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Review of Scientific Research in and around the Designated Research Area of Gray's Reef National Marine Sanctuary (NW Atlantic)

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Cover:
Densely colonized live bottom reef habitat in Gray's Reef National Marine Sanctuary. Photo: Greg McFall/NOAA

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Because of considerable differences in settings, resources, and threats, each marine sanctuary has a tailored management plan. Conservation, education, research, monitoring, and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The National Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the National Marine Sanctuary System. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and cultural sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries website (https://.sanctuaries.noaa.gov).

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Report Availability

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Abstract

A research area (8.27mi^2) was designated within the 22 mi^2 Gray's Reef National Marine Sanctuary (GRNMS) in December 2011. The purpose of this research area is to increase the opportunity to discriminate scientifically between natural and human-induced change to species, communities, and associated habitats. The ability to conduct investigations in a marine environment relatively free of direct human influences is critical to meet the resource protection and scientific research mandates of GRNMS. Although allowable fishing gear is limited in the sanctuary, recreational fishing continues to impact the sanctuary resources.

The projects described in this report demonstrate that the GRNMS Research Area (RA) is being utilized as designated. That is, it is functioning as a site to study the effects of natural variability from local and regional ecological processes (e.g., predation, competition, climate change, storms) where the direct effects of fishing will not mask, or add a degree of ambiguity, to the interpretation of results. Prior to designation of the RA in 2011, fishing was allowed throughout the sanctuary, and there were no options to study the broad suite of questions governing conservation and sustainable use of natural resources knowing that direct human uses were not directly influencing outcomes.

Over the past several years, 16 projects were implemented along three strands linked to the Research Area. On one strand are those studies that directly and explicitly compare the status of faunal groups inside and outside the RA (e.g., reef fish, invertebrate communities and key taxa on ledges, pelagic forage fish). On the second strand are those studies that simply use the RA as an unimpacted study site (e.g., high spatial resolution acoustic tagging of fishes). Finally, on the third strand are those studies that focus on processes or approaches that support work in the RA now or in the future (e.g., data buoy, sediment processes, acoustic tag detection with mobile platforms, towed video for assessing halo predators).

This report summarizes the status of projects after only five years since RA establishment (2011). This is a relatively short period of time to expect unambiguous results of contrasts due to management status. Indeed, the literature is replete with empirical data demonstrating that response to spatial management occurs over longer periods as ecological processes that mediate population and community dynamics shift due to changes in disturbance regimes and responses to protection stabilize. In any case, current results of the inside-outside comparisons, given the statistical limits in the ability to detect change, suggest that to date human uses outside the RA have minimal impacts and are sustainable. Such results demonstrate the utility of the RA as a reference site that allows continuing assessment of change from multiple drivers absent direct fishing and other use effects regardless of the status of human impacts outside the boundaries. However, the uncertainties of patterns in human use within GRNMS before and after designation of the RA and into the future are important to acknowledge. Understanding

current and future patterns of fishing and vessel use, linked to variation in ecological metrics from seafloor habitats, is needed to make optimal use of the results of comparisons between closed and open areas and to demonstrate that zoning boundaries match the reality of human pressures on the water.

Key findings from each of these projects can be found summarized at the start of each project's page.

Key Words

Research Area, Gray's Reef National Marine Sanctuary, South Atlantic Bight, Georgia, Benthic Community, Fish Community, Hard Bottom, Live Bottom, Temperate Reef, Sub-tropical Reef, Benthic Invertebrate, Fish Distribution, Movement Patterns, Water Quality, Sediment, Marine Protected Area

Introduction

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Designated in December 2011, the southern third of NOAA’s 22-square-mile Gray’s Reef National Marine Sanctuary (GRNMS) is a research area which provides the opportunity for scientists to distinguish scientifically between natural and human-induced change to species populations in the sanctuary (NMSP 2006). Fishing and diving are prohibited in the research area, but vessels are allowed to transit across the area as long as gear is stowed properly; no stopping is allowed. As part of the research area design and process, we provide this report of recent research to demonstrate that the RA is being utilized as designated.

This document highlights sixteen research projects at GRNMS that have utilized the RA in some capacity: those explicitly comparing inside and outside, those using the RA as an unimpacted area, and those that focus on processes that support or aid interpretation of work in the RA. Research topics include benthic invertebrate abundance and distribution, predator and prey fish distribution and abundance, movement patterns of demersal piscivores, and presence of halo predators.

A research area is a “region specifically designed for conducting controlled scientific studies in the absence of confounding factors” (Kendall and Eschelbach, 2006). The ability to conduct investigations in a marine environment relatively free of direct human influences is critical to meet the resource protection and scientific research mandates of GRNMS. The National Marine Sanctuaries Act (NMSA) provides NOAA the authority for comprehensive and coordinated conservation and management of natural resources of a sanctuary. To achieve this, GRNMS requires a research (reference) area where human impacts are limited. There are currently no other natural live bottom areas in the South Atlantic Bight that have been set aside for scientific use.

Because GRNMS is relatively shallow, it affords the opportunity to conduct experiments and make observations using scuba in a productive reef habitat that is relatively close to shore. The proximity of the sanctuary to coastal universities and marine research laboratories makes GRNMS a logical natural area that can be used to further the understanding and management of these complex ecosystems.

Background

The National Oceanic and Atmospheric Administration (NOAA) designated GRNMS as the nation's fourth national marine sanctuary in 1981 for the purposes of protecting the quality of its unique and fragile ecological community, promoting scientific understanding of this live bottom ecosystem, and enhancing public awareness and wise use of this significant regional resource. GRNMS is located 19 miles offshore of Sapelo Island, Georgia, on an area of continental shelf stretching from Cape Hatteras, North Carolina, to Cape Canaveral, Florida (referred to as the South Atlantic Bight).

The sanctuary protects 22 square miles of open ocean and submerged lands of particularly dense nearshore patches of productive "live bottom habitat." "Live bottom" refers to hard or rocky seafloor that typically supports high numbers of invertebrates such as sponges, corals, and sea squirts. These invertebrates thrive in rocky areas, and many attach themselves firmly to the hard substrate, as compared to sandy or muddy "soft" bottom habitats. Within GRNMS there are rocky ledges with sponge and coral live bottom communities, as well as sandy bottom areas that are more typical of the seafloor off the southeastern U.S. coast.

The sanctuary is influenced by complex ocean currents and serves as a mixing zone for temperate (colder water) and sub-tropical species. An estimated 200 species of fish, encompassing a wide variety of sizes, forms, and ecological roles, have been recorded at GRNMS. Loggerhead sea turtles, a threatened species, use GRNMS year-round for foraging and resting, and the highly endangered North Atlantic right whale is occasionally seen in Gray's Reef.

The sanctuary contains one of the largest nearshore live-bottom reefs in the southeastern United States. Within the sanctuary, rock outcroppings stand above shifting sands. The series of rock ledges and sand expanses has produced a complex habitat of burrows, troughs, and overhangs that provides a solid base for the abundant sessile invertebrates to attach and grow. This topography supports an unusual assemblage of temperate and tropical marine flora and fauna. This flourishing ecosystem attracts numerous species of benthic and pelagic fish including mackerel, grouper, red snapper, black sea bass, and angelfish. Since GRNMS lies in a transition area between temperate and tropical waters, the composition of reef fish populations changes seasonally.

The idea of a research-only area was first raised by members of the public in 1999 during the early stages of the GRNMS management plan review process at public scoping meetings. The GRNMS Sanctuary Advisory Council (SAC) set a target to increase the opportunity to distinguish, scientifically, between natural and human-induced change to species populations in the sanctuary (NMSP 2006). As a means to reach this target, the SAC formed a broad-based Research Area Working Group (RAWG) to consider the concept of a research area within the sanctuary.

The RAWG consisted of representatives from research, academia, conservation groups, sport fishing and diving interests, education, commercial fishing, law enforcement, and state and federal agencies. It employed a consensus-driven, constituent-based process and identified several general characteristics to be included for an effective RA (Kendall and Eschelbach, 2006):

1) a large number and diversity of ledge types because ledges are the most important bottom type in the sanctuary and the target of most research needs;
2) the full spectrum of other bottom types in the sanctuary besides ledges in order to encompass the full variety of habitats for research;
3) a large number of prior research sites to serve as a baseline for comparison with future studies;
4) as few of the preferred bottom fishing sites as possible (provided that guidelines 1-3 above are not compromised). Bottom fishing should be prohibited within the RA since it could confound research; and
5) a suitable number and area of ledges, other bottom types, and prior research outside the RA to serve as a comparison to sites within the RA.

In addition, a Geographic Information System (GIS) tool (Kendall and Eschelbach, 2006, Kendall et al 2008) was developed by NOAA to analyze options RAWG members brought forward; this tool is described in more detail in the environmental impact statement (2006) supporting this action.

The principal conclusion of the RAWG, which was ultimately adopted by the SAC, was that significant research questions exist at GRNMS that can only be addressed by establishing a research (reference) area. The final SAC recommendations to NOAA, presented in 2008, also included the unanimous recommendation that all fishing be prohibited in the RA.

In the decision to recommend prohibition of all fishing in the RA, the RAWG took into consideration new information on the growing knowledge of the linkages between benthic and pelagic natural communities. The RAWG also considered methods used by sport fishermen to fish both coastal pelagic and bottom fish (reef) species at the same time. In addition, downriggers and planers, types of fishing gear that are currently permitted in the sanctuary, allow anglers to fish the entire water column, including near the bottom. These gear types can impact benthic communities and allow catch of bottom fish, a primary marine resource to be studied in the RA. Therefore, allowing any fishing including trolling for pelagic fish species could significantly compromise the integrity and effectiveness of a research area.

Law enforcement officials expressed concern that the enforcement of prohibitions on fishing will be more difficult if diving or stationary vessels were allowed to continue in the RA, due to the difficulty of determining the activities of a boat’s occupants from a distance or as officers approach a boat. The SAC also observed that any recreational diving activity in the RA would make law enforcement difficult and could undermine the validity of the RA.

From 2004 to 2008, the RAWG and SAC also continued to evaluate criteria and boundaries utilizing the GIS tool and incorporating new information as it became available.

Ultimately, four boundary scenarios were recommended as viable locations for a research area in GRNMS. These boundary scenarios and several activity restrictions became the focus of public scoping during March and April 2008. After consideration of public comments and deliberations by the RAWG, the sanctuary superintendent received final recommendations from the SAC in January 2009. The action presented in this final rule is the direct result of the RAWG's recommendations that were adopted by the SAC and provided to the GRNMS superintendent, comments received during the spring 2008 public scoping, and public review of the proposal in a proposed rulemaking and draft environmental impact statement. Several alternatives to the action were analyzed in the final environmental impact statement.

Declaration of the research area within Gray's Reef National Marine Sanctuary

NOAA proposed to establish a research area in GRNMS to provide for comprehensive and coordinated conservation and management of natural resources consistent with the National Marine Sanctuaries Act (NMSA) (16 U.S.C. 1431 et. seq.). Pursuant to section 304(a)(5) of the National Marine Sanctuaries Act (16 U.S.C. 1434(a)(5); NMSA), NOAA provided the South Atlantic Fishery Management Council (SAFMC or Council) with the opportunity to develop fishing regulations to implement the goals of the RA. On March 4, 2009, the SAFMC passed a motion to: "Defer to Gray's Reef NMS for rule- making in terms of the establishment of the Research Area." On April 22, 2009, the Council's decision was formally communicated to the GRNMS superintendent.

Regulations of the RA were published in the Federal Register (Volume 76, No. 199) on Friday, October 14, 2011. After a 45-day review period, the designation and regulations took effect on December 4, 2011 (published on October 14, 2011 (76 FR 63824)).

Purpose

The purpose of a research area is to increase the opportunity to discriminate scientifically between natural and human-induced change to species populations in the sanctuary. Although allowable fishing gear is limited in the sanctuary, recreational fishing continues to impact the resources of GRNMS (ONMS 2008). Without having an area of the naturally-occurring live bottom devoted to research and zoned to be devoid of direct human impacts, it becomes difficult to scientifically understand how these reefs function. In fact, the principle conclusion of the broad-based Sanctuary Council's (SAC) RAWG was that significant research questions exist at GRNMS that can only be addressed by establishing a research area closed to fishing and other human activities. The RA allows researchers to more accurately determine the effects of natural events (e.g., hurricanes) and to study impacts of climate change and ocean acidification, which can be better determined in the absence of additional factors like fishing and diving.

The boundary option chosen for the RA was favored by most sanctuary users and was expected to displace a minimal number of sanctuary visitors. Roughly eight square miles and relatively free of human activity, the RA is the southern third of the sanctuary. As part of the RA designation and process, this document is offered as a progress report of 16 projects that have occurred throughout GRNMS during the time of the RA designation. Each of these project reports provides a brief summary of work and includes the question addressed, measurements taken, significant results, and details of the study.

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Project 1. Assessments of sessile benthic invertebrate communities inside and outside Gray's Reef National Marine Sanctuary Research Area, 2011-2016

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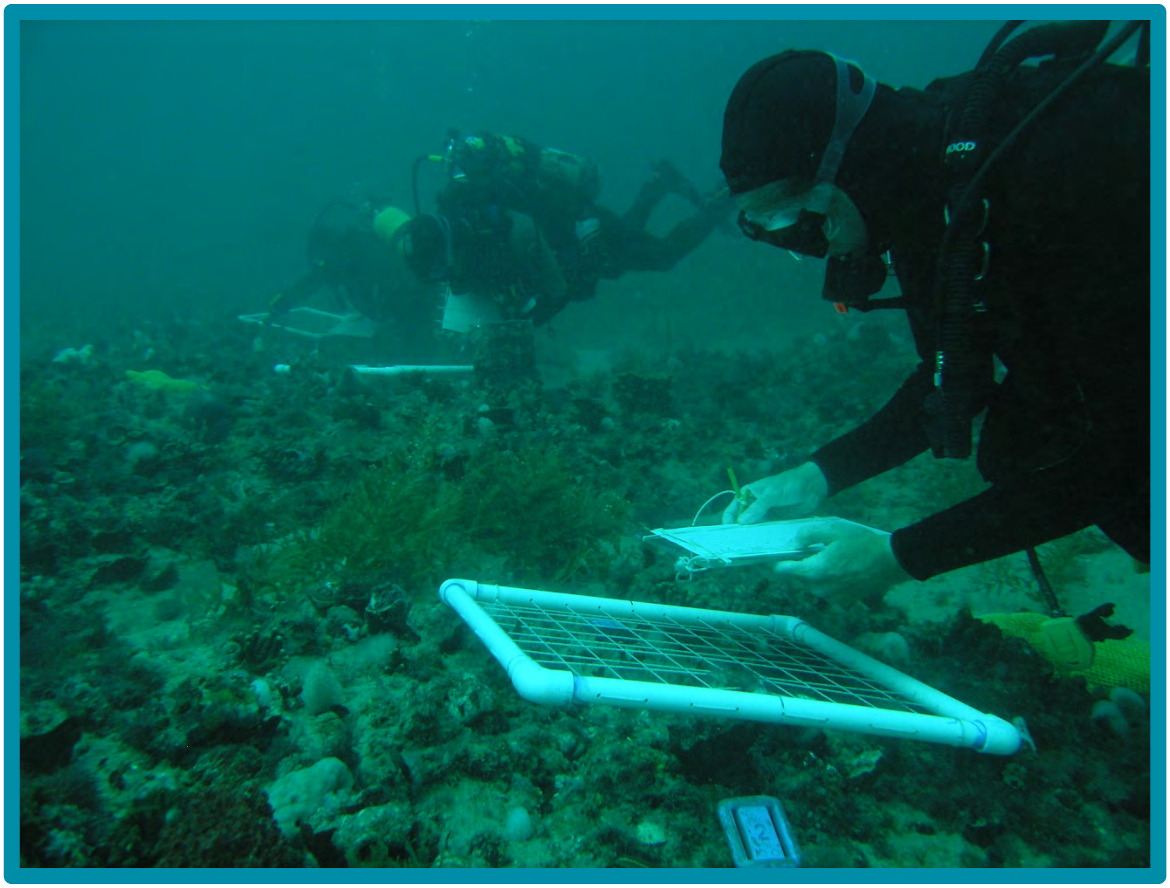

Divers document invertebrate abundance and diversity. Photo: Paula Whitfield/NOAA

Question addressed

Do the diversity and abundance of sessile benthic invertebrate populations inside and outside Gray's Reef National Marine Sanctuary Research Area differ initially and/or over time?

Measurements

Five times between 2011 and 2016, species richness, species diversity, species composition, and percent cover of the sessile benthic invertebrates encrusting rocky outcrops were quantified at sites inside and outside the RA. Quantification was completed by divers using 0.5 x 0.5 m quadrats. In each year the monitoring was carried out, there was a concerted effort to revisit the same sites and to have an equal number of sites located inside and outside the RA.

Key findings

- The sessile benthic invertebrate communities on hard substrata inside and outside the RA were similar in terms of species richness, species diversity, and percent cover within each survey year.
- The benthic invertebrate species that were the dominant space occupiers differed in 2016 from all other years, indicating that the survey methods were robust enough to detect changes in community composition.

Project narrative

In situ monitoring conducted prior to and after implementation of the RA in GRNMS documented a vibrant and diverse sessile benthic invertebrate community. The invertebrate communities on hard bottom reefs inside and outside the RA displayed high similarity within years in terms of species richness, species diversity, and percent cover. There was also high similarity across years with the exception of 2016 where, relative to the prior four sampling periods, shifts in the dominant space occupiers were detected. The result observed in 2016 suggested that the sampling scheme implemented was adequate to detect changes in invertebrate community composition and structure.

Bottom habitats of the Georgia continental shelf consist primarily of soft substrate. However, rocky outcrops covered with algae and sessile benthic invertebrates constitute approximately 20% of the bottom. These live bottom reefs provide topographic complexity and serve as critical habitat for reef fish and marine invertebrate communities (NOAA 2006). GRNMS is an excellent example of this South Atlantic Bight (SAB) hard bottom community, with 24% of the bottom classified as sparsely or moderately colonized live-bottom and approximately 1% as densely colonized (Kendall et al. 2005). In May 2011, approximately six months prior to enforcement of the RA, an initial assessment of the sessile benthic invertebrate communities (corals, sponges, sea squirts, etc.) colonizing rocky outcrops within GRNMS was conducted. The objectives were to

(1) provide "time zero" data on sessile benthic invertebrate populations to the lowest possible taxonomic level and (2) determine if sessile benthic invertebrate populations were similar inside and outside the RA. These surveys were repeated in subsequent years at as many of the original sites as time and weather allowed (Table 1.1). The goal of surveys conducted after 2011 was to determine how benthic invertebrate populations change over time inside and outside the RA, with the ultimate objective of evaluating the impact of the RA on the health of invertebrate populations.

Ledges surveyed for sessile invertebrates were medium to high in terms of relief, medium to large in terms of ledge area, and considered densely colonized hard bottom based on sites previously classified with multibeam data or by divers (Kendall et al. 2007). A potential universe of ledges that met the above criteria was created in ArcGIS and random points were then overlaid with a minimum separation distance of 50 meters. Study site locations were selected from the random points distributed approximately equally within the RA and outside the RA. Information on the mean heights for ledges used in this survey can be found in Project 5, Figure 5.3. Sessile benthic invertebrates were quantified in 0.5 x 0.5 m PVC quadrats. Scuba divers placed the quadrats haphazardly along the scarp (edge of the ledge where it drops off to sand) approximately 1 to 2 m apart and then proceeded to identify each invertebrate to the lowest taxonomic level possible. Divers moved down the ledge scarp in a "leapfrog" type fashion and continued surveys until the dive team had completed a combined total of at least 12 quadrats. This number was based on preliminary investigations determining that 12 quadrats encompassed 95% or more of all the species present at a site.

Sessile benthic invertebrate surveys were conducted each year since the RA was established, except 2015. Statistical comparisons of species richness, diversity, and percent cover inside and outside the RA were completed for all years quadrat data were collected except 2012, when tropical storm Beryl prevented an adequate number of sites from being surveyed (Table 1.1). In total, 2,047 quadrats were completed between 2011 and 2016 and, by design, were as evenly distributed as possible among rocky outcrops located inside and outside the RA.

Mean species richness ranged from 10 to 14 species/m^2 across years (Figure 1.1); however, the list of potential species continued to grow from year to year as new records appeared within the quadrats or on-going taxonomic efforts identified species that could only be classified to the generic level previously. For example, in 2015, the species identities of nine tunicates that previously were listed as unknown or were identified only to the generic level, were confirmed (L. Stefaniak, pers. comm.). In 2011, prior to enforcement of the RA, no significant differences in species richness were detected when comparing hard bottoms occurring inside and outside the RA. A two-way analysis of variance (ANOVA) using year and management zone as factors confirmed that this pattern of no significant differences in species richness between zones was maintained across years, although there were significant differences among years (Figure 1.1). The cause of these differences in species richness across years is not clear, but it is unlikely they result from the timing of the bottom surveys because all were conducted between late May and early July in each year (Table 1.1).

Percent cover and species diversity were also similar inside and outside the RA, both prior to (i.e., 2011) and after establishment of the protected zone. Interestingly, both of these metrics were significantly higher in 2014 and 2016 than in 2011 and 2013 (Figure 1.1). While it is tempting to interpret these differences as actual increases in percent cover and diversity, they are more likely a product of (1) enhanced efforts to document the presence of macroalgae in the latter two years, and (2) as noted above, the continually expanding species list.

Statistical analyses of percent cover based on major taxonomic groupings did reveal minor differences between management zones (Figure 1.2). Specifically, cnidarians and bryozoans showed inside/outside differences in 2011: percent cover of cnidarians was higher inside the RA and bryozoans outside. This pattern was maintained for cnidarians in 2013, but no significant differences in percent cover were detected for any of the invertebrate groups in 2014 and 2016. Tunicates were the dominant space occupiers in all years except 2016, but the explanation for this shift in percent cover was unclear.

In summary, *in situ* monitoring conducted prior to, and after implementation of the RA in GRNMS documented a vibrant and diverse sessile benthic invertebrate community. The invertebrate communities on hard bottom reefs inside and outside the RA displayed high similarity in all years in terms of species richness, species diversity, and percent cover. However, there were shifts in the dominant space occupiers in 2016, suggesting that the sampling scheme implemented was adequate to detect changes in invertebrate community composition and structure. Given this conclusion, future efforts to assess the effectiveness of the RA in maintaining ecosystem health within GRNMS should continue to include monitoring of the sessile benthic invertebrate assemblage.

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Table 1.1. Dates sessile benthic invertebrate surveys were conducted in Gray's Reef National Marine Sanctuary, number of rocky outcrops visited overall and based on management zone, and total number of 0.5x0.5 m quadrats completed over all sites.

Year	Survey Dates	Total Sites	Inside	Outside	Total Quadrats	Photos
2011	May 18-28	36	19	17	387	Yes
2012	June 1-5	12	6	6	178	Partial
2013	June 3-14	36	18	18	575	No
2014	June 9-19	36	18	18	492	No
2016	July 8-15	32	16	16	415	No

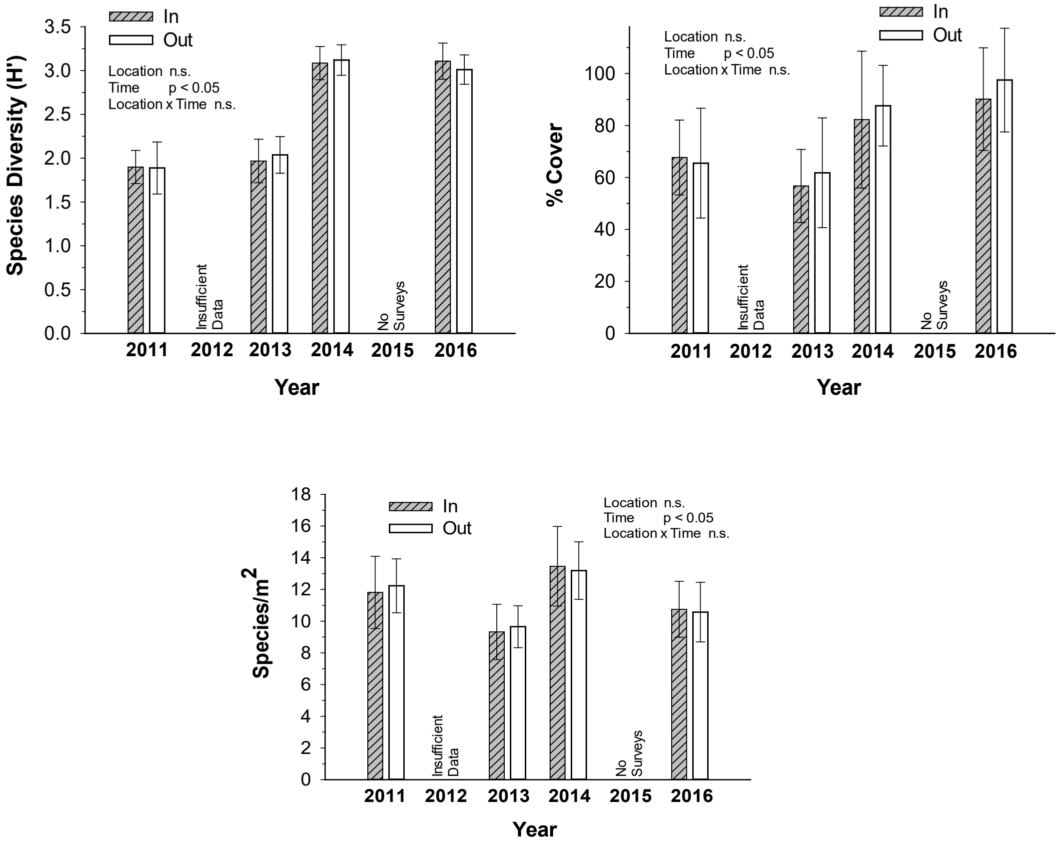

Figure 1.1. Species richness (# Species/m2), percent cover, and species diversity for sessile benthic invertebrates surveyed at Gray's Reef National Marine Sanctuary between 2011 and 2016. A two-way analysis of variance detected no significant differences in any of the parameters when comparing areas inside vs outside the Research Area, but all three measures differed significantly among years.

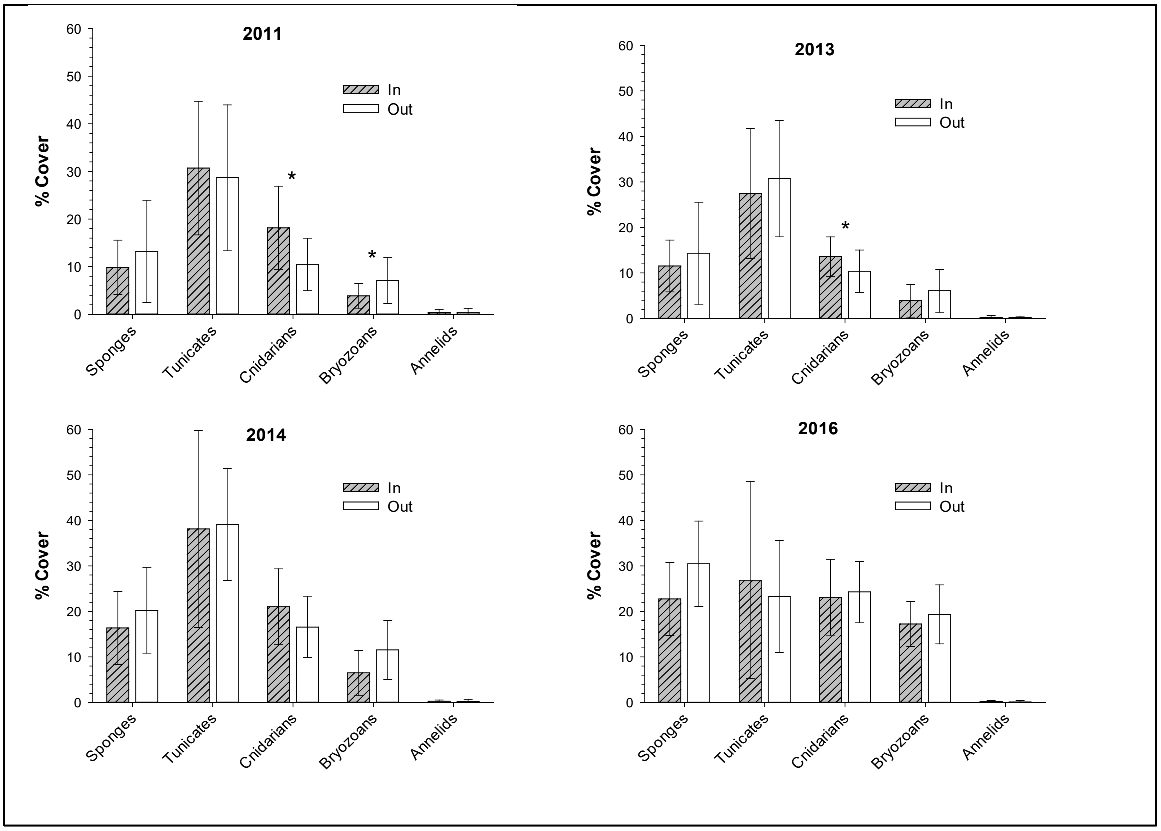

Figure 1.2. Percent cover of the dominant taxonomic groups for all years that sessile benthic invertebrate surveys have been conducted inside and outside the Research Area at Gray's Reef National Marine Sanctuary. Significant differences in percent cover, where they occur, are denoted with an *.

Project 2. Survey of sea urchins and sea stars within Gray's Reef National Marine Sanctuary, 2014-2017

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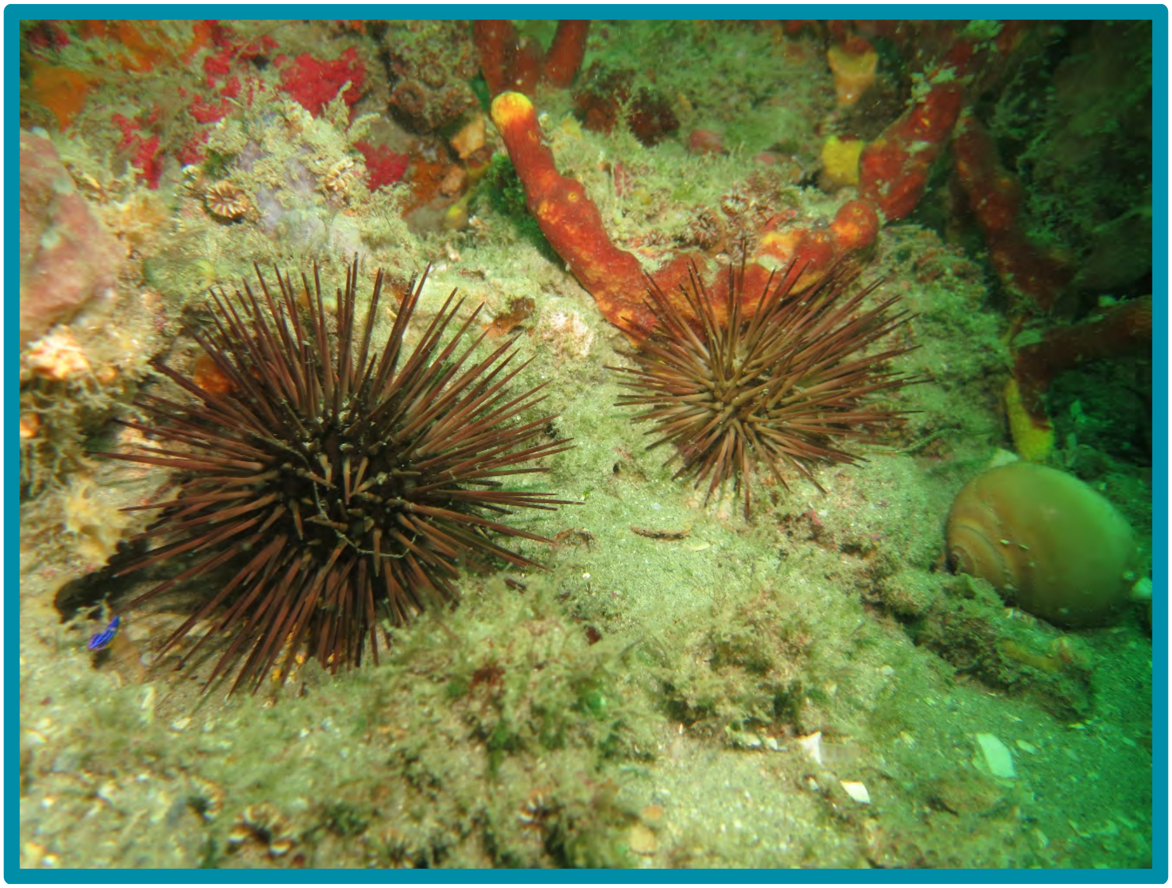

Two purple-spined sea urchins, *Arbacia punctulata*, at Gray's Reef National Marine Sanctuary. Photo: Tim Henkel/Valdosta State University

Question addressed

What is the abundance and distribution of sea urchins and sea stars living on hard bottom habitats within GRNMS?

Measurements

The density of sea urchins and sea stars were measured along linear transects. Surveys were conducted using scuba during June 2014 (n=13), Aug 2015 (n=26), July 2016 (n=63), and June 2017 (n=65).

Key findings

- Three species were regularly observed within GRNMS: *Arbacia punctulata*, *Lytechinus variegatus*, and *Echinaster spinulosa*.
- For each of the three common species, there was no difference in density between 2016 and 2017. In addition, there was no detectable difference comparing average density inside and outside the GRNMS RA.

Project narrative

The hard bottom habitat at GRNMS provides an attachment surface for a diverse array of sessile invertebrates, including corals, sponges, and ascidians, as well as algae. This living hard bottom further supports diverse assemblage of fishes. These communities have been well appreciated for some time (Kendall et al. 2007). Less is known about the mobile benthic fauna that inhabit GRNMS. The present work seeks to assess the abundance and distribution of two groups of mobile benthic invertebrates: sea urchins and sea stars.

Sea urchins and sea stars are common members of benthic communities that consume benthic invertebrates and algae. Predation pressure by both sea urchins and sea stars can have dramatic impact on subtidal community structure (Babcock et al. 1999, Duggins 1983). In addition, these species can be important prey for fishes. Specifically, urchins are known to be consumed by common fishes at GRNMS, including sheepshead, triggerfish, and nurse sharks.

Surveys were first conducted at GRNMS in June 2014. At each site, a transect line was laid along the upper ledge of exposed hard bottom when present and run parallel to the ledge. If no distinct exposed hard bottom was present, the transect line was haphazardly laid. All urchins and sea stars within 1 m either side of the transect line were identified and counted. Sampling effort was increased over the four-year period (Table 2.1), and efforts were made to balance sampling inside and outside of the designated RA in GRNMS.

In total two species of urchin and five species of sea star were found within transects (Table 2.2). The most common species encountered were the sea urchins *Lytechinus variegatus* and *Arbacia punctulata* and the sea star *Echinaster spinulosus*. The remaining four species of sea star were found in very low abundance (1-20 individuals for all four years). These species live primarily in sand plains, often not visible, just beneath the surface of sand. Thus, the low abundance in the present surveys is likely a function of sampling location and not actual abundance.

Of the three common species, *A. punctulata* was most abundant (n=518), followed by *E. spinulosus* (n=385) and *L. variegatus* (n=105). All three species have a wide distribution, occurring as far north as at least North Carolina, and south into the Caribbean (Hendler et al. 1995; Clark and Downey 1992). The densities of each species within GRNMS were extremely variable (Figure 2.1), though the variation decreased as sampling effort increased with the lowest variation observed for the sea urchins the 2016 and 2017 sampling periods. Differences in both the means and the variation observed may also be due to the different months sampled and associated abiotic or biotic environments throughout the summer months.

Based on the coefficient of variation (CV) > 1, all three species are patchily distributed within GRNMS, with *L. variegatus* exhibiting the highest CV, followed by *A. punctulata* and *E. spinulosus* (4.15, 2.23, 1.65 respectively). Across all four years, the average density (individuals per 10 m^2 ±SE) of each was 0.58 ±0.10 *A. punctulata*, 0.12 ±0.04 *L. variegatus*, and 0.40 ±0.05 *E. spinulosus*. The maximum observed density (individuals per m^2) was 13 *A. punctulata* (June 2014), 5.3 *L. variegatus* (Aug 2015), and 4.3 *E. spinulosus* (Aug 2017). Sixty-one identical sites were surveyed in 2016 and 2017 and no difference in density was detected for any of these species (Wilcoxon signed rank test, $p > 0.05$). In addition, there was also no difference in the density of these three species between inside or outside the RA in either 2016 or 2017 (Kruskal-Wallis $p > 0.05$; Figure 2.2).

The average density of *A. punctulata* was similar to densities observed in 20 m sites off the Gulf Coast, though greater densities have been found of both *A. punctulata* and *L. variegatus* in shallower sites (Hill and Lawrence 2003). Previous work has also found that temperature and to a greater extent food availability can impact energy budgets of these two species (Hill and Lawrence 2006). These two species appear to partition food resources despite the ability of both to consume invertebrates and algae. Where they co-occur, *A. punctulata* preys primarily on sessile invertebrates, though it will consume algae when it is available. *Lytechinus variegatus* consumes macroalgae and epibionts, and readily consumes drift species (Cobb and Lawrence 2005). At GRNMS, *L. variegatus* was frequently observed moving during the day, while covered with shells and rubble. Reliance on drift algae may permit greater movement of this species throughout GRNMS.

Future work should consider both the biotic and abiotic factors structuring the distribution of these species. Correlations between available benthic food as well as pelagic predators may predict the spatial variability observed at GRNMS. In addition, future efforts should examine the distribution during other times of the year. Both urchin species spawn in the spring or early summer in cooler locations such as GRNMS (Hendler et al. 1995), and habitat use may be a function of spawning as well as food availability and abiotic conditions. Given the variation observed in the present work, future efforts should also include a large sampling regime across the GRNMS.

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Table 2.1. Dates, number of transects (n) and area surveyed (m^2) both inside and outside of the Gray's Reef National Marine Sanctuary Research Area between 2014 and 2017.

	Inside Research Area		Outside Research Area		Total	
Dates	**n**	**Area (m^2)**	**n**	**Area (m^2)**	**n**	**Area (m^2)**
2014 Jun	6	140	7	140	13	280
2015 Aug	13	780	13	780	26	1,560
2016 July	33	2,140	30	1,812	63	3,952
2017 Jun	35	2,100	30	1,840	65	3,940
Total	**87**	**5,160**	**80**	**4,572**	**167**	**9,732**

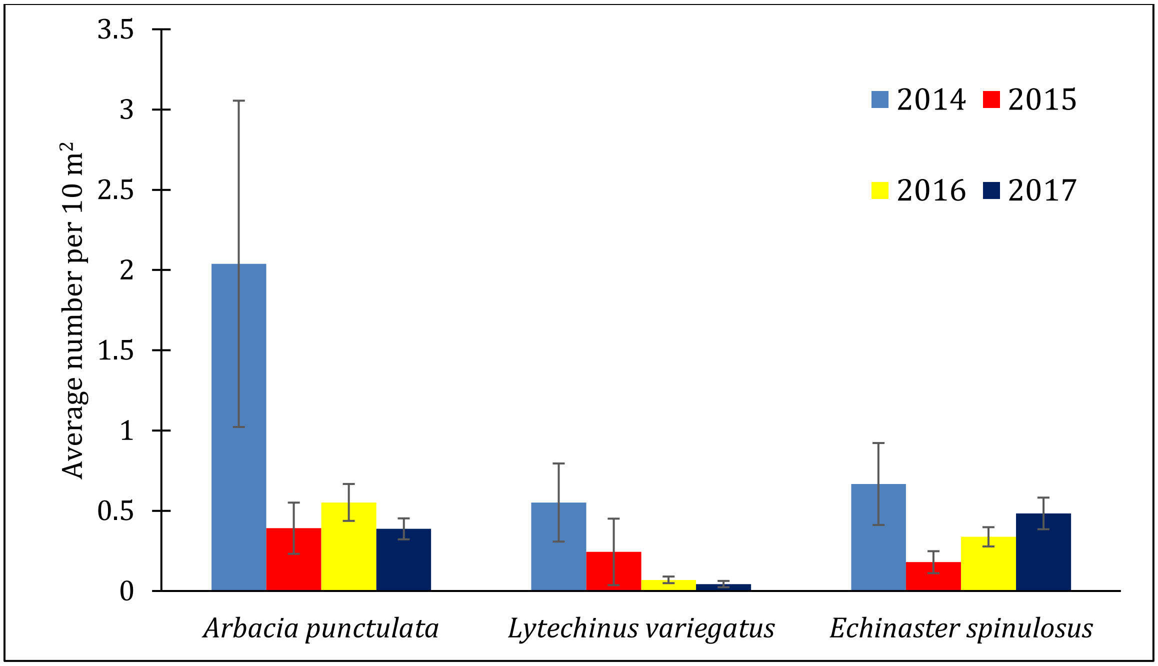

Figure 2.1. The average number of individuals per 10 m^2 (±SE) observed along transects from 2014 – 2017.

Table 2.2. Species of sea urchin and sea star observed in transects from 2014 - 2017.

Class	**Species**
Asteroidea (sea stars)	*Asterias forbesi* *Astropecten articulatus* *Astropecten duplicatus* *Echinaster spinulosus* *Luidia clathrata*
Echinoidea (sea urchins)	*Arbacia punctulata* *Lytechinus variegatus*

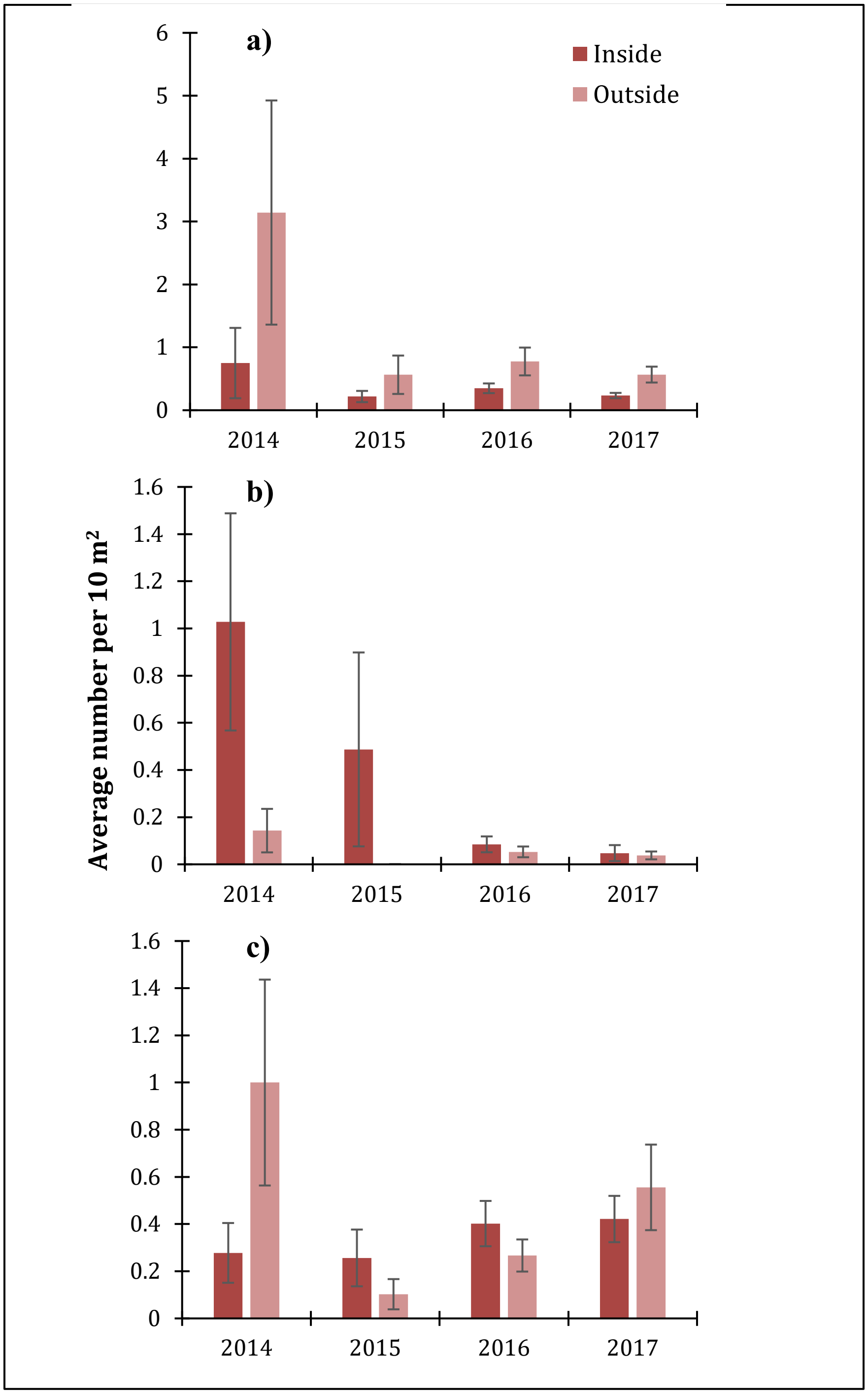

Figure 2.2. Average number per 10 m^2 of a) *Arbacia punctulata*, b) *Lytechinus variegatus*, and c) *Echinaster spinulosus* inside (dark bars) and outside (light bars) the Research Area from 2014 to 2017.

Project 3. Sessile invertebrate colonization and succession patterns on rocky outcrops, 2012-2013

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Sponges, corals, and sea squirts blanket the bottom at many areas in Gray’s Reef National Marine Sanctuary. Photo: Daniel Gleason/Georgia Southern University

Questions addressed

1) Do developing sessile invertebrate communities on rocky outcrops in GRNMS exhibit a predictable pattern of succession? 2) Are the sessile invertebrate recolonization patterns for small patches of open space that become available on rocky outcrops influenced by the composition of the invertebrate community in the immediate vicinity?

Measurements

Sessile invertebrate community development was tracked for 14 months on paving tiles (30 x 30 cm) deployed in July 2012 at four physically separated rocky outcrops within GRNMS. These tiles (15 total per site), as well as the adjacent benthic community on natural substrata, were photographed each month through September 2013. Species composition, percent cover, and diversity were quantified from the photographs each month.

Key findings

- Succession of the sessile benthic invertebrate community on hard substrata does not follow a consistent and predictable pattern.
- Differing successional trajectories for the sessile, benthic invertebrate communities among rocky outcrops may translate into bottom-up effects on mobile invertebrates and fish species.

Project narrative

The taxa of sessile invertebrates colonizing the tiles were similar across all four sites in the first three months after deployment but diverged after that. The differing patterns of community development observed among the four sites indicated that sessile invertebrate succession in this system is not predictable and that the extant community plays a role initially in determining which species are involved in the recolonization of open space.

Documenting patterns of sessile invertebrate community development is important for predicting recovery patterns after disturbance and designing effective marine reserves. In the South Atlantic Bight (SAB), invertebrate assemblages can differ significantly from one rocky outcrop to another, but the factors driving these differences are not well understood. To obtain a better understanding of the factors driving sessile invertebrate community development at GRNMS, extant community structure on natural substrata and colonizing organisms on artificial substrata were documented at sites within GRNMS over the course of 14 months. It was predicted that the surrounding natural community would influence recolonization patterns of sessile invertebrates because this result has been observed in other studies conducted in temperate marine habitats (Osman and Whitlatch 1995b, Fioravanti-Score 1998, Smale 2012). Additionally, it was predicted that the successional trajectory for sessile invertebrates would be random and would differ among the developing communities at each of the four sites because McDougall (1943) and Sutherland and Karlson (1977) showed that colonization of invertebrates in other regions of the South Atlantic Bight did not match classical succession models.

Community development was followed for 14 months on paving tiles (30 x 30 cm) deployed in July 2012 at four sites within GRNMS, two inside the RA and two outside (Figure 3.1). These tiles (15 total per site) were photographed, along with the adjacent natural community, each month through September 2013. Species composition, percent cover, and diversity were quantified from the photographs each month using Coral Point Count with Excel Extensions (CPCe) software version 6 (Kohler and Gill 2006). Organisms were identified to the lowest possible taxonomic level, most often to genus.

Over the course of the study the developing sessile invertebrate communities on the tiles diverged significantly, indicating that a predictable pattern of succession was not occurring in this system (Figure 3.2). The percent similarity between extant and developing communities was greatest at the four- to six-month mark but diverged as the study continued (Figure 3.3). This result suggested that the surrounding community did exert some influence on the successional process, but that the impact was most pronounced early in benthic community development and only evident after an initial one-to-three-month period in which the tiles were becoming "seasoned" with organisms such as bacterial biofilms and coralline algae, that promote settlement of benthic invertebrates.

If, as suggested by these results, extant and developing communities do not converge on a single end-point on SAB temperate reefs, it follows that these differences may translate into bottom-up effects on mobile invertebrates and fish species (Sale et al. 2010, Burt et al. 2011). Not only do these communities fail to converge on a single end-point, but percent cover and species diversity remained lower in all developing communities compared to the extant community after 14 months of development (Figures 3.5 and 3.6, respectively). Key benthic invertebrates in this system that include the habitat-forming species *Schizoporella cornuta* (bryozoan)*, Ircinia campana* (sponge), and *Oculina arbuscula (hard coral)*, as well as others, were not present in the developing communities at the end of the study. Given the slow recovery time of some benthic invertebrates within the communities in the SAB, it is also likely that these altered bottom-up effects may be manifested for years after a disturbance.

