Galveston Bay Foundation Oyster Shell Recycling Program - Citizen Science, Engagement, and Education

GLO Contract No. 21-060-003-C643

FINAL REPORT
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I. Project Summary

To reestablish hard substrate in Galveston Bay, the Galveston Bay Foundation (GBF) partners with restaurants to collect shucked oyster shells. The shells are transported by GBF staff to upland storage sites where they are stockpiled and sun-cured for minimum of six months. The recycled shells are then returned to the bay through shoreline protection projects, reef creation projects, and reef enhancement initiatives such as volunteer oyster gardening.

During CMP Grant Cycle 25, 126 tons of oyster shell was recycled through GBF's Oyster Shell Recycling Program (Program). The collection of these shells was conducted in Galveston from January 2021 through December 2021 and in the Houston and Clear Lake regions from June 2021 through January 2022. During this time, all recycled oyster shell was stockpiled at one of three curing sites: Red Bluff, Texas City, or Moody Gardens. The shells will continue to be stored at the respective curing sites where they will be turned intermittently to allow for proper sun curing before being returned to the Bay. The shells will be utilized in GBF's Volunteer Oyster Gardening efforts or returned to Galveston Bay through (separately funded) oyster reef restoration projects.

Cycle 25 allowed GBF to continue the expansion of the shell recycling operations to the inner loop of Houston as well as on Galveston Island. Due to the expansion effort in 2021, GBF increased shell recycling capacity which resulted in a record-breaking year. A total of 181 tons of oyster shell was recycled in 2021, which is the most oyster shell recycled in a single year since the Program began in 2011.

The CMP Grant Cycle 25 also funded the 2021 oyster gardening season during which 92 volunteers monitored and cared for their gardens throughout the summer and early fall to promote successful oyster recruitment and growth on the recycled shell. As a result, approximatley 16,524 oysters were recuirted in the volunteers' 360 gardens. These new oysters were introduced onto restoration reefs in November 2021 and January 2022 under separate grant funding.

During CMP Grant Cycle 25, 494 students participated in Oysters in the Classroom. This virtual program was adapted into a Classroom STEM Workshop once GBF staff were able to conduct in-person lessons. During the in-person workshops, students mapped local oyster reefs, discussed the importance of the ecosystem, created a filter to "out-filter" an oyster, and dissected oysters.

In addition, Texas A&M University at Galveston (TAMUG) partnered with GBF during Cycle 25 to develop volunteer-based reef monitoring protocols as well as a new service-learning curriculum that was integrated into the undergraduate Invertebrate Zoology course at TAMUG. Thanks to TAMUG's guidance, GBF piloted the new Volunteer Reef Monitoring Program under CMP Grant Cycle 25. Reef monitoring will enable GBF to link the amount of shell recycled to actual restoration numbers, which will show partners and funders their return on investment and encourage the further growth of the program.

II. Background Information

Oyster reefs are a vital component of a healthy estuary. Oysters filter contaminants from the water, protect shorelines, stabilize sediment, and provide habitat and food sources for other aquatic species. Unfortunately, oyster reefs are the most threatened marine habitat worldwide. Studies show that over 85% of oyster habitat has been lost on a global scale (Beck et al, 2011). In Galveston Bay, over 60% of the oyster reefs have been damaged, primarily due to decades of heavy exploitation combined with multiple storm events, particularly Hurricanes Ike (Hons and Robinson, 2010) and Harvey. Prior to 2008, Galveston Bay yielded 90% of the oyster harvest in Texas (Haby et al, 2009). However, the severe sediment deposition resulting from Hurricane Ike smothered oyster reefs across the bay system and eliminated a large portion of the hard substrate required for oyster development.

To help replenish hard substrate in the bay and support oyster reef restoration efforts, GBF partnered with local restaurant owner Tom Tollett of Tommy's Restaurant and Oyster Bar in 2011 and began recycling oyster shells. Before GBF's Oyster Shell Recycling Program began, oyster shells were discarded along with other restaurant waste and sent to a landfill. To avoid the disposal of this vital resource, GBF has established partnerships with local restaurants to collect their shucked oyster shell. The reclaimed shell is returned to Galveston Bay to serve as new oyster habitat, thus enhancing the local oyster populations.

With the assistance of CMP funding, GBF has expanded the Program from the pilot stage (Phase 1) with only one shell recycling partner through an initial expansion phase (Phase 2). During the evaluation phase (Phase 3), a Strategic Development Plan (SDP) was created with the goal of assessing alternative recycling methods to achieve a more sustainable program. The SDP led GBF to expand shell recycling operations to the inner loop of Houston to increase the volume of shell recycled. The second expansion phase (Phase 4) was initiated with the purchase of new recycling equipment (the dump truck) in the spring of 2021 followed by the first shell collection in the inner loop of Houston in May 2021. Phase 4 continued into Cycle 25 with an additional nine recycling partners added to the Oyster Shell Recycling Program. As of January 2022, GBF has secured a total of 21 active shell recycling partners.

With the expansion of GBF's shell recycling operations, the amount of shell collected and stockpiled is rapidly increasing. Therefore, GBF initiated a research partnership with TAMUG to ensure that all shell being returned to the Bay is done so effectively and efficiently to allow for maximum oyster recruitment and habitat sustainability. Under Cycle 25, GBF and TAMUG worked together to improve citizen science efforts and implement monitoring of oyster reef habitat created with recycled shell.

III. Project Implementation

A) Task 1: Shell Collection and Partnerships

A.1 Shell Collection Updates and Photos

A total of 126 tons of recycled oyster shell was collected with Cycle 25 funds. This shell was collected in Galveston from January 2021 through December 2021 and in the Houston and Clear Lake regions from June 2021 through January 2022. During this time, GBF and Moody Gardens staff collected oyster shell from a total of 21 shell recycling partners on a weekly basis to relieve them of their shell waste. GBF staff collected shell from recycling partners in the Clear Lake and Houston region while Moody Gardens staff collected shell from recycling partners in the Galveston region.

Throughout the week, restaurant/lab staff deposited shucked oyster shells in recycling receptacles. GBF and Moody Gardens staff transported the containers of shell to one of three curing sites where all shell was stockpiled for future use in reef restoration efforts. GBF and Moody Gardens staff followed the Sun Curing Protocol established in CMP Cycle 24 to ensure all recycled shell will be fully sun-cured prior to being returned to Galveston Bay.

The expansion of the Program began in 2021 (under Cycle 24) with the purchase of a heavy-duty truck equipped with a dump bed and bin lift (the dump truck). The dump truck facilitated the expansion of GBF's shell recycling operations to the inner loop of Houston and allowed for the addition of more restaurant partners, growing the Program from 10 to 21 recycling partners in one year. During Cycle 25, six Houston restaurants became shell recycling partners. In addition, two Galveston restaurants and the TAMUG Seafood Safety Lab were also added to the Program during Cycle 25.

This report captures all shell recycling under Cycle 25 which concluded in January 2022. As of January 31, 2022, GBF was actively recycling shell with 21 partners (Table 1). The expansion is ongoing under Cycle 26, with an additional three restaurant partners added in Galveston and two restaurants added in Houston as of March 2022.

Please refer to Table 2, Chart 1, and Chart 2 below for the shell collection numbers and associated graphs, as well as Appendix A for photos of the shell recycling process and equipment. A map of current shell recycling partners and active curing sites can also be found in Appendix A. Please note, oyster shell tonnage is based on an average weight of 182 pounds of shell per 32-gallon bin and 30 pounds of shell per five-gallon bucket and is subject to a variance of approximately five percent.

Table 1: Active Oyster Shell Recycling Partners

Shell Recycling Start Date	Shell Recycling Partner	Region
March 2011	Tommy's Restaurant & Oyster Bar	Clear Lake
August 2013	The Aquarium (Kemah)	Clear Lake
November 2013	Crazy Alan's Swamp Shack (Kemah)	Clear Lake
October 2015	Captain Benny's Seafood (Gulf Freeway)	Houston
June 2016	Tookie's Seafood	Clear Lake
January 2018	BLVD Seafood	Galveston
June 2019	Crazy Alan's Swamp Shack (Baybrook)	Clear Lake
March 2020	Sam's Boat (Seabrook)	Clear Lake
October 2020	Barge 295	Clear Lake
November 2020	Fisherman's Wharf	Galveston
February 2021	Seafood Safety Lab at TAMUG	Galveston
March 2021	Kritikos Grill	Galveston
April 2021	BB's Tex-Orleans (Webster)	Clear Lake
April 2021	Loch Bar	Houston
May 2021	Bludorn	Houston
June 2021	Eunice	Houston
June 2021	La Lucha	Houston
July 2021	BB's Tex-Orleans- Heights	Houston
July 2021	BB's Tex-Orleans- Upper Kirby	Houston
July 2021	State of Grace	Houston
November 2021	Fish Tales	Galveston
December 2021	Goode Co. Seafood	Houston

Table 2: Tonnage of Oyster Shells Recycled under Cycle 25

MONTH/YEAR	OYSTER SHELL RECYCLED (TONS)		
	Galveston Region	**Clear Lake Region**	**Houston Region**
January 2021	0.86	N/A	N/A
February 2021	0.85	N/A	N/A
March 2021	1.13	N/A	N/A
April 2021	1.08	N/A	N/A
May 2021	1.06	N/A*	N/A*
June 2021	0.93	9.83	4.28
July 2021	1.16	8.12	6.33
August 2021	1.2	8.1	7.15
September 2021	0.46	6.93	6.02
October 2021	0.74	9.41	5.49
November 2021	1.17	8.09	5.92
December 2021	1.14	7.44	6.98
January 2022	N/A	6.94	7.05
Total	**11.78**	**64.86**	**49.22**
Grand Total	***125.86 tons of shell recycled from Jan. 2021 - Jan. 2022***		

**Shell recycling for the Clear Lake and Houston Region was conducted under Cycle 24 through May 2021 and shell recycling for the Galveston Region was conducted under Cycle 26 in January 2022.*

Chart 1: Tonnage of Oyster Shells Recycled under Cycle 25

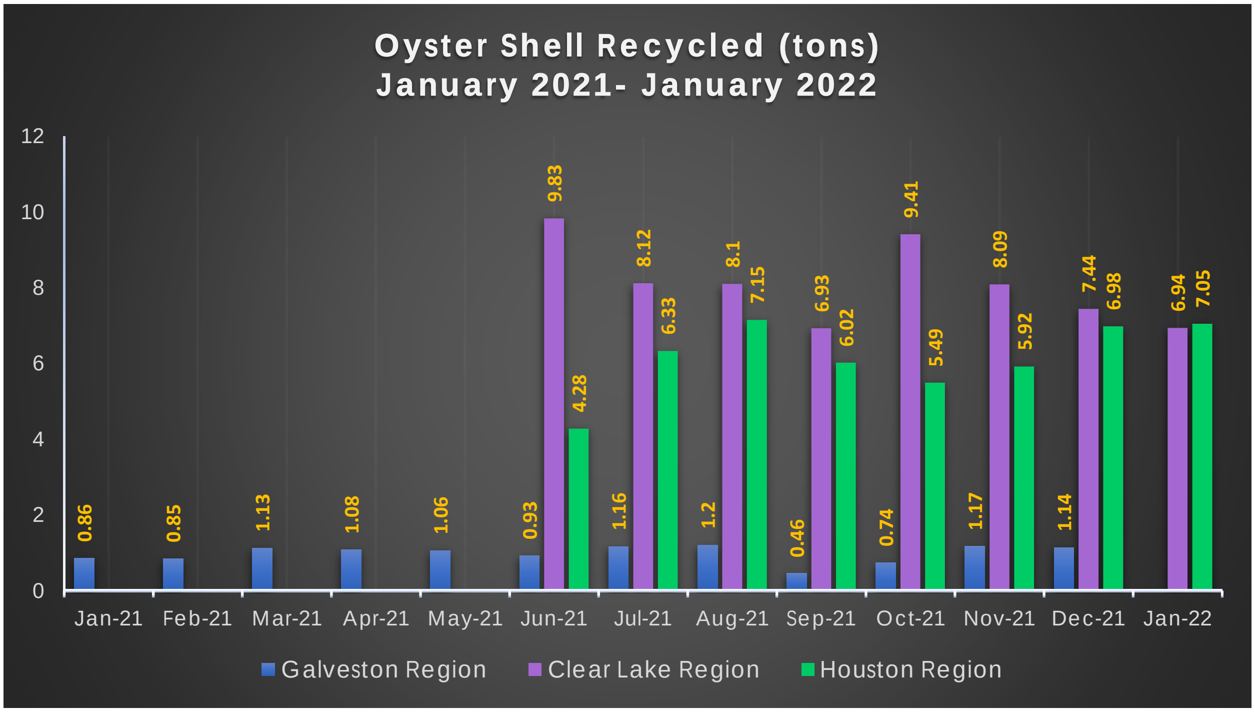
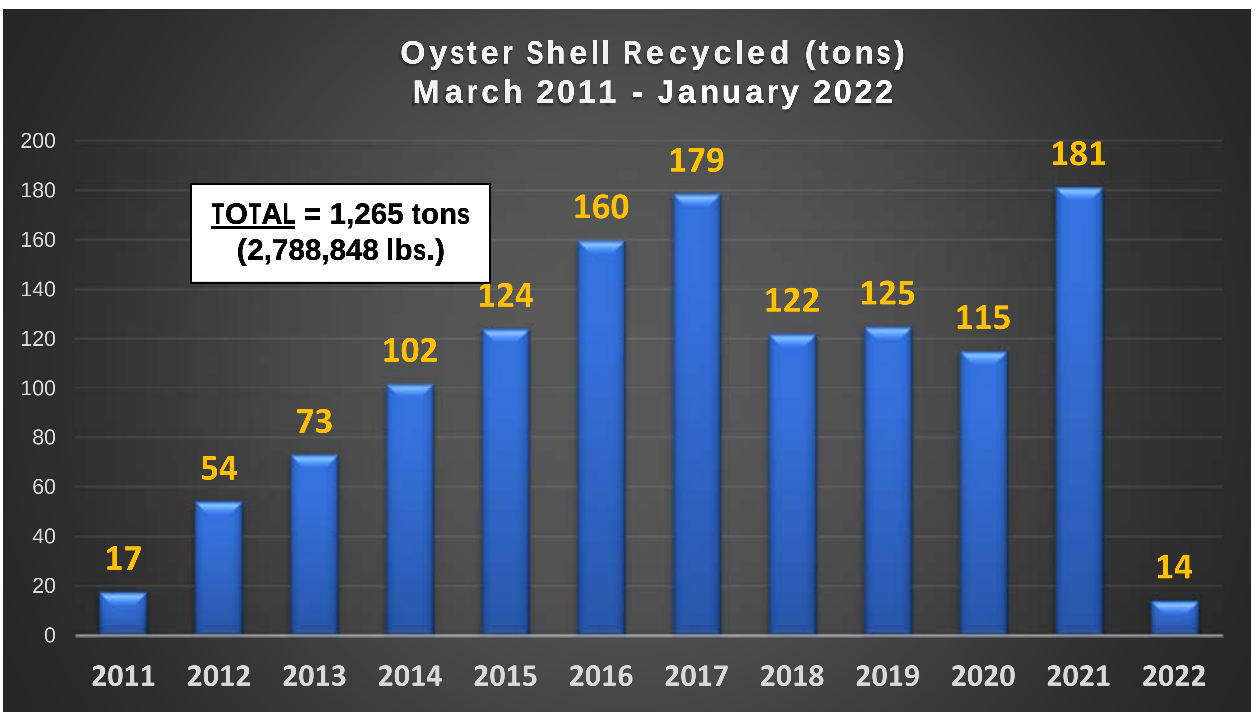


Chart 2: Tonnage of Oyster Shells Recycled to Date



A.2 Storage Site Logs

To track the amount of oyster shell recycled and where it is stockpiled, GBF and Moody Gardens staff maintain Microsoft Excel spreadsheets in which the date of collection, source of shell (e.g., recycling partner name or special event), amount of shell, curing site name, pile location, and pile rotation is recorded. GBF and Moody Gardens staff also document the date a shell pile is turned during the sun curing process and when cured shell is transported off the curing site property for restoration projects. This allows GBF to maintain an estimate of total shell available for use in reef restoration projects.

During the grant cycle, a total of 126 tons of recycled oyster shell was delivered to three curing sites: Texas City, Red Bluff, and Moody Gardens (Table 3). Due to the close proximity with the Clear Lake and Houston partners, the majority of the shell was deposited at Red Bluff. Red Bluff is also the largest property and can therefore accommodate the largest volume of shell. All shell collected from recycling partners on Galveston Island was delivered to the curing site located on Moody Gardens' property. The Texas City curing site was only used on rare occasion when the Red Bluff access road was under repair.

Table 3: Tonnage of Shells Delivered to Curing Sites during Cycle 25

Curing Site	Oyster Shell Onsite (Tons)
Texas City	2.12
Red Bluff	111.96
Moody Gardens	11.78
TOTAL	**125.86**

A.3 Storage Maintenance Updates and Photos

GBF staff developed a Sun Curing Protocol in 2020 to standardize and improve the sun curing process. Shell at different stages of sun curing (Phase 1 – Active Collection; Phase 2 – Curing; Phase 3 – Cured) is kept in individual piles separated by a 10-foot buffer. This allows GBF to track which shell is available for use in restoration projects. To better accomplish this, staff have divided sections of Red Bluff, Texas City, and Moody Gardens to monitor each phase of the curing process more precisely.

During Cycle 25, GBF staff managed and maintained two curing sites for shell storage: Red Bluff and Moody Gardens. No maintenance was required for the Texas City curing site in 2021. Red Bluff is leased from the Port of Houston Authority. Per the lease terms, GBF is responsible for all maintenance and management. As a 1.5-acre property, more time and effort is required to ensure the site meets standards for proper and efficient shell curing. GBF staff performed regular mowing and vegetation management for access, as well as shell turning, moving, and piling to comply with GBF's Sun Curing Protocol. In years past, this site was taken out of circulation during the rainy season. However, continuous improvements now allow for year-round use of Red Bluff. The Moody Gardens curing site requires minimal maintenance due to concrete road access. Moody Gardens staff maintains the shell piles according to GBF's Sun Curing Protocol. GBF staff assists Moody Gardens with maintenance of the shell piles when needed, for example when fully cured shell was relocated to a reef restoration site.

Please refer to Table 4 for the curing site maintenance log and Appendix A for photos of the curing sites.

Table 4: Log of Curing Site Maintenance during Cycle 25

Date	Curing Site	Maintenance Conducted
6/11/2021	Red Bluff	Mowed
6/25/2021	Red Bluff	Sprayed herbicide on Pile M and on vines at the gate
7/2/2021	Moody Gardens	Cured shell moved from Pile B to Pile A
8/16/2021	Red Bluff	19 dump truck loads of crushed concrete base delivered: total of 343 tons
8/17/2021	Red Bluff	Spread crushed concrete base with tractor along main road of property; one load was spread around the corner by Pile G
9/1/2021	Red Bluff	Installed t-posts, rope, and stakes with pile letter for shell piles M and D
9/17/2021	Red Bluff	Sprayed herbicide on Pile A, D, F, and K
10/12/2021	Moody Gardens	Cured shell moved from Pile C to Pile A
11/2/2021	Moody Gardens	Rotated the partially cured shell at Pile D; Relocated the fully cured shell at Pile A to GBF's Sweetwater Preserve
11/9/2021	Red Bluff	Moved shell from Pile H and I to E; Cleared the brush across from Pile K
11/10/2021	Red Bluff	Rotated and smoothed out Pile G and J
12/1/2021	Red Bluff	Mowed
1/8/2022	Moody Gardens	Cured shell moved from Pile D to Pile A
1/13/2022	Red Bluff	Smoothed out the road base with the tractor along main road of property

A.4 Restaurant Database

In 2014, GBF staff created a Restaurant Database to identify all seafood restaurants serving oysters in the Houston, Clear Lake, and Galveston regions. Each year, GBF staff review and update the Restaurant Database to analyze new potential shell recycling partners. The updated 2022 Restaurant Database is included in Appendix A.

Through analysis of restaurant location and menu items, GBF staff identified five restaurants in the Clear Lake region and five restaurants in the Galveston region as priority future partners to pursue. Based on the Houston list, GBF staff identified seven restaurants that are in or near the inner loop. Of those seven, three have high potential to join the Oyster Shell Recycling Program during Cycle 26. GBF staff initiated communications with Flying Fish and they are eager to join the Program once they begin serving oysters again. Acme Oyster House and BB's Tex-Orleans (Oak Forest location) are in the final stages of joining the Program as of March 2022.

B) Task 2: Volunteer Oyster Gardening

B.1 Number and Location of Gardens Created

Cycle 25 funded the 2021 oyster gardening season which began in the spring of 2021. In the summer of 2021, GBF hosted two Oyster Garden Creation Events, one in Tiki Island and the other in Bayou Vista. Volunteers and GBF staff worked together to build over 300 oyster gardens. To accommodate additional volunteers in more remote communities, GBF staff delivered gardens to individual homes from July through early September. All volunteers were given the option of three garden types: bags, stringers, or cages. A total of 366 oyster gardens were suspended from piers, docks, and bulkheads into Galveston Bay by September 2021 (Table 5).

B.2 Number and Location of Gardening Volunteers

A total of 92 volunteers participated in the 2021 oyster gardening season. These volunteers were located in the communities of Bayou Vista, Beach City, Dickinson, Galveston, Hitchcock, San Leon, and Tiki Island. Throughout these seven communities, oyster gardens were suspended in the water at 89 bayfront homes (Table 5). Volunteers contributed through spring garden creation efforts, ongoing oyster garden monitoring, and fall garden collection efforts. Volunteers were instructed to rinse their gardens weekly to help reduce biofouling and predation. Weekly maintenance also allowed volunteers to inspect their gardens for new oyster growth.

In November of 2021, GBF staff coordinated the collection of the oyster gardens through three community events in Tiki Island, Galveston, and Bayou Vista. Volunteers delivered their gardens to these locations where GBF staff received the gardens, documented new oyster growth, and prepped the gardens for transport. For those volunteers unable to attend a community event, GBF staff collected their gardens separately. A fourth collection event in San Leon was postponed until 2022 due to inclement weather and COVID restrictions. GBF staff collected Dickinson and San Leon volunteers' oyster gardens on January 28, 2022 and documented the oyster growth in each garden (Table 6).

Table 5: Oyster Garden Creation and Deployment

Community	Volunteer Homes	Bags Deployed	Cages Deployed	Stringers Deployed	TOTAL Gardens Deployed
Bayou Vista	30	63	0	35	98
Beach City	1	2	0	2	4
Dickinson	1	2	0	0	2
Galveston	17	47	10	11	68
Hitchcock	6	17	0	18	35
San Leon	8	30	0	17	47
Tiki Island	26	55	17	40	112
Grand Total:	**89**	**216**	**27**	**123**	**366**

Table 6: Oyster Garden Collection and Oyster Recruitment

Community	Gardens Collected	Total Oysters	Avg. Oysters per Garden
Bayou Vista	92	278	3
Beach City	4	3	1
Dickinson	2	0	0
Galveston	66	2,424	37
Hitchcock	33	469	14
San Leon	47	330	7
Tiki Island	116	13,020	112
TOTALS:	**360**	**16,524**	**46**

B.3 Report and Photos of Oyster Gardening Events

Thanks to the 92 dedicated oyster gardening volunteers, approximatley 16,524 oysters were recuirted in the oyster gardens (Table 6). These oysters were transplanted onto restoration reefs in November 2021 and January 2022 under separate grant funding to help improve the local oyster population. For additional information about the 2021 oyster gardening season, please refer to Appendix B which contains the complete Annual Oyster Gardening Report.

C) Task 3: Education and Outreach

C.1 Outreach Materials

To inform and educate restaurant patrons about the Oyster Shell Recycling Program, approximately 180 rack cards were distributed to all new restaurant partners added during Cycle 25. A total of eight window clings were distributed to new restaurant partners as well. The window clings were displayed on entry doors to identify each restaurant as a participant of the Oyster Shell Recycling Program. To further advertise active shell recycling partners, GBF updated the trailer sign (located on the back gate of the oyster shell recycling trailer) with recycling partner logos each time a new restaurant joined the Program. The truck wraps and trailer signage on GBF's recycling equipment also provide continuous advertisement as these vehicles are driven throughout the community three times a week during shell collections.

Please refer to Appendix C for depictions of outreach materials.

C.2 List of Presentations, Exhibits, Conferences, etc.

Throughout 2021, GBF conducted most outreach events in person including presentations and boothing activities, one-time shell recycling events, and volunteer oyster garden creation and collection events. Due to ongoing COVID-19 restrictions, some presentations and activities remained virtual. For instance, GBF's annual Bay Day Festival was virtual once again in 2021. Therefore, the Oyster Shell Recycling Program was represented through a video shared online via the following link (fast-forward to the 17:00 minute mark): https://youtu.be/M6Gu06eu2uY. Table 7 includes a list of all outreach activities that occurred in 2021.

In addition to these outreach activities, the Oyster Shell Recycling Program received a variety of media exposure in early 2022 due to the expansion of the Program to the inner loop of Houston. The Program was showcased on a Newsy segment that aired on January 13, 2022, the segment and article can be viewed at: https://www.newsy.com/stories/oyster-shells-recycled-to-restore-reefs/?jwsource=cl. The Houston Chronicle published an article on the Program, which can be viewed online via the following link: https://www.houstonchronicle.com/news/houston-texas/galveston/article/Galveston-Bay-Foundation-recycled-all-time-high-16773103.php. In addition, the Program was featured on the front page of the Galveston County Daily News newspaper (Appendix C, Figure 4) on January 20, 2022.

GBF originally planned to launch the expansion of the Program in April 2020 with the Inaugural Houston Oyster Festival. Due to the COVID-19 pandemic, the festival was postponed in 2020 and again in April 2021. The festival has now been rescheduled for June 2022 and will be conducted under Cycle 26. The Houston Oyster Festival will allow GBF to reach new and larger audiences in the greater Houston area. All proceeds from the festival will benefit the Oyster Shell Recycling Program and all shells produced by restaurants at the event will be recycled by GBF. It is proposed that this Festival could provide at least the baseline funding required to sustain minimum shell recycling operations.

Please refer to Appendix C for photos of outreach efforts.

Table 7: 2021 Outreach Activities

No. of Events	Date	Activity	Description	Type of Outreach	Participants
1	2/27/21	Barge 295 Oyster Cook-Off	One-time shell recycling event at Barge 295	Community Outreach	Unknown
2	3/10/21	Texan by Nature Virtual Series	Virtual presentation	Presentation	~50
3	4/24/21	Oyster Tasting at Tommy's	Oyster program booth	Community Outreach	60
4	4/1-30/21	GBF's Houston Oyster Month	Fundraising and outreach event	Community Outreach	110
5	5/11/21	Oyster Gardening Presentation	In-person presentation & recruitment event in Bayou Vista	Presentation	40
6	5/15/21	GBF's Bay Day Festival	Virtual presentation	Presentation	~3,000
7	5/15/21	Oyster Gardening Presentation	In-person presentation & recruitment event in Tiki Island and Crash Boat Basin	Presentation	33
8	6/19/21	Tiki Island Oyster Garden Creation Event	Volunteers constructed gardens	Volunteer Event	55
9	7/4/21	Kemah Fourth of July Parade	Drove the dump truck in parade	Community Outreach	~200
10	7/13/21	Bayou Vista Oyster Garden Creation Event	Volunteers constructed gardens	Volunteer Event	65
11	9/11/21	Jesse H. Jones Park Native American Heritage Day	Oyster Program booth set up in front of oyster midden	Community Outreach	267
12	10/14/21	Port of Galveston Lunch & Learn	Virtual presentation	Presentation	~15
13	10/30/21	Day by the Bay	Oyster Program booth set up at Topwater Grill	Community Outreach	~80
14	11/4/21	Oysters, Blues, and Brews	One-time shell recycling event at Armadillo Palace	Community Outreach	Unknown
15	11/12/21	University of Houston's Food Sustainability Conference	In-person presentation	Presentation	~20
16	11/6/21	Oyster Garden Collection Event	Collected oyster gardens & counted new oyster growth in Tiki Island & Galveston	Volunteer Event	41
17	11/11/21	Oyster Garden Collection Event	Collected oyster gardens & counted new oyster growth in Bayou Vista	Volunteer Event	21
18	11/15/21	Oyster Workgroup Meeting	Virtual meeting & presentation	Meeting/Presentation	~40

C.3 Number of Students Reached and Data Collected

Due to issues surrounding COVID-19, the Oysters in the Classroom program was adapted to meet the needs of regional schools. During the 2020-2021 school year, outside organizations were not allowed into schools. GBF Education Team created a virtual program to introduce students to the biology and ecology of oysters in Galveston Bay. Via live-streaming services, educators discussed the importance of oysters in the bay, regional issues, and dissected an oyster using a digital microscope to allow students to get a closer look at oyster anatomy.

