle, University of New Hampshire

settlement hindered the establishment of surfclam shell as an alternative substrate for oyster restoration within the Chesapeake Bay (2016 Oyster Restoration Report). However, none of the Virginia studies examined other ecosystem benefits of reefs beyond oyster recruitment, settlement, and growth.

In New Hampshire, the Great Bay Estuary is the center of current oyster restoration efforts. Surfclam shell is currently the primary alternative substrate used for oyster restoration completed by the University of New Hampshire (UNH) and The Nature Conservancy (TNC), with 500 cubic yards placed over 5 acres in 2016 (Grizzle and Ward 2017). The 2016 UNH report found heavy sedimentation on surfclam substrate, which was theorized to hinder settlement of live oysters (Grizzle and Ward 2016). In the 2017 report, results found relatively lower initial recruitment compared to historical spat densities in New Hampshire, but was comparable to other recently constructed reefs (Grizzle and Ward 2017). In addition to the spat results, the 2017 report emphasized the importance of site selection of the restored reefs. The recruitment of oysters to the unseeded surfclam shell reefs suggests that the chosen site has potential for continued natural spat sets (Grizzle and Ward 2017). In addition, these reefs persisted through the heavy sedimentation reported in the 2016 report, which suggests long-term potential of these alternative substrate reefs. The persistence and sedimentation highlight the dual benefits of choosing hardy alternative substrates and the optimal placement of these reefs (Grizzle and Ward 2016).

In the Chesapeake Bay, the surfclam shell used has already been reduced to the size of a quarter (J. Lazar, pers. comm.). Due to this small size, the surface complexity of the large three-dimensional reefs constructed in Maryland do not yield higher surface complexity than seed-only sites.

Dredged Shell

For decades, dredged shell has been a main alternative substrate used for replenishing harvest reefs within the Chesapeake Bay. Shell dredged up from the Chesapeake Bay are not “conventional” fossils. A more accurate definition would be to call these shells “not-fresh” or simply “dredged” shells. (The term “fresh” shell is used by Maryland DNR to describe shell from living oysters that are shucked and planted back on bars.) Dredged shells from the Chesapeake Bay are Eastern oyster shells that are buried or sit on natural oyster bars within the Bay. The age of these shells from Maryland and Virginia can be up to 4,000 years old or as young as 10 to 15 years old, depending on the location from which they were dredged. While not a conventional alternative substrate like porcelain, granite, or limestone, dredged shell has been used to supplement availability of fresh shell (Wheeler 2017). Use of dredged shell predates large-scale oyster restoration efforts in the Bay and is a finite resource that can be considered an alternative to fresh shells for replenishing harvest areas.

In Virginia, VMRC has $2 million earmarked from the Virginia General Assembly for obtaining shell with which to replenish public oyster bars; a majority of this shell has been dredged. Maryland’s dredge shell program ended in 2006. However, during its 46-year tenure, more than 200 million bushels of shells were dredged and placed on public bars (C. Judy, OAC Meeting). Current attempts to renew shell dredging in Maryland are focused in the Man-O-War Shoal, one of the Bay's largest remaining buried shell deposits, with an estimated 90 to 100 million bushels (Wheeler 2017). These dredged shell deposits will be depleted over time and therefore do not represent a long-term, sustainable solution. This, combined with the imbalanced proportion of shell being placed in and coming out of the Bay, makes the use of dredged shell in the future challenging.

Dredged shell being placed on Great Wicomico River. Photo: U.S. Army Corps of Engineers

Despite the interest in states of the Chesapeake Bay to use dredged shell, Levine et al. (2016) found that dredged shell may not persist as long as stone or concrete, making it more vulnerable to poor recruitment years or heavy sedimentation. Dredged cultch also was found to have less interstitial space, which led Levine et al. (2016) to recommend using dredged cultch to enhance degrading reefs but not to build new reefs for oyster restoration. VMRC and Maryland DNR have long records of data concerning dredged shell within the Bay through annual surveys and shell plantings. VMRC's reports indicate that dredged shell performs at least as well as fresh shell and may even have comparatively increased longevity. Despite this knowledge, studies of dredged shell have been rare in the literature.

Engineered Options

While some engineered options have already been used for restoration (i.e. Reef Balls™ and Reef Castles™), La Peyre et al. (2014) highlight the limited amount of information available on engineered approaches. Often these methods are selected without quantitative data to assess whether their typically higher cost results in added benefits in terms of oysters or other ecosystem benefits. The high cost of future engineered options may be mitigated with the advent of construction-grade three-dimensional printers that can fabricate intricate geometrics, allowing the optimization of material usage and eliminating expensive tooling (Mohammed 2016). The scale of oyster restoration in Chesapeake Bay, however, is larger than has been attempted with engineered options in the past. Results from projects such as the engineered alternative substrate from GROW LLC being used for a 2018 Nature Conservancy project in Maine (see below) could help provide information on viability and costs of engineered options at a larger scale. The benefits of these engineered options could also be considered in relation to their wider-scale ecosystem benefits. Brumbaugh and Coen (2009) introduced the idea of engineered oyster reef restoration options for the dual purposes of oyster restoration and shoreline stabilization. The consideration of additional benefits may make these projects more feasible or cost effective going forward. Studies comparing the price, effectiveness, and success of engineered options versus lower-tech alternative

Students helping build the Billion Oyster Pavilion structure. Photo: Billion Oyster Project

3D-printed ceramic oyster reefs built for Woodbury Shellfish Company.

