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Oyster reef restoration in the northern Gulf of Mexico: Extent, methods and outcomes

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ABSTRACT

Shellfish reef restoration to support ecological services has become more common in recent decades, driven by increasing awareness of the functional decline of shellfish systems. Maximizing restoration benefits and increasing efficiency of shellfish restoration activities would greatly benefit from understanding and measurement of system responses to management activities. This project (1) compiles a database of northern Gulf of Mexico inshore artificial oyster reefs created for restoration purposes, and (2) quantitatively assesses a subset of reefs to determine project outcomes. We documented 259 artificial inshore reefs created for ecological restoration. Information on reef material, reef design and monitoring was located for 94, 43 and 20% of the reefs identified. To quantify restoration success, we used diver surveys to quantitatively sample oyster density and substrate volume of 11 created reefs across the coast (7 with rock; 4 with shell), paired with 7 historic reefs. Reefs were defined as fully successful if there were live oysters, and partially successful if there was hard substrate. Of these created reefs, 73% were fully successful, while 82% were partially successful. These data highlight that critical information related to reef design, cost, and success remain difficult to find and are generally inaccessible or lost, ultimately hindering efforts to maximize restoration success rates. Maintenance of reef creation information data, development of standard reef performance measures, and inclusion of material and reef design testing within reef creation projects would be highly beneficial in implementing adaptive management. Adaptive management protocols seek specifically to maximize short and long-term restoration success, but are critically dependent on tracking and measuring system responses to management activities.

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1. Introduction

Natural resources decision-making models inherently assume that the consequences of management actions can be estimated deterministically, however imprecise the models may be (Ralls and Starfield, 1995). Structured decision making (SDM), and adaptive resource management (ARM), a specific instance of SDM, require that outcomes inform further management action by linking success criteria to specific goals, emphasizing learning through management actions (Walters, 1986, 1997; Williams, 2011; Allen et al., 2011). For ecological restoration activities in particular, the use of ARM is often encouraged, but rarely implemented rigorously, often leading to instances of intense restoration activity with little consensus emerging as to the best approach to adopt (Gregory et al., 2006). In particular, the restoration, creation and management of artificial shellfish reefs has seen extensive restoration activity, but limited long-term assessment of success (Bohnsack and Sutherland, 1985; Baine, 2001; Mann and Powell, 2007; Seaman, 2007; Feary et al., 2011; Kennedy et al., 2011). Our goal is to provide some documentation and evaluation of inshore artificial shellfish reefs along the northern Gulf of Mexico.

Significant efforts have focused on the restoration and creation of shellfish reefs, encouraged by recent reports of extensive functional loss of shellfish reefs globally (Beck et al., 2011), and quantitative estimates of the value of ecosystem services provided by oyster reefs in particular (Grabowski et al., 2012). Recent oyster reef restoration efforts often have general goals of increasing fisheries production or enhancing oyster populations, but few data relate

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reef management or restoration actions to outcome (Baine, 2001; Kennedy et al., 2011; Geraldi et al., 2013). A recent review of restoration efforts in the Chesapeake Bay, VA, USA found data were dispersed, difficult to access, and inconsistent in statistics and formats, which ultimately hindered evaluating success of restoration activities (Kennedy et al., 2011). Most restoration efforts lack quantitative data, or clearly defined long-term management goals and useful success criteria (Bohnsack and Sutherland, 1985; Hackney, 2000; Baine, 2001; Mann and Powell, 2007; Feary et al., 2011). Furthermore, evaluations of restored reef services often appear to be more largely guided by research questions than actual management needs or evaluation of management goals.

Along the northern Gulf of Mexico, significant coastal changes impacting oyster habitat, such as freshwater diversions, hurricanes and oil spills (Livingston et al., 1999; La Peyre et al., 2003, 2009; Beseres Pollack et al., 2011; McCrea-Strub et al., 2011), combined with evidence that sustainable oyster reefs provide ecosystem-level services (Coen et al., 2007), have led to increased efforts to restore and create more oyster habitat. While no central database documents oyster reef restoration and creation activities across the northern Gulf of Mexico, there has been significant reef creation activity, particularly in recent years (Scyphers et al., 2011; Beseres Pollack et al., 2009, Beseres Pollack et al., 2012; Heck et al., 2012; La Peyre et al., 2013a,b). Historical data drive selection of sites for artificial reef creation, but conditions may no longer be adequate to ensure success as river management and climate change alter estuarine water quality over historic beds (La Peyre et al., 2003; Lane et al., 2007; Beseres Pollack et al., 2011). Habitat suitability models have also been developed and identify where oysters should thrive, but have not been extensively proven in identifying where reefs may be sustainable (Johnson et al., 2009; Volety et al., 2009; Beseres Pollack et al., 2012). Given the resources, time, and costs of reef restoration, it is critical to evaluate reef success in order to adapt future management to maximize both short and long-term success (Mann and Powell, 2007; Kennedy et al., 2011).

