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ALTERNATIVE SUBSTRATES USED FOR OYSTER REEF RESTORATION: A REVIEW

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ABSTRACT Oyster populations and reef habitats have notably declined in the last century around the world. The ecological, economic, and cultural values of oysters have led to a variety of restoration efforts seeking to recover these lost benefits. Limitations of the native oyster shell substrate and the large-scale nature of many restoration projects have resulted in the increased use of a variety of alternative, or artificial, substrates to create reef structures. A text mining package was used to conduct a review of alternative substrates used for oyster restoration. Specifically, the review (1) assessed commonly used alternative substrates, (2) locations where alternative substrates are used, and (3) common performance metrics used to evaluate alternative substrates. The review demonstrated that (1) the most common substrates included porcelain, concrete, limestone, noncalcium stone, nonoyster shell, dredged shell, and engineered reefs; (2) oyster restoration with alternative substrates occurs worldwide, but evaluations of alternative substrates were primarily (79%) within the United States of America; and (3) four main categories of performance metrics are used to assess alternative substrates—biological, structural, chemical, and economic acceptability. Within the four performance metrics, however, there exists a substantial variety in terms of specific metrics used and application of metrics to assess alternative substrates. Results highlight the need for common metrics across projects to ease comparison between alternative substrate options.

KEY WORDS: alternative substrate, review, oyster, performance metrics, restoration, reefs

INTRODUCTION

Oyster populations and reef habitats have significantly decreased across the globe (Beck et al. 2011), prompting oyster restoration projects at many scales in the United States (La Peyre et al. 2014) and around the world (Carranza et al. 2011, Gillies et al. 2015, Quan et al. 2017, Fariñas-Franco et al. 2018). Restoration efforts are undertaken to work toward certain ecological, economic, and cultural goals that are associated with oyster reef habitats. The principal motivation behind early oyster restoration efforts was the enhancement of the commercial fishery, historically depressed from overharvesting and environmental degradation (Coen & Luckenbach 2000). Whereas this remains a goal in many oyster restoration efforts today, an increasing emphasis has been placed on enhancing the ecosystem services provided by oyster reefs, including shoreline protection and wave mitigation, nursery and foraging habitat for reef-associated species, and enhanced water filtration (Piazza et al. 2005, Grabowski & Peterson 2007, Borsje et al. 2011, La Peyre et al. 2014, George et al. 2015, Walles et al. 2016, Fitzsimmons et al. 2019).

The scales, methods, and projected outcomes of oyster restoration vary around the world. These different approaches and goals make comparison across restoration projects difficult and have spurred recent calls for universal metrics for guiding and assessing restoration efforts (Baggett et al. 2014, 2015, Fitzsimmons et al. 2019). The lack of such metrics to track, measure, and define "success" within restoration projects could hamper the achievements of these projects (Mann & Powell 2007). Despite projects lacking similarity, a common thread through most projects is the use of alternative substrates. An alternative, or artificial, substrate is an umbrella term that encompasses any substrate used for oyster reef restoration other than the native oyster shell of the area (Brumbaugh & Coen 2009). Restoration projects have historically used recycled, fossilized, or dredged native oyster shell, as shell was recognized as the optimal hard substrate for oyster settlement and growth (Mann & Powell 2007, Waldbusser et al. 2011, Levine et al. 2017). The increased demand for oyster shells in many systems and the decreasing overall amount of shell have limited the availability and affordability of natural oyster shells for restoration projects. In addition, the large-scale nature of oyster habitat reduction as noted in Beck et al. (2011) requires that subsequent restoration efforts be equally large in scale. The limited amount of available shells in most systems cannot fulfill the substantial demands of large-scale restoration projects, such as those in the Chesapeake Bay and Australia (U.S. Army Corps of Engineers - Baltimore District (USACE) 2009, Allen et al. 2011, Gillies et al. 2015).

Because of these limitations, many restoration projects have turned to various alternative materials to create hard reef structures where oyster larvae can naturally settle or be planted. There is a diversity of alternative substrates available for oyster restoration efforts. Determining the appropriate alternative substrate depends on the characteristics of each substrate and how well matched it is for the scale, methods, and goals of each individual restoration project. This review synthesizes results from published studies on some of the most commonly used alternative substrates for oyster reef restoration. By increasing understanding of the strengths and weaknesses of different alternative substrates, future restoration efforts will be able to more effectively and efficiently plan and execute oyster restoration projects.

