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CHAPTER 18

Comparison of Oyster Populations, Shoreline Protection Service, and Site Characteristics at Seven Created Fringing Reefs in Louisiana Key Parameters and Responses to Consider

Megan K. La Peyre, Lindsay Schwarting Miller, Shea Miller, and Earl Melancon

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18.1 BACKGROUND

Coastal erosion threatens many low-lying areas around the globe. Rising sea levels from climate change are expected to increase coastal erosion and exacerbate flooding and storm surges. This is particularly true in low-lying coastal Louisiana, which developed as the Mississippi River changed course (delta switching) over the past 7000 years. Periods of land loss and gain resulted in an intricate coastal environment composed of shallow water areas with wetlands, swamps, barrier islands, and ridges (Day et al. 2007). This complex habitat sustains high economic and biological productivity, supporting the largest commercial fishery in the lower 48 states, providing habitat for important species of fish and wildlife, mitigating storm surge, and delivering protection for oil and

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gas production facilities, including five of the nation's largest ports. Because of past and ongoing geological and physical processes, such as subsidence, sea level rise, tropical cyclonic activity, and direct human activities (Barras 2009; Chmura et al. 1992; Georgiou et al. 2005), coastal Louisiana is estimated to have lost an area almost the size of Delaware (4877 km²) between 1932 and 2010, with recent analyses indicating losses averaging 42.9 km²/year (Couvillion et al. 2011).

In response, coastal planners have identified multiple approaches to reduce this loss, resulting in more than \$50 billion worth of restoration and management projects proposed for coastal Louisiana (Coastal Protection and Restoration Authority [CPRA] 2012). These projects include significant reengineering of the rivers, sediment diversions, marsh and barrier island restoration, and shoreline protection projects, including the creation of "oyster barrier reefs" (CPRA 2012; Peyronnin et al. 2013). The use of these oyster barrier reefs to mitigate coastal erosion is an effort to capitalize on the natural benefits of a living shoreline.

If appropriately located, living shorelines offer long-term sustainability through natural building, as well as direct economic and ecosystem benefits including shoreline stabilization, resilience to subsidence and sea level rise, and the enhancement of fisheries and water quality (Grabowski et al. 2012; Humphries and La Peyre 2015; La Peyre et al. 2014). However, in coastal Louisiana, reef living shorelines are dependent on recruitment, growth, and survival of the reef building eastern oyster, *Crassostrea virginica*. These oysters require habitat with immediate and long-term acceptable water quality (i.e., salinity, food resources) and are particularly vulnerable to large-scale anthropogenic changes (Soniat et al. 2013). Understanding how local conditions and discrete events affect sustainability of oyster reef living shorelines is critical to maximizing their benefits.

Though *C. virginica* is a prolific species with a broad range of habitat in which it can survive, the conditions for eastern oysters to prosper as a reef can be limited by a number of factors. *C. virginica* reef sustainability depends on locations conducive to high production of shell substrate through settlement and growth, a necessary requirement for reef longevity (Powell et al. 2006; Walles et al. 2015b). Ultimately, *C. virginica* reef sustainability depends on the complex interaction of a number of environmental factors that affect their population dynamics, growth, reproduction, recruitment, and survival. These multiple factors include salinity, temperature, food, water circulation, sedimentation, disease, predation, and bottom type (La Peyre et al. 2009; Powell et al. 2003; Soniat et al. 1988; Wang et al. 2008).

Of the many factors affecting *C. virginica* populations and reef longevity, salinity is a key variable, as it affects many different aspects of the oyster's life including growth, mortality, reproduction, predation, and disease infection levels (Dekshenieks et al. 1993; Shumway 1996). Oysters are well known for their wide tolerance to salinity, ranging from 5 to 40 psu (Shumway 1996); however, within that range, salinity can affect basic physiological rates, affecting overall population dynamics in different ways (Newell and Langdon 1996). In Louisiana, most oyster production is limited above 15 psu because of excessive mortality owing to *Perkinsus marinus* infections (Powell et al. 2012; Soniat et al. 2012) and predation from oyster drills (Brown and Richardson 1987; Brown et al. 2008; Mackenzie 1970); however, some self-sustaining populations have been documented in areas with salinities below 3.5 psu for five consecutive months of the year (Butler 1954).

In addition to salinity, other factors interacting with reef design likely influence reef sustainability and function. Reef exposure, the percentage of time within the study period the water level is below the reef-top elevation, may affect oyster growth rates, survival, and biofouling on the reef (e.g., Bahr 1976; Byers et al. 2015; Fodrie et al. 2014; Littlewood et al. 1992; Ridge et al. 2015). Similarly, water quality variables (e.g., dissolved oxygen) and sedimentation rates can affect oyster recruitment, growth, and survival (Shumway 1996). At the same time, other variables may affect the provision of services beyond reef sustainability. For example, shoreline exposure may influence the effectiveness of the fringing reef in providing erosion protection (La Peyre et al. 2015) while adjacent habitat types may influence reef habitat value (Gregalis et al. 2009). Many of these variables interact with reef design parameters and need to be integrated into site selection and reef design decisions.