substrate options with all potential costs and benefits under consideration will be necessary if this path for engineered alternative substrates is pursued. To date, custom-designed three-dimensional printed reefs for restoration have been primarily used for coral reefs (Spieler et al. 2001, Ammar 2009, Reef Life Restoration 2017, Sustainable Oceans International 2017), but recently have been pursued for oyster reef restoration. In 2015, Woodbury Shellfish Company in New England partnered with Tethon 3D, a ceramic three-dimensional printing services bureau to develop artificial reefs to help oyster populations (Grunewald 2015). The Billion Oyster Project, a nonprofit aiming to restore oysters in New York's Hudson River estuary, partnered with Stratasys's innovation workshop, Bold Machines, to create their Billion Oyster Pavilion. The Billion Oyster Pavilion was partially made up of three-dimensional printed reef balls and other material that would all eventually be transferred for continued oyster restoration use in the Hudson (Krassenstein 2015, Black 2015, Goodman 2015). A spokesperson for the Billion Oyster Pavilion said the organization settled on three-dimensional printed reefs because of their low cost, quick production speed, and precise geometry (Krassenstein 2015). Most recently, Grow Oyster Reefs, LLC (GROW), a Virginia-based company, has developed Concrete Oyster Reef Restoration Tile (CORRT) and Concrete Oyster Reef Restoration Discs (CORRD), molded, reproducible alternative substrate designs modeled after native reef shape, surface, and chemical formula. They are made with $CaCO_3$ concrete, a concrete mix formulated to match oyster shell biochemical makeup (Grow Oyster Reefs, LLC 2017). These engineered tiles and discs will be used by the Nature Conservancy's initial artificial substrate oyster reef in Maine in 2018 for their first alternative substrates allowed in the state (E. Tickle pers. comm). The increasing opportunities and reduced cost of engineered alternative substrate options makes these avenues more feasible for future large-scale oyster reef restoration. Scientists, however, will need to collect data on the performance of these engineered options and compare their performance to other alternative substrates.

CORRT prototype (left) and CORRT (right) after one season in the Chesapeake Bay. Photos: Grow Oyster Reefs, LLC

Other Factors Influencing Oyster Restoration Planning and Implementation

Many of the studies discussed other characteristics of oyster restoration projects in addition to the type of substrate used that can influence the success of these projects. Some of the commonly mentioned additional factors included the need for oyster metrics, reef structure and complexity, timing and placement of reefs, issues with shell budget and loss, reef height, the opportunity for engineered options, and the need to analyze reef scale and interconnectedness. The selection of a biologically and ecologically acceptable substrate for oyster restoration projects is just one important element that influences oyster restoration success. Consideration of these other factors can contribute to or detract from the ability of all substrates, and therefore oyster restoration projects, to meet project goals.

Oyster Restoration Metrics

The comparisons of many of the studies on alternative substrate above are limited due to lack of consistent metrics and measurements across experiment sites, projects of various construction types, and systems. Many scientists and natural resource managers advocate for the creation of a set of standardized monitoring metrics, units, and performance criteria (Brumbaugh and Coen 2009, Bushek et al. 2015, Kennedy et al. 2011, La Peyre et al. 2014). A set of common metrics would help address some of the basic missing descriptive information concerning restoration projects (i.e. location of reefs, original configuration, source of funding, etc.). Baggett et al. (2014) followed this widely cited suggestion, and a common set of recommended metrics was produced in 2014. This report does not include success criteria, like what is being done in the Chesapeake Bay (discussed below), but provides a common set of monitoring metrics that could be used across oyster restoration projects. Common suggestions for metrics include examination of structural elements (e.g., reef dimensions, height, oyster density, oyster size-frequency distribution), environmental variables (e.g., water temperature, salinity, dissolved oxygen), and both long- and short-term analyses to consider effects such as recruitment

Goal	Success metrics (targets and/or thresholds)	Assessment Protocol	Minimum Assessment Frequency (assumes pre-restoration survey)
Operational Goals: Defined programmatic and planning outcomes for reef construction and tributary level restoration			
Reef-level 1. Appropriate amount of substrate and/or spat-on-shell was planted. 2. Presence of substrate and/or spat-on-shell within the target area.	Shell, alternative substrate, or spat-on-shell should cover a minimum of 30% coverage throughout the target reef area.	Patent tong or diver grabs	Within 6-12 months of restoration activity
Tributary-level target: 1. Appropriate amount of area within the tributary has met reef-level operational goals.	A minimum of 50% of currently restorable area that constitutes at least 8% of historic oyster habitat within a given tributary meets the reef-level goals defined above.	GIS-based analysis of restoration activity within the tributary	Annual
Functional Goals: The desired ecological outcomes at reef and tributary scales			
Reef-level goals			
Significantly enhanced live oyster density and biomass	Target: An oyster population with a minimum mean density of 50 oysters and 50 grams dry wt/m^2 covering at least 30% of the target restoration area at 3 years post restoration activity. Evaluation at 6 years and beyond should be used to judge ongoing success and guide adaptive management. Minimum threshold: An oyster population with a mean density of 15 oysters and 15 grams dry wt biomass $\cdot$ m^{-2} covering at least 30% of the target restoration area at 3 years post restoration activity. Minimum threshold is defined as the lowest levels that indicate some degree of success and justify continued restoration efforts.	Patent tong or diver grabs	Minimum 1, 3 and 6 years post restoration
Presence of multiple year classes of live oysters	Minimum of 2 year classes at 6 yrs post restoration.	Patent tong or diver grabs	Minimum 3 and 6 years post restoration

Table from the "Restoration Goals, Quantitative Metrics and Assessment Protocols for Evaluating Success on Restored Oyster Reef Sanctuaries" report from the Oyster Metrics Workshop (2011).

timing (Bushek et al. 2015, Graham et al. 2017). Brumbaugh and Coen (2009) discussed how historically, oyster restoration projects have not tracked these metrics. Lack of detailed data on how restoration is completed makes comparing methodology of projects difficult, which limits the ability to determine best practices for oyster restoration. Brumbaugh and Coen highlight how critical it is for all shellfish restoration operations to have explicit goals and appropriate assessment metrics for comparability and accountability purposes.