ALTERNATIVE SUBSTRATE OPTIONS

Restoration efforts and scientific research projects have tested and used a variety of alternative substrate options for oyster restoration. To effectively decide between alternative substrates, one must consider a variety of factors concerning the

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substrates themselves and the objectives of the restoration (Fitzsimmons et al. 2019). Quan et al. (2017) performed a literature review assessing alternative substrates solely in relation to oyster settlement, survival, and growth. This review looks to build on these results and assesses alternative substrates for additional factors. Graham et al. (2017) and others have discussed how the suitability of alternative substrates depends on the goals of specific oyster restoration projects. This review considers some of the most commonly used factors to assess restoration projects and goals of restoration projects.

METHODS

A comprehensive keyword search in multiple search engines and databases (e.g., Google Scholar, Web of Science, ScienceDirect, and JSTOR) was used to understand the type and use of alternative substrates in oyster reef restoration. The following keyword search was used; the article had to include all the words: "oyster reef," "substrate," "substrate type," "restoration," and "study"; had to include the phrase "oyster reef"; and include either "alternative" or "artificial." Results included both peer-reviewed publications and "grey literature" with publication dates ranging from 1864 to 2019. Article titles and abstracts were read to refine the results and ensure the only the inclusion of relevant articles. Articles for this review were considered relevant if they discussed or tested an alternative substrate that had been used in real-world restoration projects, not solely scientifically assessed as a bench study. The manual refinement of articles and abstracts resulted in 96 articles, with publication dates ranging from 1999 to 2019. A spreadsheet of the reviewed literature is included in the Appendix 1.

The text mining (tm) package in R was used to perform content analysis on the article abstracts to identify (1) common alternative substrate(s) examined/used for restoration, (2) the geographic location of the oyster restoration with alternative substrates, (3) and the lens through which the article examined/assessed the substrates (i.e., oyster abundance, associated fauna, and economic cost) (Feinerer & Hornik 2019, R Core 2018). The initial review of the abstracts was performed to assemble a standard set of keywords that were used to further search and summarize the different substrates examined. To focus on the alternative substrate content, the tm package offers a number of data-cleaning options, including removing common English "stop words" (i.e., the, is, what, and we) from the analysis. The initial review of the articles also resulted in the removal of other unrelated words from the analysis (i.e., boat and thesis). Commonality of alternative substrates was determined by summing the number of articles that mention each substrate. The regions of each article were also used to track trends in the use of certain alternative substrates for oyster restoration. Last, performance metrics mentioned in the articles were tracked to understand how alternative substrates were being assessed.

The tm package was run on both the entire articles and the article abstracts. Both the analysis of the entire article and the abstracts resulted in similar frequent words and important concepts. Thus, for ease of analysis, abstracts alone were used to draw results on the areas of interest for the review (Nunez-mir et al. 2015, Capano et al. 2019). Because of the specificity and level of technicality of some articles, a review of the entire article was used to supplement findings for common performance metrics used to assess alternative substrates.

RESULTS

Oyster Species and Geographic Location

Seven species of oysters were discussed in relation to alternative substrates. The species mentioned most often were *Crassostrea virginica* (Gmelin, 1791) (n = 50), followed by *Ostrea edulis* (Linnaeus, 1758) (n = 11), *Crassostrea ariakensis* (Fuijita, 1913) (n = 11), *Ostrea lurida* (Carpenter, 1864) (n = 3), *Crassostrea gigas* (Thunberg, 1793), *Crassostrea rivularis* (Gould, 1861) (n = 2 for both), and last *Crassostrea sikamea* (Amemiya, 1928) (n = 1). The division in the species examined follows the geographic makeup of the assembled articles, that is, where the studies took place.

A majority of studies (79%) was conducted in the United States (n = 76), followed by Europe and Asia (specifically China) (n = 6 for both), worldwide reviews (n = 4), and South America and Australia (n = 2 for both). Within the United States, the majority of work on alternative substrates has been within the Gulf of Mexico (n = 37) and Chesapeake Bay (n = 19) regions, with the rest being spread over the mid-Atlantic, and northeast and West Coast of the United States.

Types of Alternative Substrates

In examining the 96 documents, it was evident that many different words were used interchangeably to reference the same type of alternative substrate (e.g., granite and stone). Therefore, a single term was selected to designate each alternative substrate but accounted for all known synonyms used within the abstracts. Table 1 lists the known synonyms used during content analysis.