Identifying the correct site location for creating an oyster reef as a living shoreline is critical (Beseres Pollack et al. 2012; Coen and Luckenbach 2000). One essential requirement is the selection of suitable habitat for sustainable oyster populations (Cake 1983; Melancon et al. 1998; Soniat et al. 2013). Habitat suitability indices (HSIs) were developed for environmental impact assessments initially (Cake 1983) and more recently used for aquaculture, conservation, and restoration applications (Beseres Pollack et al. 2012; Soniat et al. 2013). These models all differ slightly in the parameters and thresholds used but essentially use a combination of salinity descriptors, substrate availability, and historic conditions to identify good sites for oyster growth or reef restoration. Despite numerous modeling and habitat suitability approaches available, results of many reef creation projects vary enormously across the Louisiana coast, possibly reflecting local site variability (Casas et al. 2015) along with rapidly changing conditions across estuaries experiencing significant subsidence, sea level rise, and large-scale river management affecting freshwater inflows into the estuaries (Soniat et al. 2013).

18.2 BIOENGINEERED EASTERN OYSTER LIVING SHORELINE PROJECTS IN COASTAL LOUISIANA

Over the last decade, a number of living shoreline projects based on *C. virginica* reefs have been developed in coastal Louisiana (Figure 18.1). These projects range from experimental oyster reefs



Figure 18.1 Location of eastern oyster living shoreline projects across coastal Louisiana.

using loose shell cultch (Casas et al. 2015; La Peyre et al. 2014), to more bioengineered reefs using a variety of techniques in demonstration projects (Melancon et al. 2013), to large-scale on-the-ground shoreline protection bioengineered projects (La Peyre et al. 2013b,c). These bioengineered reefs have used a variety of engineered base structures. These reef bases all have the common property of installing immediate vertical structure to the nearshore environment, either with concrete (i.e., A-Jack blocks, OysterBreak) or with other materials including mesh cages filled with oyster shell (i.e., ReefBlk) or mesh mats filled with limestone (i.e., Gabion Mats) (Figure 18.2).

The advantages of using oyster reefs as living shorelines include enhancing coastal Louisiana's important oyster population, reducing marsh edge retreat, and providing a potentially sustainable framework for this erosion protection through sustainable reefs. Through shell growth and the continued recruitment of new individuals, oyster reefs will physically expand and become self-sustaining over time. Specifically, in the right location, an oyster reef used for shoreline protection can respond to changing conditions including subsidence and sea level rise (Casas et al. 2015; Mann and Powell 2007; Walles et al. 2015b). While the primary goal of these projects is to help stabilize



Figure 18.2 Bioengineered reef designs along coastal Louisiana: OysterBreak ([a] Vermilion Cove), Reefblk ([b] Lake Fortuna), A-Jacks ([c] Terrebonne Bay), and Gabion Mats ([d] Terrebonne Bay]).

| Location | Material | Year Built | Length (m) | Monitoring Period | No. of Segments | Cost (\$/linear m)ª |
|----------------|----------------------------------|------------|---------------|----------------------|--------------------|------------------------|
| Terrebonne | A-Jacks; Gabion Mats; ReefBlk | 2007 | 915 | 2007–2012 | 9 | 1509; 1759; 1309 |
| Sister Lake | Loose shell cultch | 2009 | 225 | 2009–2012 | 9 | 168 |
| Grand Isle | ReefBlk | 2010 | 1400 | 2010–2014 | 3 | 653 |
| Vermilion Cove | OysterBreak rings | 2011 | 480 | 2011–2014 | 8 | 676 |
| Lake Eloi | ReefBlk | 2012 | 1300 | 2012–2014 | 3 | 653 |
| Lake Fortuna | ReefBlk | 2012 | 2400 | 2012–2014 | 3 | 653 |
| Lake Athanasio | OysterBreak rings | 2014 | 700 | 2014 | 6 | 1007 |

Table 18.1 Descriptions of Basic Parameters of the Seven Projects with Data Reported in This Work

^a Cost per linear foot depends on site location (mobilization, distance to site, and demobilization) and amount of material ordered (price per linear meter usually diminishes with bulk orders of more material). Cost includes manufacture and installation of reef, not long-term monitoring.

shoreline edges and reduce shoreline erosion, most projects promise delivery of other ecosystem services, including fisheries habitat and water quality enhancement, based on literature from other areas that quantify the contributions of healthy shellfish reefs (Grabowski et al. 2012).

Recent surge and wave modeling for the state of Louisiana's coastal restoration master plan found that waves were significantly reduced near oyster reefs (Cobell et al. 2013), which has increased interest in developing more living shorelines using the eastern oyster. More specifically, recent analyses have demonstrated that reef-based living shorelines along Louisiana's marsh edges are most effective in higher-energy locations (La Peyre et al. 2015). Initial preliminary reports of a number of the constructed living shoreline projects across coastal Louisiana indicate ambivalent results (La Peyre et al. 2013b,c; Melancon et al. 2013); however, much of this uncertainty may be resolved with longer-term data and the use of data from across multiple sites and years. Here, we present an overview of results from seven different oyster reef living shoreline projects distributed across coastal Louisiana (Figure 18.1; Table 18.1), focusing on reef sustainability, location data, and shoreline impact data.