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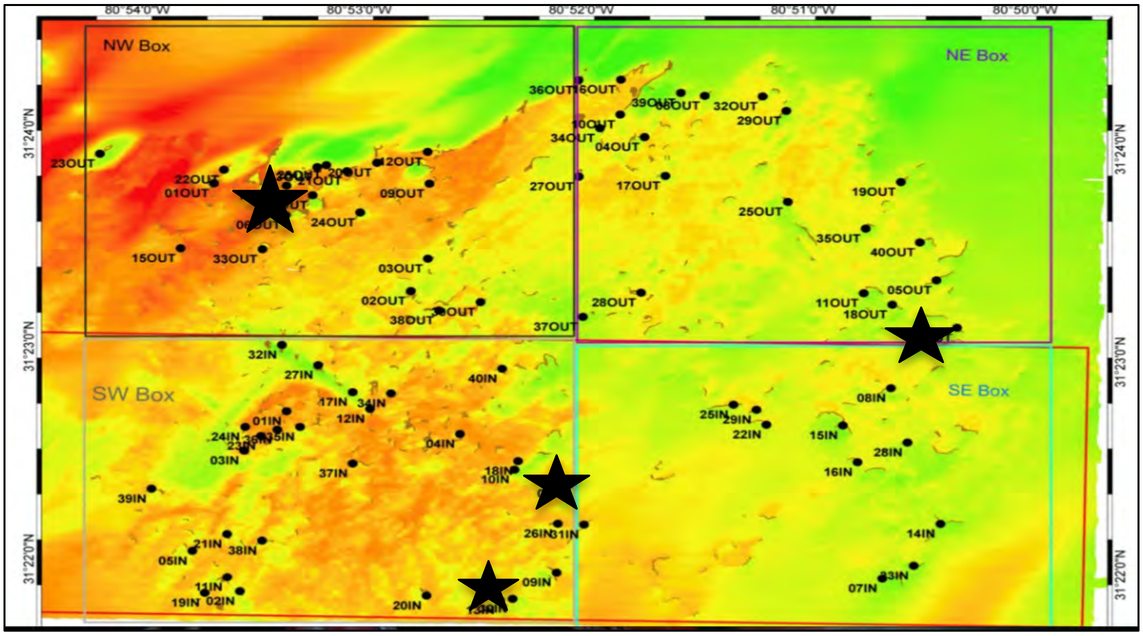

Figure 3.1. Multi-beam image showing the location of the study sites within Gray's Reef National Marine Sanctuary. The two sites in the southern portion of the sanctuary were inside the Research Area and the two in the northern portion were outside the Research Area. Image: Christine Buckel/NOAA

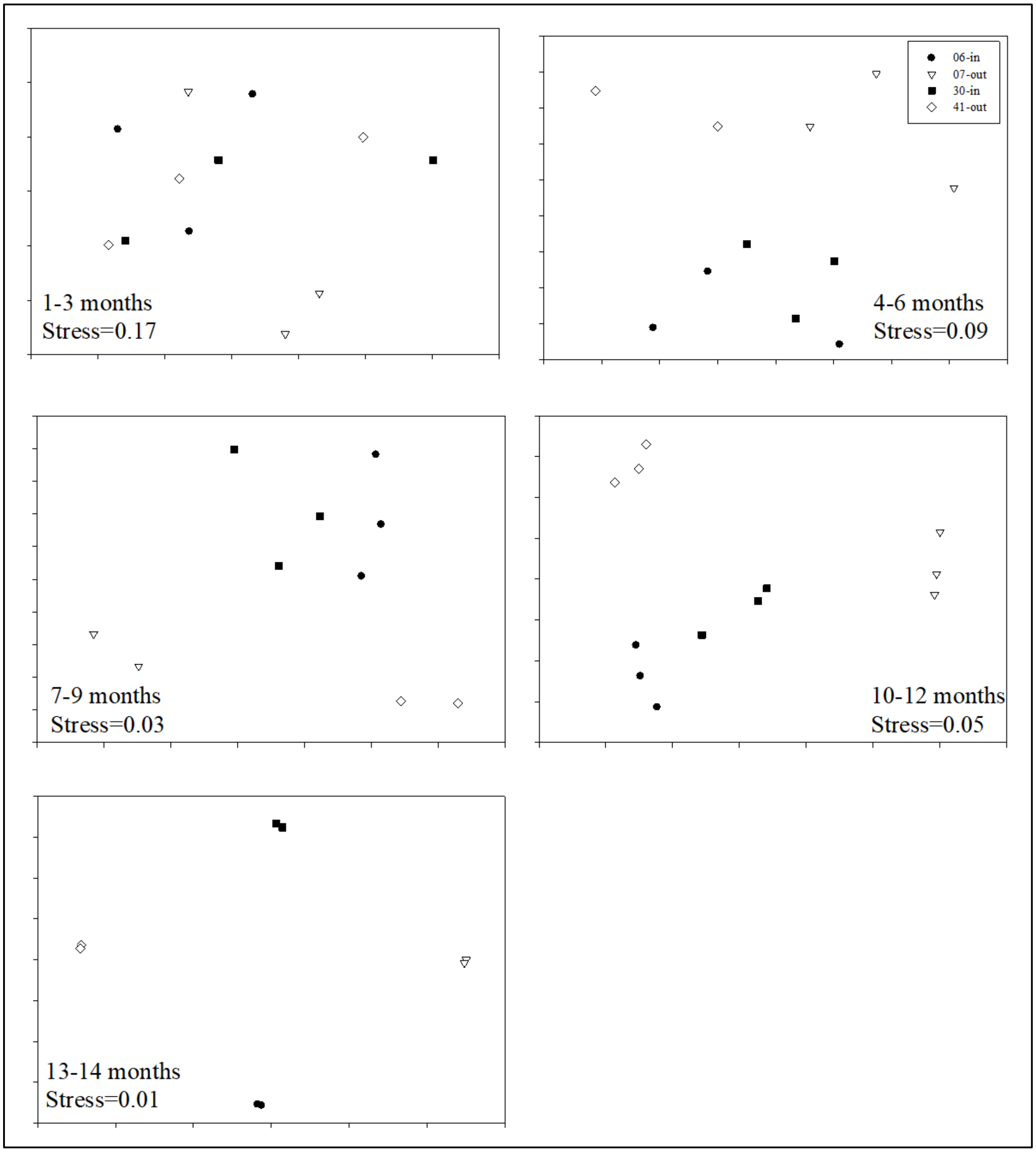

Figure 3.2. Two-dimensional nonmetric multi-dimensional scaling plot of developing communities at each site. Each point represents the square root transformed mean abundance of all organisms on the 15 replicate tiles for one month of sampling. Plots are grouped by two- or three-month time blocks. As can be seen from the successive plots, the developing sessile invertebrate communities diverge over time and would likely reach different endpoints if followed to their culmination. Image: Brittany Poirson/Georgia Southern University

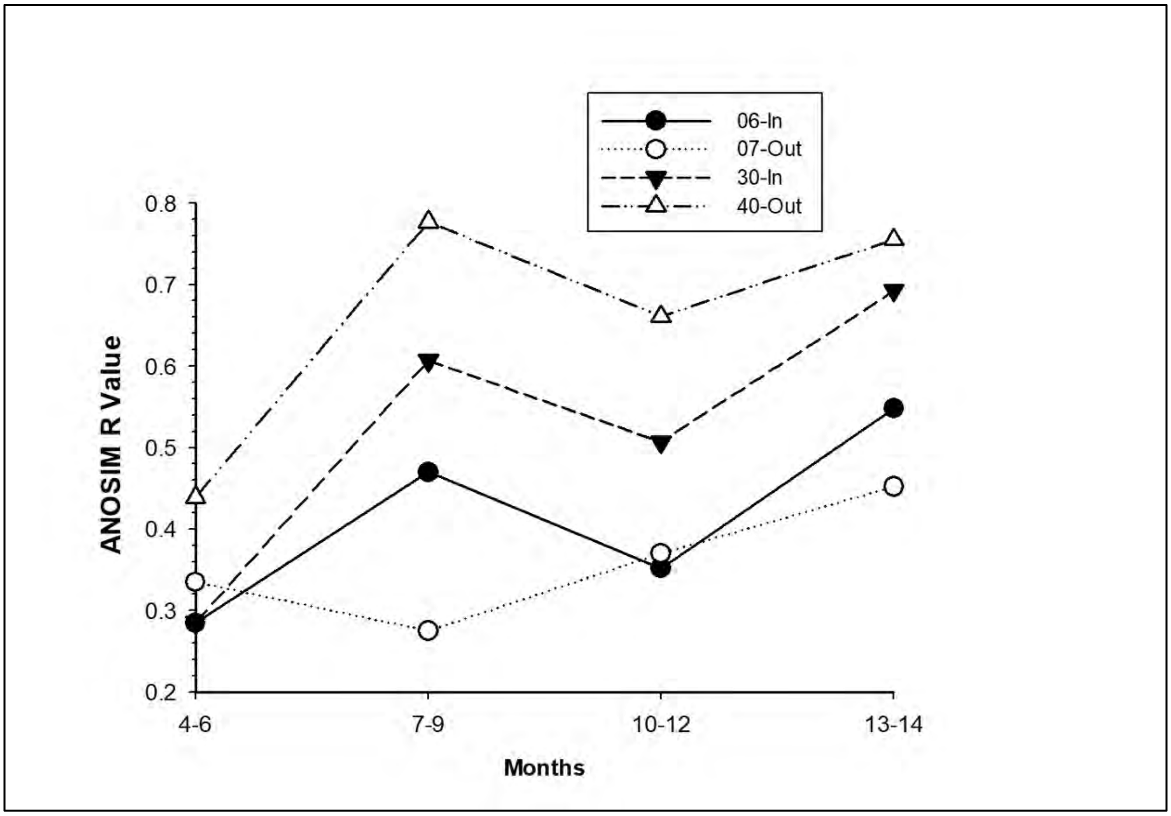

Figure 3.3. Analysis of similarity between extant and developing communities at each site in three-month time blocks. Each symbol, line combination represents a single rocky outcrop that was located either inside (In) or outside (Out) of the Research Area. Site numbers are for identification purposes only. Lower ANOSIM R values are indicative of higher similarity between the communities. All comparisons were significantly different ($p<0.0001$).

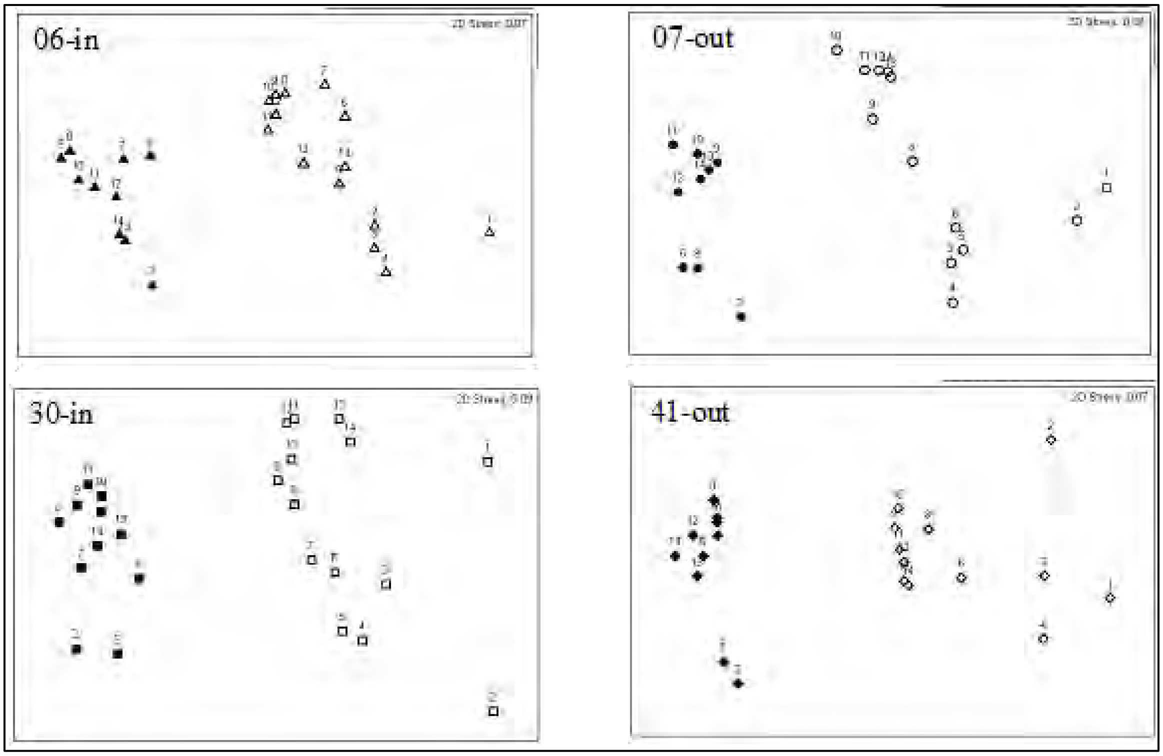

Figure 3.4. Two-dimensional non-metric multidimensional scaling (MDS) of taxa in developing and extant communities at all sites during the study period. Each point on the MDS represents the square root transformed data of mean abundance (i.e., centroids) of communities from photographs or quadrats taken for the developing (unfilled symbols) or extant community (filled symbols) during each sampling period. Numbers above points indicate how many months the study had been in effect when the data were taken. Image: Brittany Poirson/Georgia Southern University

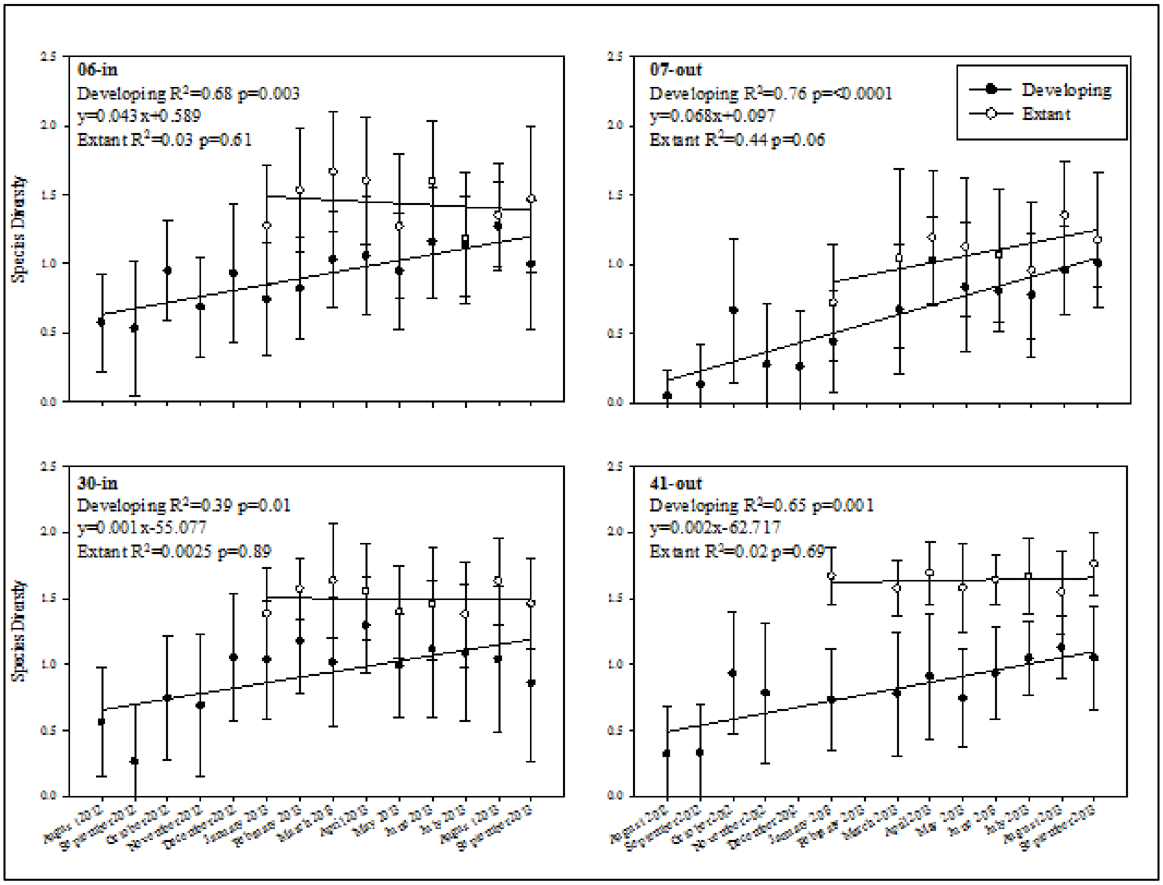

Figure 3.5. Species diversity between the extant and developing communities at each site over time. Error bars represent ± 1 SD. N=15 for each month in both communities.

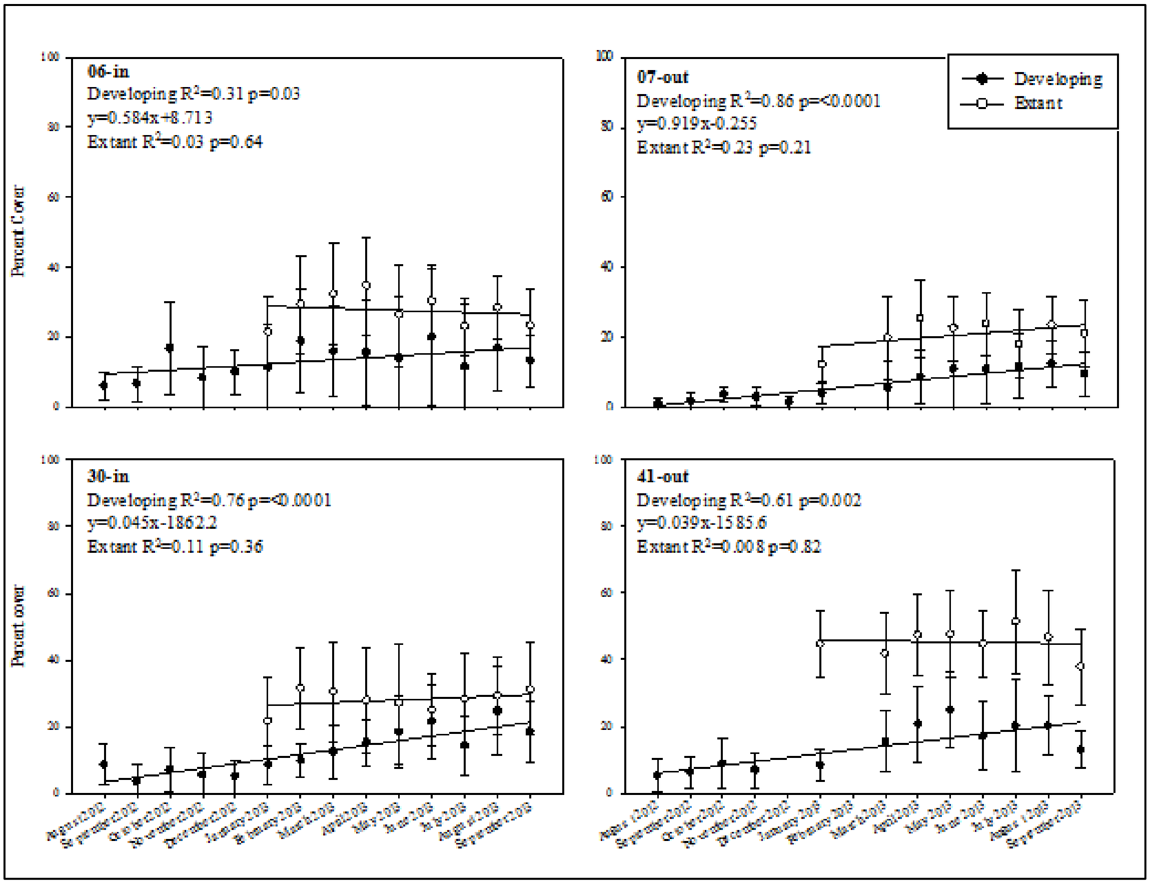

Figure 3.6. Percent cover in extant and developing communities at each site over time. Error bars represent ± 1 SD. N=15 for each month and each community.

Project 4. The role of artificial structures in facilitating range expansion of the introduced barnacle *Megabalanus coccopoma* in the southeastern U.S., 2013-2014

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The barnacle *Megabalanus coccopoma* is a recent invader of the southeastern United States. Photo: Alicia Reigel/Louisiana State University

Questions addressed

1) Do artificial structures (i.e., buoys, towers) occurring far enough offshore of Georgia for water temperatures to be moderated by the Gulf Stream provide refuges for breeding adults of *M. coccopoma*? 2) If offshore sites do provide a refuge for breeding adults, do these populations serve as the larval source for repopulating habitats along the immediate shoreline?

Measurements

At eight research sites ranging from the shoreline to ~50 km off the coast of Georgia (including the GRNMS data buoy), *M. coccopoma*, densities and shell sizes were measured to estimate population maturity. Temperature and salinity were also monitored at onshore and offshore sites to further evaluate the ability of artificial structures to serve as a refuge for breeding adults. Finally, 13 microsatellite primer pairs were developed and used to assess genetic diversity and genetic structure at the eight research sites.

Key findings

- Offshore structures such as towers and buoys house mature populations of *M. coccopoma* barnacles that have the capability to produce larvae that will repopulate areas closer to shore.
- In the Georgia Bight, *M. coccopoma* consists of one panmictic population with additional larvae dispersing in from outside the region.

Project narrative

Demographic information and temperature and salinity data collected indicated that offshore structures are able to provide a refuge for *M. coccopoma* populations consisting of larger, more mature individuals that can serve as an abundant source of larvae. The analysis of genetic structure indicated the presence of one panmictic population of *M. coccopoma* in the Georgia region and suggested the presence of additional larval sources from outside of the assessed area.

The barnacle *Megabalanus coccopoma* is a recent invader of the southeastern U.S.A. from the tropical eastern Pacific (Gilg 2010, Spinuzzi et al. 2013). *M. coccopoma* appears to grow rapidly, has high fecundity, and can reach sizes far exceeding native southeastern barnacle species. The combined life-history characteristics of *M. coccopoma* have heightened concerns that this species will outcompete native barnacles along the eastern seaboard (Spinnuzzi et al. 2013). In Georgia, *M. coccopoma* populations along the immediate coastline often suffer extensive mortality during the winter, but population rebuilding is common after these events, suggesting that there may be nearby larval sources.

This study hypothesizes that artificial structures (i.e., buoys, towers) occurring far enough offshore of Georgia for water temperatures to be moderated by the Gulf Stream provide refuges for breeding adults of *M. coccopoma* and can serve as the larval source.

The ability of offshore structures to serve as a refuge was investigated by monitoring temperature and salinity both on and offshore and also by collecting demographic information on existing populations. Temperature and salinity were measured at three sites extending from the shoreline to approximately 50 km offshore: Jekyll Bridge, GRNMS Buoy, and R2 Tower (Figure 4.1). Existing *M. coccopoma* populations were assessed at all eight sites (Figure 4.1) and the demographic information collected included population densities and shell sizes (Figure 4.2). Results indicated that seawater temperatures were higher during the winter months (Figure 4.3) and were more stable throughout the year at the offshore towers. This environmental stability translated to *M. coccopoma* populations that were more persistent and had larger individuals than nearshore sites (Figure 4.4). Thus, offshore structures do appear to provide a refuge for reproductively mature *M. coccopoma* populations.

To further evaluate the role of artificial structures in the coastal repopulation of *M. coccopoma*, both genetic diversity and genetic structure were assessed at the eight research sites (Figure 4.1). This process resulted in the development of 13 microsatellite primer pairs specific to *M. coccopoma* as well as the polymerase chain reaction (PCR) and sequencing protocols required for using these primers (Reigel et al. 2015). These 13 primer pairs were tested on 42 individuals from two populations of *M. coccopoma*. The results of the testing indicated high variation in all of the loci making these primers useful in evaluating population genetics questions related to *M. coccopoma*.

Additional genetic assessments at the eight research sites revealed high diversity and significant deviations from Hardy-Weinberg equilibrium at all locations. The analysis of genetic structure indicated the presence of one panmictic *M. coccopoma* population in the Georgia region and suggested the presence of additional larval sources from outside of the assessed area. The high diversity and stable, mature offshore populations indicate that *M. coccopoma* in the Georgia region will likely be able to persist and may continue to expand further northward should it develop an ability to withstand the cooler water temperatures.

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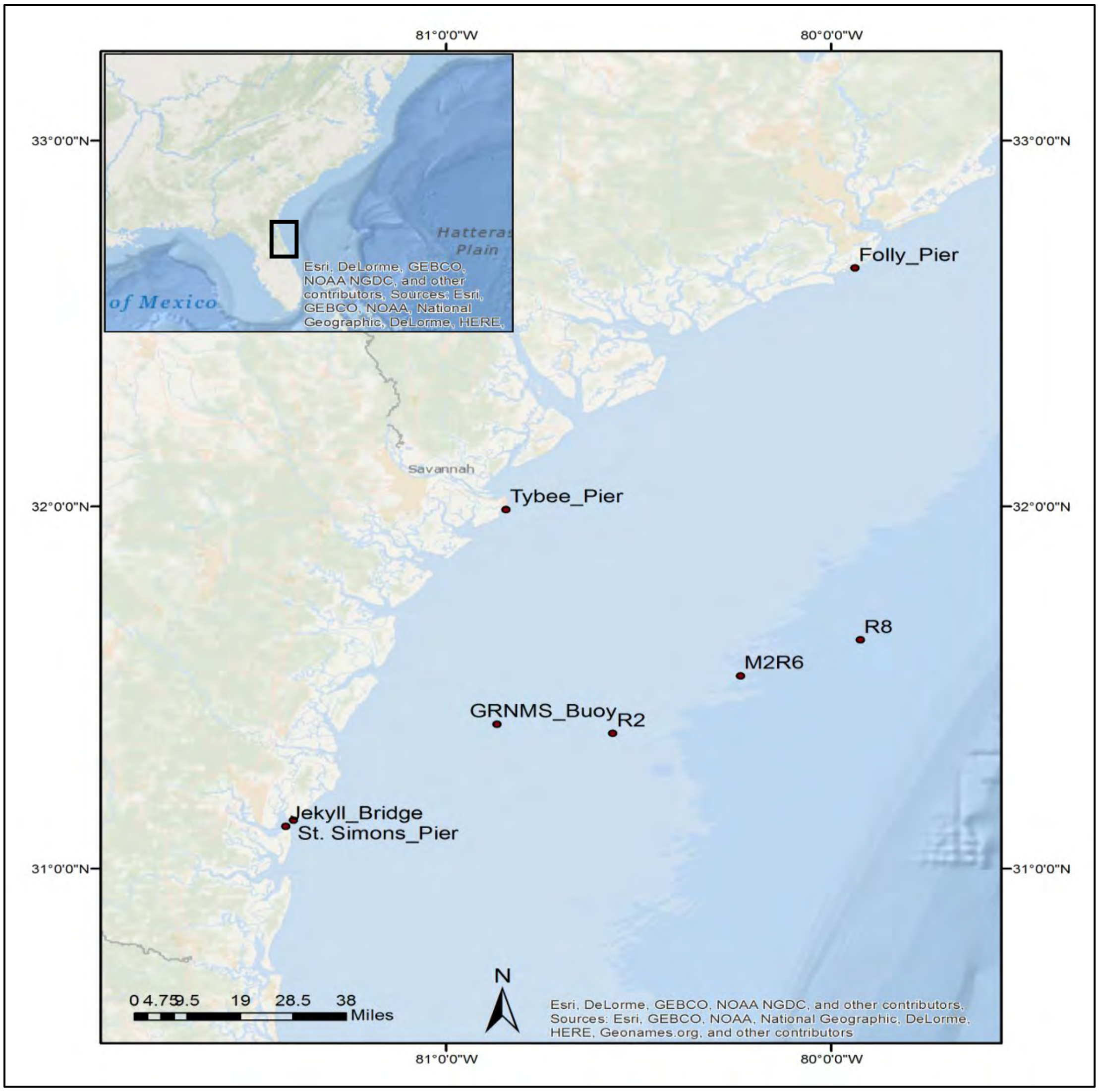

Figure 4.1. Map of the research sites within the Georgia Bight. Left inset map indicates the location of the Georgia Bight on the United States East Coast (black box). This study used four coastal collection sites (Folly Pier, Tybee Pier, Jekyll Bridge, St. Simons Pier), one buoy site (Gray's Reef National Marine Sanctuary Buoy), and three offshore Navy Tower sites (R2, M2R6, R8). Image: Alicia Reigel/Louisiana State University

Figure 4.2. An *M. coccopoma* specimen with arrows indicating the location of the three shell size measurements that were taken for this study. From left to right: diameter of opercular cavity opening at the widest point, basal diameter at the widest point and at a 90º angle to the widest point, and height at the tallest point. Photos: Alicia Reigel/Louisiana State University

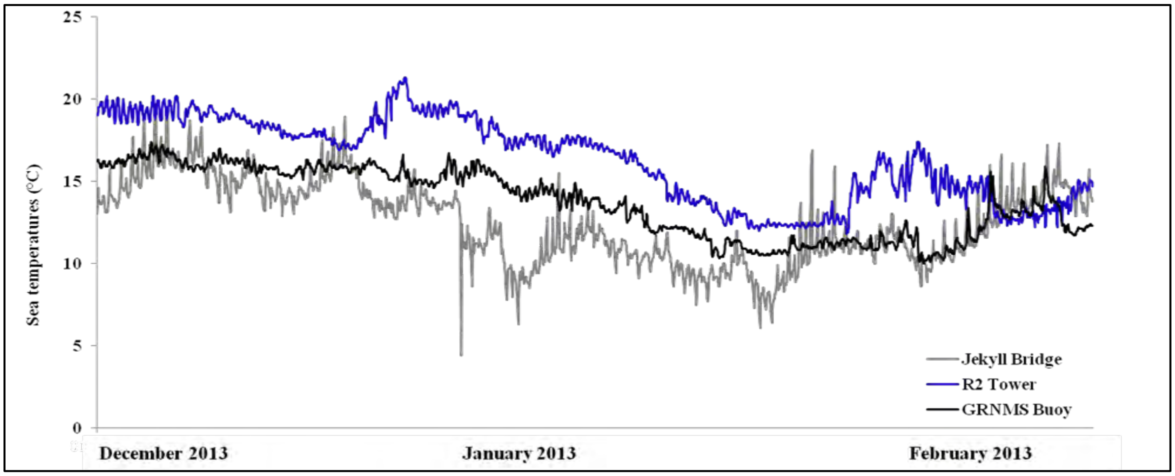

Figure 4.3. Sea temperatures (°C) from December 1, 2013, to February 28, 2014, for three sites: Jekyll Bridge (gray line), R2 Tower (blue Line), and Gray's Reef National Marine Sanctuary Buoy (black line). The lowest temperature (4.4°C) was recorded on January 3, 2014, at Jekyll Island. Throughout the winter months Jekyll Island maintained the overall lowest minimum temperatures.

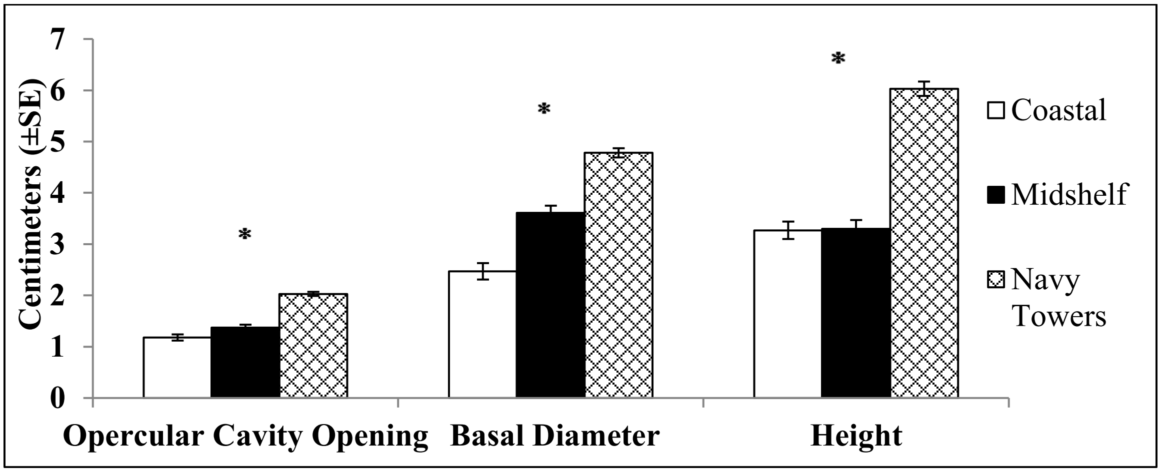

Figure 4.4. *M. coccopoma* shell size measurements collected from eight research sites in fall 2013. Individual coastal and Navy Towers sites were grouped together for clarity. Opercular cavity opening and basal diameter were significantly different for all three site types ($p<0.05$). The measurement for height showed that the Navy Tower shells were significantly taller than both other site types ($p<0.05$).

Project 5. Benthic fish communities and structural habitat measurements from Gray's Reef National Marine Sanctuary, 2010-2016

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A large school of scad and tomtate surrounds a belted sandfish and blue angelfish on the reef. Photo: Roldan Muñoz/NOAA

Questions addressed

What is the benthic fish community composition at GRNMS as measured with diver-based visual surveys? How does the benthic fish community composition at GRNMS, as represented with abundance and biomass, vary between management zones (open versus RA) between years and between ledge types? How does structural habitat vary between management zones?

Measurements

Species identification and size of all fishes encountered were determined by divers with underwater visual census (UVC) methods. Benthic habitat measurements of biotic and abiotic substrata were also taken at each site. Data collection was initiated in 2010 and has taken place annually up to the present.

Key findings

- Community structure of benthic fishes at GRNMS is generally consistent among years, although dominant components do show changes in abundance.
- Community structure for both conspicuous and prey fishes does not differ by management zone but does differ among years.
- Fish community structure differences among years reflect differences in the abundance of ubiquitous species, including longspine porgy, tomtate, black sea bass, slippery dick, and cubbyu.
- Biomass of common predators at GRNMS has fluctuated over the years since the establishment of the RA in December 2011, although estimates from the RA and open management zones mostly track each other.
- Ledges that harbor large predators may provide suitable habitat for these species over multiple years.

Project narrative

A substantial number of scientific studies indicate that marine protected areas (MPAs) such as GRNMS can have positive effects on the biomass, abundance, diversity, and size of marine species resident within, with those species exploited outside MPAs generally showing the greatest response to protection (Caselle et al. 2015, Gill et al. 2017).

This study was initiated to update the baselines of fish communities and benthic habitat established by Kendall et al. (2007) and to monitor these sanctuary resources prior to and following establishment of the RA.

Kendall et al. (2009) identified two distinct groups of fishes from GRNMS associated with tall (mean 55 cm high) and short (mean 14 cm high) ledges, and determined that the split between fish communities appeared to occur at a ledge height of 25 cm. We utilized these sites previously classified with multibeam data or by divers (Kendall et al. 2007) to select ledges that were >25 cm, of medium to large ledge area (mean 1587 m^2, N = 137), and characterized as densely colonized hard bottom. A potential universe of ledges that met the above criteria was created in ArcGIS and random points were then overlaid with a minimum separation distance of 50 m. Study site locations were selected from the random points distributed approximately equally within the RA and outside the RA.

At each site, we conducted surveys of the fish community and benthic habitat. The study began with preliminary surveys in 2010 and continues to the present. Table 5.1 outlines the number of stations surveyed per year and differing sample sizes primarily result from inclement weather or research vessel availability. Sampling was conducted from May to July using the NOAA Ship *Nancy Foster* and the GRNMS vessels *Joe Ferguson* and *Sam Gray*.

All sampling protocols have inherent biases that can favor or exclude species based on factors such as behavior, habitat preference, or size (Allen et al. 1992, MacNeil et al. 2008). For example, traditional UVC transects geared towards conspicuous and highly mobile species may miss or underestimate smaller, benthic dwelling fishes. These smaller species are often cryptically colored and can either be the juvenile stage of conspicuous species or may remain cryptic and small throughout their life cycles, where they may function as important prey species within the fish community. For this reason, we combined two different sampling approaches in order to better capture the entire fish community within a given area. We conducted the following surveys within a single 50 m transect:

1. 50 m UVC band transects swimming outward with an estimated width of 5 m on each side that targeted mobile conspicuous fishes (>10 cm total length, TL). Area surveyed = 500 m^2.

2. 25 m UVC band transects on the return with an estimated width of 1 m on each side that targeted the cryptic (or juvenile) prey species (<10 cm TL). Area surveyed = 50 m^2.

Surveys for conspicuous fishes were not attempted if underwater visibility was <5 m, whereas the minimum visibility threshold for cryptic fishes was <3 m. Densities were determined by dividing the number of fish observed by the area surveyed, and are reported in hectares. For the two surveys, the species identification and total lengths of all fishes observed were recorded. In some cases, similar looking pairs or groups of species proved difficult to identify to the species level, such as *Decapterus macarellus* and *D. punctatus*, as well as certain porgies, gobies, blennies, and sea robins. These species were identified to the genus level (Kendall et al. 2007).

We also estimated biomass for each fish species. Biomass was calculated from the length-weight relationship, $W = aL^b$, where W = weight in g and L = length in cm. The midpoint of the size categories was calculated for each 10 cm category. For example, if the size category was 20-30 cm then the length was considered 25 cm for the equation

(Kendall et al. 2009). Values for the *a* and *b* parameters were obtained for each species from http://www.fishbase.org (Froese and Pauly 2011). Species biomass is reported here as kilograms per hectare (kg/ha).

Although we selected ledges that were >25 cm in height as study sites, seasonal sand transport events that alternately cover and uncover rock ledges are a characteristic of live bottom reefs of the southeast U.S. (Renaud et al. 1997). When our project began in 2010, we found that some ledges that were originally classified (Kendall et al. 2007) as high (>25 cm in height) now appeared shorter than 25 cm. We therefore classified ledges at our study sites as tall (maximum ledge height >25 cm) or short (maximum ledge height ≤25 cm) and examined whether fish communities differed between these two ledge types.

Habitat surveys were conducted concurrently with fish surveys. To better quantify reef structure, we measured ledges and structural organisms (e.g., algae, sponges, tunicates) at each site. At fixed intervals along the fish survey transects (5, 15, 25, 35, and 45 m), three ledge measurements were collected following methods described in Kendall et al. 2007. Total ledge height was the distance from the substrate to the top of the ledge, excluding all sessile organisms attached to the substrate. Undercut depth quantified the amount of overhang of each ledge and was measured from the leading edge of the ledge to the inner most portion of the ledge. Undercut height, or the height under the ledge, was measured from the substrate surface to the underside of the leading edge of the ledge. All measurements were collected using a measurement tape or when measurements exceeded 40cm, they were visually estimated using the transect tape as a guide. At each ledge measurement location, macroalgae and invertebrate height were recorded. Maximum height of an individual plant or invertebrate was recorded to the nearest cm.

Results from annual surveys have been presented each year at the GRNMS Sanctuary Advisory Council Science Advisory Group meeting and are available as reports from GRNMS. The following will use results from the four years with the largest sample sizes (Table 5.1) to summarize and illustrate the patterns that have emerged from this sampling program that generally persist across years, although year-to-year variation can also be observed.

From 2010-2016, 102 fish species or species groups have been observed with this study. Across years, the dominant species observed, based on a multivariate analysis utilizing abundance and spatial distribution (Analysis of similarities [ANOSIM] with Similarity Percentages [SIMPER] routine), are shown in Table 5.2 and Figures 5.1 & 5.2. As observed previously at GRNMS (Kendall et al. 2007, Kendall et al. 2009) and generally across the southeast U.S. (Bacheler et al. 2017, Whitfield et al. 2014), schooling tomtate and scad, together with longspine porgy, black sea bass, and cubbyu, are among the most abundant species. Although year-to-year differences in the most abundant species are apparent and result in significant differences by year for both conspicuous and prey communities (P=0.0001), the most abundant species persist and remain dominant across years (Table 5.2). Fish community structure differences among years reflect differences in the abundance of these ubiquitous species, including conspicuous longspine porgy, tomtate, black sea bass, and cubbyu, as well as prey fishes such as juvenile tomtate, slippery dick, belted sandfish, and juvenile black sea bass.

The spatial distribution of these ubiquitous species throughout GRNMS and across management zones may play a role in the overall pattern of community structure, which for both conspicuous and prey fishes did not differ by management zone (P=0.17 conspicuous; P=0.60 prey). Differences in community structure were apparent, however, when examining both conspicuous and prey communities associated with either tall or short ledges (P=0.0001; Figure 5.3). Similar species of fish characterize community structure at both ledge types (Table 5.3) although tall ledges harbor richer fish assemblages. In addition, the fishes primarily characteristic of tall versus short ledges display greater abundance on tall ledges and include the large-bodied gag and scamp grouper, red snapper, sheepshead, Atlantic spadefish, great barracuda, greater amberjack, and Almaco jack, as well as large schools of juvenile and adult scad, longspine porgy, and tomtate. Although juveniles, and less frequently adults, are occasionally observed on short ledges, these species are most representative of high-relief habitat, especially those ledges that also include overhangs. These species were also identified by Kendall et al. (Kendall et al. 2007, Kendall et al. 2009, Kendall et al. 2008) as characteristic of tall ledges. Preliminary data suggest that certain ledges that harbor large predators may provide suitable habitat for these species over multiple years. Loggerhead turtles are another species that appears to be associated with tall ledges. Individuals of this threatened species are often seen on the surface in the vicinity of tall ledges, as well as on the seafloor resting under overhanging ledges.

Biomass of common predators at GRNMS has fluctuated over the years since the establishment of the RA in December 2011, although estimates from the RA and open management zones mostly track each other (Figure 5.4). Black sea bass (Figure 5.4A) can be observed on nearly every station visited across the sanctuary and the biomass of this common predator shows a high degree of overlap between management zones. A significant (P=0.043) increase in biomass in the RA when comparing 2013 versus 2011 had disappeared in 2014 and 2016, while biomass in the open zone did not differ significantly across years. The combined biomass of large-bodied grouper and snapper (Figure 5.4B) has also overlapped between management zones and has not decreased significantly from estimates recorded in 2011. Scamp grouper appear to show a trend over multiple years of higher biomass in the RA compared with the open management zone (Figure 5.4C), but the difference is not significant (P=0.067). Red snapper (Figure 5.4D) show the opposite pattern, with higher biomass outside the RA (P=0.023). Given the short time frame since establishment of the RA, together with uncertain levels of both fishing effort and respect for management zone boundaries at GRNMS, it remains to be determined whether species-specific patterns of biomass will persist. Elevated biomass of red snapper or grouper available to harvest at sites in GRNMS outside the RA could be rapidly depleted, as these species are relatively slow growing, late maturing, and site attached. These life history and behavioral features increase their vulnerability to overexploitation (Coleman et al. 2000, Muñoz et al. 2010).

Although among-year variation in benthic invertebrate (see Project 1, this volume) and structural habitat coverage was observed (e.g. algae, Figure 5.5), biotic habitat structure estimates within year were generally similar between management zones (e.g., algae and invertebrate, Figure 5.5). However, algal growth has usually been more luxuriant in the open area compared with the RA. Observations in 2016 revealed overlap in algal growth between management zones, reflecting an increase in algal growth in the RA compared with 2014 (P=0.003), together with a steady decline in algal growth across years in the open area. Sampling in 2016 took place later in the year (July) compared with previous years (May-June) and differences in algal growth may reflect differences in water temperature and light availability among years (Peckol and Searles 1984), although consistent differences between zones also suggest zone-specific effects that remain to be determined. Invertebrate growth was also significantly greater (P=0.015) in the RA in 2016 compared with the open area and may reflect differences in the percent cover of arborescent, structurally-complex species such as the bryozoan *Schizoporella floridana*, the colonial polychaete, *Filograna implexa*, or the colonial hydroid *Eudendrium carneum*.

Additionally, ledges in the open area are significantly taller than the research area, and tall ledges tend to be more numerous in the open area (Kendall et al. 2007) than the research area. Kendall et al (2007) observed ledges in the open area to be significantly larger in area, more undercut, and more densely covered by benthic organisms than ledges in a low boat density area, which included areas of GRNMS that would become the RA. The current study also identified more ledge complexity – higher ledge height, deeper undercuts, and larger spaces under the ledge – in the open area compared to the RA (e.g., ledge, undercut, and undercut depth, Figure 5.5). There is between-year variability for the three ledge measurements in both study areas. This may be due to variation in exact transect location among years since fixed transects were not used. Additionally, sand movement within GRNMS was not measured as part of this study but has been documented by others in similar habitats (Riggs et al. 1998). Sand movement can be substantial in response to major storms and hurricanes, which are known to also move and break apart large limestone rubble blocks, changing ledge characteristics and overhangs in the process.

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Table 5.1. Number of stations surveyed for benthic fishes and structural habitat at Gray's Reef National Marine Sanctuary by year and management zone.

	Management Zone	
Year	**Research Area**	**Open**
2010	5	6
2011	19	18
2012*	7	6
2013	30	31
2014	34	30
2015**		15
2016	34	32

*Depicts sample effort for prey fishes. Conspicuous sample effort was hindered due to low underwater visibility following passing tropical weather systems.

**Alternative survey effort concerned with juvenile fishes conducted only outside the Research Area (see Gray's Reef National Marine Sanctuary Advisory Council Science Advisory Group meeting report. March 2, 2016).

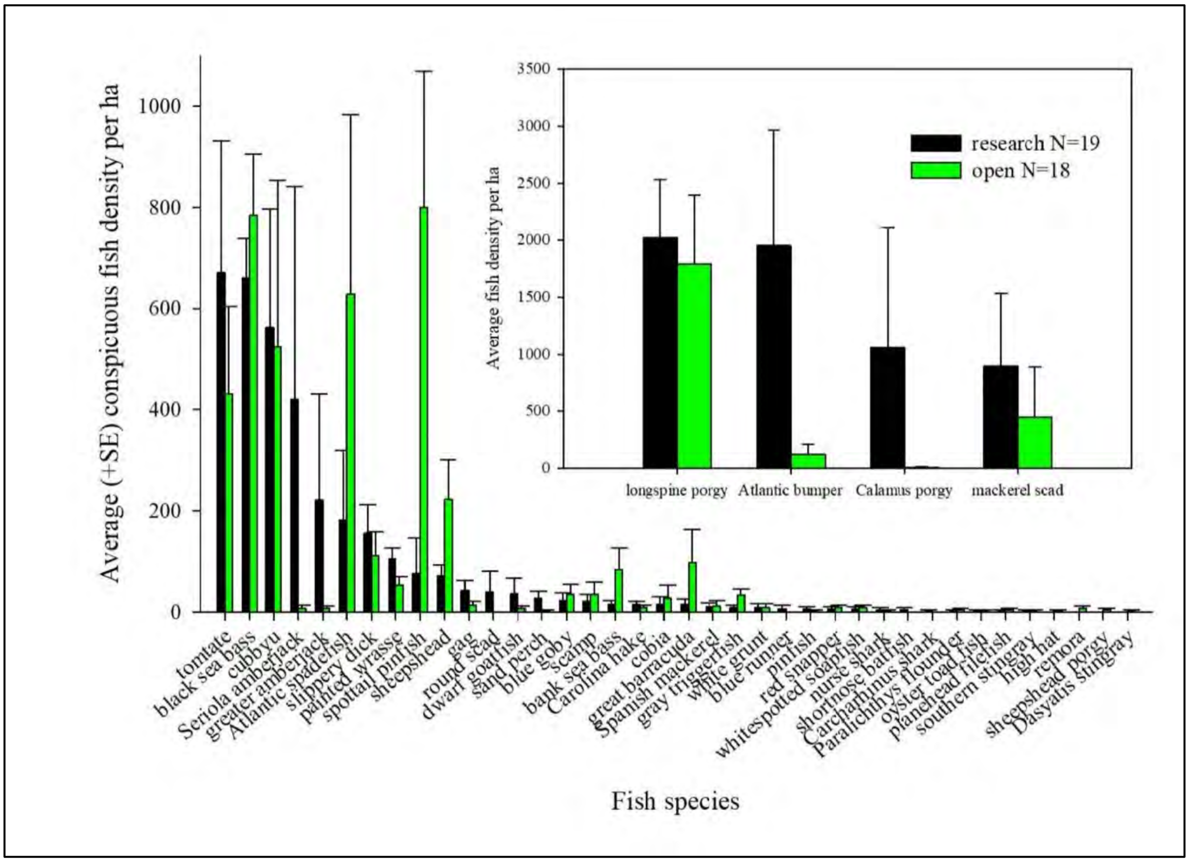

Figure 5.1. Dominant conspicuous (>10 cm TL) fish observed inside (black) and outside (green) the Research Area at Gray's Reef National Marine Sanctuary in 2011. Species are arranged in order of decreasing abundance inside the Research Area.