The goal of this study was to document the extent, methods and outcomes of inshore artificial sub-tidal oyster reef creation in the northern Gulf of Mexico. We (1) compiled information on number, location, age, material and design of sub-tidal oyster reef restoration attempts along the northern Gulf of Mexico from Texas to northern Florida, and (2) quantitatively assessed a sub-set of sub-tidal reef success using two indicators of reef success (presence of living oysters, or hard substrate). We considered reefs with hard substrate as partially successful, and reefs with oysters, *Crassostrea virginica*, as fully successful. These success criteria do not require a minimum density of live oysters. Our criteria assume that reefs with oysters have the potential to provide other ecosystem services (i.e., water filtration, nekton habitat), but those with only hard substrate may only offer a subset of services (nekton habitat) and potential for oyster recruitment.

2. Methods

2.1. Study area

The northern Gulf of Mexico region is micro-tidal with coastal areas dominated by shallow estuarine waters. The eastern oyster *C. virginica* is the dominant reef building organism in this region. Over 50% of the U.S. eastern oyster production comes from the northern Gulf of Mexico, and adult sized (>75 mm shell height) oysters can occur within one year of settlement. Significant freshwater inputs and variation in inflow from large rivers (e.g., Mississippi River, Atchafalaya River, Apalachicola River) influence both salinity and turbidity, causing freshets over oyster areas in some regions, while drought and upstream use of river water cause significant salinity increases in other areas (i.e., Livingston et al., 1999; La Peyre et al., 2003, 2009; Powell et al., 2003; Beseres Pollack et al., 2011).

We examined oyster reefs ranging from Copano Bay, Texas to Apalachicola Bay, Florida, and focused on artificial sub-tidal reefs that were located in inshore, shallow waters (<10 m depth and <10 km from shore). The study area represented a range of coastal conditions from the large open-water bays, tidal flats, and seagrass beds of the Texas coastal bend to the deltaic marshes and bays of Louisiana and the lagoon-barrier island environment of the Apalachicola Bay estuary. This coastline is dominated by extensive coastal estuaries with the majority of oyster reefs and oyster restoration occurring within these shallow-water coastal estuarine areas. We were specifically interested in oyster reef restoration and enhancement efforts that were targeted at ecological restoration, and not reef cultching for harvest purposes. Our definition of restored reefs includes enhanced, restored, and created reefs as it was often difficult to differentiate among the three activities.

2.2. Documentation of reef restoration activities

To develop a database of reef restoration activities along the northern Gulf of Mexico, we requested data from local, state and federal agencies, non-profit organizations, research organizations, consulting companies, and academic researchers involved in restoration in all five gulf coast states. We also gathered information from the internet, newspapers, fishing websites, published scientific literature, grey literature, and government permits. We created a database of oyster reef creation and restoration activities with the basic requirement being a GPS location for each identified reef. When available, we included information on physical reef description, including construction material, reef size, water depth, date of creation, initial site design, and as-built information. Other information recorded when available were the organizations involved in the reef creation, specific restoration goals, cost of materials and/or project, monitoring efforts and available data.

2.3. Evaluation of reef success

2.3.1. Sampling design

A subset of reefs was selected from the created database to evaluate reef success. Only reefs that had adequate information on reef location, construction material, and construction date were considered. We selected reefs constructed using the two dominant materials used in this region, “rock” (i.e., concrete, limestone) and “shell” (oyster shell). We also selected historic reefs near the created reefs based on maps, or information from local managers and oystermen. The initial experimental design included 18 reefs, across 7 bays, stratified by reef type (6 historic, 6 shell, 6 rock) (Fig. 1; Table 1). Each bay contained at least two reef types for paired comparisons, although not all bays had all three reef types.

Areas conducive to oysters in this region tend to exist within large coastal estuaries dominated by shallow water depths (1–3 m) throughout the coast. Because the northern Gulf of Mexico is a microtidal region, tidal variation is less than 0.5 m throughout the coast, and even the shallowest reefs are likely to rarely, if ever, be exposed. Constructed reefs varied in age, with the oldest reef constructed in 1991, and the most recent in 2009. All the reefs most likely varied in dimensions, height, design, and construction technique as there was no subset of reefs available that provided all the information.

2.3.2. Water quality

Dissolved oxygen (mg L^{-1}), temperature (°C), and salinity were recorded with a YSI 556 at each site visit. A Secchi disk was used to measure water clarity (cm). We downloaded data for the last 10

Fig. 1. Locations of artificial reef sites for sampling of oyster density and substrate volume by divers. Reefs were selected based on construction material used shell or rock (limestone or concrete aggregates). Historic reefs were located in proximity to artificial reefs.

years (or all available data) from the nearest long-term salinity stations (either continuous data recorders, or state led monitoring efforts) and calculated mean monthly salinity (±SE) for each bay (or site) in order to compare long-term site salinities.

2.3.3. *Oyster sampling*

Reef material and oysters were sampled by divers with five haphazardly tossed 0.25 m^2 quadrats in October–November, 2011. At each site, buoys attached to a weight by a 4 m line were tossed on the submerged reef surface to select a sample point. Two divers sampled a 0.25 m^2 quadrat at each sample point, which were a minimum of 5 m apart. Substrate within the quadrat was removed (10 cm depth) with gloved hands and tent stakes (as pry bars). Each sample was placed in a bucket which was pulled to the surface. Once on board the boat, each sample was placed in a labeled 3-mm mesh bag, placed on ice and transported to a cold room for storage until contents were counted, weighed, and measured within one week.