The most frequently mentioned alternative substrates were (in order): concrete (n = 416), limestone (n = 52), noncalcium stone (n = 25), nonoyster shell (n = 17), dredged shell (n = 15), engineered reefs (n = 13), and porcelain (n = 6). This order varied slightly when examining the number of abstracts (and thus articles) that mentioned each alternative substrate. In addition to concrete being the most frequently mentioned alternative substrate overall, it was also mentioned in most abstracts (n = 29), followed by limestone (n = 19), noncalcium stone (n = 13), engineered reefs (n = 7), nonoyster shell (n = 6), dredged shell (n = 5), and last porcelain (n = 4).

Geographically, concrete was mentioned with similar frequency in all regions examined (United States, Australia, Europe, China, South America, and worldwide reviews). Limestone was predominantly mentioned in the United States,

TABLE 1.

List of substrate synonyms used during content analysis.

Alternative substrate	Synonyms
Porcelain	None
Limestone	None
Noncalcium stone	Granite, rocks, stone
Concrete	Block, blocks, cement, cinder, riprap, concrete
Nonoyster shell	Nonoyster, surf, mussel, clamshell, conch
Dredged shell	Dredge, fossilized
Engineered reefs	Castles, reef balls, engineered

and less frequently in Europe, China, Australia, and worldwide reviews. The nonoyster shell substrate was mentioned exclusively in the United States for use and testing in oyster restoration. The dredged shell was mentioned primarily in the United States and South America as an alternative substrate, and once in reference to an article in China. Engineered reefs were only mentioned in relation to oyster restoration in the United States, South America, and China. Last, Porcelain was only mentioned in oyster restoration in the United States and South America.

Performance Metrics: How Alternative Substrates Are Assessed?

Four overarching categories were identified that summarized performance metrics used to assess different alternative substrates used for oyster restoration. These categories were biological (e.g., substrate supports oyster recruitment, growth, survival, and associated species), structural (Is the substrate sustainable? Will it persist in the system? Are there any immediate benefits for habitat formation, wave energy reduction, etc.?), chemical (Is the substrate chemically suitable for oyster larvae settlement? Are there leaching/pollution threats?), and economic (What is the cost of the substrate? Is it commonly available, easy to transport?). Although there are overlaps between these categories (e.g., the chemical composition of limestone contributes to its biological success), these categories adequately capture elements of interest when considering substrates for oyster restoration. Examples are presented of each of the alternative substrates in relation to the four overarching categories. Table 2 summarizes the assessed performance of the alternative substrates within each of these performance metrics.

BIOLOGICAL

Testing of alternative substrates was originally focused primarily on assessing the biological acceptability of the substrate related specifically to oysters (Sonait et al. 1991). Thus, questions of biological suitability were restricted to the considerations of oyster spat recruitment, settlement, growth, biomass, density, and survival (Haywood et al. 1999). More recently, some studies have expanded the scope of biological suitability of alternative substrates to include consideration of reef-associated species and overall ecosystem diversity (Brown et al. 2014, Graham et al. 2017).

TABLE 2.

Summary assessment of alternative substrates based on four performance metrics: biological, structural, chemical, and economic acceptability.

Alternative substrate	Biological	Structural	Chemical	Economic
Porcelain	~	~	~	–
Limestone	+	+	+	+
Noncalcium stone	+	+	~	+
Concrete	+	~	+	+
Nonoyster shell	–	–	+	+
Dredged shell	?	~	?	–
Engineered reefs	?	+	?	?

Substrates are assessed as being strong in a category (+) (i.e., they have been assessed to perform well), weak (–), undetermined (~) (i.e., conflicting reports exist about the substrates' performance), or unknown (?) (i.e., not enough data are available).

Concrete

Haywood et al. (1999), Quan et al. (2009), Burke (2010), George et al. (2015), and Quan et al. (2017), among others, have demonstrated that concrete reefs perform equal or superior to oyster shells for oyster restoration when considering spat settlement, recruitment, and growth. Beyond initial oyster establishment on reefs, further studies indicate that size, biomass, and density of oysters were again equal or superior to oyster shells (Brown et al. 2014). The biological acceptability of concrete reefs, above and beyond other alternative substrates, has been attributed to high levels of interstitial space in concrete substrates (the size and number of gaps between substrate pieces) and the ability to create reefs with higher vertical relief (Dunn 2013).

Related to wider ecosystem benefits, Brown et al. (2014) determined that older concrete reefs (defined as >6 y) supported significantly more benthic invertebrates than did similarly aged shell reefs ($P < 0.05$), suggesting a long-term biological suitability of concrete. Graham et al. (2017) demonstrated that concrete and oyster shell reefs both supported high densities of associated motile fauna.

