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The application of oyster reefs in shoreline protection: are we over-engineering for an ecosystem engineer?

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Abstract

1. Oyster reef living shorelines have been proposed as an effective alternative to traditional coastal defence structures (e.g., bulkheads, breakwaters), with the benefit that they may keep pace with sea-level rise and provide co-benefits, such as habitat provision. However, there remains uncertainty about the effectiveness of shoreline protection provided by oyster reefs, which limits their broader application.
2. We draw evidence from studies along the east and gulf coasts of the US, where much research and implementation of oyster reef restoration has occurred, to better define the existing gaps in our understanding of the use of restored oyster reefs for shoreline protection.
3. We find potential disconnects between ecological and engineering functions of reefs. In response, we outline how engineering and ecological principles are used in the design of oyster reef living shorelines and highlight knowledge gaps where an integration of these disciplines will lead to their more effective application.
4. *Synthesis and applications*. This work highlights the necessary steps to advance the application of oyster reef living shorelines. Importantly, future research should focus on appropriate designs and conditions needed for these structures to effectively protect our coasts from erosion, while supporting a sustainable oyster population, thereby providing actionable nature-based alternatives for coastal defence to diverse end-users.

1. Living shorelines for coastal defence

There is an emerging interest in harnessing the natural protection benefits offered by existing or restored/created (hereafter "restored") coastal habitats, such as dunes, biogenic reefs and vegetation (Temmerman et al., 2013; Spalding, et al., 2014). These existing or restored habitats are often presented as an alternative to the use of traditional defence structures (e.g., seawalls, breakwaters and groynes, Figure 1a) in response to the potentially negative socio-economic (Hinkel, et al., 2014) and environmental (Bulleri & Chapman, 2010) effects of the latter. For example, artificial structures replace natural shorelines with a homogeneous habitat that supports less biodiversity (Chapman, 2003) and a greater number of non-native species (Dafforn et al., 2012; see reviews by Bulleri & Chapman, 2010; Firth et al. 2016a). Recent reviews have argued that existing and restored habitats can be a cost-effective shoreline protection alternative to traditional structures under future scenarios of climate change and coastal development (Narayan et al., 2016; Reguero et al., 2018). Nevertheless, a number of knowledge gaps hinder the application of nature-based habitats for coastal defence (Feagin et al., 2010; Bouma et al., 2014), paramount among these being the dearth of field data quantifying the coastal defence value of these shoreline protection approaches, especially for restored habitats (Morris et al., 2018).

The east and gulf coasts of the United States have pioneered the introduction of "living shoreline" techniques using restored habitats, such as saltmarsh and oyster reefs (Figure 1b), sometimes in combination with hard structures (e.g., rock sills, Figure 1c), for biodiversity enhancement and erosion control in relatively low-energy estuarine settings (Bilkovic*, et al.,* 2017). Concurrent with these projects, has been the development of policy directives to promote the use of these approaches (e.g., The 2008 Living Shorelines Protection Act in Maryland). One increasingly popular approach involves the use of oyster reefs as a component of shoreline protection. In recent decades, there have been significant efforts to reverse the global decline of oysters (estimated at 85% functionally extinct; Beck et al., 2011) through oyster reef restoration (La Peyre et al., 2014a; Gillies et al., 2017). Initially, restoration focused on recovering the harvest of oysters and other fisheries associated with these reefs (Beck et al., 2011). More recently, there has been a growing focus on maximizing other services and benefits, such as water quality and shoreline protection (Grabowski et al., 2012). In addition to erosion control, another great attribute of oyster reefs (and living shorelines more generally) is that they are adaptive to environmental changes (Taylor and Bushek, 2008; Bible & Sandford, 2015). For instance, oyster reefs can recover quickly from major storm events (Livingston et al., 1999) and accrete at a rate equal to or greater than sea-level rise (Rodriguez et al., 2014) or local subsidence (Casas et al., 2015). This is in contrast to artificial structures, which have to be rebuilt, upgraded and maintained in response to a changing climate, at significant expense (Hinkel et al., 2014).