Total volume of each sample was recorded through displacement of water (L). Samples were then sorted into (1) shell hash, (2) gravel/concrete, (3) live oysters, and (4) dead oysters and total volume recorded through displacement of water (L). These substrate volumes were converted to L m^{-2} for analyses. The number of live and dead oysters, by size class (spat $<$ 25 mm, seed $>$25 mm and $<$75 mm, market $>$ 75 mm) was recorded. Oyster counts for each sample were then converted from number per 0.25 m^2 to individuals m^{-2} for further analyses. Two quadrat samples per site (as available) were randomly chosen for oyster size measurements, and all individual oysters were measured from umbo to distal edge (mm) with calipers. If less than 10 oysters were available for measurement, an additional quadrat was measured.

2.4. *Statistical analyses*

Two measures of reef success based on the quadrat sampling were used for evaluation of reefs: fully or partially successful. Fully successful reefs contained live oysters (mean live oyster density $>$ 0 oysters per m^2). Partially successful reefs are reefs that provided hard substrate above the bay bottom (mean hard substrate volume $>$ 0 L m^{-2}). Partially successful reefs represent potential reef habitat, including settlement substrate and structure for nekton. Even though these criteria are admittedly minimal, they represent a threshold between basic success and failure. Reefs not classified as partially or fully successful were not included in further analyses.

All oyster and substrate variables quantified were examined using Spearman's Rho correlation analysis; when two or more variables were highly correlated only one was retained for further analyses. Only total substrate volumes were analyzed for partially successful reefs. Live spat and adult oyster densities were used for analysis of fully successful reefs. Partially (total substrate volume) and fully successful (spat, seed + adult density) reef indicators were analyzed separately in a mixed model ANOVA (SAS 9.3; Proc Mixed) with the independent variable material (historic, shell, rock) and random variable bay. Significant differences were further examined to discern pairwise differences using Tukey's post-hoc test. A linear regression examined the relationship between oyster density and total substrate volume. All parameters were log(x+1) transformed to help meet assumptions of normality and homogeneity of variance. Results were considered statistically significant at $\alpha \leq 0.05$. Unless otherwise indicated results are reported as mean ± SE.

Table 1
List of selected sites for sampling of oyster population. Sites are listed by bay, construction material, year of construction and latitude and longitude. Discrete water quality samples were taken during quadrat sampling in October and November 2011. Salinity multi-year means were calculated from data from the Texas Water Control Board (Texas), USGS Continuous Data Recorders and Coastwide Reference Monitoring Sites (Louisiana), Mobile Bay National Estuary Program Environmental Monitoring (Mobile Bay). St. Louis Bay salinities were calculated from discrete samples taken in 2011, and discrete samples provided by M. Murphy (The Nature Conservancy). Mean ± standard error oyster density (ind m^{-2}) and substrate volume (L m^{-2}) are from diver quadrat surveys taken in October and November 2011.

