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I. PROJECT SUMMARY (from proposal)

Restoration of coastal habitats has proceeded rapidly over the last two decades and will likely continue to expand as society demands compensation for the degradation of natural resources. In the northern Gulf of Mexico (GOM), seagrass meadows, salt marshes and oyster reefs have declined precipitously over the last century. While oyster reef restoration initially began as a means to reclaim the economic benefits of harvesting oysters, restoration has increasingly been carried out for its ecological and societal benefits. Even though the economic loss of the oyster fishery has been striking, the management paradigm shift has occurred because of the recognition that the loss of ecological services provided by oyster reefs may have far greater impacts on society.

Although substantial funds have been invested in living shoreline projects in every Gulf state, a comprehensive evaluation of those projects that could be used to guide future projects has yet to be completed. The Project Director and Key Personnel are proposing to synthesize existing data from 13 existing living shoreline projects across coastal Alabama to quantify and value the services they provide, including habitat enhancement, shoreline protection and water quality benefits. The unique feature of this work is that we have access to complete datasets from all of the projects that will be gathered, checked for accuracy, and combined to evaluate the biological and physical effects of living shorelines. Additionally, the proposed work will also synthesize data from companion socioeconomic studies (e.g., Scyphers et al. 2014, 2015, Unpublished data) and use market values and non-market techniques to

estimate the value and benefits of their services to society, especially the coastal communities (e.g., nutrient offset values for nitrogen removal, travel cost assessment of recreational fishing, willingness to pay for living shorelines). The analysis will also model service delivery over different expected reef lifetimes and discounting future values to estimate the net present value of restoration efforts.

This detailed analysis will evaluate the performance and efficacy of the different restoration technologies that have been used to construct Alabama living shorelines, and will increase the efficiency of future monitoring efforts by elucidating those parameters most important to measure when evaluating key ecosystem services and social resilience. By limiting the focus to one state in the Gulf of Mexico, the resulting synthesis will be able to address, in depth, multiple facets of different living shoreline methods, their efficacy and value. The resulting document will then be applicable to other areas across the Gulf region and help inform future decision-making. It will do this by allowing more accurate and comprehensive prediction of the environmental benefits and societal values derived from living shoreline projects. This proposed synthesis will also advance and strengthen the science behind living shoreline projects at a time when numerous funding opportunities for restoration are forthcoming due to the mitigation efforts associated with the Deepwater Horizon oil spill. Thus, this effort will provide an invaluable resource for funders, managers and decision-makers and relates to Goal 3 of the Gulf Research Program's Mission.

II. PROJECT SUMMARY (from final report)

Substantial funds have been invested in living shoreline projects to restore coastal habitats, protect shorelines and enhance resiliency of coastal communities. While a variety of techniques have been implemented, we don't yet have a firm understanding of the degree of success of different reef technologies and project designs. In this study, we synthesized data from 13 living shoreline projects implemented in Alabama over the past decade to evaluate project success. All projects involved the construction of oyster reef breakwaters but were done using a variety of technologies (e.g., bagged shell, reef balls, reefBLKS). Bagged shell reefs supported the highest oyster densities. Abundance of finfish and mobile invertebrates was highly variable by site, reef type, and taxon. Shoreline protection has been highly variable by site, reef type and year. Results suggest bagged shell reefs may be the most effective in providing an array of ecosystem services. Valuation of market and non-market ecosystem services across project types and expected reef lifetimes suggest that these reefs are highly valuable. Social survey data collected in conjunction with select projects were also compiled, synthesized, and evaluated. Our results help to identify the most promising strategies to ensure that future investments in living shorelines maximize ecological and societal benefits.

III. PROJECT RESULTS

<u>Accomplishments</u>

<u>What is the problem you were trying to address?</u>

Restoration of coastal habitats has proceeded at an accelerated pace over the last two decades and will likely continue to expand as society demands compensation for growing degradation of natural resources (Vitousek et al. 1997, Botsford et al. 1997, Hobbs and Harris 2001). In the northern Gulf of Mexico, several coastal habitats have declined precipitously (more than 50% loss) over the last century, including seagrass, tidal wetlands and oyster reefs. Oyster populations, for example, have experienced more than an 85% global decline, making oyster reefs one of the most imperiled marine habitats in the world (Beck et al. 2011). Over the past century, the eastern United States has also experienced a dramatic decline in oyster populations (>90%, Rothschild et al. 1994; Hargis and Haven 1999; Zu Ermgassen et al. 2012) which has prompted increased efforts to restore this vital and productive habitat. Although the economic loss of the oyster fishery is striking (Kirby 2004) and prompted initial oyster reef restoration projects, the loss of the ecological services provided by oyster reefs may have far greater impacts on estuarine ecosystems and society (Jackson et al. 2001; Peterson and Lipcius 2003). Recognition of the importance of these services has increasingly driven recent restoration activities in attempts to restore the ecological benefits provided by oyster reefs (Dame et al. 1984; Jackson et al. 2001), and as a consequence, enhance the sustainability of coastal communities.

Restoration of oyster reef habitat results in the provision of several ecosystem services, including fisheries enhancement, shoreline protection, wave attenuation, excess nitrogen removal, and enhanced community resilience (Coen and Luckenbach 2000; Piazza et al. 2005; Grabowski and Peterson 2007; Powers et al. 2009; Piehler and Smyth 2011; Scyphers et al. 2011; Grabowski et al. 2012; La Peyre et al. 2014, Scyphers et al. 2015). Oyster reefs are often constructed as breakwaters in living shoreline projects. Living shoreline is a term used to describe a variety of nature-based approaches to shoreline stabilization. Living shoreline techniques can include planting of marsh grasses, the construction of oyster reef breakwaters, and other methods depending on the site and project goals. Living shoreline projects can maintain or restore natural coastal habitats, protect coastlines and provide many other ecosystem services, or benefits provided by nature to people. While living shorelines have been promoted as a natural, or “green” alternative to hard, “grey” structures, we don’t yet have a good understanding of which living shoreline techniques work best to protect coastlines and provide ecosystem services such as shoreline stabilization, increased fish and shellfish available for recreational and commercial fishing, and filtration by oysters to help clean bay waters. Additionally, we know very little about the attitudes, beliefs, and values of the coastal residents and key stakeholders that are directly affected by the health and management of shorelines and coastal habitats.

Although a substantial investment has been made in living shoreline projects in Alabama and across the Gulf of Mexico, a comprehensive evaluation of those projects that could be used to guide future projects has not been completed. Over the past decade, more than 3.5 miles of living shorelines have been constructed in coastal Alabama to examine, among other variables, the ecosystem service benefits obtained from restoring nearshore oyster reefs. These living shoreline projects have been funded primarily through competitive grant programs with project funding limited to a timeframe of generally two years or less after reef construction. Monitoring associated with such short-term projects can be intensive, involving numerous parameters and a sampling regime that cannot be maintained easily after project completion. While this timeframe is adequate to measure initial biological and physical parameters, it does not allow for a detailed synthesis of results. Moreover, the focus of monitoring very rarely encompasses social and economic research needed to connect ecological outcomes to society and stakeholders. Here, we bridge these gaps and evaluate and compare the performance of the various restoration technologies used for the many existing Alabama living shorelines.

The overall objectives of this synthesis are to:

1. Determine the efficacy of different living shoreline technologies for a range of metrics and ecosystem services and identify knowledge gaps in current methodologies.
2. Build a database of project information for future comparisons.
3. Identify potential cost-savings for restoration investments and streamline monitoring metrics, thereby enhancing adaptive management of existing and future restoration.