Large-scale oyster restoration under way in the Chesapeake Bay follows a set of prescribed restoration goals, quantitative metrics, and assessment protocols to evaluate success on restored oyster reefs (Sustainable Fisheries Goal Implementation Team 2011, see chart above). Chesapeake Bay restoration goals have both tributary and reef-level targets. For reef-level success, for example, parameters under evaluation include structure of the restored reef (reef spatial extent, reef height, and shell budget), population density, and a total reef population estimate. As of summer 2017, two rounds of three-year post-restoration monitoring, with six-year monitoring to follow, have been completed. A summary of success metrics, assessment protocols, and minimum assessment frequency are displayed in an example of one of the matrices from the report (see image). This clear set of metrics and long-term evaluation make the oyster restoration occurring in the Chesapeake Bay easily consulted and comparable for other oyster reef restoration projects worldwide.

Habitat Structure and Complexity

In addition to selection of alternative substrate, the placement of substrate on the bottom and reef design are also key for restoration projects. Dillon et al. (2015) and Gregalis et al. (2008) suggest that the benefits and services provided by reefs vary spatially and temporally and depend on site location. Powers et al. (2009) state that biological, chemical, and physical factors, like reef height, sanctuary status, wave action, sedimentation, and water depths, are key factors necessary to consider when selecting restoration sites.

Some studies found that the addition of hard substrate alone, regardless of the structural complexity or reef height, was the most important factor in oyster or associated nekton abundance, richness, biomass, and diversity (Manley et al. 2010, Humphries et al. 2011).

One of the most recognized structural benefits of oyster reefs is interstitial space, which can "furnish ideal spatial platforms for growth" (Bartol and Mann 1999, p. 157). Some studies advocate the use of oyster shell for restoration because of the unique three-dimensional structure of shell that can provide refuge that other substrate does not (Graham et al. 2017). However, other studies found alternative substrates can perform as well as oyster shell reefs (Dunn et al. 2014, Clark et al. 2013, Kuykenfall et al. 2015). Interstitial space can be added by building reefs up and out. Sonait et al. (2004) found that shell orientation affects the availability of habitat, and fish tended to prefer vertical reefs to horizontal reefs.

Studies have found that the vertical height of reefs provides some of the most crucial benefits for oyster restoration efforts. Sonait and colleagues proposed that vertical reefs allow organisms to get away from the bottom and offer increased surface area, which can benefit settling oysters and associated reef-oriented species. Gregalis et al. (2008) found oyster recruitment and abundance were higher on high-relief reefs, regardless of reef substrate type. This was possibly attributed to greater resiliency to fishing disturbance or decreased frequency of low dissolved oxygen events. These structural design elements may help mitigate negative location factors like high oyster mortality or low larval supply to allow restored oyster reefs to succeed in these areas (Gregalis et al. 2008). Manley et al. (2010) encourages alternative substrate oyster reefs for restoration to be built with these elements of vertical relief, height, and amount of interstitial space in mind.

Timing and Placement of Reefs

In addition to the structure of restored reefs, consideration of the timing and placement oyster reef restoration is important. Manley et al. (2010) argue the "success of oyster restoration efforts [are] contingent on the timing and placement of structurally diverse constructed oyster habitat." Placement of reef for oyster restoration within an estuary system should depend on the goals of the restoration, the surrounding biophysical and chemical conditions, and feasibility of placement (O'Beirn et al. 2000, Mann and Evans 2004, Rodney and Paynter 2006, Powers et al. 2009, Puckett and Eggleston 2012, Walles et al. 2015, Quan et al. 2017). For example, if a primary goal of oyster reef restoration is specifically to enhance its role as a nursery habitat, placement of reefs in shallow waters would help avoid large predators (Rodney and Paynter 2006).

The effects of adding hard substrate vary depending on where it is placed. Gregalis et al. (2008) constructed reefs of different structural designs at sites with different surrounding habitat like seagrass, coral reefs, or bare sediment. Authors found that associated nekton response was related to site differences rather than a response to individual reef differences. The addition of hard substrate to previously bare regions (e.g. bare sediment) provides complexity that did not previously exist in this area, whereas oyster reefs near seagrass beds simply provide additional potential habitat (Gregalis et al. 2008).

Walles et al. (2015) highlight how reef placement and future "persistence and sustainability of artificial constructed oyster reefs" depend on conditions such as intertidal (exposed at low tide) versus subtidal (always submerged) sediment dynamics and surrounding habitat. Geraldi et al. (2013) found oyster density was highest at middle salinity levels and suggested these conditions may be best for oyster restoration with the primary goal of maximizing oyster densities. Restoration work in the Chesapeake Bay, however, has shown high oyster densities on reefs constructed in the lower-salinity waters (2016 Oyster Reef Restoration Report). Placement of reefs or any restoration resource, however, needs to take into consideration multiple factors, including the limited nature of resources and the return on investment. For example, Geraldi et al. (2013) found additional seeding of spat did not enhance oyster reef restoration efforts in Pamlico Sound, North Carolina, because of the high natural recruitment that already exists in that system. They concluded the time and money spent on seeding would have been better used to increase the amount of available substrate. Knowing the advantages and limitations of the system targeted for restoration is key for helping to determine what restoration activities would have the largest effects on restoration goals. Going beyond larger-scale consideration of reef placement, Bartol et al. (1999) found mid-intertidal oyster reefs within the reef interstices performed best in terms of survival and growth compared to mid-intertidal oysters at the reef surface. This highlights the importance of location *within* the reef habitat for Eastern oysters in addition to overall placement of reefs in the estuary or coastal system.