18.3 PROJECT DESCRIPTIONS

Results from seven independent oyster reef restoration living shoreline projects were analyzed across the coast of Louisiana. Sites were spread across four different estuaries, with multiple locations in several estuaries, and included (1) Vermilion, Vermilion Cove (29°36_39.99_N, 92°3_19.70_W); (2) Terrebonne, Sister (Caillou) Lake (29°12_50.70_N, 90°56_3.12_W), and Terrebonne Bay (29°17_1.59_N, 90°37_1.32_W; 29°17_11.41_N, 90°37_9.26_W; 29°18_19.897 N, 90°34_03.958 W); (3) Barataria, Grand Isle (29°13_48.22_ N, 90°0_56.96_W); and (4) Breton Sound/Biloxi Marsh, Lake Eloi (29°45_47.4_N, 89°26_39.30_W), Lake Fortuna (29°40_47.9_N, 89°31_63.5_W), and Lake Athanasio (29°44_47.04_N, 89°26_46.73_W; Figures 18.1 and 18.2). All sites had fringing bioengineered reefs constructed between 2007 and 2011 with the primary objective of enhancing shoreline protection and secondary goals of increasing provision of ecosystem services such as fisheries habitat and water quality enhancement. Reefs were similar in that they were all located adjacent to eroding marsh (<50 m from the eroding marsh edge); reefs differed in terms of reef length, adjacent habitat, site water quality characteristics, and shoreline orientation (Table 18.1).

Vermilion Bay is a shallow, relatively fresh bay located in Iberia and Vermilion Parishes. It is separated from the saltier waters of the Gulf of Mexico by Marsh Island. On the west side of Marsh Island, the narrow, deep (>25 m in some places) Southwest Pass connects Vermilion Bay to

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the Gulf of Mexico. The study area in Vermilion Bay faces south, and is characterized by shallow mean water depths (<1 m). It is adjacent to one of Louisiana's historic public oyster seed grounds; however, increased freshwater input from the Atchafalaya River has greatly diminished oyster production in recent years (Louisiana Department of Wildlife and Fisheries 2011). Intertidal reefs were constructed in Vermilion Bay beginning in 2009 in a series of experimental reef segments located less than 25 m from the marsh edge (La Peyre et al. 2013c). The segments were composed of bioengineered Oysterbreak structures; concrete rings, ranging from 50 to 61 cm in height, placed adjacent to one another in varying sub- and intertidal formations.

Sites in Terrebonne Bay include that of Sister (Caillou) Lake (Casas et al. 2015; La Peyre et al. 2014) and the Terrebonne demonstration project (Melancon et al. 2013) located east of Sister Lake. Sister Lake has been a designated Public Oyster Seed Reservation since 1940 (Louisiana Department of Wildlife and Fisheries 2011) and approximately 30% of the area consists of subtidal reefs. Sister Lake is primarily an open body of water 1–3 m in depth, surrounded by brackish marsh. Reefs in Sister Lake were constructed in 2009 at three locations across the lake using piles of shell cultch to form fringing oyster reefs for experimental purposes and measurement of reef development and ecosystem service provision (Casas et al. 2015; La Peyre et al. 2014).

The Terrebonne project site is located along the northeast shore of Terrebonne Bay, a large open body of water with 1–3 m depth similar to that of Sister Lake. There are numerous private oyster leases near the Terrebonne site that are harvested as a subtidal fishery. Fringing intertidal oyster reefs along the northern shore of Terrebonne Bay site are scarce because of the unstable soils attributed to high shoreline erosion rates (Melancon et al. 2013). Soils along the Terrebonne Bay shoreline are composed of a Timbalier–Muck association. This soil is a very poorly drained organic soil that is found in saline marsh habitats. The organic layer extends approximately 1.5 m below the ground surface. Below this layer lies a very fluid clay substratum (USDA 2007). The Terrebonne project site is composed of three bioengineered reef features, all constructed during 2007: ReefBlk (foreshore), A-Jacks (onshore), and the Gabion Mat (onshore). The ReefBlk structures were constructed of triangular rebar frames fitted with mesh bags and filled with clean oyster shell, and placed on top of a crushed stone foundation and anchored. The A-Jack treatment consists of concrete "jack"-shaped structures, each 0.6 m (2 ft) tall, lashed together with steel cables, and also built on top of a crushed stone foundation. The Gabion Mat was fabricated of mattress-shaped mesh frames, each filled with crushed stone, and laid partially submerged on the marsh edge.