Bay	Code	Material	Year	Latitude	Longitude	Reef	DO	Temp	Secchi	Depth	Salinity	Salinity	Oyster density	Substrate volume
							mg L^{-1}	^{0}C	cm	m		Multi-Yr mean	ind m^{-2}	L m^{-2}
Copano Bay, TX	H-CB	Historic	n/a	N28 08.150	W97 04.994	H-CB	6.6	27.3	62.9	3	21.1	25.4 ± 0.8	611.2 ± 168.4	7.3 ± 0.7
	S-CB	Shell	2008	N28 07.699	W97 04.087	S-CB	6.6	26.8	70.7	3	21.5	25.4 ± 0.8	44 ± 26.3	3.2 ± 1.4
Matagorda Bay, TX	H-MB	Historic	n/a	N28 36.646	W96 29.755	H-KL	6.7	27.7	63.6	2.1	26.9	20.4 ± 1.0	177.6 ± 68.9	4.4 ± 1.4
	R-MB	Rock	2005	N28 36.252	W96 29.260	R-KL	6.1	27.3	59.7	2.1	26.9	20.4 ± 1.0	392 ± 59.9	9.8 ± 0.8
Calcasieu Lake, LA	H-CL	Historic	n/a	N29 51.804	W93 14.383	H-CL	6.4	29.3	45.9	1.8	16.5	13.9 ± 5.0	0.0	0.4 ± 0.4
	R-CL	Rock	2007	N29 40.954	W93 17.029	R-CL	7.0	29.2	46.7	2.1	17.2	16.1 ± 1.1	108.8 ± 24.9	6.8 ± 2.7
Vermilion Bay, LA	H-VB	Historic	n/a	N29 36.417	W92 01.160	H-VB	6.7	30.3	23.4	1.2	10.0	5.6 ± 0.2	2.4 ± 1.6	5.1 ± 0.7
	R-VB	Rock	2006	N29 40.678	W92 07.125	R-VB	7.6	30.2	21.5	2	10.5	5.6 ± 0.2	0.8 ± 0.8	7.1 ± 3.0
	S-VB	Shell	1991	N29 43.356	W91 52.361	S-VB	6.3	30.1	30.2	2.3	3.6	3.7 ± 1.9	0.0	0.0
Barataria/TerreB Bay, LA	R-BT	Rock	2004	N29 20.035	W89 50.702	R-BT	8.4	30.6	47.2	1.8	7.8	19.3 ± 1.2	0.0	2.7 ± 1.2
	S-BT	Shell	1997	N29 27.429	W90 22.668	S-BT	6.2	31.4	48.0	1.7	12.8	12.9 ± 0.8	5.6 ± 2.4	3.7 ± 1.0
Bay St. Louis, MS	H-SL	Historic	n/a	N30 16.853	W89 18.120	H-SL	7.1	29.1	50.2	3.7	9.8	9.8 ± 3.5	4.0 ± 3.1	7.9 ± 3.2
	R-SL	Rock	2005	N30 18.726	W89 18.015	R-SL	7.6	29.1	49.7	1.8	9.3	9.8 ± 2.7	220.0 ± 90.3	10.6 ± 2.5
	S-SL	Shell	2009	N30 20.959	W89 17.624	S-SL	6.9	28.8	52.5	1.7	7.7	6.1 ± 1.3	0.0	0.0
Mobile Bay, AL	H-MB	Historic	n/a	N30 19.105	W88 09.158	H-MB	5.8	29.0	46.7	1.8	16.5	19.1 ± 0.1	15.2 ± 8.3	3.5 ± 1.1
	R-MB	Rock	2000	N30 16.444	W88 05.799	R-MB	6.7	29.6	76.7	2.6	12.3	19.1 ± 0.1	0.8 ± 0.8	9.8 ± 2.2
	R-MB2	Rock	2001	N30 29.675	W87 55.574	R2-MB	6.7	29.6	76.7	2.6	12.3	13.9 ± 0.1	20 ± 1.5	9.5 ± 1.3

3. Results

3.1. Determination of reef restoration activities

We identified and cataloged 259 inshore artificial oyster reefs across the northern Gulf of Mexico (Table 2; on-line Appendix 1). The cataloged reefs represent only reefs where information on location could be confirmed, and thus are likely a conservative estimate of total reefs created. Reefs were distributed across states fairly equally (Florida: 22%; Alabama: 27%; Mississippi: 28%; Louisiana: 15%; Texas: 8%). We were unable to determine a construction date for one third of the identified reefs. Of the reefs with date information, the majority (75%) were built after 1999, with 25% built post-Hurricane Katrina (2005). It is likely, however, that there is some bias with recent records being more easily accessed; furthermore, some regions stated that many records were lost during Hurricane Katrina.

Very few reefs had detailed documents available regarding all physical aspects (Table 2). Water depth was rarely listed in reef documents, and was determined for all reefs from bathymetry measurements associated with GPS point locations. Information on size and reef shape or relief was found for 43% of identified reef projects. Of those with size information available, reefs ranged in size from 0.01 to 813 ha (22.8 ± 11.1; $N = 112$).

Rock-based materials accounted for more than half of the created reefs (51%) across the northern Gulf of Mexico and included crushed limestone, limestone boulders, and various forms of concrete or limestone (i.e., culverts, crushed, bridge and road bed rubble, reef-dome forms, etc.). Shell, usually from oysters and sometimes clams (*Rangia*), was the second most commonly used material (20%). The remaining reefs were classified as either mixed shell (usually rock topped by shell; 16%) or other materials (tires, barges, metal; 6%) (Fig. 2). There is no apparent temporal trend in material used for reef restoration; regardless of year, rock materials accounted for close to 50% of all reefs built.

Information on organizations involved in the creation, monitoring or design, project goals or motivation, monitoring or cost, was available for about half of the reefs (54%). Across the northern

Table 2
Summary of identified artificial inshore reefs identified from Copano Bay, Texas to Apalachicola, Florida ($N = 260$). Data are summarized by state, with the number of sites for which construction date, reef material, reef design, organizations involved, project goals, costs and monitoring information were available. Reefs were identified from published literature, grey literature, internet sites, government documents, and personal communication with reef managers. Raw data are available in Appendix A (online supplementary data).