What did you do to address this problem?

The living shoreline projects implemented in Alabama span a wide range of methods of breakwater reef construction techniques (e.g., loose oyster shell, bagged shell, reef balls, etc.), and wide range of spatial scales (e.g. meters to miles). A total of 13 individual projects were implemented in coastal Alabama between 2005 and 2013. Methodologies and project details (e.g., project timelines, sampled metrics and methods) for each project were compiled from original grant reports and other publications. A list of data collected for each project was developed. Available data were gathered, checked for accuracy, and combined.

Ecological data were synthesized to evaluate colonization and survival of oysters, and composition and abundance of associated finfish and shellfish. Sessile organism (oysters, spat, mussels, and also oyster drills) abundance data were collected at 11 of 13 projects. Monitoring occurred in a variety of ways depending on the reef technique. Thus, all methods were standardized to density. Nekton abundance data were collected consistently at 6 of 13 projects. Monitoring for abundance and biomass occurred via seines and gillnets (5 cm and 10 cm mesh sizes) at each of the six projects. Seine abundance data were standardized to density, and gillnet data to CPUE.

Physical data were compiled into individual geodatabases for each project to evaluate shoreline stabilization and erosion control. Shoreline position was monitored at 11 of 13 project sites. Historical shoreline position data were also acquired for each project site. Shoreline digital vector lines were compiled by several methods: 1) existing sources, such as from NOAA; 2) captured with a Global Navigation Satellite System (GNSS) with Differential GPS or Real Time Kinematic (RTK) capability; or 3) derived from rectified raster images by manual on-screen digitization using ERSI ArcGIS software. The shorelines depict edge-of-vegetation or shoreline at mean high water (MHW); the MHW shorelines were mainly historical in nature. Using the DSAS software extension to ESRI ArcGIS, transects were cast perpendicular to shore at 1 or 5 m intervals, depending on the site, and distance of the shore from a standard baseline was computed (Thieler et al. 2009). Shoreline movement rates between years were then calculated for each point.

Ecological and physical data were used to quantify ecosystem service values. Economic analyses using market (e.g. commercial fish dockside value) and non-market valuation techniques were used to estimate the value and benefits of services related to habitat provision, oyster production, shoreline protection, and fisheries augmentation (sensu Grabowski et al. 2012).

Over the past decade, several social science studies have been conducted across the Gulf of Mexico that examined the relationships and interdependence between human populations and ecosystems. Social data from previously conducted surveys were gathered. These data were synthesized, and models were developed to evaluate societal benefits and perceptions of living shoreline projects across coastal

Alabama. In addition, the economic benefits provided by two ecosystem services associated with these living shorelines, augmented fish production and shoreline erosion protection, were explored.

Monitoring metrics and methods were compared with the universal metrics and methods identified in the Oyster Habitat Restoration Monitoring and Assessment Handbook (Baggett, et al. 2014) to evaluate which metrics have been used most consistently in evaluating ecosystem health and services.

<u>What were your results?</u>
The timeline of project implementation and details of reef techniques are as follows:

Alonzo Landing (2005) – This project design was developed by MS-AL Sea Grant Consortium and yielded 182 precast concrete Coastal Haven™ breakwaters that were installed in two interlocking rows parallel to Saw Grass Point Marsh on the north side of Dauphin Island (Swann 2008). Each of the coastal havens unit had a base length of approximately 2.4 m and a height of approximately 1.7 m, with three 40 cm triangular openings per side and a 27-cm-diameter circular opening at the top of the hollow unit. The coastal havens were installed along the 1.3-m bathymetry contour, stretching along 162 m of shoreline (Swann 2008). Part of this project also included the removal of six derelict vessels from the marsh. Reefs were constructed in April 2005, and 1,200 Spartina alterniflora plants were planted in June 2005. However, all plants were dislodged or destroyed during Hurricane Katrina in August 2005.

Point aux Pins (2007) – The second living shoreline project implemented in coastal Alabama was developed by the Dauphin Island Sea Lab. The project was located at the southern end of the Point aux Pins peninsula in Mississippi Sound. Two subtidal breakwaters were constructed, each consisting of three mounds of loose oyster shell that measured 25 meters by 5 meters each and had a vertical relief of 1 m (Scyphers et al. 2011). The mounds had a rectangular footprint and a trapezoidal cross-section. Each mound was composed of loose oyster shell placed on a geo-textile fabric (0.05 m aperture) to prevent subsidence and secured by a plastic mesh covering (1 cm2) that was anchored by rebar (Scyphers et al. 2011). Each breakwater stretched along 65 m of shoreline, for a total of 130 m project length protecting a natural marsh shoreline. Reef segments were placed approximately 30 m waterward from the shoreline. Reefs were seeded with adult oysters purchased from the Auburn Shellfish Lab at a target density of 100-150 oysters per m2, and reefs were designated as no-harvest areas during the study period by Alabama Marine Resources Division.

> **Adaptive management: Within two years following construction, the top netting had failed to keep shell in place and reefs migrated about 5 m shoreward, resulting in base dimensions expanding to 10 m with reduced vertical relief. Thus, in April 2011, approximately 100 yd3 of oyster shell were placed along the seaward edge of each reef mound, and a three-sided fence was constructed along the seaward edge of the original reef to prevent shoreward movement of new shell. Shell bags were also placed along the shoreline to further reduce erosion (30 yd3 bagged shell over 100 m shoreline per breakwater complex). Within four months, the retaining fence had been pushed forward by new shell migrating shoreward.
> Also, the bagged shell placed along the shoreline was missing, and suspected stolen.

Alabama Port (2007) – As a comparison site for Point aux Pins (2007), this project was developed by the Dauphin Island Sea Lab, and reefs were designed in the same layout. The project site comprised a 2 km stretch of eroding shoreline on the southwestern shore of Mobile Bay, just north of the Dauphin Island bridge. Two breakwater reef complexes were constructed in the same manner as for Point aux Pins (2007), with the only difference being that these reefs were not seeded with live oysters. These reefs were also designated as no-harvest areas during the study period by Alabama Marine Resources Division.

Helen Wood Park (2008) – This project fronts a state-owned public access area on the northwest side of Mobile Bay, just north of Dog River, and was developed by Dauphin Island Sea Lab and The Nature Conservancy (Scyphers et al. 2015). The 0.63 km stretch of shoreline was characterized by retreating marsh comprised on Spartina alterniflora and Phragmites australis. The project design yielded four reefs (two replicates of two treatment types), each 25 m in length and 2 m in width with a vertical relief of 1 m. The first treatment consisted of 3 rows of 41 Lo-Pro ReefBalls (123/reef) and the second treatment was comprised of bagged oyster shell (~2,000 bags/reef). Reef segments were placed approximately 60 m waterward from the shoreline (0.75 m depth), and totaled 100 m in length. Simultaneously with reef construction and unrelated to the DISL/TNC project, controlled burns were conducted in an effort to eradicate the invasive P. australis plants. These burns, along with the observed presence of seagrass in the area, led to the decision to place reefs 60 m seaward from the shoreline.

> **Adaptive management: Two years following project implementation, no substantial effects on the shoreline were observed. It was suspected the reefs were constructed too far seaward to effectively reduce shoreline erosion. In December 2010, the two reefs constructed of Reefballs were disassembled and reused to construct reefs closer to shore as part of another project (Helen Wood Park 2011).