Bioengineered reefs were constructed along eroding shorelines at Grand Isle (bay side of island), with the goal of reducing marsh retreat. Grand Isle is a barrier island located at the mouth of Barataria Bay, where it meets the Gulf of Mexico. The Gulf side of the island is dominated by sand beaches; however, the "back" bay side is fringed with marsh habitat. Despite supporting a year-round population, as well as a substantial recreational fishing community, Grand Isle experiences heavy coastal erosion and marsh loss (La Peyre et al. 2013b). This project was constructed near the Grand Isle Oyster Hatchery, which is located just east of the reefs, and is composed of a 1.4-km-long ReefBlk segment. The reef structure was constructed in 2011, approximately 25–50 m away from the shoreline.

Two similar ReefBlk reef extents were constructed in Breton Sound (Lake Fortuna and Lake Eloi) for similar purposes and using similar design (La Peyre et al. 2013b). Both areas, located on either side of the former Mississippi River Gulf Outlet shipping channel, are considerably more exposed than Grand Isle in terms of wave energy and fetch. Bioengineered ReefBlk segments, ranging from 1.3 to 2.4 km in length, run north–south along the shoreline and were built 5–10 m away from the shoreline. In 2014, the Lake Athanasio project was added in Breton Sound and is composed of a 700-m-long Oysterbreak segment. All three sites (Lakes Fortuna, Eloi, and Athanasio) presently support extensive oyster production on both private and public leases.

18.4 METRICS

These seven projects were compared and contrasted using a set of common parameters collected at each of the projects through independent monitoring programs. Specifically, we present and discuss data on (1) environmental site conditions, (2) eastern oyster recruitment and population dynamics, (3) biotic interactions (competitors, biofouling), and (4) adjacent marsh retreat. The Terrebonne site is an 8-year project, and the data presented in this report are based on 4-year, preliminary postconstruction metrics. The Terrebonne project has three structure types with different configurations, and the data presented here are a composite of all three. The goal here is comparison of locations as opposed to comparison of engineered material or reef configuration. The assumption is that site environmental characteristics are the dominant factors controlling reef development and sustainability.

18.4.1 Environmental Data

Daily salinity, temperature, and water levels from continuous data recorders located adjacent to or near each project site were downloaded for calendar years 2008–2014. All sites also had discrete site sampling measuring water turbidity (NTU; Hach 2100P, Hach 2100Q, Hach, CO), dissolved oxygen (mg L⁻¹; YSI-85, YSI Incorporated, OH), and chlorophyll a (ug L⁻¹; EPA Method 456.0). A survey of reef top elevation using a TOPCON GTS-226 electronic total station was conducted once, approximately 1 year postconstruction at all sites, except at Terrebonne. The Terrebonne site elevations were determined immediately postconstruction (February 2008) and 3 years postconstruction (February 2011) using traditional cross-sectional transects and real time kinematic survey methods (Melancon et al. 2013). These surveys established elevations on the upper surface of the structures to document structure heights and settlement over time. All survey data were established using or adjusted to the tie-in with the Louisiana Coastal Zone GPS Network. Elevation, along with daily water levels, was used to calculate the percentage of time that reef tops were above the water line and exposed (exposure time).

18.4.2 Oyster Population

Oyster populations were measured (ind m^{-2} , shell height [mm]) annually during winter (November–February) periods to access the sites during low water periods, because of low water clarity. Sampling approach varied based on bioengineered reef material, but in all cases, we used a random sampling design, stratified by windward (bay-facing) and leeward (marsh-facing) faces of the reef. Sampling for oyster populations resulted in comparable measures of oyster density (ind m^{-2}) and population demographics (shell height [mm]).

Reefs created with Oysterbreak rings (Vermilion Bay, Lake Athanasio) with smooth cement sides were sampled visually using a 0.1-m^2 quadrat. At each location, three reef sample sites (10 m linear stretch of the reef) were selected, and five replicates were taken per site (three sites × five replicates per year). Data were converted to ind m⁻² and shell heights were recorded for all oysters found within quadrats.

ReefBlk reefs (Lake Eloi, Lake Fortuna, Grand Isle) were sampled by removing approximately 10 shells/clusters to generate density (ind m⁻²) and record shell heights of a random sample. For each sample period, three randomly selected sites were sampled by collecting five samples of approximately 10 shells/clusters, which were removed from the top half of the reef and placed in a mesh bag. Samples were taken back to the laboratory where oyster size (shell height [mm]) and density (ind m⁻²) were measured and recorded.

Shell cultch reefs (Sister Lake) were sampled at three random sites per reef (6 reefs \times 3 sites = 18) using quadrats to remove 0.25 m² of shell, excavated to 10 cm depth. All contents were taken to the laboratory where shell height (mm) was measured for all live oysters, and density was converted to ind m⁻².

At Terrebonne sites, with the three different reef structures, data were collected on oyster density (ind m⁻²), shell height (mm), and shell loss (Melancon et al. 2013). Gabion Mats and A-Jacks were sampled using random stratified (by reef side) quadrat samples (n = 45/material). ReefBlk were sampled by taking 10 stratified (by side of reef) samples at 3 reef locations (n = 30). Each of the 30 samples consisted of excavating the middle shell bag to a depth of 0.3 m (half the bag). For all sites, oyster size (shell height [mm]) and density data were recorded, and density was converted to ind m⁻².