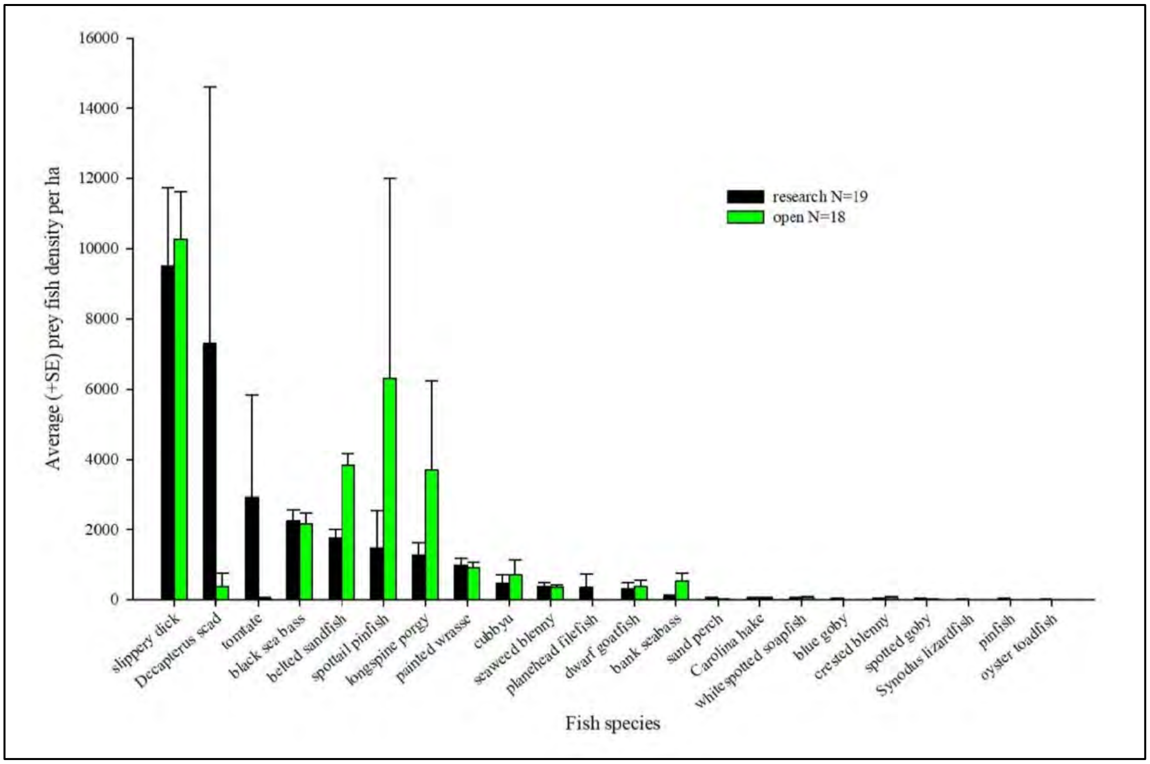

Figure 5.2. Dominant prey (<10 cm TL) fish observed inside (black) and outside (green) the Research Area at Gray’s Reef National Marine Sanctuary in 2011. Species are arranged in order of decreasing abundance inside the Research Area.

Table 5.2. Top five dominant* conspicuous and prey fish species at Gray's Reef National Marine Sanctuary.

Conspicuous 2011	**Conspicuous 2013**	**Conspicuous 2014**	**Conspicuous 2016**
black sea bass	black sea bass	black sea bass	tomtate
longspine porgy	slippery dick	longspine porgy	black sea bass
slippery dick	cubbyu	slippery dick	cubbyu
painted wrasse	longspine porgy	tomtate	slippery dick
tomtate	tomtate	cubbyu	longspine porgy
Prey 2011	**Prey 2013**	**Prey 2014**	**Prey 2016**
slippery dick	slippery dick	slippery dick	slippery dick
belted sandfish	belted sandfish	black sea bass	belted sandfish
black sea bass	black sea bass	belted sandfish	tomtate
painted wrasse	seaweed blenny	seaweed blenny	cocoa damselfish
longspine porgy	tomtate	**	seaweed blenny

*Species classified as dominant based on a multivariate analysis utilizing abundance and spatial distribution (Analysis of similarities [ANOSIM] with Similarity Percentages [SIMPER] routine).

**Only four dominant prey species emerged from the analysis for 2014.

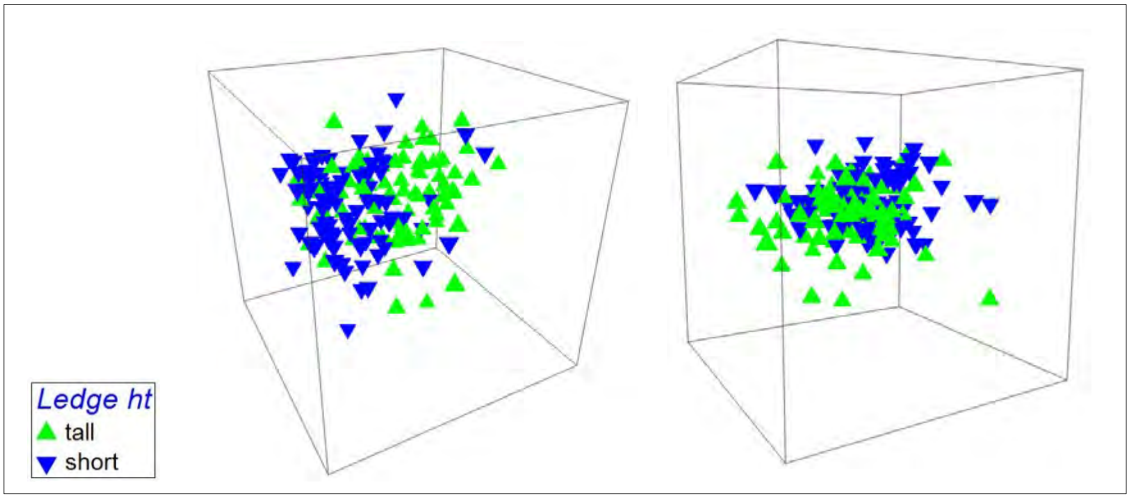

Figure 5.3. Multi-dimensional scaling plots of conspicuous (left, stress = 0.17) and prey (right, stress = 0.16) fish community structure (based on densities) by ledge height at Gray's Reef National Marine Sanctuary. Note the clustering together of stations classified as either tall or short ledges, resulting in significant differences between fish communities from these distinct ledge types.

Table 5.3. Species characteristic of and their relative abundance between major ledge types at Gray's Reef National Marine Sanctuary*

	Ledge type	
Species	**Tall (>25 cm)**	**Short (<25 cm)**
Tomtate	High	Low
Longspine porgy	Low	High
Cubbyu	High	Low
Scad	High	Low
Atlantic spadefish	High	Low
Slippery dick	Low	High
Black sea bass	Low	High
Spottail pinfish	High	Low
Atlantic bumper	Low	High
Belted sandfish	High	Low
Sheepshead	High	Low
Painted wrasse	Low	High
Sand perch	Low	High
Great barracuda	High	Low
Greater amberjack	High	Low
Gray triggerfish	High	Low
Cocoa damselfish	High	Low
Red snapper	High	Low
Gag grouper	High	Low
Scamp grouper	High	Low

*Species are listed in decreasing order that they contribute to the significant dissimilarity between ledge types as determined by ANOSIM and SIMPER. High and low refers to the relative abundance of a particular species between the two ledge types. For example, tomtate generally occur in greater abundance on high relief ledges compared with low relief ledges.

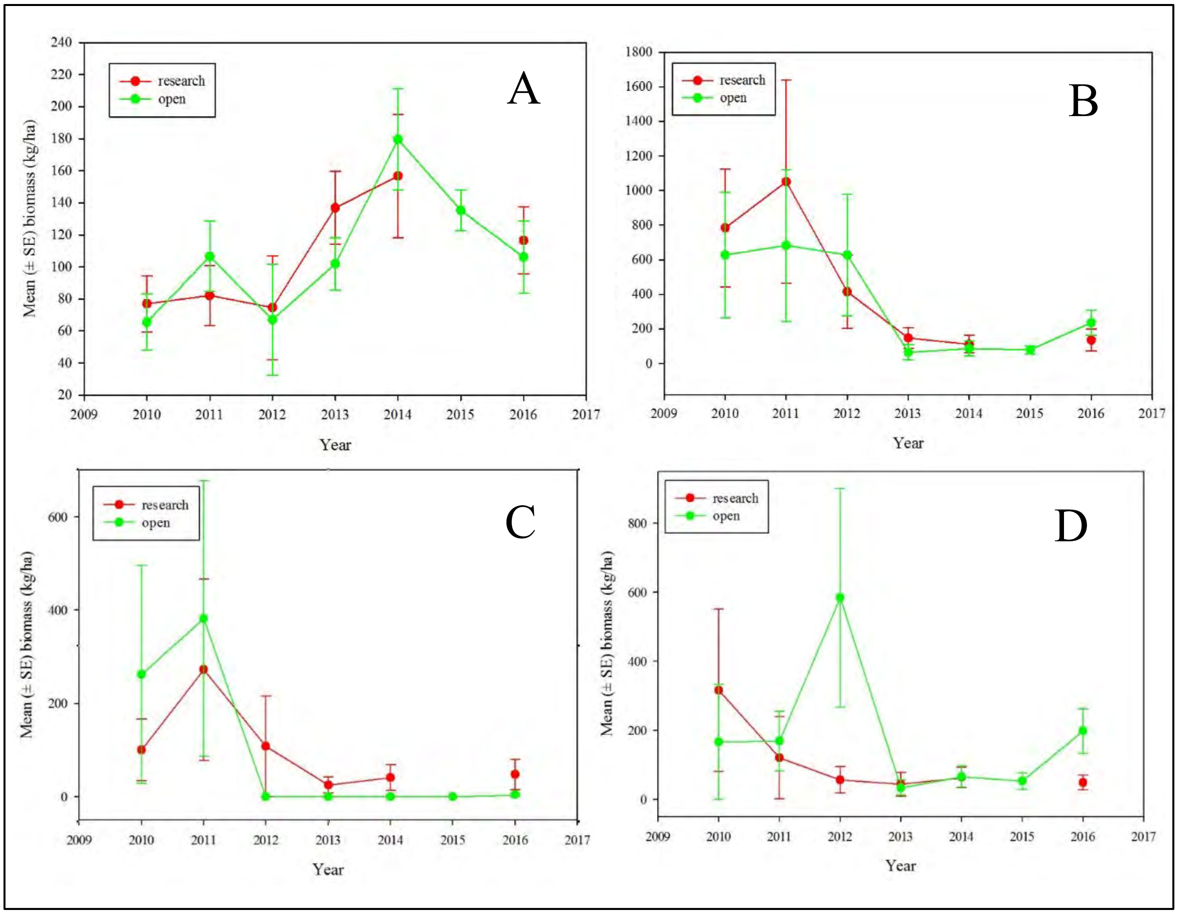

Figure 5.4. Biomass of common predators inside (red) and outside (green) the Research Area at Gray's Reef National Marine Sanctuary. A) Black sea bass. B) Combined biomass of gag grouper, scamp grouper, and red snapper. C) Scamp grouper. D) Red snapper. Table 1 provides sample sizes.

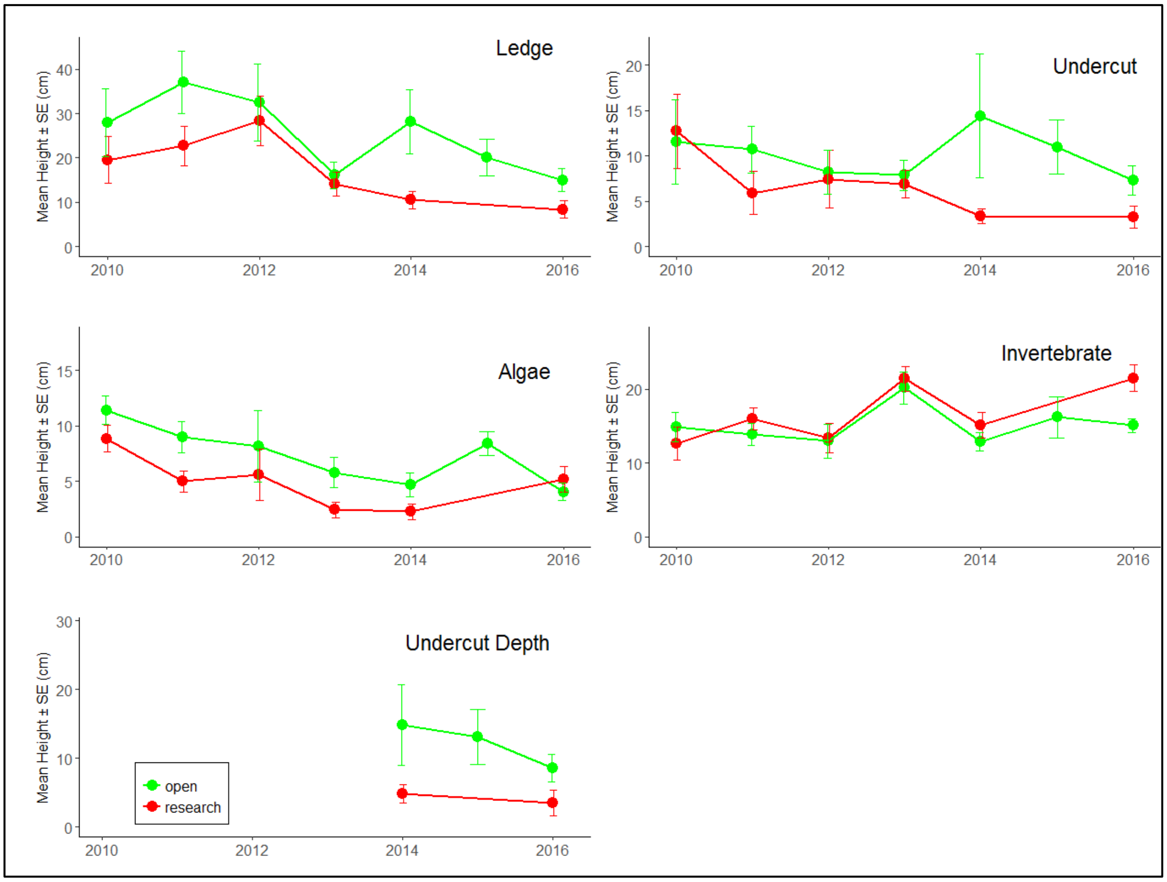

Figure 5.5. Comparison of biotic and abiotic structural habitat inside (red) and outside (green) the Research Area at Gray's Reef National Marine Sanctuary and open management zones between 2010 - 2016.

Project 6. Reef fish monitoring by MARMAP and the SERFS program at Gray's Reef National Marine Sanctuary, 1993-2014

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A black sea bass stares at an underwater video camera that is attached to the chevron traps used for sampling at Grays Reef. Photo: MARMAP/SCDNR

Questions addressed

The overall goal of the reef fish survey is to study the long-term distribution, relative abundance, life history, and critical habitat of the economically and ecologically important fishes off the southeastern U.S. (primarily reef fish species), and how these relate to environmental factors and exploitation activities. Program objectives for sampling at GRNMS were to study these parameters at GRNMS, relate them to those in comparable habitats outside the sanctuary, and compare the GRNMS RA with the non-research area in the sanctuary.

Measurements

Fish caught in baited, chevron-shaped wire fish traps were sorted to species, weighed (total wet weight of all specimens of each species, ± 10 g), and measured to the nearest cm (±1 mm starting in 2010) before being returned alive to the water as soon as possible. Analyses of catch-per-unit-effort (CPUE; number of fish caught per trap hour) and mean body length were restricted to collections in which the sampling duration was 60 to 120 minutes. During monitoring efforts, depth, salinity, and temperature were measured with a CTD profiler that was deployed at least once throughout the day. Monitoring efforts have taken place in all years except 1996, 2003, and 2008.

Key findings

- Eight taxa were caught over the years. Catches were dominated numerically and by biomass by black sea bass and *Stenotomus* spp.
- Since the peak CPUE in 2011, there has been a general decreasing trend in black sea bass abundance.
- Since 2011, the CPUE trend of black sea bass at GRNMS and Charleston inshore have mirrored each other closely, but GRNMS has maintained a higher CPUE than Charleston inshore. Both locations show the general decline in recent catches from the historic peak in 2011.
- The temporal trend in CPUE for black sea bass in the designated RA was very similar to that in the remainder of the sanctuary, showing a general increase over time, with the non-research area showing greater inter-annual fluctuations.
- The temporal trend in CPUE for *Stenotomus* spp. was also similar in the research and non-research areas, revealing a noticeable decline since a peak in the late 1990s. There appear to be more inter-annual oscillations in the CPUE in the non-research area as well as generally higher catch for *Stenotomus* spp. throughout the time series compared to the RA, but the overall trends hold true.

Project narrative

The Marine Resources Monitoring, Assessment, and Prediction (MARMAP) program has conducted research on reef fish between Cape Lookout, North Carolina, and the St. Lucie Inlet, Florida, for over 40 years. Sponsored by the National Marine Fisheries Service

(NMFS) and the South Carolina Department of Natural Resources (SCDNR), the program's mission is to determine the distribution, relative abundance, life history, and critical habitat of the economically and ecologically important fishes of the South Atlantic Bight, primarily reef fish species, and relate these to environmental factors and exploitation activities. In 2009, MARMAP was joined by the Southeast Fishery-Independent Survey (SEFIS) and Southeast Area Monitoring and Assessment Program-South Atlantic (SEAMAP-SA) to form the Southeast Reef Fish Survey (SERFS).

In 1993, the MARMAP program began to monitor species composition, abundance, and fish lengths within GRNMS, and to tag selected reef fishes (primarily black sea bass) to assess the status of fish populations within the sanctuary via a mark/recapture methodology. Due to funding constraints MARMAP and SERFS sampling at GRNMS did not occur in all years and has not been conducted since 2014. From 1993 through 2014, sampling at GRNMS took place in all years except 1996, 2003, and 2008. The R/V *Palmetto* has been the primary sampling platform for monitoring and tagging efforts for all years, except for 2012 and 2013 when the R/V *Savannah* was used.

The objectives of our reef fish sampling at GRNMS were to:

1. Conduct routine reef fish sampling in GRNMS to monitor species composition, abundance, and length-frequency parameters, and provide a time-series over time (provided sampling could be continued on a regular basis).
2. Provide a long-term time series of most abundant species, in particular black sea bass.
3. Compare results for black sea bass from GRNMS to the Charleston inshore area (32° 29.6'N / 79° 41.6'W), an area of natural reef with similar depth and habitat characteristics routinely sampled by MARMAP.
4. Compare survey results pre- and post-establishment of the RA, as well as within and outside GRNMS.

Monitoring of species composition, abundance, and length-frequency parameters

Reef fish monitoring efforts at the sanctuary included in this report have taken place from May through October, but most sampling took place from late August through mid-October. Note that sampling off the southeastern U.S. coast South Atlantic Bight (SAB) with chevron traps (Figure 6.1) outside GRNMS have been conducted consistently between mid-April and mid-October on an annual basis since 1989. Data from the sanctuary were compared with the Charleston inshore area. This area is located north of the sanctuary with a similar depth and habitat. Since the introduction of the RA, we tried to include sampling both inside and outside this area at the sanctuary (Figure 6.2 and Table 6.2).

Chevron traps (Figure 6.1 and Collins 1990) were baited with cut menhaden and deployed at randomly-selected sampling sites in GRNMS (see Figure 6.2 for locations). The soak time was approximately 90 minutes and traps were deployed in such a way that the entire catch could be worked up before the next trap was retrieved. The sampled stations were no closer than 200 m apart to ensure independence of the samples, but typically were separated by at least 400 m. Upon trap retrieval, all fish were placed in ~275-gallon containers filled with seawater and vented as soon as possible to release pressure in the swim bladders. The catch was sorted to species, all fish from each species were weighed, and individual fish were measured before being returned alive to the water as soon as possible. Analyses of CPUE and mean body length were restricted to collections with a sampling duration of 60 to 120 minutes.

During sampling, water column salinity and temperature were measured with a CTD profiler several times a day in the sampling areas. In 2008 through 2011, a digital underwater camera was deployed on each trap (taking one photo per five minutes). Beginning in 2011, one to three digital video cameras (GoPro, Canon) were attached to each trap (Figure 6.1). The photos and video are used to verify and identify bottom type, and are examined to develop a complementary standardized index of relative abundance. The analysis of the videos is the responsibility of our partner program (SEFIS), although SCDNR staff has assisted with examining the videos. Note that analyses of the video data are not included in this report.

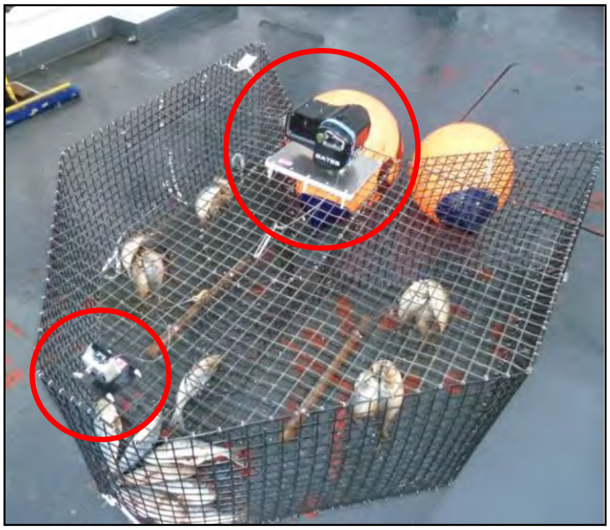

Figure 6.1. Chevron trap fully baited and rigged. The cameras (circled in red) are shown in one of several configurations used; in this one, they were located at the nose and the mouth of the trap. Photo: MARMAP/SCDNR

Black sea bass CPUE and length

The mean CPUE of black sea bass has generally increased between the earliest years of the time series and 2011, from low values of <30 in 1993-1998 to a peak of 88 during 2011 (Figure 6.3). Large increases and decreases in a relatively short period of time indicate that population size at GRNMS may have a high degree of inter-annual variability. Since the peak in 2011, there has been a general decreasing trend in black sea bass abundance, though catch in 2014 (CPUE = 44 fish per hour) was still above the median value for the time series of sampling at GRNMS.

The mean CPUE of black sea bass in GRNMS was compared to the abundance in an area of similar reef habitat, Charleston inshore (18 m; 32° 29.6'N, 79°41.6'W), that was sampled by MARMAP and SERFS annually during May through September. The magnitude of the temporal trend in CPUE from 1993-2009 was generally similar at the two areas. The direction of the temporal trends also was similar during this time period, with a few exceptions (Figure 6.3). In 2010, CPUE in the two areas moved in opposite directions, which was reflected in a five-fold greater catch at GRNMS. Since 2011, the CPUE at GRNMS and Charleston inshore have mirrored each other almost exactly in terms of direction of trends of abundance, but GRNMS has maintained a higher standardized catch than Charleston inshore. Both locations show the general decline in catches from the historical peak in 2011.

The mean length of black sea bass at GRNMS has ranged from 19 to 22 cm total length (TL) during the 1990s and increased to 23 to 26 cm TL since 2000 (Figure 6.4). The relatively consistent number of small fish caught each year suggests that the increase in mean length observed over time is probably not due to recruitment failure, but due to the increased proportion of fish caught in the larger size classes (Figure 6.5). The broader size distribution in more recent years could be indicative of a recovery from high fishing pressure in the past as a result of management actions, as fisheries tend to truncate the largest size classes in populations. Mean length exceeded 25 cm for the first time in the history of the time series in 2011 but has declined to 24 cm for 2014. The overall increase in mean size during the time series could at least partly reflect the three increases in the regional recreational minimum size limit since 1999 (10 in. [25 cm] in 1999; 11 in. [28 cm] in October 2006; 12 in. [30.5 cm] in June 2007) implemented by the SAFMC. There recently has been a fourth change in minimum size limit to 13 in. (33.0 cm) enforced in July 2013. There has been a two-year decline in size since that regulation was enacted, leading us to believe there could be another factor affecting this decrease.

Another interesting trend is the apparent signal of year classes in the length distributions throughout the time series. Regularly, including 2012 and 2014, the annual samples exhibit a multi-modal distribution of lengths with peaks (2 or 3) occurring at roughly the same sizes (Figure 6.5). These peaks represent lengths associated with specific age classes (age 2 ~ 20 cm; age 3 ~ 25 cm; age 4 ~ 29 cm) based on growth curve equations for black sea bass in the region (McGovern et al. 2002). Though these year classes are apparent in many years, there do not appear to be any instances of a particular year class driving the abundance estimates, as most years follow the same pattern, suggesting relatively consistent demographics in the population at GRNMS.

Other species – CPUE

All other species sampled at GRNMS in 2014 were below median values of the time series. Of the seven remaining taxa caught at GRNMS in 2014, *Stenotomus* spp. was the only historically prevalent species that had more than one individual caught, though its CPUE was still below the median value for the time series, continuing the low levels seen the previous two years for this species (Figure 6.6A).

Research Area of GRNMS – Black sea bass and Stenotomus spp.

The temporal trend in CPUE for black sea bass in the designated RA was similar to that in the remainder of the sanctuary, showing a general increase over time, with the non-research area showing greater inter-annual fluctuations (Figure 6.7). The same trend holds true with the size of black sea bass caught in GRNMS, with both areas showing an increasing trend over the time series (Figure 6.8). While the mean size has regularly been larger in the RA than the non-research area, this difference is not as pronounced in 2014 as it was in 2013. This difference between the previous two years was the result of a relatively low frequency of fish 21-22 cm TL during 2013 in the RA, whereas the mode for both areas in 2014 was 21 cm TL (Figure 6.9).

Temporal trends in *Stenotomus* spp. CPUE in the two areas were also similar, showing an overall decline from a peak in the late 1990s (Figure 6.10). There appear to be more inter-annual oscillations in the non-research area as well as generally higher catch throughout the time series compared to the RA, but the overall trends hold true. These differences have been less pronounced in the most recent years, with nearly identical catches following the implementation of the RA. However, the modest increasing trend in CPUE continued in 2014 within the RA while it declined outside the RA, though low catches complicate trend comparisons.

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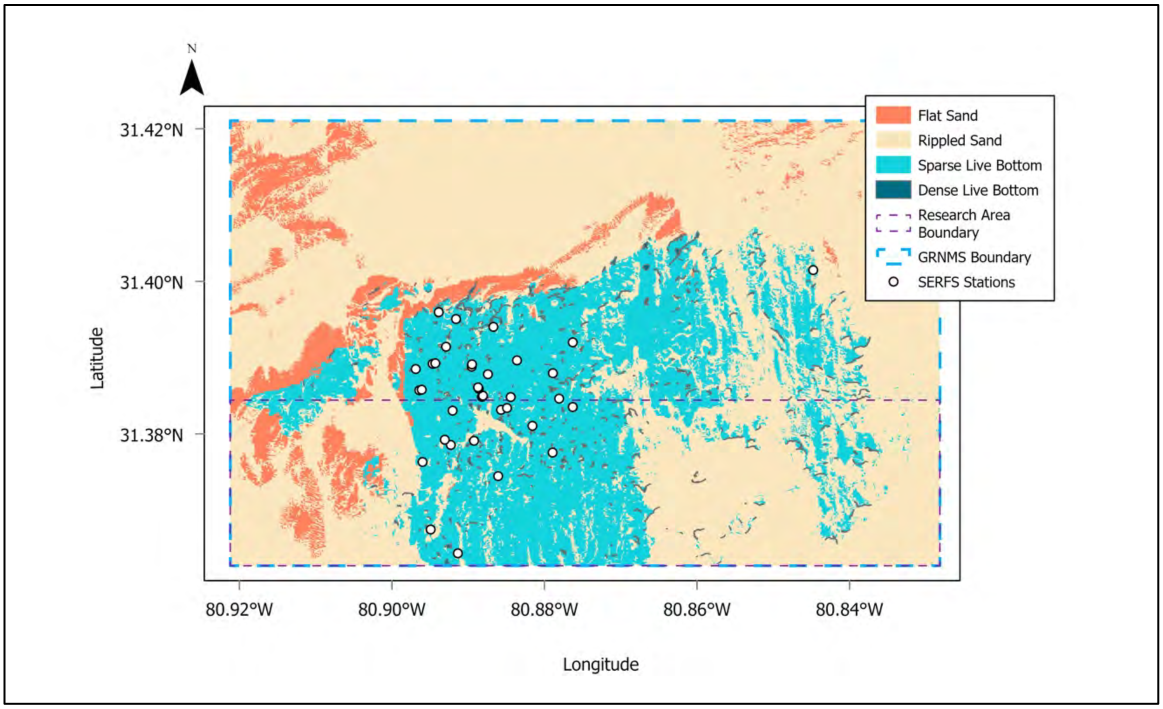

Figure 6.2. Map of Gray's Reef National Marine Sanctuary depicting habitat types and locations of all SERFS (including MARMAP) sampling stations, 1993-2014. Image: Alison Soss/NOAA

Table 6.1. Number of chevron trap stations sampled, mean water depth of all sampled stations (in m), and number of species caught at Gray's Reef National Marine Sanctuary by MARMAP and SERFS by year and area. Years 2012, 2013 and 2014 (denoted in red below) are those when Research Area was in place. Data include samples with soak times between 60 to 120 minutes.

	Nonresearch Area				**Research Area**		
Year	# of stations sampled	Mean Depth (m)	# of species		# of stations sampled	Mean Depth (m)	# of species
1993	20	17.1	11		0	-	-
1994	15	17.2	7		14	17.4	1
1995	48	16.8	9		26	16.3	5
1996	-	-	-		-	-	-
1997	7	16.3	9		1	16.0	4
1998	15	14.7	11		4	14.5	9
1999	3	15.0	3		9	17.3	3
2000	13	16.5	9		9	16.2	5
2001	10	16.7	8		6	16.8	6
2002	6	15.3	10		0	-	-
2003	-	-	-		-	-	-
2004	6	17.7	10		13	17.0	3
2005	8	16.3	8		7	16.1	4
2006	6	16.0	4		4	15.5	1
2007	8	18.5	6		2	18.0	2
2008	-	-	-		-	-	-
2009	7	17.0	6		2	17.0	4
2010	8	23.9	9		3	22.0	4
2011	11	16.9	9		7	17.4	5
2012	6	16.0	7		6	15.0	7
2013	10	15.6	6		9	17.7	9
2014	7	17.0	4		6	17.8	6

Table 6.2. Fishes captured, % abundance, wet weight of all fish, % total biomass, and length range by species of all by species collected during fishery-independent sampling with chevron traps from 1993 through 2014 at Gray's Reef National Marine Sanctuary.

Common Name	Scientific Name	# Captured	% Abundance	Biomass (kg)	% Biomass	Length Range (cm)
Black sea bass	*Centropristis striata*	394,809	90.65	66,430.4	95.10	10-43
---	*Stenotomus sp.*	29,868	6.86	2,092.9	3.00	9-24
Tomtate	*Haemulon aurolineatum*	6,582	1.51	724.7	1.04	12-25
Pinfish	*Lagodon rhomboides*	2,366	0.54	194.5	0.28	12-20
Spottail pinfish	*Diplodus holbrooki*	1,161	0.27	107.3	0.15	10-26
Cubbyu	*Pareques umbrosus*	242	0.06	29.2	0.04	16-23
Gray triggerfish	*Balistes capriscus*	200	0.05	116.3	0.17	15-50
Sharksucker	*Echeneis naucrates*	50	0.01	81.9	0.12	36-86
Toadfish	*Opsanus sp.*	45	0.01	22.9	0.03	18-40
Bank sea bass	*Centropristis ocyurus*	39	0.01	5.7	0.01	17-26
Leopard toadfish	*Opsanus pardus*	29	0.01	10.3	0.01	19-38
Northern puffer	*Sphoeroides maculatus*	28	0.01	7.2	0.01	18-26
Planehead filefish	*Stephanolepis hispidus*	27	0.01	2.9	< 0.01	11-26
Blue runner	*Caranx crysos*	25	0.01	3.8	0.01	16-32
Sand perch	*Diplectrum formosum*	20	<0.01	3.1	< 0.01	17-24
Pigfish	*Orthopristis chrysoptera*	18	<0.01	2.2	< 0.01	17-25
Banded rudderfish	*Seriola zonata*	5	<0.01	---	< 0.01	32-33
Greater amberjack	*Seriola dumerili*	5	<0.01	2.4	< 0.01	26-39
Whitebone porgy	*Calamus leucosteus*	4	<0.01	2.9	< 0.01	31-33
Gag	*Mycteroperca microlepis*	2	<0.01	2.5	< 0.01	40-52
Red snapper	*Lutjanus campechanus*	2	<0.01	7.4	0.01	34-70
Southern flounder	*Paralichthys lethostigma*	2	<0.01	1.6	< 0.01	37-44
Atlantic spadefish	*Chaetodipterus faber*	1	<0.01	0.1	< 0.01	15-15
Barbfish	*Scorpaena brasiliensis*	1	<0.01	---	< 0.01	17-17
Gulf flounder	*Paralichthys albigutta*	1	<0.01	0.8	< 0.01	43-43
Remora	*Remora remora*	1	<0.01	0.4	< 0.01	44-44
Scamp	*Mycteroperca phenax*	1	<0.01	0.9	< 0.01	41-41
Silver driftfish	*Psenes maculatus*	1	<0.01	0.2	< 0.01	21-21
Slippery dick	*Halichoeres bivittatus*	1	<0.01	0.1	< 0.01	21-21
Whitespotted soapfish	*Rypticus maculatus*	1	<0.01	0.1	< 0.01	19-19
Yellow jack	*Caranx bartholomaei*	1	<0.01	0.3	< 0.01	24-24

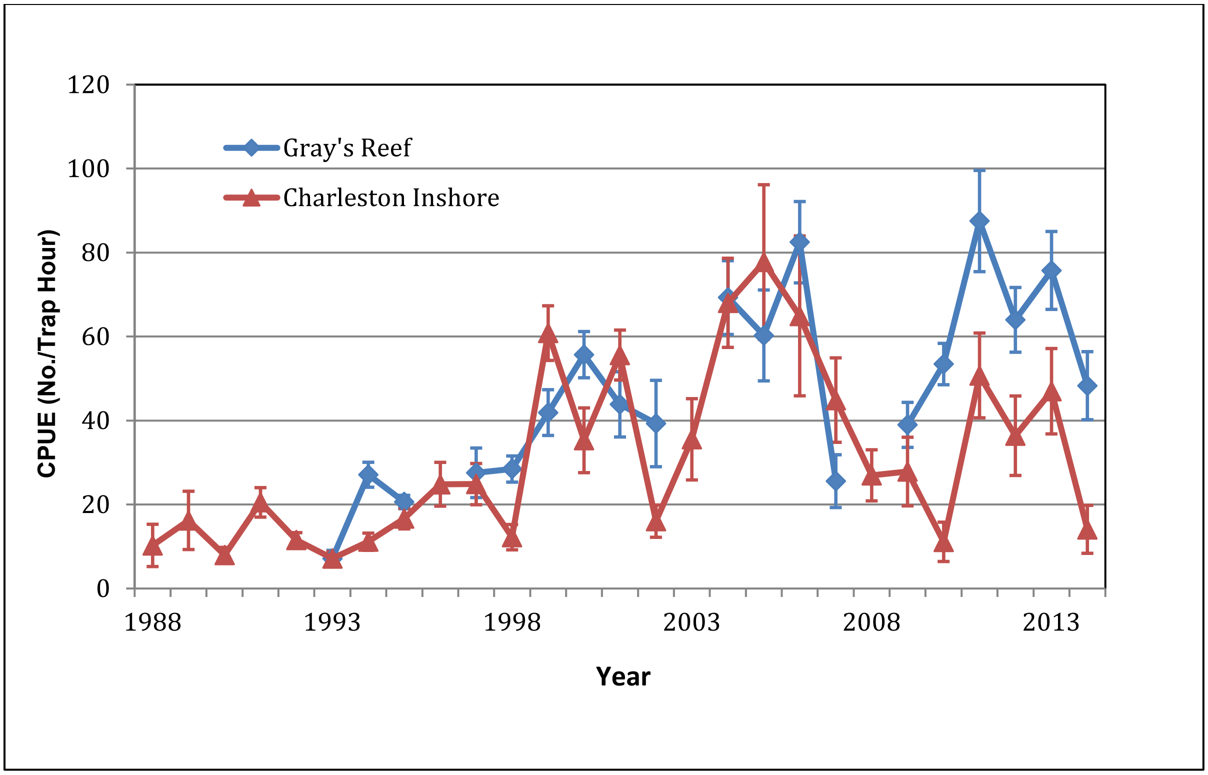

Figure 6.3. Catch per unit of effort (CPUE) for black sea bass captured reef sites with chevron traps by the MARMAP and SERFS at Gray's Reef National Marine Sanctuary (blue symbols and line) and Charleston Inshore (red symbols and line).

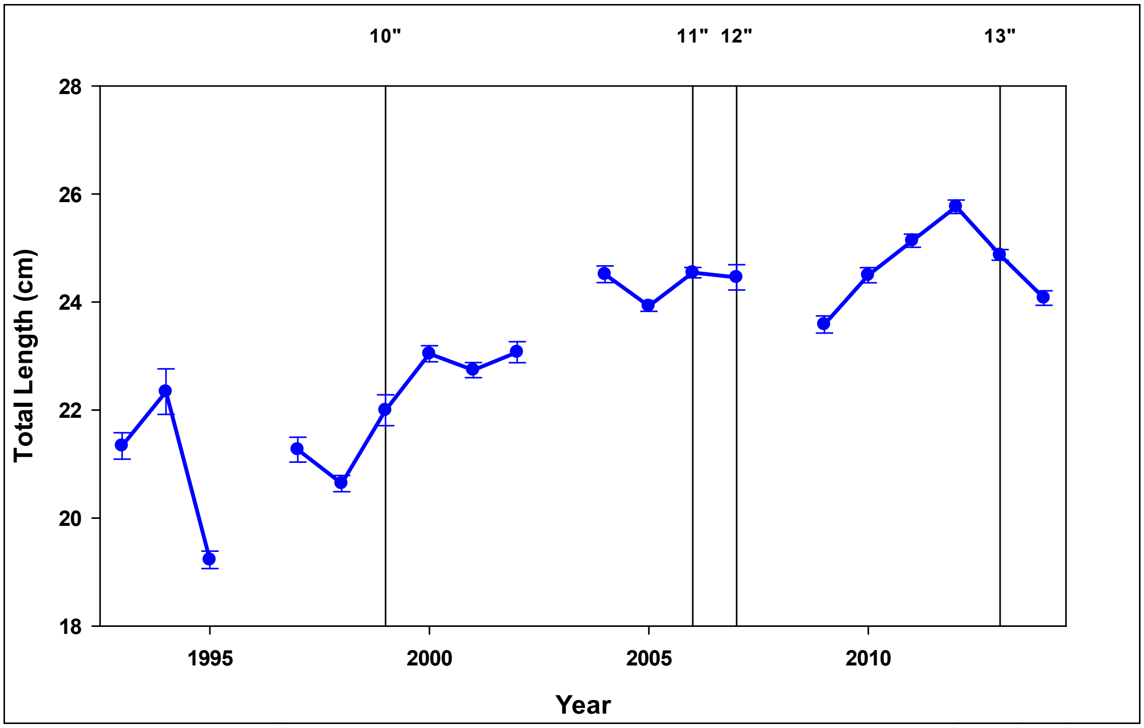

Figure 6.4. Mean length of black sea bass captured with chevron traps by MARMAP and SERFS at Gray's Reef National Marine Sanctuary. Error bars represent ± 1 Standard Error. Vertical reference lines indicate changes in the recreational size limit in inches total length (see text for details).

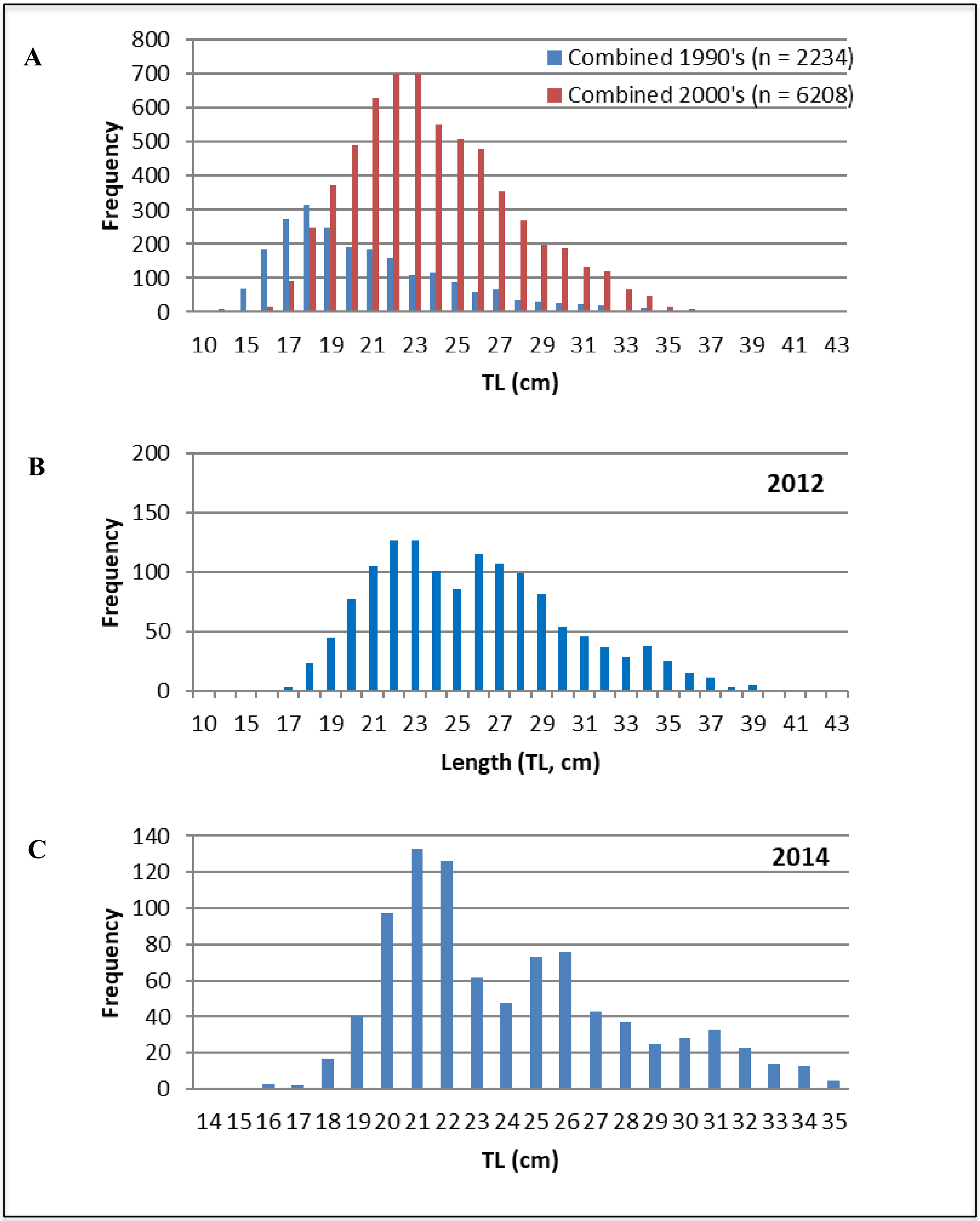

Figure 6.5. Length-frequency histograms for black sea bass captured with chevron traps by the SERFS fishery-independent sampling program at Gray’s Reef National Marine Sanctuary during (A) 1993-2009, decades combined; (B) 2012; (C) 2014. Note difference in frequency scale.

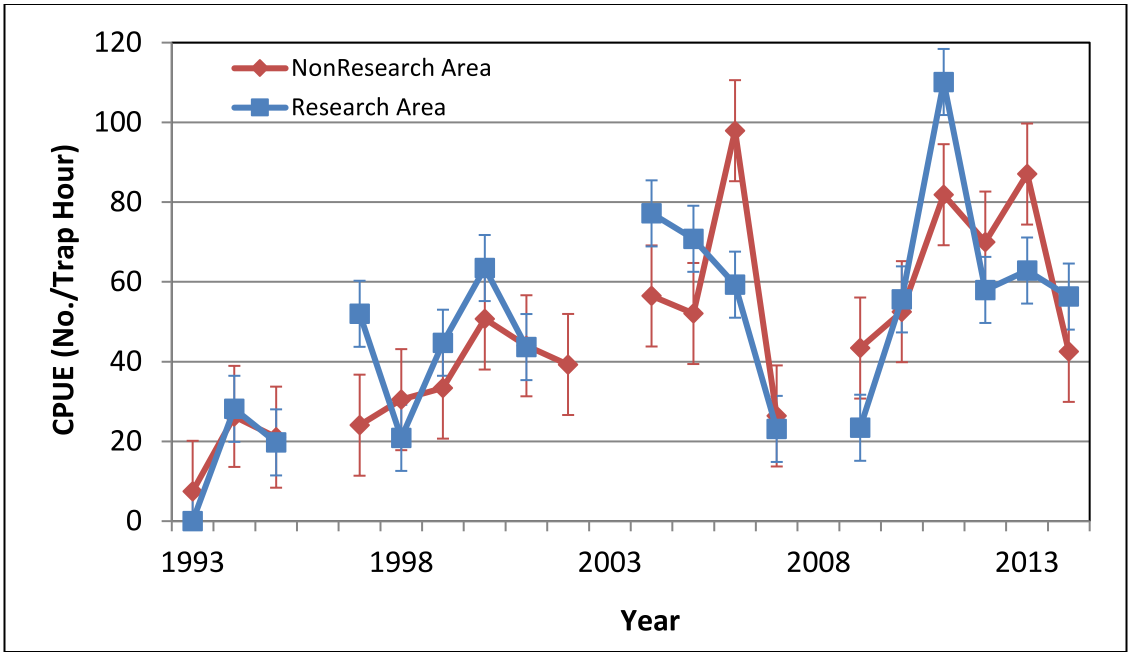

Figure 6.6. Comparisons of catch per unit of effort (CPUE) in the Research Area (blue symbols and lines) and the remainder of the sanctuary (red symbols and lines) for black sea bass captured with chevron traps by MARMAP and SERFS. Error bars represent ± 1 standard error.

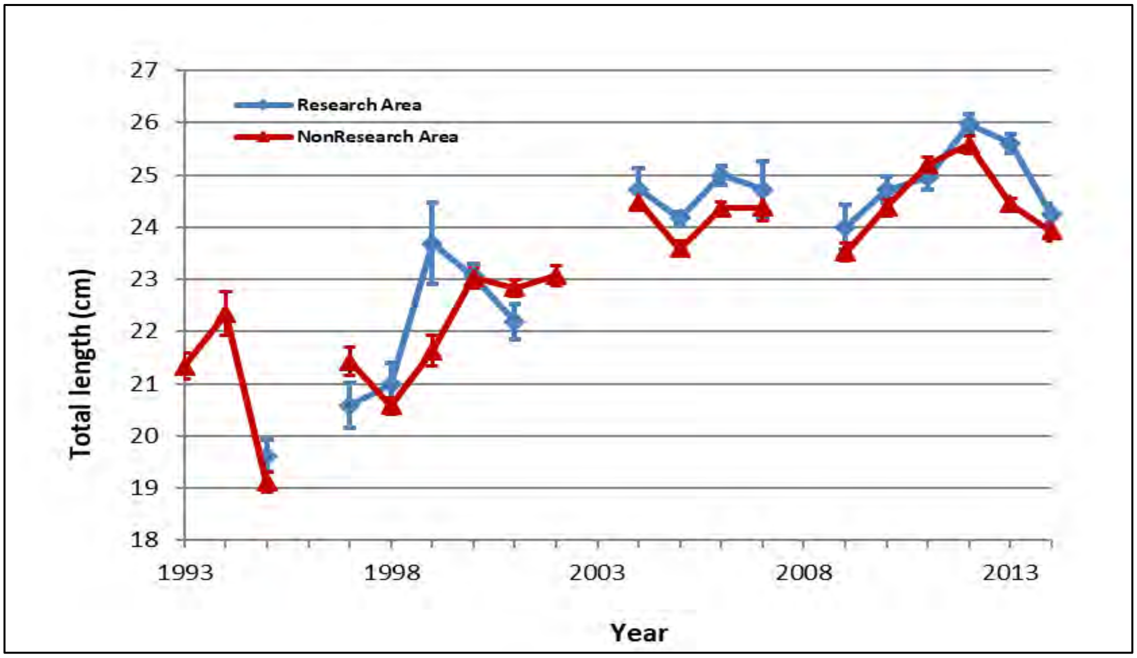

Figure 6.7. Comparisons of mean length in the Research Area and the remainder of the sanctuary for black sea bass captured with chevron traps by MARMAP and SERFS. Error bars represent ± 1 standard error.