Restoration of oyster reefs can address goals beyond those directly related to oysters. Brumbaugh and Coen (2009) recommend considering more highly engineered reefs in areas of high wave energy. In addition to adding oyster habitat, these reefs could potentially help with shoreline stabilization. More durable and heavy alternative substrates, like concrete, could be used in more exposed locations; these reefs will not disappear if recruitment does not occur immediately (La Peyre et al. 2014). Using these durable substrates in high-energy locations could free up highly limited oyster shell for use in protected, shallow-water areas close to shore or areas of high natural spat sets (La Peyre et al. 2014).

Shell Budgets and Ocean Acidification

The availability of oyster shell for oyster restoration projects faces challenges due to low supply, oyster harvest, increasing costs, and the low number of oysters in the Chesapeake Bay (Rothschild et al. 1994, Stokes et al. 2011, ORP 2017). Because oysters are broadcast spawners, releasing their eggs and sperm into the water column to reproduce, fewer oysters in the population lowers reproduction success (Bartol et al. 1999, Sonait et al. 2014). This low recruitment/reproduction causes the shell budget to decrease because no new shell is being created. Further, oyster shell, even when added into the Bay, is not a stable resource. Shell is vulnerable to natural dissolution and chipping, in addition to the previously discussed extraction (Gutierrez et al. 2003, Powell et al. 2006). In basic terms, the shell budget is the proportion of shells being added to and taken out of the Bay (Sonait et al. 2014). Using a shell budget as a tool to examine the gain, loss, and maintenance of shells could add to the use of alternative substrates to take some pressure off natural shell through determining locations for optimum cultch enhancement and areas where alternative substrates may work better (Sonait et al. 2014, Mann et al. forthcoming). A shell budget for the Chesapeake Bay, which transitions from management of the animal to a management of the habitat, would provide information that would allow managers and restoration projects to choose where to plant shell, helping lock in gains from habitat restoration (Sonait et al. 2014). In addition to other biophysical, chemical, and economic factors, use of a shell budget would provide more information for use in oyster restoration projects.

An upcoming issue facing oyster restoration projects is ocean acidification. Oysters, especially larvae, demonstrate diminishing growth rates from decreased pH, which depresses their survival (Kutihara et al. 2007, Miller et al. 2009, Watson et al. 2009, Lipcius et al. 2015). Estuarine waters are more susceptible to acidification because they are subject to multiple sources of acidity; have already been degraded by other impacts (i.e. overfishing, eutrophication); and are shallower, less saline, and do not have the benefit of marine water buffers (Lotze et al. 2006, Miller et al. 2009, Waldbusser et al. 2011a, Wallace et al. 2014). This phenomenon has been studied specifically for the Chesapeake Bay. Waldbusser et al. 2011b analyzed 23 years of Chesapeake Bay water-quality monitoring data and found daytime average pH significantly decreased across polyhaline waters. In connecting this directly to oysters, Waldbusser et al. 2011a found that under current pH levels found in mesohaline regions of the Chesapeake Bay, fresh, weathered, and degraded oyster shells experienced shell loss, which increased as pH was lowered. Future projected increases in partial pressures of CO_2 (pCO_2) in the Chesapeake Bay, combined with existing natural forcing, can significantly influence the success of larvae, which could influence the success and distribution of oysters throughout the Chesapeake Bay (Miller et al. 2009). Work done in California demonstrated that beyond reduction in shell thickness, ocean acidification has been shown to increase the vulnerability of native oysters to predation by invasive snails (Sanford et al. 2014). The threats presented by ocean acidification may suggest the use of a non-calcium carbonate alternative structure for oyster reef restoration to enhance the persistence and sustainability of these projects.

Reef Interconnectedness

A common suggestion for oyster reef restoration projects is to establish no-take sanctuaries around reefs to maintain benefits of restoration (Powers et al. 2009, Kennedy et al. 2011, Schulte and Burke 2014). Location of these sanctuaries, and by default selection of restoration sites, could be chosen to enhance the oyster and associated species ecosystem services provided by restored reefs through a type of reserve network (Puckett and Eggleston 2012). These set-aside areas could be created and designated based on their areas of strength; some reserves can be classified as strong “recruiters,” others as fast “growers,” and others as high “survivors” to enhance spatial connectivity of reefs and possibly to enhance oyster settlement and recruitment (Brumbaugh and Coen 2009, Puckett and Eggleston 2012, Schulte and Burke 2014). To accomplish this strategic planning of oyster restoration, more spatially explicit demographic data, hydrodynamic data, and information on larval connectivity in addition to biophysical and chemical information is needed (L. Kellogg, pers. comm., Puckett and Eggleston 2012). Having this information on a more regional or local scale is important within the Chesapeake Bay due to notable differences in, for example, hydrodynamic processes or larval recruitment across the Bay (Coen and Luckenbach 2000, Kennedy et al. 2011). Larval recruitment is a key piece of information for establishing knowledge about reef connectedness because it influences the need for spat addition (Gregalis et al. 2008, Brown et al. 2013, Graham et al. 2017). Geraldi et al. (2013) found that in nonrecruitment limited systems, addition of oyster seed did not enhance oyster reef restoration goals of increasing oyster density. Today, targeted tributaries in Virginia fit this description. In these cases, financial resources spent on seed may be better spent on adding additional substrate, making money spent on restoration more efficient.

