GULF OF MEXICO FISHERY MANAGEMENT COUNCIL

FINAL REPORT

ADMINISTRATIVE COOPERATIVE AGREEMENT NA10NMF4410059

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Title of Project: High-resolution Multibeam Bathymetry and Backscatter Investigation of the Edges, Northwest of Steamboat Lumps, Gulf of Mexico

Project Summary: The intent of this study was to map and evaluate an area of essential fish habitat in the northeastern Gulf of Mexico northwest of the Steamboat Lumps MPA known as The Edges Marine Protected Area (MPA) and within fish habitat areas of the West Florida Shelf identified by a passive sonar array (coordinated by Dr. David Mann and his students in collaboration and consultation with the Andrew David of the NOAA Panama City Lab). The new high resolution (70-100 kHz) KSI EM710 multibeam bathymetry and backscatter maps have been saved in numerous formats for future usage including Geographic Information Systems (GIS) applications. Due to equipment malfunction, we were unable to supplement these data with additional 200 kHz multibeam data near the "Edges" but were able to obtain such data closer to Panama City Beach as part of another project out to 100 m water depth. Furthermore, we had preexisting 300 kHz multibeam data from the Steamboat Lumps area which we have worked up into two separate publications (Allee et al., 2011 and Wall et al., 2011 – Appendix A and B). A third and final manuscript is in preparation by Ross et al., which makes use of the high-resolution (70-100 kHz) KSI EM 710 data we collected from our transit from Key West to Pascagoula MS, identifying Deep Coral areas along the west Shelf of Florida. All these data (raw, processed, and final images) are provided in the separate "GoFlex" USB disk drive for easy access and portability.

Introduction

In addition to managing fish stocks, the Gulf of Mexico Fishery Management Council has specific mandates to protect essential fish habitat (EFH) and to manage the coral and coral reef resources of the region. While the definition of EFH is broad, it is clear in the Gulf Council's EFH Amendment (GMFCM 1998) that habitat critical to the productivity of economically important species and habitat that contains coral warrant special attention. Thus, the Council has expressed a particular interest in an area in the eastern Gulf known as The Edges (Figure 1). This area contains a relatively high relief as shown in our initial surveys funded by NOAA (Figure 2). We mapped this area using our Kongsberg Simrad EM 3000 300 kHz multibeam and backscatter system, the same one that we used to fully map the Florida Middle Ground MPA for the Gulf Council. The Florida Middle Ground MPA has both stony and coral and octocorals, representing one of the northernmost coral communities in the U.S, just to the east of The Edges MPA.

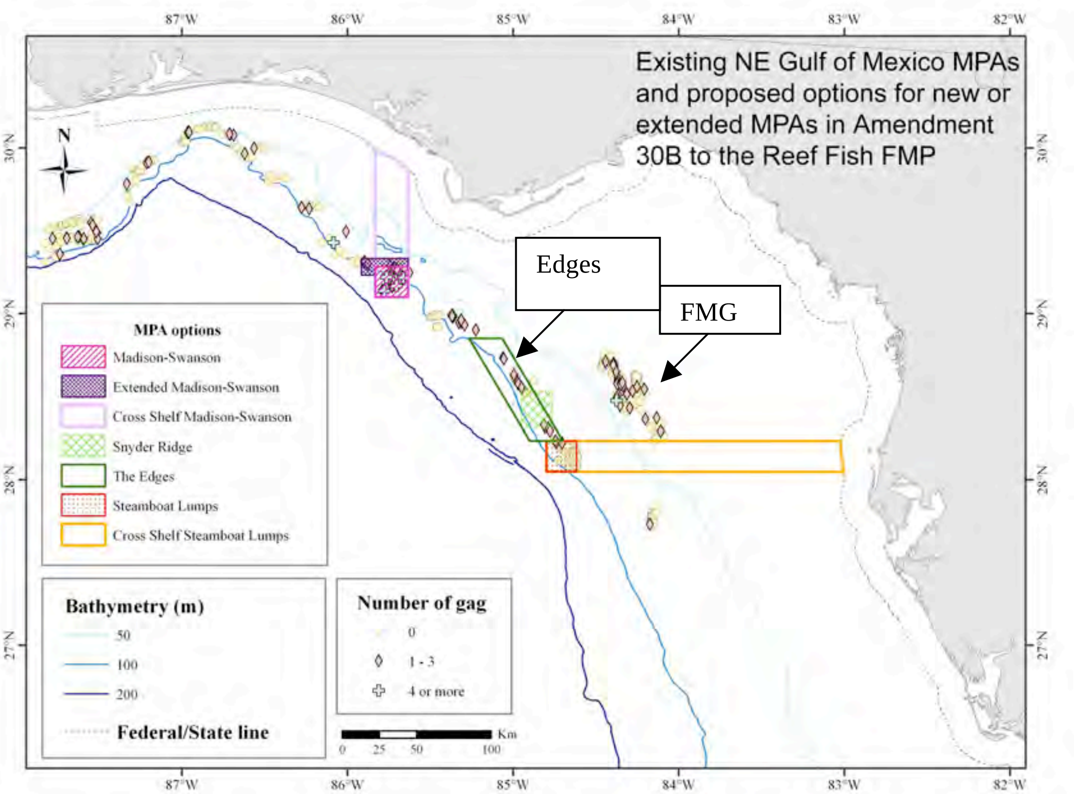

Figure 1. Location map of "The Edges" MPA (in green parallelogram), which has been partially mapped using the USF EM 3000 multibeam bathymetry and backscatter system (Figure 2). See Figure 3 for video stills of coral existing within The Edges area.