18.4.3 Biotic Interactions

At the Terrebonne project sites, densities on the competing and fouling organism, the hooked mussel, *Ischadium recurvum*, were collected using the same winter sampling periods and within the same quadrats and methods as detailed above for oyster populations.

18.4.4 Shoreline Stabilization

All projects, except the Terrebonne, measured shoreline movement using similar methods. Briefly, shoreline position change was measured using techniques similar to Meyer et al. (1997) and Piazza et al. (2005). A minimum of five sites at each project location, with nearby reference shoreline sites, was established with permanent base stakes located in the marsh and in the water. For each sample, a tape measure was stretched level between base stakes and read at the shoreline edge along the same compass heading each time. Shoreline edge is defined as the farthest waterward extent of the emergent wetland macrophytes. Change in shoreline position was calculated as the difference (cm) between measurements. Positive values indicate accretion, and negative values indicate erosion. Shoreline change for each location and observation period is reported in m year⁻¹. For the Terrebonne project, shoreline position was determined using aerial photographs and the Digital Shoreline Analysis System (DSAS version 2.1.1) extension of ArcView GIS (Thieler et al. 2003). Shoreline positions were determined by digitizing aerial photographs at a 1:800 scale following Steyer et al. (1995), which defines shoreline position as the edge of the live emergent vegetation (as above). Numerous periods were analyzed, but we present here only the shoreline change from the immediate postconstruction period (September 16, 2007) to 5 years postconstruction (October 28, 2012). Additional information on how shoreline change was determined can be found in Melancon et al. (2013).

For all sites, across all locations, we combined the measurements and focus on the relative difference between control and reef within each site, rather than across site comparisons.

18.5 RESULTS

18.5.1 Site Environmental Characteristics

Temperatures across the shallow coastal waters were similar between all sites. Mean salinity differed significantly between sites, but was within the range for development of sustainable oyster populations (9–21 psu). Dissolved oxygen, turbidity, and chlorophyll a varied between sites but were all within the same range (Table 18.2). Site characteristics varied in terms of mean, range, and timing of low and high salinities across the seven sites (Table 18.2). To compare site characteristics within similar years, daily salinities at all sites were examined between 2010 and 2014, a period when most sites had the fringing reefs in place (Figure 18.3). Interestingly, mid-salinity sites

| Location | Salinity | Temperature (°C) | Dissolved Oxygen (mg L ⁻¹) | Chl. A (µg L⁻¹) | Exposure Time (%) |
|----------------|---------------------------|-------------------------------|---|---------------------------|----------------------|
| Terrebonne | 16.2 ± 0.01 (3.7–27.0) | 22.2 ± 0.03 (1.4–36.0) | 7.8 ± 0.1 (3.0–14.6) | 18.9 ± 0.6 (7.3–31.4) | 5.5, 2.4, 0.1ª |
| Sister Lake | 10.9 ± 0.0 (0.3–29.8) | 22.7 ± 0.1 (2.2–34.4) | 7.8 ± 0.2 (0.4–17.3) | 14.6 ± 0.4 (1.8–43.6) | 14 |
| Grand Isle | 16.1 ± 0.02 (0.7–31.5) | 22.6 ± 0.03 (1.0–35.4) | 8.9 ± 1.5 (3.7–76.0) | 23.8 ± 2.9 (1.3–182.9) | n/a |
| Vermilion Cove | 9.2 ± 0.03 (0.3–39.1) | 22.1 ± 0.04 (0.3–35.3) | 6.4 ± 0.2 (0.3–9.2) | 15.6 ± 0.6 (0.8–37.3) | 66 |
| Lake Eloi | 14.2 ± 0.02 (2.3–27.9) | 22.5 ± 0.03 (0.1–37.5) | 6.1 ± 0.4 (0.4–8.8) | 17.8 ± 2.1 (4.6–115.6) | <0.1 |
| Lake Fortuna | 8.8 ± 0.02 (0.4–25.1) | 22.3 ± 0.04 (-0.6 to 36.7) | 5.8 ± 0.4 (0.4-8.4) | 12.0 ± 0.7 (3.6–36.3) | 2.2 |
| Lake Athanasio | 14.2 ± 0.02 (2.3–27.9) | 22.5 ± 0.03 (0.1–37.5) | 4.7 ± 0.1 (4.4–5.0) | 8.9 ± 0.5 (6.1–11.1) | 7.1 |

Table 18.2 Water Quality Parameters (Mean ± SE; Range) of Reported Projects

Note: Ranges reported for exposure time represent differences along the multiple sections of living reefs. Temperature and salinity data originate from Louisiana's Coastwide Reference Monitoring System stations within Terrebone (CRMS TE45H01 and TE45H02), Grand Isle (CRMS0178), Vermilion Cove (CRMS05401), Lake Eloi (CRMS1024), Lake Fortuna (CRMS0147), and Lake Athanasio (CRMS1024). For Sister Lake, data were obtained from the United States Geological Survey (USGS07381349).

^a Terrebonne site exposure times are for Gabion Mats, A-Jacks, and ReefBlks, respectively.