Porcelain

Recent work on the biological acceptability of porcelain has shown mixed results. In the Gulf of Mexico, George et al. (2015) revealed that oyster spat that settled on porcelain were significantly smaller ($P < 0.05$) than other tested substrate types except limestone. Oyster recruitment, growth, and associated nekton habitat use of porcelain reefs, however, were not different from other alternative substrates and were analogous to those on natural oyster reefs.

Limestone

The calcium-based chemical composition of limestone is suggested to play a role in its biological acceptability (Gregalis et al. 2008, Powers et al. 2009, Furlong 2012, Brown et al. 2014, La Peyre et al. 2014, George et al. 2015, Kuykendall et al. 2015, Graham et al. 2017, Quan et al. 2017). Studies have demonstrated that limestone substrates perform equal to or better than other alternative substrates—and at times, oyster shells—in terms of oyster settlement, recruitment, growth, abundance, and density (Louisiana Department of Fish and Wildlife [LDFW] 2004). The size of limestone pieces may play a role in the biological suitability of the substrate, in particular compared with other calcium-base substrates such as clamshell. Early studies on the biological acceptability of limestone demonstrated that oyster settlement was significantly greater ($P < 0.05$) on limestone than on clamshell reefs, another calcium-based substrate (Sonait et al. 1991). The structural integrity of limestone (i.e., it is less prone to fracturing) could explain this enhanced biological performance, even when chemical composition is similar.

Quan et al. (2017), however, called into question long-term biological benefits of limestone. After three years, initial high oyster settlement and recruitment on limestone plateaued; limestone no longer performed significantly better ($P > 0.05$) than the other substrates tested (oyster shell and clam shell). This suggests the need for long-term studies of this, and all, alternative substrates to understand any longitudinal changes in biological acceptability.

Noncalcium Stone

Burke (2010) determined that stone reefs in a Virginia tributary supported high oyster recruitment and long-term oyster abundance (i.e., biomass and density), with numbers comparable with the highest levels on restored oyster shell reefs. In Virginia, Tamburri et al. (2008) revealed no significant difference ($P > 0.05$) in oyster settlement between oyster shells and granite. One study showed calcium carbonate substrates (such as shells and limestone) supported higher oyster settlement than noncalcium carbonate substrates (such as stone and concrete), suggesting biological limitations of stone due to chemical composition (Dunn 2013). A recent evaluation of Harris Creek, a Maryland tributary undergoing oyster restoration, revealed the average oyster density was higher on stone reefs (Westby et al. 2017).

Nonoyster Shell

Surf clam shell reefs in Virginia exhibited recruitment and settlement suitability compared with oyster shell reefs in a Virginia study but suffered higher levels of postsettlement mortality (Nestlerode et al. 2007). Also, surf clam shell reefs did not support high levels of oyster growth or survival (Nestlerode et al. 2007). A more recent study from the United Kingdom determined that reefs constructed with mussel shells supported similar levels of species richness and abundance compared with rock and oyster shell reefs (Callaway 2018). Limited interstitial space compared with rock reefs, however, limited the performance of mussel reefs in terms of enhancing infaunal diversity.

Dredged Shell

Numerous studies have demonstrated that oyster shells are the best substrate for oyster recruitment, settlement, and growth (Mann & Powell 2007, Waldbusser et al. 2011, Kuykendall et al. 2015, Levine et al. 2017). Restoration efforts, however, have used different classifications to describe oyster shells. "Fresh" shells are classified as oyster shells that have been shucked and subsequently replanted on bars (Judy 2017). Historically, dredged shells, oyster shells that are buried or sit on natural bars within the environment, not fresh shells, have been the dominant material used to replenish oyster reefs (Pace & Boyd 2012, Paul & Tanner 2012). The lack of available dredged shells has led to the use of recycled (fresh) shells to fill the gap. On an annual basis, the current volume of available fresh shells is an extremely small fraction of the volume of dredged shells used for reef replenishment at peak availability. Whereas dredged shells theoretically have similar biologic benefits to fresh oyster shells, there is no work that the authors are aware of that specifically assesses the biological acceptability of dredged shells.

Engineered Reefs

The design and composition of engineered reefs have been used to enhance their biological benefits as alternative substrates. Oyster castles in Virginia used oyster shells, limestone, and concrete to form the structures, taking advantage of the biological benefits of these substrates for oyster recruitment (Theuerkauf et al. 2015). In this study by Theuerkauf et al. (2015), the oyster castles had double the oyster density and biomass compared with oyster shell reefs because of enhanced recruitment to the castles over the oyster shell reefs.