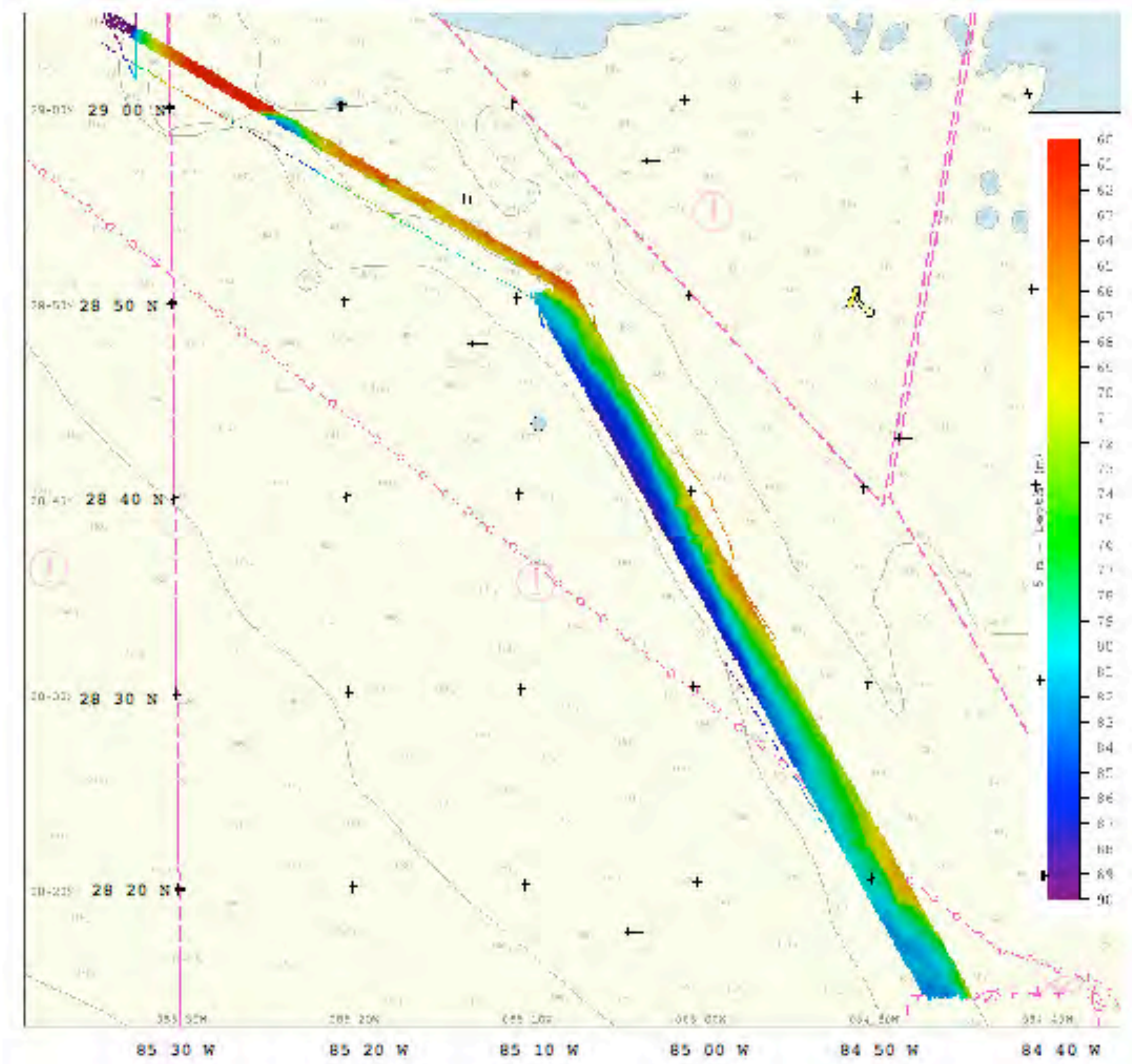

Figure 2. Area previously mapped using the USF EM 3000 (300 kHz) multibeam bathymetry and backscatter system within "The Edges" MPA, which lies within these four coordinates, NW: 28 51, N 85 16 W; NE: 28 51 N, 84 04 W; SE 28 14 N, 84 42 W; SW: 28 14 N, 84 54 W. The depth scale ranges from 60 (red) to 90 (purple) meters. We propose to build off this survey into shallower water, where the full swath and detail of the EM 3000 will be best used. See Figures 3 and 4 for examples of coral found within this mapped area.

Detailed multibeam bathymetry and backscatter maps of the seafloor is fundamental to the study and management of living natural resources. In the marine environment, the collection of systematic acoustic bathymetry and imagery maps has just begun (e.g., Wright et al., 2002). This mapping is critical in areas like The Edges because of its offshore depth range from ~50 m to ~ 90 m which is assumed to be important habitat for a number of economically important reef fish species (Koenig et al.

2000) and the existence of both photosynthetic corals as well as deeper filter feeding corals as observed further south in deeper waters of the Pulley Ridge area we have also mapped (Jarrett et al., 2005). In addition, these areas are likely to experience heavier fishing pressure, as shallower areas become depleted, and increased oil and gas exploration for new energy sources occurs. Most of these areas in the Gulf of Mexico lack adequate descriptions of the benthic geomorphology, the basis on which habitat maps should be developed. Examples of the corals so far observed in this area are shown in Figure 3 from a NOAA cruise in April 2008 we participated on.

Methods

We mapped, concentrating in high relief areas, and using the Kongsberg Simrad EM 710 multibeam bathymetry and backscatter system, using the area mapped in Figure 2 as are starting point. Our intent here is to classify, map, and structurally characterize the geomorphology of the area. We plan to further characterize the subbottom and geological history of this unique paleoshoreline and existing reef system, which would also include ROV video observations as they become available via ongoing efforts by Andrew David and others funded separately by NOAA. We provide Arc File format output for GIS use in the ESRI software packages, which have been successfully used by Andrew David and his colleagues in rapid follow up ground truth studies. We also have a 3-D viewer of the multibeam bathymetry data that comes with the 3-D data files to enable various perspective views of the bathymetry. The multibeam bathymetry and backscatter data will allow us to:

(1) map and classify major geomorphologic features of The Edges
(2) define major geomorphologic features; such as pinnacles, ridges, low relief hard bottom, and sediment cover
(3) describe the basic surficial geology using a ground-truth data that is or will become available under other follow up surveys.