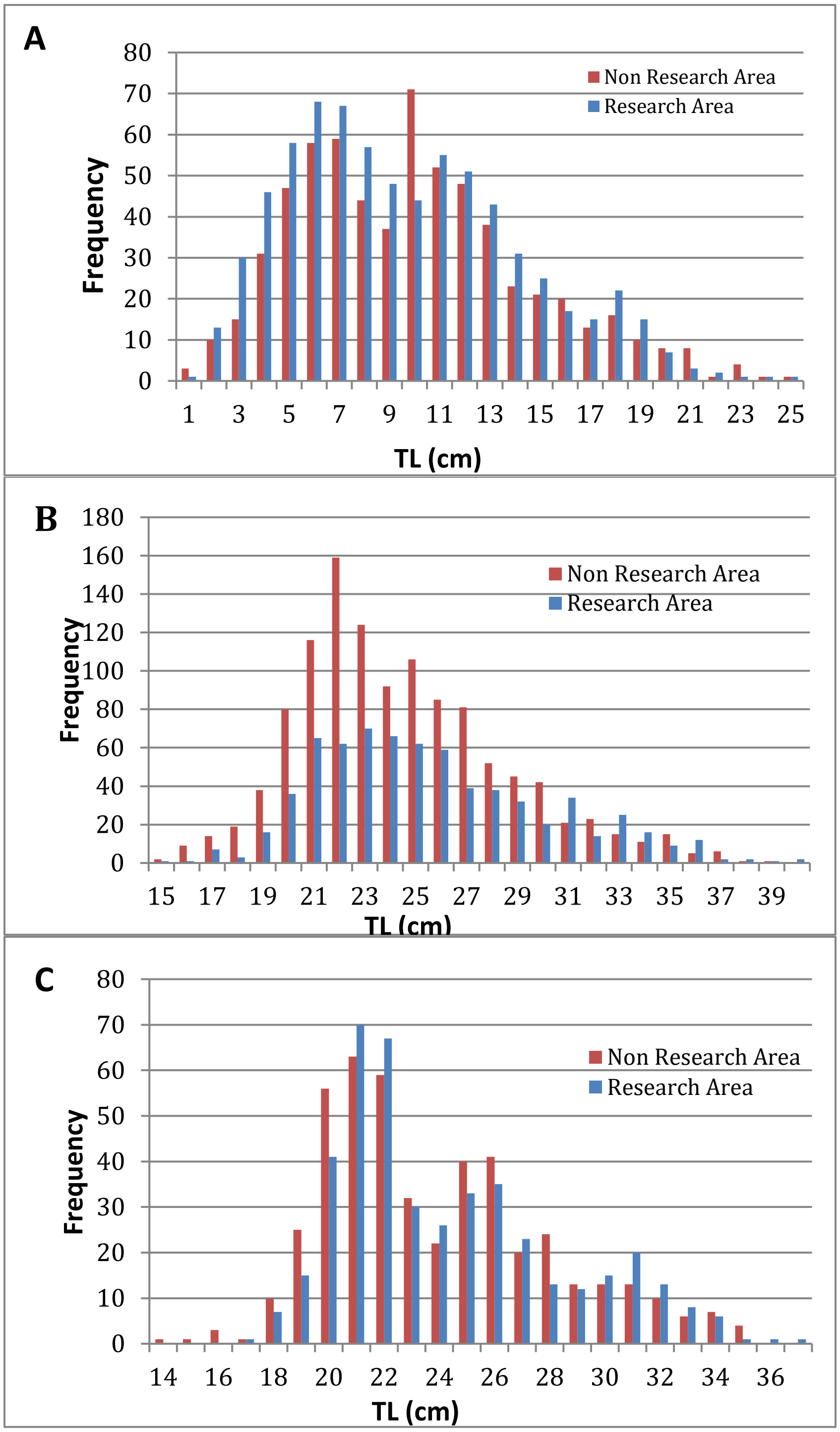

Figure 6.8. Length-frequency histograms for black sea bass captured with chevron traps by the SERFS fishery-independent sampling program at Gray's Reef National Marine Sanctuary following the designation of the Research Area, including (A) 2012; (B) 2013; and (C) 2014 both within and outside.

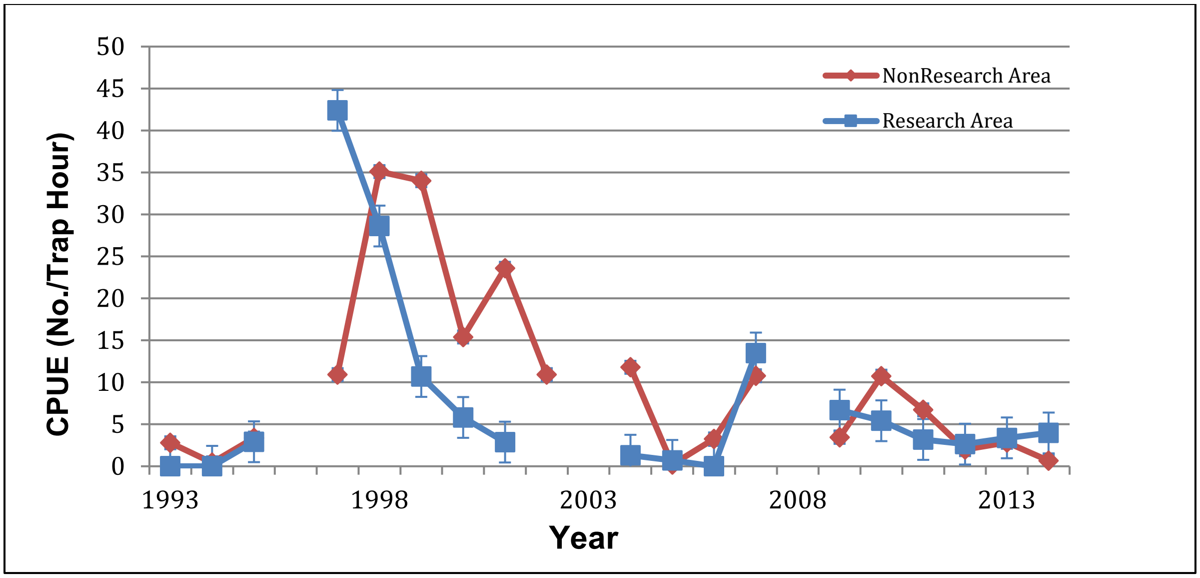

Figure 6.9. Comparisons of catch per unit of effort (CPUE) in the Research Area (blue bars) and the remainder of the sanctuary (red bars) for *Stenotomus* spp. captured with chevron traps by MARMAP and SERFS. Error bars represent ± 1 standard error.

Project 7. Fish-invertebrate associations at Gray's Reef National Marine Sanctuary, 2015

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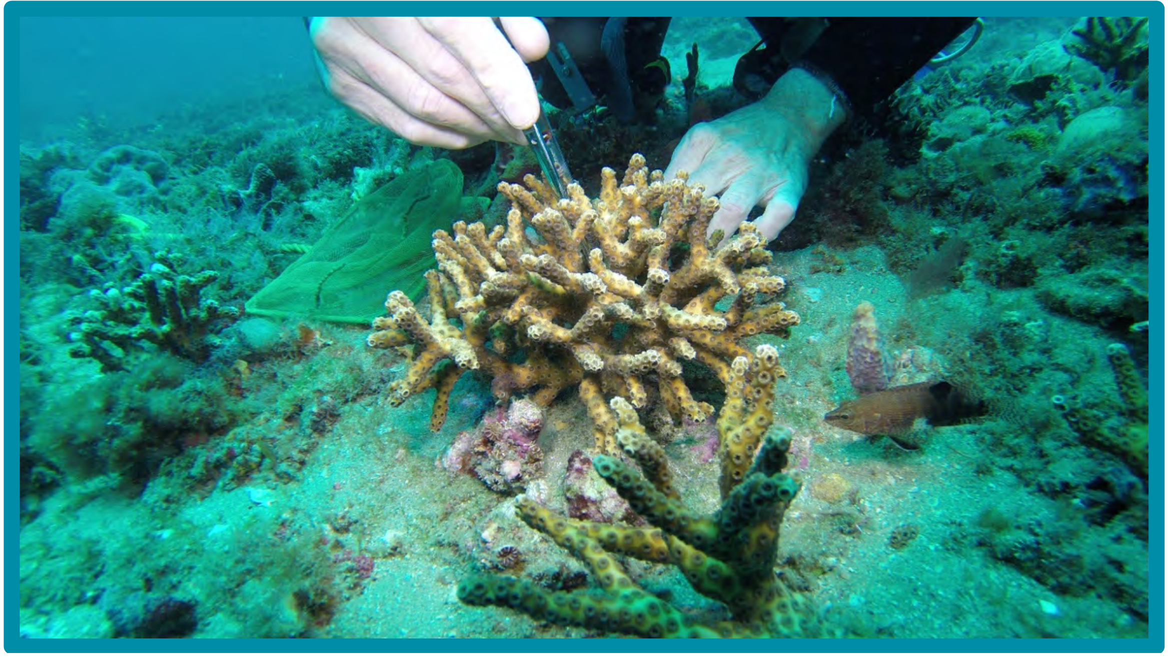

The belted sandfish, *Serranus subligarius*, is often associated with the coral *Oculina arbuscula*. Photo: Sarah Fangman/NOAA

Question addressed

Do *Oculina arbuscula* provide habitat to support fish recruitment on hard bottom reefs of the South Atlantic Bight (SAB)?

Measurements

The focal invertebrate species in this investigation was *Oculina arbuscula*, the most structurally complex branching coral found on SAB reefs. Organisms living among the branches of these corals were collected by divers, preserved, and then identified and quantified in the laboratory. The volume of each coral colony sampled was estimated based on measures of length, width, and height. The number of branch tips were also counted for each colony as an estimate of spatial complexity.

Key findings

- The temperate coral *Oculina arbuscula* provides structural habitat for at least three fish and two crustacean species.
- The ability of the temperate coral *Oculina arbuscula* to provide structural habitat for fish and crustaceans is directly related to the colony volume and number of branches per colony.

Project narrative

While strong support for the hypothesis that there is a link between *O. arbuscula* colonies and fish recruitment was not found, a consistent pattern of association was identified between this branching coral and at least three fish species: belted sandfish (*Serranus subligarius*), crested blenny (*Hypleurochilus geminatus*), and seaweed blenny (*Parablennius marmoreus*). Likewise, the arrow crab (*Stenorynchus seticornis*) and coral crab (*Mithrax hispidus*) appeared to be reliant on the habitat created by this species. The coral crab in particular was found nestled deep within colony branches and appears to be well-adapted for clinging to the coral surface and resisting removal by predators, as evidenced by the difficulty with which these crabs were removed from the coral branches with forceps.

In the SAB, rocky outcrops colonized extensively by sessile benthic invertebrates serve as foci for enhanced fish diversity and biomass (Sedberry and Van Dolah 1984, Kendall et al. 2009). The specific resources provided to fish populations by the invertebrates inhabiting these hard bottom reefs, however, has not been determined.

In July 2015, a preliminary investigation of the associations between fish and benthic invertebrates at GRNMS was initiated by addressing the hypothesis that structurally complex invertebrates provide habitat to support fish recruitment. Sampling was completed in the summer because this is the time of year when fish larvae in GRNMS, including many bottom associated species, show the highest abundance and diversity (Hare et al. unpublished manuscript).

The focal invertebrate species in this investigation was *Oculina arbuscula*, the most structurally complex branching coral found on SAB reefs. This coral is common on SAB hard bottom reefs (two to 10 colonies per m^{-2}), and like other sessile invertebrates, occurs in greatest abundance within the first one to two meters of the edge of the plateau where stress from sedimentation is lower (Divine, 2011).

Surveys conducted at 32 rocky outcrops within GRNMS in 2016 found that *O. arbuscula* is a significant contributor to the topographic complexity of these hard bottom reefs, covering 4.3% (±2.31 SD) of the substrata in the plateau edge habitats (Gleason, unpublished). The % cover documented for *O. arbuscula* in these surveys is at the upper end for those benthic invertebrates that have a growth form that contributes substantially to the three-dimensional structure of the habitat. For example, in these same benthic surveys in 2016, the amorphous, upright sponge *Ircinia felix* and vase sponge *Ircinia campana* displayed mean percent covers of 7.99 (±4.56 SD) and 2.43 (±1.96 SD), respectively, while the arborescent bryozoan *Schizoporella floridana* covered 2.88% (±4.23 SD) of the substrata.

The process of sampling organisms living among the branches of *O. arbuscula* began with two divers slowly approaching a designated colony and quickly tenting it with a nylon turkey roasting bag (48.2 cm W x 59.6 cm L). At this point one diver used both hands to hold the bag securely against the base of the colony while the other diver carefully slid the tube from a CamelBak Hydration Pack through the bag opening at the colony base. Prior to entering the water, the CamelBak was filled with a solution consisting of 5% quinaldine (a fish anaesthetic), 5% H_2O, and 90% EtOH. Approximately 150 ml of this solution was injected into the nylon bag and allowed to stay for one to three minutes, after which time all anaesthetized fishes and macro-invertebrates emerging from the colonies were collected by hand and with dip nets. The length, width, and height of each sampled colony was subsequently measured to estimate volume and the number of live branch tips was counted.

A total of 17 different taxa were found associated with the 31 *O. arbuscula* colonies sampled: 10 fish and seven invertebrates (Table 7.1). For fish, the crested blenny was the most common associate, followed by belted sandfish and the seaweed blenny. Of the fish captured, only the cocoa damselfish were small enough to be considered recent recruits.

Outside of a single brittle star and two sea urchins, invertebrate representatives were all crustaceans, primarily the coral crab (*Mithrax hispidus*) and arrow crab (*Stenorynchus seticornis)*. Like the fishes, size estimates indicated that most representatives from these two species of crabs were not recent recruits. Of the 15 arrow crabs collected, seven (47%) were female and three of these were gravid (43%). In contrast male:female ratios for the 35 coral crabs collected were 15:20 (43% to 57%), with 65% of the females being gravid.

The numbers of fish and crustaceans per coral colony were similar (Figure 7.1, t= 0.92, d.f. = 60, p = 0.36), with an overall faunal mean of 4.3 (±2.4 SD) organisms per colony. As might be expected, there was a significant positive relationship between coral colony size and faunal abundance, with colony volume and the number of branches per colony accounting for 40% and 34% of the variation in organismal numbers, respectively (Figure 7.2). This relationship between colony size and faunal numbers was driven more by fish than crustaceans with the regression line explaining approximately 40% of the variance in fish abundance (Figure 7.3). In contrast, the regression between crustacean numbers and colony volume was not significant.

This study provides baseline information on the number and diversity of fish and macroinvertebrates associated with the temperate branching coral *O. arbuscula*. While strong support for the hypothesis that there is a link between *O. arbuscula* and fish recruitment was not found, a consistent pattern of association was detected between this branching coral and at least three fish species: belted sandfish (*Serranus subligarius*), crested blenny (*Hypleurochilus geminatus*), and seaweed blenny (*Parablennius marmoreus*). Likewise, the arrow crab (*Stenorynchus seticornis*) and coral crab (*Mithrax hispidus*) appear to be reliant on the habitat created by this species.

It should be noted that while this study was conducted at a time of year when many fish species should have been recruiting to reefs within GRNMS (Hare et al. unpublished manuscript), it represented a single sampling period conducted over a brief time interval (i.e., five days). Considering the variability in fish recruitment that is possible in natural systems and the importance of live coral habitat to fish recruitment in tropical reef systems (Jones et al. 2004, Feary et al. 2007, Coker et al. 2014), replication of this study is recommended.

Likewise, this investigation was limited to a single, structurally complex invertebrate species, *O. arbuscula*. Given that other colonial benthic invertebrates, such as the bryozoan *Schizoporella cornuta* and polychaete worm *Filograna implexa*, also contribute to the topographic complexity of temperate reefs, it is suggested that future studies expand the number of species surveyed for both fish and macroinvertebrate associations.

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Sedberry, G.R. and R.F. Van Dolah. 1984. Demersal fish assemblages associated with hard bottom habitat in the South Atlantic Bight of the U.S.A. Environmental Biology of Fishes 11: 241-258.

Table 7.1. Total number and sizes of organisms found residing among branches of the temperate coral *Oculina arbuscula*. A total of 31 coral colonies were sampled July 14-18, 2015. Sizes, where more than two individuals were captured, are means and standard deviations.

Common Name	Species or Taxonomic Group	Total # Found	Size (mm)
Vertebrates			
Belted sandfish	*Serranus subligarius*	13	671.4 (±6.1)
Carolina hake	*Urophycis earllii*	1	95.0
Cocoa damselfish	*Stegastes variabilis*	3	17.5 (±5.3)
Crested blenny	*Hypleurochilus geminatus*	23	43.9 (±12.2)
Cubbyu	*Pareques umbrosus*	1	60.1
Oyster toadfish	*Opsanus tau*	1	160.0
Seaweed blenny	*Parablennius marmoreus*	8	53.0 (±15.5)
Slippery dick	*Halichoeres bivittatus*	1	28.0
Two-spot cardinalfish	*Apogon pseudomaculatus*	5	49.0 (±12.5)
Whitespotted soapfish	*Rypticus maculatus*	1	136.0
Invertebrates			
Arrow crab	*Stenorynchus seticornis*	15	28.9 (±9.5)
Banded-arm brittle star	*Ophioderma* sp.	1	11.1
Coral crab	*Mithrax hispidus*	35	17.9 (±5.8)
Dark mantis shrimp	*Neogonodactylus curacaoensis*	1	12.5
Hermit crab	Family *Diogenidae*	9	27.1 (±7.1)
Purple sea urchin	*Arbacia punctulata*	2	47.0
Snapping shrimp	*Alpheus* sp.	6	4.3 (±1.2)

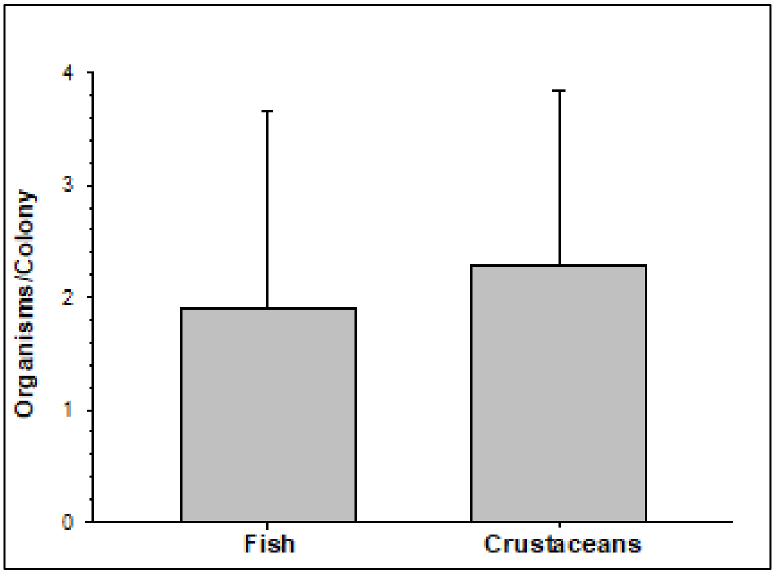

Figure 7.1. Mean (+SD) of the number of fish and crustaceans found associated with the temperate coral, *O. arbuscula*. N = 31 coral colonies.

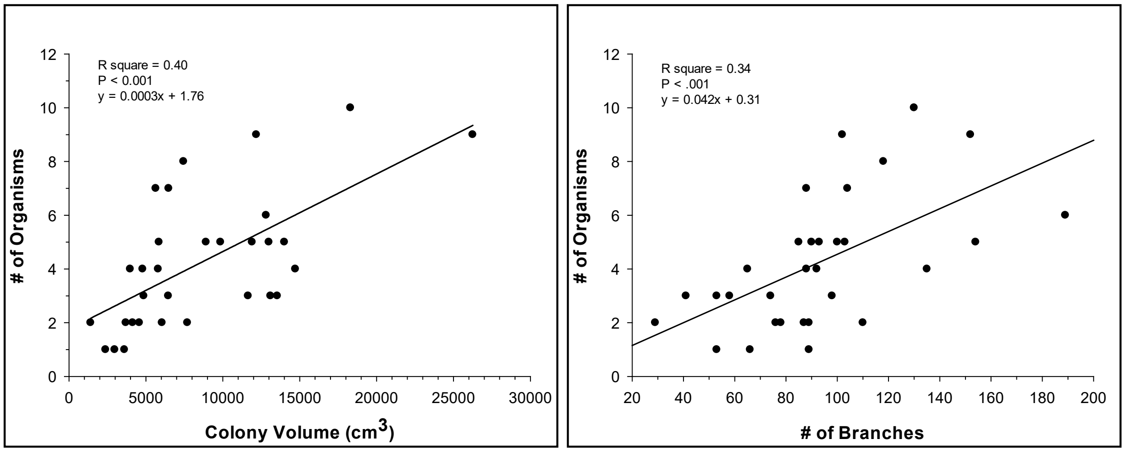

Figure 7.2. Regression analysis investigating the relationship between size of O. arbuscula colonies (i.e., estimated colony volume and number of branches) and the number of fish and macroinvertebrates that were nested within those colonies. N = 31 coral colonies.

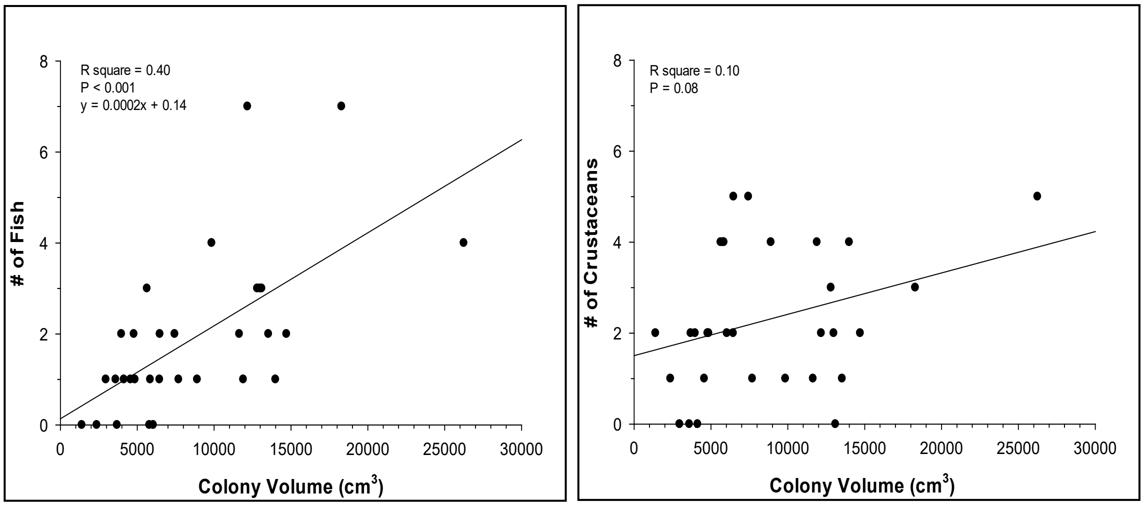

Figure 7.3. Regression analysis investigating the relationship between the estimated volume of *O. arbuscula* colonies and the number of fish and crustaceans collected from these colonies. N = 31 coral colonies.

Project 8. Assessing patterns of prey fish abundance and patchiness at live-bottom reefs using hydroacoustics, 2011-2013

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Scad (*Decapterus sp.*) aggregate densely over a ledge. Photo: Peter Auster/Mystic Aquarium/University of Connecticut

Question addressed

How does abundance of prey fish vary between reefs, inside and outside the no-take GRNMS RA, and among years?

Measurements

Distribution and abundance of prey fish at high relief reefs were analyzed to assess variation in density and patterns of patchiness using data collected from split-beam fisheries acoustics surveys in 2011, 2012, and 2013.

Key findings

- Higher densities of prey fish in 2012 and 2013 compared to 2011 as well as higher clumping or patchiness of prey in 2012 and 2013 compared to 2011, indicate an increase in both overall prey density and aggregation of prey in GRNMS.

Project narrative

Both tropical coral and sub-tropical live-bottom reefs are of particular ecological and socio-economic interest and characteristically have high fish abundance and diversity (Kracker et al. 2008). Tidal currents produce localized habitats with high delivery rates of planktonic prey that support aggregations of planktivorous fish (e.g., *Decapturus* spp.) and serve as the focus for enhanced rates of interactions with resident and transient piscivores including black sea bass, barracuda, greater amberjack, and various shark species (e.g., Kracker et al. 2008, Auster et al. 2013a). In areas such as sub-tropical reefs, variations in distribution and abundance of fish prey on reefs can be strong indicators of community structure based on direct food web and behavioral linkages to higher trophic level predators (Cury et al. 2000, Micheli et al. 2004a & b, Auster et al. 2013b).

In this study we investigated the distribution and abundance of prey fish (Table 8.1) associated with sub-tropical reefs (i.e., with medium to tall undercut rock ledges; sensu Kendall et al. 2007) at GRNMS. Total density and distribution of fish at reefs were analyzed using data collected during fisheries acoustics surveys from May 20 through 31, 2011; May 31 through June 6, 2012; and June 4 through 14, 2013. These surveys detected and quantified fish in the water column to the boundary of the seafloor using a Simrad EK-60 (200 kHz) split-beam fisheries sonar system at dawn and dusk at six sites in 2011 and 2012, and five sites in 2013. Sites were selected both inside and outside of the no-take RA at GRNMS. Only four sites were consistently surveyed across the three years (02OUT, 41OUT, 15IN, and 05IN – where "OUT" and "IN" refer to the position of the site relative to no-take zone). Fish distributions from the acoustic surveys were viewed as echograms that depict backscatter strength greater than -66 decibels (to minimize backscatter from particles, gelatinous zooplankton, and other material that can confuse interpretation). The acoustic surveys, composed of seven parallel transects with 50 m spacing and centered along a linear reef, recorded individual fish depth (calculated by the time of echo travel), individual fish length (calculated based on target strength), and fish density (calculated based on volume of backscatter). Target strength (see Kracker et al. 2008) was converted to fish length using the relationship TS=10 log (intensity level of echo/reference intensity level). In previous analyses, the acoustic data were matched with visual surveys of relevant fish community composition conducted by divers, and fish formations on the echograms were found to match characteristic spatial formations of fish aggregations (Kracker and Auster, unpublished). Numerical density of fishes was quantified in $100m^2$ bins.

Here fish <11 cm total length were assumed to function as prey based on size class estimates of prey species from visual surveys. Only prey density was addressed in this analysis. There were no significant changes in prey density between dawn and dusk among the years 2011, 2012, and 2013 (Kruskal-Wallis: $p=1.000$, $p=0.423$, $p=0.917$ respectively), so subsequent analyses compared density based on year, management status (inside or outside the no-take zone), and reef site. A nested General Linear Model (GLM) ANOVA and subsequent Tukey pairwise comparisons of densities across years, inside versus outside the no-take zone, and reef site were used to assess differences in prey fish abundance over space and across time. While positive spatial autocorrelation can be an issue for interpreting tests of significance from transect data, with nested models such as a nested ANOVA there is less concern because the analysis across factors minimizes spatial dependence in the data.

To assess differences in prey availability along the reefs over space and time, we used the Index of Mean Crowding (IMC). The IMC is an indicator of how evenly prey fish were distributed along a transect. A higher IMC value indicates a higher level of clumping, and therefore a less even distribution of individuals across each transect. K-W tests compared IMC values between dawn and dusk within years, across the years, and inside and outside of the no-fishing zone.

Results of the GLM were all highly significant for year, inside-outside status, and reef site (all $p<0.0001$; Table 8.2, Figure 8.1). There was a complex set of results from all Tukey pairwise comparisons. Most noteworthy were significant increases in prey density for all the sites over all three years ($p<0.001$ between each of the three years) and for sites inside and outside of the no-take areas within each year with significant increases in prey density outside in 2012 and 2013 ($p<0.001$, $p=0.0014$ respectively) but no significant difference in 2011 ($p=0.7576$). It is important to note that while the inside-outside comparison was significant, there are additional habitat factors that are in phase with these management designations. The differences between ledge height and extent of associated live bottom are not addressed in this analysis. Further, the density of ledges is greater in the outside region. The potential for synergies between habitats surrounding reefs as well as landscape linkages is unknown but could influence the interpretation of differences inside and outside the RA.

No significant difference was found in patterns of prey aggregation based on IMC values at sites inside compared to sites outside the RA in any of the years (K-W: 2011 p=0.3367, 2012 p=0.7488, 2013 p=0.8312). IMC values were, however, found to change significantly across the three years (K-W: Dawn p=0.003, Dusk p=0.006 respectively), with 2011 having a significantly lower level of aggregated prey than 2012 and 2013 both at dawn and at dusk (Figure 8.2). While prey clumping increased significantly from 2011 to 2013, it was not found to change in the short-term between dawn and dusk within 2011, 2012, or 2013 (Kruskal-Wallis: p=0.749, p=0.631, p=0.855).

Overall, and most significant, we found higher densities of prey overall in 2012 and 2013 compared to 2011 as well as higher clumping or patchiness of prey in 2012 and 2013 compared to 2011, indicating an increase in both overall prey density and aggregation responses of prey in GRNMS. This pattern of variation in prey distribution and abundance across the years and across reefs within years provides useful information about the state and dynamics of an important element of the larger reef community and can provide insight for interpreting results from the census of higher trophic fish.

At least two different, but not mutually exclusive, sets of factors could be hypothesized to explain the results found here. The first are environmental factors such as reef location related to local oceanography (currents, water masses with variable planktonic prey composition) and amount of shelter resources (e.g., volume of undercut ledges and habitat-forming fauna). Kracker et al. (2008) showed that environmental factors such as rock ledges and bottom habitat were the best predictor for fish biomass in the bottom 2m of the water column, and some bottom habitat types were also reliable predictors of fish biomass in the mid water column. The second set of factors that could explain the variation in prey density and distribution both within and between years are based on species interactions, particularly between the prey fish and their predators. Predators interact with prey in two distinct ways: directly by consumption, and indirectly by triggering behavioral responses in habitat choice, foraging, and movement of the prey to avoid predation even without a direct attack (Dill et al. 2003, Preisser et al. 2005, Heithaus et al. 2008). Predation removes individual prey from the population and may therefore reduce prey density directly. Additionally, the indirect threat of predation has been found to have strong behavioral effects on habitat choice, foraging, and movement of prey (Dill et al. 2003, Preisser et al. 2005, Frid et al. 2007a, Heithaus et al. 2008). The presence of predators – even without direct predation – may therefore alter prey density in a specific location (Lima 1998, Preisser et al. 2005, Frid et al. 2007b). This indirect effect of predators and the location of predators on prey location results in a “landscape of fear,” which suggests that animals exist in perceptual landscapes defined by differing levels of predation risk across space and time (Wirsing and Heithaus 2008). As we found higher densities of prey outside of the no-fishing zone in 2012 and 2013, one explanation is that prey experienced a higher perceived threat of predation and shifted distribution, or that variation in reef density and morphology produced variable responses in regard to habitat selection. Addressing the role of these physical and behavioral interactions related to availability of prey for reef predators will be the subject of future studies.

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Table 8.1. Common aggregating prey species observed at Gray's Reef National Marine Sanctuary. Asterisk indicates dominant and widespread taxa from visual surveys by divers.

Common Name	Scientific Name
Anchovy	Engraulidae
Atlantic bumper*	*Chloroscombrus chrysurus*
Redear herring	*Harengula humeralis*
Round scad*	*Decapterus punctatus*
Mackerel scad*	*Decapterus macarellus*
Scup*	*Stenotomus chrysops*
Spottail pinfish*	*Diplodus holbrookii*
Tomtate*	*Haemulon aurolineatum*

Table 8.2. Nested general linear model of prey density.

Factors	DF	F	P-Value
Year	2	698.16	<0.001
Closure status (in vs. out)	3	43.99	<0.001
Site (reef)	11	97.59	<0.001

S = 4.25121 R-Sq = 23.60% R-Sq(adj) = 23.47%

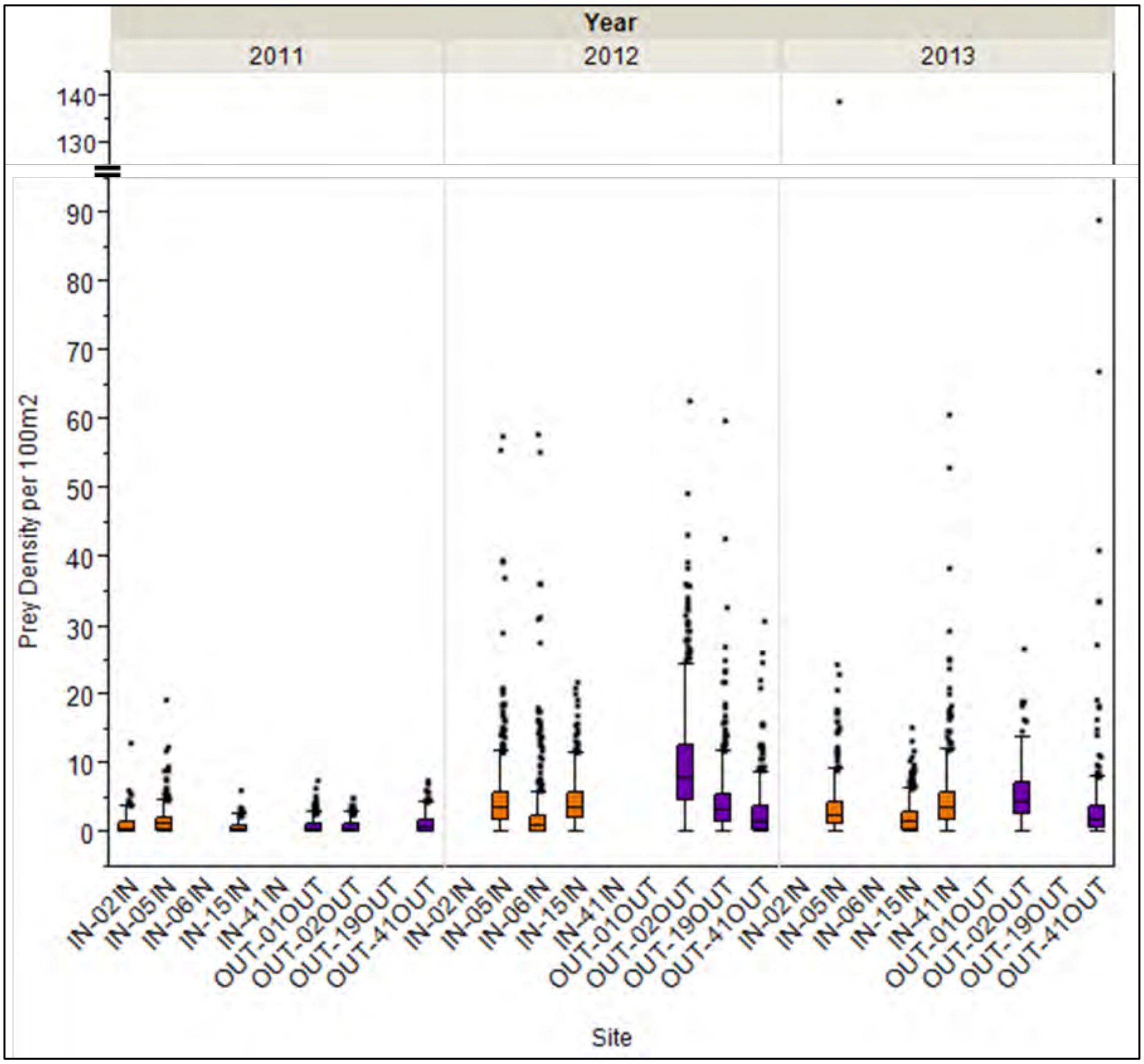

Figure 8.1. Boxplots of prey density per 100m2 at all sites outside (purple) and inside (orange) the no-fishing zone in 2011, 2012, and 2013. Box and whiskers depict median and interquartile range, with outliers shown by the dots above.

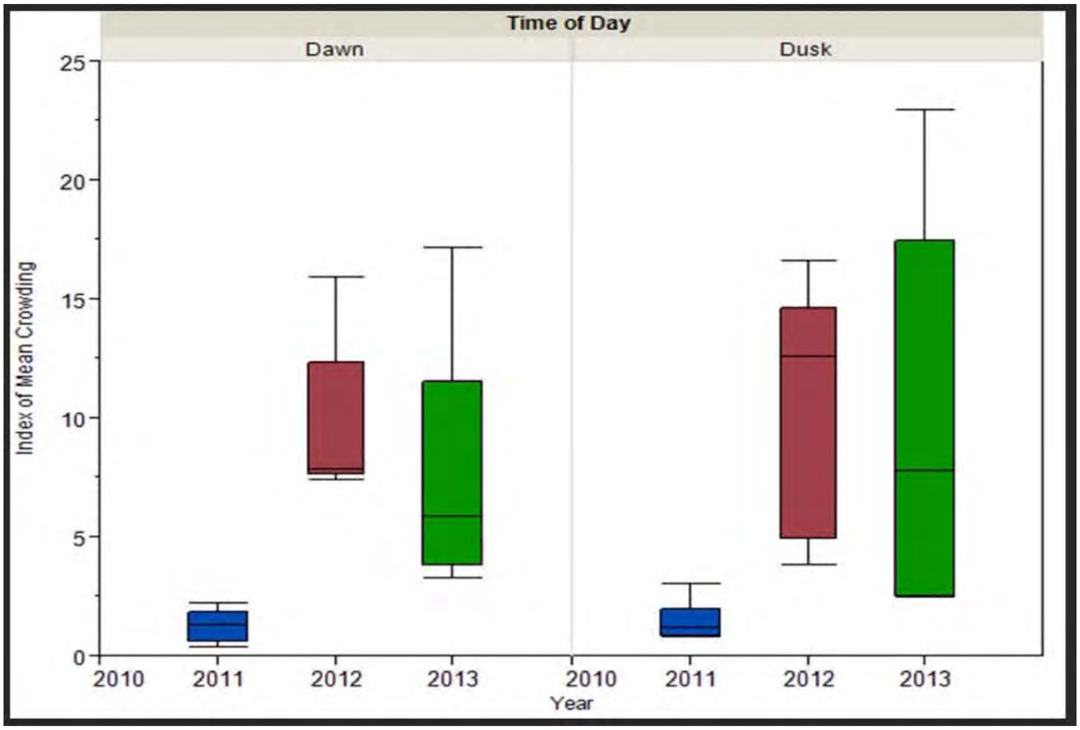

Figure 8.2. Boxplots of indices of mean crowding in 2011 (blue), 2012 (red), and 2013 (green) at dawn and at dusk. Box and whiskers depict median and interquartile range, with outliers shown by the dots above.

Project 9. Patterns of predator-prey co-occurrence and behavioral interactions over diel periods at sub-tropical reefs: results from 2016 observations

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An Almaco jack chases forage fish over a ledge at dusk. Photo: Peter Auster/Mystic Aquarium/University of Connecticut

Question addressed

How does the distribution and abundance of prey fish and co-occurring predators vary within reefs over 24-hour periods, among reefs, and at reefs inside and outside the GRNMS RA? How does the behavior of predators vary over time, especially during crespuscular periods? What role do habitat and near bottom hydrodynamics play in mediating the distribution of prey and predators?

Measurements

Distribution and abundance of fishes at select high relief reefs were collected using split-beam fisheries acoustic surveys and analyzed to assess variation in density and abundance. Surveys were conducted midday, pre-dusk, post-dusk, night, pre-dawn and post-dawn. Assignments as prey and predator were based on size class and species composition based on visual surveys by divers. Direct underwater observations of predator-prey interactions were also collected by divers during daytime and over the period of sunset.

Key findings

- Diel patterns of fish distribution, abundance, and behavior were similar across stations and consistent with diel patterns described from other complex habitats.
- While there was high variability in spatial distribution of both predators and prey, the mean density of predators was correlated with the spatial extent of hard bottom habitat and the mean density of prey was higher outside the no-take zone. However, reef habitat is more spatially extensive outside the GRNMS RA so there may be some synergistic effect on density.
- The presence of mid-water predators continuing to attack prey during and after sunset appeared to keep prey from dispersing, thereby enhancing predation opportunities for demersal reef piscivores.

Project narrative

Predation activity of piscivorous fish and predator-prey interactions are two important processes that in large part structure fish communities in many ecosystems, including tropical and sub-tropical reef ecosystems. A large number of studies have been conducted to investigate these processes in both coral and rocky reef systems using visual census and optical methods (e.g., Hixon 2011, Tupper and Boutilier 1997). Optical methods provide the highest level of detail on species behaviors, but are not able to cover large areas in relevant periods of time and are further challenged by variation in light levels to detect species and individuals, especially at night.

Fisheries acoustics has been used successfully since 2009 in the GRNMS in association with scuba diving observations to investigate fish spatial distribution patterns and estimate densities of predators and prey fish (Auster et al. 2013, Muñoz et al. 2019).

Fisheries acoustics can produce data at ecologically-relevant spatial and temporal scales to investigate changes at reefs over time. However, the limitation of fisheries acoustics is the difficulty to discriminate species, requiring a pairing of this tool with visual sampling methods that can provide species identification and patterns of species interactions.

The objectives of this work were to investigate the spatial and temporal variability of density distribution and overlap of predators and prey fish at select sites across GRNMS and identify the potential factors that affect predator-prey interactions. We also describe the diel evolution of prey fish aggregations over a range of spatial and temporal scales.

This study was conducted in June 2016 with the NOAA Ship *Nancy Foster* as the platform for acoustic surveys and the SRVx *Sand Tiger* supporting diving operations. The acoustic sampling was carried out using a SIMRAD EK60 echosounder at three frequencies (38, 120, and 200 kHz). A total of eight stations were surveyed both inside and outside of the no-fishing zone at GRNMS (Figure 9.1).

At each station an acoustic survey was repeated six times over 24 hours (pre-dawn, post-dawn, daytime, pre-dusk, post-dusk, nighttime; approximately 1.5 hours survey time each). The survey design consisted of seven parallel transects 1 nm long and spaced 50 m apart. An additional survey was implemented at night with a RD Instruments 300 kHz Workhorse Acoustic Doppler Current Profiler (ADCP) to collect data about the variability in hydrodynamic patterns over study reefs. Visual transects (for density and size class estimates) and behavioral observations were conducted using scuba at the same stations during daytime as well as over and after dusk to identify predator-prey interactions and behavioral changes during this transition phase. These direct visual observations were used to groundtruth the acoustic data.

Acoustic backscatter data were converted into fish density following two different approaches. Low density backscatter, which correspond to the backscatter coming from fish with individual swimming behavior, was analyzed using echo-counting. The high-density backscatter, which is associated with schooling fish, was analyzed using echo-integration. In both cases the estimated fish densities were divided into three classes (small - <11cm, medium 12 – 29cm, large - >30) based on the target strength (TS) used as a proxy for fish length. A generalized TS-length relationship (Love 1977) was used to estimate the fish size. We assumed that large size individual fish were predators and small and medium size schooling fish were prey based on the observation from diving surveys.

The general diel pattern of distribution and behavior of predators and prey that was observed during the 2016 survey was consistent with that reported by Helfman (1986) in similarly complex habitats. That is, small prey fish dispersed during the night in the pelagic environment or to other (presumably) feeding areas distant from ledges, then began to aggregate into schools and migrate toward high and low relief hard bottom habitats at dawn. The prey fish formed and remained in dense aggregations throughout the daylight hours and then transitioned to looser aggregations at sunset moving up and dispersing again away from ledges and in the water column.

The general view of predator fish density and activity is an increase during the crepuscular period (sunrise and sunset) when the predicted peak of predation activity occurs. Predator density (at least non-cryptic predators) is generally low during the daylight period and predators are largely absent during night hours. During the twilight period predators take advantage of the vulnerability of the prey that are transitioning from being loosely aggregated to forming dense and organized schools (or vice versa during dusk) that are more effective protection against predators. Fishery acoustics provided a unique view of the evolution of fish schools as they started to disaggregate, with the predator fish distributed in the vicinity of the aggregations (Figure 9.2).

The trend of prey and predator density grouped by time period (Figure 9.3) confirmed the general pattern described above. However, the density trend parsed by station (Figure 9.4) revealed a high level of variability across stations, especially where the peak density did not always occur at either dusk or dawn. Prey density instead seemed to follow a more stable pattern, with some exceptions. In the 41OUT site, for example, dense prey schools were observed well before and after dawn and sunset.

This variability could be explained by a combination of factors that require further investigation. First, differences in the species composition of the fish communities at different sites could largely affect the overall variation in density. Based on the diving observations, the prey fish community was composed of young-of-year and juvenile tomtate as well as round and mackerel scad. The main demersal predator species were black and bank sea bass, scamp grouper, and red snapper, and the most common mid-water predators were Spanish mackerel, Almaco jack, and greater amberjack. Observations revealed a general pattern of reduced spatial extent of dense prey fish aggregations along the front of high relief reefs from the period approximately 20 minutes prior to sunset through astronomical twilight, with fish still oriented to the undercut ledge and adjacent live-bottom habitat but rising above the seafloor up to approximately 1 to 5+ m before a rapid dispersal after sunset. Further, the spatial extent of prey fish during this period, in general, retracted from the fore and back reef region to the fore reef region, although this pattern varied with proximate threat of predation. Attacks by mid-water predators appeared to be the proximate driver of continued presence of prey aggregations on reefs after sunset (approximately 30 minutes post-twilight), with dispersal coincident with cessation of predation. The escape responses of prey from the mid-water predators, which were forced to flee toward the reef, facilitated continued predation by demersal piscivores (Figure 9.5). In the absence of mid-water predators attacking prey aggregations, prey species rapidly dispersed at the approximate time the upper disk of the sun disappeared below the horizon.

The second potential driver of the variability across stations is the habitat complexity (e.g. relief, rugosity, presence of undercut ledges) that can affect the characteristics of the fish communities and the dynamics of the predator-prey interactions (e.g., Kracker et al. 2008, Kendall et al. 2009).

Finally, variation of some environmental factors such as hydrodynamics could play an important role in enhancing the local density of prey fish by advection of planktonic prey at higher rates along particular areas of reefs that would consequently concentrate the distribution of planktivorous fish. ADCP data revealed a high level of variability of near-bottom flow rates and direction within stations that are consistent with the general patterns of prey fish patchiness (Figure 9.6). Future surveys will be conducted to better define this relationship and determine the role that variation in flow plays in mediating patterns of distribution of both prey and predators.

We did not discern any clear differences in terms of predators and prey density and distribution between the stations located inside and outside the RA. The potential differences between the two areas may be masked by the overall high variability throughout the area that can be driven by the factors described above.

The results of this preliminary analysis highlight the effectiveness of the use of fisheries acoustics in association with visual surveys via scuba diving to detect patterns of variation of predators and prey distribution and the behavioral interactions. Future analytical efforts will address diel variations in the distribution of predators and preys using, for instance, spatial statistical models that define spatial overlap at finer spatial and temporal resolutions. Moreover, the role of the habitat and hydrodynamics will be analyzed in more detail with emphasis on the variability of fish habitat selection over time.