Point aux Pins (2009) – This project was implemented by the Dauphin Island Sea Lab along a 1.3 km stretch of marsh shoreline on the northeastern side of the Point aux Pins peninsula. Four breakwater reef complexes were constructed in the same manner as for Point aux Pins (2007), except that seeding with live oysters did not occur, and a three-sided fence was incorporated in the beginning to prevent shoreward movement of oyster shell. Breakwater reef complexes totaled 260 m in length, and were placed 125 m waterward from the shoreline.

Little Bay (2010) – This project was created to close the breach from Hurricane Katrina in 2005 and restore 30 acres of salt marsh habitat on the Little Bay Peninsula to maintain the protected bay. ADCNR-SLD contracted Volkert and Associates to design the project and install 5,200 feet of segmented breakwater using wave attenuation devices or WADs® and riprap. The project design was developed by Volkert Engineering, AL Department of Conservation and Natural Resources, South Coast Engineers LLC, Geotechnical Engineering & Testing, Inc. and University of South Alabama. The design yielded 546 WAD® units (base=3m X 3m X 1.8m; top=1.5m X 1.5m), placed in two, 1-mile-long parallel lines. No geotextile was used for foundation strength and it was expected, based on soil tests, that the WADs® would settle 15 cm because of consolidation processes and differential scour through time. The WADs® were arranged as a breakwater by configuring them in two rows where one row was offset, or staggered, behind the other. The sections of the breakwater were 61 m long (16 sections total) with 12 m gaps between sections. Each breakwater section consisted of 39 WADs®, placed about 100 m offshore of the pre-project shoreline. Sand was placed south of the shoreline at a width of about 70 m to leave about 30 m of open water between the structures and the newly constructed marsh. Almost all of the sand remains within the project limits, all the native marsh in the lee of the project remains with no further erosion, the newly created habitat is a blend of growing vegetation, and there are oysters on the WADs.

Coffee Island (2010) – This project, with Alabama Port (2010), was funded through the American Recovery and Reinvestment Act (ARRA) of 2009, and was developed by The Nature Conservancy in collaboration with the University of South Alabama and the Dauphin Island Sea Lab. Coffee Island, located in Portersville Bay, is comprised of marsh and had experienced significant erosion. The project design yielded six reef treatments (two replicates of each treatment type), each 125 m in length. The three technologies included in the design of the living shoreline were bagged oyster shell mounds, Reefballs, and ReefBLKsTM. Bagged shell reefs consisted of five segments, each 17 m long by 4 m wide, separated by 10 m gaps. Each bagged shell reef segment was 4 m wide with a vertical relief of 0.7 m. ReefBLKs are triangular rebar structures with mesh side panels filled with oyster shell. Each unit was 5 feet on each side, 2 m high, and contained nine mesh bags of oyster shell. ReefBLK units were placed side-by-side in a sawtooth pattern stretching 125 m in length. Reefball reefs were constructed using the Mini Bay reefball model, which measure 0.76 m in diameter and 0.53 m in height. Each reef section consisted of three parallel rows of reefballs placed side-by-side for a total reef dimension of 125 m in length and approximately 1.6 m in width. Reef segments were placed approximately 30 m waterward from the shoreline. Given project cost savings, an additional segment (250 m in length) for each treatment was constructed at the south end of Coffee Island. Reef construction began in April 2010, but was halted following the Deepwater Horizon blowout. Construction resumed in September 2010, and all reefs were finished that month.

> **Adaptive management: Substantial dissolution of oyster shell contained in the ReefBLK structures was observed in the years following construction. A plausible hypothesis for this observed dissolution was that the relatively large amount of surface area that the shell-filled side panels allowed increased contact with water and thus made the shell particularly susceptible to dissolution due to wave energy. In September 2015, one ReefBLK reef was chosen to test strategies for combating this dissolution, including testing different substrates and filling the center of the cages in addition to the side panels. Four new fill treatments were tested: (1) limestone in center, (2) bagged limestone in side panels, (3) oyster shell in center, and (4) bagged limestone in side panels with oyster shell in center.

Alabama Port (2010) – This project was conducted concurrently with Coffee Island (2010), and located in the same area as Alabama Port (2007). The project design yielded six reef treatments (two replicates of each treatment type), each 125 m in length. The three technologies included in the design of the living shoreline were bagged oyster shell mounds, Reefballs, and ReefBLKsTM, and reefs were constructed to the same specifications as at Coffee Island (2010). Reef construction began in April 2010, but was halted following the Deepwater Horizon blowout. Construction resumed in October 2010, and lasted through spring 2011.

Helen Wood Park (2011) – This project was developed by The Nature Conservancy with ADCNR input and incorporated engineering design principles to determine reef dimensions. This design yielded twelve reefs total, each 25 meters in length. Reefs were constructed of two treatment types: bagged oyster shell and reef balls). Ninety-seven Mini-Bay ReefBalls comprised one reef (2.2 m base width and 0.5 m height), and 246 Lo-Pro ReefBalls (reclaimed from Helen Wood Park 2008 project) comprised 3½ reefs (1.8 m base width and a 0.46 m height). Approximately 23,000 bags of shell were used for the 7½ bagged shell reefs (2.5 m base width and ~0.6 m height). Reefs were separated by 7.6 m gaps. Reef segments were placed approximately 30 m waterward from the shoreline and had a total length of 335 m protecting the natural shoreline. Construction occurred over two days, with 428 community volunteers participating on the 1st day and 84 volunteers on the 2nd day, for a total of 2,391 manhours.

Swift Tract (2012) – The Swift Tract is located along an actively eroding, vegetated shoreline owned by the State of Alabama and managed through the Weeks Bay National Estuarine Research Reserve. The project design was developed by The Nature Conservancy and HESCO Bastion, Inc., and incorporated engineering design principles to determine reef dimensions. The construction technique consisted of

Hesco barriers, galvanized steel modular baskets, that were installed and then filled with gabion stone (fist-sized rock). A 0.15 m layer of oyster shell was placed on top of the gabion stone in the cages. Pockets on the front and rear sides of the Hesco barriers (~0.15 m) were filled with oyster shell for monitoring purposes. The total Swift Tract reef measures 567 m, with the 5 individual reef segments: four reefs at ~125 m in length and one reef at 75 m in length. The reefs are approximately 5.5 m wide at the base, 3.7 m wide at the crest and 0.76 m tall. Reef segments were placed approximately 12 m waterward from the shoreline. Within a short period of time after final deployment of the Swift Tract reefs, breaking waves had displaced the oyster shell from the top of the barriers. The loose shell was deposited on the back side of the reefs, forming a wedge.

> **Adaptive management: To maintain the vertical relief of substrate, and thus the wave attenuation effectiveness of the reefs, TNC implemented an adaptive management strategy immediately following construction which involved filling the voids left by the displaced oyster shell with the heavier gabion stone.

Fort Morgan (2012) – Two living shoreline projects were implemented in September 2012 on the Fort Morgan Peninsula in southeast Mobile Bay. The Fort Morgan1 shoreline project is located north of Fort Morgan Road on the Fort Morgan peninsula, involved two private landowners and is armored with a seawall that is further protected with large riprap and concrete pieces that slope into the bay. Seawalls and riprap flank the site to the east and to the west for several hundred meters. The project design was developed by TNC and incorporated engineering design principles to determine reef dimensions. This design yielded five reefs, each ~14 m in length and comprised riprap rock covered with bagged oyster shell. The reefs had a base length of approximately 14 m, base width of 4.6 m, crest width of 3 m and height of 0.76 m, with gaps of approximately 7.6 m between reef segments. Reef segments were placed approximately 27 m waterward from the base of the riprap slope.