Operational Considerations

Performance of tasks.--This study requires the combined efforts of the University of South Florida and NOAA Fisheries at the Panama City Lab. Geologists at the University of South Florida will interpret the acoustic imagery and classify geomorphological features. They will work with scientists at NOAA to relate the geomorphological units to benthic characterizations using the ground truth data from them. The investigators will develop and enter map products into an ESRI GIS framework.

*How this fits into jurisdiction's strategy.--*The Gulf of Mexico Fishery Management Council has a specific mandate to protect essential fish habitat (EFH). While the definition of such habitat is broad, it is clear in the Gulf Council's EFH Amendment (GMFCM 1998) that habitat critical to the productivity of economically important species and habitat that contains coral warrant special attention. Thus, the Council has expressed a particular interest in the unique coral formations of The Edges.

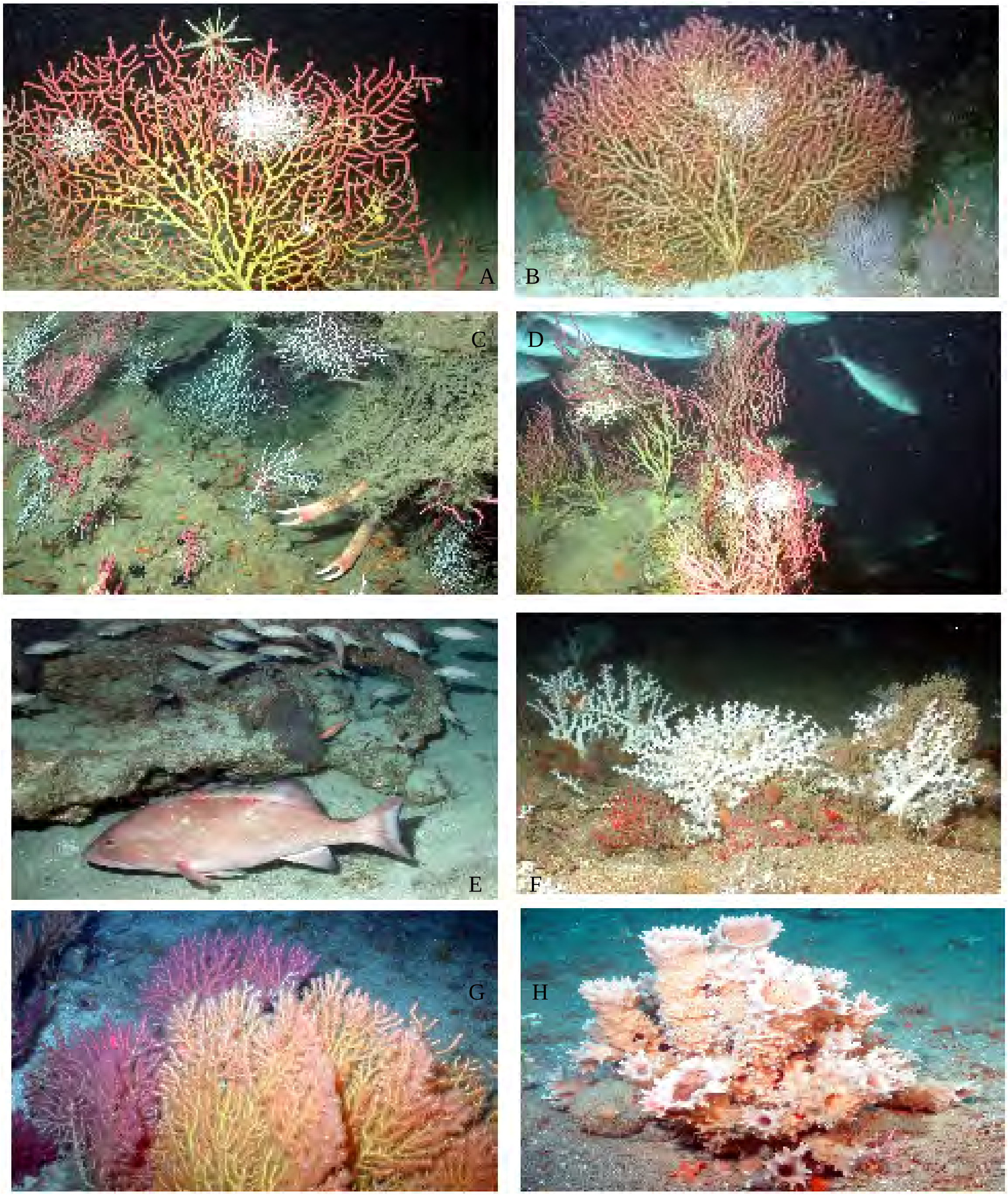

Figure 3. ROV Video stills from April 2008 in The Edges area. Red laser dots, where visible represent 10 cm. Preliminary identifications are as follows: A) Gorgonian with white basket stars (also filter feeders) and a pencil urchin at the top B) Another gorgonian octocoral C) Gorgonians with a spider crab behind the tan one D) More gorgonians and basket stars, there is an encrusting sponge or tunicate on some of the larger stalks (these are also filter feeders), the fish are amberjack E) Red grouper with several tomtates (light colored with thin head-to-tail stripes), a yellow tail reef fish (just above small hole in rock over the grouper's shoulder), a squirrel fish (behind gorgonian and above the grouper, just behind dorsal fin) and a couple of rough tongue bass (above grouper's tail, below tomtates, light colored with orange spot in middle of body). F) small red branching guy (lower left) is a gorgonian, the red encrusting organism (lower middle) is coralline algae. White creatures are zig-zag azooxanthellate scleractinian coral (Madrepora oculata) . G) color morphs of gorgonian octocorals. H) Sponge.