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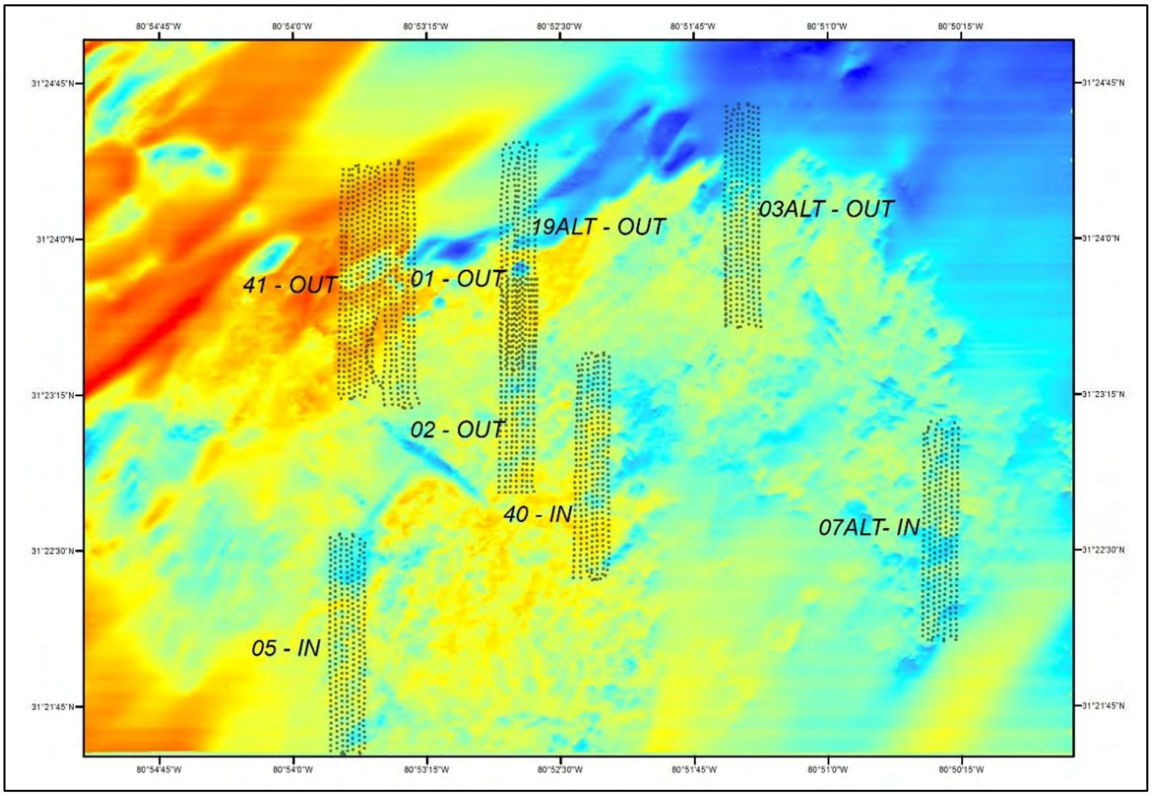

Figure 9.1. Survey sites sampled during the 2016 *Nancy Foster* cruise. IN and OUT indicate that the station is inside or outside the Research Area. Image: Fabio Campanella/NOAA

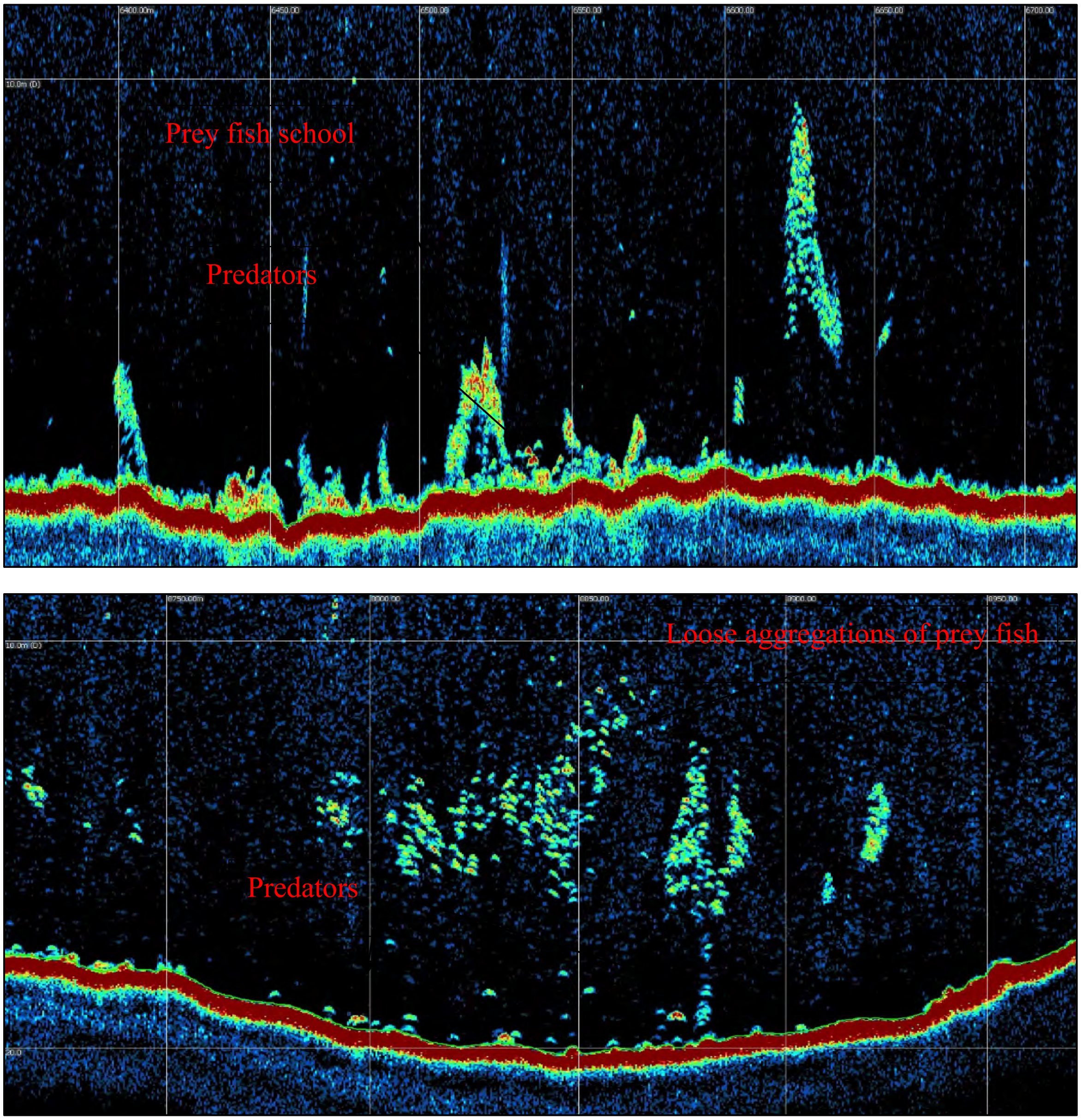

Figure 9.2. Example of an echogram of the station 41OUT at post-dusk (~20:30 – 21:00). In the top panel most of the prey schools are still densely aggregated and located next to the bottom. In the bottom panel the aggregations of prey fish are moving up in the water column shifting from dense schools to loose aggregations. Predators are distributed in both cases close to the prey schools according to both echogram and the diving observation. Predators are likely actively feeding on prey fish. Image: Fabio Campanella/NOAA

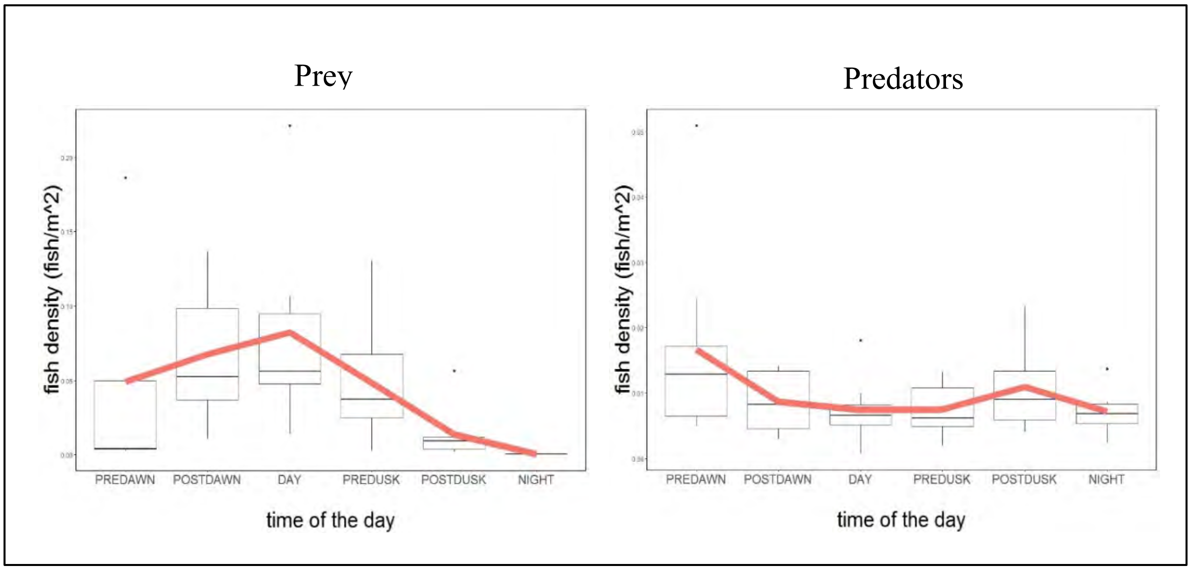

Figure 9.3. Trend in diel prey and predator fish density from the acoustic surveys by time period.

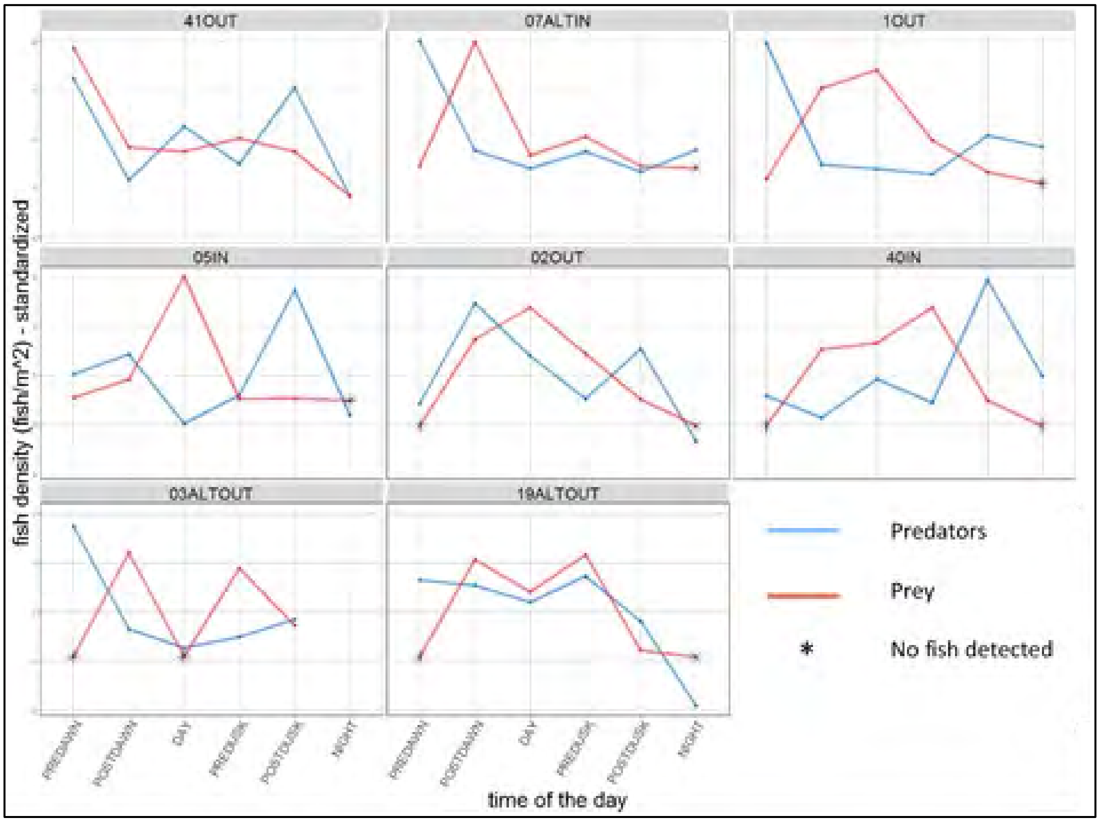

Figure 9.4. Diel prey and predator fish density (the densities are scaled to allow comparisons) estimated from the acoustic survey by station and time.

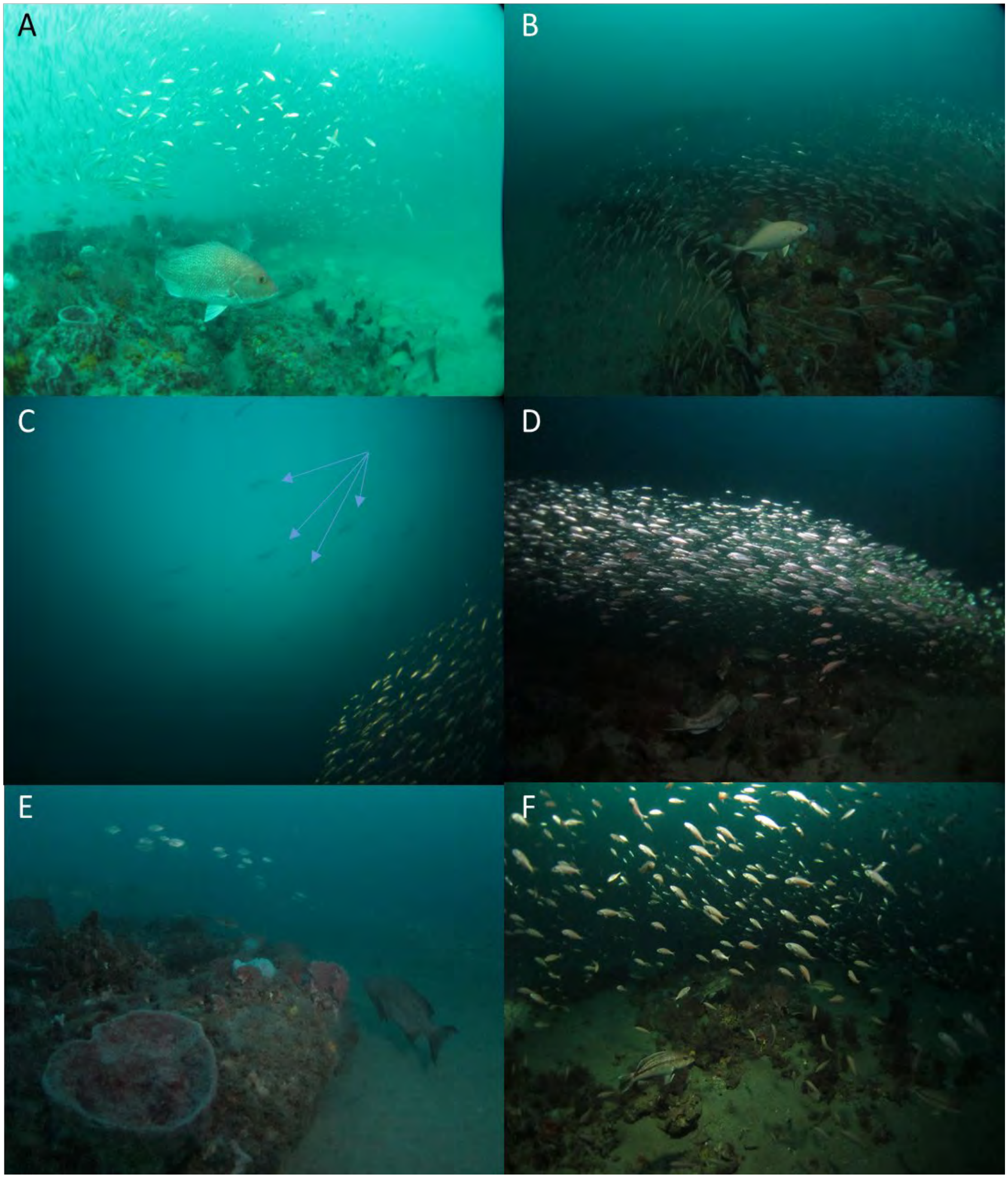

Figure 9.5. Observations of fish behavior at different times of day. (A) Daytime reef with prey school (*Decapturus* sp.) compressed towards reef by mid-water predators and stalked by red snapper. (B and C) Almaco jack (B) and Spanish mackerel (C) attacking prey school from above at dusk. (D) Black sea bass at dusk attacking compressed tubular school fleeing mid-water predators. (E) Scamp grouper at dusk approaching and stalking compressed school of prey. (F)Black sea bass attacking prey (juvenile tomtate) rising above reef before dispersal after twilight. Photos: Peter Auster/University of Connecticut/Mystic Aquarium

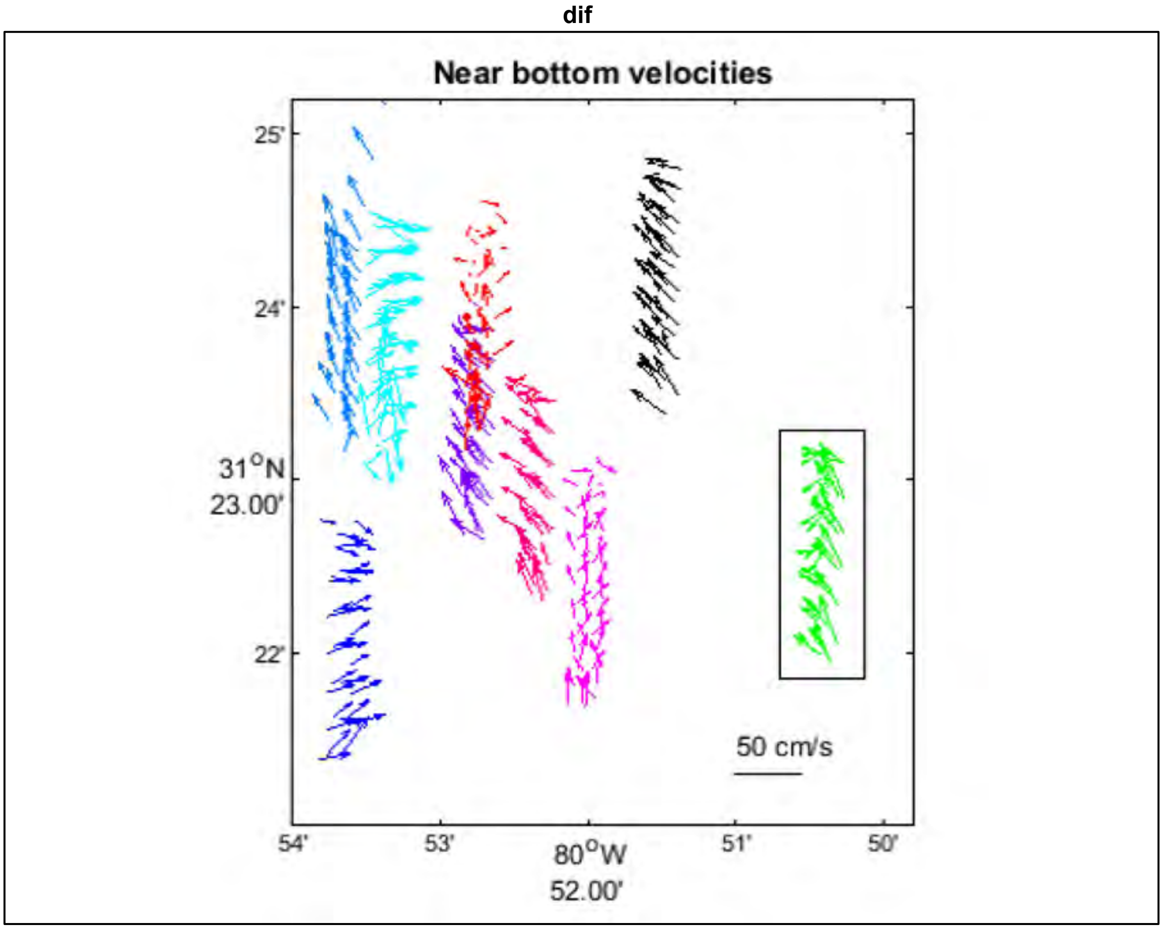

Figure 9.6. Plot of variation in near-bottom flow speed and direction in the geospatial domain of Gray's Reef National Marine Sanctuary. Each color signifies a distinct survey at a reef station (as in Figure 1). Noteworthy is variability of velocity and direction within reefs, suggesting variation in rates of advection of planktonic prey. This analysis was not normalized across tides or surveys so comparisons among reefs are not possible.

Project 10. Preliminary results assessing movement patterns of select demersal piscivores at the sub-tropical reefs of Gray's Reef National Marine Sanctuary (Northwest Atlantic, Carolinian Province), 2008-2013

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An acoustic receiver is deployed at a study reef. Photo: Peter Auster/Mystic Aquarium/University of Connecticut

Question addressed

Are there characteristic patterns of residency and movement of reef associated piscivorous fishes in sub-tropical ecosystems?

Measurements

Data were derived from fish (gag grouper, scamp grouper, red snapper, black sea bass) tagged with surgically implanted acoustic transmitters. Simple detections of transmitters were recorded at acoustic receivers deployed at 21 select reefs in study 1 (coarse-scale movement patterns) while triangulated positions were collected within a network of receivers at a single study reef in study 2 (fine-scale movement).

Key findings

- Tagging results at both coarse and fine spatial scales indicate a high percentage of these predators (i.e., fish that were released and remained within the receiver networks) site-associated over timescales of weeks to months (i.e., 79% and 55% in studies 1 and 2 respectively).
- That a portion of fish populations exhibit a degree of site fidelity while other segments of populations appear to be transient is an emerging pattern found across species in both tropical coral reef and temperate reef systems.

Project narrative

The design of marine protected areas (MPAs), as well as the subsequent evaluation of MPA success, requires both direct and indirect evidence of species responses to protection, including data on movement patterns that are related to localized recruitment, growth, survivorship, and fecundity. Much work on the role of marine protected areas has focused on long-term patterns in animal residency and any export of propagules or juveniles from MPAs to adjacent fishable areas (Auster and Shackell 2000, Micheli et al. 2004). However, ecological benefits can accrue from shorter periods of time within protected sites based on potential increases in fitness (bioenergetic benefits) mediated by species interactions. For example, increased rates of prey capture and reduced search costs could accrue for piscivores on high relief reefs in GRNMS through behavioral facilitation (e.g., Auster et al. 2013, Price et al. 2013, Vail et al. 2014).

Here we report on two preliminary studies that addressed patterns of movement for select demersal reef piscivores (gag grouper, *Mycteroperca microlepis*; scamp grouper, *Mycteroperca phenax*; red snapper, *Lutjanus campechanus*; and black sea bass, *Centropristis striata*) using surgically implanted acoustic transmitters. Results are based on transmitter detections from stationary receivers deployed at two spatial scales of resolution.

The first study was focused on coarse patterns of residency for three species (gag grouper, scamp grouper, and red snapper) moving within and among reefs monitored via acoustic receivers deployed at select reefs. Data are presence-absence of individual transmitter detections. The second study was focused on the fine-scale movement patterns of species (black sea bass, gag grouper, and scamp grouper) around a single study reef. Data are geographic coordinates of transmitter signals monitored by an array of fixed receivers configured to calculate sequential geo-referenced positions of individual fish when located within the receiver array. Results from both studies indicate that patterns of habitat use by these predators within GRNMS occur at ecologically significant periods of time for individuals to accrue potential benefits (e.g., Carey and Wahl 2010, Palacios et al. 2018). Further, these results provide the foundation for testing the demographic consequences of such patterns specifically at GRNMS and the surrounding region of sub-topical reefs.

Tagging study 1

Transmitter detections for this study segment were collected over a four-year period (May 5, 2008, to April 30, 2012) tracking the movement of gag grouper, scamp grouper, and red snapper. Data collected were from a passive acoustic telemetry array consisting of 21 receiver stations placed at fish capture sites (Figure 10.1).

Over 1.4 million detections were acquired from V13-1X, V13-1L, and V13T-1X coded acoustic transmitters (Vemco Ltd, Shad Bay, Nova Scotia) for a total of 39 fishes (23 gag grouper, 11 scamp grouper, five red snapper). Observations were restricted to the number of days fish were at large within the period predicted for life of each tag. Two scamp grouper were tagged and released but never detected, and therefore were not included in subsequent analyses.

Initial data from the receivers were consolidated using Microsoft Access. To clean the database of spurious detections, all detections were placed into one-hour bins (Chapman et al. 1999). We defined a non-spurious detection as a minimum of two detections per hour. A review of 10% of the database was performed for quality control. For the purposes of analysis, data were further grouped into 24-hour, or daily, bins. Our goal was to identify spatial and temporal patterns in fish movement (i.e., diel movement), potential seasonal migrations, movement between stations, and movement in and out of the GRNMS RA.

A summary of data by individual tagged fish demonstrates the wide variety of movement patterns and residence times found between and within species (Table 10.1). Patterns of presence and departure from specific stations (receivers) were assessed by inspection of liberty plots of individual transmitters (Figure 10.2). Noteworthy patterns of movement resulting from analyses of these data include:

- Single predators were detected at multiple reefs with individual red snapper detected at a maximum of seven stations with both scamp grouper and gag grouper at a maximum of four stations;
- Gag grouper were detected for the greatest percentage of days from their release dates to the end of potential detections based on life of the tag (65%) followed by red snapper (55%) and scamp grouper (41%)
- Departure frequency from the array (defined as periods of absence bracketed by at least one day of presence) varied between species and among individuals with red snapper departing most often (18 departures) followed by scamp grouper (8 departures) and gag grouper (5 departures)
- Scamp grouper departed the array for the greatest number of days (66 days) and then returned, followed by gag grouper (14 days) and red snapper (7 days). Examination of use of the no-take RA by individual fish revealed only a few individuals from each species moved in to or out of the RA (3 of 23 gag grouper, 3 of 5 red snapper, 1 of 11 scamp grouper). All other tagged fish remained strictly inside or outside the RA, during the time-period inclusive of positive transmitter identifications at receivers. Finally, there was no significant relationship between size and site fidelity for any of the three species (Figure 10.3; p-values from ANOVA of 0.841 for gag grouper, 0.802 for red snapper, and 0.445 for scamp grouper).

Tagging study 2

Twenty-two fish (14 black sea bass, six gag grouper, two scamp grouper) were implanted with acoustic transmitters and released within a VEMCO VR2W receiver network configured to determine fine-scale movement patterns at station FS-15 within the no-take RA (Figure 10.4). The reef area was composed of a linear undercut ledge feature with dense epifaunal cover surrounded by sparsely colonized live bottom as well as rippled and flat sand. Movement patterns of tagged fish were collected from June 19, 2012, through August 23, 2013 (431 elapsed days within the acoustic receiver network).

Seven black sea bass, four gag grouper, and two scamp grouper remained in the network of receivers at FS-15 after release. Position data for each transmitter was collected at 1 minute intervals and converted to latitude and longitude. Spatial analyses for each tag are summarized in Table 10.2 and include taxon, date tagged, dates of first and last detection within the network, total days between first and last detection (DIN), minimum convex polygon (MCP) around all detections for each tagged fish in m^2, estimated home range for approximately 90% of observations (Core), percent of observations with the core home range (%Obs), and the total number of observations/detections within the data set (Total Obs).

Data were imported into ArcGIS (10.2) as an Excel file and plotted as latitude and longitude. Data were reprojected as

NAD_1983_2011_StatePlane_Georgia_East_FIPS_1001 to match the reef base map. A minimum convex polygon (MCP) was drawn around all the data points using the ArcGIS minimum bounding geometry, minimum convex hull option. This is a polygon drawn around all points such that a line drawn between any two points does not pass outside the polygon. This represents the maximal area within which the fish was located. A kernel density estimator procedure was then applied to the data to determine areas of equal point (observation) density. The raster classification was set to four classes by quantiles. The contour tool was then used to apply contours to the observed areas of equal density. The contours were then traced by hand to produce polygons whose area could be calculated. Polygons were then be used to select observation locations within them and calculate the percentage of the total observations that they represented.

Results of accumulated position data around the study reef revealed noteworthy patterns of movement (Figure 10.5). Black sea bass remained in the receiver network to a maximum of 430 days, gag grouper a maximum of 33 days, and scamp grouper a maximum of 31 days. When present, all species exhibited limited ranges based on MCP measures (776-66,037 m^2) with core regions significantly smaller (255-8,717 m^2). The black sea bass that exhibited the longest period at large within the network occupied the largest MCP (i.e., 66037 m^2) but 94% of observations occurred within a footprint of 2462 m^2, an intermediate value. There was no significant relationship between MCP and Core area (Figure 10.6) for all tagged fish as a group (ANOVA $p = 0.156$, regression r^2=9.9%) with the same lack of significance for black sea bass ($p = 0.232$, $r^2 = 12.4\%$) and gag grouper alone ($p = 0.590$, $r^2 = 0$). Interestingly, two individual fish exhibited a bi-modal distribution with a shift in distribution from one side of the reef to the other at a specific point in the time series of data (Figure 10.7).

Tagging results at both coarse and fine spatial scales suggest a high percentage of these predators are reef-associated over ecologically relevant periods of time (i.e., of sufficient time to accrue an increase in fitness from direct predation on prey resources and through facilitative interactions with associated predators that increase predation rates and hence energetic gains, assuming such outcomes contrast with other habitats). If we assume a time threshold of 21 days recorded within the network during either study is needed to accrue gains in fitness from local ecological conditions, then 79% of tagged fish in study 1 (95% of fish if days between first and last detection are counted) and 55% of fish in study 2 meet such criteria. Such time periods have been found to exhibit increased growth rates of reef fishes (e.g., Figure 10.7 in Strelcheck et al. 2003) and prey availability can influence growth (e.g., St. John 1995). Small home ranges are a possible response to threat of predation, territorial behaviors within and between species, limited sites for shelter, and proximate access to prey. Emigration from the acoustic network in either study does not indicate that fish have left GRNMS or environs. That a segment of populations of higher trophic level species exhibit a degree of site fidelity while other segments do not is an emerging pattern found across species in both tropical coral reef and temperate reef systems (e.g., Lindholm et al. 2006, 2007, 2010). In any case these preliminary results provide a foundation for inquiry into the bioenergetic and demographic outcomes of reef versus non-reef patterns of habitat use as well as the role of no-take versus fished sites for conservation of these and related predators.

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Table 10.1. Data summary for individual transmitters by species during study period 1.

Species	Fish ID	Transmitter Number	Fork length (cm)	# Stations Visited	Stations Visited	Percent Days Recorded	Total # Days Recorded	Potential # Days Recorded	Release Date	First Detection	Last Detection
Lutjanus campechanus	LC1	49899	59.0	2	10,11	42	474	1140	19 May 2008	18 Oct 2008	20 May 2010
	LC2	49917	63.0	2	15,25	11	75	708	23 May 2010	18 Jun 2010	20 Dec 2010
	LC3	49920	80.5	3	8,19,27	11	76	711	20 May 2010	21 May 2010	30 Dec 2010
	LC4	49928	49.0	2	6,10	20	140	710	21 May 2010	21 May 2010	08 Oct 2010
	LC5	49931	60.0	7	3,4,5,6,11,15,27	35	365	1052	13 Jun 2009	15 Aug 2009	16 Dec 2011
Mycteroperca microlepis	MM1	49895	63.0	2	27,28	50	570	1140	18 May 2008	29 Oct 2008	07 Nov 2010
	MM2	49929	52.0	3	3,5,6	16	171	1051	14 Jun 2009	13 Aug 2009	05 Oct 2010
	MM3	49930	48.5	4	2,3,5,19	16	167	1051	14 Jun 2009	22 Aug 2009	27 Dec 2010
	MM4	49935	38.0	2	15,16	14	145	1051	14 Jun 2009	08 Oct 2009	21 Sep 2010
	MM5	49902	87.5	1	5	1	8	1052	13 Jun 2009	21 Aug 2009	06 Dec 2009
	MM6	49900	67.0	1	19	42	301	709	22 May 2010	22 May 2010	25 Apr 2012
	MM7	49905	56.0	2	15,25	3	20	706	25 May 2010	25 May 2010	14 Jun 2010
	MM8	49906	60.0	1	4	6	42	705	26 May 2010	11 Jun 2010	23 Sep 2010
	MM9	49909	60.0	1	15	39	275	708	23 May 2010	23 May 2010	30 Jul 2011
	MM10	49910	70.0	1	15	16	116	706	25 May 2010	31 May 2010	21 Sep 2010
	MM11	49911	65.0	2	15,25	10	72	708	23 May 2010	23 May 2010	16 Sep 2010
	MM12	49912	62.5	1	25	29	202	706	25 May 2010	25 May 2010	13 Dec 2010
	MM13	49913	58.0	4	10,15,19,28	2	12	707	24 May 2010	20 Jul 2010	12 Aug 2010
	MM14	49914	61.0	1	19	5	34	711	20 May 2010	20 May 2010	23 Jun 2010
	MM15	49916	49.0	3	11,15,18	8	55	707	24 May 2010	24 May 2010	18 Jul 2010
	MM16	49918	50.0	3	1,3,5	5	33	707	24 May 2010	01 Jun 2010	29 Jul 2010
	MM17	49921	54.0	1	19	2	14	711	20 May 2010	20 May 2010	03 Jun 2010
	MM18	49922	61.0	4	1,16,27,28	10	72	711	20 May 2010	20 May 2010	31 Jul 2010
	MM19	49923	61.0	3	1,3,5	18	129	711	20 May 2010	20 May 2010	27 Dec 2010
	MM20	49924	75.0	2	4,19	17	120	711	20 May 2010	20 May 2010	17 Sep 2010
	MM21	49925	73.0	1	19	5	33	711	20 May 2010	20 May 2010	22 Jun 2010
	MM22	49927	61.0	1	19	4	25	711	20 May 2010	20 May 2010	14 Jun 2010
	MM23	49937	62.5	1	19	5	35	709	22 May 2010	22 May 2010	14 Feb 2011
Mycteroperca phenax	MP1	49894	74.0	1	28	1	13	1140	18 May 2008	29 Oct 2008	23 Nov 2008
	MP2	49896	75.0	1	28	19	222	1140	18 May 2008	29 Oct 2008	21 Nov 2009
	MP3	49897	83.0	1	3	1	13	1140	19 May 2008	01 Jan 2010	25 Mar 2010
	MP4	49898	58.0	2	10,11	38	434	1140	15 May 2008	17 May 2008	09 Jul 2010
	MP5	49901	84.0	1	11	8	93	1140	16 May 2008	17 May 2008	17 Aug 2008
	MP6	49915	79.0	1	19	46	330	711	20 May 2008	20 May 2010	01 Mar 2012
	MP7	49919	71.0	4	1,7,19,25	18	129	710	21 May 2008	21 May 2010	15 Jan 2011
	MP8	49926	59.0	1	19	18	125	711	20 May 2008	21 May 2010	05 Jun 2011
	MP9	49932	80.0	1	19	29	205	709	22 May 2008	23 May 2010	10 Mar 2012

Table 10.1. Continued.

Species	Fish ID	Transmitter Number	Tag Life	End of Tag Life	End of Study	# Departures	Average Duration of Departure (Days)	Min Departure Duration (Days)	Max Departure Duration (Days)
Lutjanus campechanus	LC1	49899	1140	03 Jul 2011	30 Apr 2012	13	8	1	82
	LC2	49917	1140	06 Jul 2013	30 Apr 2012	22	5	1	22
	LC3	49920	1140	03 Jul 2013	30 Apr 2012	21	7	1	63
	LC4	49928	1140	04 Jul 2013	30 Apr 2012	0	0	0	0
	LC5	49931	1140	27 Jul 2012	30 Apr 2012	34	14	1	194
Mycteroperca microlepis	MM1	49895	1140	02 Jul 2011	30 Apr 2012	7	24	1	161
	MM2	49929	1140	28 Jul 2012	30 Apr 2012	23	11	1	92
	MM3	49930	1140	28 Jul 2012	30 Apr 2012	10	33	1	128
	MM4	49935	1140	28 Jul 2012	30 Apr 2012	7	29	1	197
	MM5	49902	1140	27 Jul 2012	30 Apr 2012	24	17	1	275
	MM6	49900	1140	05 Jul 2013	30 Apr 2012	3	33	11	66
	MM7	49905	1140	08 Jul 2013	30 Apr 2012	0	0	0	0
	MM8	49906	1140	09 Jul 2013	30 Apr 2012	3	26	15	45
	MM9	49909	1140	06 Jul 2013	30 Apr 2012	9	18	1	152
	MM10	49910	1140	08 Jul 2013	30 Apr 2012	0	0	0	0
	MM11	49911	1140	06 Jul 2013	30 Apr 2012	10	4	1	10
	MM12	49912	1140	08 Jul 2013	30 Apr 2012	0	0	0	0
	MM13	49913	1140	07 Jul 2013	30 Apr 2012	3	4	3	7
	MM14	49914	1140	03 Jul 2013	30 Apr 2012	0	0	0	0
	MM15	49916	1140	07 Jul 2013	30 Apr 2012	0	0	0	0
	MM16	49918	1140	07 Jul 2013	30 Apr 2012	0	5	3	11
	MM17	49921	1140	03 Jul 2013	30 Apr 2012	1	1	1	1
	MM18	49922	1140	03 Jul 2013	30 Apr 2012	1	2	2	2
	MM19	49923	1140	03 Jul 2013	30 Apr 2012	1	93	93	93
	MM20	49924	1140	03 Jul 2013	30 Apr 2012	1	1	1	1
	MM21	49925	1140	03 Jul 2013	30 Apr 2012	0	0	0	0
	MM22	49927	1140	03 Jul 2013	30 Apr 2012	0	0	0	0
	MM23	49937	1140	05 Jul 2013	30 Apr 2012	10	23	1	202
Mycteroperca phenax	MP1	49894	1140	02 Jul 2011	30 Apr 2012	2	88	13	163
	MP2	49896	1140	02 Jul 2011	30 Apr 2012	3	82	1	163
	MP3	49897	1140	03 Jul 2011	30 Apr 2012	4	166	1	591
	MP4	49898	1140	29 Jun 2011	30 Apr 2012	19	13	1	138
	MP5	49901	1140	30 Jun 2011	30 Apr 2012	0	NA	0	0
	MP6	49915	1140	03 Jul 2013	30 Apr 2012	17	16	1	168
	MP7	49919	1140	04 Jul 2013	30 Apr 2012	1	113	113	113
	MP8	49926	1140	03 Jul 2013	30 Apr 2012	6	43	1	245
	MP9	49932	1140	05 Jul 2013	30 Apr 2012	19	8	1	39

Table 10.2. Data summary for individual transmitters by species during study period 2. Tag: individual tag number. Species: Bsb = black sea bass. Tagged: date tagged. 1st Record: first appearance in acoustic data set. Last record: last appearance in acoustic data set. DIN: Days between first and last detection. MCPm2: minimum convex polygon, in meters squared. Core m2: area encompassing approximately 90% of observations, in meters squared. % Obs: actual percent of observations within core area. Total Obs: total number of detections for that tag number in the data set.

Tag	Species	Tagged	1st Record	Last Record	DIN	MCP m^2	Core m^2	% Obs	Total Obs
30474	Bsb	5/15/2012	6/19/2012	4/13/2013	299	41296	3071	98	65535
30476	Bsb	5/17/2012	9/9/2012	4/27/2013	231	776	255	97	434
30477	Bsb	5/16/2012	6/19/2012	7/17/2012	29	27967	5868	96	1545
30478	Bsb	5/15/2012	6/19/2012	7/14/2012	26	18445	2770	94	946
30480	Bsb	5/17/2012	6/19/2012	8/7/2013	415	21906	1364	90	13122
30481	Bsb	5/17/2012	6/19/2012	8/22/2013	430	66037	2462	94	47163
46026	Bsb	5/17/2012	6/20/2012	5/19/2013	334	54548	8717	96	34752
30475	Gag	5/15/2012	6/19/2012	7/16/2012	28	13670	4842	92	404
30479	Gag	5/15/2012	6/19/2012	7/7/2012	19	16407	5287	90	273
46024	Gag	5/22/2012	6/19/2012	7/21/2012	33	12015	1808	90	870
49907	Gag	5/23/2012	6/20/2012	7/19/2012	30	9729	4519	91	121
30473	Scamp	5/16/2012	6/19/2012	7/19/2012	31	6162	1577	91	333
46025	Scamp	5/16/2012	6/19/2012	7/16/2012	28	6162	2746	95	333

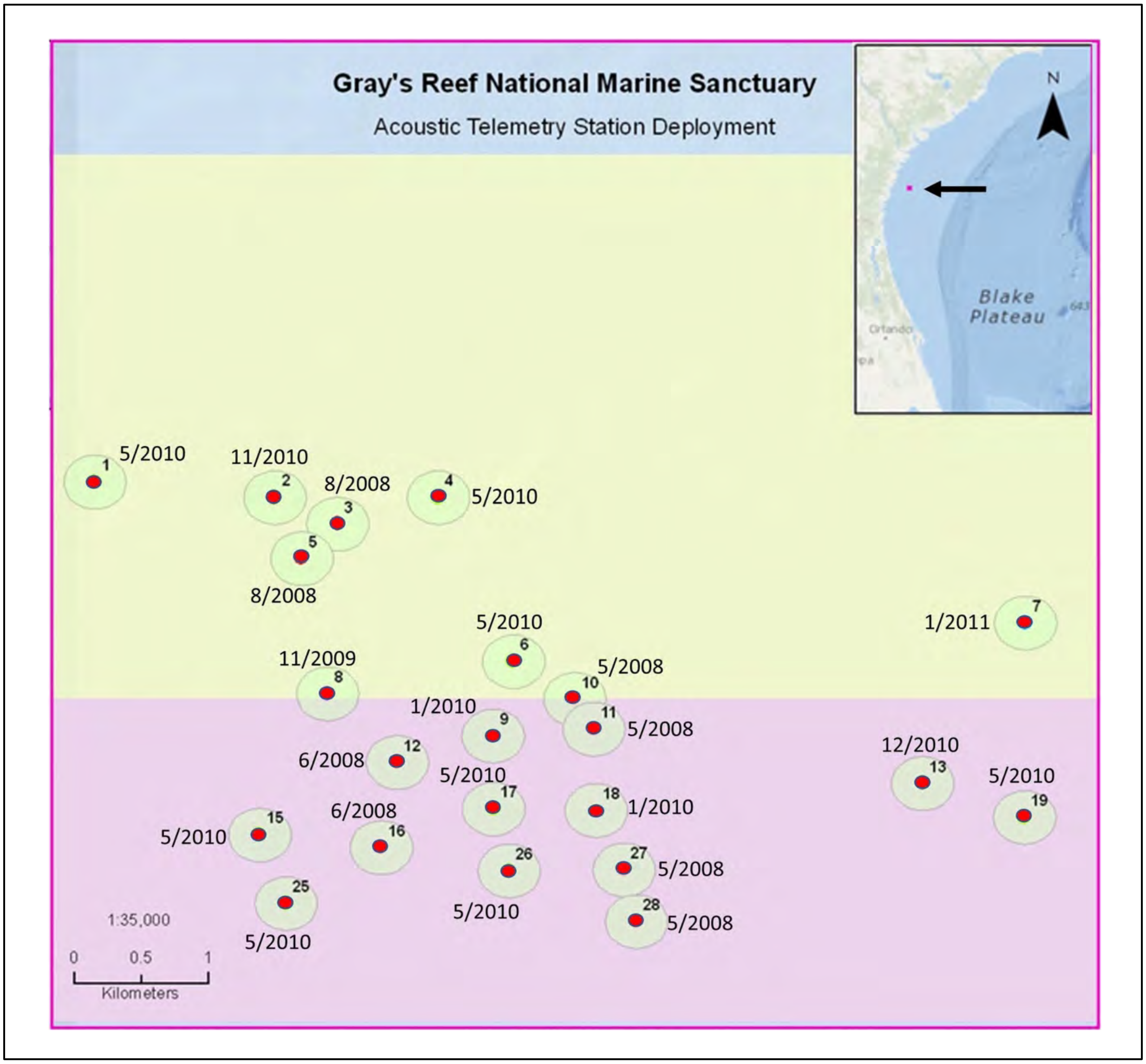

Figure 10.1. Receiver locations for Tagging Study 1 focused on coarse-scale movement patterns. Twenty-one passive acoustic stations used within this study. Noted are the date of installation and the theoretical detection range. Image: L.A. Jensen/California State University Monterey Bay and Harrison Franklin/NOAA

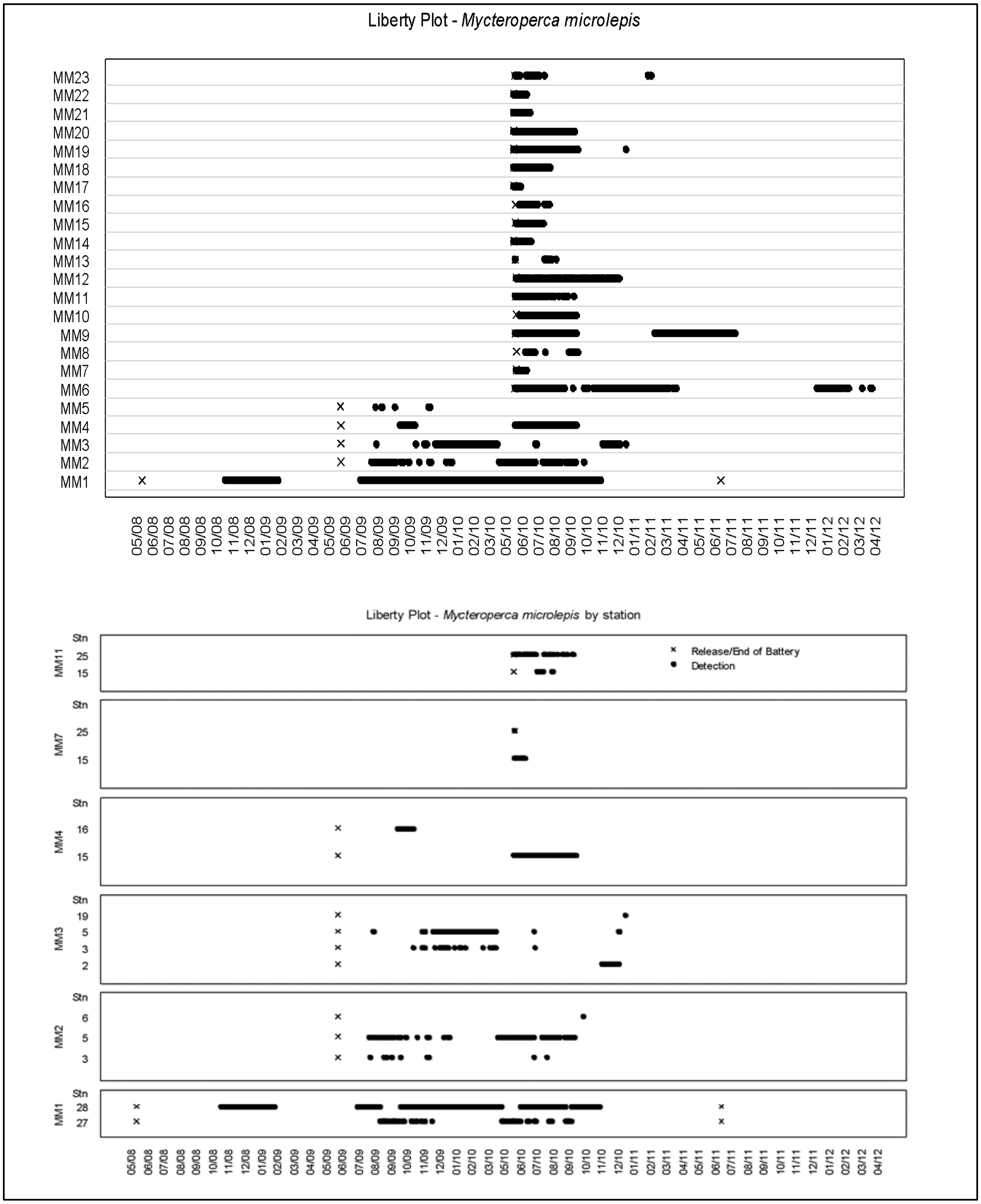

Figure 10.2. (Top) Example of liberty plot for gag grouper used to detect patterns of presence and departure from network of receivers within Gray's Reef National Marine Sanctuary. (Bottom) Example of liberty plot for gag grouper based on detections of individual transmitters at multiple stations.

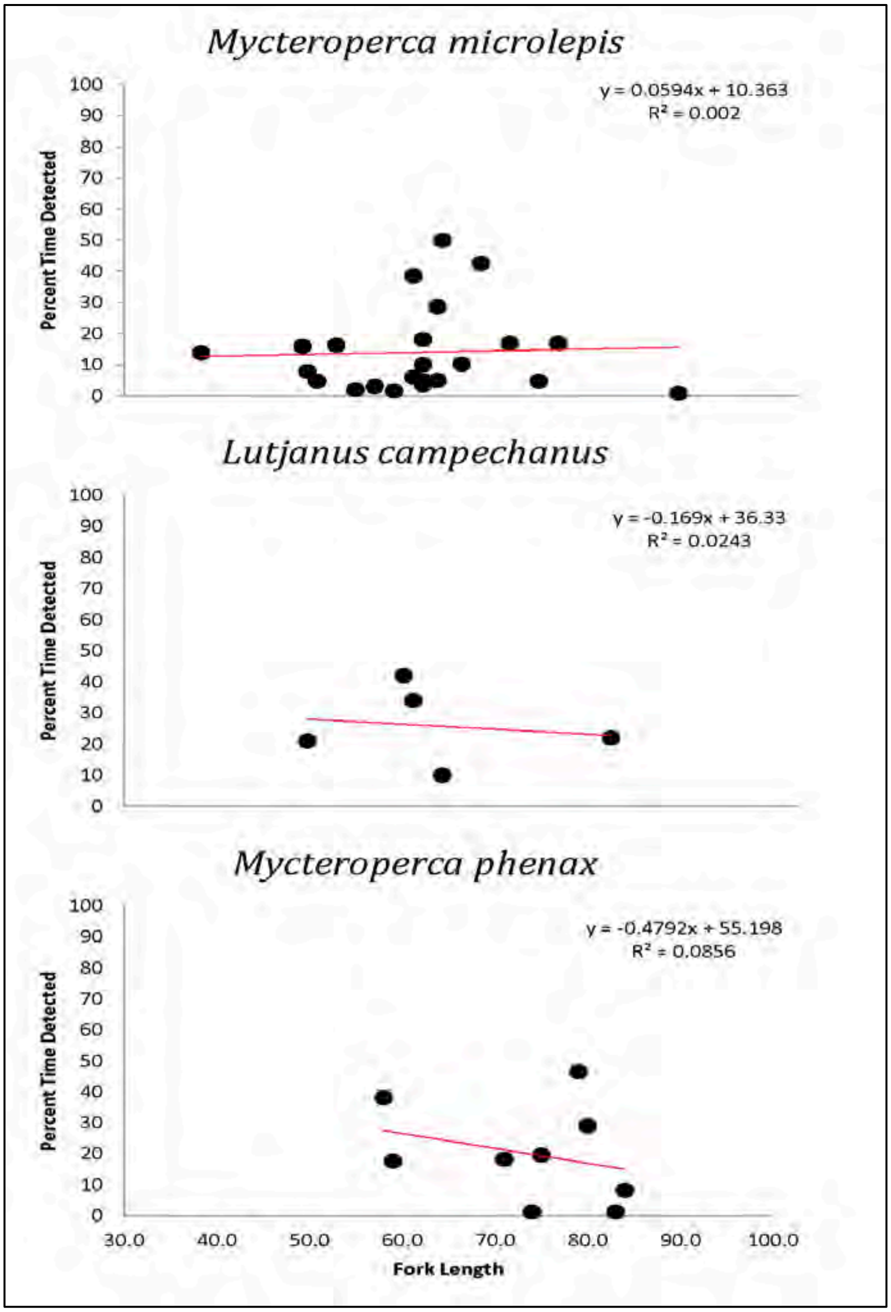

Figure 10.3. Relationship of fish size (fork length in cm) and time detected within the receiver network.