Figure 18.3 Mean monthly salinity at all study sites from 2010 to 2014. Breton Sound data represents three individual sites from this study: Lake Eloi, Fortuna, and Athanasio.

(Sister Lake, Terrebonne, Lake Eloi, Lake Fortuna, and Lake Athanasio) had smaller ranges of salinity (0.4–27.5 psu). These areas are all adjacent to productive subtidal state oyster-producing grounds. In contrast, both low (Vermilion) and high (Grand Isle) mean salinity sites (9.2 and 21.0 psu, respectively) had much larger ranges of salinity over the 5 years examined (from 0.3 to 39.1 psu). These sites are located adjacent to and near areas where subtidal oyster production has historically been extremely low, or only viable when protected by predator cages (i.e., Grand Isle).

For sites where we had elevation data, reef exposure periods ranged from less than 1% exposure to more than 50% exposure periods. As this region is microtidal, exposure events were not regular and occurred more during fall and winter months from storm passage than during other times of the year (Table 18.2).

18.5.2 Oyster Populations

On-reef density and population size distribution differed between reef sites and by age of reef (Figure 18.4). Specifically, two of the mid-salinity sites (Sister Lake, Terrebonne) had the highest densities of oysters, exceeding more than 500 ind m^{-2} , 2 years postconstruction. The other three mid-salinity sites (Lake Eloi, Lake Fortuna, and Lake Athanasio), located within the same coastal



Figure 18.4 Comparison of oyster density (mean ± SE) by living shoreline reef age.



Figure 18.5 Shell height (mm) by age of reef. Collecting shell heights on OysterBreak reefs was not possible, so no data from Vermilion or Lake Athanasio are reported.

area, also recruited oysters, but densities remained low after their first year of construction (range, 50–150 ind m⁻²). In contrast, the low-salinity (Vermilion) and high-salinity (Grand Isle) sites maintained low or no oyster density on reefs.

Oyster size class information further informs these results with Sister Lake and Terrebonne populations showing slowly increasing mean sizes and increasing ranges of oyster class sizes over time. This indicates continued recruitment and survival of different age oysters over time (Figure 18.5). Lake Eloi and Lake Fortuna show similar trends, but on a much slower time scale. In contrast, the high-salinity site, Grand Isle, indicates oyster recruitment but no long-term survival, as the size range does not increase over time.

18.5.3 Biotic Interactions

The dominant competitor for space and food with the oyster was the hooked mussel (Figure 18.6). Mussels were three times more abundant than oysters on the three Terrebonne structure types in winter surveys (Figure 18.7), causing significant concern about the long-term sustainability of these living shoreline projects. Specifically, in Gulf Coast estuaries, only the eastern oyster builds true three-dimensional reefs; if prevented from doing so by a competitor such as the hooked mussel, which does not cement into reefs and has comparatively fragile shell that fragments easily, the living shoreline will not ultimately be sustainable and provide shoreline protection. Under certain circumstances and specific restoration goals, the presence of multiple foundation species has been argued to be a benefit to a restoration project, such as enhanced filtration capacity and valuable structured habitat (Coen and Luckenbach 2000; Coen et al. 2007; Crain and Bertness 2006; Gedan et al. 2014). For example, Gedan et al. (2014) found that hooked mussels may in fact complement oyster filtration services by more effectively filtering smaller plankton (1.5–3 μ m) and, except with larger size



Figure 18.6 Hooked mussels on A-Jacks structure embedded with oysters, observed during the winter 2011 survey at Terrebonne Bay.



Figure 18.7 Mussel-to-oyster ratio (bars indicate standard error) at Terrebonne project site comparing winter 2009 and winter 2011 surveys. The hooked mussel (*Ischadium recurvum*) is a major competitor for reef space and resources.

class mussels, this filtration was complementary and not competitive with the eastern oyster. The presence of multiple foundation species (i.e., hooked mussel and eastern oyster) could also have the added benefit of expanding the environmental conditions under which the reef may provide ecosystem services (Crain and Bertness 2006) and help provide resiliency to reefs particularly in areas with changing conditions. However, if the competing species does not function as a true foundation species (i.e., building reef) and excludes the targeted reef-building organism, this will result in a failure of three-dimensional reef building and maintenance. In Gulf Coast estuaries, where the creation of living shorelines with eastern oyster reefs has a primary goal of shoreline stabilization, projects are not likely to be resilient long term if the eastern oyster is outcompeted by hooked mussels, and any enhancement from increased filtering capacity and other ecosystem service provision will remain secondary to that of shoreline protection.

Further interacting with the competition at some sites from hooked mussel, one site in particular, the Terrebonne Bay project, also began to experience shell loss within the ReefBlk structures





Figure 18.8 Failure of ReefBlk 4 years postconstruction in Winter 2011. Failure (shell loss within bags) can be seen across multiple blocks (a) and within a single block (b). (From Melancon EJ, Jr., Curole GP, Ledet AM and Fontenot QC. 2013. 2013 Operations, maintenance and monitoring report for Terrebonne bay shore protection demonstration (TE-45), Coastal Protection and Restoration Authority of Louisiana, Thibodaux, Louisiana, 75 pp. and Appendices.)