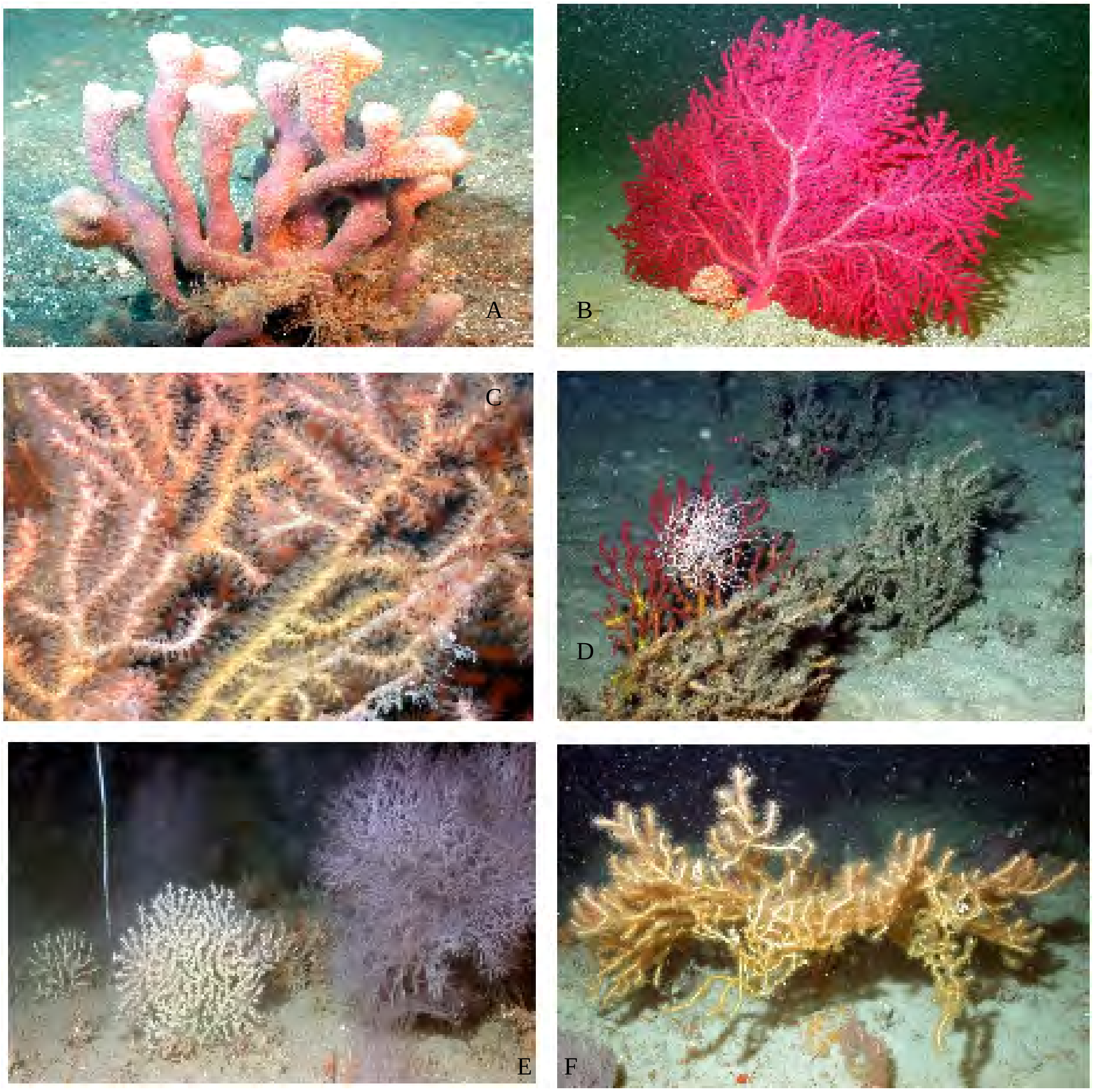

Figure 4. Additional images from Edges ROV cruise. Red dots, where visible, represent 10 cm. A) Sponge. B) Gorgonian. C) Close up of gorgonian polyps, filter feeding tentacles can be seen. D) The red and tan creatures to the left and in background are gorgonians, there is a white basket star on one. The thin white whip-like creature to the right is a black coral (the skeleton is black, the animal's tissue is white). E) the white corals are gorgonians, the purple is either another gorgonian or a bryozoan. F) Another gorgonian.

How this coordinates with relevant local government and non governmental agencies.
The principal investigators on this project routinely give talks to state and federal natural resource managers, to peers at scientific meetings, and to environmental groups. They also provide radio and television interviews as part of their interest in outreach to the community. We have worked closely with the Gulf of Mexico Fishery Management

Council, the Florida Fish and Wildlife Conservation Commission, and such non-governmental agencies as The National Geographic Society and the Environmental Defense. These organizations make a considerable contribution to research through their outreach components, acting as liaisons between our research group and the public. The intent of their cooperation is to raise an awareness of fishery and ocean ecology among the public, Gulf region fishery managers and regulators, and the fishing industry so that marine resources can be better managed to provide benefits now and in the future. Information will reach the public through these venues as well as through websites maintained by the principal investigators. We will present results to the Gulf of Mexico Fishery Management Councils and other fishery managers and fishing industry groups. Finally, results will be published in peer-review journals.