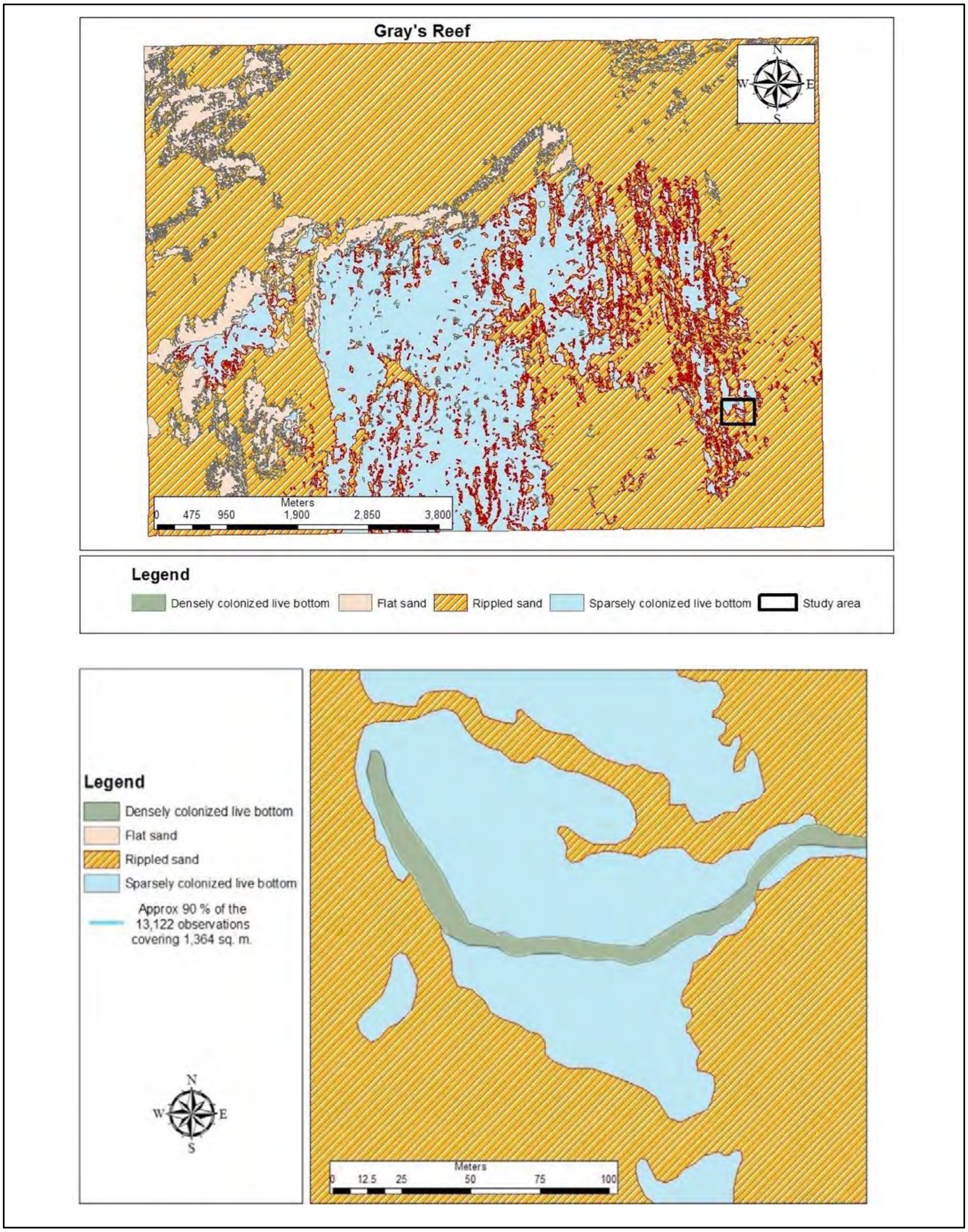

Figure 10.4. (Top) Station location for Tagging Study 2 focused on fine-scale movement patterns. (Bottom) Distribution of habitat types at receiver network. Image: Jose Pereira and Harrison Franklin/NOAA

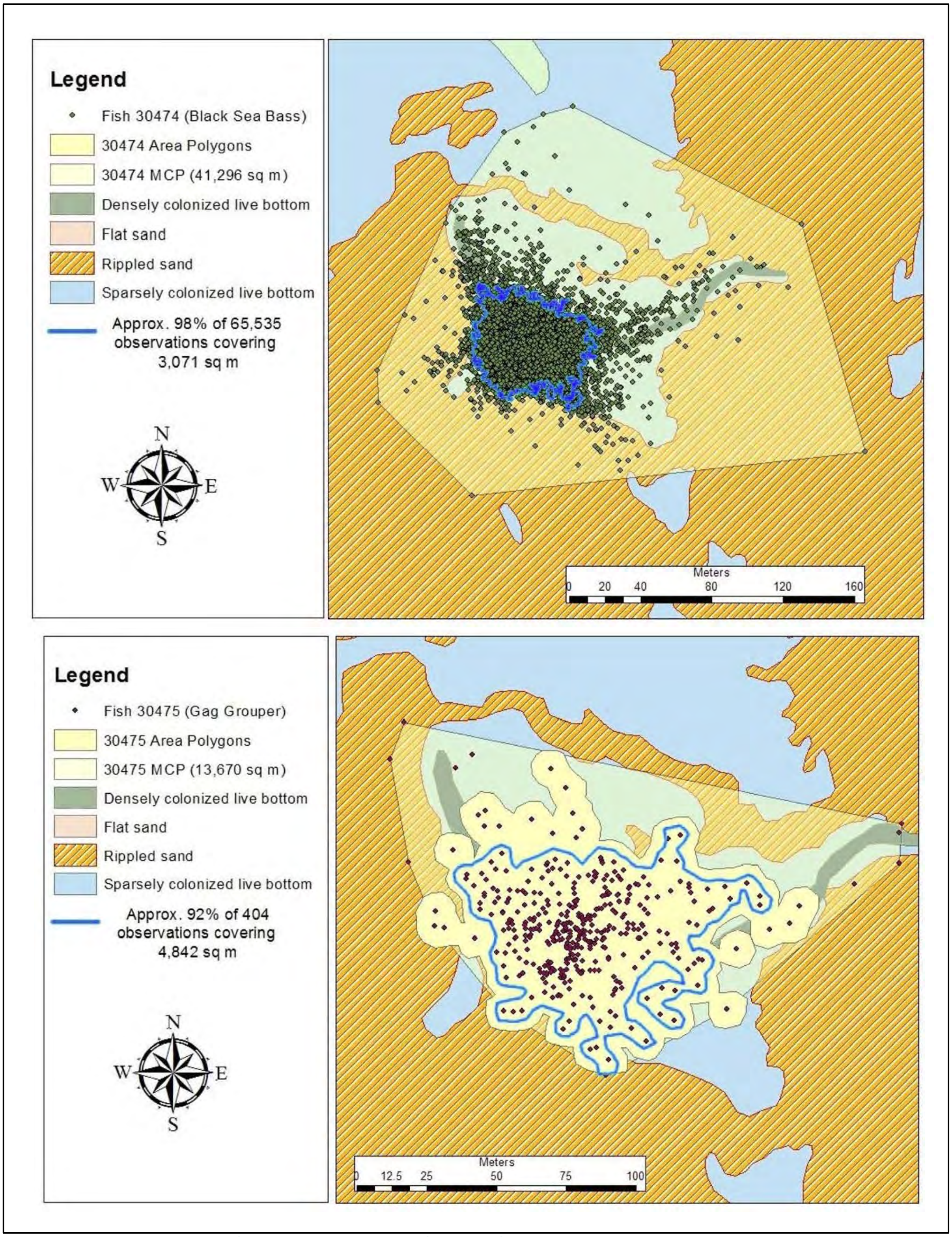

Figure 10.5. Examples of movement patterns of tagged fish. Image: Jose Pereira and Harrison Franklin/NOAA

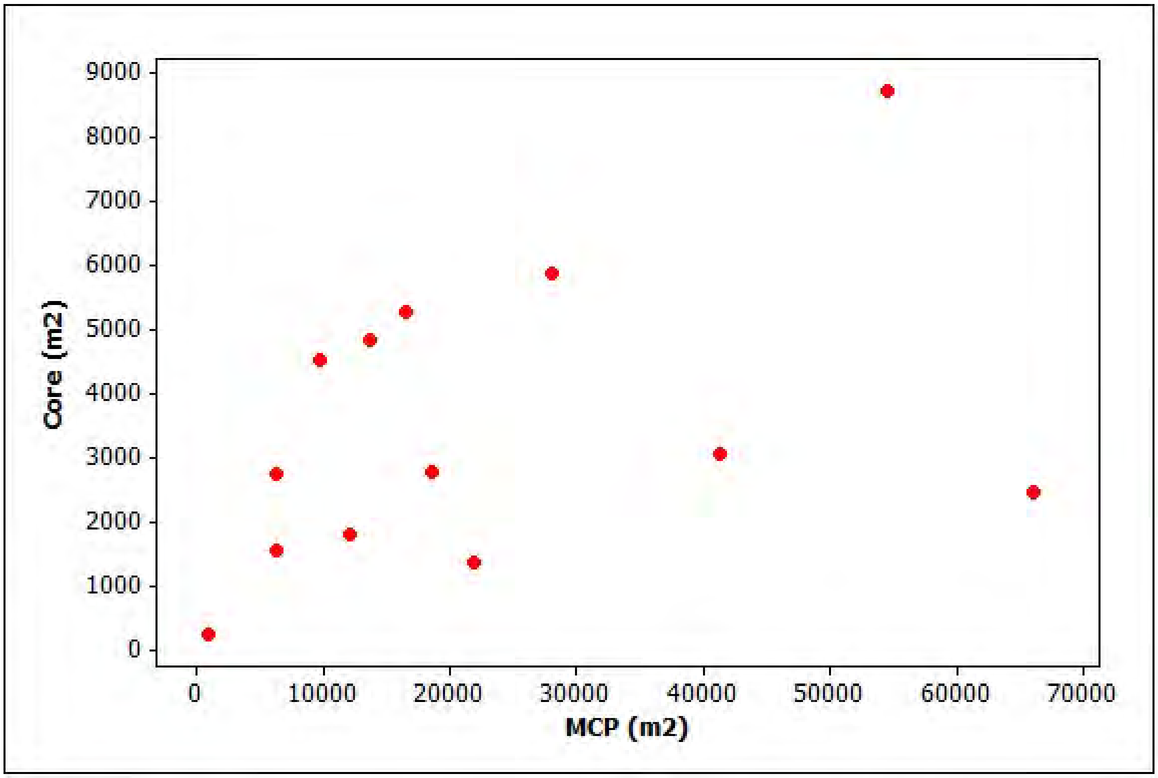

Figure 10.6. Relationship between MCP and Core area for each tagged fish at FS-15 acoustic network.

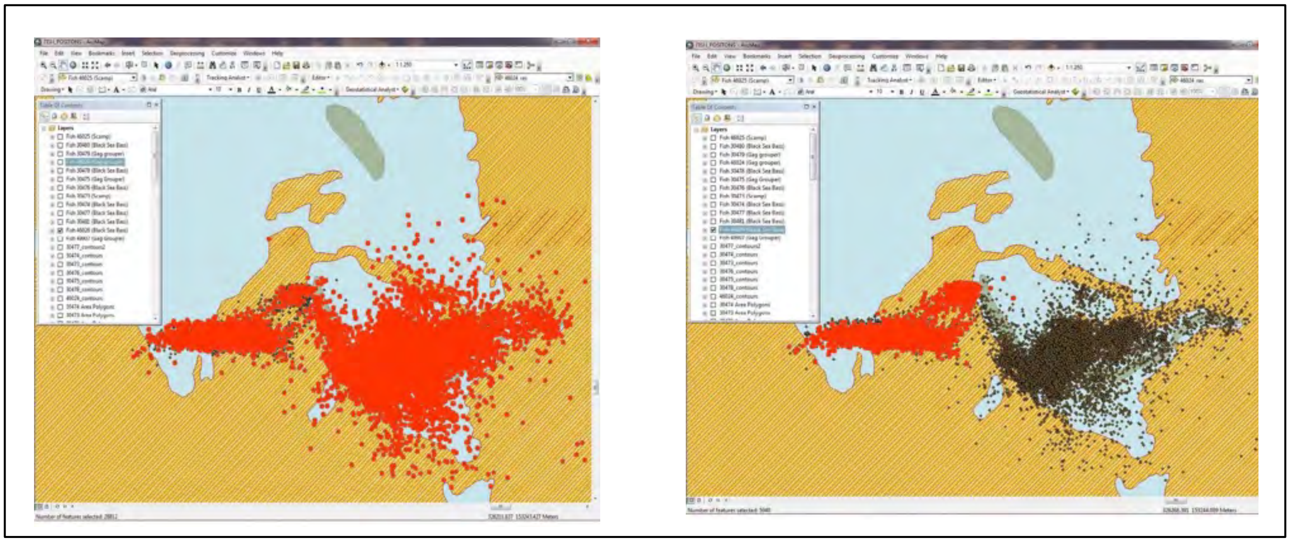

Figure 10.7. Fish 46026, a black sea bass, was tracked beginning in June of 2012 and continuing through May 2013. Observations prior to 1 January 2013 are focused on the west side of the reef (left) and after 1 January the distribution shifts to the east side of the reef (right). Image: Jose Pereira and Harrison Franklin/NOAA

Project 11. Assessing variation in composition of mixed-species groups of piscivores, 2009-2011 and 2013-2014

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Red snapper, black sea bass, and scamp grouper move as a loose group to stalk and attack forage fish.
Photo: Peter Auster/University of Connecticut/Mystic Aquarium

Question addressed

Does the species composition and abundance of piscivores in mixed species groups vary over time as well as inside and outside of the no-take GRNMS RA?

Measurements

Roving diver transects were conducted at medium and high relief live bottom reefs from 2009 to 2011 and 2013 to 2014. The "predation event" was the sample unit for this study and included any component of a detection (based on visually identified changes in predator behavior with regard to orientation toward potential prey), stalk, attack, and capture sequence (sensu Lima and Dill 1990). Predator-prey interactions were described by enumerating the number of individuals and species of mid-water and demersal piscivores per event, abundance of prey taxa, sequence of behaviors related to predation events, interactions with associated species and habitat, and additional elements of behavioral interactions.

Key findings

- A total of 82 predation events were observed inside the RA and 72 outside during 2011 surveys at the time of closure.
- Multivariate analyses did not reveal any clear inside-outside groupings of species, although results of the analysis of similarities (ANOSIM) routine were marginally significant and driven principally by higher abundance of young-of-year barracuda inside the RA.
- Species richness per event declined over time when samples were grouped by time period (2009-2011 vs. 2013-2014).
- Weather, visibility, and sample size issues impeded more detailed analysis post-designation.

Project narrative

Hunting by predators in single- and mixed-species groups has been shown to enhance predation success in terrestrial, freshwater, and marine species. In the ocean the role that pelagic fish and marine mammal predators play in facilitating the feeding of seabirds by driving prey to the surface is relatively well documented (Safina 1990, Clua and Grosvalet 2001). Such interactions are common elements of pelagic food webs and shifts in the abundance of interacting species may have cascading effects on population processes of those species (Hebshi et al. 2008). Understanding the interactions of hunting in groups of piscivores around reefs has received less attention, although the behavioral elements of such top-down interactions may be important at population and community levels (e.g., Auster et al. 2013). General patterns in the behavior webs of interacting predators were described initially in Auster et al. (2009, 2011, 2013). A dominant type of interaction involved groups of mid-water predators (e.g., greater amberjack, Spanish mackerel) attacking prey (e.g., scad, young-of-year tomtate) that would rapidly retreat to reefs where demersal piscivores (e.g., black sea bass, scamp grouper) would attack those schools responding to threats from the water column above (Figure 11.1). This study was focused on assessing the dynamics of mixed-species groups and interactions at GRNMS over time as well as whether there were measurable effects from fishing (i.e., comparison inside and outside the no-take RA).

Roving diver transects were conducted at medium and high relief "live-bottom" reefs from 2009 to 2011 and 2013 to 2014. The "predation event" was the sample unit for this study and included any component of a detection (based on visually identified changes in predator behavior regarding orientation toward potential prey), stalk, attack, and capture sequence for a coherent group of animals (Lima and Dill 1990). Some events were identified from the attack phase of the sequence while others began with predators orienting toward or stalking prey and the sequence ended before an attack if prey avoided or reacted in a manner that caused the predator to end the predation sequence. Prey capture was not required for an event to be included as a sample. In all cases, a predation event required a predator or group of predators to alter prior behavior and direct movement toward potential prey and for prey to react. Predator-prey interactions were described by enumerating the number of individuals and species of mid-water and demersal piscivores per event, abundance of prey taxa, sequence of behaviors related to predation events, interactions with associated species and habitat, and additional elements of behavioral interactions. Since 2011 our focus has been to parse observation into inside and outside the RA to test whether behavioral networks change between the fishing and no-fishing treatments (assuming fishing effects are higher in the open area based on patterns of use and compliance with regulations).

Surveys during the initial year of designation of the RA (2011) described the state of predator interaction at the time of closure. A total of 161 predation events (sample units) were observed during survey dives with species composition and abundance quantified for each event. Removal of single species events (that appeared as outliers in initial multivariate analyses) left 154 events for subsequent analysis (n = 82 events inside RA, n = 72 events outside). Hierarchical clustering and multidimensional scaling (MDS) did not reveal clear inside-outside groupings, which is an expected outcome at the initial time of change in management. However, a test for ANOSIM based on grouping stations inside and outside the RA was marginally significant at p = 0.10. Results from a similarity percentage analysis (SIMPER) revealed young-of-year great barracuda were the dominant drivers of the difference, contributing 37% to the inside-outside difference in predation event composition. (We made the a priori decision to quantify young-of-year great barracuda as a separate taxon in our surveys due to differences in their distribution, behavior, and interactions with associated predators and prey at reefs. See Auster et al. 2013 for details.) Mean abundance of young of year (YOY) fish in predation events inside the RA (mean = 13.45 individuals) was twice that of fish outside (mean = 6.75 individuals). In addition to YOY barracuda, the dominant members of mixed-species predation events were black and bank sea bass, scamp grouper, spottail pinfish, large juvenile and adult great barracuda, greater amberjack, and red snapper. Only scamp grouper and black and bank sea bass (species combined) did not have significant differences in abundance within predation events inside and outside the RA based on Kruskal-Wallis paired sample tests for each taxon. While composition of predation events inside and outside the RA is not maximally similar, the results from 2011 form the basis for tracking change over time.

An analysis of species richness per predation event, using data aggregated before (2009-2011, n = 274, mean = 2.16 spp per event, median = 2 spp per event) and after the designation of the RA (2013-2014, n = 132, mean = 1.58 spp per event, median = 1 spp per event), revealed a significant decline in species richness within groups (Mann-Whitney U-test, W = 62290.5, $p<0.0001$; Figure 11.2). We still do not have enough data to conduct inside-outside contrasts post designation of the RA, although multivariate analyses using 2011 data indicated there were existing differences between the designated zones, driven by differences in abundance of YOY barracuda and marginally by black sea bass.

Understanding the role of all forms of species interactions (predation, competition, facilitation, parasitism) is important for managing and sustaining healthy ecosystems (Travis et al. 2014). A fundamental understanding of the role that behavioral interactions play in this regard is just now emerging (e.g., Heithaus et al. 2008). Future studies will be directed at linking the consequences of behavior to population and community responses (e.g., Hinke et al. 2004).

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Figure 11.1. Top: An aggregation of Spanish mackerel attacks a school of scad spp that have retreated to the reef below. Bottom: A scamp grouper attacks the school of scad that has reduced nearest-neighbor distance in response to predators. Photos: Peter Auster/University of Connecticut/Mystic Aquarium

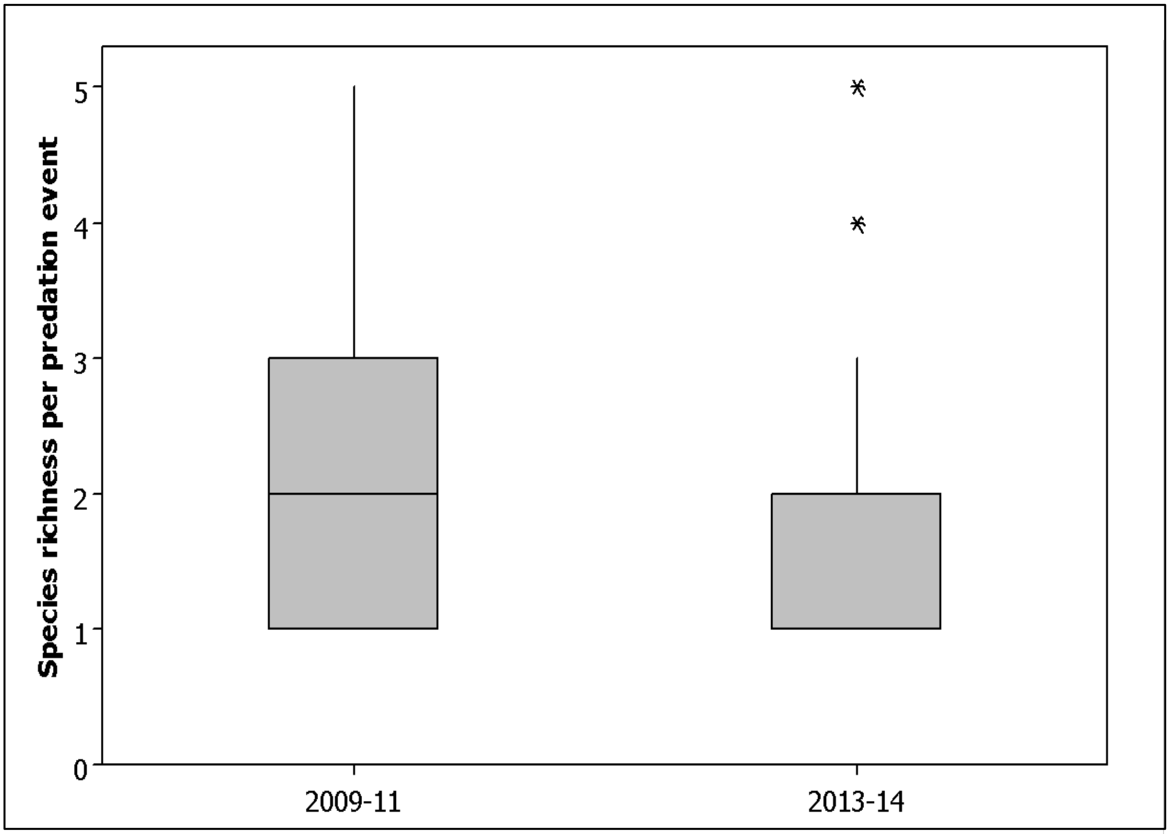

Figure 11.2. Box and whisker plot of species richness per predation event comparing the period prior to designation of the no-take Research Area (2009-2011) and post-designation (2013-14).

Project 12. Assessing the presence of halo predators at sub-tropical Reefs, 2014

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A frame capture from TowCam/GoPro video shows greater amberjacks following artificial baits and lures used to assess halo predators associated with reefs. Photo: Peter Auster/University of Connecticut/Mystic Aquarium

Question addressed

What is the utility of using towed video with standardized artificial hook-less baits to assess presence of “halo” predators in the region over and around reefs?

Measurements

Data were derived from video records collected 3-5 m height off the seafloor and towed at ca. 100 cm s-1 across reefs (based on vessel speed over ground). Measures include species composition, time to first predator observation per tow, direction of tow in relation to the current, and species-specific behavioral interactions with baits.

Key findings

- Twelve species were observed, most commonly greater amberjack, great barracuda, and black sea bass.
- Following baits from a distance, without attacks, was the typical response.
- The first predator generally was sighted less than five minutes after the start of transects, suggesting that predators were “local” and within an area surrounding a focal reef.
- Noteworthy is that some species were observed by towed video and not divers at some sites, while the reverse occurred at other sites.

Project narrative

Piscivores at sub-tropical reefs are important elements of reef fish communities due to their cascading influence through prey populations (Frid et al. 2007, Heithaus et al 2008, Auster et al. 2013). While visual surveys by divers are effective for demersal predators and prey highly associated with reefs, they may not capture all of the reef-associated mid-water predators (i.e., those beyond the range of visibility or with large ambits) (Figure 12.1). In this study we assessed the utility of a novel method to assess the presence of reef associated “halo” predators (i.e., those high in the water column and immediately away from reefs; ca. 3-10s of meters) using towed underwater video with artificial baits during a cruise from May 29 to June 4, 2014.

Underwater video transects were conducted using a commercially available Trollpro tow body with a GoPro Hero2 high-definition digital video camera (1080 lines resolution) installed within and towed in front of a spreader with artificial baits from a surface vessel. Baits used were hook-less 16 cm rubber fish mimics and 8.5 cm silver spoons, arranged with fish on the most distal attachment points and spoons inside with four total of each type (Figure 12.2). An analog SeaViewer drop camera (800 lines resolution) was used for real-time viewing and monitoring altitude and baits during tows. The cameras and baits were towed at approximately 3-5m from the seafloor and approximately 2 knots (100 cm s-1) speed. Video from both the SeaViewer and GoPro were recorded for analysis.

Eighteen transects were collected with a total of approximately six hours of video over a six-day period. All tows were conducted during daylight hours. Metrics derived from video records included composition of species attracted to baits, time to first predator observation per tow, direction of tow in relation to the current, and species-specific behavioral interactions with baits (i.e., close approach within one body length, far approach, close sustained follow, far sustained follow, strike at bait). Figure 12.3 illustrates the field of view from each video source. The video results were qualitatively compared to diving surveys taken at the same stations to compare methods.

A total of 12 piscivore species were observed following and attacking the artificial baits in the water column. Greater amberjack, great barracuda, and black sea bass were the most common species (Figure 12.4). The most common behaviors were “far follows” of the camera and baits (Figure 12.5). In more than half of the transects, the first predator was sighted less than five minutes after the start of the transect as we approached reefs, suggesting that predators were “local” and within an area surrounding a focal reef (Figure 12.6). Comparison between transects taken at the same location towing the camera and baits with, against, and perpendicular to the current revealed that the highest number of piscivores were observed when towing perpendicular to the current (Figure 12.7). Noteworthy is that some species were observed by towed video and not divers at some sites, while the reverse occurred at other sites.

The use of a towed video with artificial baits to assess the presence of mid-water halo predators was successful and could be used for future surveys in order to develop a complete assessment of the local piscivore guild. Tracking camera position and depth throughout each transect would allow linking observations to the location and orientation of reefs and related landscape elements. Tows perpendicular to the current, regardless of reef orientation, were most efficient in terms of encounter rates with piscivores present over reefs.

This approach is complementary to visual surveys by divers and should be used in addition to, not instead of, diver surveys. Future studies should also assess the role of different size and types of baits to assess species-specific encounter rates with predators. In addition, temperature and depth sensors would better characterize tow conditions.

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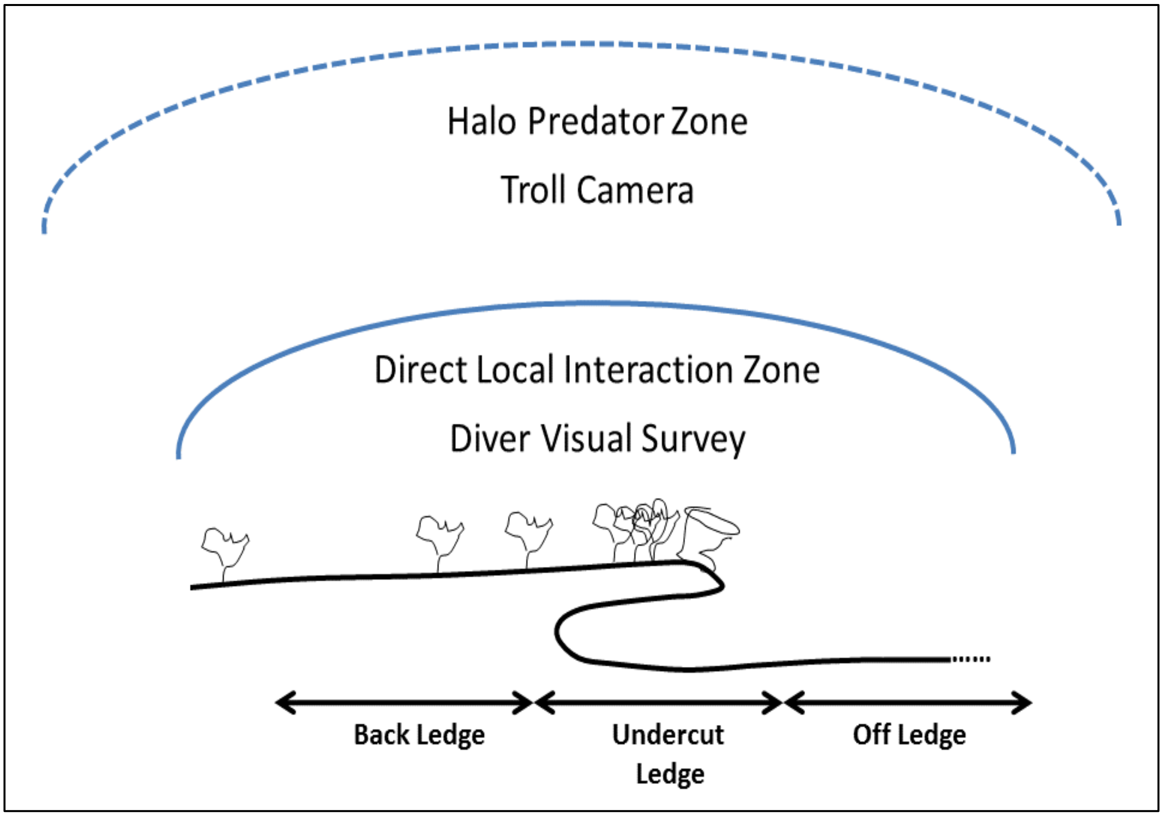

Figure 12.1. Conceptual view of space around reefs with zone for direct local interactions between predators and prey amenable to assessment via visual survey by divers and the halo zone over and distal to reefs where alternative approaches are required.

Figure 12.2. The Troll Pro (blue tow body) is arranged with a spreader in the center with artificial baits and spoons. The person at left holds the cannonball weight and SeaView drop camera. The drop camera, Troll Pro, and baits are lowered and towed from the downrigger at right. Photo: Peter Auster/University of Connecticut/Mystic Aquarium

Figure 12.3. Top left: A screen capture from SeaView video shows position and time data windows. Top right: A black sea bass attacks a rubber bait fish mimic. Bottom left: Greater amberjack follow the spreader with baits; they subsequently attacked a silver spoon. Bottom right: This was the typical orientation of the two types of baits when towed. Photos: Sofia Gabriel and Peter Auster/University of Connecticut/Mystic Aquarium

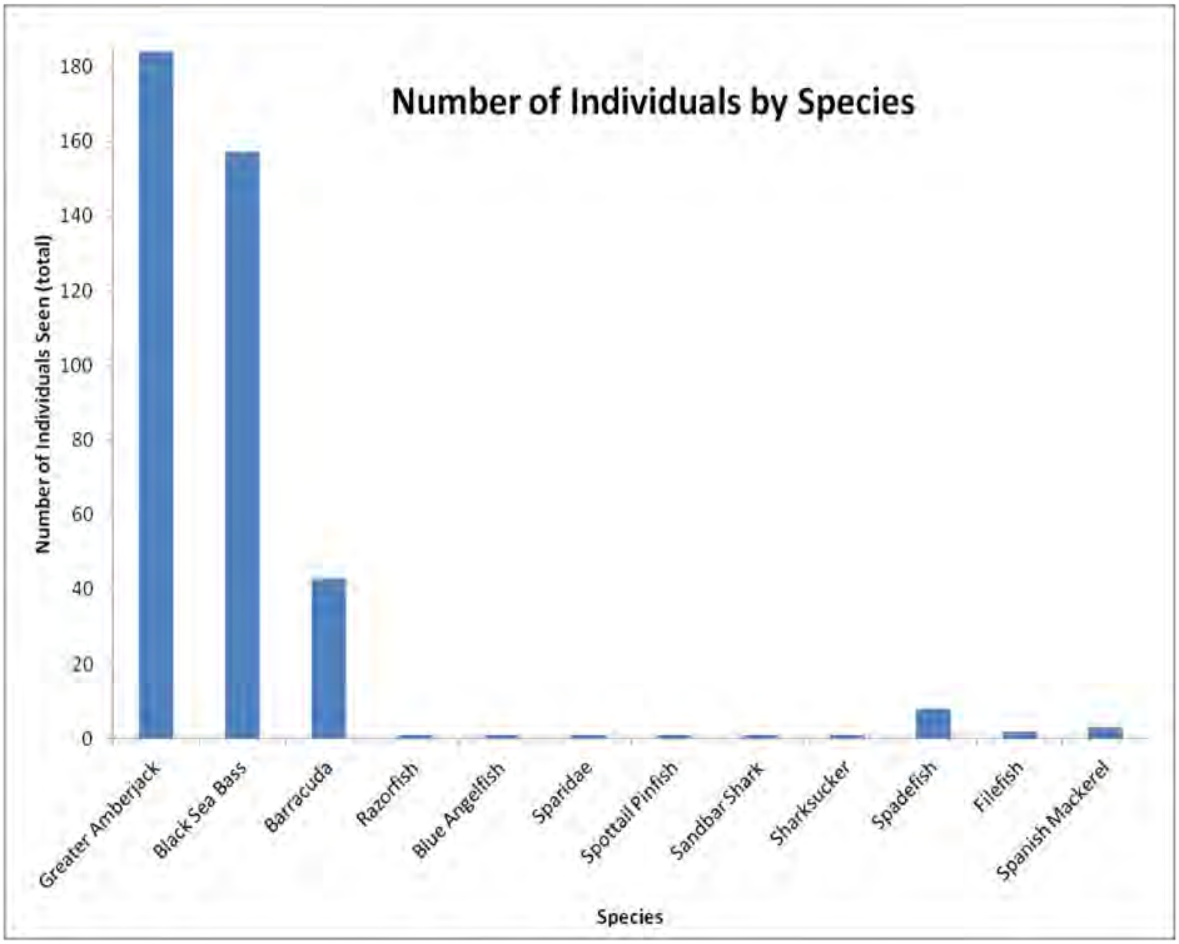

Figure 12.4. Number of individuals by species for all survey tows.

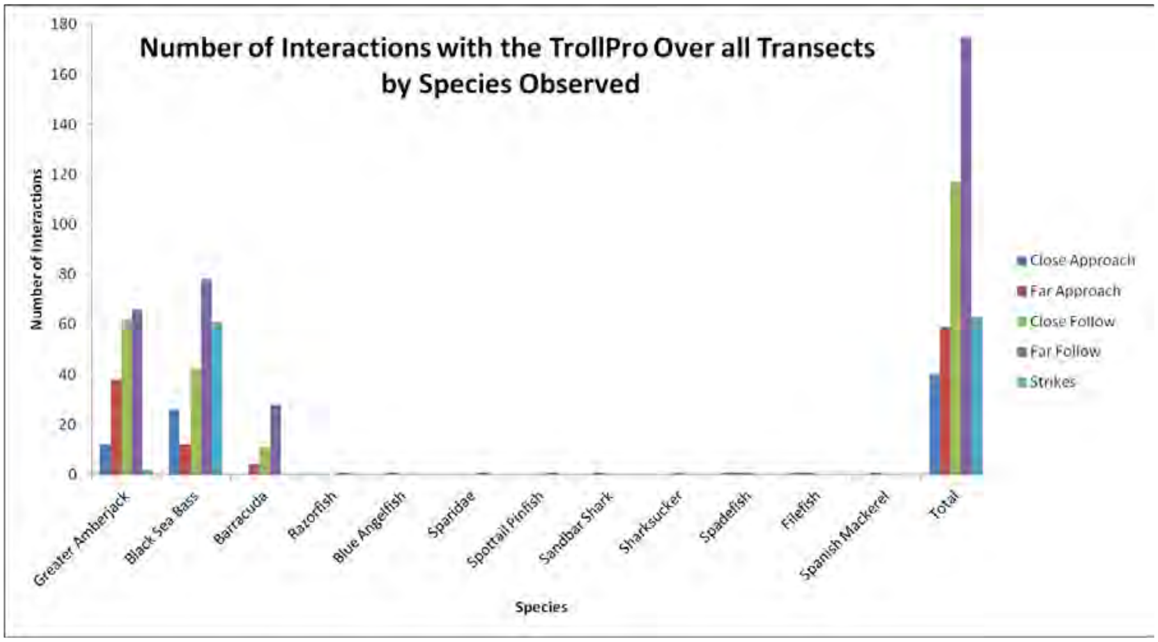

Figure 12.5. Number and classification of interactions by species across all transects.

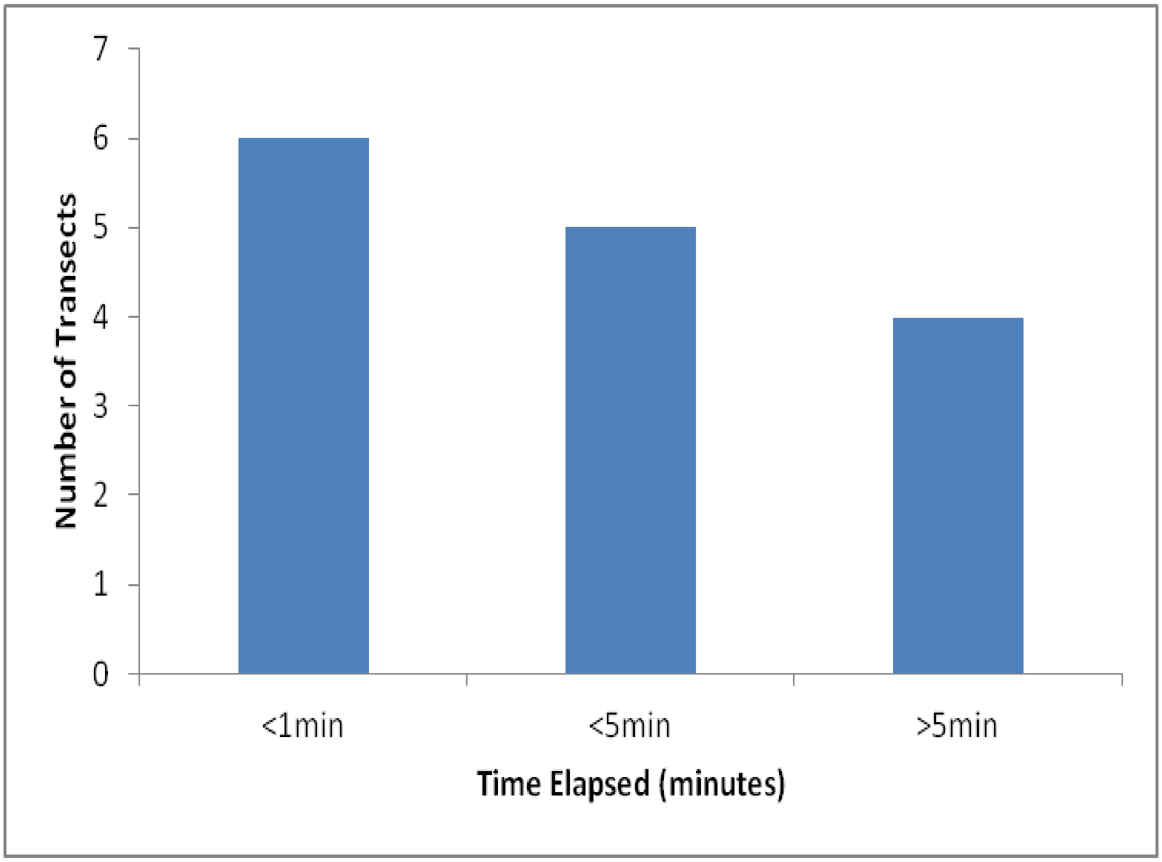

Figure 12.6. Time of first contact with predator along transects.

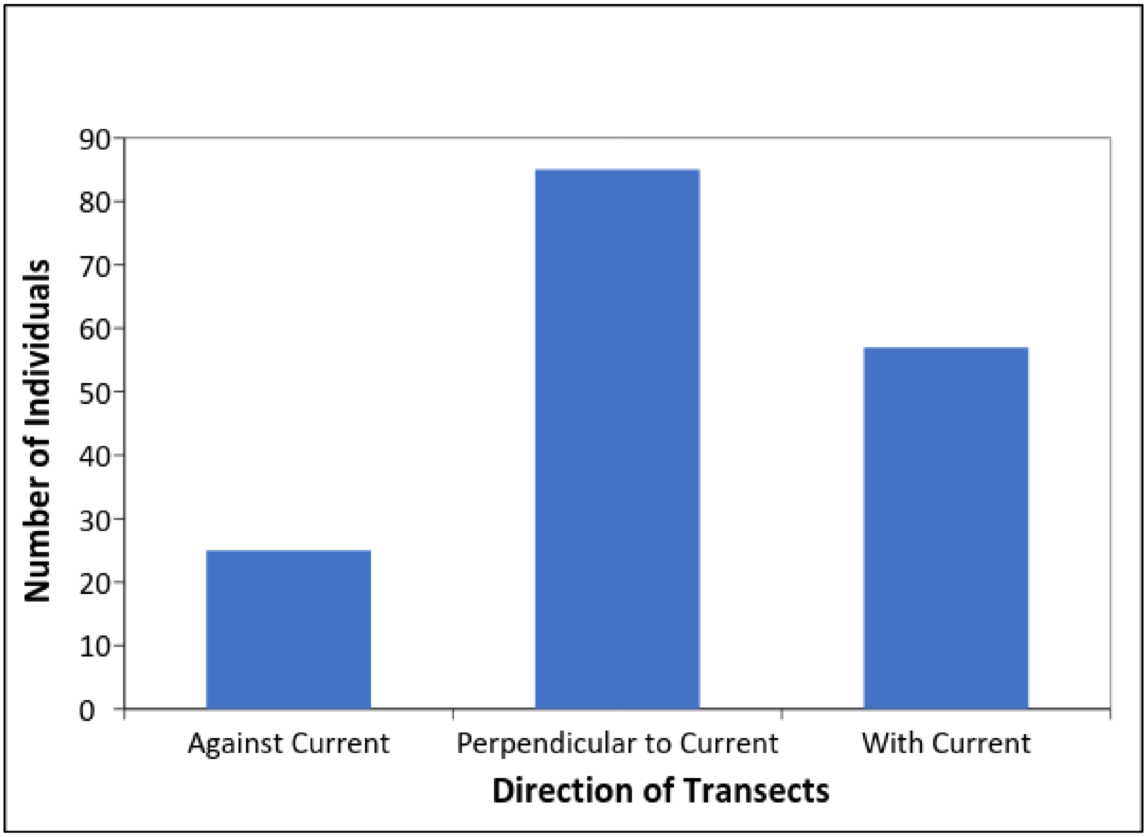

Figure 12.7. Individual fish encountered based on direction of tow and current direction. Note that four transects were taken perpendicular to current, compared to two transects each against and with the current.

Project 13. Reported lionfish sightings throughout Gray's Reef National Marine Sanctuary, 2007 and 2012-2017

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A lionfish swims near reef structure at Gray's Reef National Marine Sanctuary. Photo: Kimberly Roberson/NOAA

Question addressed

What is the distribution and abundance of lionfish within GRNMS? How does the distribution and abundance compare inside and outside the sanctuary?

Measurements

Lionfish data in GRNMS are an opportunistic byproduct from all dive research conducted in the area. During dives, lionfish counts are recorded when seen by divers. All divers on science missions are instructed to log sighted lionfish, their dive location, and date of sighting. The GRNMS management plan (ONMS 2014) suggests lionfish removal when seen. To assist in removal, dive teams are strongly encouraged to carry spears if doing so does not hinder research.

Due to higher numbers of observations than in previous years, two dives were conducted in 2017 specifically for lionfish removal. Site selections were made by determining sites with more than one lionfish observed. Also in 2017, a reconnaissance dive was completed on Snapper Banks, approximately 20 miles northeast of GRNMS, in adjacent, deeper waters where general presence or absence of lionfish was assessed.

Key findings

- From 2012 to 2017, a total of 88 lionfish were sighted in GRNMS.
- From 2012 to 2017, a total of 54 lionfish were removed in GRNMS, an average lionfish removal rate of 61.3%.
- The lionfish population in GRNMS is considered sparse, but existing data from reported sightings indicate distribution is likely throughout the entire sanctuary (Figure 13.1).
- Lionfish both inside and outside the GRNMS RA were found in habitats that have ledges and are less likely to be sighted in low relief sites.
- Lionfish outside of GRNMS in deeper waters appear to be far more abundant than inside GRNMS.

Project narrative

The Indo-Pacific lionfish (*Pterois volitans* and *P. miles*), a venomous invasive species, was first reported within GRNMS in 2007. No additional sightings were reported in 2008, and the two individuals seen in 2007 were not present at the same location in 2008. No lionfish were reported again until 2012. In 2012, divers reported seeing 28 lionfish and removed 16 of those sighted. Since 2012, there has been a downward trend of the number of lionfish seen, except in 2017 when 28 lionfish were reported (Figure 13.2). At least 82% of the lionfish reported in 2017 were removed (Table 13.1).

During the 2017 NOAA Ship *Nancy Foster* mission, reconnaissance dives were conducted by three separate dive teams at a site named "South Ledge" of the Snapper Banks at approximately 110 feet, totaling 90 minutes of logged bottom time. Due to the exploratory nature and limited bottom time of these deeper dives, the numbers of lionfish sighted were not quantified. However, to all observers, there appeared to be many more lionfish observed at these locations than during dives within GRNMS. There also appeared to be a presence of large mature lionfish (Figure 13.3). In addition, recreational divers who frequent the old Navy towers in proximity to GRNMS anecdotally report seeing lionfish in large numbers. These towers are in somewhat deeper waters (110 feet and deeper) and are closer to the Gulf Stream.

Colder winter water temperatures, assumed lack of annual recruitment, and the removal management approach may all be responsible for keeping the numbers of lionfish under some control within GRNMS. The management approach will continue to be remove upon sighting, as appropriate (ONMS 2014). If the numbers of lionfish increase from the 2017 observations in 2018, there is high potential for more dives to be conducted specifically for lionfish control.

With all the anecdotal data for lionfish sightings and removals, there are information gaps that may cause the data to be misconstrued. For example, if there is more than one sighting, it is difficult to assess if a lionfish sighting is a new previously-unreported fish or one that has been sighted before. Also, dive tasks and actual bottom time can affect how many lionfish are likely to be seen. Future data collected will take these variables into account to help inform for a "lionfish observation effort" value. Until that measure of effort is known, minutes of dive time per year (Figure 13.4) may serve as a rough proxy of survey effort for lionfish abundance and removal efforts. It is important to keep in mind that during much of the annual dive time, divers are often multi-tasked and are not focused solely on searching for and removing these invasive predators. A true measure of observation and removal efforts will help better guide future management strategies of the invasive species.

Removal and other actions, including monitoring, research, and education and outreach are direct management measures that will minimize impacts caused by the lionfish invasion (Johnston et al. 2015). Sanctuary divers and researchers remain diligent in looking for and removing this invasive species inside and outside of GRNMS.

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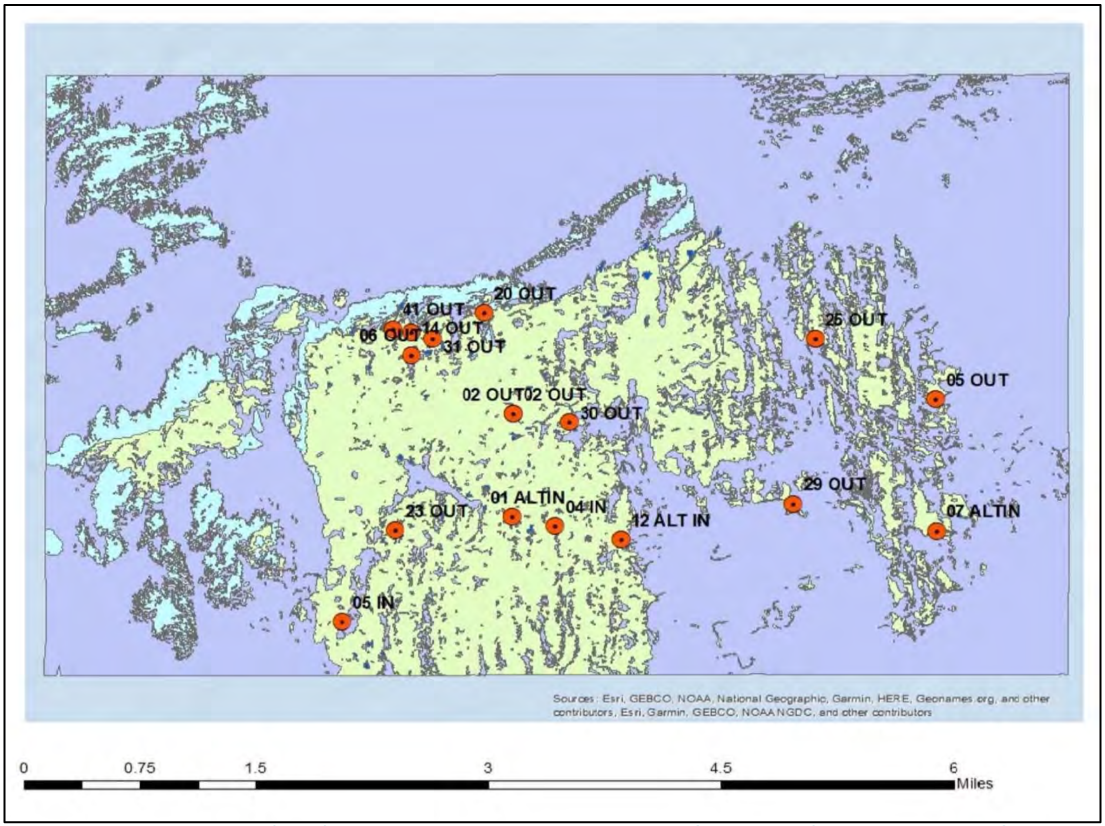

Figure 13.1. Distribution of lionfish recorded sightings throughout Gray's Reef National Marine Sanctuary for 2017. Image: Erika Sawicki/Pacific Islands Water Science Center

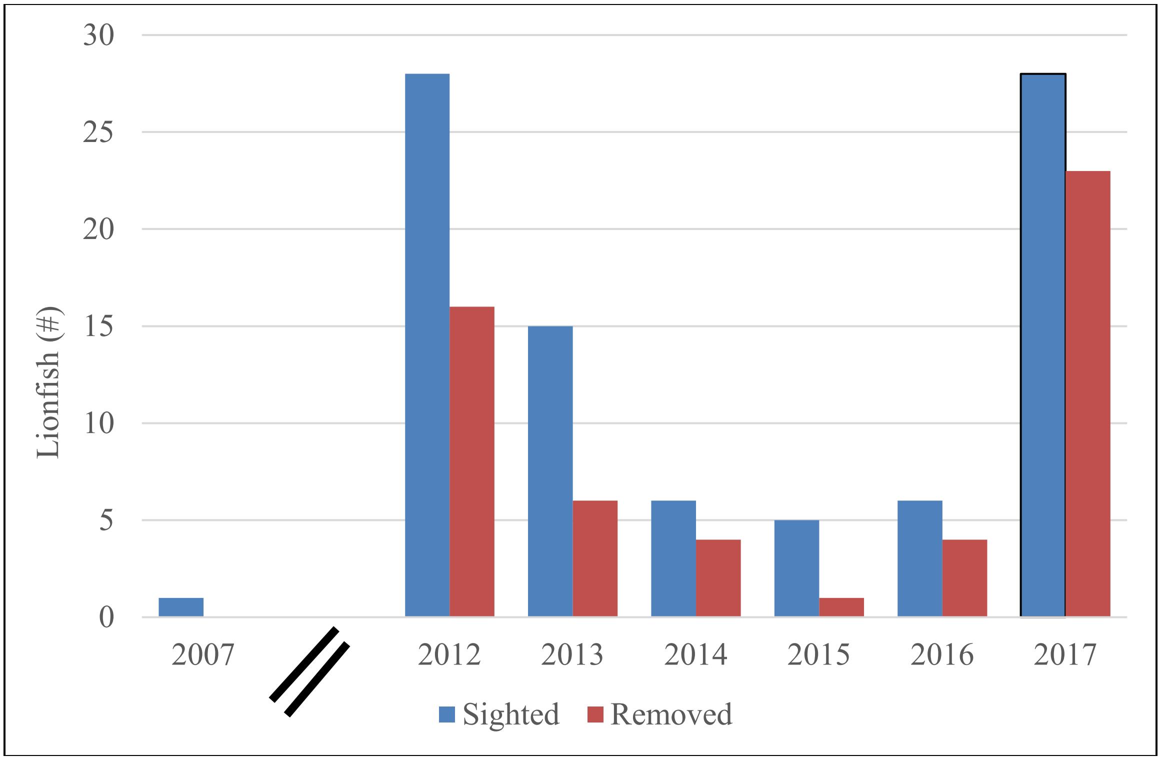

Figure 13.2. Number of lionfish sightings reported and number reported as removed throughout Gray's Reef National Marine Sanctuary 2007 and 2012 to 2017. No lionfish were recorded as seen from 2008 to 2011.