References

Alden, R., Luckenbach, M., Dombrowski, A., Harlow, V., Abbgy, A., Ramirez, L., & Weber, I. (1996). *An evaluation of the feasibility and environmental acceptability of using pelletized coal fly ash as a substrate for oyster reef development.* (No. 3013). Norfolk, VA: AMRL Old Dominion University.

Ammar, M. (2009). Coral reef restoration and artificial reef management, future and economic. *The Open Environmental Engineering Journal, 2*, 37-49.

Andrews, R., Alden III, R., Luckenbach, M., & Wesson, J. (1997). The use of coal combustion by-product as substrate for oyster reef development. *Proceedings of the 22nd International Technical Conference on Coal Utilization and Fuel Systems. Coal and Slurry Technology Association of America,* Washington, DC. 363-375.

Baggett, L., Powers, S., Brumbaugh, R., Coen, L., DeAngelis, B., Greene, J., Hancock, B., & Morlock, S. (2014). *Oyster Habitat Restoration - Monitoring and Assessment Handbook.* Arlington, VA: The Nature Conservancy.

Baggett, L., Powers, S., Brumbaugh, R., Coen, L., DeAngelis, B., Greene, JK., Hancock, BT., Morlock, SM., Allen, BL., Breitburg, DL., Bushek, D., Grabowski, JH., Grizzle, RE., Grosholz, ED., La Peyre, MK., Luckenbach, MW., McGraw, KA., Piehler, MF., Westby, SR., & zu Ermgassen, PS. (2015). Guidelines for evaluating performance of oyster habitat restoration. *Restoration Ecology, 23*(6).

Bartol, I., Mann, R., & Luckenbach, M. (1999). Growth and mortality of oysters (*Crassostrea virginica*) on constructed intertidal reefs: Effects of tidal height and substrate level. *Journal of Experimental Marine Biology and Ecology, 237*, 157-184.

Beck, M., Brumbaugh, R., Airoldi, L., Carranza, A., Coen, L., Crawford, C., Defeo, O., Edgar, GJ., Hancock, B., Kay, MC., Lenihan, HS., Luckenbach, MW., Torpova, CL., Zhang, GF., & Guo, XM. (2011). Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management. *Bioscience, 61*, 107-116.

Biohabitats. (2017). Jamaica Bay Oyster Restoration Pilot Project. Retrieved from http://www.biohabitats.com/projects/jamaica-bay-oyster-restoration-pilot-project/

Black, S. (2015). BOPavilion Open for Business! Retrieved from http://www.billionoysterproject.org/bopavilion-open-for-business/

Brown, L., Furlong, J., Brown, K., & La Peyre, M. (2013). Oyster reef restoration in the northern Gulf of Mexico: Effect of artificial substrate and age on nekton and benthic macroinvertebrate assemblage use. *Restoration Ecology, 22*(2).

Brumbaugh, R., & Coen, L. (2009). Contemporary Approaches For Small-Scale Oyster Reef Restoration To Address Substrate Versus Recruitment Limitation: A Review and Comments Relevant for the Olympia oyster, *Ostrea lurida* Carpenter 1864. *Journal of Shellfish Research, 28*(1), 147-161.

Burke, R. (2010). *Alternative substrates as a Native Oyster (Crassostrea virginica) Reef Restoration Strategy in Chesapeake Bay.* (PhD Dissertation). Virginia Institute of Marine Science.

Cast-off toilets flush with oysters after two years. (2004, November 1). *Bay Journal*

Clark, K., Hunter, J., Bundy, M., & Kang, D. (2013). *Evaluation of Waste Concrete Road Materials for use in Oyster Aquaculture.* (State Highway Administration Research Report for MD Department of Transportation No. SP109B4E). Morgan State University.

Coen, L., & Luckenbach, M. (2000). Developing success criteria and goals for evaluating oyster reef restoration: Ecological function or resource exploitation? *Ecological Engineering, 15*, 323-343.

Dahle, C. (2012). *The Oyster Opportunity - Uncovering Solutions that Drive Reef Restoration in the Gulf of Mexico - Report Prepared for the National Fish and Wildlife Foundation.* Future of Fish.

Dillon, K., Peterson, M., & May, C. (2015). Functional equivalence of constructed and natural intertidal eastern oyster reef habitats in a northern Gulf of Mexico estuary. *Marine Ecology Progress Series, 528*, 187-203.

National Fish and Wildlife Foundation (Producer), (2014). *The Disappearing Oyster Population of Chesapeake Bay: Could 3 million year old fossils hold the key to saving this valuable resource?* [Video] Mother Nature Network.

Drexler, M., Parker, M., Geiger, S., & Arnold, W. (2014). Biological assessment of eastern oysters (*Crassostrea virginica*) inhabiting reef, mangrove, seawall, and restoration substrates. *Estuaries and Coasts, 37*, 962-972.

Dunn, R. (2013). *Oyster demographics and Cliona boring sponge on Potential Reef-Building Substrates - Implications for Oyster Restoration.* (M.S. Thesis). North Carolina State University,

Dunn, R., Eggleston, D., & Lindquist, N. (2014). Effects of substrate type on demographic rates of eastern oyster (*Crassostrea virginica*). *Journal of Shellfish Research, 33*(1), 177-185.