In the summer of 2021, GBF staff were able to enter classrooms, however teachers were overwhelmed with the idea of having an aquarium with live oysters in their classroom. Acknowledging their concerns and wanting to keep the program as inclusive as possible, GBF adapted the virtual program into a Classroom STEM Workshop. With this workshop, GBF educators implemented one to seven 45-minute workshops at each school, becoming the classroom teacher for the day. All materials for the lessons were supplied to make things easy on the schoolteacher. During the Oysters in the Classroom "All About Oysters" workshop, students mapped local oyster reefs in the bay, discussed their importance to the ecosystem as well as to humans, conducted an investigation to see if they could create a filter that would "out-filter" an oyster, and dissected oysters to learn more about their anatomy. During the workshop, students completed an accompanying All About Oysters worksheet (Appendix C) so the teacher could use the workshop as an actual grade. After each workshop, teachers completed an evaluation to gather student data and assess the program overall. Below are some quotes from participating teachers:

> "I am participating in a classroom STEM workshop program with GBF because we are happy with the knowledge and expertise of GBF and it aligns with Texas education standards. This program aligns to interdependence occurring in living systems and the environment and that human activities can affect these systems."

> "GBF has always been good in working with schools and providing fun, engaging activities. We are learning about marine invertebrates right now and the oyster workshop was a fun highlight on this subject matter. I think my marine science kids learned a lot about oysters and why they are important."

Please refer to Table 8 for a list of the 2021-2022 Oyster in the Classroom Events.

Table 8: 2021-2022 Oysters in the Classroom Events

Program	Date	School	District	Grade	No. of Students	% Low Income
Virtual Oysters in Classroom	22-Jan-21	Bellaire High School	Houston ISD	12th	154	80
Virtual Oysters in Classroom	20-Apr-21	Girl Scouts Virtually Wild	N/A	8-12th	11	n/a
Oysters in Classroom	24-Jun-21	La Porte Junior High	La Porte ISD	6-8th	25	53
Oysters in Classroom	22-Jul-21	La Porte Junior High	La Porte ISD	6-8th	28	53
Oysters in Classroom	29-Sep-21	St. Johns School	N/A	11-12th	35	15
Oysters in Classroom	8-Dec-21	Victory Lakes Intermediate	Clear Creek ISD	7th	76	20
Oysters in Classroom	9-Dec-21	Brookside Intermediate	Clear Creek ISD	6-8th	30	31
Oysters in Classroom	14-Jan-22	Kranz Junior High	Dickinson ISD	7th	110	66
Oysters in Classroom	26-Jan-22	Creekside Intermediate	Clear Creek ISD	7th	25	18
TOTALS:	**9 events**	**8 different organizations**	**6 ISD's or other**	**Grades 6-12th**	**494 students**	**42% low income**

D) Task 4: Monitoring of Recycled Shell-Based Reef Habitat

During Cycle 25, GBF partnered with TAMUG, specifically Dr. Laura Jurgens and her lab, to develop oyster reef monitoring methods and guide the development of a Volunteer Reef Monitoring Program.

In 2019, GBF staff began a basic assessment of the Sweetwater Lake Oyster Shell Breakwater project (Sweetwater), with the goal of determining whether the use of recycled oyster shell in a living shoreline was sustainable and how successful this technique was in establishing oyster habitat. GBF staff documented the average amount of oyster recruitment on the linear reef by sampling one standard size shell bag, typically 30 pounds in weight, from each section. At the same time, a graduate student in Dr. Jurgens' lab, Emily Hubbard, initiated a project to document oyster recruitment in smaller sample bags made from recycled shrimp netting rather than the traditional, plastic-based aquaculture net utilized in oyster shell breakwater projects. Ms. Hubbard's work provided baseline data for the Sweetwater site as well as the Trinity Bay Discovery Center Oyster Shell Breakwater project site.

The focus of reef monitoring under Cycle 25 was the Sweetwater site due to the previous data collection at this location as well as the close proximity to the TAMUG campus. GBF staff continued to refine the reef monitoring methodologies in 2020 and created a basic volunteer reef monitoring protocol. In March 2021, TAMUG provided reef monitoring training for GBF staff. The smaller sample bags originally created by Ms. Hubbard in 2019 were utilized as the reef monitoring samples moving forward. The smaller sample sizes increased data collection efficiency while also allowing for annual and seasonal comparisons of each section of reef.

D.1 Signed partnership Agreement MOU

Upon execution of the agreement between GBF and TAMUG in June 2021 (Appendix D), TAMUG began to develop a more sophisticated reef monitoring protocol for use by GBF staff, volunteers, and TAMUG students.

D.2 Volunteer Monitoring Protocols and Guidance Documents

A new datasheet was created to simplify data collection and align with an online data entry form developed by TAMUG in 2021. This "Google Form" was created to facilitate data entry by GBF staff, GBF volunteers, and/or TAMUG students. It is accessible online via: https://forms.gle/vh1EhmumrA5rsQBT6. TAMUG also created a "Field Guide to Galveston Bay Oyster Reefs" to supplement the monitoring process. GBF utilized this guide and the new methodologies to finalize the Volunteer Oyster Reef Monitoring Instructions as shown in Appendix D. This protocol was implemented in 2021 as GBF piloted volunteer-based reef monitoring with two volunteer groups in August and September. The data from these activities was uploaded to the online data repository and processed by Dr. Jurgens' lab. The tables and charts included in Section D.5 show the results of monitoring in 2021.

D.3 Curriculum Summary for Undergraduate Course(s)

In addition to assisting with the development of GBF's Volunteer Reef Monitoring Program, TAMUG also created a service-learning curriculum that has been incorporated in the Invertebrate Zoology undergraduate course (Appendix D). This curriculum will be utilized for the first time during the 2022 spring semester. During the week of March 28th, 2022, students will participate in lab sessions at Sweetwater and collect data on oyster density (live and recently dead), size distribution (shell height), and the presence of other organisms in the sample such as hooked mussels, dark false mussels, shrimp, crabs, and fish. Students will use the same datasheet and online form developed by TAMUG. The new curriculum will not only provide students with real-life, hands-on learning opportunities, it will also create a long-term, self-sustaining monitoring program that benefits students, the bay, and GBF's reef restoration efforts. GBF will utilize the findings from the monitoring efforts to adaptively manage existing projects and inform the best approach for utilizing recycled oyster shell in future reef restoration efforts.

D.4 Number and Location of Monitoring Sites

To date, GBF has utilized oyster shell reclaimed through the Oyster Shell Recycling Program in five living shoreline projects and one subtidal reef restoration project. To pilot the Volunteer Reef Monitoring Program, GBF selected the Sweetwater site due to the location (sheltered lake adjacent to a GBF-owned preserve), accessibility (gravel road accessible by car), and available baseline data. The Sweetwater site also provides the ideal location for lab field trips associated with TAMUG's new curriculum for Invertebrate Zoology.

A second site, the Dickinson Bay Oyster Reef Restoration project, was selected for subtidal reef monitoring via TAMUG's Scientific Diving and/or Advanced SCUBA course(s). Under Dr. Jurgens' instructions, the student divers will collect samples from the reef site, constructed entirely with recycled oyster shell by GBF in 2018. Students will document reef width and height to assess any changes in the original shell placement area and assess oyster recruitment, density, abundance, size, and mortality. TAMUG will manage all data management and post-processing. The initial monitoring effort at the Dickinson Bay Reef was scheduled for spring 2020 but was postponed due to COVID-19 restrictions. Dr. Jurgens plans to conduct the first assessment in April 2022, pending COVID-19 conditions.

Please refer to Appendix D for a location map of the two reef monitoring sites.

D.5 Monitoring Results and Data

<u>Table 9</u>: Summary data from first monitoring efforts from new volunteer monitoring program at Sweetwater Reef. Data are from 2-gallon monitoring bags affixed to the mid-reef at fixed locations and include live and dead oysters plus other bivalves. Dark false mussels are *Mytilopsis leucophaeata,* oysters are *Crassostrea virginica,* and hooked mussels are *Ischadium recurvum* (TAMUG).

DATE:	**3/9/2021**	**8/12/2021**	**9/23/2021**	**Overall Averages**
Number of bags sampled:	10	4	1	N/A
Mean (average) count of LIVE oysters:	29	43	62	45
Mean (average) count of recently DEAD oysters:	2	2	13	6
Mean (average) dark false mussel count:	1	6	2	3
Mean (average) hooked mussel count:	26	26	73	42
Mean (average) LIVE oyster length in mm (with number of oysters sampled):	56.9 (292)	47.9 (174)	44.1 (62)	50
Mean (average) DEAD oyster length in mm (with number of oysters sampled):	43.4 (25)	63.8(10)	57.6 (13)	55

<u>Table 10</u>: Repeated samples at location C115 on Sweetwater reef showing per-bag changes in bivalve density (TAMUG).

Date	**Live oyster count**	**Recently dead oyster count**	**Dark false mussels count**	**Hooked mussels count**
3/9/2021	52	2	0	12
8/12/2021	30	1	4	16
9/23/2021	62	13	2	73

Chart 3: Mean oysters per month per bag (note small sample size in September 2021). Chart 3 shows a typical boost in abundance over summer from newly settled spat. Contrast with Chart 4, which shows a decrease in mean size, also consistent with spat set over summer (TAMUG).

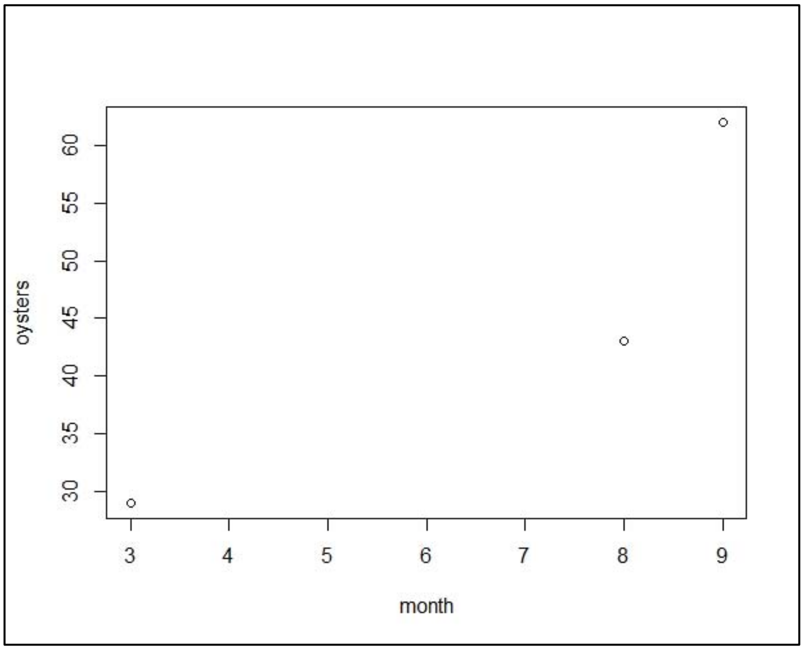
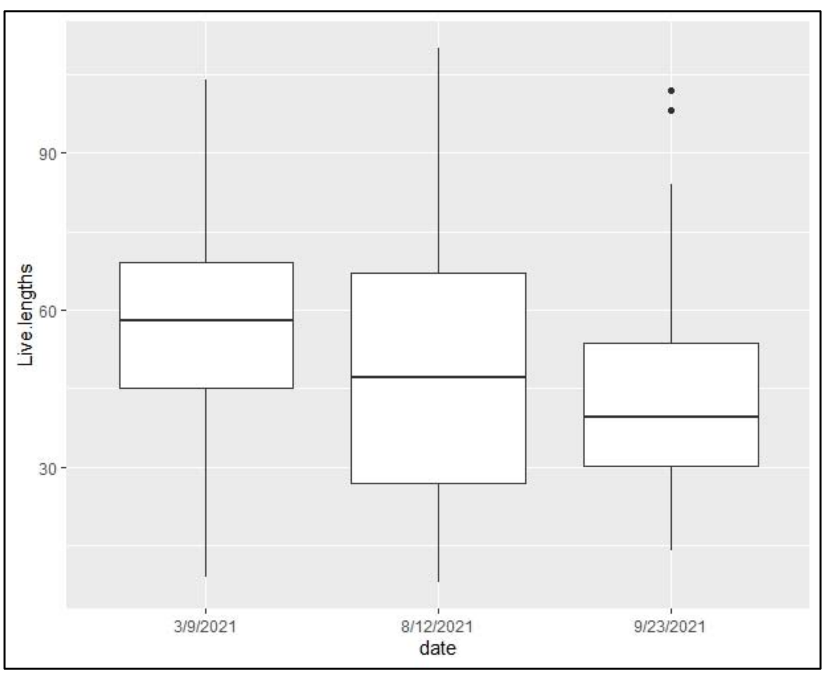


Chart 4: Sizes of live oysters over the sampling period, shown as boxplots (median and quartiles). Note the median size decreases with the newly settled spat arriving over summer as expected (TAMUG).



IV. Results

GBF utilized Cycle 25 funds to continue the Oyster Shell Recycling Program's expansion to the inner loop of Houston. During Cycle 25, 126 tons of oyster shell was collected, and nine new shell recycling partnerships were secured. All oyster shells collected during Cycle 25 are currently undergoing the sun curing process. Upon completion of the sun curing process, these shells will be utilized in GBF's Volunteer Oyster Gardening Program and oyster reef restoration efforts.

Due to the Houston expansion and new partnerships in Galveston, GBF recycled a record-breaking tonnage of shell in 2021, a total of 181 tons. Based on this new record in 2021, GBF is now collecting an average of 15 tons of oyster shell per month. As of January 2022, GBF has recycled a total of 1,265 tons of oyster shells since the inception of the Program.

Cycle 25 also funded the 2021 oyster gardening season. Ninety-two volunteers participated in oyster gardening during 2021 and helped grow 16,524 oysters which were transplanted onto restoration reefs under separate grant funding.

GBF's Education Team adapted the virtual Oysters in the Classroom program into a Classroom STEM Workshop during Cycle 25. During the 2021-2022 school year, nine workshops were conducted at eight different organizations (public schools, private schools, scout organizations, etc.). As a result, a total of 494 students (grades 6 through 12) were engaged in Oysters in the Classroom.

During Cycle 25, TAMUG trained GBF staff on reef monitoring methodologies, designed an online datasheet to help streamline data collection, produced a "Field Guide to Galveston Bay Oyster Reefs," and created a service-learning curriculum that has been incorporated in TAMUG's Invertebrate Zoology undergraduate course. GBF piloted the new Volunteer Reef Monitoring Program under Cycle 25, implementing these new tools and techniques with two volunteer groups in August and September of 2021.

V. Lessons Learned

Shell Recycling Operations

GBF plans to continue recruiting additional shell recycling partners as Program capacity allows. The threshold for expansion will be dictated by the shell-hauling capacity of the recycling equipment (dump truck, landscape trailer, Moody Gardens' equipment), storage capacity at the curing sites, and/or funding availability. The largest expenses documented thus far are associated with travel, vehicle/equipment maintenance, and staff time (salary and fringe).

Limited curing site capacity may require the acquisition of additional property in closer proximity to the inner loop of Houston. If the dump truck reaches maximum hauling capacity prior to the end of a single shell collection day, a closer curing site will be necessary. By securing another curing site near or within the inner loop of Houston, GBF staff will be able to deliver a full load and then continue with the remainder of the shell collection route without having to drive a further distance to the Red Bluff curing site.

The shell recycling operations on Galveston Island are near capacity due to the current equipment in use: Moody Gardens staff's personal vehicle. Thanks to Moody Gardens, three additional partners have been secured on the Island under Cycle 26. To continue the addition of new recycling partners, GBF secured funds to purchase a small utility trailer. This trailer will be used by Moody Gardens staff to haul a larger quantity of oyster shell so multiple trips will no longer be needed. If the Galveston shell recycling operations continue to expand, additional equipment may be required in the future.

Due to the low volume of shell recycled by some Houston partners, shell collections could occur once or twice a week instead of three times a week. Since most Houston restaurants are in residential areas or high-rise office buildings, odor is a concern and more frequent shell collection is often requested. The Houston restaurant partners that were concerned about odor are satisfied with shell collections three times a week thus far. GBF staff found adding cinnamon to the bottom of empty recycling bins helps reduce the smell, therefore GBF staff add cinnamon to foul bins when needed and recommend this solution to restaurants as well.

A staff member from the Seafood Safety Laboratory at Texas A&M University in Galveston reached out to GBF requesting to recycle oyster shells they obtain from monitoring *Vibrio* bacteria in oysters. The Seafood Safety Laboratory became a shell recycling partner in February 2021. Up to this point, the Oyster Shell Recycling Program has only partnered with restaurants that serve oysters. The lab partnership indicates there may be potential to partner with other groups/companies rather than solely with restaurants.

Volunteer Oyster Gardening

In an effort to streamline the Volunteer Oyster Gardening Program and reduce expenses, GBF staff plan to at least limit, if not eliminate, garden deliveries to individual volunteers. This option arose during the COIVD-19 pandemic when in-person events were not possible. However, it has proven costly and time consuming. It is recommended that volunteers who cannot attend community events pick up their gardens from GBF's office in Kemah. The office is central to all participating communities and an in-person, scheduled pick-up will provide an opportunity for the volunteers to meet with GBF staff and receive proper instructions.

To further improve the cost effectiveness of the Volunteer Oyster Gardening Program, GBF plans to limit the number of oyster gardens managed by each volunteer to a maximum of three. This will reduce the annual supply needs and allow the focus of the spring Garden Creation Events to be education. In addition, as the number of participating volunteers has increased, the time commitment for staff has risen dramatically, particularly in the fall when gardens are collected. Documentation of oyster growth in each individual garden is a time consuming process. Therefore, reducing the number of gardens per volunteer will reduce expenses associated with staff time while continuing to facilitate the collection of valuable data.

In 2021 it became evident the fall Garden Collection Events are the highlight of the program for many volunteers. They are able to see and understand the oyster recruitment and growth process as GBF staff help them assess their gardening results. However, it was observed that volunteers are disppointed, and less willing to participate in the future, if there are no oysters in their gardens. Therefore, GBF staff have begun educating volunteers on the importance of recycled oyster shell and reef habitat for additional organisms such as mussels, barnacels, and bryozoans, rather than just oysters. While these species need food and shelter too, GBF explains the purpose of oyster gardening is to give oysters a boost since their populations in Galveston Bay have suffered over the last decade. GBF staff plan to incorporate these lessons into the the spring events and throughout the entire gardening season to help retain volunteership and increase stewardship among the communities.

Volunteer Reef Monitoring

Thanks to the assistance of TAMUG, GBF implemented the first volunteer reef monitoring activities in 2021. GBF incorporated TAMUG's monitoring methods and worked with staff and small groups, such as the Houston Zoo Educators, to further refine and streamline the monitoring process. The smaller sample bags will be used moving forward. Instead of removing the standard 30-pound bags from the breakwater structure, the smaller bags are zip-tied to the edge/top of the breakwater for easy access and removal. The smaller samples are also more manageable due to the lighter weight and can be easily transported via a five-gallon bucket. The shrimp netting appears to last longer than the plastic mesh and can be reused at least two to three times. However, the shrimp net bags are more tedious to make.

Locating the sample bags was a challenge in 2021. Although the sample locations were marked by PVC pipes, the turbid water made it challenging to locate the samples, particularly at high tide, and often the PVC marker was washed away during storms. In February 2022, GBF staff worked with TAMUG to attach floats and lines to each sample bag to facilitate location of the samples even at high tide. In addition, GBF staff have found that monitoring all ten samples at the Sweetwater site requires at least four to six hours with four people. Therefore, volunteer groups will likely focus on only two to four samples depending on the group size and allotted time for the activity. While data collection is important, the focus of volunteer involvement will be on education and instilling stewardship. TAMUG's complementary curriculum will be the main source of data utilized to assess GBF's oyster shell-based reef restoration efforts.

VI. References

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VII. Appendix

APPENDIX A: Task 1

- Task 1 Photographs
- Map of Shell Recycling Locations
- Restaurant Database

APPENDIX B: Task 2

- Task 2 Photographs
- Oyster Gardening Project Location Map
- Annual Gardening Report

APPENDIX C: Task 3

- Task 3 Photographs
- Oyster Shell Recycling Program Outreach Materials
- All About Oysters Worksheet

APPENDIX D: Task 4

- Map of Reef Monitoring Sites
- Volunteer Monitoring Protocols and Guidance Documents
- Curriculum Summary for Undergraduate Course(s)

APPENDIX A
Task 1 Deliverables

SHELL COLLECTION AND PARTNERSHIPS

Task 1
Photographs

Figure 1. New recycling bins branded with GBF logo on the lid and HEB logo on the side used for shell recycling

Figure 2. Dump truck in front of State of Grace, a Houston region oyster shell recycling partner

Figure 3. Dump truck in front of Goode Co. Seafood, a Houston region oyster shell recycling partner

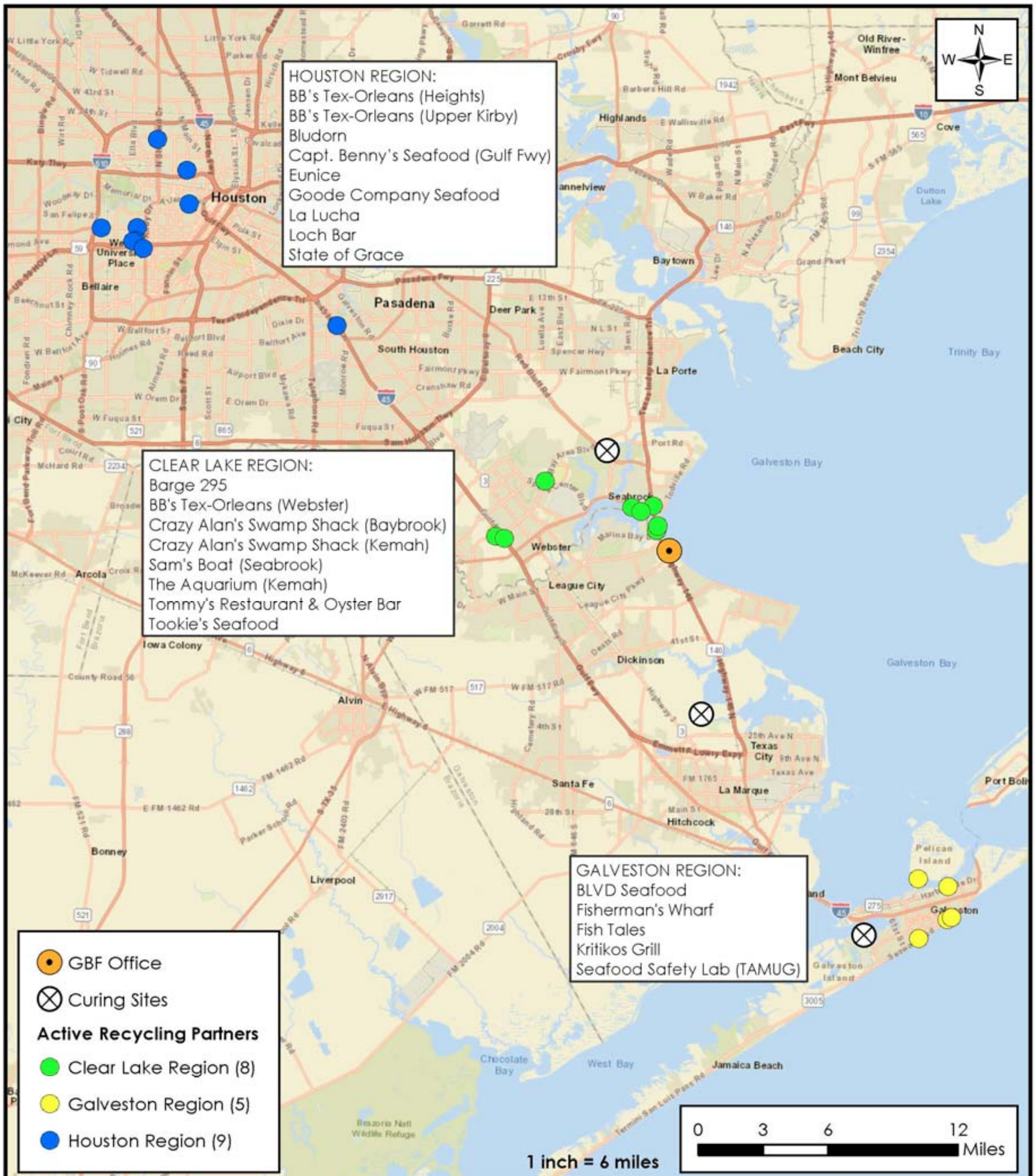
Figure 4. Recycled shell being delivered to the Red Bluff curing site with the new equipment

Figure 5. Installed t-posts, rope, and stakes with pile letter for shell piles D and M at Red Bluff curing site

Figure 6. GBF staff moving cured shell to consolidate piles and make space for future recycled shell at Red Bluff curing site

Figure 7. GBF staff relocating fully cured shell from Moody Gardens curing site to GBF's Sweetwater Preserve and Moody Gardens staff rotating a semi-cured shell pile

Task 1
Map of Shell Recycling Locations



OYSTER SHELL RECYCLING LOCATIONS

Project Name: Oyster Shell Recycling Program

Project Location: Harris & Galveston County, TX

Image Source: ESRI World Street Map

Projection: NAD 1983, UTM Zone 15N

Date Drawn: 3/8/2022 | Drawn by: H.Leija

GALVESTON BAY FOUNDATION

1725 Highway 146, Kemah, TX; (281) 332-3381

Task 1
Restaurant Database

RESTAURANT DATABASE
Clear Lake Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #
			Raw (Y/N)	Cooked						
1	Barge 295	Seabrook	Y	5	10-12 sacks/wk	Current Partner	Yes	Jose Castillo Jessica Connor	Kitchen Manager General Manager	(281) 549-7603
2	BB's Tex-Orleans	Webster	Y	0	5 sacks/wk	Current Partner	Yes	Adam Gilvarry Brady Porter	VP of Operations GM of Webster	(281) 767-9644
3	Captain Benny's Seafood	Deer Park	Y	4		No				(281) 476-1513
4	Crazy Alans Swamp Shack	Kemah	Y	4	About 3 sacks/wk	Current Partner	Yes	Alan Franks Robert (Bob) Deering (GM)	Owner	(281) 334-5000
5	Crazy Alans Swamp Shack	Friendswood	Y	4	About 3 sacks/wk	Current Partner	Yes	Alan Franks Bettina Noel (GM)	Owner	(832) 284-4895
6	East Star Chinese Buffet	Webster	Y	0		No				(281) 280-8822
7	Floyd's Cajun Seafood and Steakhouse	Webster	Y	6		No				(281) 332-7474
8	Flying Dutchman	Kemah	Y	4		Yes	*Past partner*	Sean Smith	Manager	(281) 334-7575
9	Gilhooley's Restaurant	San Leon	Y	4		Yes	No			(281) 339-3813
10	Jackie's Brickhouse	Kemah	Y	1		No				(832) 864-2459
11	La Costa Seafood Grill	Alvin	Y	3		No				(281) 824-4384
12	LA Crawfish	Webster	Y	3		No				(832) 905-5154
13	LA Crawfish	Baytown	Y	3		No				(832) 479-8081
14	LA Crawfish	Pasadena	Y	3		No				(832) 288-4494
15	Landry's Seafood House	Kemah	Y	1		Yes	*Past partner*	Brandy Carter	Manager	(281) 334-2513
16	Little Daddy's Gumbo Bar	League City	Y	2		No				(281) 524-8626
17	Main St Bistro	League City	Y	0		No				(281) 332-8800
18	Mambo Seafood	Baytown	Y	0		No				(832) 926-7551
19	Marais	Dickinson	Y	4		No				(281) 534-1986
20	Monument Inn	La Porte	Y	0		No				(281) 479-1521
21	Noah's Ark Bar & Grill	Bacliff	Y	4		No				(281) 339-2895
22	Opus Bistro & Steakhouse	League City	Y	4		Yes		Charlie Felts	Owner	(281) 334-0006
23	Pappas Seafood House	Webster	Y	1		No		Steve Sims		(281) 332-7546
24	Perry's Steakhouse & Grille	Friendswood	Y	0		Yes	Maybe	Patrick Niemeyer		(281) 286-8800
25	Pier 6 Seafood & Oyster House	San Leon	Y	4		No	No			(281) 339-1515
26	Sam's Boat	Seabrook	Y	0		Current Partner	Yes	Kris Zachmeyer	Assistant General Manager	(281) 326-7267
27	Schafer's Coastal Bar & Grille	Clear Lake Shores	Y	3		No				(281) 532-6860
28	The Aquarium Restaurant	Kemah	Y	0		Current Partner	Yes	Jim Prappas	Director of Biology	281-334-2521 (Bio and Edu Dept.) 281-334-9010 (Restaurant)
29	The Reef Seafood House	Texas City	Y	0		No				(409) 945-6151
30	The Rouxpour	Friendswood	Y	4		Yes	Maybe			(281) 480-4052
31	TJ Reed's Flippers	Dickinson	Y	2		No				(832) 340-7340
32	Tommy's Restaurant & Oyster Bar	Houston	Y	5		Current Partner	Yes	Tom Tollett	Owner	(281) 480-2221

RESTAURANT DATABASE
Clear Lake Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #
			Raw (Y/N)	Cooked						
33	Tookie's Seafood	Seabrook	Y	6	40-60 sacks/wk Use 8-10 sacks of oysters per day and 15 sacks of oysters on Fridays and Saturdays (8/27/18)	Current Partner	Yes	Rey Montemayor	General Manager	(281) 942-9445
34	Topwater Grill	San Leon	Y	5		Yes	*Past partner*	Robert Jackubus Joshua	Owner General Manager	(281) 339-1232
35	Valdo's Seafood House	Seabrook	Y	4		No				(281) 326-3866