Despite recent advances in the promotion of living shorelines over traditional defence structures for shoreline protection, there remains uncertainty in the efficacy of shoreline protection provided by some living shoreline designs, including existing and restored oyster reefs. Indeed, scant data exists that evaluate the effectiveness of existing and restored oyster reefs at curbing shoreline erosion. Where data are available, the results are often highly variable (e.g., La Peyre et al., 2013; see meta-analysis by Morris et al., 2018). Here we draw evidence from studies along the east and gulf coasts of the United States, where considerable research and implementation of oyster reef restoration has occurred, to better define the existing gaps in our understanding of the use of restored oyster reefs for shoreline protection. This information may be particularly useful to practitioners that are considering or beginning to apply living shorelines using shellfish reefs in other locations (e.g., *Saccostrea glomerata* [Sydney Rock oyster] in Australia, Coghlan et al. 2016; *Crassostrea gigas* [Pacific oyster] in the Netherlands, Walles et al. 2016; *Ostrea lurida* [Olympia oyster] on the US west coast; and *Geukensia demissa* [Ribbed mussel] along the US Atlantic coast, Moody, 2012), as well as for prospective oyster reef living shorelines along the east and gulf coasts. We use lessons learned from these regions to outline future considerations towards the effective use of restored oyster reefs for preventing shoreline loss worldwide, with the main goal of providing valuable, applicable information to scientists and managers.

2. Oyster reef living shorelines

The primary expectation of an oyster reef living shoreline is that it will protect against waves that cause erosion. To establish an oyster reef, all species, including the Eastern oyster (*Crassostrea virginica*) native to the east and gulf coasts of the US, require a hard substratum for juvenile settlement (Bayne, 2017). This has resulted in the development of many different types of units to construct artificial reefs, which have been deployed for oyster establishment in living shorelines (Table 1). These artificial reefs vary in construction materials, unit shape, reef size (i.e., height, length, and width), and placement (i.e., distance) relative to the shoreline (e.g., depth, intertidal vs. subtidal) (Table 1; Hernandez et al. 2018). Creating reefs using recycled oyster shell, which may be deployed as loose shell, or shell within netted bags or attached to mats, is common practice (Hernandez et al. 2018). The expectation is that oyster larvae will recruit to the shell and form a reef over the top of the shell mound, cementing the shell together. In comparison with loose shell, bags or mats may prolong the integrity of the shell mound while oysters attach. The attachment of oysters is contingent on there being larvae available to settle and environmental conditions that will allow for settlement (e.g., wave exposure, salinity; La Peyre et al., 2015). Where a natural supply of larvae is not available, projects may seed reefs with spat settled elsewhere (Geraldi et al. 2013), or adult oysters (Strain et al. 2018). Oyster mats purposely have a low reef profile, whereas multiple bags can be used to build reefs of different heights and shapes (Table 1). These structures may be built on the footprint of dead natural reefs (e.g., Florida; Walters, 2014) or, alternatively, if no previous hard substrate is present the reefs are deployed onto soft sediments.

An increasing number of commercial businesses and contractors are providing reef substrates made of steel, rip-rap, limestone and crushed or pre-cast concrete. These structures include multiple designs, which vary in shape, height, width and complexity (Table 1). Among these diverse reef substrates, some used are very large, akin to traditional breakwater units (e.g., La Peyre et al. 2013; Table 1). This begs the question of whether we are over-engineering these structures, when their purpose is to provide substrate for a living, growing reef through the sustenance of an oyster population. Ideally, reefs should be carefully designed to optimise abiotic and biotic conditions using just enough substrate to allow the colonization and development of an oyster population. Thus hypothetically, shoreline protection increases as oysters grow and then provides a consistent level of protection over time (Figure 2). This will require coastal management that is forward-thinking, with an early investment in living shorelines, rather than reacting to failure. Few comparisons exist of sustainability (i.e., oyster reef development) and efficacy in shoreline protection among different reef types, and across the diversity of environmental settings that may affect shoreline protection and oyster reef development and persistence (for an example see Walles et al. 2016, Salvador de Paiva et al. 2018). This gap in knowledge that combines both engineering and ecological function is a significant challenge and there is a need to better define engineering designs to protect shorelines, keeping in mind that the engineered structure is also meant to become a living, growing oyster reef through recruitment, growth and accumulation of oysters (Walles et al., 2016). In the following sections we outline how engineering and ecological principles are currently applied in oyster reef living shorelines, and highlight how an integration of these disciplines could lead to more effective shoreline protection.