Environmental Protection Agency. (2017). Coal ash reuse. Retrieved from https://www.epa.gov/coalash/coal-ash-reuse

Fly ash Oyster Reef Experiment Yields Promising Results. (1996). *PR Newswire.*

George, L., De Santiago, K., Palmer, T., & Pollack, J. (2015). Oyster reef restoration: Effect of alternative substrates on oyster recruitment and nekton habitat use. *J. Coast Conserv, 19*, 13-22.

Geraldi, N., Simpson, M., Fegley, S., Holmlund, P., & Peterson, C. (2013). Addition of juvenile oysters fails to enhance oyster reef development in Pamlico Sound. *Marine Ecology Progress Series, 480*, 119-129.

Goodman, W. (2015). Inside Governors Island's new oyster pavilion. Retrieved from http://nymag.com/daily/intelligencer/2015/06/billion-oyster-pavilion.html?mid=twitter-share-di.

Grabowski, J., Hunghes, A., Kimbro, D., & Dolan, M. (2005). How habitat setting influences restored oyster reef communities. *Ecology, 86*(7), 1926-1935.

Graham, P., Palmer, T., & Pollack, J. (2017). Oyster reef restoration: Substrate suitability may depend on specific restoration goals. *Restoration Ecology, 25*(3), 459-470.

Gregalis, K., Powers, S., & Heck Jr, K. (2008). Restoration of oyster reefs along a bio-physical gradient in Mobile Bay, Alabama. *Journal of Shellfish Research, 27*(5), 1163-1169.

Grizzle, R., Burdick, D., Greene, J., Abeels, H., & Capone, M. (2006). *Reef structure alternatives for restoration of oyster (Crassostrea virginica) populations in New Hampshire.* (No. Paper 272). PREP Publications.

Grizzle, R., & Ward, K. (2016). *Assessment of recent eastern oyster (Crassostrea virginica) reef restoration projects in the Great Bay Estuary, New Hampshire: Planning for the future.* (No. Paper 353). PREP Publications.

Grizzle, R., & Ward, K. (2017). *Oyster reef restoration in Great Bay Estuary.* (No. Paper 368). PREP Publications.

Grow Oyster Reefs, L. (2017). CORRT, CORRD, CACO3 Concrete. Retrieved from http://www.growoysterreefs.com/about/.

Grunewald, S. (2015). Oyster growers use 3D printed structures to help restore New England's reef ecosystem. *3Dprint.Com.*

Gutierrez, J., Jones, C., Strayer, D., & Iribarne, O. (2003). Mollusks as ecosystem engineers: The role of shell production in aquatic habitats. *Oikos, 101*, 79-90.

Hafner, K. (2017). Scientists used coal ash to build oyster reefs off the Eastern Shore. How is the project holding up? *The Virginian-Pilot.*

Hidu, H., Chapman, S., & Soule, P. (1975). Cultchless setting of European oysters, *Ostrea edulis*, using polished marble. *Proc. Natl. Shellfish. Assoc., 65*, 13-14.

Homziak, J., Bennett, L., Simm, P., & Herring, R. (1993). Metal leaching from experimental coal fly-ash oyster cultch. *Bulletin of Environmental Contamination and Toxicology, 51*(2), 317-324.

Humphries, A., La Peyre, M., & Decossas, G. (2011). The Effect of Structural Complexity, Prey Density, and "Predator-Free Space" on Prey Survivorship at Created Oyster Reef Mesocosms. *PLoS One, 6*(12).

Humphries, A., La Peyre, M., Kimball, M., & Rozas, L. (2011). Testing the effect of habitat structure and complexity on nekton assemblages using experimental oyster reefs. *Journal of Experimental Marine Biology and Ecology, 409*, 172-179.

Judy, C. (2017). *DNR repletion program 1960-2006.* Presentation to OAC.

Kellogg, L. (2017). To Goelz T., *Personal communication.*

Kennedy, V., Brietburg, D., Christman, M., Luckenbach, M., Paynter, K., Kramer, J., Sellner, KG., Dew-Baxter, J., Keller, C., & Mann, R. (2011). Lessons Learned from Efforts to Restore Oyster Populations in Maryland and Virginia, 1990 to 2007. *Journal of Shellfish Research, 30*(3), 719-731.

Krassenstein, E. (2015). The Incredible Billion Oyster Pavilion is constructed with the help of 3D printing. Retrieved from https://3dprint.com/70092/billion-oyster-pavilion/.

Kurihara, H., Kato, S., & Ishimatsu, A. (2007). Effects of increased seawater pCO_2 on early development of the oyster *Crassostrea gigas*. *Aquat. Biol.,* 91-98.

Kuykendall, K., Moreno, P., Powell, E., Sonait, T., Colley, S., Mann, R., & Munroe, D. (2015). The Exposed Surface Area to Volume Ratio: Is Shell More Efficient than Limestone in Promoting Oyster Recruitment? *Journal of Shellfish Research, 34*(2), 217-225.

La Peyre, M., Furlong, J., Brown, L., Piazza, B., & Brown, K. (2014). Oyster reef restoration in the northern Gulf of Mexico: Extent, methods and outcomes. *Ocean & Coastal Management, 89*, 20-28.

Lazar, J. (2017). To Goelz T., *Personal communication.*

Leard, R., Dugas, R., & Berrigan, M. (1999). Resource management programs for the eastern oyster, *Crassostrea virginica*, in the U.S. Gulf of Mexico...past, present, future. *Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches; Proceedings from the Symposium, Williamsburg, VA, April 1995,* Williamsburg, VA. 63-91.