LEGEND
Current Partner
Priority
Contact for Houston Oyster Festival
Low Priority

RESTAURANT DATABASE
Galveston Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #	Restaurant Address
			Raw (Y/N)	Cooked							
1	Black Pearl Oyster Bar	Galveston	Y	4		Yes	Yes			(409) 762-7299	327 23rd St
2	BLVD Seafood	Galveston	Y	3		Current Partner	Yes	Aubree Martorell	Manager	(409) 762-2583	2804 R 1/2
3	Cajun Greek	Galveston	Y	0	10 sacks/wk	Current Partner	Yes	Luis	Manager	(409) 744-7041	2226 61st St
4	Fish Tales	Galveston	Y	0		Current Partner	Yes	Patrick Loughran	General Manager	(409) 762-8545	2502 Seawall
5	Fisherman's Wharf	Galveston	Y	0	About 14-20 boxes/sacks/wk	Current Partner	Yes	Farhad Veyssi	General Manager	(409) 765-5708 (940) 300-9571 (Patrick)	2200 Harborside Dr
6	Gaido's/Nick's Kitchen & Beach Bar	Galveston	Y	8	20-60 sacks/week	Current Partner	Yes	David Sosa Nick Gaido Luiggi	Manager Owner Executive Chef	(409) 761-5500 (281) 386-7176 (Nick Cell) (832) 494-4606 (Luiggi Cell)	3802 Seawall Blvd
7	Katie's Seafood House	Galveston	Y	2		Yes	Yes			(409) 765-5688	2000 Wharf Rd.
8	Kritikos Grill	Galveston	Y	0	2 sacks/wk	Current Partner	Yes	Wendy Hartman	Manager	(409) 539-5915	4908 Seawall Blvd.
9	Landry's Seafood House	Galveston	Y	1		No	Maybe			(409) 744-1010	5310 Seawall Blvd
10	Little Daddy's Gumbo Bar	Galveston	Y	2		No				(281) 524-8626	2107 Post Office Street
11	Number 13	Galveston	Y	0		Yes	*Past partner*	Marita Schultz		(409) 572-2650	7809 Broadway St
12	Shuck's Tavern & Oyster Bar	Galveston	Y	3	5 sacks/wk from Prestige 8-10 sacks/wk from east coast	Current Partner	Yes	Nick Kovich	Owner	(409) 444-1700	414 21st St
13	The Spot	Galveston	Y	0		No		Lauren Desormeaux		(409) 621-5237	3204 Seawall
14	Willie G's	Galveston	Y	1		No				(409) 762-3030	2100 Harbor Side

LEGEND
Current Partner
Priority
Contact for Houston Oyster Festival
Low Priority

RESTAURANT DATABASE
Houston Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #
			Raw (Y/N)	Cooked						
1	1751 Sea and Bar	Houston	Y	2		No				(832) 831-9820
2	A'Bouzy	Houston	Y	1		No				(713) 722-6899
3	Acadian Coast	Houston	Y	3		No				(713) 432-9651
4	Acme Oyster House	Houston	Y	2		Yes	Yes	Vanessa Romans	Operations Manager	(346) 571-2071
5	B&B Butchers & Restaurant	Houston	Y	1		No				(713) 862-1814
6	B.B. Lemon	Houston	Y	0		No				(713) 554-1809
7	BB's Tex-Orleans	Houston- Briargrove	Y	0		No	No	Adam Gilvarry	VP of Operations	(713) 339-2566
8	BB's Tex-Orleans	Houston- Heights	Y	0	10-15 sacks/wk	Current Partner	Yes	Adam Gilvarry Jorge Carrillo	VP of Operations General Manager	(713) 868-8000
9	BB's Tex-Orleans	Houston- Montrose	Y	0		No	No	Adam Gilvarry	VP of Operations	(713) 524-4499
10	BB's Tex-Orleans	Houston- Upper Kirby	Y	0	8 sacks/wk	Current Partner	Yes	Adam Gilvarry Jasmine Bryant	VP of Operations General Manager	(713) 807-1300
11	BB's Tex-Orleans	Houston- Pearland	Y	0		No	Yes	Adam Gilvarry	VP of Operations	(832) 856-3200
12	BB's Tex-Orleans	Houston- Oak Forest	Y	0		Yes	Yes	Adam Gilvarry	VP of Operations	(832) 318-6533
13	Bludorn	Houston	Y	2	28 sacks/wk	Current Partner	Yes	Aaron Bludorn Chase Voelz	Chef Chef De Cuisine	(713) 999-0146
14	Brasserie 19	Houston	Y	1		No				(713) 524-1919
15	Brennan's of Houston	Houston	Y	2		No				(713) 522-9711
16	Cajun Kitchen	Houston	Y	4		No				(281) 495-8881
17	Captain Benny's Seafood	Houston	Y	4	20 sacks/wk	Current Partner	Yes	Adam Baker Elida Reyes	Part Owner Manager	(713) 643-0589
18	Captain Benny's Seafood	Houston	Y	4		No				(713) 666-5469
19	Captain Benny's Seafood	Stafford	Y	4		No				(281) 498-3909
20	Captain Benny's Seafood	Houston	Y	4		No				(713) 680-1828
21	Captain Tom's Seafood & Oyster	Houston	Y	0		No				(713) 451-3700
22	Caracol	Houston	Y	1		No				(713) 622-9996
23	Chilos Seafood & Oyster Bar	Houston	Y	No menu online		No				(713) 947-8700
24	Christie's Seafood & Steaks	Houston	Y	2		No				(713) 978-6563
25	Drunken Oyster	Spring	Y	0		No				(832) 843-6196
26	Eddie V's Prime Seafood	Houston- West Ave	Y	4		No				(713) 874-1800
27	Eddie V's Prime Seafood	Houston- CityCentre	Y	4		No				(832) 200-2380
28	Eugene's Gulf Coast Cuisine	Houston	Y	5		No				(713) 807-8889
29	Eunice	Houston	Y	2	40 sacks/wk	Current Partner	Yes	Justin Solomon	Manager	(832) 491-1717
30	Famous Crab	Houston	Y	3		No				(281) 484-2722
31	Flying Fish	Houston	Y	4		Yes	Yes			(713) 377-9919
32	Field & Tides	Houston	Y	1		No				(713) 861-6143
33	Floyd's Cajun Seafood and Steakhouse	Sugar Land	Y	6		No				(281) 240-3474

RESTAURANT DATABASE
Houston Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #
			Raw (Y/N)	Cooked						
34	Floyd's Cajun Seafood and Steakhouse	Pearland	Y	6		No				(281) 993-8385
35	Frank's Americana Revival	Houston	Y	Unknown		Yes				(713) 572-8600
36	Georgia James	Houston	Y	1		No				(832) 241-5088
37	Good Vibes Burgers & Brews	Pearland	Y	1		No				(832) 569-4141
38	Goode Company- Seafood	Houston- Westpark	Y	4	45 sacks/wk	Current Partner	Yes	Christian Dorsey	General Manager	(713) 523-7154
39	Hugos	Houston				Yes	Yes	Chris Loftis	Manager? Chef?	(713) 524-7744
40	Julep	Houston	Y	Unsure		No				(832) 371-7715
41	Kata Robata	Houston	Y	0		No				(713) 526-8858
42	LA Crawfish	Houston- Greenway	Y	3		No				(832) 767-1533
43	LA Crawfish	Houston- Memorial	Y	3		No				(713) 461-8808
44	LA Crawfish	Houston- Willowbrook	Y	3		No				(281) 809-5722
45	LA Crawfish	Houston- Langwood	Y	3		No				(832) 491-1121
46	LA Crawfish	Houston- Wallisville Rd & Beltway 8	Y	3		No				(281) 416-5352
47	LA Crawfish	Katy	Y	3		No				(346) 251-5902
48	LA Crawfish	Pearland	Y	3		No				(832) 781-4946
49	LA Crawfish	Houston- Gulfgate	Y	3		No				(832) 804-6901
50	LA Crawfish	Missouri City	Y	3		No				(281) 208-7759
51	La Lucha	Houston	Y	3	100 sacks/wk	Current Partner	Yes	Bobby Matos	Executive Chef	(713) 955-4765
52	Liberty Kitchen & Oysterette	Houston- River Oaks	Y	2		No				(713) 622-1010
53	Liberty Kitchen at the Treehouse	Houston- Memorial	Y	2		No				(713) 468-3745
54	Loch Bar	Houston- River Oaks District	Y	5	30 sacks/wk	Current Partner	Yes	Andrew Ojeda	General Manager	(832) 430-6601
55	Mambo Seafood	Houston- 45S & Edgebrook	Y	0		No				(713) 946-0000
56	Mambo Seafood	Houston- 290 & Tidwell	Y	0		No				(713) 462-0777
57	Mambo Seafood	Houston- 45N & West Rd	Y	0		No				(281) 820-3300
58	Mambo Seafood	Houston- Airline & Tidwell	Y	0		No				(713) 691-9700
59	Mambo Seafood	Houston- Gessner & Long Point	Y	0		No				(713) 465-5009
60	Mambo Seafood	Houston- Hillcroft & Bellaire	Y	0		No				(713) 541-3666
61	Mambo Seafood	Houston- I-10 & Federal	Y	0		No				(713) 637-0553
62	Mambo Seafood	Katy	Y	0		No				(832) 391-6644
63	Mannie's Seafood	Houston	Y	2		No				(713) 641-5003
64	Marcos Seafood & Oyster Bar	Houston	Y	0		No				(713) 946-1168
65	Mastro's Steakhouse	Houston	Y	1		No				(713) 993-2500
66	McCormick & Schmick's Seafood & Steaks	Houston- Town & Country Village	Y	4		Yes				(713) 465-3685
67	McCormick & Schmick's Seafood & Steaks	Houston- Uptown Park, Galleria	Y	4		Yes				(713) 840-7900

RESTANT DATABASE

Houston Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #
			Raw (Y/N)	Cooked						
68	McCormick & Schmick's Seafood & Steaks	Houston- Downtown	Y	4		Yes				(713) 658-8100
69	Musaafer	Houston	Y	1		No				(713) 242-8087
70	Nick's Fish Dive & Oyster Bar	Woodlands	Y	1		No				(281) 419-8885
71	One Fifth Southern Comfort	Houston	Y	1		No				(713) 955-1024
72	Orleans Seafood Kitchen	Katy	Y	1		No				(281) 646-0700
73	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #11	Y	1		No				(713) 921-1800
74	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #1	Y	1		No				(281) 999-3995
75	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #3	Y	1		No				(713) 330-4419
76	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #4	Y	1		No				(281) 447-5061
77	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #5	Y	1		No				(713) 974-6828
78	Ostioneria Michoacan Seafood and Oyster Bar	Woodlands- #6	Y	1		No				(281) 292-6811
79	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #7	Y	1		No				(713) 463-5410
80	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #8	Y	1		No				(281) 877-8855
81	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #15	Y	1		No				(281) 477-7697
82	Ostioneria Michoacan Seafood and Oyster Bar	Houston- #16	Y	1		No				(832) 672-4139
83	Pappadeaux Seafood Kitchen	Houston- Hobby Airport	Y	1		No				(713) 847-7622
84	Pappadeaux Seafood Kitchen	Houston- Galleria	Y	1		No				(713) 782-6310
85	Pappas Bros. Steakhouse	Houston- Galleria	Y	0		No				(713) 780-7352
86	Pappas Seafood House	Houston- Shepherd	Y	1		No				(713) 522-4595
87	Perry's Steakhouse & Grille	Houston- Champions	Y	0		No				(281) 970-5999
88	Perry's Steakhouse & Grille	Katy	Y	0		No				(281) 347-3600
89	Perry's Steakhouse & Grille	Houston- Memorial City	Y	0		No				(832) 358-9000
90	Perry's Steakhouse & Grille	Houston- River Oaks	Y	0		No				(346) 293-8400
91	Perry's Steakhouse & Grille	Sugar Land	Y	0		No				(281) 565-2727
92	Perry's Steakhouse & Grille	Woodlands	Y	0		No				(281) 362-0569
93	Ragin' Cajun	Houston- The Original	Y	1		No		Kelli Anderson	Senior General Manager	(713) 621-3474
94	Ragin' Cajun	Houston- Westchase	Y	1		No				(832) 251-7171
95	Relish Restaurant & Bar	Houston	Y	1		No				(713) 599-1960
96	Riel	Houston	Y	1		No				(832) 831-9109
97	Sam's Boat	Pearland	Y	0		No				(713) 436-0201
98	Sam's Boat	Houston	Y	0		No				(713) 781-2628
99	State of Grace	Houston	Y	1	~80 sacks/wk	Current Partner	Yes	Bobby Matos	Executive Chef	(832) 942-5080
100	Steak 48	Houston	Y	0		No				(713) 322-7448
101	The Annie Café & Bar	Houston	Y	0		No				(713) 804-1800

RESTAURANT DATABASE
Houston Region

No. of Restaurants	Restaurant Name	Location	Oyster Items on Menu		Oysters Purchased (Sacks per week?)	Contacted?	Interested?	Point of Contact	POC Title	Restaurant Phone #
			Raw (Y/N)	Cooked						
102	The Chalet at Rosie Cannonball	Houston	Y	0		No				(832) 380-2471
103	The Crawfish Pot & Oyster Bar	Houston	Y	2		No				(713) 360-6547
104	The Hay Merchant	Houston	Y	1		No				(713) 528-9805
105	The Oceanaire	Houston	Y	1		Yes				(832) 487-8862
106	The Original Ninfa's	Houston- Navigation	Y	1		No				(713) 228-1175
107	The Original Ninfa's	Houston- Uptown	Y	1		No				(346) 335-2404
108	The Oyster Bar at Prohibition	Houston	Y	6		No				(832) 301-8833
109	The Pearl Restaurant & Bar at The Sam Houston Hotel	Houston	Y	3		No				(832) 200-8817
110	The Rouxpour	Sugarland	Y	4		No				(281) 240-7689
111	The Rouxpour	Katy	Y	4		No				(281) 394-5013
112	The Rustic	Houston	Y	2		No				(832) 321-7775
113	Tobiuo Sushi & Bar	Katy	Y	1		No				(281) 394-7156
114	Tony Mandola's Gulf Coast Kitchen	Houston	Y	2		No				(713) 528-3474
115	Toulouse	Houston	Y	1		No				(713) 871-0768
116	Traveler's Table	Houston	Y	3		No	Yes	Thy Mitchell		(832) 409-5785
117	Truluck's Seafood Steak & Crab House	Houston	Y	1		No				(713) 783-7270
118	Truluck's Seafood Steak & Crab House	Woodlands	Y	1		No				(281) 465--7000
119	Turner's	Houston	Y	1		No				(713) 804-1212
120	UB Preserv	Houston	Y	1		No				(346) 406-5923
121	Weights + Measures	Houston	Y	1		No				(713) 654-1970
122	Willie G's	Houston	Y	8		No				(713) 840-7190
123	Winnie's	Houston	Y	Unknown		No				Not open yet
124	Xochi	Houston	Y	1		No				(713) 400-3330

LEGEND
Current Partner
Priority
Contact for Houston Oyster Festival
Low Priority

APPENDIX B
Task 2 Deliverables

VOLUNTEER OYSTER GARDENING

Task 2
Photographs

Figure 1. Volunteers building stringer oyster gardens at Garden Creation Event (Summer 2021)

Figure. 2. Volunteers building bag oyster gardens at Garden Creation Event (Summer 2021)

Figure 3. Volunteers documenting oyster growth at Tiki Island Garden Collection Event (Fall 2021)

Figure 4. Volunteers and GBF staff documenting oyster growth at Tiki Island Garden Collection Event (Fall 2021)

Figure 5. Bayou Vista volunteer with spat on shell from her oyster garden (Fall 2021)

Figure 6. Volunteer and GBF staff documenting oyster growth at Bayou Vista Garden Collection Event (Fall 2021)

Figure 7. Oyster growth on a single recycled shell from a Galveston oyster garden (Fall 2021)

Figure 8. Oyster growth on a Tiki Island stringer garden (Fall 2021)

Figure 9. Spat on recycled oyster shell found in a Bayou Vista oyster garden (Fall 2021)

Figure 10. Oyster shell from a Bayou Vista garden encrusted with barnacles and mussels (Fall 2021)

Figure 11. Oyster growth on recycled shell from a San Leon oyster garden (Jan. 2022)

Figure 12. Volunteers placing oysters and recycled shell onto Sweetwater Lake Oyster Shell Breakwater (Fall 2021)

Figure 13. GBF staff placing oysters and recycled shell onto Dickinson Bay Reef Restoration Project site (Jan. 2022)

Figure 14. Bag oyster garden

Figure 15. Stringer oyster garden

Figure 16. Cage oyster garden

Task 2
Oyster Gardening Project Map Location

2021 OYSTER GARDENING	
Project Name: Volunteer Oyster Gardening Program	
Project Location: Galveston Bay & adjacent Sub-bay Systems	
Image Source: ESRI World Street Map	
Projection: NAD 1983, UTM Zone 15N	
Date Drawn: 3/31/2022	Drawn by: H.Leija

GALVESTON BAY FOUNDATION

1725 Highway 146, Kemah, TX; (281) 332-3381

Task 2
Annual Gardening Report

ANNUAL OYSTER GARDENING REPORT
TASK 2 DELIVERABLE

Project Name: Galveston Bay Foundation Oyster Shell Recycling Program – Citizen Science, Engagement, and Education

GLO Contract No: 21-060-003-C643

Deliverable: Task 2 – Volunteer Oyster Gardening

Due Date: 03/31/2022

I. PROJECT DESCRIPTION

Since 2012, the Galveston Bay Foundation (GBF) has fostered relationships in bayfront communities to "garden" oysters. Waterfront homeowners in these communities volunteer as oyster gardeners and suspend mesh bags, metal lines (stringers), or cages containing recycled oyster shells ("oyster gardens") from their piers, docks, or bulkheads to recruit oyster larvae. The oyster gardens are submerged in the bay during the spawning season, approximately May through November. Volunteers monitor and care for the oyster gardens throughout the summer and early fall to promote successful growth of baby oysters (spat) recruited on the recycled shell. In the fall, GBF staff collect the oyster gardens and spread the shells and new oysters on nearby restoration reefs to enhance the local oyster population. The volunteers not only learn about the life cycle of the Eastern oyster and the importance of oyster reefs in the Galveston Bay ecosystem, they are also exposed to a variety of marine life that find shelter in the oyster gardens. Furthermore, oyster gardening volunteers have the opportunity to participate in citizen science through GBF's oyster recruitment studies.

II. SUMMARY OF 2021 VOLUNTEER OYSTER GARDENING

a) Oyster Garden Creation Events

In the summer of 2021, GBF hosted two Oyster Garden Creation Events. The first event was held in Tiki Island on June 19, 2021, followed by a second event in Bayou Vista on July 13, 2021 (Figures 1-2). Volunteers and staff worked together to build over 300 oyster gardens. At these events, volunteers were also educated on the oyster gardening process and oyster reef ecology. To accommodate additional volunteers in more remote communities, GBF staff delivered gardens to individual homes from July through early September. All volunteers were given the option of three garden types: bags, stringers, or cages. A total of 366 oyster gardens were suspended off piers, docks, and bulkheads at 89 bayfront homes in 2021 (Table 1).

Table 1: Oyster Garden Creation

Community	Volunteer Homes	Bags Deployed	Cages Deployed	Stringers Deployed	TOTAL Gardens Deployed
Bayou Vista	30	63	0	35	98
Beach City	1	2	0	2	4
Dickinson	1	2	0	0	2
Galveston	17	47	10	11	68
Hitchcock	6	17	0	18	35
San Leon	8	30	0	17	47
Tiki Island	26	55	17	40	112
TOTALS:	**89**	**216**	**27**	**123**	**366**

b) Oyster Garden Monitoring

Throughout the remainder of 2021, volunteers monitored their gardens for oyster recruitment. Volunteers were instructed to rinse their gardens weekly to help reduce biofouling and predation. Weekly maintenance also allowed volunteers to inspect their gardens for new oyster growth. GBF staff sent out maintenance and monitoring reminders via email and Facebook to help support the volunteers throughout the gardening season. Facebook posts and regular emails also provided an opportunity for questions and answers, further supporting volunteers in their gardening efforts.

To capture the volunteers' time committed to monitoring and maintaining their oyster gardens, GBF staff created an online form to allow volunteers to log their hours on a monthly basis. GBF staff sent out monthly reminders via email containing a link to the new form. While this new approach helped improve documentation of volunteer hours, only a small portion of the volunteers utilized the online form. Similarly, GBF staff developed an online form for entering oyster recruitment data. GBF originally planned to introduce this recruitment data form to volunteers in 2021. Due to staff changes mid-year and the added request for logging volunteers' hours, it was decided this additional form would be revisited in 2022.

c) Oyster Garden Collection

In the fall of 2021, GBF staff coordinated the collection of the oyster gardens through three community events. Two events were held at volunteers' homes in Tiki Island and Galveston on November 6, 2021. A third event was held at a volunteer's home in Bayou Vista on November 11, 2021. Volunteers delivered their gardens to these locations where GBF staff received the gardens, documented new oyster growth, and prepped the gardens for transport (Figures 3-6).

For those volunteers unable to attend a community event, GBF staff collected their gardens separately. In addition, a fourth collection event in San Leon was postponed until 2022 due to inclement weather and COVID restrictions. GBF staff collected Dickinson and San Leon volunteers' oyster gardens on January 28, 2022 and documented the oyster growth in each garden.

Thanks to the 92 dedicated volunteers who participated in oyster gardening in 2021, approximatley 16,524 oysters were recruited in the oyster gardens (Figures 7, 8, 9, 11). Please note, the total number of oysters documented in each garden includes both live and recently dead oysters to provide an estimate of overall recruitment (Table 2). These oysters were introduced onto restoration reefs in November 2021 and January 2022 under separate grant funding (Figures 12-13). Table 3 shows the total number of oysters and the total amount of oyster shell transplanted at each restoration site. Please note, GBF holds permits via the Texas Parks and Wildlife Department, Texas General Land Office, and U.S. Army Corps of Engineers to introduce oysters and shell into Galveston Bay and the respective sub-bay systems. These permits are available upon request.

Table 2: Oyster Garden Collection and Oyster Recruitment

Community	Gardens Collected	Oysters Recruited	Avg. # Oysters per Garden
Bayou Vista	92	278	3
Beach City	4	3	1
Dickinson	2	0	0
Galveston	66	2,424	37
Hitchcock	33	469	14
San Leon	47	330	7
Tiki Island	116	13,020	112
TOTALS:	**360**	**16,524**	**46**

Table 3: Oyster Introductions

Date of Introduction	CY of Shell Transplanted	Total Oysters Introduced	Source Location	Introduction Location	
				Bay/Sub-bay	***GBF Project***
11/06/21	0.81	13,142	Bayou Vista Galveston Hitchcock Tiki Island	West Galveston Bay	Sweetwater Lake Oyster Shell Breakwater (Sec. D)
11/11/21	0.40	2,555	Bayou Vista Hitchcock Tiki Island	West Galveston Bay	Sweetwater Lake Oyster Shell Breakwater (Sec. D)
11/28/21	0.04	140	San Leon	Central Galveston Bay	TPWD San Leon Reefs
11/30/21	0.10	494	Bayou Vista Galveston Tiki Island	West Galveston Bay	Sweetwater Lake Oyster Shell Breakwater (Sec. D)
12/10/21	0.02	3	Beach City	Trinity Bay	TBDC Living Shoreline
01/28/22	0.21	190	San Leon Dickinson	Dickinson Bay	Dickinson Bay Oyster Reef Restoration
	1.57 Cubic Yards	**16,524 Oysters**	**Please note, all oyster introductions were conducted under separate funding.*		

III. FINDINGS & LESSONS LEARNED

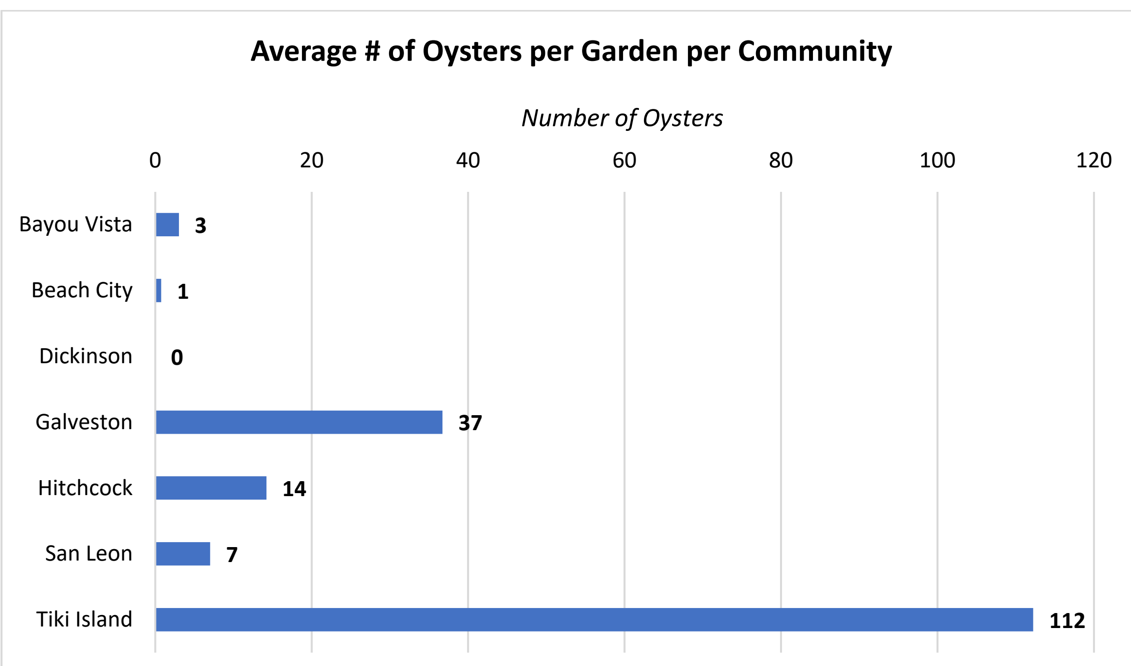
a) Community Assessment

In 2021, the West Bay communities documented the highest amount of oyster growth in their gardens while the central and north bay communities observed lower levels of oyster recruitment, similar to the 2020 oyster gardening season. Tiki Island led the way with an average of 112 oysters per garden and the Galveston oyster gardens contained an average of 37 oysters per garden. Hitchcock had slightly lower recruitment with an average of 14 oysters per garden. Bayou Vista experienced lower recruitment with an average of three oysters per garden (Chart 1). In Bayou Vista, the majority of oyster growth was observed along the marsh edge, off Blue Heron Street and along Highland Bayou, whereas the gardens within the canals were overgrown with barnacles and mussels (Figure 10). The highest amount of oyster recruitment was observed in the oyster gardens located along the West Bay side of the Tiki Island community which is directly adjacent to an intertidal reef complex.

The communities in central and northern Galveston Bay received realtively lower oyster recruitment. Two volunteers in this region attempted oyster gardening for the first time in 2021, specifically in Dickinson and Beach City. The oyster gardens in Dickinson were inhabitated solely by barnacles and hooked mussels. However, three oysters were documented within the Beach City gardens, which resutled in an average of one oyster per garden.

Compared to 2020, the San Leon oyster gardens had higher recruitment levels, sepficially in the canal community of Little Riveria, directly adjacent to Dickinson Bay. GBF staff documented 330 oysters in the San Leon gardens, which resulted in an average of seven oysters per garden. For all seven communites, an average of 46 oysters per garden was recorded.

Chart 1: Oyster Recruitment per Community



b) *Garden Type Assessment*

Since 2018, GBF has utilized three different garden types, bags, stringers, and cages (Figures 14-16), and has continued to assess the pros and cons of each. Oyster growth documentation in 2021 indicates cages had the highlest levels of oyster recruitment and oyster retention with an avearge of 109 oysters per cage. The bags and stringers had similar levels of oyster recruitment and retention with an average of 42 and 40 oysters per garden respectively (Chart 2). These results are consistent with observations made in 2020 (Chart 3), indicating the cages may be more effective in oyster recruitment and retention.

As suggested in the 2020 Annual Oyster Gardening Report, it is proposed that the larger openings in the cages provide more water flow than the bags, thus allowing oyster larvae to easliy enter the cages and come in contact with the shells. It appears the stringers have limited room for oyster larvae to attach as a result of the way the shells are stacked on the metal wire. The bags are difficult to rinse and often capture heavier loads of sediment, thus covering viable shell and potentially preventing larvae attachment. An additional benefit of the cages is their ability to be reused for at least one to two years whereas bags and stringers are single use only.

While these findings point to the cages as the most effective garden type, additional data is needed to confirm this conclusion. GBF plans to continue to offer all three garden types to volunteers for at least one to two additional years. In 2022, volutneers will be encouraged to document oyster recruitment throughout the season, rather than solely in the fall during the collection events.