Table 13.1. Annual counts of lionfish sighted and removed within Gray's Reef National Marine Sanctuary.

Year	Sighted	Removed	% Removed
2007	1	0	0
2012	28	16	57
2013	15	6	40
2014	6	4	67
2015	5	1	20
2016	6	4	67
2017*	28	23	82

*Number of lionfish sighted in 2017 is an estimate only.

Figure 13.3. Very large mature lionfish spotted at Snapper Banks in June 2017 during the NOAA Ship Nancy Foster mission. Photo: Paul Chetirkin/NOAA

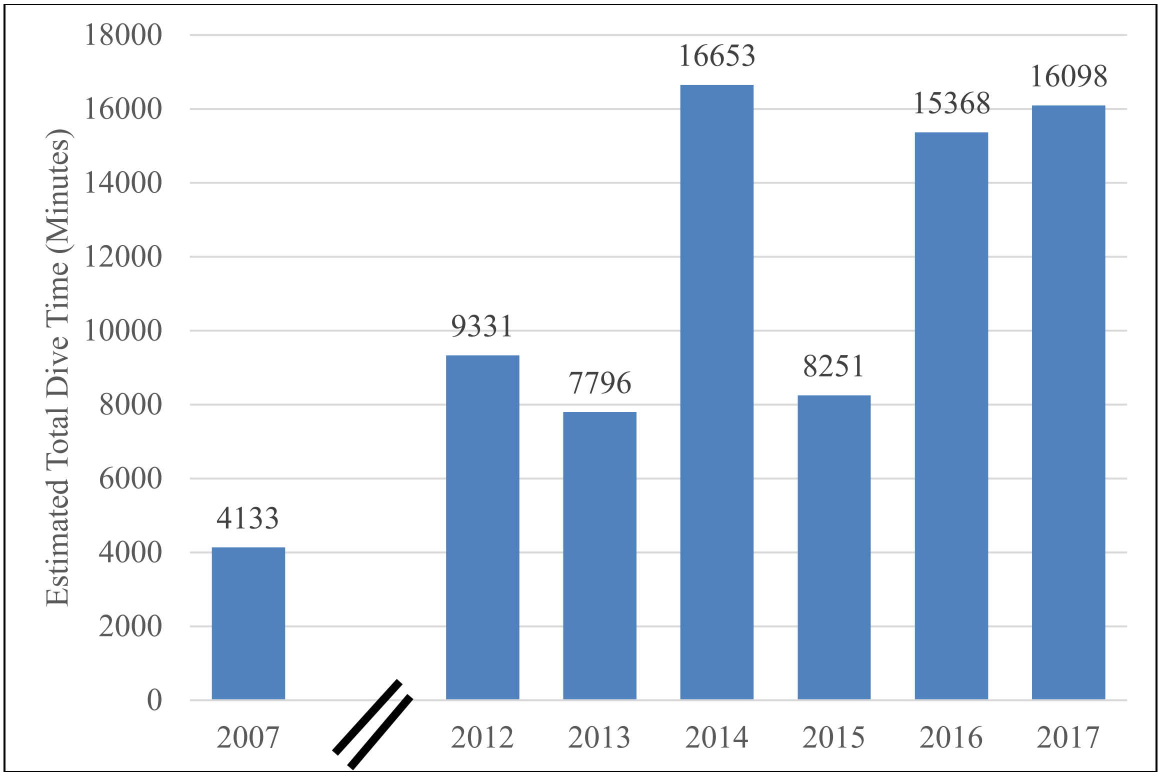

Figure 13.4. Estimated total dive time in minutes for all dives recorded per year where lionfish may have been observed throughout GRNMS 2007 and 2012 to 2017. Data compiled by Jasmine Pacheco-Ramos for GRNMS.

Project 14. Carbon dioxide and water quality monitoring at Gray's Reef National Marine Sanctuary, 2006-2014

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Scott Noakes updates components on Buoy 41008 at Gray's Reef National Marine Sanctuary. Photo: NOAA

Question addressed

How is the carbon dioxide and water quality changing at GRNMS over time?

Measurements

The comprehensive monitoring effort began in 2006 with sensors added to the 41008 GRNMS buoy and has continued with only minor interruptions to date. A seafloor platform was added and in 2008 seafloor monitoring was started to complement the surface monitoring effort. Parameters monitored include carbon dioxide (CO_2) in the atmosphere, sea surface and seafloor CO_2, temperature, pH, salinity, dissolved oxygen, chlorophyll, and turbidity.

Key findings

- Seawater pCO2 at GRNMS is increasing faster than expected. (Note: seawater pCO2 is increasing faster than atmospheric pCO2.)
- Major storm events are associated with rapid change in seafloor seawater pCO2.
- Seawater temperature plays a major role in pCO2 concentration, with seasonal changes being apparent.
- GRNMS is acting as a net pCO2 sink.

Project narrative

Gray's Reef National Marine Sanctuary sits in a unique and dynamic region along the divide between the inner and middle shelf with water depths in the 20 m range. The water at the sanctuary is primarily controlled by the middle shelf oceanic dynamics, but during heavy rain events, it can be affected by freshwater plumes coming from numerous rivers along the coast. Temperature plays a major role in CO_2 variability with seasonal changes being apparent. During the winter months, more of the seawater CO_2 is dissolved into various carbon species, decreasing CO_2 concentrations to levels below the atmospheric concentrations and making the Gray's Reef area a net CO_2 sink. During summer months when the water warms up, the dissolved carbon is converted back to CO_2 to levels above that found in the atmosphere, making it a CO_2 source.

In an effort to understand the South Atlantic Bight (SAB) and its role in the global carbon budget, a monitoring station was established at GRNMS to quantify CO_2 exchange with the atmosphere. The station currently collects data every three hours and includes atmospheric pCO2 at the air-sea interface as well as surface water variables including pH, temperature, dissolved oxygen, chlorophyll, turbidity, and salinity. The water quality data are transmitted from the buoy to NOAA by satellite every 24 hours. Once the data have passed quality control measures, they are available online.

As a result of these monitoring efforts, a distinct seasonal relationship has been observed between the pCO2 concentrations and water temperature. As the seawater temperature increases, so does the pCO2 (Figure 14.1) in both the seafloor and sea surface. The average atmospheric pCO2 as measured at GRNMS is approximately 400 micro-atmospheres (μatm). This concentration is typically exceeded in the water column during the warm summer months, forcing CO_2 out of the water into the atmosphere. In the cooler winter months, the process is reversed, with seawater taking in excess CO_2. Overall, the seawater pCO2 is increasing at an annual rate of approximately 2.5% while atmospheric pCO2 is increasing at a rate of approximately 0.78%. Given that seawater pCO2 is increasing at a faster rate than atmospheric concentrations, it is indicative of additional sources.

GRNMS is home to a vibrant live bottom community so water quality is of utmost concern for the sanctuary. As a secondary benefit to the sanctuary, it was anticipated that surface monitoring could potentially be used to determine the effects of ocean acidification on the seafloor community. Under perfect conditions, this assumption was not completely off base. However, after a series of pCO2 sensor deployments on the seafloor, it was determined that surface monitoring did not always reflect seafloor conditions. As a result, a seafloor observatory was established that houses pCO2, pH, and water quality instruments.

Early in the seafloor data collection, it was noticed that the seafloor and surface pCO2 were in agreement most of the time. However, on several occasions, seafloor pCO2 levels spiked by an additional 50%, which was not reflected by the sea surface pCO2. It was also noted that the seafloor pCO2 spikes were not temperature driven as were the seasonal changes previously mentioned. In 2013, the February winter storm (aka "Nemo" by the Weather Channel) and Tropical Storm Andrea (June) both skirted the Georgia coast on a north-northeast track and were shown to correlate to two short-lived seafloor pCO2 spikes (Figure 14.2). It was anticipated that the seawater pH would drop as part of the seasonal pCO2$_2$/temperature relationship, but seafloor pH also notably dropped at the beginning of both Nemo and Andrea as the seafloor pCO2 increased (Figure 14.3).

Abrupt pCO2 increases and the corresponding pH decreases have been shown to be detrimental to developing larval marine organisms as well as the ability of marine fish to properly function (Clark et al. 200, Wang et al. 2016, Kroeker et al. 2010, Munday et al. 2008). Given that the pCO2 spikes at GRNMS were short-lived, widespread mortality or organism degradation is not expected. However, these events do represent a marine organism stress factor that had previously not been known.

In the SAB, winter and tropical storms can cause considerable seafloor turbulence as they pass over an area. Many factors can come into play affecting seafloor conditions including temperature, salinity, atmospheric pressure, wind direction, and wave action. Freshwater intrusion can also affect the pCO2 levels offshore.

Starting immediately before Nemo, both the seafloor and surface salinity dropped, indicating that lower salinity water made it to GRNMS (Figure 14.2). However, the salinity continued to remain lower throughout the summer, indicating it was a seasonal event and not necessarily storm-related. There was a major drop in sea surface salinity immediately after Nemo, indicating that the freshwater from the rain-swollen rivers had eventually made it offshore. However, lower salinity was not detected on the seafloor, indicating that the freshwater had stayed near the surface.

Given the right coordination of the physical actions, it may be possible for pCO2 to be forced from the sediment pore waters or upwelled from deep Atlantic waters beyond the shelf. Storms can also cause turbulence which can re-suspended sediment affecting the pCO2 levels near the seafloor. During both Nemo and Andrea, the maximum seafloor pCO2 spikes were preceded by considerably lower atmospheric pressure as the storms passed through (Figure 14.4). However, the sea surface pCO_2 did not appear to be affected by the storms, indicating that the water quality was most affected at depth.

Both storms had increased wave action immediately preceding the storm, but the waves diminished quickly. Nemo's wave action did rebuild immediately after the initial wave surge, but peaked well after the seafloor pCO2 peaked. The wave action for Andrea diminished considerably after the leading edge passed, allowing very little time for sediment disturbance. The southerly wind patterns which would be required for upwelling were not present for Nemo, but may have been favorable for Andrea. If wind conditions were conducive for upwelling to occur, the upwelled water would have remained close to the seafloor since it wasn't detected by surface parameters. Since seafloor temperature and salinity were not affected during the pCO2 spikes, it could be possible that the upwelled water was mostly intermixed with shelf water by the time it reached GRNMS, diluting the gradients.

At this point, it is hard to conclude which factor(s) led to the storm -induced seafloor pCO2 spikes. However, the low atmospheric pressure and high wave action preceded both storms, indicating that the cause was most likely from seafloor turbulence re-suspending sediment or forcing pCO2 out of the pore water. A remotely possible option is that the wind direction was potentially favorable for upwelling related to Andrea and may have pushed pCO2-rich Atlantic deep water onto the shelf. What is evident is that both storms appeared to have triggered the high pCO2 events at GRNMS and that water quality was affected.

These previously undocumented events have indicated a previously unknown stress factor on the benthic community. Given that the GRNMS benthic community and thriving fishery have adapted to the natural seasonal water quality changes, it is hoped that they can also adapt as storm intensity increases due to global climate change (Hartmann et al. 2013).

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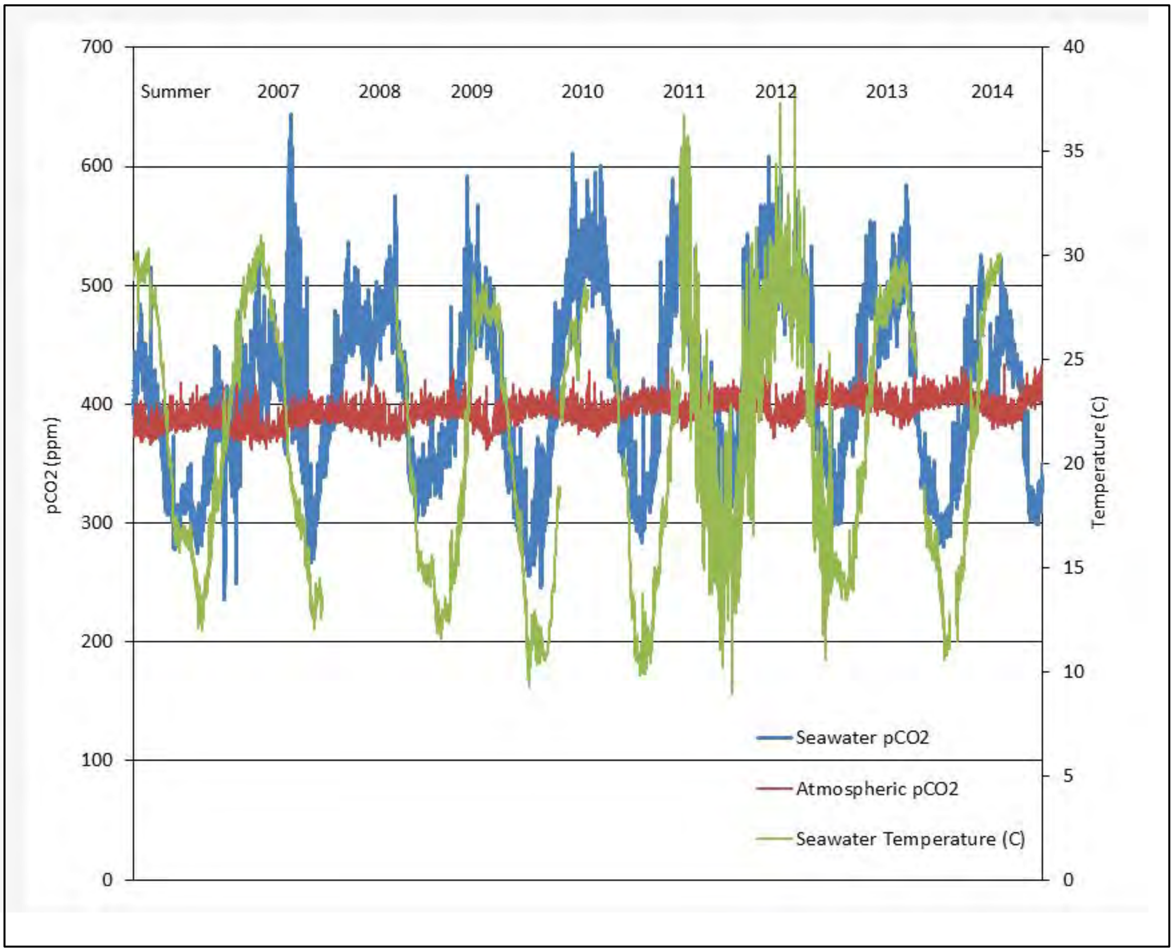

Figure 14.1. Gray's Reef National Marine Sanctuary time-series data.

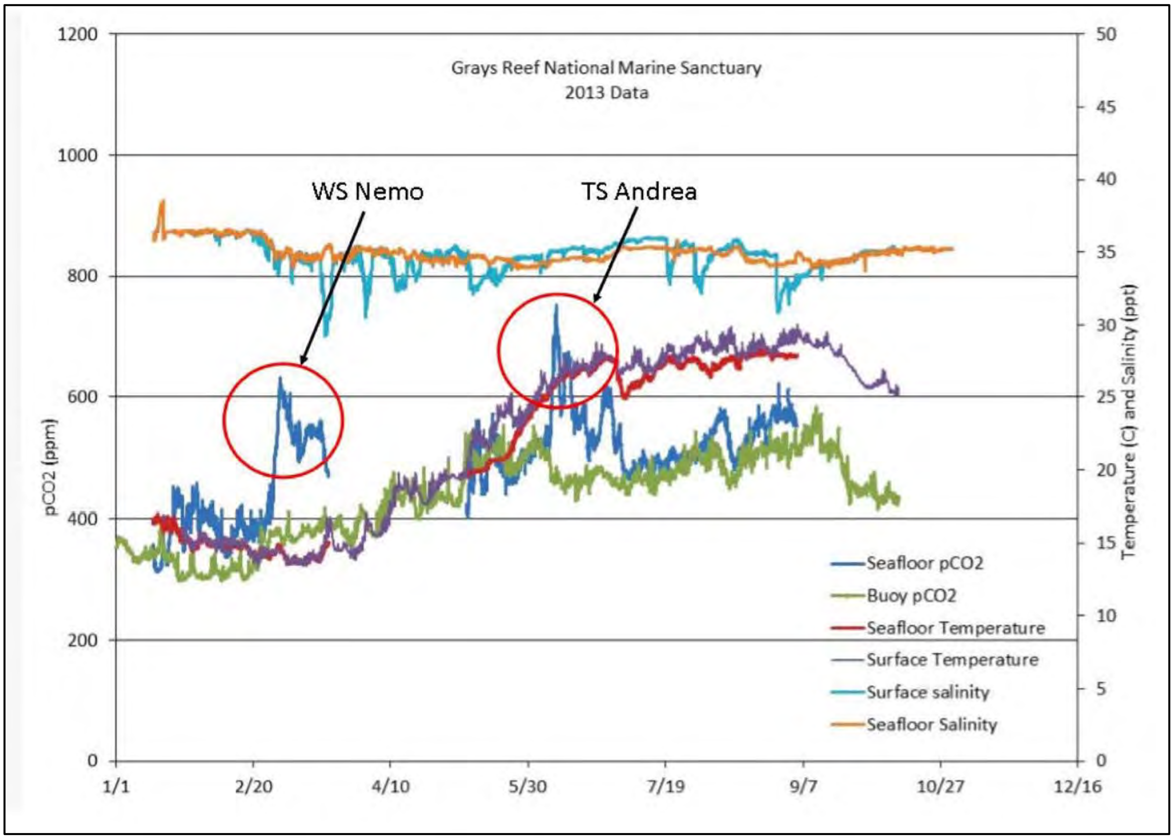

Figure 14.2. Gray's Reef National Marine Sanctuary water quality data.

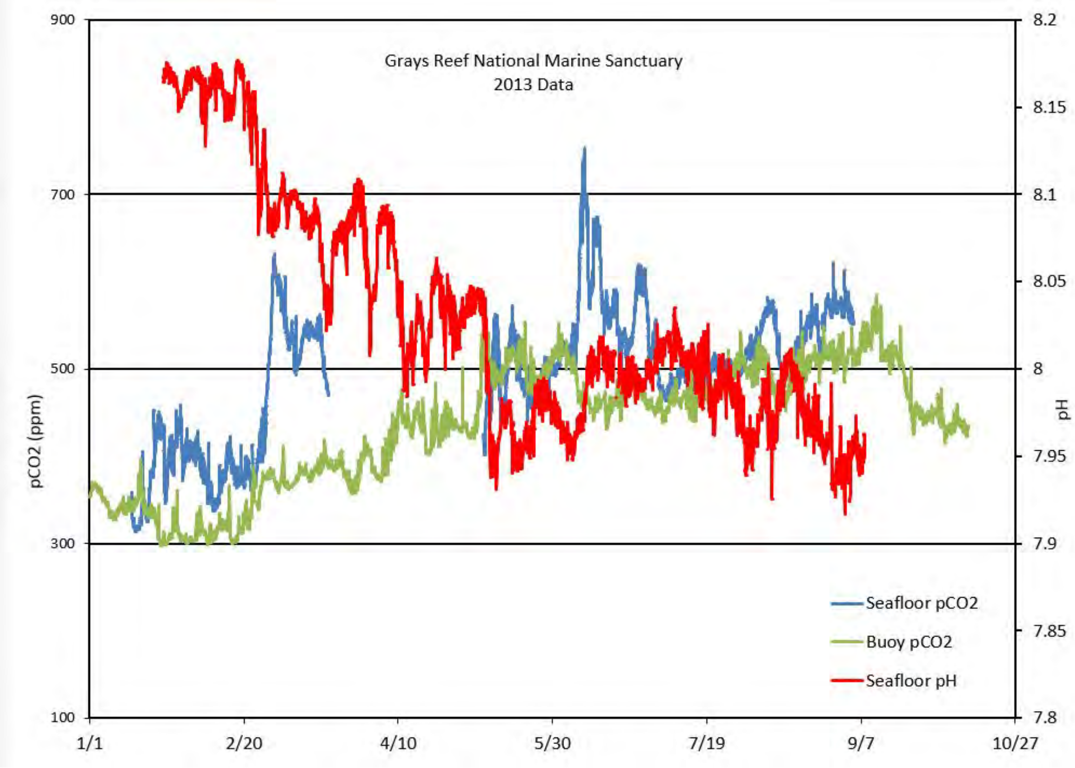

Figure 14.3. Gray's Reef National Marine Sanctuary seafloor pH.

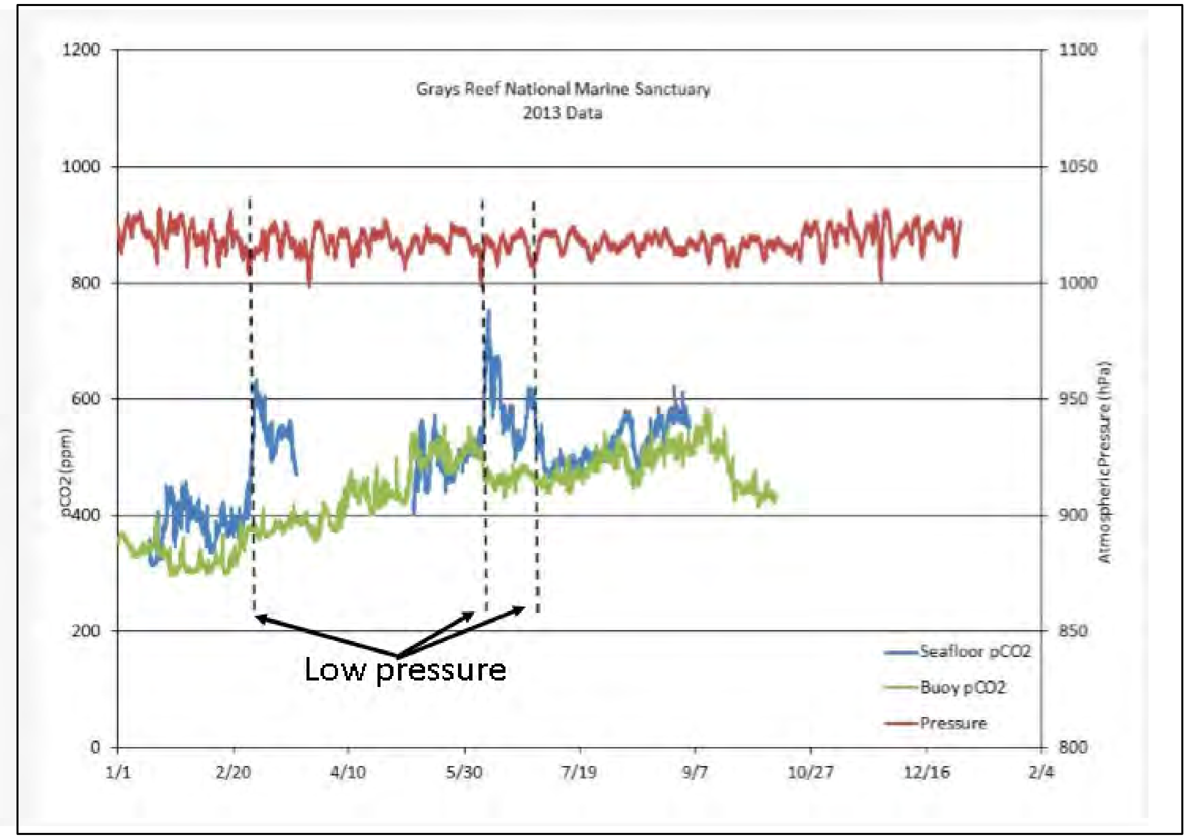

Figure 14.4. Atmospheric pressure.

Project 15. Geospatial sediment assessment for Georgia estuarine, coastal, and shelf environments

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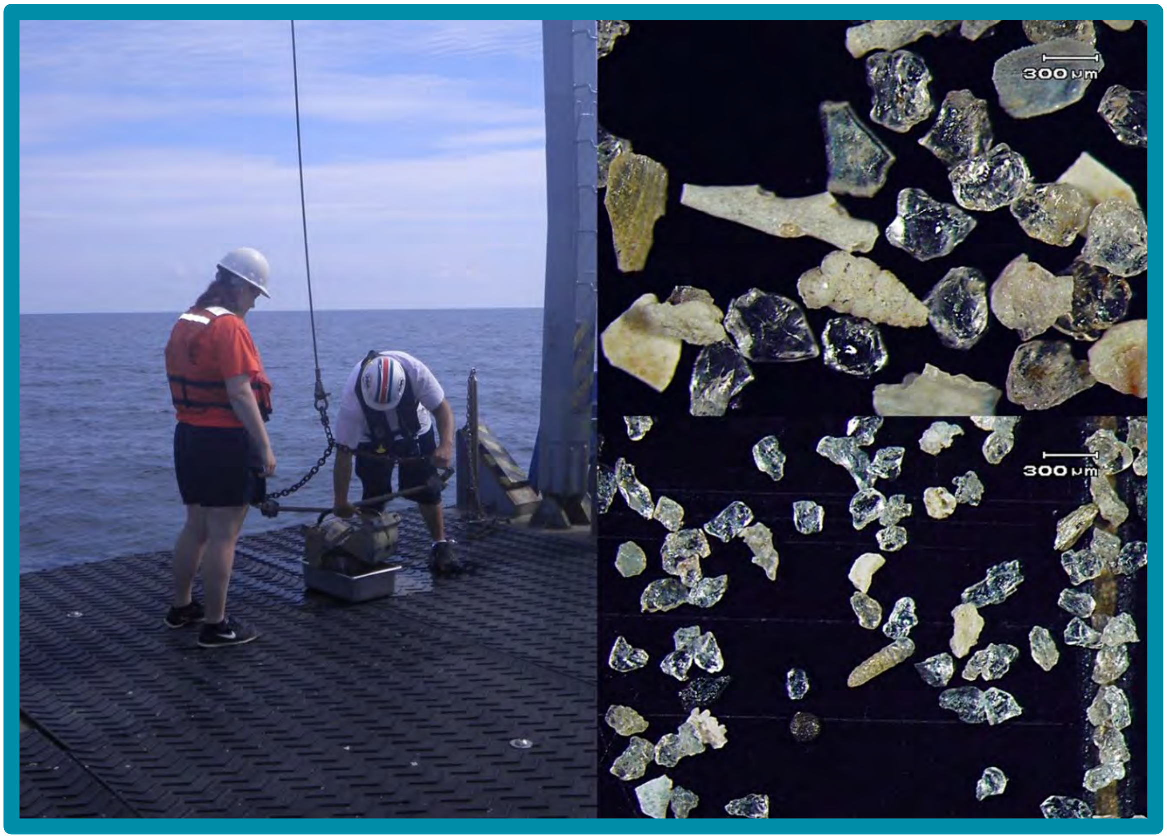

Left: Researchers collect seafloor sediments using a Van Veen Grab Sampler. Right: Clear quartz grains dominate sediments from the Georgia shelf, but biological components are also commonly observed. Photos: Claudia Venherm/UGA Skidaway Institute of Oceanography

Question addressed

What is the detailed range and distribution of sediment grain sizes within the Georgia estuarine, coastal, and shelf systems, particularly as it reflects the distribution of modern, continent-derived sediments?

Measurements

Data were sourced from several agencies for this project. We compiled a dataset of descriptive and quantitative sediment observations from six federal, state, academic, and commercial sources. After excluding non-quantitative and duplicate samples, the final dataset representing grain size records across the Georgia coastal and shelf system totaled 1,142 records. Quantitative datasets, the bulk of which were produced in the Alexander lab, were generated using laboratory analyses and computational geospatial methods. Sediment samples were analyzed using standard techniques for determining textural parameters and composition using stacked sieves (for the sand fraction), which measures sand particles' intermediate axis length, and a Sedigraph (for the silt and clay fractions), which measures particle fall velocity via x-ray beam attenuation. Sediment statistics (mean size) and sediment composition (% gravel, % sand, % mud) were computed from analytical results.

Geospatial datasets were created in the ArcGIS 10.4 desktop environment. All geospatial datasets have Federal Geographic Data Committee (FGDC)-compliant metadata. Alexander actively supports the Georgia Coastal Hazards Portal (gchp.skio.uga.edu) to distribute these results, and the sediment size and composition datasets are viewable on the portal.

Key findings

- Sediments actively control the distribution of distinct infaunal and epifaunal biological communities, sequester contaminants within the environment, and illuminate energetics and directions of material transport.
- Sediments range widely in size within and across the Georgia shelf with finer, beach quality sands located closer to shore.
- Comparing the sediments within the boundaries of GRNMS with those elsewhere on the shelf, those at GRNMS are coarser than sediment on the open shelf, reflecting the availability of coarser particles from the local environment (i.e., eroding rocky outcrops).

Project narrative

The relatively coarse scale of data available for the Georgia shelf provides the ability to broadly outline the geological conditions on the shelf. In general, the shelf is veneered by a Quaternary (0-1.8 million years before present) surficial sand sheet which averages about 5 m thick (range 0-12 meters; Henry and Hoyt 1968; Milliman et al. 1972; Foyle et al. 1999). Fine sands are generally restricted to a nearshore zone landward of the 10 m isobath; these sediments are thought to represent the modern sediment discharged from the southeastern U.S continent (i.e., the zone of modern influence; Pilkey and Frankenberg 1964; Bigham 1973). Seaward of this zone, the shelf is dominated by relict (i.e., not tied to a modern dispersal system) medium to coarse sands and local gravel that occur seaward to the shelf break (Milliman et al. 1972). Active reworking of these shelf deposits, presumably by annual tropical and extra-tropical storms and strong tidal bottom currents, is indicated by well-sorted, unimodal grain-size distributions, and the lack of significant fine-grained material (typically <2%) in these deposits (Milliman et al. 1972, Alexander, unpublished data).

Depending on grain size, sediments actively control the distribution of distinct infaunal and epifaunal biological communities, sequester contaminants within the environment, and illuminate energetics and directions of material transport. Earlier work has highlighted the response of biological communities to these distributions in Georgia and at Grays Reef National Marine Sanctuary (Alexander et al. 1997, Kendall et al. 2005, Hyland et al. 2006).

Sediments range widely in size within and across the Georgia shelf with finer, beach quality sands located closer to shore (Figure 15.1A and 15.1B): estuarine and sound sediments exhibit a mean size of 2.5 +/- 2.2 phi and span from -1.1 to 8.5 phi; sediments in state waters (0-3 nm from the coast) exhibit a mean size of 2.4 +/- 1.2 phi and span from -0.5 to 6.4 phi; and sediments in the nearshore outer continental shelf (OCS) zone (3-8 nm from the coast) exhibit a mean size of 2.4 +/- 0.9 phi and span from 0.3 to 5.7 phi. Sediments in the offshore OCS (8-400 nm from the coast) exhibit a much coarser mean grain size of 1.5 +/- 0.8 and span from -2.2 to 6.2 phi. These findings validate the concept of a zone of modern sediment influence in state waters and the nearshore OCS zone. The general location of the boundary between the modern and relict sediments does not appear to have changed, within the limits of our analyses, since previous studies in the 1970s first observed this pattern (Pilkey and Frankenberg 1964, Bigham 1973). However, the boundary's sinuous location on the shelf is now much better constrained given the much higher sample density that we now have.

Project 15: Geospatial Sediment Assessment for Georgia Estuarine, Coastal and Shelf Environments

Comparing the sediments within the boundaries of GRNMS with those elsewhere on the shelf, those at GRNMS are coarser than sediment on the open shelf, reflecting the availability of coarser particles from the local environment (i.e., eroding rocky outcrops), with a mean size of 1.13 phi (0.46 mm), which span from 0.07 to 1.88 phi (0.95 to 0.27 mm). In the Folk (1974) descriptive nomenclature for describing sediment types, all sediments in GRNMS are gravelly sands or slightly gravelly sands, with average percentages of 2.9% gravel, 97.0% sand, and 0.2% mud. Active reworking of all the shelf deposits, presumably by annual tropical and extra-tropical storms and strong tidal bottom currents, is indicated by these coarse sediments, which exhibit well-sorted, unimodal grain-size distributions, and the lack of significant fine-grained material (typically <2%) in these deposits.

We have used geostatistical techniques (kriging) on this large database of sediment grain size to develop a predicted surficial sediment grain size map of the Georgia shelf (Figure 15.2). Areas of coarser mean grain size adjacent to GRNMS identify where extensions of hard bottom habitat similar to that at GRNMS are located. Other areas on the shelf shown as generally coarser should be explored further to investigate the potential for significant additional areas of hard bottom habitat.

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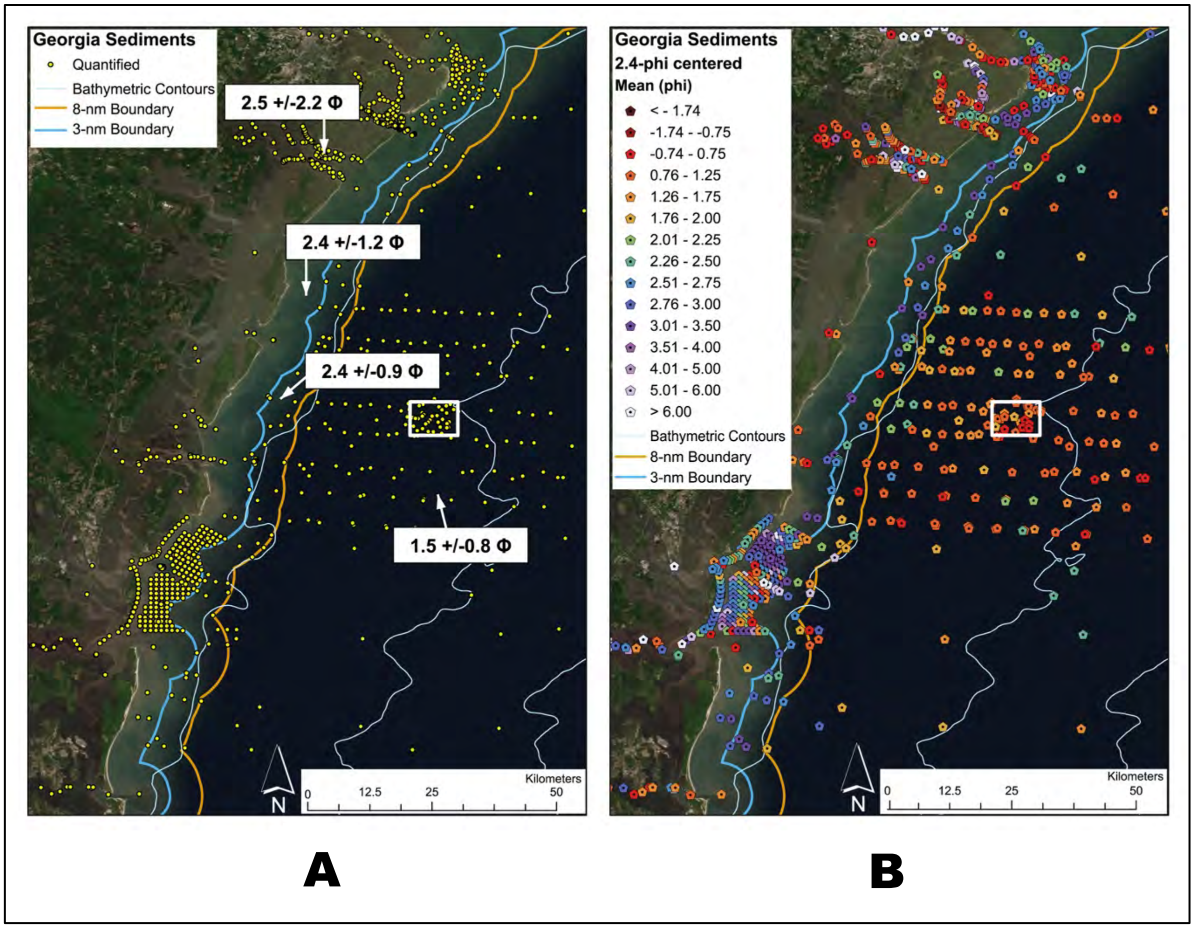

Figure 15.1. Bottom sediment grain size on the Georgia shelf (geologic phi units of size: size in mm = 2^(-phi)). Note finer sizes nearshore (<8 nm) and coarser sediment offshore; location of Gray's Reef National Marine Sanctuary shown by white box. Image: Clark Alexander/Skidaway Institute of Oceanography

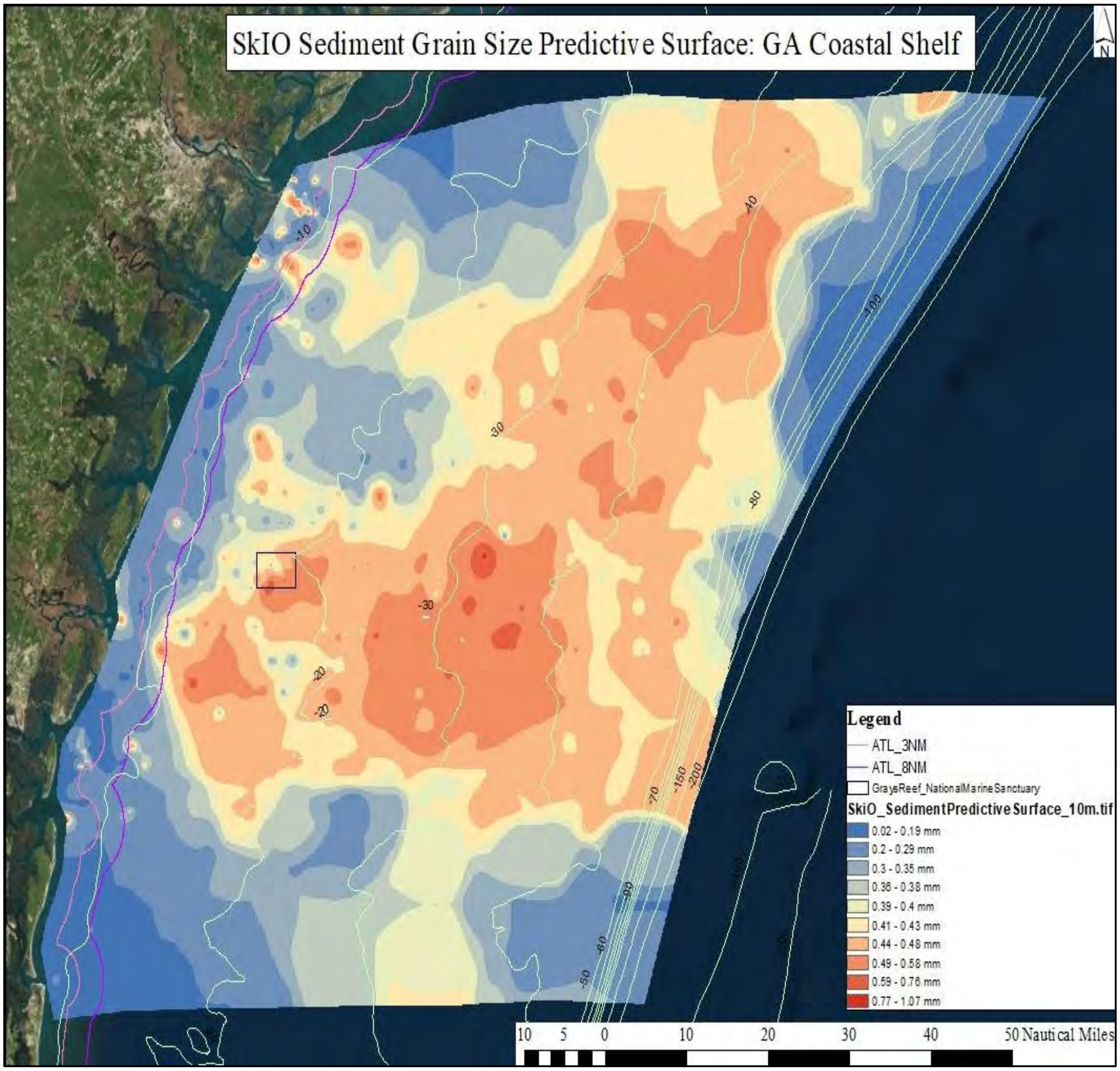

Figure 15.2. Predicted distribution of Georgia shelf sediment grain size based on kriging analysis of the extensive dataset shown in Figure 1. Image: Clark Alexander/Skidaway Institute of Oceanography

Project 16. Field and numerical studies to assess performance of acoustic telemetry collected by autonomous mobile platforms, 2014

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Gray's Reef National Marine Sanctuary science divers collect underwater video footage of glider deployment in the research area during the 2014 glider acoustics experiment. Photo: Alison Scott/NOAA

Questions addressed

Are gliders and other mobile platforms useful for collecting acoustic telemetry at GRNMS? What factors affect the performance of mobile and moored acoustic arrays? What are the bounds of performance of acoustic receivers in the field under variable environmental conditions? Can glider data help interpret the variability in stationary and mobile acoustic telemetry arrays in GRNMS?

Measurements

Physical, bio-optical, and acoustic data were collected using a combination of moored and mobile assets and used to assess how acoustically tagged fish are detected under changing environmental conditions. The experiment was sited within the GRNMS RA to complement other ongoing research, minimize the effect of trolling on the subsurface array, reduce interference with the glider at the surface by boaters, and minimize other external pressure on the experiment (anchoring, trawling, etc.).

Moored acoustic telemetry array

A course of 14 stationary tags and eight reference receivers was deployed between August 20 and October 12, 2004. The receivers and tags were installed by divers at known positions in the GRNMS RA (Figure 16.1), placed with 400m spacing based on prior field work (Mathies et al. 2014). The long axis of the array is aligned with the semimajor axis of the semidiurnal tide, which dominates variability in the currents at GRNMS (Seim and Edwards, 2007). Each receiver was outfitted with a vertical taut-line subsurface float and one, two, or three Vemco V13 reference tags attached at 6, 12.5, and/or 18.6 meters above bottom (mab) to compare detection rate near-bottom (B), mid-depth (M), and near-surface (S). Each tag is referenced by its horizontal position (receiver number from Figure 16.1) and vertical placement (S, M, or B), with a distribution as given in Table 16.1. Tags were programmed to ping at 69kHz (power output 147dB) once randomly in every 45s interval to minimize collisions (Vemco, pers. comm.). The array was recovered by divers October 12, 2014, after 53 days of data collection.

Glider

To estimate density stratification and sound speed, the Skidaway Institute of Oceanography glider *Modena* was deployed within the GRNMS RA on September 17, 2014, and was recovered on October 10, 2014. This Slocum G2 glider was equipped with a Seabird pumped conductivity, temperature, and depth (CTD) sensor, an Aanderaa oxygen optode, and a Wet Labs EcoPuck fluorometer that measures response to three channels corresponding to chlorophyll-a, colored dissolved organic matter (CDOM), and backscatter. The pumped CTD provides CTD data approximately every second, which corresponds to approximately 10 cm vertical resolution. The glider was also outfitted with two internally-powered, internally-recording Vemco VMT units for detection of array tags and any tagged animals moving through the volume of detection around the instruments.

ADCP

A 600kHz upward-looking Acoustic Doppler Current Profiler (ADCP) was moored nearby to collect observations of vertical profiles of currents, acoustic backscatter, and their variability in time over the month-long experiment every 10 minutes at 1m vertical resolution. The ADCP was deployed between August 20 and December 11, 2014, and was sited approximately 1.1km away to remove the potential for interference between the ADCP and the acoustic array (Vemco, pers. comm.).

Key findings

- Detection rates within the moored array were dominated by current variability driven by tidal currents, which account for over 90% of the kinetic energy at GRNMS, though mean alongshore flow may enhance detection rate downstream.
- During stratified periods under weak tidal flow, detection rate within the moored array increases when the flow direction is oriented along the cross-shore direction, with greater detection rate when the flow is offshore compared to onshore flow. Tidal straining can affect the ability to detect acoustic tags by changing stratification and thus sound speed. Lower detection rate associated with stronger stratification when the currents are directed offshore, and higher detection rate and weaker stratification with onshore flow.
- During periods with weaker stratification and/or stronger spring tides, detection rate is higher overall, and can vary at both semidiurnal and quarterdiurnal periods. Stratification may vary each M2 tidal period, but the frictional effects of mixing in the bottom boundary layer on tag detection rate are larger than that of tidal straining.

Project narrative

Gliders are autonomous underwater vehicles (AUVs) that have proven to be robust scientific tools for coastal ocean sampling (e.g., Schofield et al. 2007), with long range and endurance that make them attractive as mobile platforms for acoustic telemetry in the coastal ocean. Since 2013, gliders outfitted with miniaturized Vemco acoustic receivers have been used regularly in coastal glider work, and data have been compiled and cross-referenced with the vehicles' positions at detection to provide a measure of acoustic data that would be unattainable with traditional methods. However, little is known about how effectively the glider-mounted receivers can be expected to detect tags on a moving platform in the field, since detection range depends strongly on stratification and other environmental factors, and detectability of tagged animals can depend on the relative angle of the fish and receiver, which can vary significantly using glider-based measurements.

Previous work within GRNMS (Mathies et al. 2014) found that the detection rate of two receivers located 200m apart changes significantly with seasonal stratification. Maximum detection rate was found to be 97% in February, when the water column is most likely to be well-mixed by winter storms, and falls below 10% in summer, when solar heating and fresh water both contribute to seasonal stratification. While typical 50% detection range of these instruments has been found to be approximately 200m (Carroll 2010), synoptic, tidal, and event-scale variability of stratification can reduce the 50% effective range to 100m or shorter. This unknown variability of the detection range of the receivers limits the ability to interpret detection rate as a tool to improve fisheries monitoring or management. Glider-based acoustic telemetry complements traditional stationary arrays because of the glider's long endurance and ability to monitor the full water column in three dimensions (Oliver et al. 2013). Perhaps more significantly, the CTD and acoustic receivers provide co-located acoustic detection and sound speed variability, which enhances the ability to interpret the acoustic detections.

As part of a 2014 field study designed to assess and define bounds of performance of glider-mounted receivers in the field, a combination of moored and mobile assets was deployed in the GRNMS RA in 2014. The following section describes methods used to process and analyze data from a moored 3D array of acoustic telemetry receivers and tags, an ADCP, and a Slocum glider deployed within the GRNMS RA during the fall transition, as summertime stratification breaks down due to mixing from storms and surface cooling.

Receiver data

Moored and mobile receiver data were downloaded sequentially post-recovery on a single computer with a current synchronization to the nist.gov time server to achieve a common time reference. However, the last prior date of clock synchronization for each receiver is unknown. Receiver 3 malfunctioned within three hours of deployment and was removed from the following analysis.

With one ping randomly in every 45 second interval, each tag should ping 80 times per hour, but there were a few instances of a receiver recording more than 80 detections in an hour. Further, efforts to use sequential pairs of detections as a time stamp or common reference for any of the receiver pairs (moored-moored or moored-mobile) failed as a method to cross-reference detections among receivers. Clock drift or error in programming may account for these deviations from expected behavior. Given the above difficulties, detection rate is given here as an hourly total of detections rather than an estimate defined by single pings.