The Fort Morgan2 shoreline project is located north of Fort Morgan Road on the Fort Morgan peninsula and approximately 610 m to the west of Fort Morgan1. The construction technique used for reefs along this shoreline was riprap covered with bagged oyster shell. This site is flanked on either side by shorelines that are armored with seawalls and riprap. The project design was developed by TNC and incorporated engineering design principles to determine reef dimensions. This design yielded six reefs, each ~25 m in length comprised riprap rock covered with bagged oyster shell. The reefs had a base width of 4.6 m, crest width of 3 m and height of 0.76 m, with gaps of approximately 7.6 m between reef segments. Reef segments were placed between approximately 27 m waterward from the base of the riprap slope. Due to the curvilinear nature of the sandy shoreline, the reefs ranged from 11 m from the shore at the eastern and western ends to 41 m from the shore near the middle and ranged in base length from 15 m to 32 m.

Pelican Point (2013) – This project was developed by TNC and Allied Concrete, and incorporated engineering design principles to determine reef dimensions. Oyster CastleTMreef breakwaters were constructed in May 2013 to protect approximately 100 m of shoreline owned by the state of Alabama at the mouth of Weeks Bay. The design yielded four reefs constructed with interlocking Oyster CastlesTM, each ~17 m in length and ~6 m in width with a vertical relief of ~1 m. The project included ~14,000 Oyster CastlesTM (~3,500/reef) and reef segments were placed approximately 30 m waterward from the shore. The Pelican Point project was a volunteer reef building event organized to construct Construction occurred in Spring 2013 and over two days: 565 volunteers, including 411 volunteer airmen and women from Keesler Air Force Base, on the 1st day and 357 volunteers, including 246 volunteer airmen and women from Keesler Air Force Base on the 2nd day – a total of 6,555 manhours. In December 2013, the Baldwin County Grasses in Classes Program planted 150 smooth cordgrass (Spartina alterniflora) plants on the beach behind the breakwaters to help stabilize the shoreline and enhance marsh habitat.

Of the 13 living shoreline projects implemented in coastal Alabama between 2005 and 2013, three projects were not included in our final data synthesis for a variety of reasons. Alonzo Landing (2005) had very little to no data collected following project implementation. Additionally, this project included the removal of several derelict vessels and the construction of a 100-foot public pier, which confounded impacts to shoreline change in the project area. Helen Wood Park (2008) was constructed too far from the shoreline for any noticeable impacts on shoreline erosion in the following years. Thus, in 2011, reef balls used in the original project were reclaimed and used to construct reefs closer to shore. Additionally, during project construction in 2008, a controlled burn was conducted on shore to eradicate invasive Phragmites, further confounding impacts to the project site. Little Bay (2010) was a highly engineered project, involving the placement of large Wave Attenuating Devices (WADs) to create breakwater reefs, and the addition of substantial amounts of sand to recreate the peninsula forming Little Bay followed by marsh grass plantings. Because of the sand placement, impacts to shore could not be evaluated based on the breakwaters alone. Additionally, ecological data related to oyster settlement and nekton use were not collected in a consistent manner to allow inclusion and comparison with the other projects. Data commonly collected at the remaining 10 projects included: (1) density of oysters, spat, mussels, and oyster drills; (2) CPUE of nekton (fishes, crustaceans); and (3) shoreline position.

To facilitate synthesis of data across the variety of reef technologies, reef types were grouped into descriptive categories. At the highest level, reefs were considered “Natural” if they incorporated oyster shell as their primary structural component, and “Engineered” if they were constructed of concrete or cage structures. Natural reefs included those constructed of bagged oyster shell (6 projects) and loose oyster shell (3 projects). Engineered reefs included those constructed of concrete reef balls or castles (5 projects) and caged substrates, such as ReefBLKs and HESCO cages (3 projects). Wave Attenuating Devices (WADs), such as those used at Little Bay and the Coastal Havens used at Alonzo Landing, were not evaluated because those projects did not include consistent monitoring and were thus excluded from the overall synthesis.

Sessile Habitat

Bagged shell reefs supported the highest oyster densities, averaging 55.5 ± 5.9 adult and 98.0 ± 12.0 spat oysters m-2 (mean ± SE) across six projects, with the largest densities observed at the Coffee Island site (average of 114.4 adult and 235.2 spat oysters m-2). This supports evidence that oysters prefer a natural oyster shell substrate for settlement. Oyster densities were likely higher on bagged shell reefs compared to loose shell reefs (averaging 12.6 ± 0.9 adult and 68.6 ± 5.0 spat oysters m-2) due to the movement and spreading of the loose shell. Loose shell reefs are subject to spreading and have resulted in flattened reefs. Oyster densities were lowest on concrete reefs (average 1.2 ± 0.1 adult and 0.5 ± 0.1 spat oysters m-2).

Oyster drills were most abundant on loose shell reefs, averaging 4.9 ± 0.3 drills m-2 (mean ± SE). This suggests that oyster drills also prefer the natural oyster shell substrate, but the mesh bags used for bagged shell reefs (average 1.4 ± 0.3 drills m-2) may inhibit movement and foraging. However, oyster drills were observed at ReefBLK reefs at higher densities (average 2.4 ± 0.3 drills m-2) than bagged shell reefs, even though the shell used in ReefBLK structures is bagged. Anecdotal observations suggest drills may use the rebar cage structure to move along the reef while foraging on exposed oysters that have settled on the cage structure or the outside of the mesh bags.

Significant loss of oyster shell has been observed in ReefBLK cages. There are several possible reasons, including water chemistry, breakdown by other organisms (e.g., stone crabs, boring sponge), and physical breakdown by water energy. Adaptive management strategies were implemented at one ReefBLK reef to test the hypothesis that shells are being broken down by water energy due to the relatively high surface area exposed compared to other reef types. Different types of substrates were used to fill the center and sides of ReefBLK cages in 2015. Continued monitoring conducted by The Nature Conservancy will assess success of this strategy.

Nekton Habitat

The abundance or CPUE of nekton was highly variable by site, reef type, and taxonomic group. In total, 107 species were collected by seine and/or gillnet at the six project sites that included nekton monitoring: Point aux Pins 2007, Alabama Port 2007, Helen Wood Park 2008, Point aux Pins 2009, Alabama Port 2010, and Coffee Island 2010.

Seine net sampling collected a total of 83 species across all treatments and projects. The top five most abundant species groups were: Anchoa mitchilli, Brevoortia patronus, Anchoa spp., Menidia spp., and Sciaenidae fishes. Overall, natural reef types supported higher nekton densities (1.06 ± 0.09 individuals m-2; mean ± SE) than engineered reef types (0.85 ± 0.16 individuals m-2). Nekton densities at control sites averaged 0.97 ± 0.11 individuals m-2. Reefs composed of loose oyster shell performed the best in terms of supporting nekton, averaging 1.16 ± 0.11 individuals m-2, which represents an augmentation of about 0.2 individuals m-2 compared to control samples. Bagged shell reefs supported the lowest nekton densities, averaging 0.63 ± 0.09 individuals m-2, which is less than control sites by 0.34 individuals m-2. Overall, the highest average nekton density was determined to be at Coffee Island control sites, with an average of 2.91 ± 1.96 individuals m-2; the lowest density was observed at Helen Wood Park control sites, with an average of 0.10 ± 0.03 individuals m-2.