Chart 2**:** Oyster Recruitment in Different Garden Types in 2021

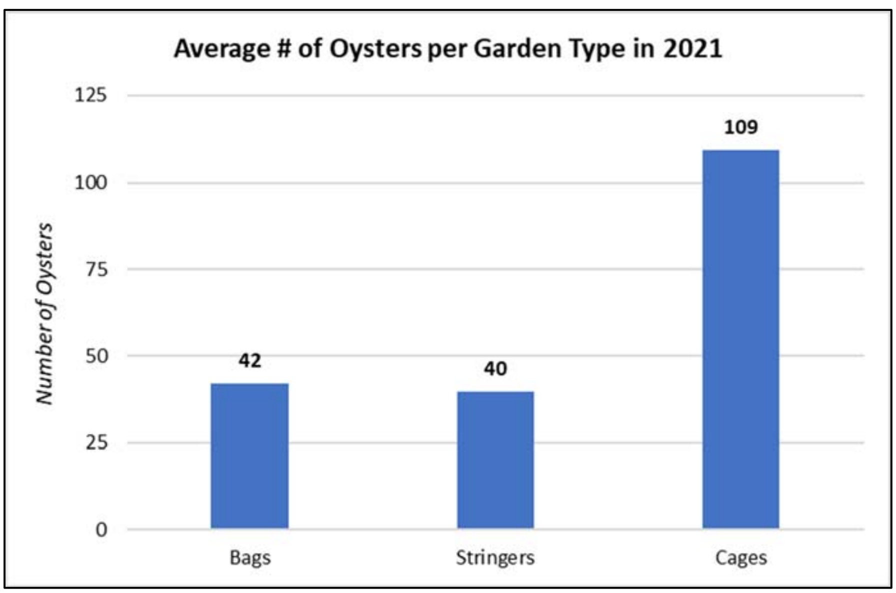
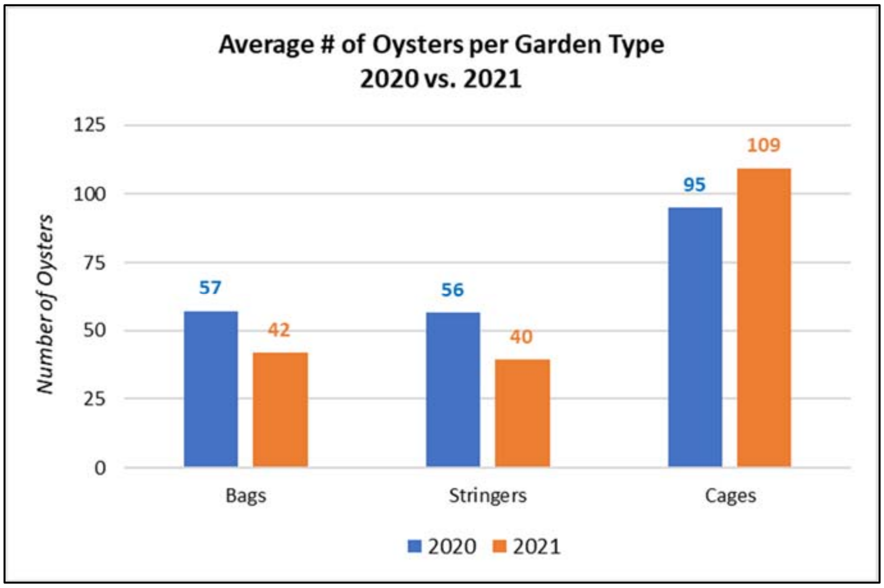


Chart 3: Oyster Recruitment in Different Garden Types 2020 vs. 2021



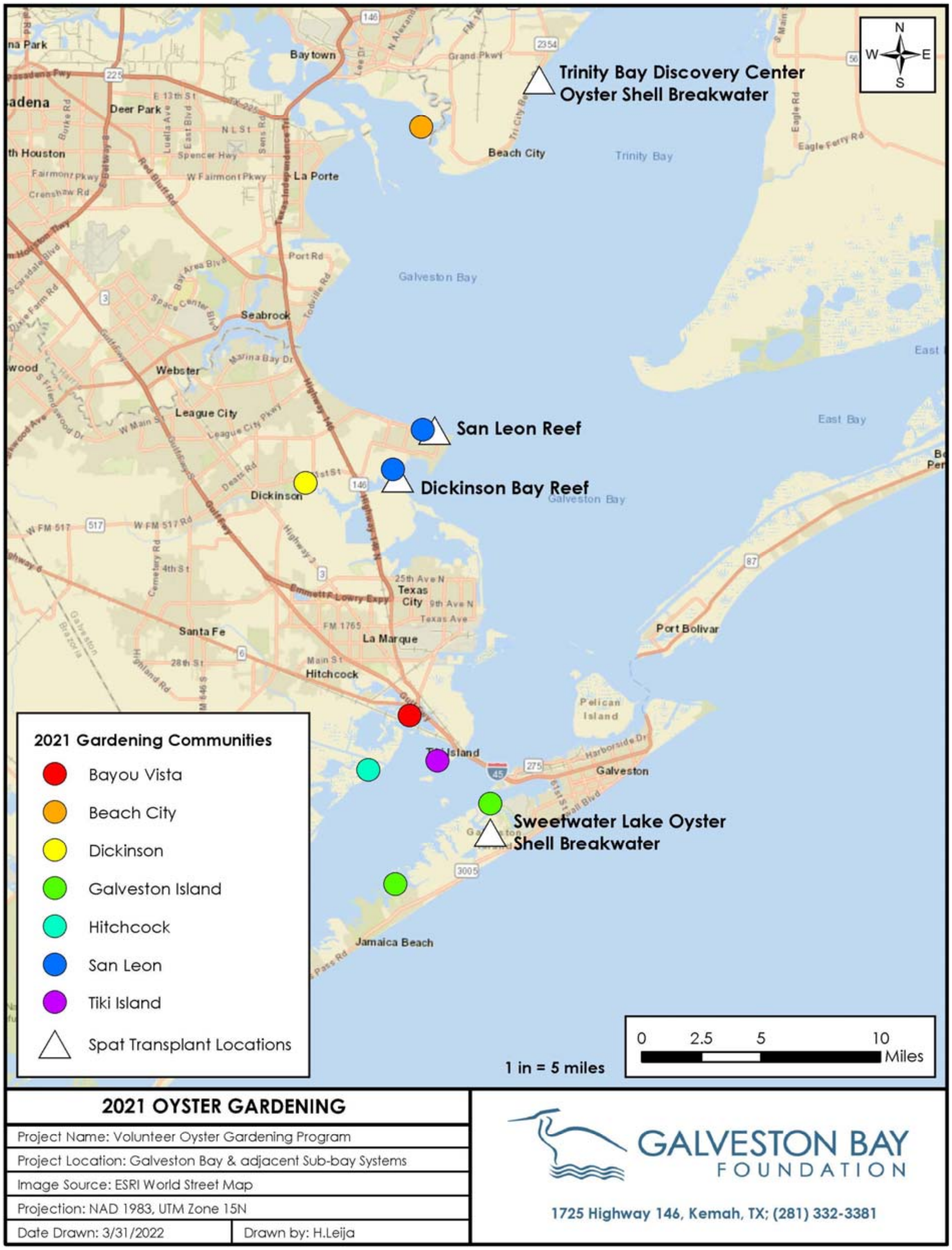
c) Considerations for Future Oyster Gardening

In an effort to streamline the Volunteer Oyster Gardening Program and reduce expenses, GBF staff plan to at least limit, if not eliminate, garden deliveries to individual volunteers. This option arose during the COIVD-19 pandemic when in-person events were not possible. However, it has proven costly and time consuming. It is recommended that volunteers who cannot attend community events pick up their gardens from GBF's office in Kemah. The office is central to all participating communities and an in-person, scheduled pick-up will provide an opportunity for the volunteers to meet with GBF staff and receive proper instructions.

To further improve the cost effectiveness of the Volunteer Oyster Gardening Program, GBF plans to limit the number of oyster gardens managed by each volunteer to a maximum of three. This will reduce the annual supply needs and allow the focus of the spring Garden Creation Events to be education. In addition, as the number of participating volunteers has increased, the time commitment for staff has risen dramatically, particularly in the fall when gardens are collected. Documentation of oyster growth in each individual garden is a time consuming process. Therefore, reducing the number of gardens per volunteer will reduce expenses associated with staff time while continuing to facilitate the collection of valuable data.

In 2021 it became evident the fall Garden Collection Events are the highlight of the program for many volunteers. They are able to see and understand the oyster recruitment and growth process as GBF staff help them assess their gardening results. However, it was observed that volunteers are disppointed, and less willing to participate in the future, if there are no oysters in their gardens. Therefore, GBF staff have begun educating volunteers on the importance of recycled oyster shell and reef habitat for additional organisms such as mussels, barnacels, and bryozoans, rather than just oysters. While these species need food and shelter too, GBF explains the purpose of oyster gardening is to give oysters a boost since their populations in Galveston Bay have suffered over the last decade. GBF staff plan to incorporate these lessons into the the spring events and throughout the entire gardening season to help retain volunteership and increase stewardship among the communities.

IV. PROJECT LOCATION MAP



V. PROJECT PHOTOGRAPHS

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Figure. 2. Volunteers building bag oyster gardens at Garden Creation Event (Summer 2021)

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Figure 14. Bag oyster garden

Figure 15. Stringer oyster garden

Figure 16. Cage oyster garden

APPENDIX C
Task 3 Deliverables

EDUCATION AND OUTREACH

Task 3
Photographs

Figure 1. New shell recycling dump truck at the Kemah Fourth of July Parade

Figure 2. Outreach booth for the Native American Heritage Day at Jesse H. Jones Park & Nature Center

Figure 3. Outreach booth for the Day By The Bay event at Topwater Grill

Thursday, January 20, 2022 • GalvNews.com 50 36 » A8 • $2

OBITUARY: Pioneering fashion journalist André Leon Talley dies at 73 » **B4**

GALVESTON COUNTY

The Daily News.

TEXAS' OLDEST NEWSPAPER • PUBLISHING SINCE 1842 • CELEBRATING 179 YEARS

ENVIRONMENT | OYSTER SHELLS RECLAMATION PROJECTS

Shell game

Nonprofit collects record oyster tonnage for bay projects

JENNIFER REYNOLDS/The Daily News

Kirsten Nichols, an oyster shell recycling assistant with the Galveston Bay Foundation, empties recycled oyster shells at the foundation's curing site in Pasadena on Friday. The Oyster Shell Recycling Program collected a record-setting 181 tons of shells in 2021.

By KERI HEATH
The Daily News

» KEMAH

The Galveston Bay Foundation last year collected more tons of oyster shells to use in reclamation projects than it has any year since the program began in 2011, a welcome change for the nonprofit after several years of less than stellar collections.

Despite the harsh effects of heavy rains and storms on Galveston Bay and reduced shell donations because of COVID, researchers are hopeful the

See SHELLS » A3

JENNIFER REYNOLDS/The Daily News

Kirsten Nichols, an oyster shell recycling assistant with the Galveston Bay Foundation, checks to see how full an oyster shell recycling bin is Friday at Tookie's Seafood in Seabrook.

GOVERNMENT | VOTING RIGHTS BILL

Voting bill blocked by GOP filibuster, Dems try rules change

By LISA MASCARO
Associated Press

» WASHINGTON

JOE BIDEN

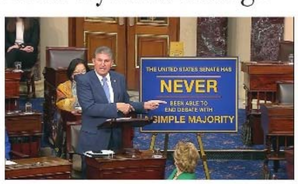
Voting legislation that Democrats and civil rights groups argued is vital for protecting democracy was blocked Wednesday by a Republican filibuster, a setback for President Joe Biden and his party after a raw, emotional debate.

Democrats were poised to immediately pivot to voting on a Senate rules change as a way to overcome the filibuster and approve the bill with a simple majority. But the rules change was also headed toward defeat, as Biden has been unable to persuade two holdout senators in his own party, Kyrsten Sinema of Arizona and Joe Manchin of West Virginia, to change the Senate procedures for this one bill.

"This is not just another routine day in the Senate, this is a moral moment," said Sen. Raphael Warnock, D-Ga.

The initial vote was 49-51, short of the 60 votes needed to advance over the filibuster. Senate Majority Leader Chuck Schumer, D-N.Y., voted no for procedural reasons so Democrats can revisit the legislation.

See VOTING BILL » A6



AP

Sen. Joe Manchin, D-W.Va., speaks on the floor of the U.S. Senate Wednesday at the U.S. Capitol in Washington.

ELECTIONS | MAIL-IN BALLOTS

After law changes, county rejecting some mail-in ballot apps

By JOHN WAYNE FERGUSON
The Daily News

» GALVESTON

DWIGHT SULLIVAN

The Galveston County Clerk's office has rejected dozens of requests for mail-in ballots for this year's primary election.

The county clerk's office said 37 of 168 ballots have been rejected in recent days because they lack information required under a new state law that legislators said was meant to improve election integrity.

There's less than a month left until the deadline for people who are qualified for a mail-in ballot to ask for one ahead of the primary election.

People whose ballot applications were rejected are being notified and given an opportunity to apply again, Galveston County Clerk Dwight Sullivan said.

The ballot rejections are mostly due to missing information on the applications, Sullivan said. Under a new law passed last year,

See BALLOT » A3

COMING FRIDAY

Looking for something to do this weekend? Be sure to check out Angela Wilson's Hot Ticket in Friday's entertainment section.

POLICE | STABBING DEATH

Woman charged in stabbing death called it self-defense, police say

By JOHN WAYNE FERGUSON
The Daily News

» LA MARQUE

KERRIEANNA VASQUEZ

A woman arrested earlier this month told police she stabbed a man in the chest during a struggle and assault inside a home on Tallow Drive.

Police doubted her story of self-defense and charged her with murder, according to arrest documents released to The Daily News.

Kerrieanna Vasquez, 20, of La Marque, was arrested and charged with murder on Jan. 2. She's accused of killing her boyfriend, Phillip Green, 22, of Galveston, inside her mother's home on a Sunday afternoon.

Vasquez was arrested hours after calling police to report the

See STABBING DEATH » A6

GOVERNMENT | GULF BREEZE DEVELOPMENT

Large Hitchcock housing development at 'stalemate' after tabled vote

By JOHN WAYNE FERGUSON
The Daily News

» HITCHCOCK

The developer of a housing development and the city were at loggerheads on Wednesday night, after the council chose to table a vote that would approve a plan that could add as many as 700 homes to the city.

City officials said there was simply more work to be done before they could give approvals to the development, known as Gulf Breeze, which is proposed to be built on 200 acres along FM 2004.

Randy Hall, the developer behind the project, asked for the council to meet and give approval to his development plan, he said.

Hall said he had been in talks with city officials about the project for 14 months and told The Daily News he could walk away from the project if the council didn't grant an approval.

Most of the council's discussion on Wednesday took place in a closed-door executive session. When they emerged, George Hyde, an attorney representing the city, spoke and said it was too early to recommend that the council approve a development plan.

First, the city must go through

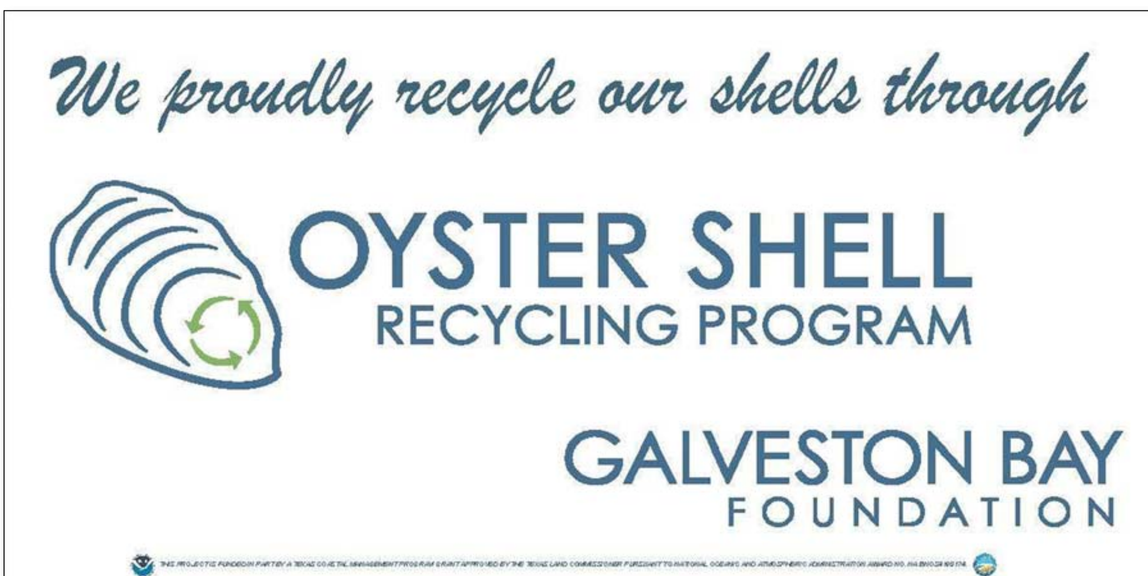
See DEVELOPMENT » A3

Vol. 179, No. 203

Figure 4. Front page of the Galveston County Daily News newspaper

Task 3
Oyster Shell Recycling Program Outreach Materials

Rack Cards



Window Clings

Trailer Sign

Task 3
All About Oysters Worksheet

Name: ____ Date: ____________

Part 1: Can You Out-Filter an Oyster?

Chosen filter materials:

-
-

Filter drawing:

Results:

1. What happened with your filter?

2. How did your filter do compare to the others?

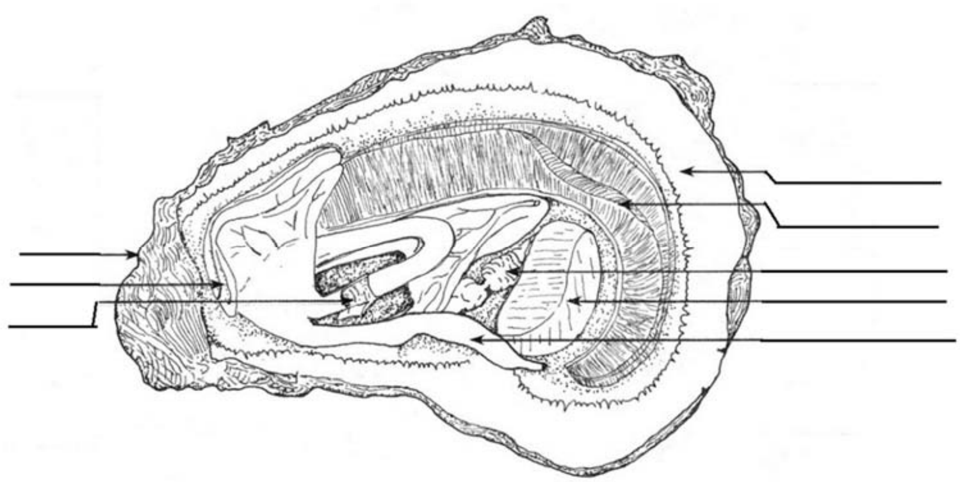
3. Did you out-filter an oyster? Why or why not?

Part 2: Oyster Anatomy

Label the oyster diagram with the correct body parts:

Body parts:

- Umbo
- Stomach
- Adductor Muscle
- Gills
- Anus
- Mouth
- Mantle
- Heart



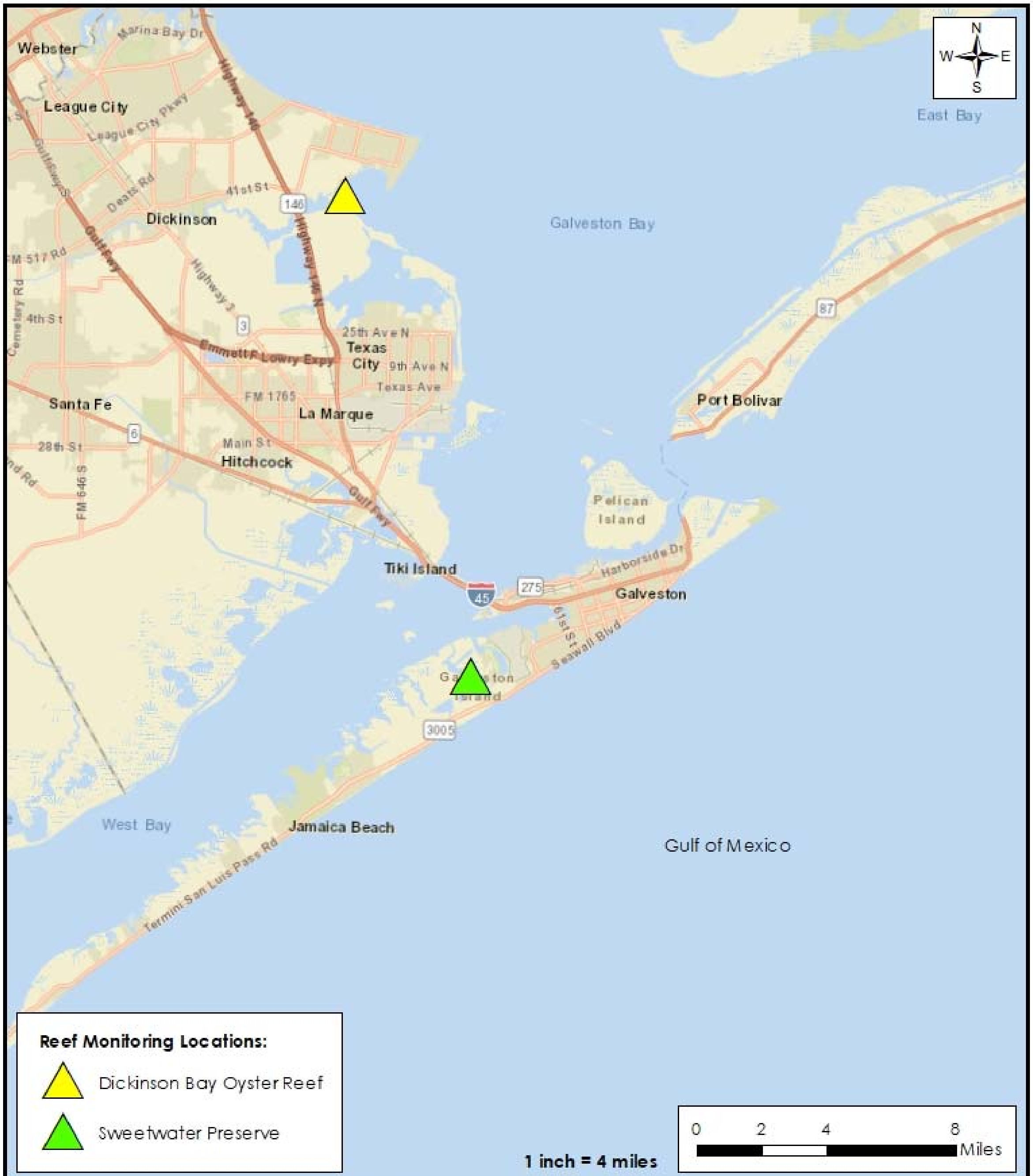
Part 3: Reflection

What is the importance of oysters to Galveston Bay? What are some ways you can help protect them?

APPENDIX D
Task 4 Deliverables

MONITORING OF RECYCLED SHELL-BASED REEF HABITAT

Task 4
Map of Reef Monitoring Sites



2021 OYSTER REEF MONITORING

Project Name: Volunteer Reef Monitoring Program	
Project Location: Chambers & Harris County, TX	
Image Source: ESRI World Street Map	
Projection: NAD 1983, UTM Zone 15N	
Date Drawn: 3/15/2022	Drawn by: H.Leija

GALVESTON BAY FOUNDATION

1725 Highway 146, Kemah, TX; (281) 332-3381

Task 4
Volunteer Monitoring Protocols and Guidance Documents

VOLUNTEER OYSTER REEF MONITORING INSTRUCTIONS

Location: Sweetwater Lake

Updated 5/1/2021

<u>Step 1</u>: Set up Monitoring Supplies on Shore

***Supplies needed**: 2 gray tubs, 3 buckets, trash bag, calipers, whiteboard + marker, hand towels, clipboard, mesh bag pieces*

- Under the shade structure, layout 2 gray tubs and 1 empty bucket to sort through each sample
- Fill 1 bucket with bay water
- Put trash bag in 1 bucket
- Set out calipers, whiteboard + marker, and hand towels
- Place a new datasheet on each clipboard
- Set out new mesh bag pieces

<u>Step 2</u>: Collect First Samples (Monitoring Bags)

***Supplies needed**: gloves, snips, 4+ buckets, laminated map*

- Wade out to the northern most sections
  - Slowly walk on the outside of the oyster shell breakwater in the water
  - You may also walk on land if preferred – please use road
- Collect all monitoring bags from **2 to 3 sections at a time**
  - Each monitoring bag will be marked by a PVC pipe
  - Each monitoring bag will have a tag with an ID
  - Refer to the map for bag locations and corresponding ID
- Use snips to detach monitoring bag from oyster shell breakwater *(each bag is secured with a zip tie)*
- Place 1-2 monitoring bags in each empty bucket
- Return to shade structure with samples

<u>Step 3:</u> Prep Sample for Analysis

Supplies needed: gloves, snips, 2 gray tubs, 1 bucket with bay water, trash bag

- Prep only 1 sample at a time
- Select a single monitoring bag for the first sample
- Remove the monitoring tag from bag with snips
  - Set tag aside on whiteboard to assist with photo ID
- Cut open the monitoring bag using a pair of snips
- Place entire contents of monitoring bag in 2 gray tubs
- Add water to each tub using a bucket
  - Any live crabs, shrimp, fish, etc. found in sample may be placed in bucket with water or returned directly to Sweetwater Lake
- Place old mesh in trash bag

<u>Step 4</u>: Analyze Sample

Supplies needed: gloves, calipers, clipboard, datasheets, pen/pencil, whiteboard + marker, hand towels, 2 gray tubs, 1 empty bucket, 1 bucket with bay water

- Analyze only 1 sample at a time
- For each sample, designate 1-3 observers and 1 recorder

  <u>Observer(s)</u> – measure and count all oysters and critters
    - Select live and recently dead oysters from gray tubs one at a time
    - Use calipers to measure the lengths of live and recently dead oysters
    - Call out the length measurement of each live and each dead oyster to the recorder in millimeters
    - Call out any mussels or other species observed
      (refer to "A Field Guide to: Galveston Bay Oyster Reefs")
    - Place all shell, live oysters, and dead oysters in the empty bucket
    - Place any live crabs, shrimp, fish, etc. in bucket with water

  <u>Recorder</u> – fill out datasheet
    - Complete the top three rows of the datasheet
    - Record all oyster lengths (live & dead) measured by observer(s)
    - Record number of mussels observed
    - Check off any other mobile species present
    - Upon completion of sample analysis, add the total LIVE and total DEAD oyster count at the top of the datasheet
    - Add any additional notes to bottom of datasheet
    - Take 1-3 pictures of live and dead oysters on the whiteboard

<u>Step 5:</u> Prepare Sample for Return

Supplies needed: gloves, 1 mesh bag piece, 1 zip tie

- Return all live crabs, shrimp, fish, etc. to the water
- Using a new piece of mesh, prepare a new monitoring bag
    - Tie a knot in one end and open up the other end
- Slowly pour the contents of both gray tubs (shells & oysters), now in a bucket, into the mesh bag
- Tie a knot at the end to seal the bag
- Using a zip tie, connect the monitoring ID tag to the bag

Repeat Steps 2-5 until all samples have been analyzed.

Keep complete monitoring bags in the shade or in a bucket of bay water.

Make sure ALL bags have a monitoring ID tag before returning them to the oyster shell breakwater.

<u>Step 6:</u> Return Sample

Supplies needed: gloves, monitoring bag, empty bucket, zip ties

- Place monitoring bag in empty bucket
- Wade out to the location where the monitoring bag was retrieved
    - Slowly walk on the outside of the oyster shell breakwater in the water
    - You may also walk on land if preferred – please use road
- Find PVC marker that correlates with the location of the monitoring bag
- Place bag on top of oyster shell breakwater, using 1-2 zip ties to secure it

Repeat Steps 2-6, collecting monitoring bags from 2 to 3 sections at a time for analysis, until all samples have been analyzed.

<u>Step 7</u>: Clean Up

- Rinse all buckets and gray tubs in Sweetwater Lake
    - Scrub with towels to remove any excess mud/debris
    - Set aside to dry
- Wipe down calipers, snips, whiteboard, pens/pencils, etc. with towels
- Place complete datasheets back in clipboards

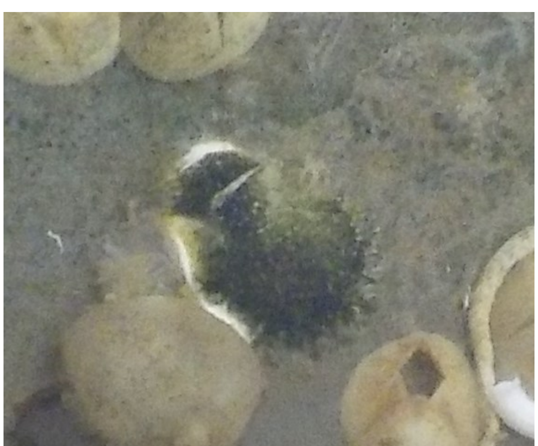
A Field Guide to:

Galveston Bay Oyster Reefs

BIVALVES

[oysters, mussels, clams]

Eastern oyster, *Crassostrea virginica*



Oyster spat, center

Eastern oyster, *Crassostrea virginica*

Description: *Crassostrea virginica,* the eastern oyster, has a rough grey or white exterior that may be cemented to rocks or other shells. The interior is white with a large purple or darkly colored muscle scar. Spat is often a dark gray-purple color, with only one valve visible.