Engineered reefs can also be designed to enhance vertical relief, allowing them to sit higher in the water column, which has been demonstrated to improve oyster settlement (Breitburg 1999, Klotzbach 2013). Last, engineered substrates can be designed with irregular surfaces and rugged textures to enhance the available interstitial space to benefit oyster recruitment and settlement (Tickle 2019).

STRUCTURAL

In addition to their biological benefits, oyster reefs are recognized for their structural advantages, including shoreline stabilization, wave attenuation, and erosion control (Meyer et al. 1997, Grabowski et al. 2012). Reef structures, including height and interstitial space, also play a role in the biological feasibility of alternative substrate reefs (Dunn 2013). Also, within a restoration context, the persistence of a chosen substrate has both economic and labor implications; the longer a chosen substrate can last, the less additional material must be used to enhance the reefs (La Peyre et al. 2014). Thus, evaluations of alternative substrates must also consider these structural elements of native oyster reefs.

Concrete

Structurally, concrete benefits from its longevity (Haywood et al. 1999). The structural complexity of concrete reef habitats, the irregular surface and spaces, provides enhanced predation protection to associated reef species than fragile shell substrates (nonoyster shell) (USACE 2009). The volume of concrete substrate has also been shown to enhance the settling environment for oysters. Furlong (2012) demonstrated that adult oyster densities on concrete surpassed densities on oyster shells in the Gulf of Mexico. But similar to limestone, Quan et al. (2017) described how the structural benefits of concrete reefs degraded over time, calling into question their long-term viability. More longitudinal data are needed to evaluate the structural benefits of concrete over time.

Shoreline stabilization and wave attenuation benefits have been attributed to concrete substrates through engineered reefs; many engineered reefs use concrete in their formation (Theuerkauf et al. 2015). Hard substrates for shoreline stabilization, however, are increasingly being substituted with the idea of "living shorelines," or the preservation of a narrow band of intertidal habitats (Currin et al. 2010). Hard substrates in these vulnerable coastal areas have been shown to accelerate erosion and increase siltation and stability of nearby waters (Pilkey & Wright 1988, Currin et al. 2010). Thus, the benefits attributed to the use of concrete reefs for oyster restoration need to be considered alongside any potential negative impacts on the surrounding ecosystem.

Porcelain

The persistence of porcelain is a natural trait of the substrate; it will not degrade like calcium carbonate structures and, thus, can offer habitat structures for long periods of time. New York City used porcelain to create reefs, specifically referencing the persistence of porcelain as the reasoning behind their selection (New York City Department of Environmental Protection

2018). No work, however, has tested the long-term persistence of porcelain. In terms of structural elements such as shoreline stabilization or wave reduction, no work has assessed porcelain reefs. Further research would be necessary to ascertain these factors.

Limestone

Similar to other stone-based substrates, one of limestone's principal benefits is its persistence (Kuykendall et al. 2015). The persistence, paired with the diversity in possible sizes, allows limestone reefs to be built upward. Gregalis et al. (2008) and others have recognized the importance of vertical relief of reefs. More vertical space on reefs has been shown to support higher oyster recruitment and persistence, especially in areas where hypoxia is common (Lenihan & Peterson 1998, Breitburg 1999). Focused work would be necessary to assess the benefits of limestone reefs in terms of other structural services such as wave reduction or shoreline stabilization.

Noncalcium Stone

The durability of stone reefs has been commonly referenced in the literature. Tamburri et al. (2008) and Burke (2010) emphasized the importance of the persistence of stone reefs. Hard substrates such as stone are particularly beneficial in areas of soft sediment, such as sand and mud; the type of the substrate is less important than simply the presence of a hard substrate for oysters to recruit to in an otherwise soft-substrate environment (Grizzle & Ward 2016, Smyth et al. 2018). This highlights the importance of awareness of the natural benefits or limitations of the system under restoration consideration. Understanding recruitment variability, habitat availability, temperature, salinity, and other biotic and abiotic factors is key when selecting an alternative substrate.

Nonoyster Shell

Surf clam shells were tested in the early 2000s in Virginia (Coen & Luckenbach 2000, O'Beirn et al. 2000, Nestlerode et al. 2007) and were deemed unsuitable for reef building. This unsuitability stemmed from its fragility; surf clam shells fractured easily during handling, which limited critical interstitial space and surface complexity. Other nonoyster shell substrates likely suffer from the same issue, although there has not been any discussion of structural elements of other shell types.