<u>REVISED (X) Task timetable with interim benchmarks (2010-2011)</u>

Objectives	10	11	12	1	2	3	4	5	6	7	8	9
Cruise Preparation, Bathymetry and	x											
Ground Truth Data Mining, and Data				x	x	x	x					
Integration,												
Multibeam Mapping (bathy, backscat)		x	x			X	X					
Data processing and analysis			x	x	x	x	x	x	x	x	x	
Progress Reports and Manuscripts										x	x	x

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Appendix A

Two Shelf Edge Marine Protected Areas in the Eastern Gulf of Mexico

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Abstract:

The Madison-Swanson Marine Protected Area is located off the Florida coast in the Gulf of Mexico at the margin of the continental shelf and slope in 60 to 140 m of water. Prominent within Madison-Swanson is a limestone ridge, thought to be the remnant of a 14,000+ year-old coral reef. The Pulley Ridge Habitat Area of Particular Concern is a 100+ km-long series of N-S trending, drowned, barrier islands on the southwest Florida Shelf. It appears to be formed on top of an ancient coastal barrier island or strand line during a period when sea levels were ~ 65 to 80 m lower and is believed to be the deepest hermatypic coral reef on the continental shelf of the United States. The depth ranges from ~ 55 m near the eastern edge of Pulley Ridge down to about 115 m on the western edge. Fisheries studies of Madison-Swanson indicate that *Mycteroperca* spp. (grouper) and *Lutjanus campechanus* (red snapper) are associated with hard bottom features, with spawning aggregations of *M. microlepis* (gag) and/or *M. phenax* (scamp) confirmed at several sites. Canonical Correspondence Analyses (CCA) conducted on fish and habitat data from Madison-Swanson indicated gag are most closely associated with relict coral reefs and to a lesser degree with greater depth and higher relief while red snapper had a higher correlation with soft corals. Remotely Operated Vehicle (ROV) observations were used to associate fish species with habitat types for Pulley Ridge. The loose rubble found in Pulley Ridge was conducive for *Epinephelus morio* (red grouper) to excavate pits in the sediment and they were the most abundant large grouper species in that area.

Key Words

Drowned Barrier Islands, Hermatypic Corals, Mounds, Paleoreef, Paleoshoreline, Ridges, Pinnacles, Grouper, *Mycteroperca*, Spawning aggregation

Introduction:

The Madison-Swanson Marine Protected Area (MPA) and Pulley Ridge Habitat Area of Particular Concern (HAPC), two protected areas off the Florida shelf in the eastern Gulf of Mexico (Fig. 1), were established by the

Gulf of Mexico Fishery Management Council and the U.S. National Oceanic and Atmospheric Administration to protect benthos-associated organisms. However, the types of organisms and the reasons for the protection are quite different (1, 2). Madison-Swanson is used by an economically valuable reef fish species, the gag grouper, as a spawning ground (3, 4). Pulley Ridge contains the deepest hermatypic scleractinian coral colonies in the continental United States (5, 6). Madison-Swanson was closed to most fishing activity in 2000 to improve reproductive output and subsequently stock size of the grouper, which in turn was hoped to produce financial benefits to the fishery. Pulley Ridge was closed to most fishing activity in 2005 to maintain the biodiversity associated with the coral formations.

Madison-Swanson is a 394 km^2 area located ~60 km southwest of Cape San Blas, Florida, at the margin of the continental shelf and slope in 60 to 140 m of water and is a site of spawning aggregations of gag (*Mycteroperca microlepis*) and other reef fish species (4). High-resolution seismic stratigraphy (7) and 300 kHz multibeam data (8) show that the Madison-Swanson MPA is a drowned river delta that is estimated to have formed between 58,000 and 28,000 years ago (9). Prominent within Madison-Swanson is a continuous ~13 km long curved ridge ~ 6 m tall and ~ 80 m wide in ~ 80 m of water depth (Fig. 2) interpreted by Gardner et al. (9) to be a barrier island that formed contemporaneously with the delta, but then was preserved with the onset of rapid sea level rise ~14,000 years ago. An upwelling current flows perpendicularly to the long axis of the feature and has undermined the sand at its base creating a trench along the offshore face. This current has undercut the rock structure to a sufficient degree that numerous large boulders have calved off the offshore face and now lie in the trench. This boulder field, and the ridge itself, form the type of highly rugose habitat preferred by gag. Pulley Ridge (Fig. 3) is a 100+ km-long series of N-S trending, drowned barrier islands on the southwest Florida shelf ~ 250 km west of Cape Sable, Florida.
It appears to be formed on top of an ancient coastal barrier island or strand line dating back approximately 14,000 years before present when sea level was ~ 65 to 80 m lower (5). Presently, Pulley Ridge periodically underlies the Loop Current, which feeds into the Gulf Stream western boundary current. The Loop Current brings warm, nutrient-rich waters that are clear enough to allow 1-2 % of sunlight to reach the ~ 65 m water depth (5). Biological assessments of these protected areas were carried out in generally similar fashions; initial mapping with multibeam sonar followed by targeted observations with remote still and video cameras.

Geomorphic features and habitats:

The formation of the Florida carbonate platform began when North America and Africa rifted apart during the opening of the Atlantic Ocean. This occurred approximately during the late Triassic to early Jurassic (~ 200 Ma) (10; and references therein). This rifting caused substantial faulting and subsidence of the original continental crust, and the formation of shallow seas, coral reefs, and the deposition of relatively flat layers of carbonate sediment, approximately 1 to 5 km thick, primarily composed of limestone over the original crystalline basement forming the majority of the Florida carbonate platform. The depositional history, however, was complicated during this long interval, because of the repeated rises and falls of sea level during glacial events and terrestrial (siliclastic) sediment transport from the north. The most recent rise in sea level occurred after the last deglaciation (~14 Ka), and evidence of this rapid sea level transgression has been observed in the preservation of several paleoshorelines at the approximate depths of 65, 70, and 80 m in the Pulley Ridge area (5, 6) and Madison-Swanson area (9), which correlate well with similar depths near the Marquesas Keys along the southern edge of the Florida platform (11). Initial data collection was aboard the R/V Suncoaster operated by the Florida Institute of Oceanography. The sonar head was fixed on a secure pole mount, with metal brackets and metal stays to insure maximum rigidity. Seafloor patch tests were conducted before and after the cruise, using the KSI acquisition and post-processing software. An Applanix POS/MV (Version 3.0) was used to measure ship attitude (heading, roll, pitch and heave) and position and velocity. Additional post-processing has been applied to the data using CARIS HIPS software. A real-time surface sound velocity sensor was used to measure variations of the surface waters, as well as routine CTD casts.