Figure 18.9 Shoreline erosion rates by site, comparing reef and adjacent mud-bottom reference sites. Sites report the overall mean over different periods (Table 18.1). During this time, four hurricanes (Gustav, 2008; Ike, 2008; Ida, 2009; and Isaac, 2012) and four named storms (Edouard, 2008; Bonnie, 2010; Lee, 2011; and Karen, 2013) affected the Louisiana coastline.

(Figure 18.8) and showed evidence of extensive colonization by boring sponges, polychaetes, and Gulf stone crabs, *Menippe adina*. By winter 2011, 4 years postconstruction, the ReefBlk structures at one of the three experimental sites had experienced greater than 50% shell loss (Melancon et al. 2013). Such a large quantity of shell loss equates to structure failure in its ability to support oyster populations and reef building. Observations at the other two experimental sites for the Terrebonne Bay ReefBlk indicate that some shell loss is beginning to occur there as well (Melancon, personal observation).

18.5.4 Shoreline Stabilization

All sites continued to show marsh retreat at both reef and reference sites, with the exception of Lake Athanasio, which had a very short study duration (Figure 18.9). Marsh retreat rates were lower at most reef sites compared to their paired mud edge reference sites, although differences were not consistent across reef sites. Marsh edge retreat rates ranged from 0.5 to 23 cm month⁻¹ at all sites, except Lake Athanasio where marsh edges (reef and reference) appeared to be relatively stable over the short period of data collection (4 months). While not presented in this work, there was no evidence that shoreline protection effectiveness increased with reef age.

18.6 LESSONS LEARNED

The use of oyster reefs as a living shoreline in estuarine environments requires development of a sustainable oyster population where high production of shell over time, through settlement and growth, are a necessity (Powell et al. 2012; Walles et al., 2015a,b). Within the required temperature conditions, and when bioengineered substrate is provided for a starting base, salinity drives oyster population development on reefs. There is an extensive literature documenting the effects of salinity

on oyster populations (i.e., Shumway 1996) that supports this observation. It is clear that salinity regimes conducive to recruitment, growth, and shell sustainability are critical determinants of success in oyster reef creation. In this region, sites with moderate mean salinities (11–16 psu), and not experiencing extreme salinity (<5 or >25 psu) for extended periods, seemed more conducive to the rapid population development and high production necessary to build sustainable oyster populations and maintain reefs over the long term.

In addition to oyster population responses to environmental factors, biotic interactions need to be considered in site selection. The Terrebonne Bay project demonstrated that, under the right conditions, organisms, such as hooked mussels, may be a significant competitor with oysters in terms of space and food. This is not a new phenomenon, as hooked mussels associated with oysters have been documented from Chesapeake Bay (Lipcius and Burke 2006) to Texas, with Abbot (1974) reporting that it was first described from the mouth of the Mississippi River in 1820. The impact of hooked mussel abundance on long-term reef development and provision of ecosystem services requires further investigation.

Understanding the factors driving shell loss at the Terrebonne site appears to be as important as understanding oyster population dynamics for predicting long-term reef sustainability. The shell loss at the Terrebonne site appears to result from a combination of biofouling by shell pests such as boring sponges and shell brittleness created by polychaete worms. The abundance of sponges and worms was probably stimulated by two factors: salinity and reef exposure time. The Terrebonne site where shell loss occurred was near the upper range of ideal salinities (Figure 18.3) and inundated more than 99% of the time (Table 18.2). This combination of salinity and inundation likely enabled sponge and polychaete colonization and also allowed for Gulf stone crabs, *M. adina*, to enter the shell bags and feed on the colonized shell pest and encrusting organisms such as bryozoans and in the process crush shell.

Although the relationships between inundation duration and oyster reef dynamics have not been clearly delineated for this region, in general, given the right salinity conditions, inundated reefs experience higher rates of predation and biofouling than exposed reefs (Fodrie et al. 2014). While high inundation times have been associated with increased growth owing to more access to food resources and lower stress from decreased exposure (e.g., Bahr 1976; Bartol et al. 1999; Byers et al. 2015), other studies have suggested that regularly exposed oysters have accelerated growth and improved survival, reduced poychaete infestations, and lowered disease and predation (Littlewood et al. 1992; Moroney and Walker 1999; O'Beirn et al. 1994). In coastal North Carolina, intertidal reefs with 20%-40% regular exposure rates were found to have the greatest growth rates, with lower and upper boundaries at 10% and 55% exposure for reef growth (Ridge et al. 2015). With one exception (Sister Lake), reefs studied here fall outside this exposure range. This suggests that the relationship between exposure and reef growth dynamics may be slightly more complex in a region such as the Gulf Coast where exposure is not tidal, but rather more influenced by seasonal storm and weather patterns. The relatively higher salinities near and above the ideal range, combined with high inundation times at this site likely enabled sponge and polychaete colonization (Table 18.2). Oyster population dynamics and biotic interactions in relation to inundation and salinity regimes should be explored to help inform the design of living shoreline reefs as the synergism of these factors seems to be a significant factor in reef creation success.