Gillnet sampling collected a total of 63 species across all treatments and projects. The top five most abundant species groups were: Micropogonias undulates, Bairdiella chrysoura, Cynoscion arenarius, Brevoortia patronus, and Cynoscion nebulosus. Again, natural reef types supported higher nekton CPUE (3.64 ± 0.17 individuals hr-1; mean ± SE) than engineered reef types (3.16 ± 0.24 individuals hr-1). Nekton CPUE at control sites averaged 3.53 ± 0.16 individuals hr-1. Again, reefs composed of loose oyster shell performed the best in terms of supporting nekton, averaging 3.89 ± 0.20 individuals hr-1, which represents an augmentation of about 0.36 individuals hr-1 compared to control samples. Again, bagged shell reefs supported the lowest nekton CPUE, averaging 2.74 ± 0.28 individuals hr-1, which is less than control sites by 0.79 individuals hr-1. Overall, the highest average nekton CPUE was determined to be at South Point aux Pins loose shell reef sites, with an average of 4.53 ± 0.32 individuals hr-1; the lowest CPUE was observed at Helen Wood Park bagged shell reef sites, with an average of 1.75 ± 0.24 individuals hr-1.

Overall, the average number of species composing seine and gillnet samples was just under 3 species (2.93 ± 0.06 species m-2 and 2.76 ± 0.05 species hr-1, respectively). The maximum number of species collected in a single seine sample was 14 species at a South Point aux Pins control site. The maximum number of species collected in a single gillnet sample was 13 species, and occurred at a South Point aux Pins control site and at loose shell reefs at both South Point aux Pins and Northeast Point aux Pins. Generally, natural reefs supported the highest number of species, with averages of 3.16 ± 0.09 species m-2 from seine samples, and 2.92 ± 0.09 species hr-1from gillnet samples. Among natural reef types, more species were collected by seine at bagged shell reefs (3.37 ± 0.23 species m-2) compared to loose shell reefs (3.12 ± 0.09 species m-2), while more species were collected by gillnet at loose shell reefs (3.17 ± 0.10 species h-1) compared to bagged shell reefs (1.99 ± 0.14 species h-1). Seine species diversity was substantially lower at Helen Wood Park control sites (average 1.22 ± 0.15 species m-2) compared to all other sites. Gillnet species diversity was lowest at Helen Wood Park bagged shell reef sites (average 1.74 ± 0.17 species h-1), but was generally low (< 2 species h-1) across treatments at Helen Wood Park and Coffee Island projects.

Shoreline Erosion

Shoreline movement was highly variable by site, reef type, and year. It is also very difficult to establish true control shoreline sites to compare with breakwater reef sites. Across all project sites and reef types, a 17% decrease in erosion rates was observed following project implementation. Pre-restoration rates of erosion across the total shoreline length of all projects averaged 1.62 m y-1; post-restoration rates averaged 1.35 m y-1. While the living shoreline projects did not reverse total erosion trends to accretion, they did reduce the rate of erosion by 0.27 m y-1.

Natural reef types generally provided better shoreline protection than engineered reef types. Natural reefs reduced the rate of erosion by an average of 0.70 m y-1, while engineered reefs exhibited slightly minor increases in erosion rates by 0.09 m y-1. This suggests that oysters themselves are an important component of breakwaters designed for shoreline protection. Oyster recruitment to concrete reef types was extremely low, and the disappearance of shell from ReefBLKs also led to reduced oyster populations at most sites. Despite the high vertical relief maintained by engineered reefs, and the reduction of vertical relief observed at natural reefs via shell spreading, rates of shoreline change indicate that the presence of oysters supports reductions in wave energy and thus shoreline erosion.

In addition to examining shorelines as a whole and by treatments, we also examined the shoreline movement at the scale of 1 to 5 meters – the placement interval for transects created during data processing. Across all projects and treatments, the percentage of individual transects exhibiting trends of erosion pre-restoration averaged 95.4%. Post-restoration, only 78.4% of transects exhibited erosion. Thus, a total of 17% of all transects have made a complete switch from trends of erosion pre-construction to accretion post-construction.

Sociological Surveys

We reviewed and compiled data representing six surveys of the general public in coastal Alabama (1999, 2002, 2005, 2006, 2010, 2014) and two surveys of waterfront homeowners (2010, 2014). These data cover a wide variety of topics related to coastal habitats and shorelines such as perceived condition, stressors, management support, pro-environmental behaviors, and willingness to pay for restoration. Because multiple different methodologies (telephone, mail, online) were used in these surveys, we limited our analyses to qualitative comparisons of overall percent responses. Some of the more recent surveys focused more explicitly on habitat restoration and subsets of these datasets have been described in peer-reviewed publications (e.g., Scyphers et al. 2014, 2015a; Gittman & Scyphers 2017).

1999 General Population (PI: J. Steven Picou): the oldest survey we reviewed was a 1999 survey funded by the Alabama Center for Estuarine Studies (ACES). This telephone survey of 1,270 Mobile and Baldwin county residents covered issues of general pro-environmental attitudes, health and threats to Mobile Bay, safety of seafood consumption, outdoor recreational behaviors, and extensive demographics including religion. Notably, this study found that 59% of coastal residents considered “erosion of the waterfront” to be a serious problem for Mobile Bay.

2002 General Population (PI: J. Steven Picou): another ACES funded survey in 2002 revisited many of the questions in the 1999 survey and expanded the seafood consumption questions to quantify species-specific perceptions and consumption patterns, as well as concerns for methyl-mercury contamination. Related to this synthesis, this study revealed that Spotted Seatrout and Flounder were highly valued and frequently consumed by coastal Alabama residents. Approximately 16% and 36% of respondents stated consuming Spotted Seatrout and Flounder within the last month. This telephone survey represented a sample of 855 coastal Alabama residents.

2005 General Population (PI: J. Steven Picou): a 2005 telephone survey of 1,001 coastal Alabama residents was funded by the Alabama Oyster Restoration Program and focused “Assessing Public Awareness of the Benefits of Oyster Reef Restoration: Laying the Technical Groundwork for an Educational Outreach Program”. This survey was also the first survey to consider the role of living shorelines. These results included findings that 84% of residents considered oyster reefs important for stabilizing shorelines during hurricanes and 89% perceived oyster reefs to be important for protecting marsh habitat.

2006 General Population (PI: J. Steven Picou): another ACES-funded survey in 2006 revisited many of the topics and questions from 1999 and 2002 with an expanded focus on environmental justice. This survey also included questions related to living shorelines with 59% and 56% of respondents citing coastal erosion and the loss of wetlands, respectively, as major problems. This telephone survey sampled 817 coastal Alabama residents.

2010 General Population (PI: Steven Scyphers): one of the most directly relevant surveys for this synthesis was funded by the American Recovery and Reinvestment Act (ARRA) and alongside the Coffee Island and Alabama Port living shorelines projects described above. This telephone survey focused on coastal habitats, fisheries, and shorelines. This survey found that 80% of respondents believed that ARRA funding was somewhat to very important for “rejuvenating coastal Alabama fisheries”; however, only 13% were directly knowledgeable of local funded projects. More broadly, this survey found that 53% of residents felt that “habitat restoration and protection” was the highest priority for research funding. This survey data set also includes information on outdoor recreational behaviors and other attitudinal questions used in the the previous ACES surveys led by S Picou.

2014 General Population (PI: Steven Scyphers): the topics covered in this survey were very similar to the 2010 survey but a key difference being that this survey was conducted using online panels.