Distribution/Habitat: Eastern oysters are found along the Gulf of Mexico and Atlantic coasts, from Mexico to Canada. Oyster larvae attach themselves to submerged objects like rocks, logs, man-made structures or the shells of other oysters and then develop into spat, juvenile oysters.

Natural History: Oysters can build large, complex reefs that provide us with many ecosystem services. Oysters feed by filtering phytoplankton, microscopic plant-like organisms, out of the water. One oyster can filter up to 50 gallons of water in a single day. Through filtration, they remove micro-organisms, nutrients, and sediment particles from the water. Filtration improves water quality and clarity.

Oysters create physical habitat by creating hard surfaces for other animals to live. Without oyster reefs, Galveston would have few natural hard structures since the bay is mostly covered in soft-sediment. These reefs provide a unique habitat for a wide variety of organisms like fish, barnacles, crabs, and other bivalves. Waves also break on them, reducing erosion and protecting the coastline in storms.

In addition to their ecological significance, oysters are a commercially important fishery.

BIVALVES

Hooked mussel, *Ischadium recurvum*

Hooked mussel, *Ischadium recurvum*

Description: The hooked mussel is brown or dark grey with prominent ribs radiating from the beak (the oldest and usually smallest point on a shell, close to the hinge). The interior of the shell is shiny, purple, pink or brown. This mussel gets its name from its triangular shape that curves or hooks to one side.

Distribution/Habitat: It is native throughout the Gulf of Mexico, north to the Chesapeake Bay. Hooked mussels attach to submerged objects like rocks, logs, oyster shells or man-made structures using byssal threads.

Natural History: Hooked mussels can form large groups on oyster reefs, and help create a matrix of habitat for other animals. They also are a food source for small fish and crabs. Like most bivalves, the hooked mussel feeds by filtering microscopic organisms from the water, their filtration can improve water quality in the bay.

Hooked mussels, *Ischadium recurvum*, growing on oysters

Dark false mussel, *Mytilopsis leucophaeata*

Dark false mussel, *Mytilopsis leucophaeta*

Description: *Mytilopsis leucophaeata,* also known as the dark false mussel or Conrad's false mussel, are small bivalves that are dark brown as adults and may be zebra-striped as juveniles. Their siphons can be golden/orange, with black speckles. They are related to, and look similar to the invasive Zebra mussel, but these native bivalves are important to a healthy bay ecosystem.

Distribution/Habitat: *Mytilopsis leucophaeata* is native from Mexico to Massachusetts, but invasive elsewhere in the world. These mussels are euryhaline, meaning they can live in a range of different salinities, and attach to submerged objects like rocks, logs, oyster shells or man-made structures using byssal threads, filaments a bivalve can excrete to cling to surfaces. On oyster reefs they are often found tucked into crevices, and beneath *Ischadium recurvum.*

A dense aggregation of *Mytilopsis leucophaeata*, with their siphons out.

Natural History: *Mytilopsis leucophaeata* can grow in dense aggregations, but populations can be ephemeral and unpredictable. Like most bivalves, *M. leucophaeata* feeds by filtering microscopic organisms from the water. Through filter feeding, they help clean the water. They are also a food source for small fish and crabs.

POLYCHAETES

[marine segmented worms]

Serpulid worms, *Ficopomatus miamiensis, F. enigmaticus* and *Hydroides dianthus*

Description: Serpulid worms form a calcium carbonate tube, have feathery appendages, and have a specialized operculum, an appendage used to seal the tube shut. The operculum shape is a key feature used to identify each species. *Ficopomatus miamiensis* has a smooth round operculum, *F. enigmaticus* has black spikes on the operculum, and *H. dianthus* has a 2-tiered crown shaped operculum.

Distribution/Habitat: Serpulid worms can tolerate a wide range of temperature and salinities. Serpulids grow on hard surfaces such as oysters, pilings, and rocks.

F. miamiensis is native in the Gulf of Mexico; *H. dianthus* is considered native in North America; *F. enigmaticus* is not considered native in the Gulf of Mexico, it is found globally, and its native range is debated.

Natural History: Serpulid worms feed by using their feathery appendages to filter particles out of the water. Populations of serpulids can be dense enough to form reefs.

Serpulid worm tube, under no magnification.

F. miamiensis, with rounded operculum. Viewed under a microscope.

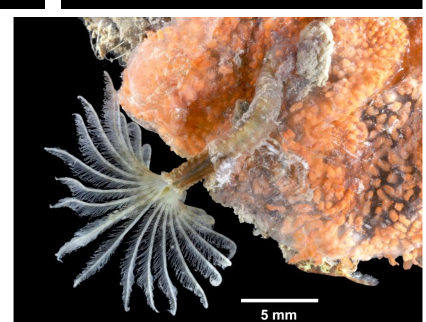
F. enigmaticus, with black spiked operculum. Viewed under a microscope.

H. dianthus, with 2 layered operculum showing. Viewed under a microscope.

Sabellid worms, *e.g. Parasabella microphthalma*

Description: Sabellid worms, or feather duster worms, are a tube worm similar to Serpulids. As their name suggests, they have feathery appendages, which are used for filter feeding. They differ from Serpulids in that they lack a specialized operculum, and their tubes are not calcified, but are soft.

Distribution/Habitat: A species commonly found on Galveston Bay oyster reefs is *Parasabella micropthalma.* This species is native to Galveston Bay.



Parasabella microphthalma.
E.A. Lazo-Wasem,
Wikimedia Commons.

POLYCHAETES

Two spionid worms in soft tubes attached to an oyster shell. Their 2 palps are visible. These are used for feeding. Viewed under magnification.

A spinoid worm, removed from its tube, viewed under magnification

Spionid worms, *Polydora sp.*

Description: Spionid worms also live in soft tubes, however they lack the feathery appendages of Sabellids. Instead, they have 2 long appendages, called palps. The palps are lined with cilia that carry food particles to their mouth. The worms are cream-pink in color.

Distribution/Habitat: Spionids are marine worms. The species in Galveston Bay inhabit hard substrates and muddy substrates.

Natural History: Spionids feed using their two long palps. The spionid worms found on the oyster reefs in Galveston Bay are in the genus *Polydora*. This genus includes the shell-boring "mud worm", *Polydora websteri*. This species can be detrimental to oyster health, and reduce the value of commercial oysters. As of now, we have not documented any concerning amount of these worms on the reefs in Galveston Bay.

Nereid worms, e.g. *Alitta succinea*

Description: Nereid worms are mobile predators. A common species on the reef is *Alitta succinea*, the pile worm. These worms can reach up to 6 inches long.

Natural History: *Alitta succinea* is notable for the swarms it produces when spawning. This phenomenon happens with the lunar cycle, and the worms metamorphose, modifying their appendages for swimming.

As predators on the oyster reef, Nereid worms feed on many of the sessile animals that colonize the surface of the oysters. These worms are also an important food source for birds, fish and crabs.

Nereid worm. Viewed through a microscope.

Nereid worm, with jaws everted. Viewed through a microscope.

CNIDARIANS

[hydroids, anemones, jellies, corals]

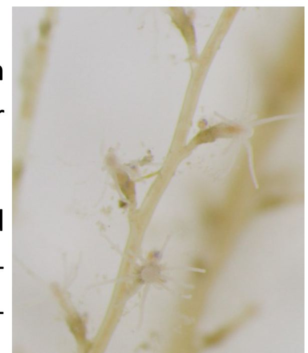
Hydroids, *Obelia sp.* and *Bougainvillia sp.*

Description: Hydroids are colonial animals with polyp and medusa life stages like corals and jellies. Polyps often occur on stalks and are the attached life stage that live on oyster reefs, while the medusae swim freely. The polyps are small, tentacled buds, growing on stalks. Species in the genera *Bougainvillia* and *Obelia* have been documented on oyster reefs in Galveston Bay. *Bougainvillia sp.* can grow quite large, with thick, golden stalks. *Obelia sp.* are a clear and small

Distribution/Habitat: The polyp stages of hydroids are found on hard substrates around Galveston Bay, including on oyster reefs.

Natural History: Hydroids often have two life stages, polyp and medusa. Polyp and medusae are predatory and feed on microscopic organisms in the water. Medusa stages are often jelly-like and free swimming.

A stalk of *Bougainvillia sp.*



Bougainvillia sp. **polyps viewed through a microscope.**

Obelia sp. **polyp, viewed through a microscope.**

Orange striped green anemone, *Diadumene lineata*

Description: *D. lineata* is a small anemone, typically <1.2”. It has many colorations ranging from a green or brown anemone with vertical green, orange, yellow or white stripes.

Distribution/Habitat: Non-native in the Gulf of Mexico. Originally from Japan, it is now widespread across the Pacific and Atlantic oceans. It likely was introduced to new locations through the transport of larvae in ballast water of boats. It can live in a range of salinity and temperature conditions.

Natural History: *D. lineata* can asexually reproduce through a process called longitudinal fission, where one anemone splits into two. It can quickly increase its population this way.

D. lineata**, a green color morph. Viewed through a microscope.**

A darker brown color morph of *D. lineata*.

A clear color morph of *D. lineata*. Viewed through a microscope.

BRYOZOANS

[colonial, “moss animals”]

Encrusting bryozoan, *Conopeum sp.*

Description: Encrusting bryozoans in the genus *Conopeum*, have calcified walls between zooids (individuals). Zooids are often rectangular to oval in shape. Each zooid has a set of feeding tentacles. Zooids may have orange or brown coloration from their diet, from diatoms or other organisms growing on their surface, or have coloration on their operculum, or “door”.

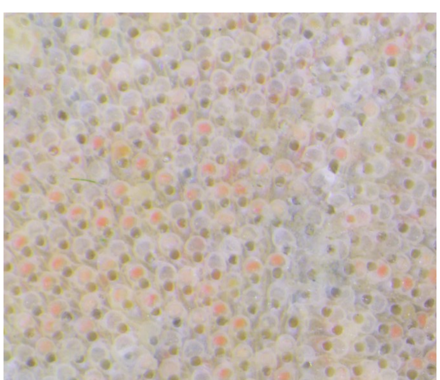
Distribution/Habitat: *Conopeum sp.* are found across a broad range of salinities, and occur on hard substrates, including oyster reefs in Galveston Bay.

Natural History: Bryozoans filter feed from the surrounding water, using their tentacle rings. They are a food source for small animals like snails, nudibranchs, fish, and crabs. Colonies grow outwards from a singular individual, called the ancestrula.

Conopeum sp. **colonies.**

Conopeum sp. **colony. Viewed under a microscope.**

Feeding tentacles of *Conopeum sp.* Viewed under a microscope.



Hippoporina indica**, some individuals have pink eggs present. Viewed under a microscope.**

Encrusting bryozoan, *Hippoporina indica*

Description: *Hippoporina indica* is an encrusting bryozoan, with calcified walls between zooids (individuals). Zooids are rounded-tear drop shaped. Zooids will appear pink when they are full of eggs.

Distribution/Habitat: It is non-native in the Gulf of Mexico. Considered native to India and China. It grows on hard substrates including oysters, docks, and buoys.

Natural History: Although *H. indica* is not native in the Gulf of Mexico, negative impacts of its presence have not been documented. Colonies grow outwards from a singular individual, called the ancestrula.

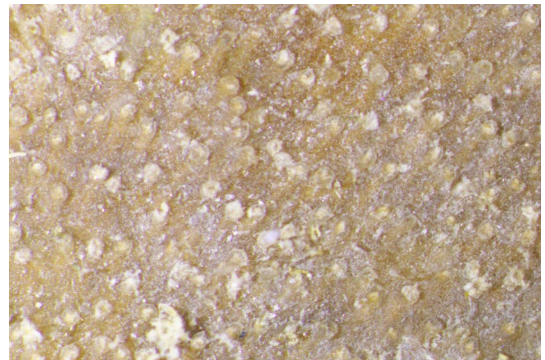
BRYOZOANS

Gelatinous bryozoan, *Alcyonidium sp.*

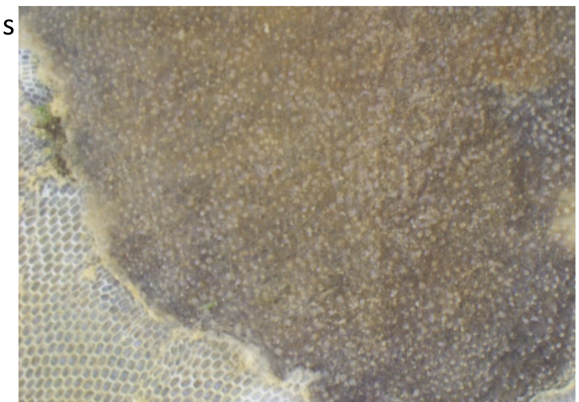
Description: Bryozoans in the genus *Alcyonidium* form an uncalcified gelatinous sheet across the surface of the substrate. The tentacle rings emerge out of small nubs on the surface of the bryozoan.

Distribution/Habitat: *Alcyonidium sp.* are found on hard substrates around Galveston Bay.

Natural History: Like other bryozoans, *Alcyonidium sp.* feeds from the surrounding water using its feeding tentacles.



Alcyonidium sp. **viewed under a microscope.**



Alcyonidium sp. **(top) and** ***Conopeum sp.*** **(bottom) colonies. Viewed under a microscope.**

Soft bryozoan, *Amathia imbricata*

Description: *Amathia imbricata* is colonial, like other bryozoans, however it lacks the calcification seen in the encrusting bryozoans, *Conopeum sp.* and *Hippoporina indica*. Individuals are soft brown tubes, connected by a stolon, and each individual has tentacles for feeding. Without magnification, it can be difficult to see, but is part of the soft brown matrix growing on the surface of hard substrates.

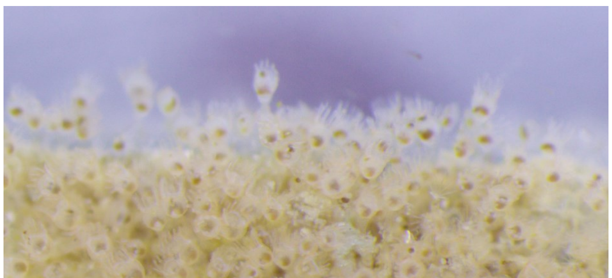
Distribution/Habitat: *A. imbricata* can be found growing on hard substrates around Galveston Bay, across a range of salinities. Available surface area may be a limiting factor in their abundance, for example, they may be out competed for space by encrusting bryozoans (*Conopeum sp.*).

Natural History: They are food for small grazers like nudibranchs and flatworms.

A soft bryozoan, growing on pieces of a barnacle. "Bowerbankia gracilis" by Marine Biodiversity Class is marked under CC0 1.0. https://creativecommons.org/publicdomain/zero/1.0/

KAMPTOZOANS

A colony of kamptozoans growing on an oyster shell. Viewed through a microscope.



A colony of kamptozoans, viewed through a microscope.

Kamptozoans, *Bartensia sp.*

Description: Kamptozoans, also called Entoprocts, are small, colonial animals. They are stalked, with a tentacle ringed cup on the end of the stalk. Without magnification, these are hard to see, but are often part of the soft, brown matrix growing on the surface of hard substrates.

Distribution/Habitat: Kamptozoans can be found growing on hard substrates around Galveston Bay, across a range of salinities. Available surface area may be a limiting factor in their abundance, for example, they may be out competed for space by encrusting bryozoans (*Conopeum sp.*).

Natural History: Kamptozoans feed by collecting food with the cilia on the ring of tentacles around their mouth. They are food for small grazers like nudibranchs and flatworms.

TUNICATES

[sea squirts, sea grapes]

Sea grape, *Molgula manhattensis*

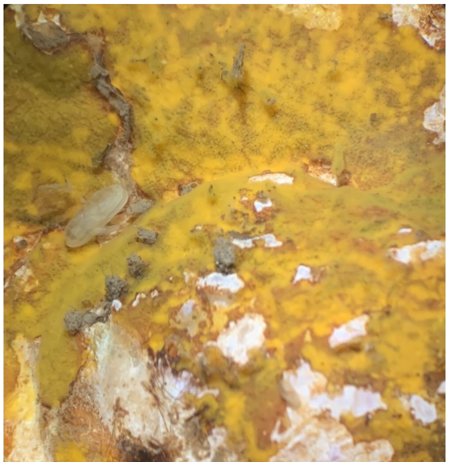
Description: Tunicates are soft bodied marine invertebrates. The native species of tunicate is *Molgula manhattensis*, or the sea grape. This is a relatively small tunicate, generally less 1 inch in size.

Distribution/Habitat: Native to the Gulf of Mexico. It grows on hard substrates in the bay, and is typically restricted to the higher salinity waters in the southern portions of the bay.

Natural History: It filter feeds by drawing water in through its incurrent siphon and filtering out the particles. The filtered water is expelled through its excurrent siphon.

Molgula manhattensis. Image by Decleer, Misjel (CCA 4.0 license)

SPONGES



Encrusting sponge growing on the surface of an oyster shell. Viewed under a microscope.

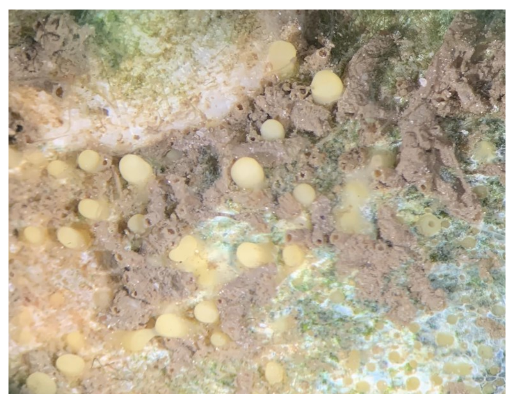
Encrusting sponge growing on the surface of an oyster shell.

Encrusting sponges

Description: Yellow, brown, and orange encrusting sponges are often observed on Galveston Bay oyster reefs.

Distribution/Habitat: Sponges are found on hard substrates throughout Galveston Bay, observed more frequently in higher salinity sites.

Natural History: Sponges are filter feeders. They often have chemical defenses or spines (spicules) to deter predators.



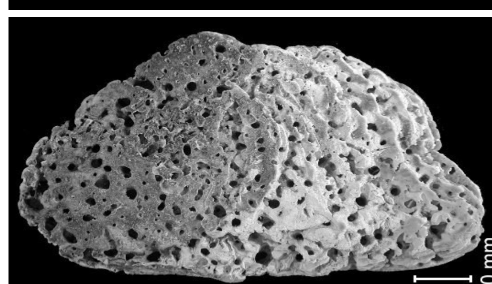
Cliona sp. growing on an oyster shell. Viewed under a microscope.

Boring sponge, *Cliona sp.*

Description: This sponge looks like small yellow-ish lumps protruding from the surface of an oyster shell.

Distribution/Habitat: This particular sponge lives on oyster shells, where it will bore channels into the shell and reside within them.

Natural History: As the name implies, the boring sponge will chemically etch tunnels and holes into oyster shells, and reside within these channels. If you have ever found a shell covered in small holes, it was likely from this sponge. Colonization by *Cliona sp.* may have negative effects on oysters, however research on this has been inconclusive.



An oyster shell with holes from the boring sponge, *Cliona sp.*
Tom Meijer, (Wikimedia Commons)

BARNACLES

Barnacles, *Amphibalanus sp.*

Evidence of predation on barnacles, the white circles are the base of the barnacles.

A barnacle, growing on an oyster shell.

Description: Barnacles are sessile marine crustaceans that build plated calcium carbonate domes. At least three species in the genus *Amphibalanus* occur within Galveston Bay, *A. ebernus, A. improvisis,* and *A. subalbidus*, but dissection is required for species identification. The outside of barnacles will often be colonized by bryozoans, kamptozoans, spionid worms, or sponges.

Distribution/Habitat: Barnacles are found in marine environments on hard substrates.

Natural History: Barnacles have a planktonic larvae, which settles onto hard substrates. Barnacles live within the calcareous plates, cemented to the substrate, and extend a feathery leg out the opening to feed. Barnacles are a food source for fish, crabs, and flatworms.

AMPHIPODS

Amphipods

Amphipod, viewed under a microscope.

Description: Amphipods are small shrimp-like crustaceans with laterally compressed body shapes. Most are very small and clear, white, or gray in color.

Distribution/Habitat: This diverse group can be found in most aquatic and marine environments. On oyster reefs they can be highly abundant.

Natural History: These small crustaceans are abundant invertebrates in marine ecosystems. On the oyster reef and other hard substrate communities, many build soft tubes, but are mobile in their search for food. Most are detritivores or scavengers. Amphipods are an important food source for fish.

Amphipod, viewed under a microscope

Amphipod, viewed under a microscope

CRABS

[mud crabs, stone crabs, blue crabs]

Flat-back mud crab, *Eurypanopeus depressus*

E. depressus, the flat-back mud crab.

Description: The flat-back mud crab is a small crab, no more than a half inch in width, with a mottled dark brown carapace, and unequal claw sizes. Claws have a white tip. Spines are present on the edge of the carapace.

Distribution/Habitat: Mud crabs are found throughout Galveston Bay, including on oyster reefs.

Natural History: These mud crabs are omnivorous and can feed on algae, detritus, and many of the small animals that live on the oyster reef. Mud crabs can be parasitized by a type of barnacle (*Loxothylacus panopaei*), that grows within their abdomen and functionally castrates males.

Oystershell mud crab, *Panopeus simpsoni*

P. simpsoni, showing the large tooth on the top portion of the major claw.

Description: *Panopeus simpsoni* is similar to *E. depressus*, but can be larger in size, up to 2-1/5 inches in carapace width. The distinguishing feature is the presence of a large tooth on the movable (top) major (larger) claw.

Distribution/Habitat: Mud crabs are found throughout Galveston Bay, including on oyster reefs.

Natural History: These mud crabs are omnivorous and can feed on algae, detritus, and many of the small animals that live on the oyster reef.

Major claw of *M. adina*, showing 2 prominent teeth on both the top and bottom finger.

Menippe adina, with a dark purple coloration.

Gulf stone crab, *Menippe adina*

Description: The gulf stone crab has a dark brown to purple carapace, with darker coloration on the tips of the claws. They are larger than *E. depressus* and *P. simpsoni*, growing up to 6” in length, and can be distinguished from these by the presence of 2 teeth on the major claw (one on the top and one on the bottom).

Distribution/Habitat: Stone crabs are found throughout Galveston Bay, including on oyster reefs.

Natural History: Stone crabs are predatory, and their strong claws can even break open oysters! Their claws will regenerate, which makes stone crab claws a sustainable seafood.

CRABS

Blue crab, *Callinectes sapidus*

Description: Blue crabs are a swimming crab, with the rear pair of legs modified for swimming. The carapace is wide with a sharp point on each side, called a lateral spine. The claws are skinny and sharply pointed. The claws and legs have a bluish tint. However, juveniles, which are commonly found on the oyster reef, may lack the blue coloration.

Distribution/Habitat: Blue crabs are widespread throughout the East Coast and Gulf of Mexico. Juveniles are especially found within the oyster reef due to the abundance of food.

Natural History: Blue crabs are omnivores, and will eat almost anything, but the oyster reef can provide them a feast of bivalves and worms! They are eaten by some fish, and are an important commercial fishery.

A juvenile blue crab, *C. sapidus*, note the rear swimming legs. This juvenile lacks blue coloration on the claws and legs.

PORCELAIN CRABS

Green porcelain crab, *Petrolisthes armatus*

Description: Porcelain crabs are not true crabs, rather, they are more closely related to hermit crabs, mole crabs, and squat lobsters. They look like true crabs in form, but are very flat, and have a flexible abdomen. They are fairly small (<1" carapace width), have large claws, and two long antennae.

Distribution/Habitat: *P. armatus* has a wide range, and its native range is uncertain. It is found throughout the Gulf of Mexico in intertidal habitats, like oyster reefs.

Natural History: *P. armatus* is quick to drop legs and claws when threatened. It can regenerate these appendages. The flattened shape allows them to fit into small crevices, such as the spaces between mussels and oysters. Porcelain crabs are filter feeders, and collect food particles from the surrounding water.

***P. armatus*, note the long antennae and large claws.**

SHRIMP

[snapping shrimp and grass shrimp]

Bigclaw snapping shrimp, *Alpheus heterochaelis*

***A. heterochaelis*, note the large (right) claw.**

Description: As indicated by the name, this shrimp has one disproportionately large claw.

Distribution/Habitat: This species is found in shallow water throughout the Gulf of Mexico.

Natural History: Snapping shrimp, also called pistol shrimp, use their large claw to produce a cavitation bubble to stun prey. This also creates a snapping sound that can be heard on the reef. There is evidence that the big claw snapping shrimp will live in burrows of mud crabs.

Grass shrimp, *Palaemonetes pugio* and *P. vulgaris*

Grass shrimp, *Palaemonetes sp.*, these shrimp are very small, each square is 0.5" x 0.5".

Description: Grass shrimp are small and clear. These two species are very similar, and both have teeth on their rostrum. However, *P. vulgaris* has a tooth near the tip of the rostrum, and *P. pugio* (the daggerblade grass shrimp) lacks this tooth.

Distribution/Habitat: Grass shrimp are common to estuarine waters in the Gulf of Mexico, often associated with aquatic vegetation, they are also found near the oyster reef.

Natural History: These shrimp are an important food source for carnivorous fish.

GASTROPODS

[snails, nudibranchs]

Oyster mosquito snail, *Boonea impressa*

Description: *Boonea impressa* is a tiny white snail, growing to only 3/10 of an inch. The shell has distinct whorls, and spiral ridges present.

Distribution/Habitat: *Boonea impressa* is an ectoparasite on eastern oysters. It can be found along the Atlantic Coast down through the Gulf of Mexico.

Natural History: As the name "oyster mosquito" may imply, *B. impressa* feeds on the body fluids of oysters. They can be found in large abundances on oysters.

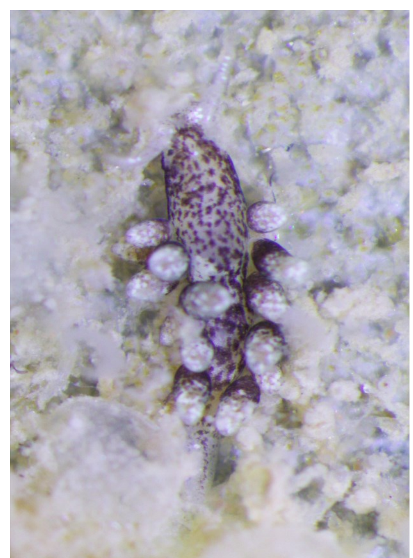
***Boonea impressa*, viewed under a microscope.**

Nudibranchs

Description: Nudibranchs are soft-bodied gastropod mollusks. The nudibranchs observed on Galveston Bay oyster reefs tend to be small or juvenile aeolids (unidentified species), with two sensory structures at the head (rhinopores), two oral tentacles, and dorsal cerata (appendages along their body that sequester defenses and aid in respiration).

Distribution/Habitat: Nudibranchs are widely distributed marine predators. They have been observed in Galveston Bay mostly at higher salinity locations.

Natural History: Nudibranchs are carnivorous and feed on the small organisms that grow on the surface of the oyster shells, such as bryozoans and hydroids.



A small nudibranch, viewed under a microscope.

FISH

[gobies, toadfish]

Gulf toadfish, *Opsanus beta*

Image credit: USGS.

Image credit: USGS.

Description: The Gulf toadfish is a small mottled grey and brown fish. It is well camouflaged along the oyster reef. It has a somewhat flattened body, suitable for life on the bottom. They have a wide mouth with small sharp teeth.

Distribution/Habitat: Native to the Gulf of Mexico benthos.

Natural History: Gulf toadfish are predatory, often ambushing prey from below. They can make sounds with their swim bladder, and a common sound is similar to that of a toad, giving the fish its common name.

Gobies, e.g. *Gobiosoma bosc*

Image credit: Georgia Department of Natural Resources (CC BY-NC-ND 2.0.).

Description: Gobies are small fish, with fused pelvic fins that form a sucker. This allows them to stick to rocks or other surfaces.

Distribution/Habitat: Gobies are a diverse group of fish, with members found around the world in various, often shallow, marine habitats. Locally, gobies have been found among the oyster reefs in Galveston Bay.

Natural History: Gobies eat small invertebrates, such as marine worms and amphipods. Most live in burrows, but some have been documented using empty oyster shells to lay their eggs in!

Task 4
Curriculum Summary for Undergraduate Course(s)

Service Learning Lab Lesson Plan: Sweetwater Reef Living Shoreline Oyster Monitoring

Learning objectives:

- Students will learn the purpose and basic design of living shoreline approaches in ecological restoration
- Students will get hands-on experience with ecological monitoring in the field, collecting real data that will actually be used by the restoration organization and landowner (Galveston Bay Foundation) to assess their restoration goals
- Students will develop skills in data analysis and interpretation of ecological data

Required materials:

- For the field trip: Field-suitable clothing and personal items (clothes that can get wet, closed-toed old sneakers or sturdy water shoes, hat/sunglasses, sunscreen, reusable water bottle, etc.).
- For the lab: Installed R and R studio on a laptop. Please see your TA at least a week in advance if you have no access to a laptop.

Assignment due by the start of lab time, week 1:

Read Piazza et al. 2005 and Scyphers et al. 2011 and answer the following questions in your notebook.

1. What are 3 new ideas or concepts you learned by reading these papers? Explain what was new or different and how the paper presented those ideas.
2. Based on your reading, what do you expect to see or find in the oyster reef at the field site? What species do you think will be most abundant?
3. What do you currently think are the biggest challenges to conducting living shoreline restoration?