Levine, E., Gosnell, J., Goetz, E., & Malinowski, C. (2016). Natural cultch type influences habitat preference and predation, but not survival, in reef-associated species. *Restoration Ecology, 25*(1), 101-111.

Liddel, M. (2008). *A Von Bertalanffy Based Model for the Estimation of Oyster (Crassostrea virginica) Growth on Restored Oyster Reefs in Chesapeake Bay.* (PhD Dissertation). University of Maryland.

Lipcius, R., & Burke, R. (2006). *Abundance, Biomass and Size Structure of Eastern Oyster and Hooked Mussel on a Modular Artificial Reef in the Rappahannock River, Chesapeake Bay.* (Special Report in Applied Marine Science and Ocean Engineering No. 390). Virginia Institute of Marine Science.

Lipcius, R., Burke, R., McColloch, D., Schreiber, S., Schulte, D., Seitz, R., & Shen, J. (2015). Overcoming restoration paradigms: Value of the historical record and metapopulation dynamics in native oyster restoration. *Frontiers in Marine Science, 2.*

Lotze, H., Lenihan, H., Bourque, B., Bradbury, R., Cooke, R., Kay, M., Kidwell, SM., Kirby, MW., Peterson, CH., & Jackson, J. (2006). Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science, 312*, 1806-1809.

Louisiana Department of Wildlife and Fisheries. (2004). *Louisiana's Oyster Shell Recovery Pilot Project.* (No. NA96FK0188).

Louisiana Natural Resources Trustees. (2015). *Deepwater Horizon NRDA Early Restoration Project Progress Report: Louisiana Oyster Cultch Project.*

Luckenbach, M. (2017). To Goelz T., *Personal communication.*

Maryland Department of Natural Resources. (2013). *Little Choptank FAQ: Oyster Restoration in the Little Choptank River.*

Maryland Department of Natural Resources. Oyster Advisory Commission (OAC) Meeting. August 1, 2016. Meeting Summary, Annapolis, MD.

Maryland Department of Natural Resources. Oyster Advisory Commission (OAC) Meeting. May 15, 2017. Meeting Summary, Annapolis, MD.

Mohammed, J. (2016). Applications of 3D printing technologies in oceanography. *Methods in Oceanography, 17*, 97-117.

Nestlerode, J., Luckenbach, M., & O'Beirn, F. (2007). Settlement and survival of the oyster *Crassostrea virginica* on created oyster reef habitats in Chesapeake Bay. *Restoration Ecology, 15*(2), 273-283.

New York City Office of the Mayor. (2016, September 6). 50,000 oysters being installed in Jamaica Bay to help improve water quality and protect wetlands.

O'Beirn, F., Luckenbach, M., Nestlerode, J., & Coates, G. (2000). Toward design criteria in constructed oyster reefs: Oyster recruitment as a function of substrate type and tidal height. *Journal of Shellfish Research, 19*(1), 387-395.

Oyster Metrics Workgroup. (2011). *Restoration Goals, Quantitative Metrics and Assessment Protocols for Evaluating Success of Restored Oyster Reef Sanctuaries - Report to the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program.*

Oyster Recovery Partnership. (2016). *2016 Impact Report.* https://oysterrecovery.org/wp-content/uploads/2017/02/ORP_2016_ImpactReport.pdf.

Oyster Recovery Partnership. (2017). Shell Recycling Alliance. Retrieved from https://oysterrecovery.org/sra/.

Powell, E., Kraeuter, J., & Ashton-Alcox, K. (2006). How long does oyster shell last on an oyster reef? *Estuarine, Coastal and Shelf Science, 69*, 531-542.

Puckett, B., & Eggleston, D. (2012). Oyster demographics in a network of no-take reserves: Recruitment, growth, survival, and density dependence. *Marine and Coastal Fisheries, 4*(1), 605-627.

Quan, W., Fan, R., Wang, Y., & Humphries, A. (2017). Long-term oyster recruitment and growth are not influenced by substrate type in China: Implications for sustainable oyster reef restoration. *Journal of Shellfish Research, 36*(1), 79-86.

Reecy, S., & Jordan, W. (2013). To Kotulak P., *Engineering Monitoring Services Summary Report - Gulf Coast Aggregates Rail Siding Oyster Shell Loading Into Gondola Train Cars Telogia, Florida.* Ardaman & Associates, Inc.

Reef Life Restoration. Engineered Reef Systems. Retrieved from http://www.reefliferestoration.com/engineered-reef-systems.

Reynolds Westby, S. (2017). To Goelz T., *Personal communication.*

Reynolds Westby, S., Allen, S., Gross, K., Sowers, A., & Weissberger, E. (2014). *2013 Oyster Restoration Implementation Update - Progress in the Choptank Complex (Harris Creek, Little Choptank River, and Tred Avon River Oyster Sanctuaries).* Maryland Oyster Restoration Interagency Workgroup of the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team.

Reynolds Westby, S., Allen, S., O'Neill, C., Sowers, A., & Weissberger, E. (2013). *2012 Harris Creek Oyster Restoration Tributary Plan Implementation Update.* Maryland Oyster Restoration Interagency Workgroup of the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team.

Reynolds Westby, S., Bruce, D., Slacum, W., French, E., Sowers, A., & Weissberger, E. (2016). *2015 Oyster Restoration Implementation Update - Progress in the Choptank Complex (Harris Creek, Little Choptank River, and Tred Avon River Oyster Sanctuaries).* Maryland Oyster Restoration Interagency Workgroup of the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team.