2010 & 2014 Waterfront Resident Surveys (PI: Steven Scyphers): two mail (2010) and mixed-mode (2014) surveys of of waterfront residents were extensively focused on shoreline and habitat restoration. The 2010 survey revealed that cost, maintenance, and durability were the most highly prioritized factors influencing homeowners’ shoreline development decisions (Scyphers et al. 2014). This study also revealed that residential shoreline decisions are highly influenced by neighboring shorelines. The 2014 involved an expanded focus on the financial cost living shorelines compared to traditional structures (Gittman and Scyphers 2017) and incentives for living shoreline implementation (Scyphers et al. In Revision). The 2014 survey also assessed the social benefits of community-based living shorelines projects in Baldwin County and found that they can play a significant role in building social capital by connecting local residents with shared values and interests (Josephs & Scyphers, In Prep).

Collectively, these studies generally show that residents of coastal Alabama: 1) highly value and prioritize healthy coastal ecosystems and natural resources, 2) recognize interdependencies between healthy shorelines, coastal habitats, and ecosystems, 3) are concerned with shoreline erosion and coastal habitat loss, and 4) recognize the need to prioritize restoration science and practice. We are currently working on a peer-reviewed publication describing temporal patterns and stratification in pro-environmental and recreational behaviors from the 1999-2010 telephone surveys. In the future, we hope to compare these resources with other data sets on tourism and park visitation to further expand our understanding of how coastal restoration influences residents and key stakeholders.

<u>Economic Analyses</u>

To value ecosystem services provided by Alabama reefs, we focused on augmented fish value and erosion control. For augmented fish value, we used methodology described in Grabowski and Peterson (2007) and Grabowski et al. (2012). Specifically, Grabowski and Peterson (2007) utilized augmented fish production estimates from Peterson et al. (2003) and estimated that the annual estimate of fish value at $3.70 per 10m2. Grabowski et al. converted this value to 2011 dollars, which resulted in a value of $4,123 per hectare of oyster reef habitat per year. This value accounts for the dockside value of commercially valuable fish species, and not the value to recreational fishers.

By 2013, Alabama had created a total of 2.01 acres of reef habitat. Using the estimate of fish production per unit reef from Grabowski et al. (2012), these reefs were worth a total of $8,809 in 2013 dollars annually. The cumulative value of these reefs could be calculated under different life span scenarios. For instance, if they exist for an additional 10 years, they would produce an additional $77,393, whereas maintaining them through 2032 would result in an additional $134,980 in fish value in 2013 dollars over this 20-year time span. Future values were adjusted using a discount rate of 3% under these scenarios. These scenarios illustrate the importance of maintaining these reefs well into the future to maximize the return on investment.

The above analyses provide a mechanism to value fish utilization of reef habitat. However, several caveats are worth mentioning. First, Peterson et al. (2003) focused on oyster reef habitat, whereas many of the studies that we examined in Alabama used artificial substrates. However, these studies also quantified fish and mobile invertebrate use of artificial habitat, and found that many of the species that use these substrates are also found on oyster reefs. Second, Peterson et al. (2003) focuses on studies from throughout the Gulf of Mexico and eastern U.S. Zu Ermgassen et al. (2016) revisited and improved upon the methods used in Peterson et al. (2003). Zu Ermgassen et al. (2016) also focused on the Gulf of Mexico region separate from the southeastern U.S.

We are in the process of revisiting and improving upon the economic analyses of fish utilization conducted in Grabowski and Peterson (2007) and Grabowski et al. (2012). Specifically, we are using fish productivity estimates in Zu Ermgassen et al. (2016) to provide regionally specific estimates of fish value. Zu Ermgassen et al. (2016) made several methodological advancements over Peterson et al. (2003), such as including uncertainty in fish density estimates and accounting for age-specific mortality. Therefore, these improvements will enhance our confidence in the economic estimates conducted using this study.

Interestingly, the inclusion of ~30 new studies in Zu Ermgassen et al. (2016) didn't change the estimate of fish production substantially: Peterson et al. (2003) found that oyster reefs throughout the southeastern U.S. and Gulf of Mexico produce 2.6 Kg/yr./10 m2, whereas Zu Ermgassen et al. found that oyster reef in the Gulf of Mexico produce 3.9 Kg/yr./10 m2. In addition to using Zu Ermgassen et al. (2016), we intend to use our review of fish use of the Alabama reefs as a case study once we have updated our valuation of augmented fish production from oyster reef habitat. In particular, we will groundtruth these estimates with the nekton sampling conducted in each study (where available) to make certain that species that are generally augmented by oyster reef habitat were present at a particular site and on each substrate type (including both engineered and natural substrates).

The second ecosystem service providing by reef habitat that we focused on was erosion control. In Grabowski et al. (2012), we used replacement cost valuation to estimate the value of this ecosystem service provided by oyster reef habitat that fringes salt marsh habitat. In particular, we estimated the cost of using breakwaters, stone groins, and stone sills to protect shoreline habitat, which resulted in a shoreline protection value of $85,998 per hectare of oyster reef habitat assuming a 5-m wide reef. While this estimate is likely high, it illustrates that engineering structures aimed at providing similar ecosystem services can be very expensive. In particular, these engineered structures can cost over $500 per m of shoreline (Allison 2001, Grabowski et al. 2012).

The Alabama reefs collectively span ~5.09 km of shoreline. To determine the value of shoreline marsh habitat protected, first we used the shoreline comparisons above of the amount of shoreline erosion/accretion behind these reefs vs. at nearby controls to calculate the amount of habitat loss avoided. Specifically, we calculated the amount of habitat accretion or erosion that occurred behind each reef structure per year during the time period observed by comparing each reef structure to adjacent control treatments without reef structure present. In particular, we used this difference in annual habitat erosion/accretion between reef structures and adjacent controls during the post-restoration time period, typically from the date of construction until 2016 or 2017. We then multiplied this difference for each project by the length of shoreline protected by each structure and summed all of the projects to determine the total amount of habitat protected. For studies that constructed multiple types of reef structures, such as Alabama Port 2011 where bagged shell, engineered concrete, and engineered reef cages were used, we calculated accretion/erosion rates for each structure type separately and then multiplied the difference between each structure type and control by its length and summed these estimates to determine the total habitat protection estimate for the project. For studies without shoreline habitat erosion/accretion data, we used the average accretion/erosion differences for all projects constructed using similar materials (e.g., bags of shell, shell mounds, engineered concrete, or engineered cages). Our estimates suggest that the reef projects collectively protected 0.050 hectares of salt marsh habitat from being lost annually.

To determine the value of erosion control provided by the Alabama living shorelines, we used the following two approaches. First, we used existing data on the cost of conducting salt marsh restoration. Bayraktarov et al. (2016) conducted a review of habitat restoration cost and found that the total restoration cost associated with salt marsh restoration projects was $151,129 per hectare in 2010 dollars. They also reported that the median survival for saltmarsh projects was 64.8%. Therefore, we adjusted our estimates to account for the fact that one third of salt marsh restoration projects typically fail. Using this approach, the total value of tidal wetland erosion control provided by Alabama oyster projects is $12,250 in 2013 dollars. The cumulative value provided by this habitat if it persists for two decades is $187,718 in 2013 dollars.

The second method that we used involves using estimates of ecosystem service functions and associated values provided by salt marsh habitat, such as those provided in Barbier et al. (2011). Barbier et al. (2011) provides values for multiple ecosystem services provided by salt marshes, including raw materials, coastal protection, water purification, fisheries, carbon sequestration, and tourism and recreation. The net value of coastal protection, water purification, fisheries, and carbon sequestration ranged from $26,189 to $61,300 per hectare. Thus, it is preventing the loss of .05 hectares of salt marsh per year that provide ecosystem services worth $1,297-3,035. This estimate is conservative because the economic values associated with many of the ecosystem services provided by salt marshes are not well known for the Gulf of Mexico region, such as those associated with production of raw materials, enhancing recreation and tourism, and upland habitat erosion control, and consequently were not included in our calculations. If the reef structures provide this function over a 20-year lifespan, the cumulative value ranged from $189,209-$442,880 after accounting for annual creation of 0.05 additional marsh habitat and discounting future values by 3%. And while a 20-year functional lifespan for these structures might seem long, monitoring of reef accretion/erosion provisioning by Alabama reef projects covered up to 9 years post restoration. Furthermore, evidence from other oyster reef restoration projects suggest that they can persist well over a decade, especially in the intertidal zone (Powers et al. 2009).