3. Evaluation of oyster reef living shorelines

3.1 Application of engineering principles

The primary engineering goal of oyster reef living shorelines is to create a structure that remains intact and can provide coastal defence through energy attenuation and shoreline stabilization. There are a number of different ways engineering principles can enhance the design of oyster reef living shorelines for shoreline protection (Table 2). Much of the work to understand wave attenuation by oyster reef living shorelines has taken a similar approach to that used for traditional breakwaters (Chasten et al. 1993). Performance is evaluated on the basis of the ability of the structure to reduce wave height shoreward of the structure, with the relative importance of key design parameters assessed, e.g., structure porosity, reef crest height and width, water depth and freeboard (i.e., difference between structure height and still water depth) (U.S. Army Corps of Engineers, 2002). There is a focus on applying this information to develop empirical equations characterizing hydrodynamics and wave attenuation by oyster reef breakwaters, and predicting the resulting effects on sediment dynamics and coastal stability (Allen & Webb 2011; Webb & Allen 2015).

For instance, the trend that wave attenuation is greatest when the crest of the structure is at or above the still water level, with little wave attenuation during submergence (Allen & Webb 2011; Webb & Allen 2015) should also apply to oyster reef breakwaters (Servold et al., 2015; Chauvin, 2018; MacDonald, 2018; Wiberg et al. 2018). In a controlled hydrodynamic study within a newly-deployed oyster reef living shoreline, Spiering et al. (2018) found that wave attenuation was maximized (83 ± 5 %) when water levels were 1 cm below the crest of the reef structure. When mean water levels were 5 cm above the reef structure, wave heights were reduced by 42 ± 3 %. This was similar to the attenuation observed in a shoreline vegetated by mature mangrove (36 ± 6 %) and exceeded that observed in a bare shoreline (11 ± 7 %). However, crest height may be compensated with crest width regarding wave attenuation; a higher, narrower crest may attenuate as much as a lower, wider crest, with the latter being akin to how naturally occurring oyster reefs attenuate waves (Allen and Webb, 2011). This information on crest height and width is important, as justification for oyster reef living shorelines comes from evidence (both anecdotal and scientific) showing that natural intact habitats provide efficient protection (e.g., Brandon et al. 2016). However, these natural oyster reefs were expansive (Woods et al., 2005) and such reefs no longer exist. Due to the logistics of restoring oyster reefs, there are few projects where restoration occurs at the scale that natural reefs would have once existed (e.g., in some areas of Chesapeake Bay reef footprints were an average of 102,508 m^2 in the 1870s; Woods et al., 2005, but oyster reef living shorelines are a maximum of 865 m^2; Table 1). Thus, applying engineering principles to help understand the scale required for an oyster reef living shoreline to effectively protect the coast is a critical need.

In this regard, it is noteworthy that few studies have incorporated what happens to the relevant hydrodynamics once a structure becomes fully colonized by oysters (but see Manis et al., 2015; further discussed in section "Filling in the gaps: integrating ecology and engineering" below). Empirical approaches to describe oyster reef living shorelines need to incorporate an understanding of the coupled bio-hydrodynamic interactions within newly-deployed reef structures and throughout stages of recruitment and development, using the growing scientific literature on oyster reef hydrodynamics (e.g., Whitman & Reidenbach, 2012; Manis et al., 2015; Styles, 2015). This would result in a combined ecological-engineering approach that acknowledges the heterogeneity of shorelines and dynamic nature of living organisms.