The development of highly productive reefs for long-term sustainability and shoreline protection effectiveness is particularly important within coastal Louisiana given the high subsidence rates and high relative sea level rise (1–35 mm year⁻¹; CPRA 2012). For the reef to remain viable over the long term, shell accretion would need, at a minimum, to keep pace with site-specific relative sea level rise. Recent work on the Sister Lake reef documented shell accretion rates, which kept pace with local subsidence rates (Casas et al. 2015); this is important because Terrebonne Basin is one of the areas experiencing highest subsidence rates along the coast. These findings, however, suggest that the two best-performing reefs in this study, based on oyster recruitment and survival

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(Sister Lake and Terrebonne), may be the only reefs of the seven producing at a rate sufficient to keep pace with relative sea level rise over the long term. However, this shell accretion at both sites could be jeopardized by biotic interactions resulting in decreased oyster shell accretion (through competition for space) and shell loss. Understanding how exposure time may influence boring sponges and crab predation rates on these living shoreline reefs could be useful in designing reefs with targeted elevations.

Sustainable oyster populations on these fringing oyster reefs hold the key to the bioengineered reef functioning as living shorelines and providing associated ecosystem services. Both hurricanes (Morton and Barras 2010; Stone et al. 1997) and cold fronts (Watzke 2004) have been found to erode coastal marshes, and these narrow fringing shoreline reefs have been suggested as an approach to help reduce these effects (i.e., Piazza et al. 2005; Scyphers et al. 2011, 2015). Since the end of 2007 when the first project reported above was constructed, a multitude of tropical storms and hurricanes have crisscrossed and skirted the Louisiana coast, causing high wind and wave activity resulting in coastal erosion: Tropical Storm Edouard (August 2008), Hurricane Gustav (September 2008), Hurricane Ike (September 2008), Hurricane Ida (November 2009), Tropical Storm Bonnie (July 2010), Tropical Storm Lee (September 2011), Hurricane Isaac (August 2012), and Tropical Storm Karen (October 2013) (NOAA National Hurricane Center).

Despite significant storm activity across all the sites, marsh retreat was generally lower at shorelines adjacent to reefs as compared to mud-bottoms, confirming previous findings that fringing oyster reefs may provide marsh stabilization services (La Peyre et al. 2014; Meyer et al. 1997; Piazza et al. 2005; Scyphers et al. 2011). All comparisons, however, had large error bars, indicating that other factors, such as shoreline exposure, adjacent marsh characteristics, or local subsidence may be critical to identifying the most likely sites for successful shoreline protection. A recent analysis involving several of these sites indicated that shoreline exposure (wave energy + fetch) explained a lot of the variation in fringing oyster reef impacts on shoreline retreat (La Peyre et al. 2015). Success in developing eastern oyster–based living shorelines will require consideration of not only oyster habitat suitability but also predator and competitor habitat suitability, as well as energy exposure. While some factors (energy exposure and oyster population dynamics) are dependent on local conditions, other factors (e.g., initial inundation regime and exposure to competitors and predators) may be manipulated through bioengineering of the reef bases.

18.7 FUTURE CONSIDERATIONS

Given the importance of site selection in the success of living shorelines based on oyster reefs, developing models for site selection that incorporate not only present conditions at sites but also projected future conditions is critical. Data from monitoring of the seven reefs examined in this work illustrate the importance of salinity and inundation time, which should inform both site selection and reef design criteria. In coastal Louisiana, rapid land loss and subsidence alter the sediment and marsh properties along shorelines, changing site conditions across the coast at rapid rates (Couvillion et al. 2013). Similarly, significant coastal restoration activities, including river and sediment management, alter salinity regimes and sediment loads in the water, further affecting conditions important to oyster production (La Peyre et al. 2013a; Soniat et al. 2013). As a result, selecting sites for sustainable oyster populations needs to consider not only current habitat and water conditions but also future scenarios.

In coastal Louisiana, modeling efforts to predict future estuarine conditions and to understand impacts of proposed restoration activities have been developed (Peyronnin et al. 2013). These efforts provide an opportunity to examine potential living shoreline reef locations under future conditions. For oyster production, Soniat et al. (2013) applied an HSI to Breton Sound, Louisiana, under three potential future conditions of average, low, and high river inflow rates. The results of this exercise demonstrated dramatic changes in locations deemed suitable for oyster growth. Selecting which scenarios to use for restoration decision making can be tricky. However, consideration of a broad range of potential conditions can provide planners with the ability to make informed management decisions, including those that might affect the selection of sites for oyster reefs as living shorelines.

ACKNOWLEDGMENTS

These data were made possible by funding and support from the Louisiana Department of Wildlife and Fisheries; The Nature Conservancy, Louisiana Chapter; the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA); and the Louisiana Coastal Protection and Restoration Authority (CPRA). We thank the many students and colleagues who helped with field work and laboratory processing through these projects. Thank you to Dr. Lesley Baggett for a critical review that improved this manuscript, as well as comments from two anonymous reviewers. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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