These two approaches of valuing erosion control could be enhanced by a better understanding of the costs of constructing salt marsh and the value of ecosystem service benefits associated with intact salt

marshes. Yet they produced roughly comparable estimates of the cumulative value of erosion protection provided by the Alabama reef sites. Both of these estimates were also ~1.5 to 3 times greater than the value provided by enhancing economically valuable fish species.

Monitoring Metrics

Metrics monitored following the implementation of living shoreline projects in Alabama were compared with those universal monitoring guidelines proposed by Baggett et al. (2014). Baggett et al. (2014) developed a set of Universal Metrics that should be monitored in conjunction with all oyster restoration projects. These metrics focus on oyster recruitment and reef structure, and include: (1) reef areal dimension, (2) reef height, (3) oyster density, and (4) oyster size-frequency distributions. Baggett et al. (2014) also developed a set of Restoration Goal-based Metrics that are recommended to assess ecosystem service-based restoration goals, including: (1) brood stock and oyster population enhancement, (2) habitat enhancement for resident and transient species, (3) enhancement of adjacent habitats, and (4) water clarity improvement.

Numerous metrics were monitored in conjunction with the original 13 living shoreline projects implemented in Alabama. These metrics differed depending on the specific goals of the project and the expertise of the project personnel. No metrics were monitored consistently across all projects.

Oyster recruitment was monitored at least once at all projects. We were able to only identify one sampling event at Alonzo Landing 2005, and no details of sampling methods were provided. At Little Bay 2010, oysters were sampled, but only in terms of presence or absence. Additionally, live and dead oysters were sometimes counted together. Thus, we could not determine if a ‘presence’ value actually included live oysters. All other projects included counts and length measurements of oysters. Due to the variety of reef technologies used across projects, methods were reviewed to determine accurate area estimates for each sampling technique so that data could be compiled and compared across projects. Reefballs were the most difficult to monitor in the field. They were too heavy and/or encrusted within the row of reefballs to remove and count all oysters, but they were too small to utilize standard 0.25 m2 sampling quadrats.

Reef dimensions were monitored at 10 projects. Reef areal dimension, or footprint, was monitored by walking the edge of the reef with the same geospatial units used to collect shoreline position data. Reef height was not directly measured, though vertical profiles were collected by pounding a pole into the sediment at 5 m intervals from the shoreline seaward past the reef. Several problems with these data were identified during data analysis. Reef footprint data varied substantially depending on the sampling date. All reef types were assessed, and even static reef types, such as reefballs and reefBLKs, showed substantial movement. Reef footprints were not always recorded by the same person at each site during each year, and thus, differences in walking methods may have caused these extreme observations. Vertical profile data also varied substantially. Each profile was eye-balled to be walked at the center of each reef or control treatment site, without any permanent guiding markers. Thus, the reef crest did not align from year to year due to differences in shoreline orientation, and starting position and direction of profile collection.

Resident and transient nekton were monitored at seven projects. Six of the seven utilized both seine nets and gillnets to monitor nekton. These projects were all implemented by the same labs, and thus all methods and data were easily compiled and compared. The seventh project, Little Bay 2010, had slightly different goals and was implemented by a different lab. They focused on species using the restored marsh habitats rather than those associated with the breakwater reefs, and used fyke nets for sampling. Thus, these data were not necessarily relevant for assessing habitat enhancement by breakwater reefs. Nekton were also monitored at other projects, but data were not collected according to sound sampling principles, and are useful for providing only anecdotal observations.

Shoreline position was the only adjacent habitat monitored across projects. While these data did not exhibit the extreme variance that reef footprint data did, they were collected in the same manner. Most projects did not include pre-restoration shoreline monitoring, so those data were obtained from aerial imagery or other public sources.

Water clarity parameters were typically monitored, but these impacts are so ephemeral that most assessments of water clarity improvements are conducted via modeling methods.

Overall, we found oyster density, nekton abundance, and shoreline position were the most commonly monitored metrics. These are also critical in assessing the major services associated with living shorelines. When breakwater reefs are a primary component of living shoreline projects, oyster density is a necessary metric. Our results indicate that reef structure or height itself is not enough to provide shoreline protection services, and the recruitment and growth of oysters is important. We also suggest that time is spent during the planning stages of a project to determine the most efficient way to monitor oysters within a known area so that density can be quantified and data can be compared to other projects.

It is critical that metrics can be collected consistently over time and by different personnel and under very limited budgets. Projects implemented by academic researchers involved more technical and/or expensive methods and included more metrics. Projects implemented by practitioners or non-profit entities included less metrics and less technical methods. These less technical methods sometimes resulted in data that were not useful, and thus represent a waste of time and effort that could have been directed elsewhere. Additionally, some of the more technical metrics collected by academic researchers were not relevant at the scale of synthesis science. Thus, unless there is a specific and necessary reason for collecting certain data, the funds and time used to do so should be directed elsewhere. We also observed changes to sampling methods by all parties during the course of the projects. We encourage researchers and practitioners to thoroughly document sampling methods, challenges in the field or lab, reasons for changing sampling protocols, and how new methods will be comparable to previous methods. This adaptive approach to monitoring is important in assessing restoration projects, and can help inform adaptive management strategies for improving the project or future projects.

Implications

The results of this project have been informative to the project team. Academic and practitioner partners have identified changes to make in both focus and practice. We have learned that natural reef technologies are performing better than engineered technologies in general, and this information will be invaluable for planning future projects. We have also been able to streamline our priority monitoring metrics, and have identified the best methods for monitoring. Certain metrics that yielded useless data are now being excluded from future efforts or revised substantially so that efforts will be useful. This project has also allowed the development of new collaborations. We hired a postdoctoral researcher that had not worked with any of the other project team members, and their network is now greatly expanded with new research and practitioner-based colleagues.

The results of this project will be useful for other researchers or practitioners working on living shoreline and oyster reef restoration projects across the Gulf of Mexico and beyond. Valuable information related to the performance of various reef technologies, as well as the usefulness of various monitoring metrics and methods, will help other teams implement successful restoration projects. This will help propel the field of restoration ecology. Synthesis science can provide more direction for future research than individual projects, and thus, this work is important for guiding future science. By informing restoration practitioners and scientists about what reef technologies are providing the most services, this project has importance for society as well. By informing, and thus improving future restoration efforts, more benefits will be provided by these projects for coastal communities and society as a whole.

Unexpected Results

N/A

Project Relevance

The following audiences would be most interested in the results of this project:

- Researchers
- Local Government Officials
- State Government Officials
- Federal Government Officials
- Non-Profit Private Sector
- For-Profit Private Sector
- Other: Coastal homeowners

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Researchers and practitioners will be interested in this project for information about what reef technologies are performing best, and what metrics should be monitored and how. Government officials at all levels will find this project useful. At local and state levels, understanding what living shoreline approaches work best can help inform efforts to implement nature-based shoreline management strategies in their State or locality. Federal government officials will also be interested in these results, but can also use this work to help prioritize projects seeking limited funding pools. Practitioners within the non-profit sector will find this work useful for helping to prioritize their plans for implementing similar projects. For-profit private sectors, including marine contractors, will find this work useful for informing them which reef technologies to focus on training personnel for, obtaining specialized construction equipment, and for helping them to inform clients of what methods work best in providing various benefits they may be seeking. Similarly, as living shorelines are promoted for residential use, coastal homeowners will find the result of this project useful for helping them to understand what reef technology options are available, which methods provide the benefits they are seeking, the economic benefits associated with the ecosystem services they provide, and how they have been perceived by other homeowners.