3.2 Application of ecological principles

The adaptive ability (i.e., to environmental changes, see section above "Living shorelines for coastal defence") of oyster reefs is a key consideration for their use in lieu of traditional breakwaters. This adaptive ability depends on successful oyster colonization and growth on the reef substrate. Therefore, the objectives of ecological research on oyster reef living shorelines should focus on the factors that affect the persistence of oysters on the reef structure (Table 2). Key parameters that have been used to assess oyster reef persistence include recruitment, growth and survival, which are normally surveyed along with environmental factors such as sedimentation, salinity and elevation (e.g., Walles et al. 2016). The development of models of oyster habitat suitability can help predict the locations for successful oyster growth and oyster reef living shorelines (e.g., Fuchs and Reidenbach, 2013; La Peyre et al. 2015).

Although there has been a number of field studies assessing oyster colonization and shoreline change following reef deployment (e.g., Piazza et al., 2005, Scyphers et al., 2011), the link between the two has not been investigated. Work to date shows variable performance of oyster reef living shorelines regarding both oyster colonization and shoreline stabilization (Morris et al., 2018). For instance, La Peyre et al. (2013) showed that reefs constructed of ReefBLK^{SM} in Louisiana promoted shoreline accretion at one site, reduced shoreline erosion in a second site, and had no effect on shoreline stabilization in a third site. Furthermore, recruitment of oysters was observed at the first two sites, but not at the third (La Peyre et al., 2013). It should be noted, however, that much longer times may be needed to observe changes in shoreline stabilization in relation to oyster colonization (La Peyre et al., 2014b). The variability in success among studies and locations highlights the gaps in our understanding about how to design a living shoreline, which supports a self-sustaining oyster population that provides effective coastal defence. It is imperative that we learn from both successes and failures when moving forward in oyster reef living shoreline research (Firth et al. 2016b).

4. Filling in the gaps: integrating ecology and engineering

Living shorelines have been proposed as a solution to both ecological (i.e., the loss of habitats) and engineering (i.e., non-adaptive traditional structures) challenges in increasingly human-impacted coasts (Temmerman et al. 2013; Figure 2). Oyster reef living shorelines will only be successful at protecting the coast and restoring ecosystem services if both engineering and ecological principles are married in their design such that persistent and efficacious oyster reefs are constructed. However, studies to date have been focused separately on either engineering or ecological purposes, with little merging of the two. There are multiple examples where an integration of ecological and engineering research is needed to better understand and implement the use of oyster reef living shorelines for coastal protection (Table 2a).

One example is the effect of live oysters on hydrodynamic processes and sediment stabilization. For instance, *in situ* hydrodynamic measurements indicate that, given similar flow conditions, production and dissipation of turbulent energy are an order of magnitude greater on existing healthy oyster reefs than on degraded reefs with no live oysters (Kitsikoudis et al., in review). A recent study showed that sediment accumulation by Pacific oyster (*Crassostrea gigas*) reefs is dependent on oyster density as well as the length to width ratio of the reefs, where longer and narrower reefs with higher oyster density tend to trap more sediment (Salvador de Paiva et al., 2018). This link is important, as the purpose of oyster reef living shorelines is to provide sustained coastal defence over time through a growing oyster population (Figure 2).

Another example is the effect of wave and current-induced turbulence on spat settlement to the reef. In a study of living shoreline hydrodynamics, flow-structure interaction over newly-deployed reefs created with bagged oyster shell increased shoreline velocities by over an order of magnitude as compared to two nearby control shoreline sites (Spiering et al., 2018). Such differences in turbulent conditions, as well as settlement surfaces can affect oyster recruitment (Whitman and Reidenbach, 2012). Consequently, knowledge of the appropriate benthic topography to create the optimum recruitment conditions (i.e., hydrodynamics, settlement surface, protection from predators, sedimentation, etc.) and how this might need to alter under changes in climate (e.g., by facilitating certain growth forms that mitigate extreme temperatures while maintaining other target functions, including coastal defence; McAfee et al., 2018) will increase the chances of creating a self-sustaining reef (Whitman and Reidenbach, 2012; Kitsikoudis et al., in review).