Project information	Texas	Louisiana	Mississippi	Alabama	Florida	Total	
						Number	Percent
Total number of reefs	21	39	72	71	56	259	n/a
Construction date	20	39	9	70	44	182	70.3
Pre-2005	18	15	3	59	22	117	45.2
2005–2011	2	24	6	11	22	65	25.1
Reef material	21	39	71	56	56	243	93.8
Rock	20	21	50	11	31	133	51.4
Shell	1	14	15	3	19	52	20.1
MixedShell	0	4	6	32	0	42	16.2
Other	0	0	0	10	6	16	6.2
Reef design/Area	20	14	7	63	8	112	43.2
Organizations	21	40	0	27	52	140	54.1
Project goals	2	34	2	56	45	139	53.7
Project costs	0	18	0	30	0	48	18.5
Monitoring information	1	20	1	30	0	52	20.1

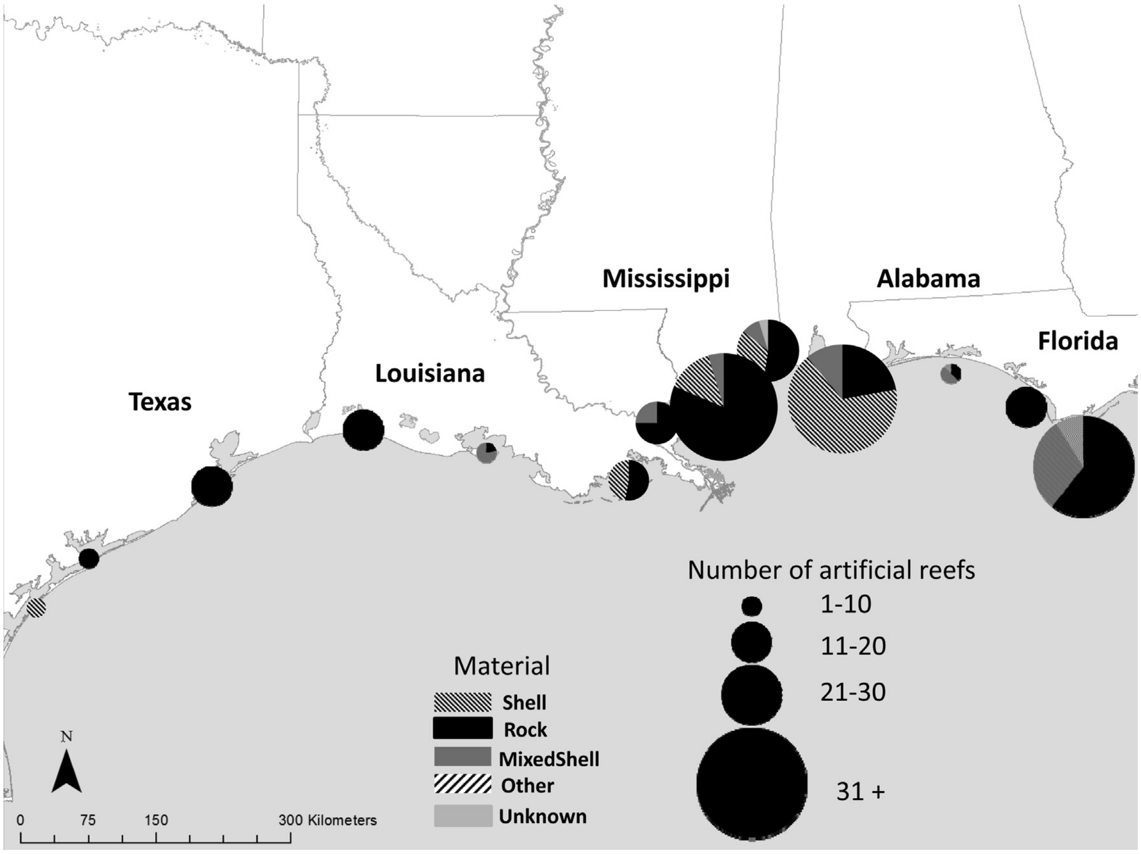

Fig. 2. Distribution of artificial reefs created prior to 2011 with location information was found through federal, state and local records, non-profit and for-profit organizations, and through published and grey literature. Pie charts indicate both number of reefs created as well as the material used for creation.

Gulf of Mexico, there are multiple groups implementing artificial reefs for restoration purposes including conservation non-profits, state and federal management agencies, private companies, research programs, and combined efforts/partnerships from these differing sectors.

Not all reefs had explicitly defined goals, but most were built for the generic reason of habitat restoration and/or recreational fishing enhancement, and to a lesser extent, for shoreline protection, water quality enhancement, and to meet mitigation requirements. Monitoring efforts were documented for less than 20% of the artificial reefs, and ranged from opportunistic checks on reef existence and oyster density, to more scientifically sound, designed monitoring programs. This low percentage may not be a true reflection of monitoring efforts, and instead reflect un-coordinated and/or publicly unavailable monitoring efforts.

From the few reefs (<20%) where cost and area were available, cost per hectare ranged from $12,000 to well over $1M. Due to inconsistent and sometimes ambiguous reporting it was difficult to discern if the costs accounted for only material costs or the total project (design, construction, transportation, etc.).

3.2. *Evaluation of reef success*

3.2.1. *Water quality*

Water temperature and dissolved oxygen levels were similar among all sites and typical of waters in this region in October/November. Temperature ranged from 26.8 to 31.4 °C, and dissolved oxygen from 5.8 to 8.4 mg L^{-1}. Secchi disk depths were also typical of the region with lowest water clarity measured at Vermilion Bay, LA sites (21.5–30.2 cm), and the remainder of the sites ranging from 45.9 to 76.7 cm. Salinity did vary between sites ranging from a measured low of 3.6 at the Vermilion Bay shell site to 26.9 at the Matagorda Bay, TX sites (Table 1). Our discrete one-time salinity samples matched the long-term salinity trends (5–10 yr means) when comparing between bays, with higher variation, and slightly lower mean salinities overall at shell sites.