Education and Training

Number of students, postdoctoral scholars, or educational components involved in the project:

- Undergraduate students: 4
- Graduate students: 3
- Postdoctoral scholars: 1
- Other educational components: 0

IV. DATA AND INFORMATION PRODUCTS

This project produced data and information products of the following types:

- Data

DATA

See attached Data Report.

Relationships between data sets:

Biophysical and ecological datasets relate to metrics that were measured at the living shoreline projects (e.g., oyster abundance, nekton abundance, shoreline position). The social datasets include compiled survey data related to the attitudes, beliefs, and values of the coastal Alabama public and key stakeholders (waterfront residents, recreational fishers) regarding the condition and management of coastal habitats and shorelines. The biophysical and ecological data were analyzed across project locations and technologies to determine the efficacy of different projects in providing environmental benefits and ecosystem services. The social data were reviewed and synthesized to assess potential societal outcomes associated with coastal restoration and living shoreline projects.

Additional documentation produced to describe data:

Workflow procedures used for creating each dataset have been documented for internal use and reference.

Other activities to make data discoverable:
All datasets will be referenced in upcoming scholarly publications so that others can easily discover project data.

V. PUBLIC INTEREST AND COMMUNICATIONS

Most Unique or Innovative Aspect of the Project
This project is one of the first comprehensive analyses of living shoreline projects. Multiple projects implemented over the course of a decade utilized a variety of techniques at a variety of scales to restore oyster reef habitat and protect nearly 3.5 miles of Alabama's coastline. This project evaluates the ecological, physical, economic and social benefits resulting from these projects to identify what techniques are proving most successful from a holistic perspective. The interdisciplinary nature of this synthesis project, and the temporal and spatial scales involved, make this project unique in its ability to provide valuable information about living shoreline projects in the Gulf of Mexico.

Most Exciting or Surprising Thing Learned During the Project
Bagged shell reefs, those constructed by stacking mesh bags filled with oyster shell, work really well. This is exciting because it is one of the most common techniques used to construct oyster reefs in intertidal areas. It is a relatively easy technique to implement, with no heavy-duty equipment or specialized skills needed. This method is also the most amenable to including community volunteers in the restoration process. Community-based restoration projects, though typically small in scale, provide valuable experiences that have large social impacts (Josephs and Scyphers, In Prep). Community involvement in restoration projects connects contemporary societies to cultural keystone species such as oysters, educates the public, and fosters environmental stewardship.

Most Important Outcome or Benefit of Project
This synthesis of living shoreline techniques and benefits will provide information to coastal property owners about the benefits living shorelines can provide and what techniques work best. At both the homeowner and practitioner scales, this work will help those planning living shoreline projects by providing evaluation of a variety of commonly used techniques. This will help ensure future projects are successful in providing numerous benefits for coastal communities.

Communications, Outreach, and Dissemination Activities of Project
This work has been presented to several scientific audiences at Regional and International conferences, including:
Coastal and Estuarine Research Federation Conference (11/2017, Blomberg - Ignite-style talk); Benthic Ecology Meeting (4/2017, Blomberg - Plenary talk); Gulf of Mexico Alliance Meeting (2017, Haner – Oral); Restore America's Estuaries (12/2016, Haner – Oral; Brown – Oral; Blomberg - Poster); A Community for Ecosystem Services (12/2016, Blomberg - Poster);

A press release was prepared in conjunction with Blomberg's plenary presentation at the Benthic Ecology Meeting in April 2017. Information related to this presentation was also released via the following press releases: http://www.wsmv.com/story/35132826/ccu-hosts-international-marine-science-conference- helps-students-find-jobs and https://skimmer.disl.org/issues/article/disl-represented-well-at-benthic-ecology-meeting.

A short video highlighting the project was produced by the Dauphin Island Sea Lab, and can be viewed online: https://www.schoolandcollegelistings.com/US/Dauphin-Island/63383555027/Dauphin-Island-Sea-Lab/videos/10154681285710028.

Project updates were provided to the scientific community on ResearchGate: https://www.researchgate.net/project/Living-Shorelines-Synthesizing-the-results-of-a-decade-of-implementation-in-Coastal-Alabama/update/58fa41021042bf25c0ca91a8.

Scyphers described the project in a 2017 briefing on Capitol Hill to an audience of congressional members, federal agency leadership, and NGO's.
https://news.northeastern.edu/2017/04/27/northeastern-co-hosts-capitol-hill-briefing-on-coastal-sustainability/#_ga%3D2.198581990.873826644.1515761364-2071219220.1451776730

Project Title: Living Shorelines: Synthesizing the Results of a Decade of Implementation in Coastal Alabama										
Project Director: Kenneth Heck										
Data Report										
DataType	**DigitalResourceType**	**Title**	**FileName**	**Creators**	**PointofContact**	**PublicationYear**	**RepositoryName**	**DOIorPersistentURL**	**Keywords**	**Publications**
Ecological/Biological	Tabular/Spreadsheet	Oyster density synthesis	NAS_oyster.xlsx	Blomberg, Brittany	Brittany Blomberg, bblomberg@disl.org, 251-861-2141 x7535	2016	Dauphin Island Sea Lab Data Management Center	TBD	living shoreline, oyster re	TBD
Ecological/Biological	Tabular/Spreadsheet	Nekton density synthesis	NAS_nekton.xlsx	Blomberg, Brittany	Brittany Blomberg, bblomberg@disl.org, 251-861-2141 x7535	2016	Dauphin Island Sea Lab Data Management Center	TBD	living shoreline, oyster re	TBD
Earth and Environmental Sciences	Tabular/Spreadsheet	Shoreline position synthesis	NAS_shoreline.xlsx	Blomberg, Brittany	Brittany Blomberg, bblomberg@disl.org, 251-861-2141 x7535	2017	Dauphin Island Sea Lab Data Management Center	TBD	living shoreline, shoreline	TBD
Geospatial	Geospatial (vector, raster, or gridded)	Swift Tract Shoreline	SwiftTract.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Pelican Point Shoreline	PelicanPoint.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Fort Morgan PLS1 Shoreline	PLS1.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Fort Morgan PLS2 Shoreline	PLS2.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Coffee Island Shoreline	CoffeeIsland.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Alabama Port Shoreline	AlabamaPort.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Helen Wood Park Shoreline	HelenWoodPark.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	South Point aux Pins Shoreline	SouthPointAuxPins.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Geospatial	Geospatial (vector, raster, or gridded)	Northeast Point aux Pins Shoreline	NortheastPointAuxPins.mdb	Knight, Dina	Dina Knight, dina.knight@tnc.org, 251-431-6830	2017	TBD	TBD	living shoreline, shoreline	N/A
Social/Cultural	Geospatial (vector, raster, or gridded)	Social Survey Synthesis	NAS_Social.mdb	Scyphers, Steven	Steven Scyphers, s.scyphers@northeastern.edu, 781-581-7370	2016	Northeastern University Digital Repository Service	TBD	living shoreline, shoreline	N/A