Session 1: Field visit at Sweetwater Lake, week 1

Activities:

Oyster monitoring

1. Collect a monitoring bag from the reef and bring back to shore in a bucket/bin
2. Empty the contents of the bag into a bin or bucket and add seawater to keep shell covered
3. Remove oyster shell from the bin, tallying the oysters (*Crossostrea virginica*), hooked mussels (*Ischadium recurvum*) and false mussels (*Mytilopsis leucophaeata*) on the data sheet. Also measure all live and dead oysters with calipers and record those data.
4. Count and identify motile species (crabs, shrimp, fish) present to the lowest level possible based on their age and the field guide resources you are given. Slowly pour water out of bin over a sieve to collect these animals from the bottom of the bin and beware claws on larger mud and stone crabs!
5. Place shell back in the mesh bag and return to the reef; return any motile species to the water.

Environmental/site data

1. Measure salinity, temperature, and dissolved oxygen with the YSI
2. Measure height of the reef at sampling locations

End of lab assignments:

- Enter data in the google form
- Answer the following questions in your lab notebook (drawings are welcome too):
    1. Reflecting on your pre-trip expectations, what did you notice that was the same or different than you expected? Were there any species patterns that were different than you expected?
    2. Which ideas or concepts from the two papers you read did you observe in action today? Explain.

Session 2: Lab, week 2

Activities:

Data analysis

1. Students will download the full course's (all sections) available data to use in analysis
2. Using template R code, students will analyze make figures of the available data during the lab time

Discussion and Interpretation

1. Students will present and discuss their figures and findings in 2-3 small groups
2. The full lab section will compare findings, and discuss the topics below along with the assigned papers on oyster restoration and living shorelines

Discussion topics:

- Site considerations for living shoreline restoration (high vs low energy; transport of larvae; rate of subsidence; proximity to other habitats; salinity and water quality).
- How would you describe the physical features of the site at Sweetwater (wave energy, other physical stressors – like subsidence of the reef)?
- Discuss oyster and mussel data – are they recruiting to these sites?
- Do we consider mussel recruitment a positive outcome? Why or why not?
- Based on the assigned readings, what ideas or concepts did you see in action? What was similar to the projects described in the readings and what was different? Why do you think that is?
- What are the key findings from our data that could be of interest to Galveston Bay Foundation and others considering implementing these types of reefs for shoreline protection and/or habitat restoration?

The Potential for Created Oyster Shell Reefs as a Sustainable Shoreline Protection Strategy in Louisiana

Bryan P. Piazza,[1] Patrick D. Banks,[2] and Megan K. La Peyre[1,3]

Abstract

Coastal protection remains a global priority. Protection and maintenance of shoreline integrity is often a goal of many coastal protection programs. Typically, shorelines are protected by armoring them with hard, non-native, and nonsustainable materials such as limestone. This study investigated the potential shoreline protection role of created, three-dimensional Eastern oyster (*Crassostrea virginica*) shell reefs fringing eroding marsh shorelines in Louisiana. Experimental reefs (25 × 1.0 × 0.7 m; intertidal) were created in June 2002 at both high and low wave energy shorelines. Six 25-m study sites (three cultched and three control noncultched) were established at each shoreline in June 2002, for a total of 12 sites. Shoreline retreat was reduced in cultched low-energy shorelines as compared to the control low-energy shorelines (analysis of variance; $p < 0.001$) but was not significantly different between cultched and noncultched sites in high-energy environments. Spat set increased from 0.5 ± 0.1 spat/shell in July 2002 to a peak of 9.5 ± 0.4 spat/shell in October 2002. On average, oyster spat grew at a rate of 0.05 mm/day through the duration of the study. Recruitment and growth rates of oyster spat suggested potential reef sustainability over time. Small fringing reefs may be a useful tool in protecting shorelines in low-energy environments. However, their usefulness may be limited in high-energy environments.

Key words: ***Crassostrea virginica*, fish, Louisiana, oyster reefs, restoration, shoreline protection.**

Introduction

With global warming and rising sea levels, coastal protection remains a global priority. In many coastal areas, management objectives generally include maintenance of shoreline integrity and reduction of shoreline erosion (Yohe & Neumann 1997; Mimura & Nunn 1998; Klein et al. 2001). A common tool used to combat shoreline erosion involves armoring the land/water interface. Typically, this is done with materials such as limestone rock, metal sheet pile, and concrete mats (Hillyer et al. 1997). The soft sediment composition of many deltaic estuaries is such that heavy and dense materials often sink over time, requiring additional effort and funds for maintenance of breakwater structures (Zabawa et al. 1981; Brodtmann 1991). In areas not prone to strong storm or human-created wave energies (i.e., boat wakes), the planting of native marsh vegetation along shorelines has been used effectively for shoreline stabilization (Gleason et al. 1979). Vegetative plantings, however, also pose challenges to restoration or protection success because high erosive forces may overcome possible shoreline stabilization properties of the plantings (Williams 1993). Particularly in areas with soft sediments, such as are often found along the edges of many salt marshes, alternative approaches are needed.

The Eastern oyster (*Crassostrea virginica*; hereafter oyster) has been called an "ecosystem engineer" (Jones et al. 1994; Micheli & Peterson 1999) because its reefs provide many benefits to coastal and estuarine systems, including provision of habitat, water quality maintenance, and shoreline stabilization (e.g., Bahr & Lanier 1981; Newell 1988; Jones et al. 1994; Breitburg 1999; Coen et al. 1999*a*; Dame 1999; Mann 2000). In particular, oyster reefs are hypothesized to contribute to shoreline stabilization by providing coarse material to reduce wave and other erosive energies along eroding marsh and estuarine shorelines. Oyster reefs also may contribute to shoreline stabilization by producing a crystallizing cement of calcium carbonate (Harper 1997), which allows them to bond together and expand their reefs spatially in three-dimensional space. One study conducted in North Carolina intertidal marshes found that small fringes of oyster cultch resulted in lower marsh edge retreat at one of three sites tested and less retreat following a winter storm at a second site (Meyer et al. 1997).

In coastal Louisiana, protection of shorelines and existing marshes is a top priority (Louisiana Coastal Restoration and Conservation Task Force and the Wetlands Conservation and Restoration Authority 1998). Natural delta subsidence and sea level rise coupled with anthropogenic alteration of hydrologic flow regimes, severance of

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river flooding, and canal dredging have combined to create loss rates in Louisiana over 64 km^2/yr (Britsch & Dunbar 1993; Turner 1997; Barras et al. 2003). As coastal wetlands convert to open water, wetland shorelines become especially susceptible to erosion due to continuous erosive wind and wave forces. This fact has caused Louisiana's coastal restoration program to identify shoreline erosion as a significant coastal loss threat and focus on shoreline protection as one of its three major coastal restoration techniques (Louisiana Coastal Restoration and Conservation Task Force and the Wetlands Conservation and Restoration Authority 1998).

Along with its extensive marshes, Louisiana also contains an extensive oyster fishery, evidenced by the $30 million industry in 2002 supported by oyster beds (NOAA Fisheries, Annual Commercial Landings by Group 1950–2003). Although still a highly productive and viable industry, many of the fringing three-dimensional reefs historically found in Louisiana are gone due to increased saltwater and its accompanying predators and pathogens. To find optimum salinity conditions for oyster production, the fishery has moved steadily inland into areas that are subsiding and eroding rapidly. Cultivated oyster reefs now typical in Louisiana are two-dimensional cultched beds that are consistently reworked by a cycle of resource planting and harvesting. Restoration of three-dimensional living reef structures, in addition to benefiting the estuarine landscape, may provide critical shoreline habitat protection.

We examined the potential for created oyster shell reefs to be used as a natural shoreline protection tool in the soft sediments of coastal Louisiana by determining if small, created shell reefs protected adjacent shorelines. Specific to our study site, we also determined if the experimental reefs were potentially sustainable over the long-term.

Study Area

The study was conducted in Sister (Caillou) Lake in the Terrebonne basin, Terrebonne Parish, Louisiana. This area was selected as being a typical brackish marsh system along the Louisiana coast. Terrebonne basin is an area of high wetland loss (>2,500 ha/yr, Barras et al. 2003), mostly attributed to high (0.6–1.1 meters per century) subsidence rates (Gagliano 1998). Sister Lake is primarily an open water system, fringed by brackish marsh. Water depths in the lake range from 1 to 3 m. Freshwater inputs into Sister Lake are from precipitation run-off and drainage of fresher marshes to the north. Marine inputs result from lunar and wind tides. Dominant winds are typically from the southeast, except in the winter when northerly winds accompany cold fronts. Fetch distance is quite large, and wind-induced erosion is the dominant mechanism of shoreline loss in the lake. Tides range from −0.8 to 1.1 m National Geodetic Vertical Datum (NGVD; 0.3 ± 0.03 m NGVD, $\overline{X}$ ± SE). Marsh level in the area is 0.5 ± 0.1 (SE) m NGVD, and wind-induced flooding of the marsh surface occurs on an average 50% of days per year. Flooding frequency is highest in the summer months (June–September) and lowest during the winter months (December–February).

Mean (±SE) water temperature between 1985 and 2003 was 22.5 ± 0.1°C (range of 0.9–34.9°C; LDWF/USGS 07381349—Caillou Lake southwest of Dulac, LA, U.S.A.). Mean annual salinity between 1985 and 2003 in Sister Lake was 10.9 ± 0.1 ppt (range of 0.1–31.0 ppt; LDWF/USGS 07381349—Caillou Lake southwest of Dulac, LA, U.S.A.). This salinity is conducive to oyster recruitment and oyster spat growth and survival (Chatry et al. 1983; Perret & Chatry 1988). Sister Lake has served as one of the state public oyster seed reservations since 1940 and is managed by the Louisiana Department of Wildlife and Fisheries (LDWF).

Methods

Shoreline Selection

In April 2002, two 450-m study shorelines were selected in Sister Lake. Based on the direction of prevailing winds, one shoreline was located in a high wave energy environment and the other was located in a low wave energy environment. Each shoreline was located on a Digital Orthophoto Quarter Quadrangle image, divided into six equal (75 m) shoreline sections and numbered. One 25-m site was randomly located within each 75-m shoreline section and randomly assigned for reef placement (cultched) or no reef placement (noncultched). Adjacent sites were not selected. Six 25-m study sites (three cultched and three noncultched) were established at each shoreline, for a total of 12 sites. Each study site (cultched and noncultched) was delineated with 5 cm × 6–m PVC poles anchored in the sediment along the shoreline.

Experimental Reef Deployment

Experimental oyster shell reefs were deployed in June 2002. A total of 17.5 m^3 of shucked oyster shell (cultch material) was off-loaded at each cultched site, and an experimental reef (25 × 1.0 × 0.7 m) was constructed similar to Meyer et al. (1997). Reefs were built as close to the shoreline as possible. All reefs were placed within 5 m of the shoreline and were intertidal (Fig. 1). In-depth monitoring of the marsh, shorelines, and oyster shell reefs occurred monthly from June 2002 through June 2003.

Marsh Characterization

Water quality (salinity, temperature, dissolved oxygen), vegetation, and soils data were collected monthly to characterize the study site and detect any changes that may occur during the project period. Triplicate plots were established at each site within 5 m of the water–marsh interface for monthly measurement of percent vegetative cover and oxidation-reduction (redox) potential. Percent vegetative cover (by species) was assessed inside a 1-m^2 PVC quadrat (Pahl et al. 1997). Redox potential was measured monthly using a standard calomel electrode (Patrick et al. 1996).

Figure 1. Cultched shoreline created at Sister Lake, Louisiana, showing intertidal oyster reef (25 × 1.0 × 0.7 m). Each reef was created with 17.5 m^3 of shucked oyster shell.

Triplicate measurements were taken at each of the vegetation plots used for percent vegetative cover.

Quarterly evaluation (September 2002, December 2002, March 2003, June 2003) of aboveground vegetative biomass, belowground biomass, soil organic matter, and soil bulk density was conducted at randomly placed triplicate plots. To measure aboveground biomass, three randomly placed, 0.25-m^2 quadrats were cleared of all vegetation at the soil surface. Vegetation was returned to the lab where it was separated by species into live and dead stems, dried at 60°C for 48 hours, and weighed (0.001 g; Kuhn et al. 1999). Triplicate, random, 4 × 15–cm cores were collected for measurement of belowground biomass, soil organic matter, and soil bulk density. Belowground biomass was determined by sieving cores of mineral matter. Material remaining was dried at 60°C for 48 hours and then weighed (0.001 g). Percent soil organic matter was determined by loss on ignition in a muffle furnace (Cahoon & Turner 1989). Soil bulk density cores were divided into three 5-cm sections. Sections were dried at 60°C for 48 hours and then weighed (0.001 g). Bulk density was calculated as gram per cubic centimeter.

A survey of marsh elevation was conducted once in January 2003 at each shoreline with a survey transit and staff. Water quality data were obtained from a U.S. Geological Survey real-time data collection platform located between study shorelines (LDWF/USGS 07381349—Caillou Lake southwest of Dulac, LA, U.S.A.). Hourly data (June 2002–June 2003) were downloaded to calculate salinity, water temperature, stage, and flooding frequency and duration during the research project.

Shoreline Change

Shoreline advance or retreat was measured at each site using techniques similar to Meyer et al. (1997). Specifically, triplicate transects were established within each site with permanent base stakes (2 × 3–cm PVC) located in the marsh and in the water. A shoreline marker stake was placed at the shoreline edge. A tape measure was stretched level between base stakes and read at the shoreline marker. Baseline measurements of shoreline position were made at each site immediately after placement of the shell reefs, and transects were visited monthly, at which time shoreline markers were replaced. To ensure consistent measurements throughout the study, monthly shoreline position was measured by the same investigator. Shoreline edge was defined as the farthest waterward extent of the wetland macrophytes. Mean shoreline retreat rates were calculated at each site based on the triplicate measures and standardized to 28-day rates for analysis and interpretation.

Reef Sustainability

Triplicate, randomly selected, 0.06-m^2 shell samples were removed from each reef monthly. Oyster spat ($\leq$30 mm) on each shell were counted, measured, and categorized as live/dead (Supan 1983; Chatry et al. 1983). Mean number, size, and proportion of live versus dead oyster spat per shell were recorded monthly.

Statistical Analyses

Data were tested for normality with the Shapiro–Wilks test. When necessary, data were logarithmically transformed to achieve normality. Means of subsamples (triplicate measurements) were calculated for each sampling date per site and used for analysis. Analysis of variance (ANOVA; SAS, PROC GLM) was used to test, separately, for statistical differences in shoreline retreat, soil, and vegetation data between treatments (cultched vs.

noncultched) and wave energies (high and low). Comparison of least-square means was used, post-ANOVA, to detect significant differences ($p < 0.05$). Data are reported as mean ± SE unless indicated differently.

Results

Study Site Characteristics

Environmental characteristics during our study were typical of long-term (18 years) means. Mean (±SE) salinity was 9.4 ± 0.0 ppt (range of 0.1–24.0 ppt). Mean water temperature was 23.2 ± 0.1°C (range of 5.6–34.2°C). Tides averaged 0.4 ± 0.2 m NGVD (range of −0.2–1.4 m NGVD). On average, marshes were flooded 8.8 ± 1.1 hour/day. No significant differences were found between sites in temperature, salinity, or dissolved oxygen.

Marsh Site Characteristics

Vegetation percent cover, above- and belowground biomass were similar at all study sites (ANOVA; $p > 0.05$). Marsh areas in Sister Lake were dominated by Smooth cordgrass (38%; *Spartina alterniflora*), Saltgrass (27%; *Distichlis spicata*), and Black needlerush (27%; *Juncus romerianus*). Vegetation species found in lesser abundance included Salt meadow cordgrass (*Spartina patens*), Marsh elder (*Iva frutescens*), Saltmarsh morning-glory (*Ipomoea sagittata*), Saltwort (*Batis maritima*), Virginia glasswort (*Salicornia virginica*), and Black mangrove (*Avicennia germinans*). Aboveground vegetation averaged 76.1 ± 4.8 stems/m^2 and 75.4 ± 3.2 g/m^2. Belowground biomass averaged 6.6 ± 0.3 g/cm^3. Mean bulk density in the marsh soil was 0.44 ± 0.01 g/cm^3, and mean organic content was 21%. Soils were highly reduced ($E_H = -235 \pm 0.08$ mV).

Shoreline Change

For all sites, mean monthly retreat ranged from 0.03 to 0.15 m. Shoreline retreat differed significantly by treatment and energy over the 1-year time period of the study (Table 1). Mean shoreline retreat from June 2002 to June 2003 was significantly lower at cultched sites (ANOVA; $p = 0.007$, 0.08 ± 0.02 m/month) and at low-energy shorelines (ANOVA; $p < 0.001$, 0.06 ± 0.01 m/month) as compared to noncultched (0.12 ± 0.01 m/month) and high-energy shorelines (0.14 ± 0.01 m/month). Significant differences in shoreline retreat were found between cultched and noncultched treatments only for low-energy sites; however, significant differences were found by energy for both cultched and noncultched plots (Table 2). Highest shoreline erosion rates during any time period occurred between October and November following two significant storm events impacting the study site (Table 2).

Table 1. Results of ANOVA for differences in shoreline erosion rates by treatment and energy at Sister Lake, Louisiana, from June 2002 to June 2003 ($N = 12$).

Source	df	$\overline{X}$	F Value	p Value
Energy	1	0.018	42.73	<0.001
Treatment	1	0.005	13.23	0.007
Energy × treatment	1	0.0009	2.11	0.18

Reef Sustainability

A total of 30,527 oyster spat (≤30 mm) were counted on 6,044 sampled shells (4.9 ± 0.1 spat/shell). Recruitment of oysters began immediately upon creation of reefs in June 2002. Oysters began setting within 1 month of shell placement. Spat set averaged 0.5 ± 0.1 spat/shell ($N = 460$) in July 2002 and peaked in October 2002, with an average of 9.5 ± 0.4 spat/shell ($N = 542$; Fig. 2). No significant difference in oyster spat numbers was detected between low- and high-energy sites.

Oyster spat growth was positive throughout the year (Fig. 2). Spat averaged 3.4 ± 0.2 mm after 1 month (July 2002; $N = 579$) and 23.0 ± 0.4 mm ($N = 2,252$) after 1 year (June 2003). Maximum monthly mean spat size was observed in May 2003 (28.4 ± 0.3 mm; $N = 1,963$). On average, oyster spat grew at a rate of 0.05 mm/day. Smaller mean spat sizes in June and July 2002 corresponded with the spring spat set. No significant difference in oyster spat size was detected between low- and high-energy reefs.

Discussion

Shoreline Retreat

Shoreline retreat was reduced in cultched low-energy environments (Table 2) as compared to noncultched low-energy environments but was not significantly different between cultched and noncultched sites in high-energy environments or following two tropical storm systems (Table 2). These results suggest that small, created fringing reefs may be effective in low-energy environments with retreating shorelines but not in higher energy environments, including storm events. The lack of shoreline protection in the higher energy environment likely indicates that either (1) the small created reefs in this study were inadequate for the higher energy environment or (2) in high-energy environments (i.e., constant prevailing winds across a large, shallow, open fetch), fringing oyster shell reefs alone may not be a viable option to fully protect shorelines.

In a similar study completed in North Carolina, Meyer et al. (1997) found almost no differences between cultched and noncultched study sites over a 1.7-year period when created reefs were placed along created dredge material marshes. Shoreline change in that study resulted in an advance of 0.26 m for both cultched and noncultched treatments. This contrasts with our results, which show a mean overall shoreline retreat of 0.10 ± 0.01 m for both

Table 2. Mean monthly shoreline change (m) standardized into a 28-day rate.

Energy	Treatment	Shoreline Change (m) by Date: June 2002–July 2002	July 2002–August 2002	August 2002–September 2002	September 2002–October 2002	October 2002–November 2002	November 2002–December 2002	December 2002–January 2003	January 2003–February 2003	February 2003–March 2003	March 2003–April 2003	April 2003–May 2003	May 2003–June 2003	June 2003–July 2003
High energy	Cultch	0.04	−0.01	−0.20[b]	−0.16	−0.33	−0.17	−0.04	−0.02	−0.30	−0.15	−0.12	−0.09	−0.13[b]
	Noncultch	0.07[c]	−0.20	−0.45	−0.14	−0.30	−0.07	−0.09	−0.04	−0.11	−0.08	−0.22	−0.18	−0.15[c]
Low energy	Cultch	−0.42	0.17	0.17[b]	−0.09	−0.37	−0.02	0.00	0.03	−0.03	−0.10	0.15	−0.10	−0.03[a,b]
	Noncultch	−0.42[c]	0.07	−0.08	−0.03	−0.37	−0.04	−0.02	0.00	−0.05	−0.11	−0.16	−0.10	−0.09[a,c]

Positive values indicate marsh edge advance, and negative values indicate marsh edge retreat. Dashed borderline represents time period of two landfalling tropical storm system (TS Isidore and Hurricane Lili). Solid borderline represents time period of highest shoreline change rates.
[a] Significant difference between cultched and noncultched plots ($p < 0.05$).
[b] Significant difference between high- and low-energy sites for cultched plots ($p < 0.05$).
[c] Significant difference between high- and low-energy sites for noncultched plots ($p < 0.05$).

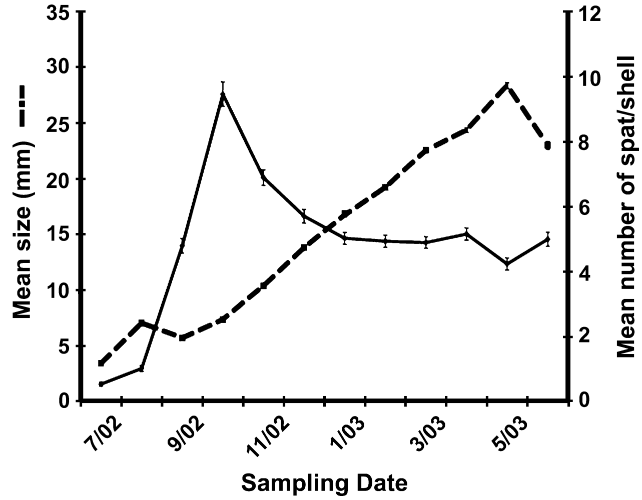

Figure 2. Mean (±SE) number and size of oyster spat per shell sampled monthly from experimental oyster reefs from June 2002 to June 2003 at Sister (Caillou) Lake, Louisiana.

cultched and noncultched treatments (cultch = 0.08 ± 0.02; noncultch = 0.12 ± 0.01), suggesting that these researchers were working in a very different environment compared to the eroding coastal marshes of Louisiana. Meyer et al. (1997) also found lower marsh edge retreat in cultched areas during the period in which a late-winter storm hit one of their sites (Harker's Island) in 1993. This also contrasts with our findings of higher shoreline retreat following two heavy tropical storm events.

Although our experimental reefs proved to be able to withstand strong tides and winds, the reefs did not appear to prove beneficial in protecting the shorelines following two landfalling tropical systems a week apart in 2002 (Table 2). The first system (TS Isidore) came ashore as a strong tropical storm and made landfall at Grand Isle, Louisiana (approximately 90 km east of Sister Lake), on 26 September 2002. Winds in that system exceeded 28 m/second, and the study area was affected by high winds. Sister Lake, located west of the system, was unaffected by the storm surge. Mean water level during the storm was 0.47 m NGVD. The second system (Hurricane Lili) came ashore as a category 2 (Saffir Simpson) hurricane and made landfall at Intracoastal City, Louisiana (approximately 110 km west of Sister Lake), on 3 October 2002. Sister Lake was located in the northeast quadrant of the landfalling hurricane and was affected by hurricane force winds and storm surge. Anemometers and water level gauges failed during the storm; however, maximum sustained winds during landfall exceeded 41 m/second, and storm surge was estimated at 3–4m NGVD at Cocodrie, Louisiana, just east of Sister Lake. Hurricane Lili did substantial damage to coastal infrastructure, docks, and residences in the Sister Lake area. Rapid elevation of wind and water level certainly produced very high wave energies and situations for transgressive movement of reef material. Our experimental reefs did not move or roll over after a direct hit by the storm.

Hurricanes have been responsible for massive shoreline erosion, particularly along barrier islands (Stone et al. 1997). In Louisiana, shoreline retreats of up to 30 m have been shown for the Chandeleur Islands during Hurricane Frederick (category 3) in 1979 (Kahn & Roberts 1982). Similarly, the Isles Dernieres underwent widespread breaching during Hurricane Juan (category 1) in 1985. Rapid water level increase associated with storm surge has been predicted to be the time for the most destruction (Halford 1995). Although our study did not take place on barrier islands, we expected to see some dramatic changes at our sites immediately following the two storms. Shoreline change during the month in which both storms passed over Louisiana was not outside the range of all other months, although (1) shoreline change for all treatments was highest in the month following the storm events (October 2002–November 2002; Table 2) and (2) the pattern was reversed with higher shoreline retreat at cultched sites as compared to noncultched sites during the month in which both storms passed over the study site (September 2002–October 2002; Table 2).

The high shoreline retreat rates following the storms may be due to the shoreline being made more susceptible to erosion or "softened up" by the passage of the extreme event. This phenomenon has been documented for shoreline bluffs in the Neuse River estuary, North Carolina, after passage of hurricanes Bertha and Fran (Phillips 1999).

The higher shoreline retreat at cultched sites during the time in which both storms passed over the area may be due to a combination of scour and water trapping behind the reef and may also explain the lack of significant difference between cultched and noncultched sites in the higher energy environment. During storm events our intertidal reefs were submerged. Submerged reefs cause waves to shoal and break, thereby dissipating part of their energy over the reef crest (Stauble & Tabar 2003). Water passing the ends of the reef structure is only partially slowed, causing a current that wraps around the end of the structure and an effect known as scour. In certain situations, this scour can cause accelerated erosion immediately behind the ends of structures such as seawalls, breakwaters, and reefs (Hughes & Schwichtenberg 1998). In a review of six installations of modular submerged, narrow-crested breakwaters, Stauble and Tabar (2003) found in all instances (1) evidence of scour at the landward edge of the breakwaters and (2) settlement of the breakwaters caused by toe scour and turbulence induced by trapped water interacting with waves. In two of the six cases where single-solid line reefs were employed, this interaction caused scour and erosion of the beach behind the structures. Larger reefs may prove less susceptible to the combined effects of scour and water trapping. Our experimental reefs were so short (25 m) that scour from both ends may have affected the entire length of shoreline behind them. Longer reefs may potentially provide a larger area protected from these effects.

Sustainability

Oysters in the northern Gulf of Mexico generally experience two spawning events (Supan 1983; Banks & Brown 2002); and thus, new individuals are readily available to recruit to existing reefs, contributing quickly to reef maintenance and sustainability. Oyster larvae are gregarious (Crisp 1967; Hidu 1969; Kennedy 1996), and water-borne chemicals from conspecifics are known to stimulate settlement (Hidu et al. 1978). This allows oyster reefs to maintain themselves as new recruits settle and grow. Oyster larvae quickly recruited to the created reefs and showed a general increase in mean size during the course of the experiment, indicating that reef maintenance was not likely to be a problem in this region. Created intertidal reefs in North Carolina, as measured by oyster cluster production, also proved to be self-sustaining because created reefs produced oyster clusters at levels equal or above that of adjacent natural reefs (Meyer & Townsend 2000). Sustainability is an important component to note because maintenance requirements would likely be reduced on created oyster shell reefs as opposed to other heavier shoreline protection structures (i.e., limestone rock breakwaters) that usually necessitate placement of additional material over time to maintain their effectiveness.

Although oyster reefs are often cited as providing valuable forage and shelter habitat for reef-associated fauna (Coen et al. 1999*b*; Glancy et al. 2003; Minello 1999; Posey et al. 1999; Plunket 2003), vegetated shoreline habitat (i.e., marsh edge) has also been shown to provide valuable nekton habitat (e.g., Baltz et al. 1993; Peterson & Turner 1994; Peterson et al. 2003), and a potential concern of artificial reef systems placed near shore is their impact on nekton habitat and use, including shoreline (flooded marsh) accessibility. Placement of our fringing created reefs did not significantly alter nekton shoreline use between clutched and noncultched sites (M. La Peyre, B. Piazza, and P. Banks, unpublished data), which may be due to the small reefs and/or the location of the created reefs (within 5 m of shoreline but not on the shoreline).

Practicality

Whole oyster shell is an ideal material with which to protect shorelines because the shell is native to coastal Louisiana, becomes tightly packed, and is lighter than traditional shoreline protection materials (i.e., limestone rock). The sustainability and continual growth and hardening of created oyster shell reefs should cause them to become more effective over time. Heavier shoreline armoring techniques, such as limestone rock breakwaters, are difficult to support in soft sediments and usually necessitate placement of additional material over time to maintain their effectiveness.

Although not an insurmountable problem, one issue to be resolved in using oyster shell as a shoreline protection tool lies in the difficulty in obtaining enough shell to properly fringe an eroding shoreline. Problems of low oyster shell supply and large spatial dispersion of shell sources may result in higher project costs, possibly making large-scale restoration projects cost prohibitive. This experiment used only 107 m^3 of shell material to construct each of the six experimental reefs, and far more shell material would be required to construct shoreline protection breakwaters for coastal restoration purposes. Although minimal amounts are used by the LDWF for cultch planting activities on the public oyster seed grounds (Dugas 1988), similar to other states (i.e., South Carolina), most shell is used in roadbed and parking lot construction poultry feed additive, or as discarded in landfills, or sold to out-of-state purchasers of oysters. In South Carolina, an experimental shell recycling program (South Carolina Oyster Restoration and Enhancement Program, 2005) is being used to return more shell to the coastal waters. Although a similar program is being investigated for Louisiana, no such program yet exists. Although oyster shell reefs may provide a self-sustaining shoreline protection tool for certain environments, the use of oyster shell reefs may not be a practical tool, until the issue of shell availability is resolved.