3.2.2. *Reef substrate and oysters*

Of the created reefs originally selected, one shell reef was inaccessible during sampling because of historic floods along the Mississippi River and not sampled. A second shell reef was reclassified as rock (R-SL) because of the discovery of concrete in samples. Of the final 17 reefs sampled, 13 reefs were found to have live oyster populations and were considered fully successful. Of the remaining four reefs, we measured hard substrate above the mud bottom on 2 (R-BT and H-CL), while we failed to collect hard substrate above the mud bottom on the remaining 2 reefs (S-VB, S-SL). Reef H-CL was a historic reef in Calcasieu Lake, Louisiana that is identified on fishing maps. This reef was typically laced with crab traps, but primarily consisted of patches of clam shell with no live oysters. Reef R-BT was created with limestone in 2004 in Barataria Bay, Louisiana and limestone was recovered, but no live oysters. Adult oyster shells and/or clam shells (all dead) were dug from the soft bay bottom by divers at reef S-SL indicating some scattering or burial of this newer (2009) shell reef. This reef was laid in a series of rows of shell mounds, and recent tonging in the area located above ground shell resources for this reef with live oysters, although it is extremely patchy. Divers found no sign of reef S-VB, a shell reef that was listed by Louisiana Department of Fish and Wildlife as being placed in 1991.

Analysis of the 15 reefs with hard substrate indicated a significant source material effect ($F_{2,66} = 4.16$; $p = 0.02$) with rock reefs providing greater substrate volume than shell or historic reefs, which did not differ in substrate volumes (Fig. 3).

Of the subset of reefs with live oysters ($N = 13$), total live oyster density (ind m^{-2}) differed significantly by treatment, with historic and rock reefs having greater density than shell reefs ($F_{2,65} = 7.94$; $p = 0.0008$; Fig. 5). When separated into adult (>25 mm) and recent recruits (spat <25 mm), results differed. Adult oyster densities varied by treatment ($F_{2,65} = 3.35$; $p = 0.04$) with rock reefs having significantly greater densities as compared to historic or shell reefs. In contrast, spat densities were significantly greater on historic reef and rock reefs as compared to shell reefs ($F_{2,66} = 9.58$; $p = 0.002$) (Fig. 4). Oyster density was positively and significantly correlated with total substrate volume ($F_{72,1} = 18.9$; $p < 0.0001$, $r^2 = 0.20$).

Size class distribution differed among treatments. Historic reefs had a greater number of smaller (<30 mm) oysters than either rock or shell reefs, and shell reefs contained fewer large oysters (>80 mm) than either historic or rock reefs (Fig. 5). Historic reefs showed a population distribution of oyster sizes which extended up to large-sized oysters from multiple year classes (>100 mm). In contrast, shell reefs had few oysters greater than 60 mm.

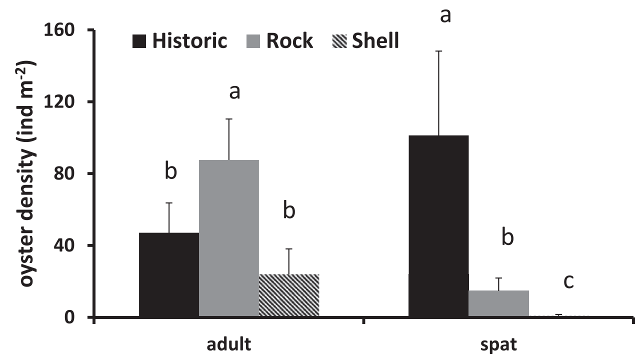

Fig. 4. Mean (±SE) oyster density (ind m^{-2}) of adult (>25 mm shell height) and spat (<25 mm) sampled on historic, rock and shell reefs.

4. Discussion

Restoration decision-making and management depend on knowledge about system function and the ability to measure responses to proposed activities; adaptive management specifically seeks to maximize restoration success, but is critically dependent on measuring system responses to management activities (Irwin and Freeman, 2002; Williams et al., 2007). In documenting reef restoration activities for the northern Gulf of Mexico, specific reef creation information was often difficult to find or acquire and generally inaccessible or non-existent. This lack of basic information on reef restoration efforts hinders the use of adaptive resource management, and thus our ability to maximize short and long-term success rates based on past experience.