In summary, successful oyster reef living shorelines combine engineering and ecological principles to meet both types of needs. The design and placement of a reef will affect the recruitment and resilience of the oyster population on the reef, and thus the reef effectiveness in restoring ecosystem services and values including coastal protection. Undoubtedly, targets can only be achieved with collaborative research and common integrated goals involving ecologists and engineers.

5. Conclusions

The application of oyster reef living shorelines requires a change in how ecologists and engineers approach and evaluate their respective disciplines. Many oyster reef living shorelines as currently designed are neither representative of natural oyster reefs (but see oyster mats, Table 1), nor do they perform as traditional breakwaters. Thus, it is critical to better understand how and when they work through integrated studies (Table 2b). Research on reef hydrodynamics has focused on identifying the optimal characteristics (e.g., crest height, width) of the reef base for wave attenuation. This approach, however, may result in over-engineering of oyster reef living shorelines, when the original intent was to provide a base for oyster reef development. Over time oyster accretion will cause a change in reef structure, and a key unknown is how this will alter shoreline protection. In contrast, projects that are primarily concerned with ecological values of oyster reef living shorelines (habitat provision, water quality) may fail to achieve the objective of coastal defence. Although the majority of information to date has been acquired from research on *C. virginica*, the questions that need to be addressed (Table 2b) are applicable to all shellfish reef living shorelines. Projects in their infancy have the opportunity to be forward-thinking about the information required prior to broad implementation. In order to increase uptake, oyster reef living shorelines will need to be included as a standard tool in engineering guidelines for coastal defence. Developing such guidelines will require a greater understanding of how to create a sustainable oyster reef living shoreline that provides shoreline protection. Performance data that incorporate design criteria related to both ecological and engineering function is the critical next step to achieving this goal.

Authors' contributions

All authors conceived the ideas; RLM led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data accessibility

Data have not been archived because this article does not use data.

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Table 1. Examples of oyster reef living shorelines used throughout the United States of America. Values for reef size are presented as an estimated range of length (L) width (W) and height (H) from smallest to largest projects. WAD/WAU = Wave Attenuating Device/Unit. All examples are from microtidal locations (defined as a tidal range of 0-2 m as per Davies, 1964).

State	*Structures used*	*Size (m)*	*Tidal height*	*Example*
New Jersey	Bagged shell Oyster castles®	L: 1.8 – 9.1 W: 1.0 – 5.8 H: 0.5 – 1.0	Intertidal	
Virginia	Bagged shell Oyster castles® Ready Reef Reefball™	L: 1.2 – 278.9 W: 0.6 – 3.1 H: 0.3 – 1.0	Intertidal Subtidal	
Florida	Bagged shell Oyster mats	L: 6 – 83 W: 3 – 10 H: 0.05 – 0.13	Intertidal	
Alabama	Loose shell Bagged shell Reefball™ ReefBLK℠ WAU®	L: 17.0 – 250.0 W: 2.3 – 6.0 H: 0.5 – 2.0	Intertidal Subtidal	