Mounds

The Mounds is a relatively small area of exposed relict coral in the central portion of the Madison-Swanson MPA (Fig. 2). There are no dramatic bathymetric changes in the vicinity of this feature and the vertical relief of the carbonate outcrops can be as high as 3 m. The exposed margin of the feature is ephemeral as currents and large storm events bury and uncover rock with the surrounding unconsolidated small grain sand, clay, and silt. Despite its small size, the Mounds is very biologically rich with large numbers of reef fishes and invertebrates.

Pinnacles

The Pinnacles of Madison-Swanson is a relict coral reef with relief approaching 10 m. Depth increases drastically beyond the offshore face while the inshore face transitions smoothly into a sandy substrate. This area has the high rugosity associated with living coral reefs and supports high abundance of octocorals, sponges, nonhermatypic corals and other encrusting invertebrates.

Pockmarks

EM 3000 multibeam sonar has detected very circular but low relief (<1 m) pits or depressions that range from 5 to 15 m in diameter in both areas and most everywhere in between during transits over smooth sediments in water depths of about ~ 80 m (+/- ~ 20 m). This abundance of pockmarks or circular depressions has been noted and documented by others using both side-scan sonar and multibeam data. Video data (12) document that these pits are created by red grouper.

Ridge

Madison-Swanson

This prominent feature within Madison-Swanson is a continuous ~13 km long curved ridge ~ 6 m tall and ~ 80 m wide in ~ 80 m of water depth (Fig. 2). There are also shorter and smaller ridges, some of which have been classified as small, partially buried calcareous pinnacles; however, the majority of the major ridge appears to be an aggregate reef (D. Palandro, pers. comm.) and is interpreted to have formed on top of the remnants of drowned barrier islands (9, 11). The Ridge is an area of high relief, as much as 10 m in some areas.

Pulley Ridge

The southern edge of Pulley Ridge marks the very edge of the southern part of the Florida carbonate platform where the depth drops down to 150 m in a short distance (Fig. 3). The Ridge itself reflects drowned barrier island morphology at depths of ~80, ~70, ~ 65 m. Smaller ridge-like features are interpreted to be re-curved spits as seen on present day barrier islands and cuspate forelands (relict inlets, ridges, and/or marsh/lagoon areas). The extensive crosscutting N-S and E-W preserved bed form structures in Pulley Ridge were most likely formed and then modified by the rapid fluctuations in sea level described earlier.

Sediments

Madison-Swanson MPA consists of drowned, karst, hard bottom, rocky outcrops several kilometers in length, and variable thickness of fine-grained and apparently mobile coarse-grained sediments. Pulley Ridge hosts linear coral reefs that reside on drowned barrier reefs but with less sediment over the limestone basement.

Trough

Lying between the curved ridges of Madison-Swanson in about 60 m water, extending at least 10 km is a ~ 8 m deep trough (Fig. 2). The ~ 2 km gap between the two curved ridges appears to be covered by the sediment of the drowned delta rising 40 m above the limestone basement (9).

Biological communities:

The principal biological interest in Madison-Swanson was a large and mobile apex predator while in Pulley Ridge it was a sessile invertebrate (Fig. 4). The mobility, or lack thereof, of these biological targets shaped the biological assessment strategies. In Madison-Swanson the initial effort was complete multibeam bathymetric and backscatter mapping. These maps were used to stratify the entire reserve into seven regions. The bathymetry was used to segregate the high relief areas while the backscatter data were used to differentiate low relief areas with different sediment types. ROV video transects were surveyed to confirm the habitat types within each strata. ROVs were a poor choice for the fishery assessment however. The lights, noise and movement of ROVs alter fish behavior, attracting some species and repelling others. Gag grouper are not as inquisitive as other grouper species and tend to flee upon the approach of an ROV. Therefore stationary camera arrays, using only ambient light, were found to be the most effective tool to evaluate gag grouper populations. These were deployed in a stratified random fashion to produce statistically robust estimates of grouper abundance and distribution. Gag also migrate seasonally between winter spawning grounds on the outer continental shelf and midshelf foraging areas during the spring, summer and fall. For this reason all sampling had temporal stability with annual surveys beginning within a two week window in late January and concluding by mid-March.

The primary goal of the Pulley Ridge HAPC was to define the extent, health and abundance of scleractinian corals within and adjacent to the protected area; the secondary goal was to identify and quantify the fish assemblages present. Unlike Madison-Swanson, the biological targets on Pulley Ridge, stony corals, are immobile and thus the survey design was able to exploit the mobility of ROVs without concern for target avoidance. Seasonality was similarly not a concern, other than a general avoidance of periods with high hurricane or winter storm activity which would interfere with vessel operations. The persistent nature of the corals also allowed for another modification of the survey design used to the north at Madison-Swanson; mapping and biological assessments were conducted concurrently rather than consecutively. After one portion of the HAPC was mapped, ROV survey transects were selected and executed. The ROV results contributed to the selection of subsequent areas to be mapped. Once the mapping data from the new area was processed, further ROV transects were planned and completed.