This inability to learn from past efforts is particularly troubling given the high level of current reef restoration across the northern Gulf of Mexico and the increasing scrutiny related to restoration projects. Specifically, the lack of information related to design, cost and success of reefs prevents managers from making informed decisions on current restoration projects. For example, while many materials have been used for reefs, a current trend is towards more engineered approaches (i.e., placed concrete structures) as opposed to material dump installations (i.e., shell, limestone). These engineered approaches tend to be more expensive (Lukens et al., 2004), but there is a lack of quantitative data to assess whether the extra cost results in added benefits (e.g., reef longevity, enhanced provision of ecosystem services), or to identify which specific reef designs provide the best success under specific conditions (Stokes et al., 2012). For example, seeding of reefs with juvenile oysters is often discussed for new reefs in northern Gulf of Mexico, and has occurred extensively along the east coast (Brumbaugh and Coen, 2009; Geraldi et al., 2013). A recent study examined the effectiveness of seeding reefs in a subtidal oyster sanctuary in North Carolina, USA and found that seeding efforts failed to enhance oyster reef restoration in this region, and suggested that resources could be better used increasing substrate (Geraldi et al., 2013). More studies explicitly testing the effectiveness of specific restoration strategies would be beneficial.

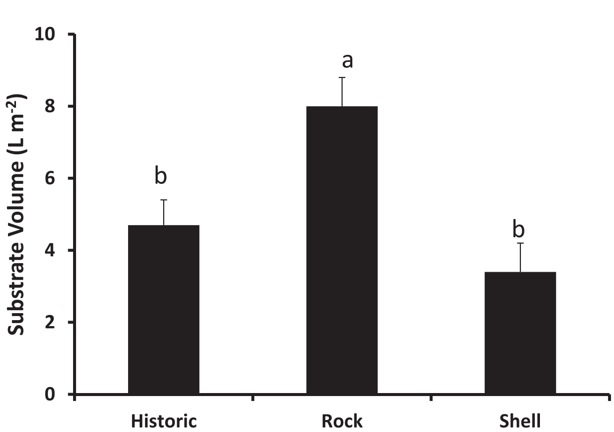

Fig. 3. Mean (±SE) substrate volume (L m^{-2}) for historic, rock and shell reefs sampled. Letters located above bars indicate significant differences.

Although this study is the first attempt that we are aware of which aggregates data and evaluates reef restoration efforts across the northern Gulf of Mexico, our findings related to a lack of data and monitoring are not unique to this region. Attempts to aggregate data and evaluate reef efforts in Maryland and Virginia (Kennedy et al., 2011), the Persian Arabian Gulf (Feary et al., 2011), the United States (Bohnsack and Sutherland, 1985), and globally (Baine, 2001) have found similar issues with a lack of clear goals, no post-construction monitoring, a lack of quantitative reef data, and inconsistency in data reporting. Restoration efforts in general are often cited as being limited by incomplete knowledge related to the effectiveness of alternative restoration options. Funding constraints further emphasize the need to use past restoration activity as a means to improve future success rates, and identify explicit trade-offs (Hobbs and Harris, 2001; Mann and Powell, 2007; North et al., 2010).

In-situ sampling of selected reefs found that 73% of reef restoration efforts were fully successful, using the bare minimum criterion of a single living oyster on the reef. To ensure long-term viability of oyster reefs, oyster populations need to be sustainable. In this study, historic reefs had significantly higher oyster densities (148.4 ± 60.1 ind m^{-2}) than all the created reefs (rock: 102.8 ± 27.5; shell: 24.8 ± 14), and these high densities were attributed to much higher recruitment measured in fall 2011 (spat size oysters) rather than higher adult oyster densities at each site. Lack of sustained recruitment at sites may lead to loss of substrate over time, and any services associated with the hard substrate. Recruitment is a critical mechanism for restoration success (Powers et al., 2009) and may depend not just on local site water quality, but on meta-population dynamics which are poorly understood within northern Gulf of Mexico estuaries. For example, extremely low spat densities on one successful shell reef (S-CB) are in sharp contrast to the paired historic reef within the same bay (H-CB) sampled on the same day, and located within 1.6 km, which had the highest mean spat density of