Conclusions

The establishment of fringing oyster shell reefs in coastal marsh environments is a particularly attractive shoreline stabilization method because it involves (1) the use of native materials; (2) the potential for sustainability and possible growth over long temporal scales; and (3) the added value of contributing to overall ecosystem stability and quality through its habitat creation and water quality functions. Because oyster reefs are common in many estuarine habitats, their use as a shoreline protection tool would be convenient and relatively cheap, if a steady supply of shell exists. Our results demonstrated that in low-energy environments, the creation of small fringing reefs may be useful in slowing shoreline erosion. Furthermore, the reefs were found to have high spat recruitment and growth, suggesting potential sustainability. In coastal Louisiana where oyster reefs are extensive and other hard materials such as limestone are virtually nonexistent in the coastal zone, the use of small, created, fringing oyster shell reefs has the potential to provide a useful shoreline stabilization tool to coastal managers under low-energy environments.

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PLoS one

Oyster Reefs as Natural Breakwaters Mitigate Shoreline Loss and Facilitate Fisheries

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Abstract

Shorelines at the interface of marine, estuarine and terrestrial biomes are among the most degraded and threatened habitats in the coastal zone because of their sensitivity to sea level rise, storms and increased human utilization. Previous efforts to protect shorelines have largely involved constructing bulkheads and seawalls which can detrimentally affect nearshore habitats. Recently, efforts have shifted towards "living shoreline" approaches that include biogenic breakwater reefs. Our study experimentally tested the efficacy of breakwater reefs constructed of oyster shell for protecting eroding coastal shorelines and their effect on nearshore fish and shellfish communities. Along two different stretches of eroding shoreline, we created replicated pairs of subtidal breakwater reefs and established unaltered reference areas as controls. At both sites we measured shoreline and bathymetric change and quantified oyster recruitment, fish and mobile macroinvertebrate abundances. Breakwater reef treatments mitigated shoreline retreat by more than 40% at one site, but overall vegetation retreat and erosion rates were high across all treatments and at both sites. Oyster settlement and subsequent survival were observed at both sites, with mean adult densities reaching more than eighty oysters m^{-2} at one site. We found the corridor between intertidal marsh and oyster reef breakwaters supported higher abundances and different communities of fishes than control plots without oyster reef habitat. Among the fishes and mobile invertebrates that appeared to be strongly enhanced were several economically-important species. Blue crabs (*Callinectes sapidus*) were the most clearly enhanced (+297%) by the presence of breakwater reefs, while red drum (*Sciaenops ocellatus*) (+108%), spotted seatrout (*Cynoscion nebulosus*) (+88%) and flounder (*Paralichthys* sp.) (+79%) also benefited. Although the vertical relief of the breakwater reefs was reduced over the course of our study and this compromised the shoreline protection capacity, the observed habitat value demonstrates ecological justification for future, more robust shoreline protection projects.

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Introduction

Nearshore, biogenic habitats of estuaries support a broad spectrum of marine life and serve as nursery grounds for economically-important fishes and shellfish [1–4]. Estuarine and vegetated nearshore habitats comprise only 0.7% of global biomes, yet the value of their ecosystem services has been estimated at $7.9 trillion dollars annually, or 23.7% of total global ecosystem services [5]. Nearshore ecosystem services include disturbance resistance, nutrient cycling, habitat, food production, and recreation. Unfortunately, coastal and estuarine shorelines are among the most degraded and threatened habitats in the world because of their sensitivity to sea level rise, storms and increased utilization by man [6,7]. Many previous efforts to protect shorelines have involved the introduction of hardened structures, such as seawalls, rocks or bulkheads to dampen or reflect wave energy [8–10]. Although such structures may adequately mitigate shoreline retreat, the ecological damages that result from their presence can be great [8,10,11]. The cumulative effects of habitat alteration and losses in the nearshore have had substantial economic and ecological consequences [12,13] and threaten the sustainability of many ecosystem services. Efforts to combat degradation and loss of nearshore, biogenic habitats have increased over the last decade [7,14,15]. Unfortunately, many shoreline protection approaches still value engineering over ecology in determining mitigation and restoration efficacy.

The "engineering first" approaches, including vertical bulkheads, concrete and granite rip-rap revetments and seawalls, are often used by coastal engineers because they are viewed as permanent and non-retreating structures. Unfortunately, insufficient concern may have been given to the ecological, aesthetic or socioeconomic impacts of these hardened structures. A major concern in implementing bulkheads and seawalls for coastal property protection is that erosive wave energies are reflected back into the water body, instead of being absorbed or dampened [10]. This subjects adjacent shorelines to even greater wave energy and can cause vertical erosion down the barrier with subsequent loss of intertidal habitats [10,16].

The benthic setting adjacent to many armored shores is generally absent of complex, structured habitats [16]. Most structurally complex, natural habitats are thought to function as nurseries for many finfish and shellfish species because of their elevated faunal densities, enhanced growth or survival rates, or higher contribution of individuals that emigrate offshore to adult habitats [1,4]. Biogenic, three-dimensional structure can reduce water velocities, increase sedimentation rates and enhance propagule settlement and retention, indirectly creating a more suitable environment for many species [17–20]. Despite the known lack of ecological benefits, shoreline hardening has continued to increase for decades primarily due to a lack of practical and ecologically valuable alternatives. However, a growing initiative for sustainable shoreline protection has focused on balancing effective protection and habitat creation by a variety of new methodologies collectively termed "living shorelines" [8].

Living shoreline projects often involve the planting or restoration of naturally-occurring biogenic habitats that have numerous ecological benefits, in addition to providing a buffer for wave action. In their natural setting, oyster reefs are often found seaward of salt marshes and can attenuate erosive wave energies, stabilize sediments and reduce marsh retreat, thereby making them an attractive living shoreline approach [19,21,22]. Beyond the targeted shoreline protection, living oyster reefs may provide many ecosystem services including seston filtration, benthic-pelagic coupling, refuge from predation and abundant prey resources [2,18]. Given adequate recruitment and survival, oyster reefs could be self-sustaining elements of coastal protection [21,22] that enhance other habitats of the natural landscape, although few studies have examined the premise of restoration through facilitation [17,23].

Located on the northern Gulf of Mexico, Mobile Bay is one of the best examples of a classic estuary [3] and, like many other coastal areas, is highly developed with a large and increasing proportion of its shorelines armored by bulkheads and seawalls [10] (Figure 1). At last analysis in 1997, Douglass and Pickel estimated that over 30% of the bay's available coastline was armored with over 10–20 acres of intertidal habitat lost, a high percentage in this microtidal bay (<0.5 m tidal amplitude). The historical armoring and marsh-edge losses have already had negative fisheries consequences, with projections of further reductions of blue crab harvest if armoring continues [24].

In this study, we experimentally examined the ecological effects of constructing subtidal breakwater oyster reefs for coastal and estuarine shoreline protection. In addition to documenting changes in the physical setting near breakwaters and unaltered control treatments, we quantified the habitat value for oysters, fishes and mobile invertebrates. We focus particular attention on the potential impacts on economically-important species, as this provides insight into the economic implications of different shoreline protection alternatives. We hypothesized that the addition of breakwater reefs of oyster shell would: 1) mitigate shoreline retreat, (2) provide substrate for recruitment and survival of oysters, (3) support higher densities of small fishes, mobile macro-invertebrates and larger and transient fishes and (4) promote higher species richness and a different community structure than unaltered control areas.

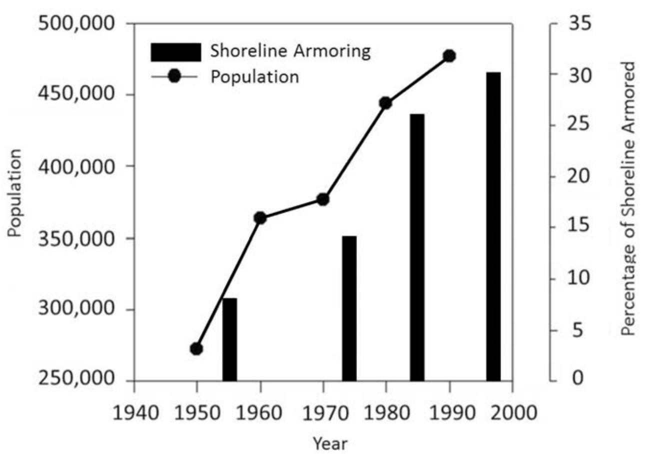

Figure 1. Population Growth and Shoreline Armoring in Mobile Bay, Alabama. Adapted with permission from Douglass and Pickel 1999, this figure depicts the rate and extent of shoreline armoring in Mobile Bay. The vertical bars in the main graph show the proportion of armoring while the line depicts the increasing population levels for Mobile and Baldwin Counties.
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Methods

Ethics Statement

This study was conducted in accordance with the laws of the State of Alabama and under IACUC protocols (Permit # 05047-FSH) approved by the University of South Alabama.

Study Setting and Site Selection

To determine the ecological and physical effects of created breakwater oyster reefs, we conducted a manipulative field experiment at two sites in coastal Alabama that contained stretches of rapidly eroding coastlines. Study sites were selected within regions known to have adequate larval supply of oysters [25] and moderate wave climates [26]. At each site, we constructed two breakwater reefs of loose oyster shell and designated non-restored plots as controls in a randomized, paired design (Figure 2). The first site, known locally as Point aux Pins, received breakwater reefs in May 2007. The treatments at Point aux Pins (site center point: 30.370098, −88.308578) were located along the southern extent of a peninsula of eroding salt marsh habitat, largely comprised of fringing cordgrass (*Spartina alterniflora*) and black needlerush (*Juncus roemerianus*). Remnants of oysters (*Crassostrea virginica*) are found throughout the marsh and buried in the subtidal sediments. The second site, Alabama Port (site center point: 30.347917, −88.121338), is located along the southwestern shore of Mobile Bay, just north of the Dauphin Island bridge. The treatments at Alabama Port were located along a two kilometer stretch of eroding shoreline that has been encroached by armoring at its northern and southern extents. Small patches of *Spartina alterniflora* can be found at Alabama Port, but the most abundant vegetation is *Phragmites* sp., which is largely present in the upper intertidal zone. Both sites were selected within regions of high oyster spat settlement (40–180 spat m^{-2} day^{-1}) [25].

Breakwater Reef Dimensions

The experimental oyster reefs were designed as subtidal wave-attenuating breakwaters, a common coastal engineering approach [8]. Each reef complex was comprised of three 5 m×25 m rectangular-trapezoid sections (Figure 3B). Each section consisted of loose oyster shell, purchased from a local seafood processing plant, placed on a geo-textile fabric to prevent subsidence and secured by a plastic mesh covering (with 1 cm^2 openings) that was anchored by rebar. The purpose of the mesh covering was to help maintain the vertical relief of breakwaters until adequate recruitment of oysters cemented the loose shell in place. The initial height of each reef was slightly above MLLW (~1 m), under the assumption that the loose oyster shell would settle below that level and eventually become subtidal. The subtidal design of the reefs allowed for maximum exposure for oyster settlement and increased available substrate for foraging by transient and larger

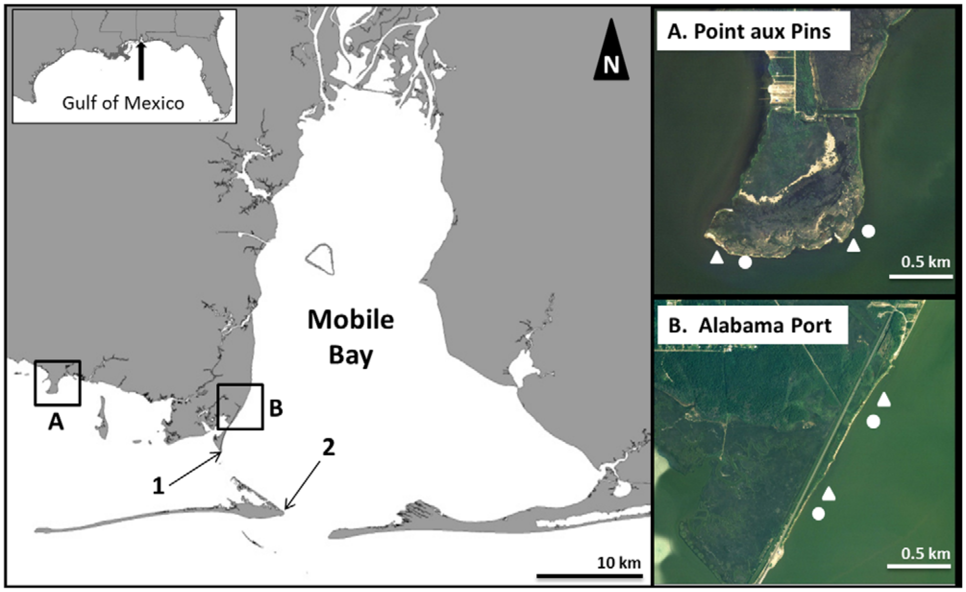

Figure 2. Map of Study Sites in Mobile Bay and Mississippi Sound, Alabama. White triangles represent breakwater reef complexes and white circles represent control treatments at the two restoration sites of (A) Point aux Pins and (B) Alabama Port. The locations of the (1) Cedar Point and (2) Dauphin Island hydrographic monitoring stations are denoted by the numbered arrows.
doi:10.1371/journal.pone.0022396.g002

resident fishes, while maximizing potential capacity for wave attenuation.

Hydrographic Environment

Mean surface water temperatures, recorded by electronic thermometer, and salinity, measured by a refractometer, were recorded during each sampling event. To observe longer term patterns in salinity, we utilized publicly available data recorded by hydrographic monitoring stations located at Cedar Point and Dauphin Island, AL. The Cedar Point station is approximately 17.5 km from Point aux Pins and 4.0 km from Alabama Port site center points. The Dauphin Island station is approximately 25.5 km from Point aux Pins and 11.0 km from Alabama Port site center points. The Cedar Point station has been active since 2008 and the Dauphin Island station since 2003. To consider the effects of wave climate and dominant wind direction and magnitude on our study setting, we reviewed historical and recently published coastal engineering studies [26,27].

Shoreline and Bathymetry Change

Vegetation retreat and changes in nearshore depth profiles were monitored to evaluate the effect of the breakwaters on the nearshore setting. Bathymetry surveys were conducted at both sites during preliminary site selection and yearly following construction at Point aux Pins. Bathymetric data was collected using a Ceeducer Pro DGPS system with an integrated depth sounder mounted to a 1 m×2 m platform on pontoons. We surveyed each site manually by walking the pontoon through multiple parallel transects of the reef and control treatments. At each reef treatment, the breakwater reef footprint was delineated using the Ceeducer DGPS to measure reef spreading and consequential reduction in reef height. The width of each reef section was also measured by transect tape at reef construction and the end of the study to measure changes in reef footprint. The data collected by the Ceeducer unit was imported in ESRI's ArcView, corrected for tidal amplitude, and maps depicting depth at mean low water (MLW) were created. To measure the shoreward retreat of emergent vegetation, permanent rebar stakes were installed at 25 m intervals along the 100 m stretch of shoreline at each replicate treatment. Each 6 m rebar stake was driven into the marsh edge so that 1 m remained visible. These shoreline stakes were installed shortly after breakwater construction at both Point aux Pins and Alabama Port and were monitored periodically thereafter. During each survey, marsh retreat was measured as the distance from the rebar stake to the living vegetation line. Mean differences between vegetation retreat rates adjacent to breakwaters and controls were analyzed by repeated-measures analysis of variance (ANOVA). Because of differences in reef creation dates and sampling period, Point aux Pins and Alabama Port were analyzed separately.

Oyster Recruitment

To assess the value of the breakwater reef complexes for oysters and other sessile invertebrates, we periodically collected quadrat samples. Oyster settlement, growth and survival were quantified using a 0.25 m^2 quadrat, which was haphazardly placed at three locations on each reef section ($n = 9$ per replicate reef). The exposed layer of shell within the quadrat was collected and placed in a large container. Juvenile (≤3 cm) and adult oysters (>3 cm) were enumerated and measured in the field, and then returned to the reef. Mortality was quantified by enumerating dead oysters, which had both valves still articulated and were absent of fouling organisms inside the shell. We sampled the breakwater reefs at Point aux Pins in July, August and November 2007, May and October 2008 and June 2009. We sampled the reefs at Alabama Port in March, June and October 2008 and June 2009. For the final sampling period of June 2009, six 0.25 m^2 quadrats were sampled from each section ($n = 18$ per replicate reef) to account for the reef spreading and to assure a similar proportion of reef surface area was sampled.

We used univariate one-way ANOVA to test for differences in densities of live juveniles, live adults and dead oysters among

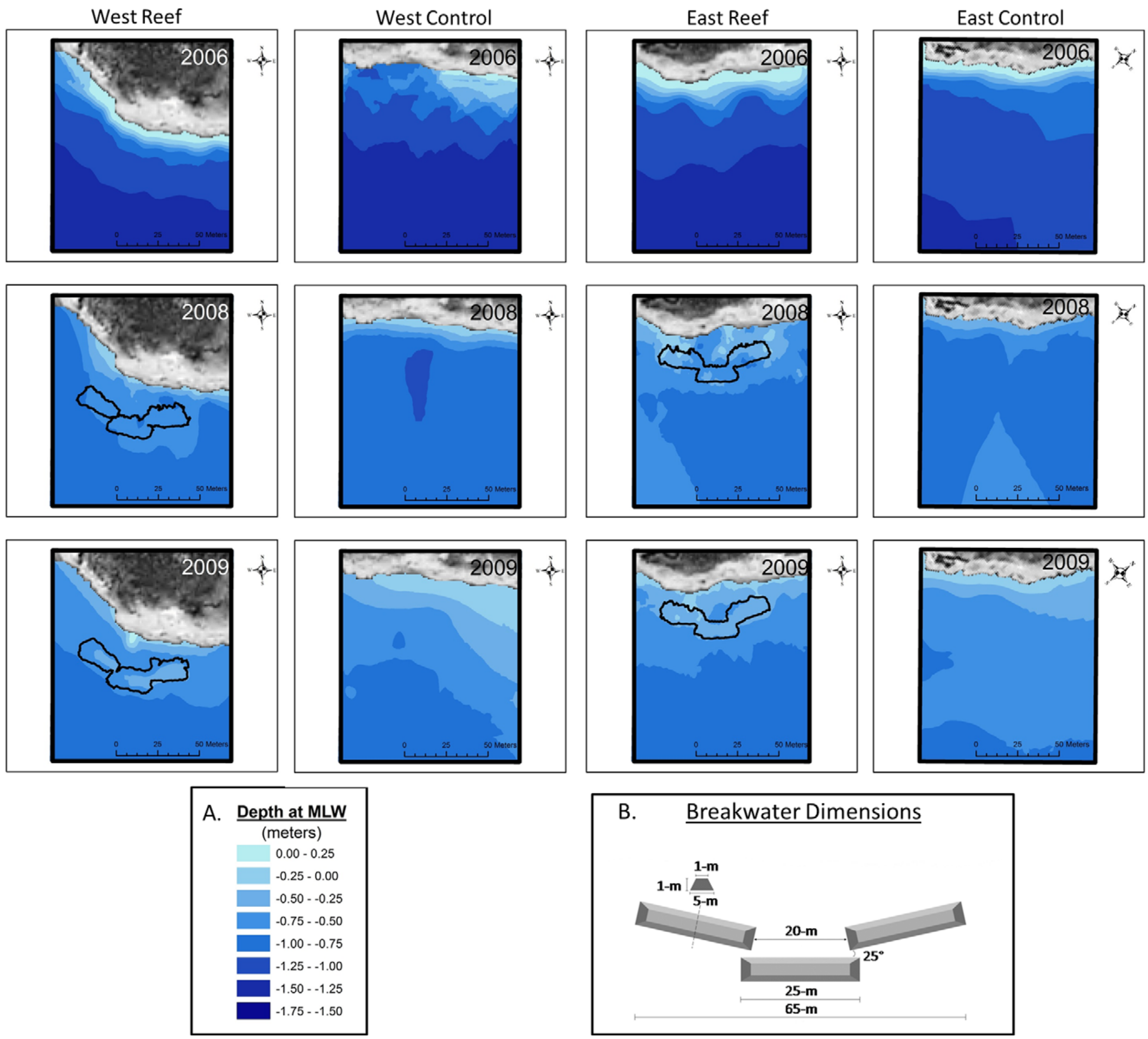

Figure 3. Bathymetry Plots from the Western Experimental Breakwater Reef and Control Treatments at Point aux Pins. The top row of 2006 plots was approximately one year prior to construction. The 2008 and 2009 plots are from one and two years post construction. Depth gradients are shown in inset (A). A schematic of the initial reef shape is depicted in (B). The crest width of each reef was approximately 1-m at MLLW.
doi:10.1371/journal.pone.0022396.g003

sampling events. Point aux Pins and Alabama Port recruitment data were analyzed separately because the independent variable of sampling date was different at each site. Density estimates determined by individual quadrat samples ($n = 3$ all, except $n = 6$ for June 2009) for each reef section were averaged. The pooled values from each of the three reef sections for each of the two replicated treatments were used as replicates in a one-factor ANOVA to test the effect of sampling date. These data were tested for normality using the Kolmogorov-Smirnov test and homogeneity of variances using Bartlett's test. To meet the assumptions of ANOVA, all values were log transformed and retested. After transformation, minor violations of normality and equal variances were still present for live adults and dead oysters at both sites. Because the violations from quadrat sampling are generally minor and ANOVA is considered robust to such violation [28], we proceeded with parametric ANOVA. When ANOVA results showed significant differences, we used Tukey's HSD post-hoc test for multiple comparisons.

Fishes and Mobile Invertebrates

The response of fishes and mobile invertebrates was measured using a combination of gear types to target small and large individuals. Experimental gillnets (2 m×30 m) were used to capture larger species and individuals of coastal finfish species. Sampling occurred twice each month for one year following construction and monthly thereafter through all seasons, but was reduced to every other month during winter. Gillnets were deployed on adjacent sides of each reef or control treatment and perpendicular to shore. Each net was comprised of two 15 m panels (5 cm and 10 cm maximum opening) to broaden the size range and body shape of animals captured. Gillnets were fished for two hours starting one hour prior to sunrise. During winter months, low tides prevented crepuscular sampling so nets were fished for two hours starting one hour prior to sunset. Gillnets were retrieved in the same order they were deployed, and soak time was recorded as the time from when the net was first deployed until the time retrieval began. All specimens captured were placed in labeled bags and returned to the lab where they were identified, measured and their biomass recorded.

To quantify smaller fishes and invertebrates, we seined adjacent to each breakwater reef and control monthly, except every other month during winter. At each treatment, a 6 m wide bag seine with 6.25 mm mesh was towed three times between the treatment and shore. All seine distances were 15 m and terminated into the shore at Point aux Pins or a 4 m wide block net at Alabama Port. All captured mobile invertebrates and fishes were placed in labeled bags and returned to the laboratory where they were identified to the lowest taxonomic level possible, measured and biomass recorded.

To determine the effects of site and treatment on the communities of fishes and invertebrates, we used multivariate and univariate analyses. Differences in community structure between reef and control treatments and between Alabama Port and Point aux Pins sites were tested for each gear type using permutational analysis of variance (PERMANOVA). Multivariate PERMANOVA used Bray-Curtis similarity matrices of log (x+1) transformed abundance data with 4,999 permutations [29]. Logarithmic transformations were applied to reduce the influence of overwhelmingly abundant species. For univariate analyses on gillnet data, PERMANOVA was used to test for site and treatment effects on the total abundance, species richness and abundance of demersal fishes in an approach similar to parametric ANOVA. Univariate PERMANOVA tests were run on Euclidean distances matrices with 4,999 permutations [30]. PERMANOVA was chosen for univariate analyses because it allows for two-factor designs, considers an interaction term and does not assume a normal distribution of errors. The environmental classifications of demersal, pelagic (including benthopelagic, pelagic, and pelagic-neritic) and reef-associated fishes were acquired from FISHBASE [31]. Seine data were analyzed identically to gillnet data analyses as previously stated with the addition of a response variable containing only decapod crustaceans. All multivariate tests and univariate PERMANVOA were run in the software package PRIMER-E v6 [32] with the PERMANOVA extension.

To determine the effects of breakwater reefs on the most common demersal fishes and decapods, we analyzed these taxa separately as they include many economically-important coastal species. We used Wilcoxon signed-rank tests to compare relative abundances of each species (≥1%) between the paired breakwater reef and mudflat control treatments. This approach allowed us to test for overall treatment effects, while controlling for date and site variability through the paired experimental design but ignored their interactive effects. Certain species that were closely related or difficult to distinguish were analyzed as grouped taxa (e.g. *Menidia* sp., *Paralichthys* sp.). For all tests, we considered results of $p \leq 0.05$ to be significant. The ANOVA and Wilcoxon tests were run using the R Statistical Platform Version 10.1.1 [33].

Results

Hydrographic Environment

At Point aux Pins, mean surface water temperature over all sampling events was 21.4°C (±10.1 SD) measured by digital thermometer, and salinity averaged 23.1 PSU (±8.7 SD) measured by refractometer. Mean water temperature at Alabama Port was 21.8°C (±7.8 SD) and salinity averaged 16.1 PSU (±7.4 SD). Salinity data, shown as box and whisker plots, was acquired from hydrographic monitoring stations at Cedar Point (Figure 4A) and Dauphin Island (Figure 4B) to further investigate the salinity regime over a longer time period. Cedar Point data shows 2008 to have the highest salinity regime of the 2008–2010 years (Figure 4A). The Dauphin Island station shows a similar pattern with 2007 and 2008 having higher salinities than all other years between 2003 and 2010. In addition to higher average salinity, the outliers representing the lowest salinity measurements in 2007 and 2008 are substantially higher the other recent years indicating fewer freshets.

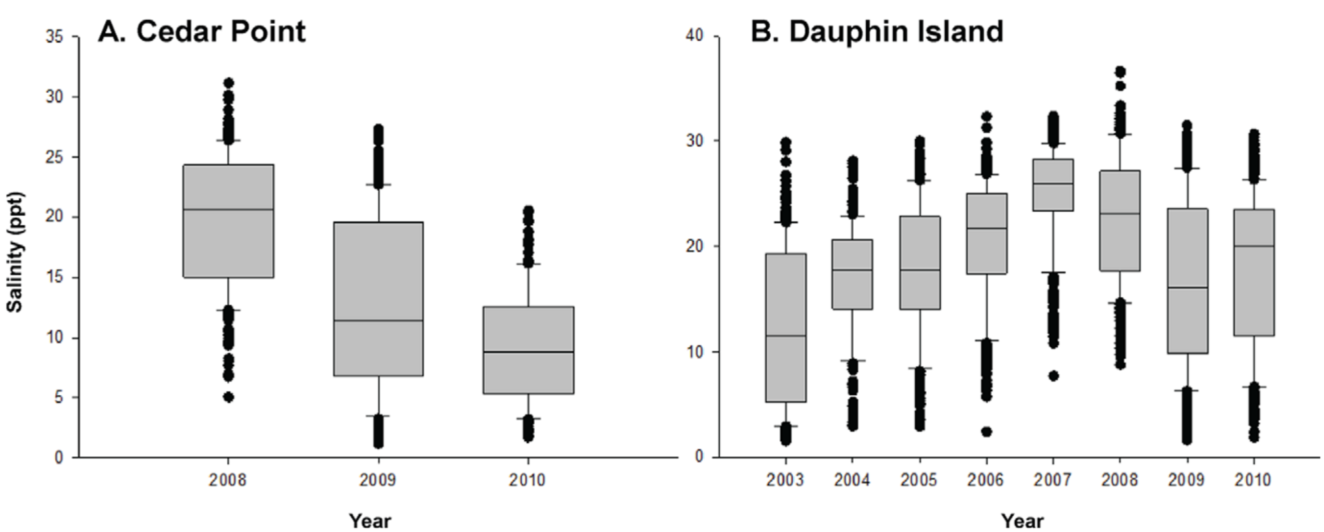

Figure 4. Salinity Ranges Recorded by Hydrographic Monitoring Stations in Coastal Alabama. Box and whisker plots of salinity data recorded by the hydrographic monitoring stations at (A) Cedar Point and (B) Dauphin Island. The Cedar Point Station has been active since 2008 and the Dauphin Island Station since 2003.
doi:10.1371/journal.pone.0022396.g004

Most wind-driven wave energies along coastal Alabama shorelines are generated by dominant south to southeasterly winds from spring through early fall and north-oriented winds from late fall throughout most of winter [26,27]. Fetch at Point aux Pins averages approximately 15 km with a longest fetch of 32 km. The erosion rate at this site has potentially increased in recent years after Hurricane Katrina opened a one mile gap termed "Katrina Cut" in Dauphin Island, a protective barrier island located due south of Point aux Pins. The wave climate near Alabama Port is strongly affected by prevalent southeast winds, as well as the wakes of ships utilizing the Mobile shipping channel less than ten kilometers to the East. At Alabama Port, average fetch is approximately 21 km with a longest fetch of 34 km. For more detailed discussion of wind and wave climates, erosion, sediment sizes, Keddy exposure values and Knutson et al.'s vegetation success scores, refer to Roland and Douglass (2005) [26].