A total of 544 stationary camera array drops were conducted in the Madison-Swanson MPA between 2001 and 2009 (Fig. 5). The stationary camera array utilized four orthogonally spaced cameras in a circular aluminum frame. Each camera had a 75° field of view resulting in a 15° gap in coverage between adjacent cameras and a total coverage of 300°. At each station the cameras were deployed for 30 min. A 20 min segment of the recorded video was later analyzed and all species identified to the lowest possible taxonomic level. Thirty three ROV dives were conducted between 2007 and 2009 in and adjacent to the Pulley Ridge HAPC (Fig. 6). Starting and ending positions for each dive were preselected and the support vessel moved along the transect at speeds between one and three km/hr. A downweight was used to stabilize the ROV umbilical against the prevailing currents while a 30 m ‘leash’ below the weight allowed a significant range to investigate targets to either side of the planned transect. The survey protocol involved continuous video recording with downward looking digital still photographs taken every two minutes. The video was used to identify all vertebrate and major invertebrate species as well as the gross habitat types. The still images were used to determine percent cover of species, species groups, and benthos types. A distinct difference in habitat types existed inside and outside the HAPC. Sites to the north of the HAPC as well as some dives to the west of the HAPC primarily supported a heterotrophic octocoral-dominated community lacking the reefal accumulation which is characteristic inside the HAPC. Habitats within the HAPC as well as some dives to the west of the HAPC were consistently similar, but drastically different from the other sites. The habitat in this area was characterized as rock rubble with varying coverage of algae, coralline algae, hermatypic corals, solitary and encrusting sponges, octocorals, and antipatharians. Sand tilefish (*Malacanthus plumieri*) mounds and red grouper (*Epinephelus morio*) pits were common in this area.

The Pulley Ridge HAPC was characterized as having anywhere from 70-100% rock rubble covered in varying degrees with encrusting organisms providing some vertical relief. Coral species observed included *Agaricia undata, Agaricia lamarcki, Montastraea cavernosa*, and *Leptoseris cucullata*. We observed *Agaricia* spp. only on rock rubble habitat inside the HAPC and a single observation on a single dive to the west of the HAPC. In the areas it exists, *Agaricia* can be quite abundant as we had several ROV transect with over 100 colonies sighted. *Agaricia* was found in depths between 61 and 89 m with plates of coral ranging in diameter between 5 and 30 cm. One interesting observation was the abundance of dead *Agaricia*. It was common to see plates of coral which contained significant areas of dead tissue, however no stressed or bleached corals were seen. Corals appeared to be either healthy or dead. Overall, 106 species of fishes have been identified within Madison-Swanson and 73 within Pulley Ridge.

These values must be evaluated in the context of the total effort and methods employed. Nearly 550 camera deployments were made in Madison-Swanson compared to 33 ROV dives in Pulley Ridge. Also it was previously noted the camera array is less disturbing to fish than the ROV. It is highly likely a greater number of species are present in Pulley Ridge than in Madison-Swanson. In Madison-Swanson gag were present at 45% of all sites surveyed. Other economically valuable species were seen at similar levels: scamp at 65%; red snapper (*Lutjanus campechanus*) at 48%; and red grouper at 38%. In Pulley Ridge, the rock rubble habitat (the only habitat found in the HAPC) had the highest fish diversity with 51 different species. Some fish species were observed in all habitat types such as: tattlers (*Serranus phoebe*); reef butterflyfish (*Chaetodon sedentarius*); and yellowtail reeffish (*Chromis enchrysurus*). Some species were observed exclusively over rock rubble such as: cherubfish (*Centropyge argi)*; blue chromis (*Chromis cyaneus*); yellowtail damselfish (*Microspathodon chrysurus*); bicolor damselfish (*Chromis partitus*); yellowhead wrasse (*Halichoeres garnoti*); parrotfish (*Sparisoma* spp.); blue tang (*Acanthurus coeruleus*); and yellowhead jawfish (*Opistognathus aurifrons*).

Surrogacy:

A series of Canonical Correspondence Analyses (CCA) were conducted on fish and habitat data from Madison-Swanson. CCA of fish species and habitat indicated gag are most closely associated with relict coral reefs and to a lesser degree with greater depth and higher relief (Fig. 7), red snapper had a higher correlation with soft corals. The analysis of habitat and strata revealed the Pinnacles was associated with increasing depth and coral density, the Mounds was associated with increasing depth and the Ridge was associated with greater sponge, seawhip and soft coral density. Species and strata associations indicated gag most correlated with the Pinnacles and red snapper with the Ridge.

A total of 131 grouper were observed on the ROV dives in Pulley Ridge in 2009; 51 grouper were observed over pavement, 40 over moderate relief outcrops, 28 over low relief outcrops, and 10 over rock rubble (Fig. 8). Even though grouper abundances were not high on rock rubble, diversity of grouper species was the highest on this habitat type along with moderate relief outcrops. The loose rubble in the HAPC was conducive for red grouper to excavate pits in the sediment and they were the most abundant grouper species in that area, however, scamp was the most frequently observed grouper outside the HAPC. Rock hind (*Epinephelus adscensionis*) and speckled hind (*Epinephelus drummondhayi*) were only found on moderate relief outcrops. Black grouper (*Mycteroperca bonaci*) were only observed on rock rubble.

ACKNOWLEDGEMENTS

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Ships Gordon Gunter, R/V Caretta, R/V Gandy, the NASA Ship M/V Freedom Star and the Florida Institute of Oceanography Ships R/V Suncoaster and R/V Weatherbird provided the research platforms for these efforts. ROV services were provided by NURC-UNCW and NURC-UConn and particular recognition is due to Lance Horn and Glenn Taylor of NURC-UNCW. Brian Donahue has played a leading role in all aspects of the USF EM 3000 multibeam mobilization, acquisition, data post-processing, figure preparation, and data dissemination. More than two dozen individuals from the NOAA Fisheries Laboratories in Panama City, FL and Pascagoula, MS and the University of South Florida in St. Petersburg, FL assisted with the collection, processing and analysis of data. A special thank you is given to David Palandro for his consultation on classifying these habitats.

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Figure Captions

Figure 1. The locations of the Madison-Swanson MPA and Pulley Ridge HAPC off the west coast of Florida, USA.