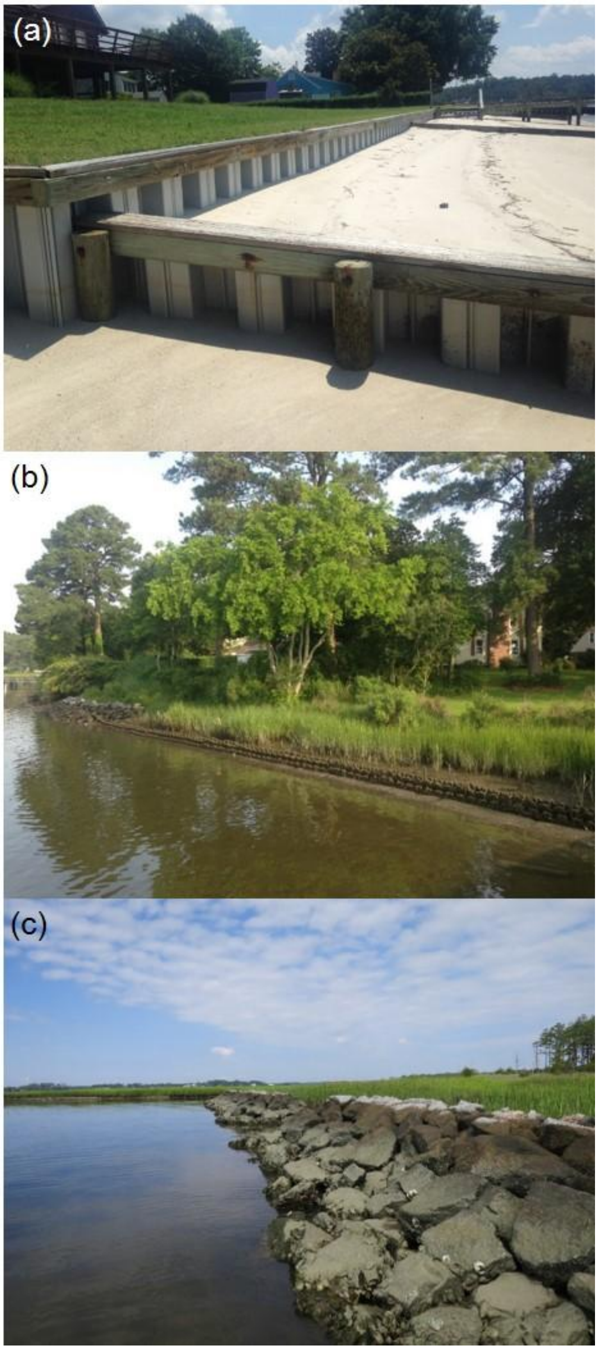
Louisiana	ShoreJAX™ Oysterbreak™ Reefball™ ReefBLK℠ WAD®	L: 25.0 – 9656.0 W: 1.0 – 6.5 H: 0.75 – 1.4	Subtidal	

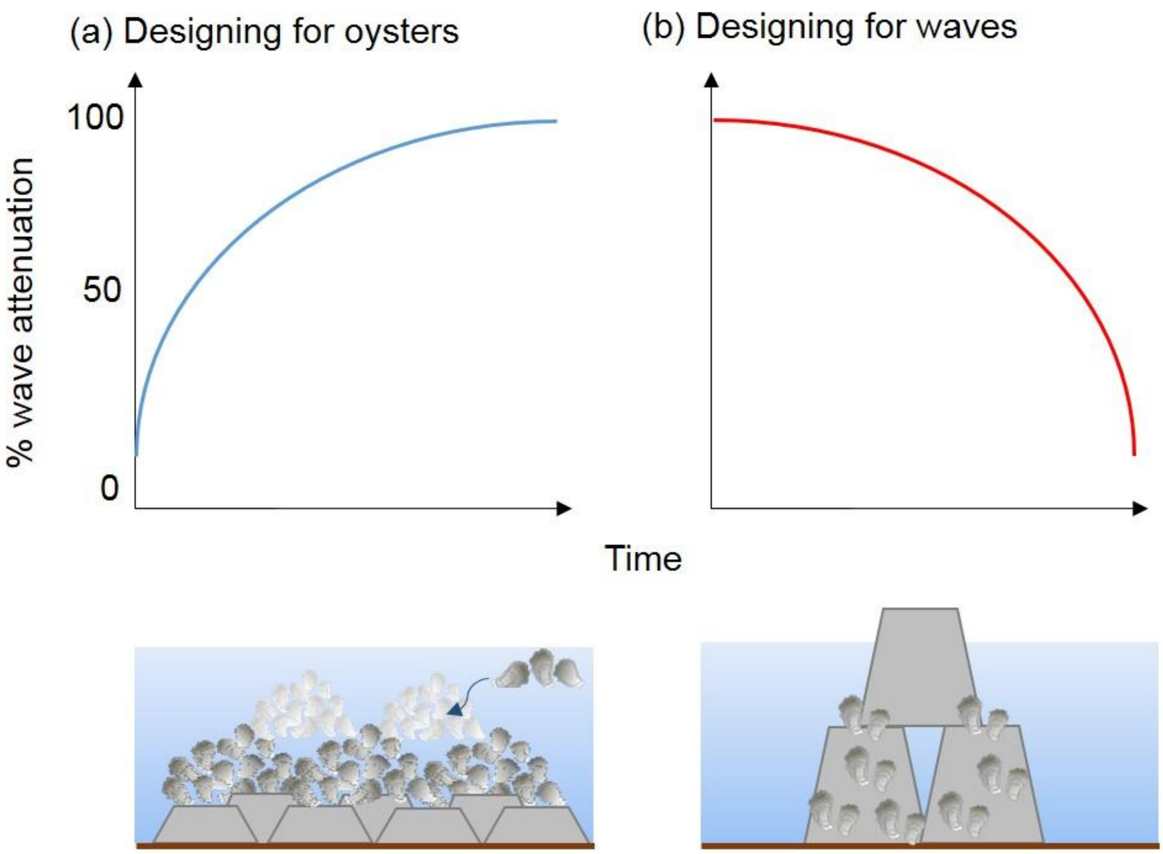
Table 2. Examples of (a) important design criteria to be addressed from an ecological, engineering or interactive perspective for oyster reef living shorelines where the ecological goal is a self-sustaining oyster reef and the engineering goal is to provide coastal defence; and (b) key research questions that arise from the integration of ecology and engineering to inform when and where oyster reef living shorelines are a viable alternative to traditional structures.