Glider

Gliders ‘fly’ by changing their buoyancy and center of gravity, resulting in a yo-yo-like pattern of upcasts and downcasts in the vertical, with horizontal and vertical speeds of approximately 25 and 10 cm/s, respectively. While deployed, the glider was set to fly along a 1 km box centered on the receiver array, but measured tidal and wind-driven currents exceeded the forward speed of the glider, so the glider was unable to hold station within the science array. A buoyancy pump error further reduced the glider’s ability to correct for strong wind-driven alongshore currents that displaced the glider over 10 km to the south of the receiver array for portions of the deployment, resulting in reduced detection capability of the VMTs during this time. For these reasons, the analysis that follows is primarily based on the detection efficiency within the receiver array and variability explained by changes in stratification and flow measured by the glider and ADCP, respectively. Conductivity, temperature, and depth data from the CTD are used to calculate salinity and density at approximately 1 s intervals over the glider deployment, corresponding to a vertical resolution of about 10 cm.

ADCP

A 600 kHz upward-looking acoustic Doppler current profiler (ADCP) was moored approximately 1.1km away to remove the potential for interference between the ADCP and the acoustic array (Vemco, pers. comm.). The data were processed to remove bins above the water surface, as well as bins contaminated by surface effects and side-lobe interference as defined by thresholds in echo intensity and percent good. Horizontal currents were further averaged to 30-minute temporal resolution, and rotated -6.91 degrees to account for local magnetic variation. Along- and cross-shore components of flow were derived by rotating 30 degrees such that cross-shore direction is positive offshore and alongshore is positive northeast. The t_tide toolbox (Pawlowicz et al. 2002) is used for tidal analysis of measured currents and detection rate. Wind data from National Data Buoy Center (NDBC) buoy 41008, located within GRNMS near the acoustic array, are used for context on wind forcing.

The results presented here focus on detection rate within the moored array, identifying spatial and temporal patterns using currents and density stratification measured by the ADCP and the glider, respectively. The following section first describes the oceanographic setting and forcing conditions from ADCP, glider, and buoy wind data, then characterizes average spatial and temporal patterns in detection rate, and uses two case studies to better understand how environmental conditions affect the ability to detect acoustic tags at GRNMS.

The observed winds, currents, and density field capture the transition from summer into fall conditions. Measured currents are strongly tidal and aligned cross-shore (Figure 16.2), with little vertical variability for most of the record. The barotropic tide accounts for approximately 90% of the depth-averaged currents. The ~14.7-day spring-neap cycle (a lunar-solar modulation) is clearly visible in the cross-shore currents, as well as the longer period modulation by the N2 tide, which results in further enhanced tidal signal with a 27.55-day period. In the mean taken over August 20 through October 10, when the glider was recovered, there is a net southward alongshelf flow of 0.016 m/s, with a weak mean downwelling signature in the mean cross-shore currents (~0.015 m/s offshore flow near-bottom, 0.004 m/s onshore flow near-surface). Alongshelf winds drive 20-30 cm/s southward alongshelf flow for several days in late August, and again over a longer period in late September, typical for the onset of "mariner's fall" (Weber and Blanton, 1980).

Figure 16.3 shows the effect of the fall transition over the inner shelf, as the water column cools and freshens slightly (3.96 deg C and 1.49 psu change from September 17 to October 10). Stratification at the beginning of the glider deployment is fairly weak (approximately 0.15 kg/m^3, Figure 16.4a). This difference between surface and bottom density is further reduced by wind mixing as the entire water column becomes more dense. Stratification is quantified in terms of the square of the Brunt Vaisala frequency N, calculated as a bulk estimate from the surface and bottom density:

$$N^2_{bulk} = -1/\rho_o \, (\rho_{bot}-\rho_{surf})/\Delta z,$$

where ρ_{bot}, ρ_{surf}, and ρ_o are bottom, surface, and mean densities, and Δz is the vertical difference in the position of the near-bottom and near-surface measurements. Over the deployment, N^2_{bulk} varies at tidal, diurnal/diel, and synoptic (3-7 day) time scales.

Figure 16.5 shows hourly detection rate, averaged over the receiver array deployment, for all tags and receivers. Maximum mean detection rate is approximately 56%, though detection rates of 10-20% are more typical. Overall, tags closer to the bottom were detected more often than tags at the same horizontal position but located near-surface. While detection probability was predicted to be highest over the shortest distance, consistent with Kessel et al. 2013, the two receivers centrally located within the array were better able to detect tags located 400-1200m away in the horizontal direction than tags 5-13m away in the vertical (Figure 16.5). While stratification may prevent clear transmission in the vertical, receivers 2 and 5 lie within 400m distance of 10 and 7 tags, respectively, and signal collision probability of 70% is predicted by the metrics of Binder et al. 2015.

Analysis of detections within the receiver array suggests that the M_2 barotropic tide, which dominates current variability in GRNMS and the shelf of the South Atlantic Bight (Seim and Edwards 2007), exerts strong control on detection rate. Harmonic analysis of the time series of detection rate using the *t_tide* toolbox (Pawlowicz et al. 2002) is used as a tool to evaluate tidal variability. Signal to noise ratio (SNR) is given as the square of the ratio of amplitude to amplitude error at the 95% significance level for each tidal constituent; values greater than 1 suggest statistically significant tidal variability. Signal to noise ratios of the detection data for the eight largest constituents of the velocity record (M_2, N_2, S_2, K_2, O_1, K_1, P_1, and Q_1) are greatest for the M_2 tidal constituent, and range from 0.15 to 34. Tag 1M is detected by receiver 4 (R4,1M) with a SNR>1 for all eight tidal constituents, while the rest of the receiver/tag pairs are significant for five to seven tidal constituents.

Since the M_2 tide explains over 90% of the variance of the currents and is significant for all but two receiver/tag pairs (R7,5M and R8,2M), SNR of the M_2 constituent is used to evaluate the relationship between flow direction and detection rate. Pairwise comparison of detection rate and SNR indicates that detections among tag/receiver pairs with an alongshore orientation are more likely than among cross-shore aligned pairs (Figure 16.6). Tidal analysis of detection rate also suggests that detection rate increases when the flow direction is oriented along the cross-shore direction, with greater detection rate with the flow is offshore compared to onshore flow. Up- or downstream position does not significantly affect detection rate among alongshore pairs in the mean but can be significant for cross-shelf pairs. However, this difference is largely driven by the tidal phase. Comparison of minimum and maximum hourly detections as a function of tidal phase (not shown) indicates a strong preference for tidal phase in maximum detections that is not observed in the minimum detections, suggesting that the difference in detection rate may not be depending on the travel path of the ping but rather the phase of the tide.

The above results indicate mean detection rate over the full deployment, but since stratification and mixing change over the measurement period, it is useful to compare detection data over a range of oceanographic conditions. Given the preference for detections among alongshore tag and receiver pairs, receivers and tags at locations 1 and 4 are used to demonstrate patterns in detection variability with respect to stratification, tidal currents, position within the water column, and upstream or downstream location. Two time periods are chosen for analysis: 1) September 18 to 20, when the water column is weakly stratified near the beginning of the glider deployment, and 2) October 7 to 9, when the water column is observed to be more well-mixed.

During September 18 to 20, weak stratification is observed at GRNMS, and the time period coincides with a small neap tide (max cross-shore flow ~+/-0.25 m/s). Alongshore winds are variable but net downwelling favorable (mean=1.19 m/s) in advance of a larger storm system, and depth-averaged flow is 0.048 m/s to the southwest, so receiver 1 is downstream of receiver 4. Detections of tag 4M at receiver 1 show a strong M_2 tidal signal, with lower detection rate associated with stronger stratification when the currents are directed offshore, and higher detection rate and weaker stratification with onshore flow (Figure 16.7). Time series of detections among most of the receiver/tag pairs follow this same temporal pattern, with a strongest variability approximately every 12 hours, regardless of cross- or along-shore orientation.

Hourly detection rate of in the upstream direction, for tag 1M at receiver 4 (R4,1M) is comparable in magnitude or slightly larger than R1,4M. However, phase-locking to the M_2 tide is less clear than the downstream direction; R4,1M often has a broader window of detection that leads the signal of R1,4M. Tag position in the vertical does not have a strong effect on the magnitude of upstream detections over this period, but the timing of maximum detection rate of the three tags over each tidal interval can vary by hours. In the mean over the deployment, R4,1B > R4,1M>R4,1S (Figure 16.5), but over these two days, detection rate of the near-bottom tag 1B is smaller than that of 1M and 1S.

About two weeks later, conditions have changed at GRNMS: alongshore winds are stronger and upwelling favorable, with a mean northeastward 3.14 m/s wind driving a mean depth-averaged alongshore flow of 0.050 m/s. Due to a strong spring tide, the magnitude of the cross-shore tidal flow is 0.40-0.45 m/s, approximately twice the strength during the weak neap two weeks before. In this case, relative to the mean flow, receiver 1 is downstream of receiver 4. Overall detection rate is higher (Figure 16.8), and the time series of detections (up- and downstream) show a strong quarterdiurnal signal corresponding to half the M_2 tidal period. In the upstream direction (R1,4M), the quarterdiurnal variability is smaller than that in the downstream direction (R4,1M), and overall detection rate is higher. Stratification is much weaker than in the first case, and detection rate does not appear to vary significantly as a function of vertical tag position. Comparison of other tag/receiver pairs suggests temporal variability in alongshore pairs is more strongly quarterdiurnal than in that of cross-shore pairs (e.g., R6,5M, R1,2M), which are dominated by semidiurnal variability during both periods.

In summary, detection of acoustic tags is highly variable in space and time at GRNMS Detection rate is surprisingly low, with an average hourly detection rate of 10-20% at just 400m distance; time series reveal that it is common to receive zero detections over up to a quarter of each tidal cycle. While harmonic analysis, taken as an average over the deployment, suggests that detection rate among alongshore receiver/tag pairs is greater than that among cross-shore pairs, case studies reveal different spatial and temporal patterns in detection rate that depend on tidal variability and stratification.

Stratification can reflect, refract, or absorb sound propagation, and the M_2 (lunar semidiurnal) barotropic tide appears to alter the propagation characteristics of sound by changing stratification in two ways. First, for portions of the experiment, stratification is enhanced when tidal currents are oriented offshore, and diminished when tidal currents are oriented onshore. Sound propagation is enhanced when the water column is less stratified on the ebb tide, and more detections are observed within the receiver array – even between a bottom-moored receiver and a tag in the mid- or upper water column. Tidal variability in stratification is consistent with strain-induced periodic stratification (SIPS, Simpson et al., 1990). SIPS, or tidal straining, is often observed in estuaries and other regions of freshwater influence, where the stratification present during the ebb tide can be mixed completely during the flood tide within the vertical shear of the bottom boundary layer. Gray's Reef falls into the coastal frontal zone (CFZ, e.g., Blanton et al. 1994), and the phase of maximum detections relative to flood and ebb is more consistent with SIPS than horizontal advection of the front alone, which would alter stratification each tidal period but with a phase corresponding to maximum displacement rather than maximum current.

The second mode of tidal modification of sound propagation appears to be more directly related to bottom boundary layer mixing. There are times during which detection rate is strongly quarterdiurnal, consistent with an increase in bottom boundary layer mixing associated with stronger flow along the M_2 semi-major tidal axis at both maximum flood and ebb tides. Stronger depth-averaged flow induces stronger mixing at the bottom, and the shallow depth within Gray's Reef, and possibly the relief of the reef structures within, leads to a bottom boundary layer structure that extends all the way to the surface, which is not uncommon on the shelf in this region. As a result, stratification is reduced, and more detections are observed within the array on max flood and max ebb. Vertical position of the tag has a reduced effect on detection rate, since the water column is more well mixed. This second mode of detection rate variability was observed more typical in the latter half of the deployment, when the water column was more well-mixed due to wind forcing, particularly on the constructive phase of the spring-neap cycle and the N_2 modulation.

The above dynamical interpretation of detection data based on event-scale data is consistent with the mean pictures derived from averaging and harmonic analysis. Strong SNR at the M_2 frequency for alongshore receiver/tag pairs versus cross-shore pairs may indicate the role of horizontal stratification. If the cross-shelf density structure is consistent along isobaths and strains each tidal cycle, the alongshore direction may be a preferable channel for sound propagation, as there would be a greater chance for reflection, refraction, or absorption by stratification in the cross-shore direction. In the absence of wind forcing, it is unclear if the tidal straining observed during the first period would persist under the tidal mixing from a strong spring tide like that observed in the second period, but it is clear from the data that both types of tidal variability (as well as synoptic scale mixing from storms) alter the ability to monitor animals within Gray's Reef, and care must be taken in interpreting the receiver data without closely examining the oceanographic conditions.

Future work will investigate the intermittency of these links between stratification and detection rate using a combination of glider, acoustic, meteorological, and oceanographic data. Repeating the experiment under a wider range of stratification conditions and wind events will help better understand the competition between tidal mixing and stratification. Careful time synchronization practices pre- and post-deployment will minimize time drift issues and adjusting the tag set-up may permit per-ping analysis of detection efficiency. Integrating receiver detections into the data stream of the glider will facilitate a more sophisticated analysis of detection efficiency with respect to stratification and sound speed, and better allow analysis of detection efficiency for mobile receivers.

Preliminary work with an inertial model developed for this experiment suggests that vehicle attitude and angle between the tag and receiver may cause significant differences between predicted and actual detection rates. Traditional localization techniques can use time difference of arrival (TDOA) over multiple detections (e.g., Ehrenberg and Steig 2002; Espinoza et al. 2011) to localize the detected tags; these techniques can be significantly improved by first localizing the glider itself, taking advantage of algorithms that combine an odometry model and passive acoustics (Cho et al. 2015; Cho 2017).

The combination of this and other ongoing work will lead to greater understanding of the processes that affect sampling procedure, measurement, and interpretation of telemetry data on autonomous platforms, and ultimately lead to guidance for future efforts to acoustic telemetry with AUVs and other emerging technologies.

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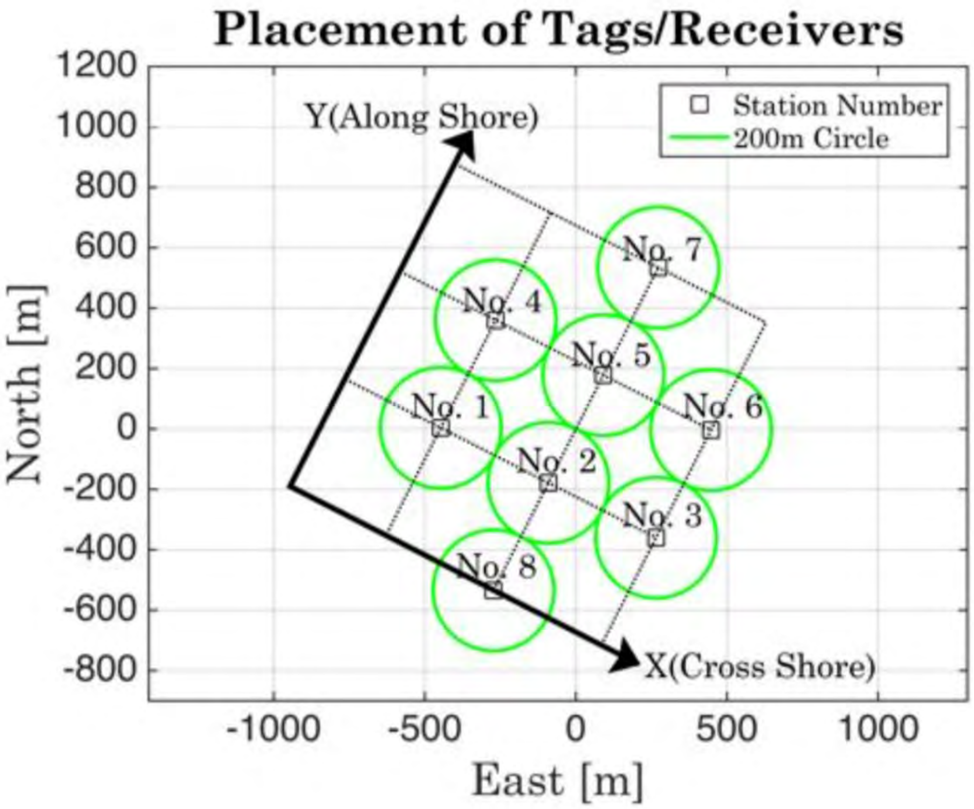

Figure 16.1. Two-dimensional array of receivers and tags. The origin of the figure lies 3.09km ENE of the National Data Buoy Center (NDBC) buoy at Gray's Reef (31.400N, 80.868W). The green circle reflects a 200m radius of detection suggested by Mathies et al. 2015.

Table 16.1. Tag names, given by receiver location and vertical position, where S, M, and B indicate position near the surface, mid-depth, or near the bottom.

Receiver number	Tags	Notes
1	1S, 1M, 1B	
2	2M	
3	3S, 3M	Receiver malfunctioned
4	4M	
5	5S, 5M	
6	6M	
7	7S, 7M	
8	8M	

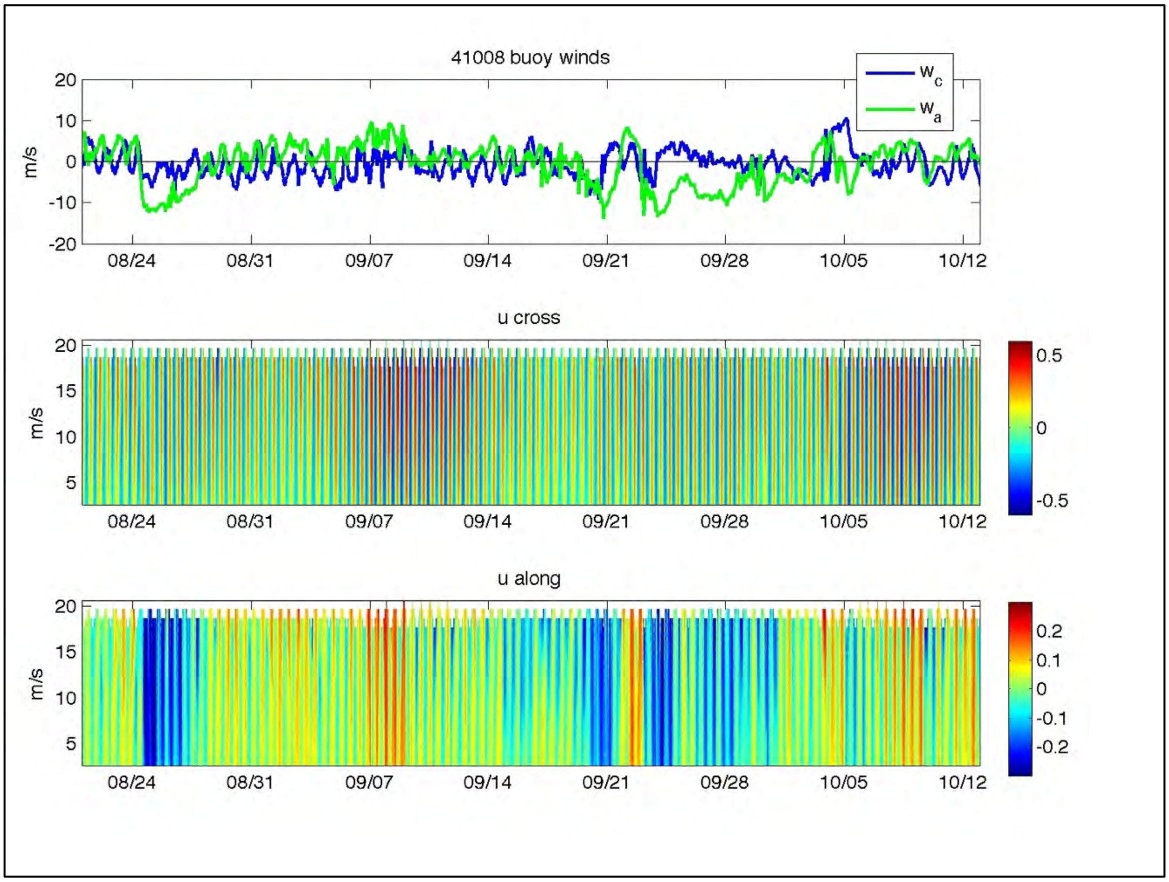

Figure 16.2. Time series of buoy-measured winds (upper panel), rotated into cross (blue) and along (green) shore components, and cross- and along shore components of currents measured by the ADCP (middle and lower panels, respectively). The data are shown from the beginning of the ADCP record through recovery of the glider. Note the magnitude of flow compared to forward speed of the glider, approximately 0.25 m/s in shallow water.

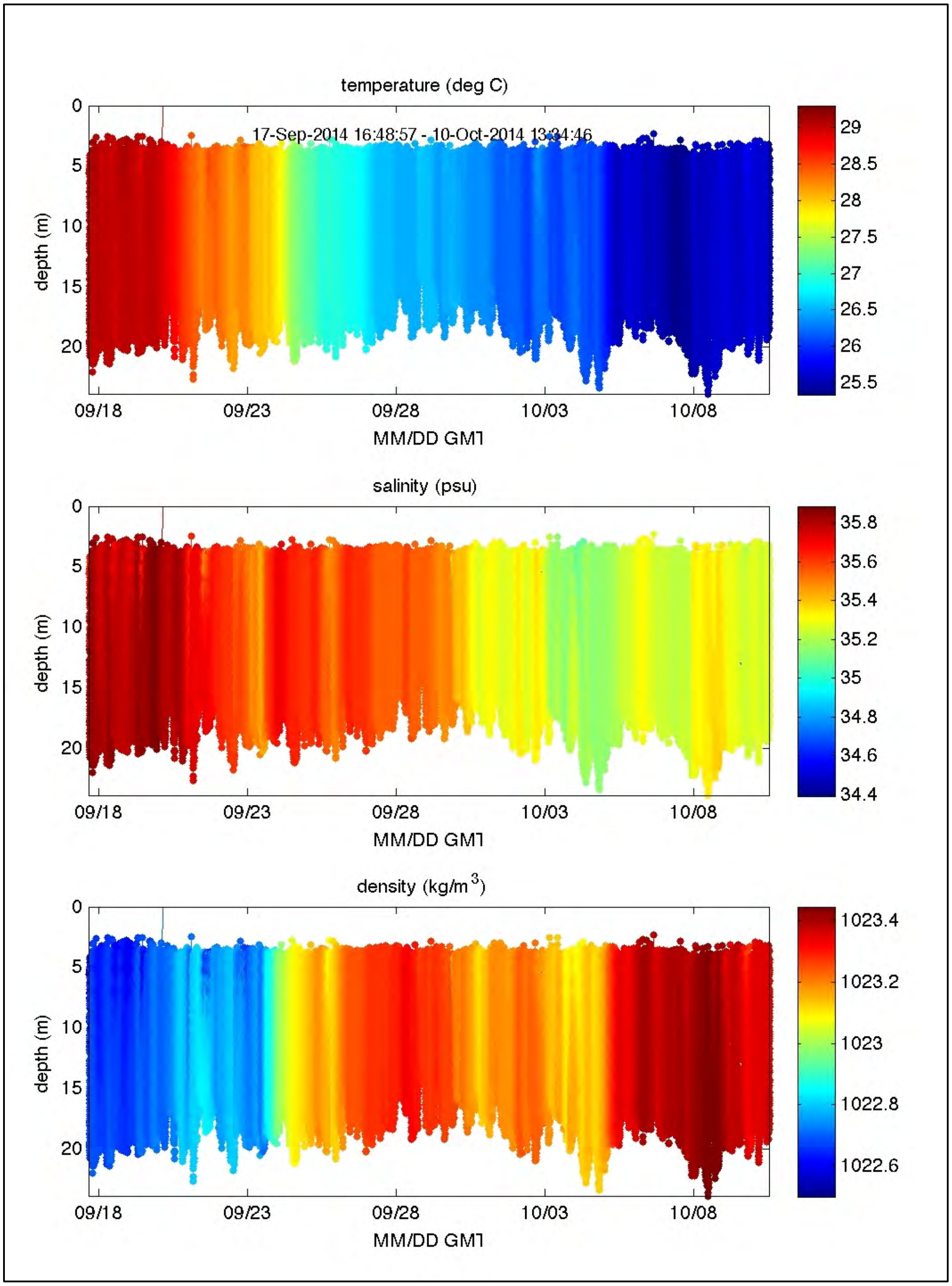

Figure 16.3. Glider-measured temperature (upper), salinity (middle), and density (lower) over the 23-day deployment.

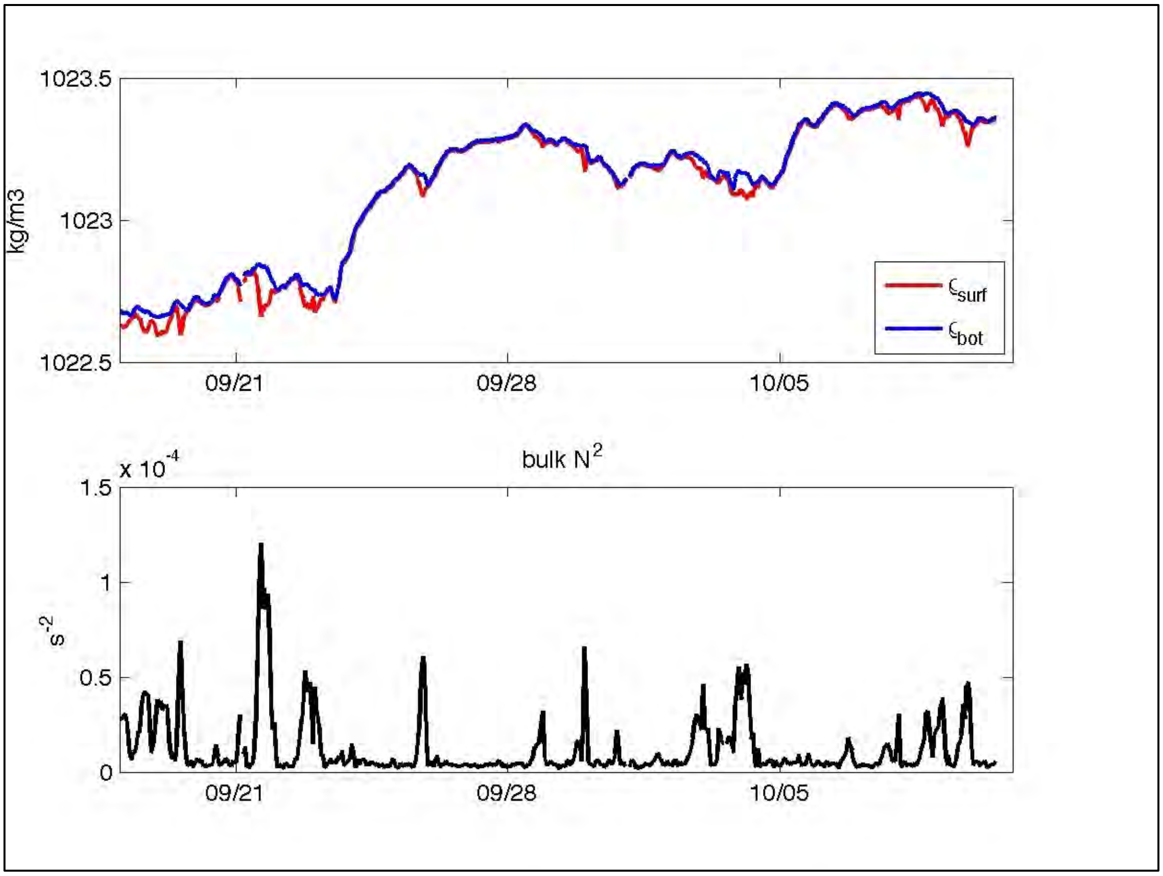

Figure 16.4. Upper panel: time series of hourly averaged near-surface (red) and near-bottom (blue) density measured by the glider. Lower panel: time series of estimate of bulk stratification (bulk N^2) derived from near-surface and near-bottom data.

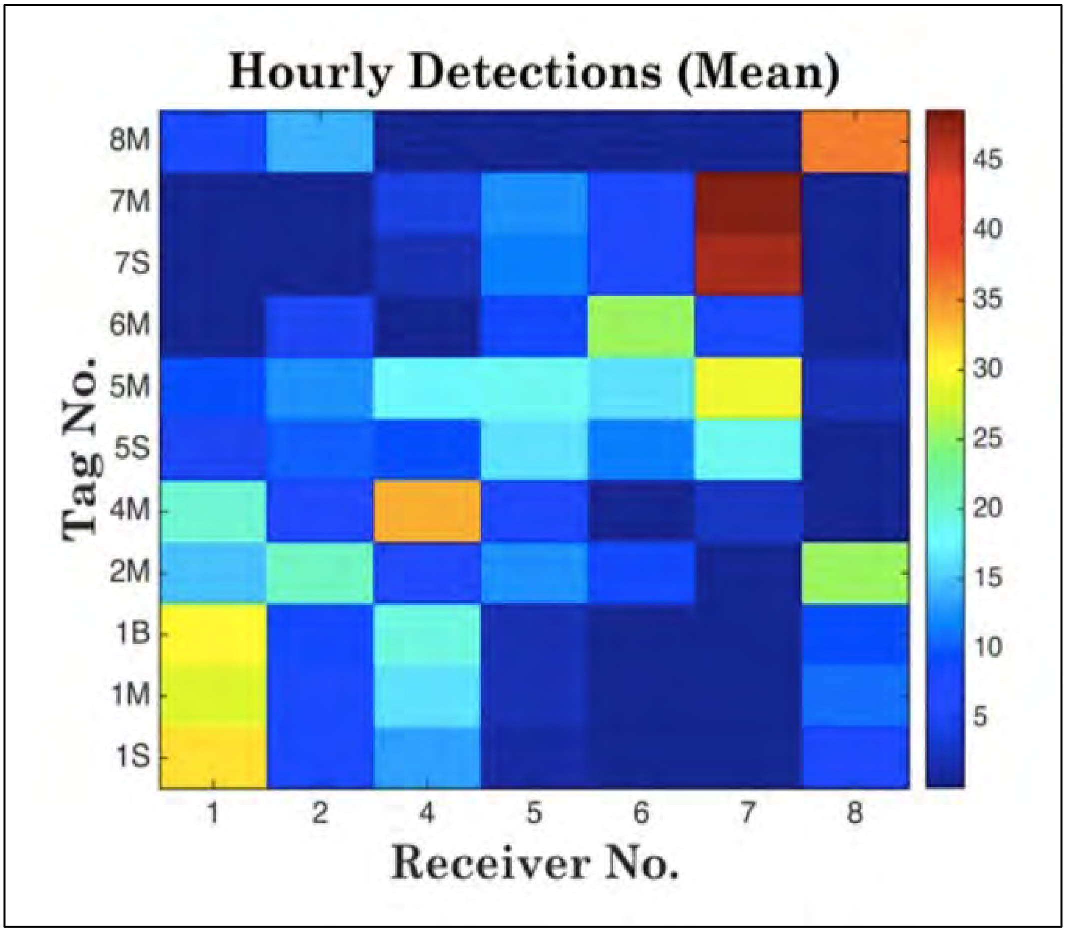

Figure 16.5. Mean hourly detections by receiver number (x-axis) and tag number (y-axis), with S, M, and B representing tag location at the surface, mid-water column, and near bottom. 40 hourly detections represent the 50% detection level (80 total detections per hour).

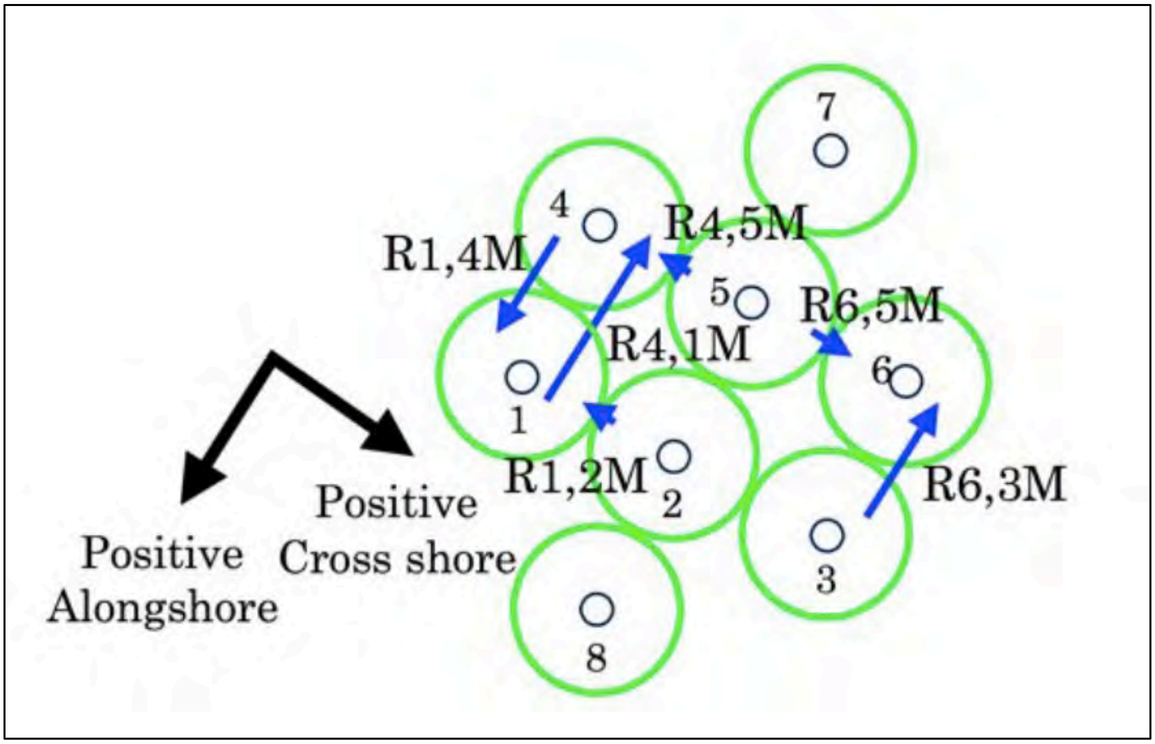

Figure 16.6. M_2 signal to noise ratios (SNR) for receiver/tag pairs in the array. The direction of each arrow indicates the direction from the tag to the receiver, and the length of the arrow indicates the strength of the SNR. Alongshore pairs have stronger SNR than cross-shore pairs.

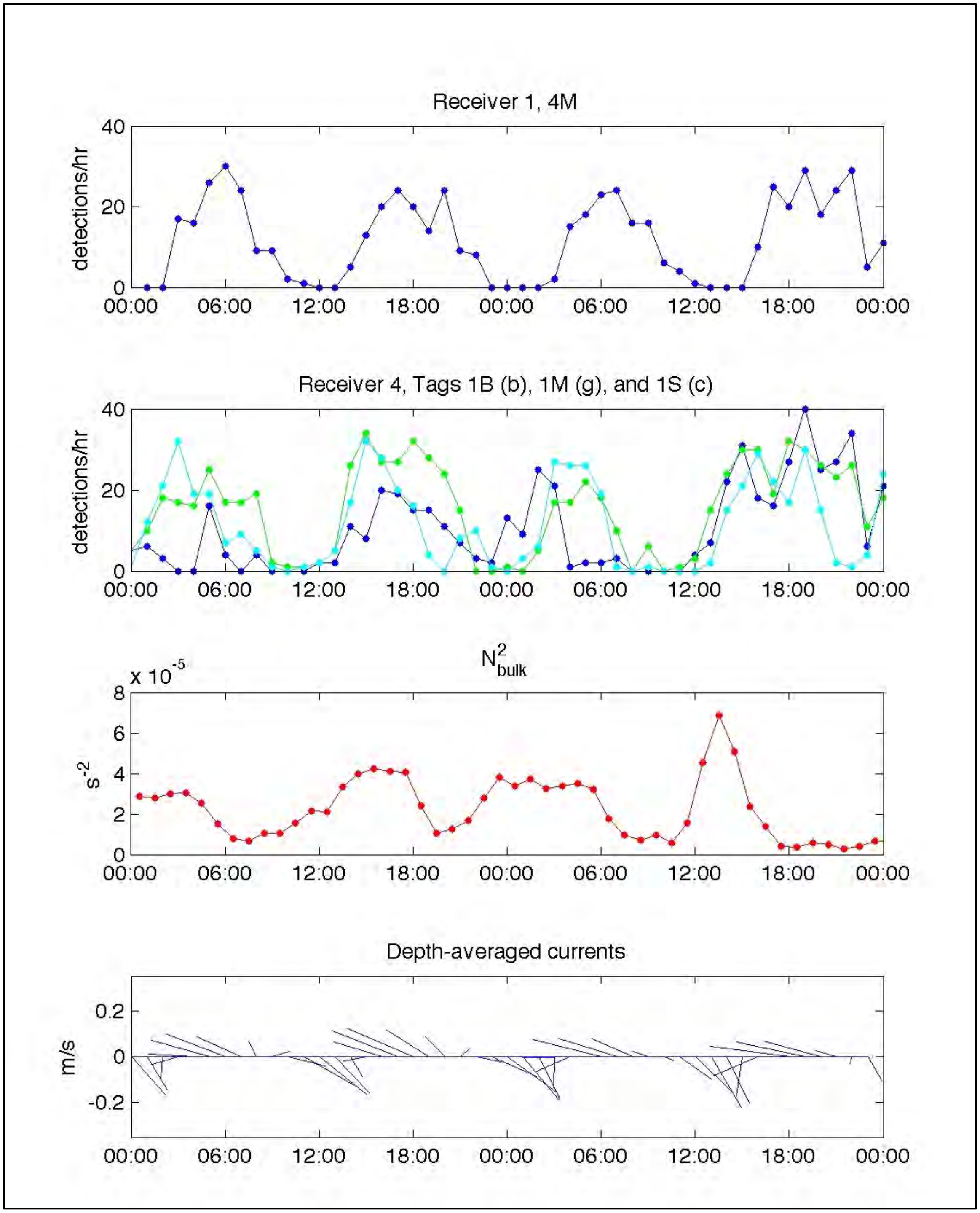

Figure 16.7. Upper panels: Hourly detections of tag 4M at Receiver 1 (upper), and of tags 1B (blue), 1M (green), and 1S (cyan) at receiver 4 (panel 2). Lower panels: bulk N^2 (middle, s-2), and depth-averaged ADCP currents (bottom, m/s).

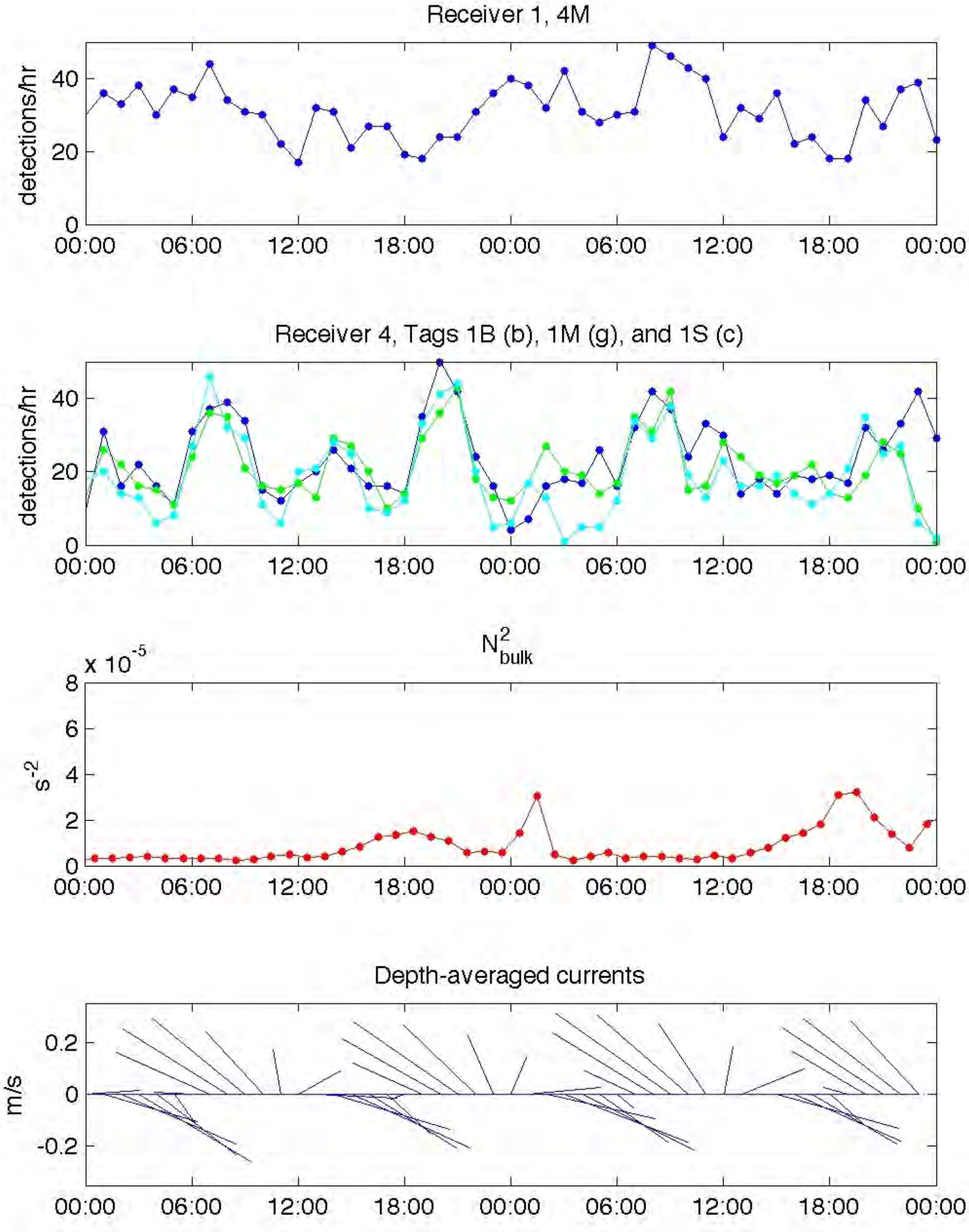

Figure 16.8. Upper panels: Hourly detections of tag 4M at Receiver 1 (upper), and of tags 1B (blue), 1M (green), and 1S (cyan) at receiver 4 (panel 2). Lower panels: bulk N^2 (middle, s-2), and depth-averaged ADCP currents (bottom, m/s).

Discussion

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The projects described in this report demonstrate that the GRNMS RA is being used as designated. That is, it is being used to study the effects of natural variability from local and regional ecological processes (e.g., predation, competition, climate change, storms) where the direct effects of fishing will not mask, or add a degree of ambiguity to, the interpretation of results.

Prior to designation of the RA in 2011, fishing was allowed throughout the sanctuary, and there were no options to study the broad suite of questions governing conservation and sustainable use of natural resources with the assurance that direct human uses were not directly influencing outcomes. Over the past several years, 16 projects were implemented along three strands linked to the RA. On one strand are those studies that directly and explicitly compare the status of faunal groups inside and outside the RA (e.g., reef fish, invertebrate communities and key taxa on ledges, pelagic forage fish). On the second strand are those studies that simply use the RA as an unimpacted study site (e.g., high spatial resolution acoustic tagging of fishes). Finally, on the third strand are those studies that focus on processes or approaches that support work in the RA now or in the future (e.g., data buoy, sediment processes, acoustic tag detection with mobile platforms, towed video for assessing halo predators).

Noteworthy is that this report summarizes the status of projects up to five years since closure, with some projects not designed as inside-outside comparisons. Five years is a relatively short period of time to expect unambiguous results of contrasts due to management status. Indeed, the literature is replete with empirical data demonstrating that response to spatial management occurs over longer periods as ecological processes that mediate population and community dynamics shift due to changes in disturbance regimes and responses to protection stabilize (e.g., Micheli et al. 2004, Lester et al. 2009, Babcock et al. 2010). In any case, current results of the inside-outside comparisons, given the statistical limits in the ability to detect change, suggest that to date, human uses outside the RA have minimal impacts and are sustainable. Such results demonstrate the utility of the RA as a reference site that allows continuing assessment of change from multiple drivers absent direct fishing and other use effects regardless of the status of human impacts outside the boundaries.

However, the uncertainties of patterns in human use within GRNMS before and after designation of the RA, and into the future, are important to acknowledge. While there was minimal fishing in the RA region prior to designation, the assumption that fishing is absent from within the designated site generally fits within the scope of direct observations. Enforcement reports from United States Coast Guard and Georgia Department of Natural Resources to the GRNMS Sanctuary Advisory Council indicate little to moderate use of the sanctuary by recreational fishers and overall compliance with RA boundaries. For example, enforcement trips to GRNMS early in 2014 (32 person-hours) resulted in three vessel sightings throughout the sanctuary. An additional 132 person-hours of patrols during the same period resulted in boardings of seven vessels with no violations. Finally, 31person- hours of enforcement patrols in GRNMS from September through November 2014 resulted in no vessel sightings. In contrast, a recent recreational fishing survey of 1,965 anglers and 83 saltwater fishing guides, conducted for Georgia DNR by Response Management (2017), suggests that use of the sanctuary could be significantly greater. Survey results found that 27% of anglers fished offshore waters (defined as 3 to 200 miles offshore), and of those, 18% fished Gray's Reef (mean days fished = 5.7, median = 3). Further, 19% of guides brought customers to Gray's Reef (mean days fished = 9.9, median = 3). Given 210,000 resident Saltwater Information Program permit holders (GADNR 2018) in Georgia and 134 licensed guides during the 12-month period prior to the survey, and extrapolating from the survey to the fishing public, there would be 10,206 anglers and 25 guides who fished Gray's Reef. Using the median value of three fishing days per angler and guide, this yields 30,618 angler days (and 75 guided days) fished over 12 months. While roughly 84 anglers per day (total days/365 days yr^{-1}) at Gray's Reef does not comport with much lower patterns of observed use overall, casual observations indicate pulses of angler effort during some periods (e.g., weekends with optimal weather conditions, seasons for regulated species, tournaments). Indeed, size of black sea bass, scamp grouper, and gag grouper has been demonstrably truncated in areas subject to high fishing density in GRNMS (Kendall et al. 2008) and fishing has historically occurred across the sanctuary although over a range of densities related to density of ledge habitats (Bauer et al. 2008). Understanding current and future patterns of fishing and vessel use, linked to variation in ecological metrics from seafloor habitats, is needed to make optimal use of the results of comparisons between closed and open areas and to demonstrate that zoning boundaries match the reality of human pressures on the water.

The results from project reports presented here also point to potential synergies for future work. For example, dynamics and long-term changes in water temperature and acidity can produce stress in organisms (e.g., reduced feeding and related negative bioenergetic responses) and affect population processes (survivorship, growth, reproduction). Early detection of changes based on biochemical indicators and telemetry studies of behavior, linked to acute and chronic events, could yield insights into regional scale processes affecting natural resources in GRNMS (e.g., Metcalfe et al. 2012, Cooke et al. 2014). Increasing the temporal resolution of field observations linked across trophic guilds and major taxa could increase understanding of links between local and regional scale patterns of connectivity, recruitment, survival, growth, and reproduction of key species, and quantify the scope of species-interactions (predation, competition, mutualisms, commensalisms, parasitisms) that mediate local abundance (e.g., Houde 2008, Sale et al. 2005).

In conclusion, the project narratives presented here demonstrate that the RA is providing a useful and important function and is being used to inform GRNMS of the status and dynamics of the natural resources for which it has a stewardship role and identify related management issues (e.g., improvement of visitor use data). However, much work remains to both expand the scope of our understanding of status and change in reef habitats as well as expanding to low relief live-bottom and sand habitats within the sanctuary. Hopefully future reports will summarize and synthesize the results of this expansive research.

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Glossary of Acronyms

ADCP – Acoustic Doppler current profiler
ANOSIM – Analysis of similarities
ANOVA – Analysis of variance
AUV – Autonomous underwater vehicle
CDOM – Colored dissolved organic matter
CFZ – Coastal front zone
CPCe – Coral Point Count with Excel Extensions
CPUE – Catch per unit effort
CTD – Conductivity, temperature, depth device
CV – Coefficient of variation
DIN – Days between first and last detection
DNR – Department of Natural Resources
DOC – Department of Commerce
EIS - Environmental impact statement
FEIS – Final environmental impact statement
FGDC – Federal Geographic Data Committee
GIS – Geographic information system
GLM – Generalized linear model
GRNMS – Gray's Reef National Marine Sanctuary
IMC – Index of mean crowding
K–W – Kruskal-Wallis
MARMAP – Marine Resources Monitoring, Assessment, and Prediction program
MCP – Minimum convex polygon
MDS – Multi-dimensional scaling
MPA – Marine protected area
MPAFAC – Marine Protected Area Federal Advisory Committee
NDBC – National Data Buoy Center
NMFS – National Marine Fisheries Service
NMS – National Marine Sanctuary
NMSA – National Marine Sanctuaries Act
NMSP – National Marine Sanctuary Program
NOAA – National Oceanic and Atmospheric Administration
OCS – Outer continental shelf
ONMS – Office of National Marine Sanctuaries
pCO2 – CO_2 partial pressure
PCR – Polymerase chain reaction
RA – Research Area
RAWG – Research Area Working Group
R/V – Research Vessel
SAB – South Atlantic Bight
SAC – Sanctuary Advisory Council

SAFMC – South Atlantic Fishery Management Council
SCDNR – South Carolina Department of Natural Resources
SD – Standard deviation
SEAMAP-SA – Southeast Area Monitoring and Assessment Program – South Atlantic
SEFIS – Southeast Fishery-Independent Survey
SERFS – Southeast Reef Fish Survey
SIMPER – Similarity percentage analysis
SIPS – Strain-induced periodic stratification
SkIO – Skidaway Institute of Oceanography
SNR – Signal to noise ratio
TDOA – Time difference of arrival
TL – Total length
TS – Target strength
UVC – Underwater visual census
YOY – Young of year

NATIONAL MARINE
SANCTUARIES

AMERICA'S UNDERWATER TREASURES