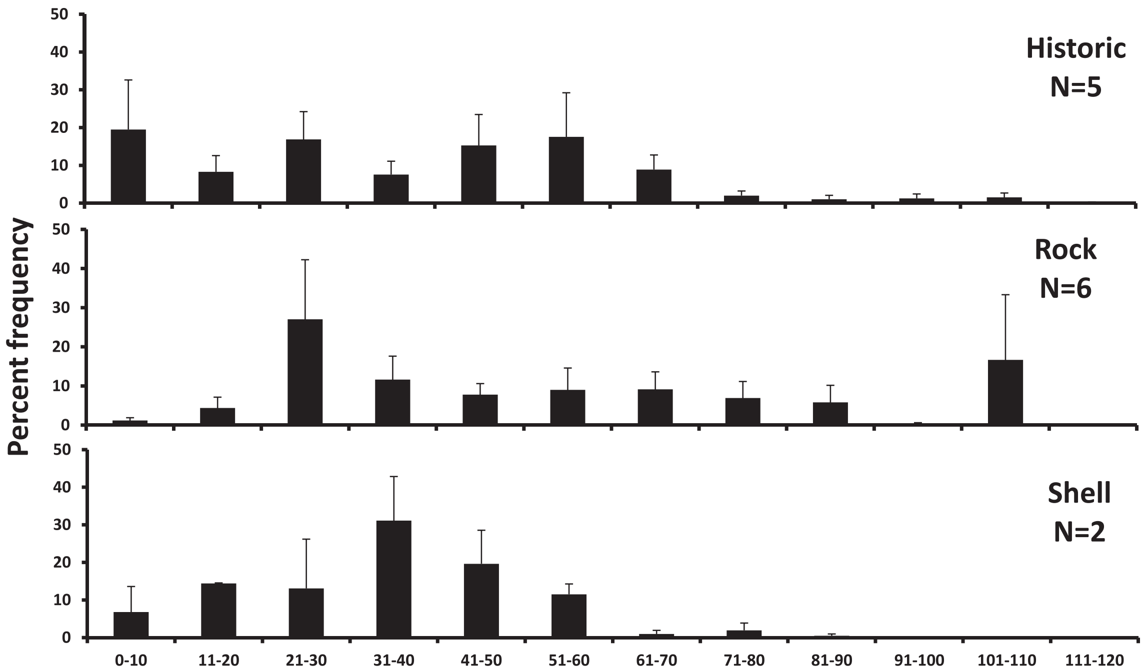

Fig. 5. Size frequency (mm) of oysters collected from quadrats on historic, rock and shell reefs.

all reefs. Whether differences in spat recruitment were related to local hydrodynamics, unmeasured bathymetric differences, differences in actual substrate availability, or bio-fouling (Lukens et al., 2004) are difficult to determine without intensive sampling and better understanding of small and large scale population dynamics. In assessing reef restoration locations, distance to nearest living reef, local hydrodynamic patterns, and the interaction of these two factors could be of critical importance and needs to be better understood (Lipcius et al., 2008; Puckett and Eggleston, 2012).

In assessing reef success using diver sampling, we were unable to identify a set of reefs that allowed us to control for reef design. Variation in reef success has been shown to be related to reef architecture (i.e., reef height, size, shape, location, material) and furthermore, may interact with the local physical variables (Lenihan, 1999; Luckenbach et al., 2005; Gregalis et al., 2009). For example, in our study, non-native materials (rock) in our sampled reefs had significantly greater substrate volume (L m^{-2}) than both historic and shell reefs. However, whether this greater volume is due to initial design and construction differences, or an outcome of the type of material used remains unclear. Reefs created with loose shell, of which our two failed reefs were built, may be more susceptible to failure within the first couple years if the reefs do not experience immediate recruitment and subsequent growth. Shell reefs are created with loose, lightweight materials, and if placed in areas with too much energy or sedimentation, they may quickly become scattered, or buried in sediment (Lukens et al., 2004). One fully-successful 15 year old shell reef (S-BT) was located in a protected area, with shallow waters, and relatively close to the shore (<500 m) which may have contributed to its success. In contrast, the heavy, durable, typically bulky nature of concrete is better adapted to maintain structure in more exposed locations, and the substrate will not disappear if recruitment does not occur immediately (Lukens et al., 2004).

This project focused on documentation of reef activities, and reef success as defined simply by basic sustainability measures (i.e., oysters). In reality, many recent reef projects seek to provide associated ecosystem services, including support for nekton and shoreline stabilization. Similar to reef sustainability, the provision of other ecosystem services may also be affected by numerous factors including reef height, size, complexity and local water quality characteristics (i.e., Lenihan, 1999; Coen and Luckenbach, 2000; O'Beirn et al., 2000; Gregalis et al., 2008, 2009; Powers et al., 2009; La Peyre et al., 2013a,b). For example, variations in reef relief, area, location and structural complexity may affect the support for various nekton communities (i.e., Grabowoski et al., 2005; Gregalis et al., 2009; Humphries et al., 2011a,b). Similarly, shoreline protection services may vary as a function of local site bathymetry, energy exposure, and reef height (i.e., Piazza et al., 2005; Scyphers et al., 2011). Documenting basic performance measures in the future will help ensure that projects meet restoration and ecosystem service goals established for created reefs.

5. Conclusion

Oyster reefs remain highly valued for their provision of ecosystem services, and efforts to restore and create artificial reefs are expected to continue. Our documentation and evaluation of reefs within the northern Gulf of Mexico, combined with past studies in other regions, suggest several critical steps necessary to help move forward reef restoration science. (1) Track and maintain a database of reef restoration and creation projects which documents key elements including location, size, material, design, cost, goals and performance measure outcomes. (2) Establish and collect a standard set of reef performance measures to help assess reef sustainability and project success. (3) Understand key meta-population drivers of individual reef success and use this information to properly place reefs. The use of past and current projects to improve our knowledge of reef performance and the impact of design, construction and location considerations would significantly help restoration managers; the challenge for adaptive management often lies in finding the correct balance between increasing our knowledge to improve long-term success, while also achieving short-term success based on current knowledge (Allan and Stankey, 2009).

Ethical statement

This work is original and has not been published elsewhere. Conceptualization of work was done by Megan La Peyre, Bryan Piazza, Ken Brown. Collection of samples and analyses were completed by Jessica Furlong, Laura Brown, Ken Brown and Megan La Peyre. Manuscript preparation was completed by Megan La Peyre and Jessica Furlong. All authors have approved the final version of this manuscript.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ocecoaman.2013.12.002

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