Dredged Shell

Levine et al. (2017) suggested that dredged shells may last longer than fresh oyster shells, especially in low-pH environments. Their results drew on a study from Waldbusser et al. (2011) that explained that dredged shells had a lower dissolution rate than fresh shells across pH levels; this could contribute to enhanced reef persistence. The calcium carbonate composition of dredged shells means that it will still degrade and require further addition of substrates later. Data in the literature on the structural characteristics of dredged shells remain limited, hindering the ability to draw conclusions.

Engineered Reefs

Structural benefits are some of the main drivers of engineered options for oyster reef restoration. The design and creation of these engineered options emphasize maximizing vertical relief and interstitial space, attempting to capitalize on structural elements deemed crucial for oyster recruitment, settlement, and growth (Gregalis et al. 2008). In addition, structural benefits of wave attention, shoreline stabilization, and erosion control have been discussed and tested within the literature (Brumbaugh & Coen 2009, Dehon 2010, Servold 2015, Theuerkauf et al. 2015).

Most recently, Grow Oyster Reefs, LLC (GROW), a Virginia-based company, developed concrete oyster reef restoration tiles and concrete oyster reef restoration discs specifically aimed for use in oyster restoration projects. They are molded reproducible alternative substrate designs modeled after native reef shape, surface, and chemical formula (Tickle 2019). The use of these made-to-order substrates will continue to grow as oyster restoration projects continue.

CHEMICAL

The primary consideration of chemical suitability of alternative substrates is based on the calcium content. Substrates high in the calcium content may, through surface chemistry or biofilm chemicals, induce oyster larvae to settle (Bavestrello et al. 2000, Sonait & Burton 2005). Enhancing settlement, then, makes these substrates more effective for oyster restoration purposes. Some chemical concerns related to leaching, however, have arisen because of varying levels of public or regulatory acceptance or comfort using particular substrates (e.g., recycled porcelain and repurposed concrete) (Fitzsimmons et al. 2019). Both chemical concerns have an impact on the selection of alternative substrates.

Concrete

Concrete lacks the chemical cues that calcium-based substrates possess which have been shown to enhance biological acceptability. In addition, there are negative public perceptions associated with the use of concrete centered around potential chemical leaching into the surrounding water column. Any use of concrete for oyster restoration is subject to thorough cleaning and removal of any building debris, if it is repurposed (e.g., concrete from demolished buildings or bridges); however, some groups remain concerned. Work carried out by the U.S. Army Corps of Engineers in the Chesapeake Bay demonstrated that no damaging levels of contaminants are released into the water column due to concrete substrates (USACE 2009). A more controlled study has since been conducted in the Chesapeake Bay with similar results; oyster growth and survival suffered no adverse effects from the use of repurposed concrete substrates (Clark et al. 2013).

Porcelain

Limited available data on porcelain reefs hinder any definite conclusions concerning chemical suitability; porcelain, however, lacks the calcium base present in other alternative substrates. Similar to concrete, porcelain reefs have been subject to negative public and regulatory attitudes because of the nature of the substrate source (e.g., postconsumer toilets and tubs). No work has been carried out on any leaching possibilities for porcelain substrates. Restoration projects, like that in New York City, discuss the importance of cleaning porcelain pieces before they are added to water, a point emphasized for all substrate materials (New York City Department of Environmental Protection 2018). Despite biological and structural benefits to porcelain reefs, selection of the substrate always has to consider public and regulatory perceptions.

Limestone

The biological acceptability of limestone for oyster recruitment, settlement, and growth has been suggested to be heavily influenced by the chemical composition of the substrate (Gregalis et al. 2008, La Peyre et al. 2014, Graham et al. 2017). The difference in alternative substrate chemical compositions (e.g., calcium versus silicon materials) could have short- and long-term impacts on oyster populations and should be evaluated longitudinally to understand differences.

Noncalcium Stone

Stone is a noncalcium carbonate structure, meaning it lacks the chemical composition that has been suggested to promote oyster larvae recruitment and settlement (O'Beirn et al. 2000, Sonait & Burton 2005). Despite its chemical composition, stone has been shown to be a successful alternative substrate type for oyster settlement, recruitment, growth, and ecosystem services (Tamburri et al. 2008, Burke 2010).

Nonoyster Shell

The suggested chemical importance of calcium carbonate for oyster larvae settlement (Hidu et al. 1975, Sonait & Burton 2005) led to the use of nonoyster shells for oyster reef restoration. Studies have shown that although larvae settlement is similar across surf clams and oyster shells, postsettlement mortality was significantly higher on surf clam shells, resulting in significantly different oyster densities ($P < 0.05$). These differences are likely because of structural differences between oysters and surf clam shells (O'Beirn et al. 2000, Nestlerode et al. 2007). Despite chemical suitability, structural issues (its ease of fracture) limit the usefulness of some nonoyster shells as an alternative substrate.