Reynolds Westby, S., Bruce, D., Slacum, W., Gross, K., Sowers, A., & Weissberger, E. (2015). *2014 Oyster Restoration Implementation Update - Progress in the Choptank Complex (Harris Creek, Little Choptank River, and Tred Avon River Oyster Sanctuaries).* Maryland Oyster Restoration Interagency Workgroup of the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team.

Reynolds Westby, S., Sowers, A., Lazar, J., Slacum, W., & Paynter, K. (July 2017). *2016 Oyster Reef Monitoring Report: Analysis of Data from Large-Scale Sanctuary Oyster Restoration Projects in Maryland.* Maryland Oyster Restoration Interagency Workgroup of the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team.

Rodney, W., & Paynter, K. (2006). Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay in Maryland. *Journal of Experimental Marine Biology and Ecology, 335*, 36-51.

Rothschild, B., Ault, J., Goulletquer, P., & Heral, M. (1994). Decline of the Chesapeake Bay Oyster Population: A Century of Habitat Destruction and Overfishing. *Marine Ecology Progress Series, 111*, 29-39.

Sanford, E., Gaylord, B., Hettinger, A., Lenz, E., Meyer, K., & Hill, T. (2014). Ocean acidification increases the vulnerability of native oysters to predation by invasive snails. *Proc. R. Soc. B, 28.1*

Schulte, D., & Burke, R. (2014). Recruitment enhancement as an indicator of oyster restoration success in Chesapeake Bay. *Ecological Restoration, 32*(4), 434-440.

Sonait, T., Broadhurst, RC., Haywood, EL. (1991). Alternatives to clamshell as cultch for oysters, and the use of gypsum for the production of cultchless oysters. *Journal of Shellfish Research,* 10, 405-410.

Sonait, T., & Burton, G. (2005). A comparison of the effectiveness of sandstone and limestone as cultch for oysters, *Crassostrea virginica*. *Journal of Shellfish Research, 24*(2), 483-485.

Sonait, T., Cooper, N., Powell, E., Klinck, J., Abdelguerfi, M., Tu, S., Mann, R., & Banks, P. (2014). Estimating Sustainable Harvests of Eastern Oysters, *Crassostrea virginica*. *Journal of Shellfish Research, 33*(2), 381-394.

Speiler, R., Gilliam, D., & Sherman, R. (2001). Artificial substrate and coral reef restoration: What do we need to know to know what we need. *Bulletin of Marine Science, 69*(2), 1013-1030.

Stokes, S., Wunderink, S., Lowe, M., & Gereffi, G. (2012). *Restoring Gulf Oyster Reefs - Opportunities for Innovation.* Duke Center on Globalization, Governance & Competitiveness.

Sustainable Oceans International. Projects - Fisheries Enhancement & Multipurpose reefs. Retrieved from http://www.sustainableoceans.com.au/Projects/.

Tamburri, M., Luckenbach, M., Breitburg, D., & Bonniwell, S. (2008). Settlement of *Crassostrea ariakensis* larvae: Effects of substrate, biofilms, sediment and adult chemical cues. *Journal of Shellfish Research, 27*(3), 601-608.

Tamburri, M., Zimmer-Faust, R., & Tamplin, M. (1992). Natural sources and properties of chemical inducers mediating settlement of oyster larvae: A re-examination. *Biol. Bull., 183*, 327-338.

Tethon 3D. Oyster growers use 3D printed structures to help restore New England's reef ecosystem. Retrieved from http://tethon3d.com/oyster-growers-use-3d-printed-structures-to-help-restore-new-englands-reef-ecosystem/.

Theuerkauf, S., Burke, R., & Lipcius, R. (2015). Settlement, Growth, and Survival of Eastern Oysters on Alternative Reef Substrates. *Journal of Shellfish Research, 34*(2), 241-250.

Tickle, E. (2018). To Goelz T., *Personal communication.*

U.S. Army Corps of Engineers: Baltimore and Norfolk Districts. (March 2012). *Chesapeake Bay Oyster Recovery: Native Oyster Restoration Master Plan.* State of Maryland and Commonwealth of Virginia.

Waldbusser, G., Steenson, R., & Green, M. (2011). Oyster shell dissolution rates in estuarine waters: Effects of pH and shell legacy. *Journal of Shellfish Research, 30*(3), 659-669.

Waldbusser, G., Voigt, E., Bergschneider, H., Green, M., & Newell, R. (2011). Biocalcification in the Eastern Oyster (*Crassostrea virginica*) in Relation to Long-term Trends in Chesapeake Bay pH. *Estuaries and Coasts, 34*(2), 221-231.

Wallace, R., Baumann, H., Grear, J., Aller, R., & Gobler, C. (2014). Coastal ocean acidification: The other eutrophic problem. *Estuarine, Coastal and Shelf Science, 148*, 1-13.

Walles, B., Troost, K., van den Ende, D., Nieuwhof, S., Smaal, A., & Ysebaert, T. (2016). From Artificial Structures to Self-Sustaining Oyster Reefs. *Journal of Sea Research, 108*, 1-9.

Watson, S., Southgate, P., Tyler, P., & Peck, L. (2009). Early larval development of the Sydney rock oyster *Saccostrea glomerata* under near-future predictions of CO_2-driven ocean acidification. *J. Shellfish Res., 28*, 431-437.

Wheeler, T. (2015, May 28). Watermen win changes to oyster reef restoration. *The Baltimore Sun.*

Wheeler, T. (2017). Chesapeake losing its oyster reefs faster than they can be rebuilt. *Bay Journal.*