<table>
<tr><th>(a) Effect of:</th><th>Ecology</th><th>Engineering</th><th>Interaction</th></tr>
<tr><td>Restored reef presence</td><td>Larval supply – availability and timing
Habitat suitability (e.g., salinity, hydrology)
Trajectory of colonization</td><td>Decrease in cross-shore sediment transport
Wave attenuation</td><td>Influence of oyster metrics (e.g., density, size) on waves and sediment transport
Influence of wave energy on oyster persistence (e.g., recruitment, survival, mortality)
Sediment accretion and oyster settlement, survival</td></tr>
<tr><td>Reef material</td><td>Spat settlement
Refuge from predation</td><td>Structural integrity</td><td>Wave-induced turbulence on spat settlement and how this changes with different reef complexity or rugosity</td></tr>
<tr><td>Reef length (parallel to shore)</td><td rowspan="2">Patch size and shape – impacts on reef recruitment (e.g., edge effects)
Spatial configuration of patches – impacts on reef recruitment and survival (e.g., edge effects on settlement, food)</td><td>Enhancement of shore-parallel currents</td><td>Influence of oyster metrics (e.g., density, size) on currents</td></tr>
<tr><td>Reef width (perpendicular to shore)</td><td>Relationship between width of the reef and incident wavelength for wave attenuation</td><td>Reef edge effects (e.g., velocity magnitude) on oyster metrics and persistence (e.g., recruitment, survival, mortality)</td></tr>
<tr><td>Reef height / depth</td><td>Optimum tidal range and depth for oyster settlement, growth and survival</td><td>Wave breaking
Wave set-up</td><td>Change in wave breaking and set-up with oyster colonization over time</td></tr>
<tr><td colspan="4">(b) Key research questions
What is the optimum environment and reef material required for settlement of oysters?
What is the effect of oyster colonization and growth on reef hydrodynamics?
What is the timeline for oyster reef living shorelines to provide coastal defence?
What is the scale of oyster reef needed for coastal defence?
What factors affect the resilience of oyster populations and is there any risk associated with this?</td></tr>
</table>

Figure 1. Coastal protection provided by (a) a traditional bulkhead, (b) a living shoreline with an oyster sill and (c) a living shoreline with a rock sill.

Figure 2. Hypothesized effect on wave attenuation for oyster reef living shorelines that are designed for oysters (a) or waves (b). It is expected that wave attenuation will improve over time with the accretion of oysters under appropriate environmental conditions. In contrast, reefs that are not designed to maximize oyster colonization will have a design life akin to traditional breakwaters. Symbols are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).


(a)
(b)
(c)


(a) Designing for oysters
(b) Designing for waves
100
50
0
% wave attenuation
Time