Dredged Shell

Dredged shells, like other shell substrates, benefit from the calcium carbonate composition (Paul & Tanner 2012). Limited studies testing dredged shells or restoration efforts monitoring dredged shells hinder the ability to make conclusions on their chemical suitability, in particular on how dredged shells may differ from fresh oyster shells.

Engineered Options

Enhancing the chemical acceptability of substrates inspired the design of Grow Oyster Reefs concrete oyster reef restoration tiles and concrete oyster reef restoration discs products. They are made with $CaCO_3$ concrete, a concrete mix formulated to match oyster shell biochemical makeup (Tickle 2019). GROW products demonstrate that chemical elements of substrates can be incorporated into engineered options. In addition, the use of new materials for the construction of many engineered reefs limits chemical leaching concerns from these substrates.

ECONOMIC

Economic analysis of alternative substrates has always been a consideration of hands-on oyster restoration work (Hicks et al. 2004, LDFW 2004). Until recently, however, explicit economic analysis has been lacking within the peer-reviewed literature (Baggett et al. 2015, Graham et al. 2017). The use of economic considerations and analysis techniques could be a way to more holistically assess the benefits and costs of different alternative substrates (e.g., ability to support commercially valuable species, increases in oyster harvest, cost of material shipping and placement, and substrate availability). Economic analyses are particularly important in the face of increasingly large-scale, expensive restoration projects that require choosing the substrate that "will deliver the greatest value within financial and operational limitations" (Graham et al. 2017, p. 468, Wilson et al. 2011).

Concrete

Concrete is an economically attractive substrate in part because of its diversity in size and shape, its ready availability, and the ease of manufacture (Haywood et al. 1999, Lipcius & Burke 2006, Theuerkauf et al. 2015). Concrete can be obtained from old pavements or road infrastructure (Clark et al. 2013), or manufactured and engineered specifically for restoration projects and created into whatever size is appropriate for the restoration project at hand (Drexler et al. 2014, Theuerkauf et al. 2015).

Graham et al. (2017) illustrated that oyster shells and concrete both returned similarly high benefit-to-cost ratios (BCR) for motile fauna, meaning that the costs of both substrates returned high numbers of associated motile fauna, and in fact, concrete returned a higher BCR than shells in terms of oyster abundance. This BCR technique is an example of how ecosystem services of alternative substrates can be incorporated into economic analysis and considerations.

Porcelain

Although porcelain is readily available in the form of old toilets and sinks, the associated costs of this alternative substrate are high. Oyster reef restoration efforts in Virginia showed that moving and preparing the porcelain were more expensive than using natural oyster shells (Schnaars 2001, Paul & Tanner 2012). These results are dated, but no further work has assessed the economic feasibility of porcelain. The increasing cost of native oyster shells in recent years could make porcelain economically feasible going forward.

Limestone

The LDFW (2004) concluded that limestone is more expensive to obtain than crushed concrete or crushed oyster shells. Since this report was published, further studies have called limestone a "cheaper" alternative substrate option (Theuerkauf et al. 2015). Kuykendall et al. (2015) demonstrated that economically, limestone performed similar to oyster shells. The benefit of large volumes of limestone was attributed to the relative proportion of small to large particles; the mix allows for increased interstitial space and surface areas.

Australian oyster restoration efforts have also emphasized the economic benefits of limestone beyond in-the-water costs due to the logistics and transport of limestone from quarries to the restoration sites (Gillies et al. 2015). This economic benefit would apply to any alternative substrate that needed to be transported to restoration sites.

Noncalcium Stone

Stone has become a frequently used alternative substrate for oyster restoration because of its ready availability in many regions and its relatively reasonable price compared with oyster shells (USACE 2009). More recent work by Graham et al. (2017) revealed that stone substrates cost more than limestone, concrete, and oyster shells and these reefs had the lowest oyster density and motile fauna production BCR of the four substrates. These findings demonstrate how the lens of evaluation can impact the perceived benefits of alternative substrates.

Nonoyster Shell

The USACE (2009) report revealed the cost of nonoyster shells (surf clam) to be lower than any other alternative substrate except dredged oyster shells. Paul and Tanner (2012), however, discuss how the limited supply of nonoyster shells and their lack of durability hinder the long-term economic benefit of these shell substrates.