Shoreline and Bathymetry Changes

Changes in the nearshore and shoreline environments of reef and control sites were observed from measuring vegetation retreat and bathymetric surveys. Bathymetric surveys at Point aux Pins found that, in addition to a general trend of decreasing depth, areas inshore of breakwater reefs appeared to gain more sediments than areas inshore of control plots (Figure 3). The footprint of East and West breakwaters expanded approximately 300% over the course of the study, and reef crest height was reduced from approximately 1 m to 0.3 m. The living vegetation line at Point aux Pins retreated nearly 6 m on average in slightly over two years (Figure 5A). Repeated measures ANOVA found no differences in the vegetation retreat rates between treatments, a strong effect of time and no interaction between the two factors (Table S1). At Alabama Port, breakwater reefs mitigated vegetation retreat by more than 40% over two years (Figure 5B). Repeated measures ANOVA found a marginally-significant treatment effect ($p = 0.089$) and a strong effect of time with no interaction (Table S1).

Oyster Recruitment

Point aux Pins reefs were constructed in May 2007 and first sampled for oyster recruitment the following July. Densities of juvenile oysters continually increased until peaking at greater than 700 oysters m^{-2} in November 2007, but were much lower the following year with ranges between 50 and 150 m^{-2} ($F_{5,30} = 28.15$, $p \leq 0.001$, Figure 6A). Adult oysters were found in highest densities during November 2007 and May 2008 sampling with approximately 35 oysters m^{-2} ($F_{5,30} = 38.29$, $p \leq 0.001$, Figure 6B). The highest mortality was observed during the October 2008 sampling event ($F_{5,30} = 22.492$, $p \leq 0.001$, Figure 6C) and 88% of measured dead oysters were juveniles (≤ 3 cm).

Alabama Port reefs were constructed in October 2007 and were first sampled in March 2008. Live juveniles densities at Alabama Port were between 70 and 140 m^{-2} in the last three sampling events and higher than the first sampling event in March 2008 ($F_{3,20} = 47.40$, $p \leq 0.001$, Figure 6D). Adult oysters were observed first and at a maximum in October 2008 ($\sim$75 oysters m^{-2}) and found in lower densities in June 2009 ($\sim$20 oysters m^{-2}) ($F_{3,20} = 18.82$, $p \leq 0.001$, Figure 6E), although October and June were not significantly different. The first and highest mortality ($\sim$70 oysters m^{-2}) was recorded in October 2008 ($F_{3,20} = 114.29$, $p \leq 0.001$, Figure 6F), and juvenile oysters accounted for 80% of the total dead.

Fishes and Mobile Invertebrates

Gillnet and seine sampling near breakwater reefs and controls captured a diverse assemblage of fishes and mobile macro-invertebrates. From the use of multiple gears, over 100 species of fish and invertebrates were collected during the 30 month sampling period. Gillnet sampling collected nearly 8,000 individuals of 45 different species in 5 cm mesh panels while larger 10 cm panels captured over 1,500 individuals of 44 different species. Seines captured 71,640 individuals that represented 88 species or grouped taxa. Demersal fishes appeared to be the most broadly enhanced by the oyster reef structure when the overall percent difference in CPUE between oyster reefs and mudflat controls was calculated across both sites and all sampling events (Table S2). The dominant pelagic and reef-associated species did not appear strongly affected by oyster reef presence. Of the twelve species that comprised at least 1% of the 5 cm gillnet catch, six were categorized as demersal species. Four of these six demersal taxa were more abundant on breakwater reefs than controls. Spotted seatrout were 38% more abundant near breakwater reefs, and displayed the strongest trend of enhancement among 5 cm captured fishes. Twenty species comprised at least one percent of the 10 cm gillnet catch, and eleven of these were demersal fishes. Fourteen of the twenty species were captured more often

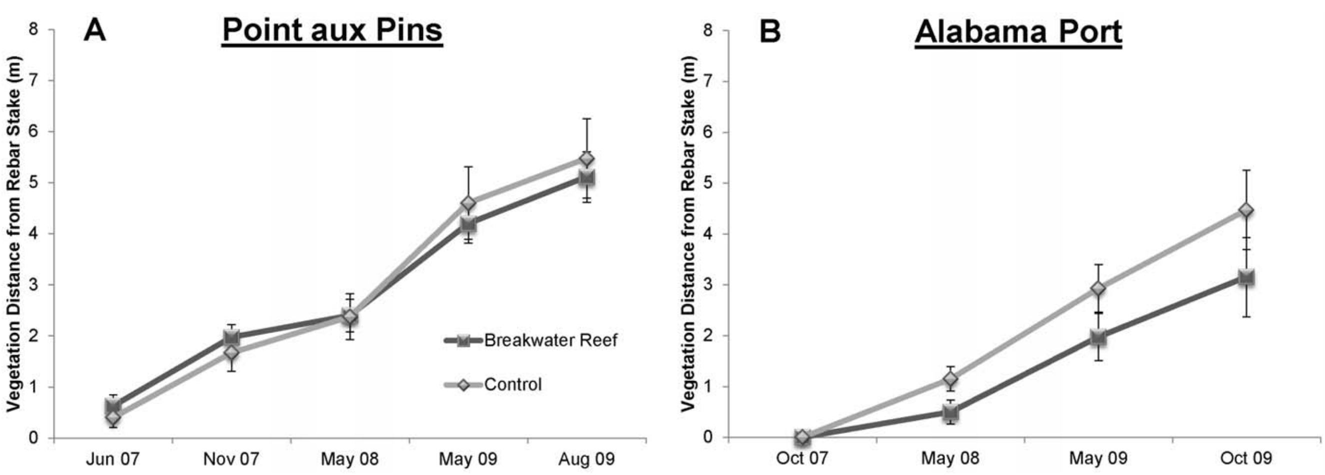

Figure 5. Shoreline Vegetation Retreat. Mean retreat (± SE) of living vegetation shoreward of each treatment at (A) Point aux Pins and (B) Alabama Port.
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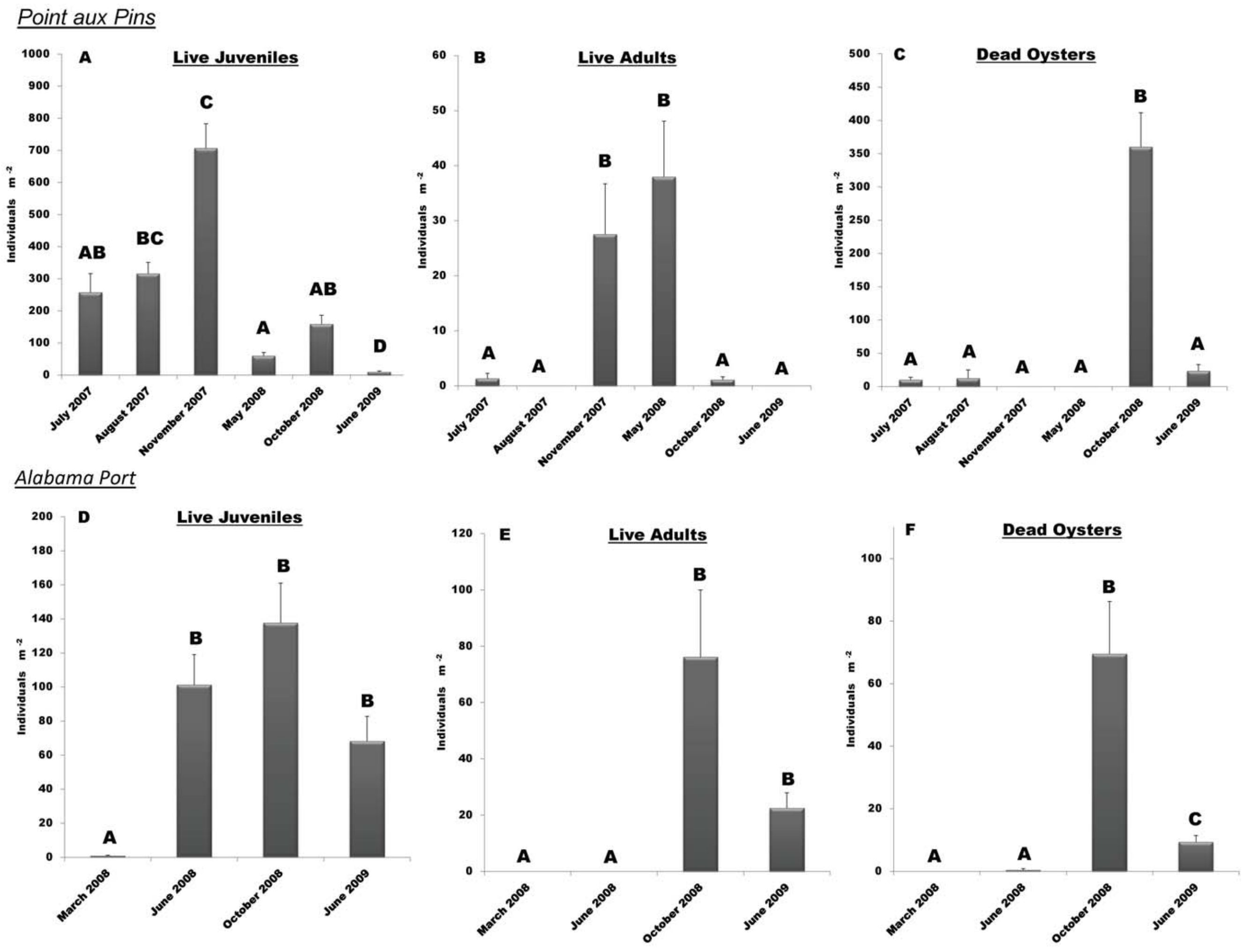

Figure 6. Oyster Recruitment and Survival. Mean oyster densities (+SE) of live juvenile, live adult and dead oysters at Point aux Pins (A–C) and Alabama Port (D–F). Different letters indicate statistical differences ($p<0.05$) from Tukey's HSD post-hoc tests.
doi:10.1371/journal.pone.0022396.g006

near breakwater reefs than controls. Nine species or grouped taxa comprised at least one percent of seine catches, seven of which were more frequently captured near breakwater reefs. Included in these seven were three demersal fishes and three decapod crustaceans.

We used multivariate PERMANOVA to test for differences in the community structure between breakwater reef and control treatments. PERMANOVA tests on 5 cm gillnet catches found that site and the site-treatment interaction were both significant factors (Table S3). There were no community-level differences between our breakwater and control treatments with 5 cm captured fishes. The communities of larger fishes captured by 10 cm gillnets differed significantly by site, treatment and the interaction of the two factors (Table S3). The community structure of smaller and juvenile fishes and mobile invertebrates captured by seines were different between sites and treatments, with no interaction between the two factors (Table S3).

We used univariate PERMANOVA tests on total abundance, species richness and demersal and decapod abundances to detect differences between breakwater reef and control treatments and between Alabama Port and Point aux Pins. For 5 cm total abundance, a significant interaction between site and treatment was observed (Table S4) because total abundance was higher near breakwaters at Point aux Pins but higher near controls at Alabama Port (Figure 7A). For 10 cm gillnet catch, total abundance was higher adjacent to oyster reefs than controls (Table S4). For both 10 cm and seine data, abundances were significantly higher at Point aux Pins than Alabama Port, and no interaction was observed between site and treatment (Table S4). The PERMANOVA tests on species richness found significant differences between sites across all gear types, between treatments only for 10 cm catches and no significant interactions (Table S4). For 10 cm catches, species richness was significantly higher near reefs than controls (Table S4) and higher at Point aux Pins than Alabama Port. Demersal fishes showed no differences between reef and mudflat treatments for 5-cm catches (Table S3), but again there was a significant interaction between site and treatment(Figure 7B). For 10 cm, demersal fishes were more abundant near breakwater oyster reefs (Figure 8A) and higher at Point aux Pins. From seine catches, demersal fish abundance showed no differences, but decapod crustacean abundance was higher near reefs than mudflat controls (Table S4 and Figure 8B).

The relative abundance of each demersal fish and decapod species ($\geq$1%) between breakwater and control treatments was tested using paired Wilcoxon signed-rank tests. For 5 cm gillnet samples, six demersal species contributed $\geq$1% of the total catch

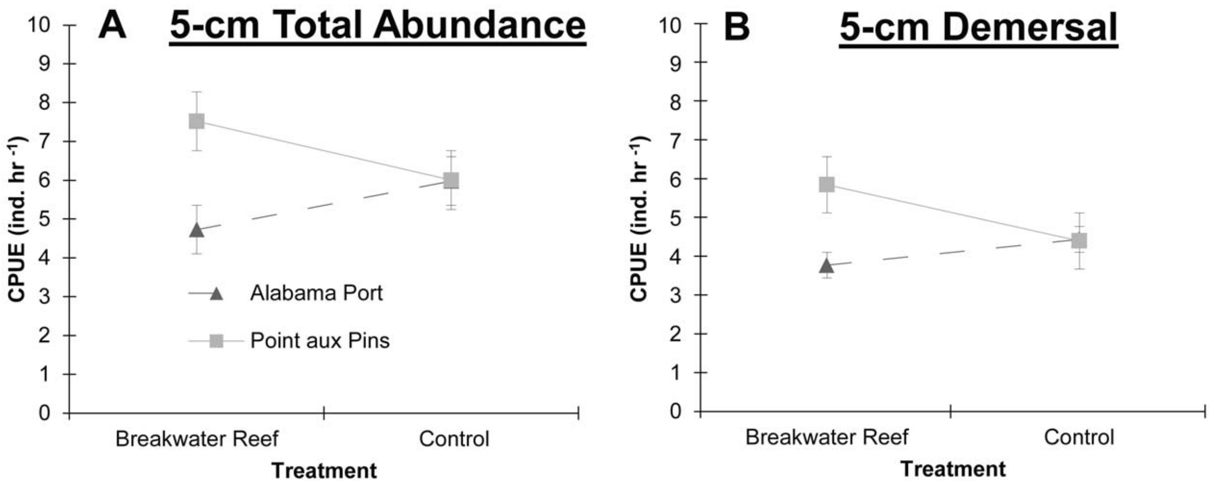

Figure 7. Relative Demersal Fish and Decapod Crustacean Abundance. Mean ±1 SE CPUE of (A) demersal fishes separated by collection method and (B) decapod crustaceans collected by seines near breakwater reefs and controls. Significant differences at P≤0.05 from univariate PERMANOA tests are indicated by asterisks.
doi:10.1371/journal.pone.0022396.g007

(Table S5). Of those, only sand seatrout abundance was significantly enhanced by breakwater reefs (Figure 9A). Silver perch, spotted seatrout and southern kingfish showed positive trends of enhancement, but not statistically significant. Eleven demersal fishes were analyzed from the 10 cm catches, seven of which were significantly enhanced by reefs including sand seatrout, spotted seatrout, red drum and black drum (Table S5 and Figure 9B). Only finetooth shark abundance in 10 cm gillnets was significantly greater on controls than breakwater reef treatments. Seine samples had nine species or taxa that comprised ≥1% of the total catch, including three demersal fish species and three decapods. Of the demersal fishes, which were silver perch, Atlantic croaker and juvenile sciaenids, only silver perch showed a significant difference and were more common near breakwater reefs (Figure 9C). All three decapods, caridean shrimp, penaeid shrimp and blue crabs were present in significantly higher densities near breakwater reefs.

Discussion

Our study found that breakwater reefs constructed of loose oyster shell provided substrate for oyster recruitment and harbored a more diverse community of fishes and mobile invertebrates than control areas without reefs. This habitat enhancement is uncommon among shoreline protection schemes and could be a vast improvement over traditional armoring techniques, many of which have detrimental impacts on nearshore species [16]. While our experimental breakwaters were an "ecology-first" approach

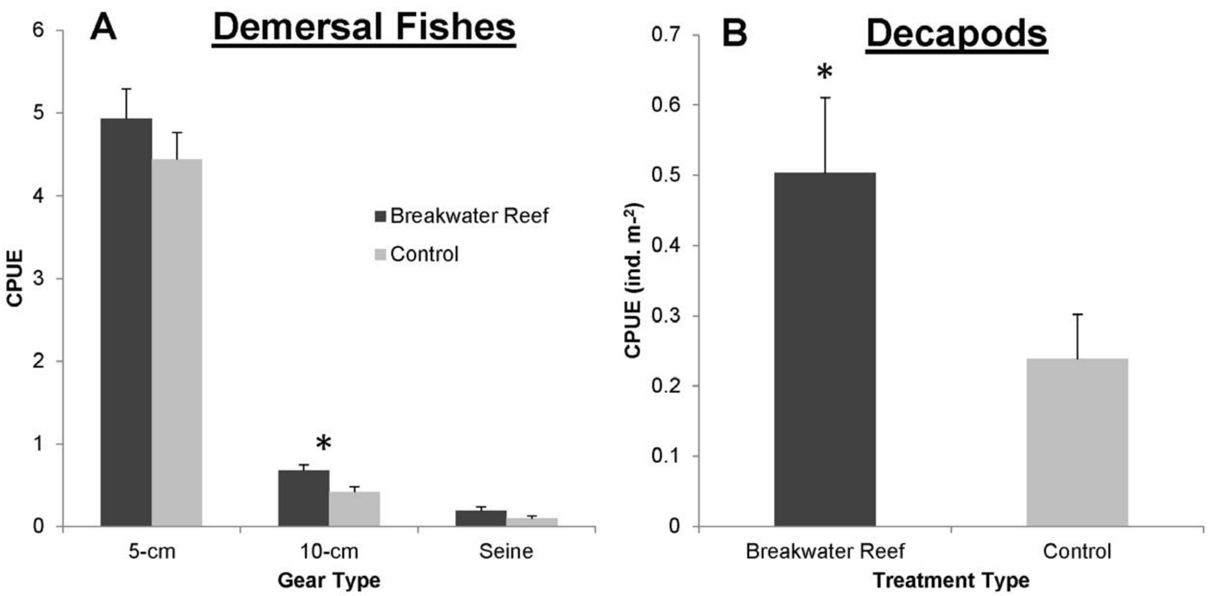

Figure 8. Total Abundance and Demersal Fish Abundance Separated by Site. Mean+1 SE catch per unit effort of (A) total fish and invertebrate abundance and (B) demersal fish abundance collected by 5 cm gillnets. CPUE is presented as the total individuals captured for each hour of soak time.
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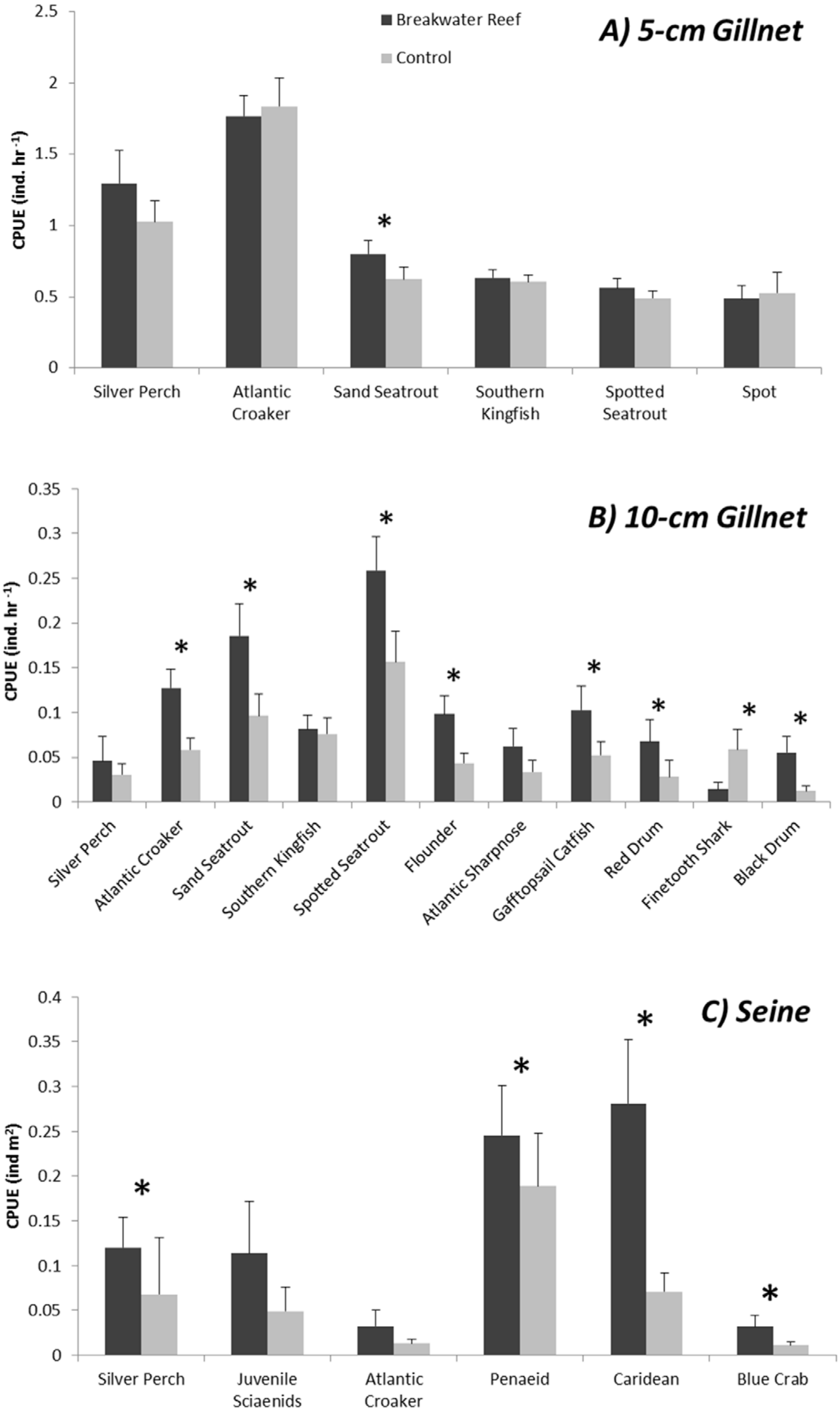

Figure 9. Relative Abundance of Dominant Demersal Fish and Decapod Taxa. Mean+1 SE CPUE of dominant demersal and decapod species or grouped taxa between treatments. Significant differences at P≤0.05 from Wilcoxon signed rank tests comparing paired breakwater reef and control treatments.
doi:10.1371/journal.pone.0022396.g009

and were successful in creating valuable habitat, they did not provide the amount of protection that could be offered by well-engineered methodologies. This shortcoming highlights the need for coastal protection philosophies that balance ecology and engineering. However, an approach similar to ours could serve as an immediate solution to the habitat losses experienced along many sheltered coasts. In these settings, breakwater oyster reefs that were installed seaward of already armored shorelines could mitigate losses of fish and shellfish habitat.

Roland and Douglass (2005) found that many stretches of Alabama's shoreline are faced with wave energies well above critical limits where vegetation can naturally persist and proposed breakwaters as a potential mechanism to reduce wave energies [26]. The wave-attenuating capacity of the breakwaters in our study was compromised because the loose shell reefs expanded and flattened prior to the cementing together that could result from oyster settlement and survival. The mesh covering used in our study to maintain the breakwater reefs' integrity was not rigid enough to withstand the wave energy of our sites, but an improvement in this aspect of the breakwater design could allow for better shoreline protection and less disturbance of the reef. To mitigate reef spreading and flattening, we suggest the introduction of a more rigid structure as a temporary backbone which would deteriorate or could be removed after reef cementing occurred.

At both Alabama Port and Point aux Pins, we documented oyster recruitment and survival to reproductive size, but substantial mortality limited reef cementing and success. The high mortality recorded at both sites during October 2008 sampling appeared to be caused by predation or physical disturbance, such as wave energy. During this sampling period, very few exposed oysters were observed to be alive. In contrast, nearly all live oysters observed were found sheltered inside of dead, but still hinged oyster shells. This suggests that it is unlikely disease was the cause of mortality, since structurally-protected oysters would have no reprieve. Another factor that frequently affects oyster survival is reef height as tall reefs escape the poor water quality sometimes found near the sediment [34]. As previously discussed, the vertical relief of our reefs did decline over time, but again it is unlikely that sheltered oysters would survive if water quality caused the observed mortality. Physical disturbance could have caused many of the oyster shells that were on the surface and available for settlement to be buried under other shells, also explaining the lowered densities of live oysters. Predation is likely the most plausible explanation for the differential mortality between sheltered and exposed oysters. We frequently observed black drum, southern oyster drills (*Stramonita haemastoma*) and several species of crabs near the reefs. Stomach content analysis of the black drum collected in gillnets usually found oyster shell remains and dead oysters often showed signs of predation (S Scyphers, Pers. Observ.). A recent mark and recapture study of subtidal oyster reefs in coastal Alabama waters also documented drills as the most prevalent cause of mortality due to visible scarring on dead spat shells [35]. The high salinities and absence of freshets observed during the drought conditions 2007 and 2008 were likely beneficial for the oyster drill predators which thrive in higher salinity conditions [36,37].

The communities of fishes and mobile invertebrates that benefit from oyster reefs have been well-described, but very few studies have examined the enhancement from oyster reefs designed for protecting shorelines. The elevated species richness and densities that we observed during our study concur with most literature describing oyster reef habitats [2]. From our seines, we found blue crabs, penaeid and caridean shrimp, and juvenile silver perch were more abundant near oyster reefs than mudflat controls. Higher blue crab densities near reefs were likely due to the refuge value, as their recruitment and survival is largely augmented by structured habitats [38]. Blue crabs support an important commercial fishery throughout Gulf and Atlantic estuaries and, along with caridean and penaeid shrimp, are commonly found in the diets of several of the larger fishes. From our 10 cm gillnet sampling, we found that spotted seatrout, drum and flounder were substantially enhanced by oyster reefs. The paradigm of abundance, biomass and species richness being higher in structured areas and further increasing with habitat complexity is a pattern observed in nearly all nearshore ecosystems [20,39–41], but the relative importance of food versus refuge within structured habitats remains unresolved [42,43].

Landscape attributes, such as adjacent habitats or bathymetric features, commonly influence community composition [44–46] and are probably responsible for the interaction between site and treatment for the total abundance and demersal abundance of 5 cm gillnet catches. The interaction was driven by demersal fishes (Figure 7) and these catches were dominated by Atlantic croaker and silver perch, both which are recognized to predominately feed in non-structured habitats [47]. Geraldi et al. (2009) found very little evidence of enhancement by oyster reefs restored in marsh tidal creeks and concluded that the area was not limited by complex structure and therefore the addition of oyster shell was functionally redundant. Grabowski et al. 2005 concluded that small or few reefs may not measurably enhance transient predators. Interestingly, the broad enhancement we observed occurred in a similar setting with each reef located near structurally-complex saltmarsh habitat and of moderate size ($\sim$225 m^2).

It has proven quite challenging to predict the ecosystem services to be expected from restoring reefs at different scales or in different settings [34,41,42]. Ecosystem services provided by shallow marine habitats have received considerable attention from natural and social scientists seeking to quantify and predict potential benefits from protection or restoration [5,48,49]. Historically, most of these studies have focused on wetlands, seagrass meadows, coral reefs and mangroves [5,50,51], all habitats that receive considerable protection because of their productivity. Oyster reefs also provide important ecosystem services [18], but are more challenging to protect and manage because they are an exploited fishery [2]. A long history of excessive and destructive harvesting coupled with natural stressors like disease and storms have left shellfish populations in global demise [52–54]. Most large or landscape scale oyster reef restoration efforts have primarily targeted the re-establishment of harvestable oysters, many of which failed to achieve previous population levels. Some recent studies have detailed shortcomings of oyster restoration and cast serious doubts on the ability to achieve restoration success in subtidal and often large-scale efforts [55]. However, other recent studies have documented restored reefs that have persisted over decades [56] and on unrivaled spatial scales [57]. Attempts to quantify the economic benefits from restoring oyster reefs are very recent and forthcoming and could provide more support for protecting and restoring oyster reefs for the goods and services they provide [58,59].

Awareness of the detrimental impacts of shoreline armoring has increased in recent years, but movement towards more ecologically-responsible methods has been limited by the lack of cost-effective alternatives. ''Living shoreline'' approaches, including breakwater reefs, that protect coastal uplands could provide a more ecologically-responsible alternative to traditional armoring and not only mitigate coastal erosion, but also enhance certain economically-valuable fish stocks. However, as our study demonstrated, efforts to sustainably and responsibly protect coastal shoreline habitats must balance both engineering and ecology.

Supporting Information

Table S1 Results of Repeated-Measures ANOVA on Vegetation Retreat.
(DOCX)

Table S2 Relative Abundance of the Most Abundant Fishes and Mobile Invertebrates.
(DOCX)

Table S3 Results from Multivariate PERMANOVA Tests.
(DOCX)

Table S4 Results from Univariate PERMANOVA Tests.
(DOCX)

Table S5 Results from Wilcoxon Signed-Rank Tests on Single Species or Grouped Taxa.
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Author Contributions

Conceived and designed the experiments: SS SP KH DB. Performed the experiments: SS SP KH DB. Analyzed the data: SS SP KH DB. Contributed reagents/materials/analysis tools: SS SP KH DB. Wrote the paper: SS SP KH DB.

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