Dredged Shell

The USACE (2009) report revealed the cost of dredged oyster shells to be among the lowest among alternative substrates. Changing conditions since this report, i.e., the decrease in available dredged shells in many areas such as the Chesapeake Bay, the Gulf of Mexico, and Australia, render the report results out of date. The finite nature of dredged shells limits the long-term viability and economic benefit of this substrate source.

Engineered Reefs

Engineered reefs naturally have higher costs because of the need to design and construct these substrates (USACE 2009, Paul & Tanner 2012). The continued use of these engineered reefs assumes that the benefits accruing from the high level of design specificity outweigh the higher costs. La Peyre et al. (2014), however, highlighted the lack of information available on many engineered products. Limited data on their effectiveness make the selection of these higher cost options riskier (Lowe et al. 2011, La Peyre et al. 2014). The cost of engineered options may be mitigated in the future with the advent of construction-grade three-dimensional printers, allowing for the optimization of material usage and eliminating expensive tooling (Mohammed 2016). The feasibility of using engineered options for large-scale restoration efforts, however, remains to be seen.

CONCLUSION AND DISCUSSION

This review provides an overview of alternative substrates used for oyster reef restoration. Results demonstrate the global nature of oyster restoration, but with the dominance of projects and literature originating in the United States. The most commonly discussed substrates included concrete, limestone, porcelain, noncalcium stone, nonoyster shell, dredged shell, and engineered reefs. From the literature, four performance metrics were derived that have been commonly used to assess and evaluate different alternative substrates: biological, structural, chemical, and economic acceptability. Examples from the literature within these four categories have been presented.

Oyster restoration projects are growing in scale and quantity. These projects need substrates, and in many locations, there are not enough oyster shells available. Policy shifts (e.g., incentivizing shell recycling programs (Levine et al. 2017) or creating and enforcing a shell budget (Sonait et al. 2012)) could help increase the amount of shells available. These policy shifts alone are unlikely to result in the volume of shells needed for oyster restoration projects, especially as restoration projects continue to focus on goals beyond enhancing local oyster fisheries. Although oyster shells are the best substrates for enhancing oyster populations, it might not be the best choice if restoration goals include long-term sustainably of reefs or creating more complex habitat structures. The results from this review support the suggestion in Graham et al. (2017) that the alternative substrate of choice will depend on the goals of the specific restoration project.

Despite the four overarching performance metrics discussed, the lack of comprehensive, universal performance metrics to assess oyster restoration projects was evident during this review. The need for universal metrics has been widely discussed in the literature (Allen et al. 2011, Baggett et al. 2014, Grizzle & Ward 2016, Bardar 2019, Fitzsimmons et al. 2019). Some universal metrics have even been proposed, including reef areal dimension, reef height, and oyster density; however, there have not been concentrated efforts to adopt and use these suggestions (Baggett et al. 2014). Through the application of consistent metrics, more complete information on the strengths and weaknesses of different substrates will be available, including basic information such as restoration project descriptions, reef location, original configuration, source of funding, or overall goals of restoration. This is especially important because of the wide range of systems in which oyster restoration is being conducted (e.g., high versus low recruitment and other varying abiotic and biotic factors, including salinity, temperature, and turbidity). Any universal metrics must be broad enough to consider the variability of systems being restored, to allow managers and policy makers to compare their system and others when designing restoration projects and selecting substrates. Finding the balance between specific goals of each individual restoration project and overall restoration approaches and methods will aid in the selection of an alternative substrate.

Last, any set of common metrics moving forward must account for climate change–induced impacts when assessing the strengths and weaknesses of substrates. For example, estuarine waters, the location of many oyster reef restoration projects, are more susceptible to acidification because of their shallower depths, less saline waters, and lack of marine water buffers (Waldbusser et al. 2011). The calcium bases of many substrates (oyster, nonoyster shell, and limestone) are more vulnerable to decreased pH, which may hinder their effectiveness in the long term (Waldbusser et al. 2011). Alternative substrates such as stone or many engineered options could become de facto choices to ensure the persistence of restoration projects in the face of lowering pH levels.

Selection of alternative substrates for oyster restoration will occur in the face of different project goals, scales, outlooks, challenges, and limitations. Both ecosystem and economic benefits must be considered when selecting an alternative substrate; in the end, the specific goals of specific restoration projects will dictate the choice of the substrate. As oyster restoration projects continue to grow in number, scope, and diversity of techniques, the creation and use of a set of common metrics would allow these projects to have more complete information when selecting substrates.

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APPENDIX 1: ARTICLES INCLUDED IN THE ALTERNATIVE SUBSTRATE REVIEW

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