Figure 2. Color-shaded multibeam bathymetry (mostly 100 kHz except for 300 kHz in NE corner separated by diagonal gap). Illumination is from the SE at an elevation of 60 degrees with 10:1 vertical exaggeration. Following and adding to a previously published interpretation(9), the following geomorphology is identified: 'R' denotes ridges, 'S' denotes sedimentary back ridge area, 'M' denotes mounds, 'T' denotes trough, 'B' denotes bedforms of variable dimensions, and 'K' denotes karst-like geomorphology. The smooth (deeper) areas that exist outside the denoted area are likely to be of sedimentary origin.

Figure 3. Plan view of 300 kHz multibeam bathymetry over Pulley Ridge area. There are two primary drowned barrier island ridges (Pulley Ridge West and East) at a depth of ~80 and 65 m (the western most orange strip next to green and the eastern most red color identified by numbers 1 and 3). Number 2 represents an intermediate paleo-shoreline of about 70 m. Numbers 4, 5, 6, and 7 represent recurved spits in the north, crescent shoreline typical of barrier islands, cuspate foreland (relict inlets and ridges), and extensive cross-cutting N-S and E-W preserved bedform structures.

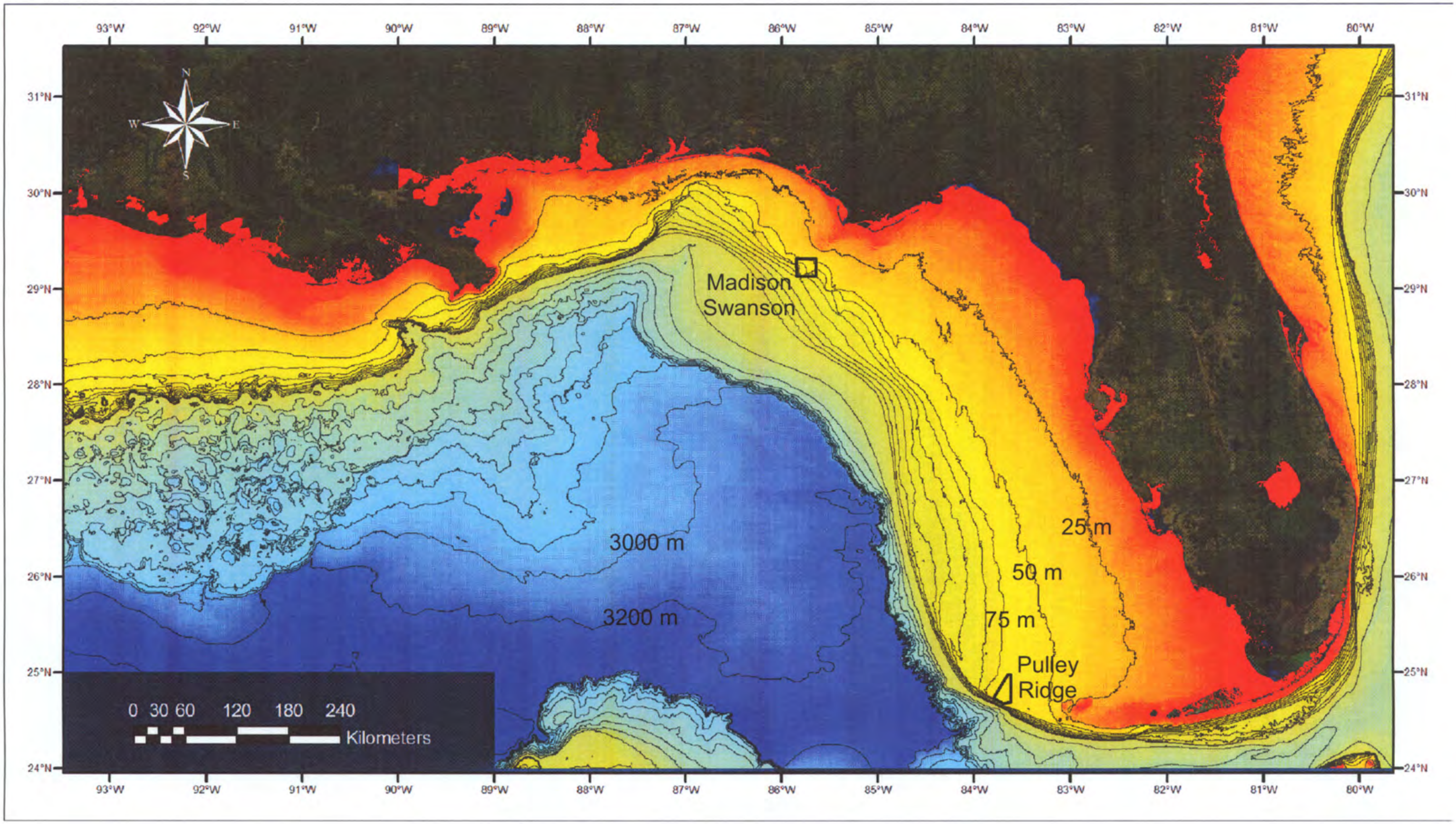
Figure 4. Coral habitats and associated fauna found in Pulley Ridge and Madison-Swanson. **A)** *Agaricia* sp. coral in the Pulley Ridge HAPC. The fish to the left is a rock beauty (*Holacanthus tricolor*). **B**) A sand tilefish (*Malacanthus plumieri*) mound in the Pulley Ridge HAPC. The mounds are created when the fish pile up loose rubble and normally have a single entrance at the base. The small fish above the mound is a yellowtail reeffish (*Chromis enchrysurus*). **C)** A gag grouper (*Mycteroperca microlepis*) in the Madison-Swanson MPA. The red dots are from a laser measuring system on the camera array and are 10 cm apart. **D)** A black grouper (*Mycteroperca bonaci*) in the Pulley Ridge HAPC. **E**) A dense stand of octocorals in the Pinnacles stratum in the Madison-Swanson MPA.

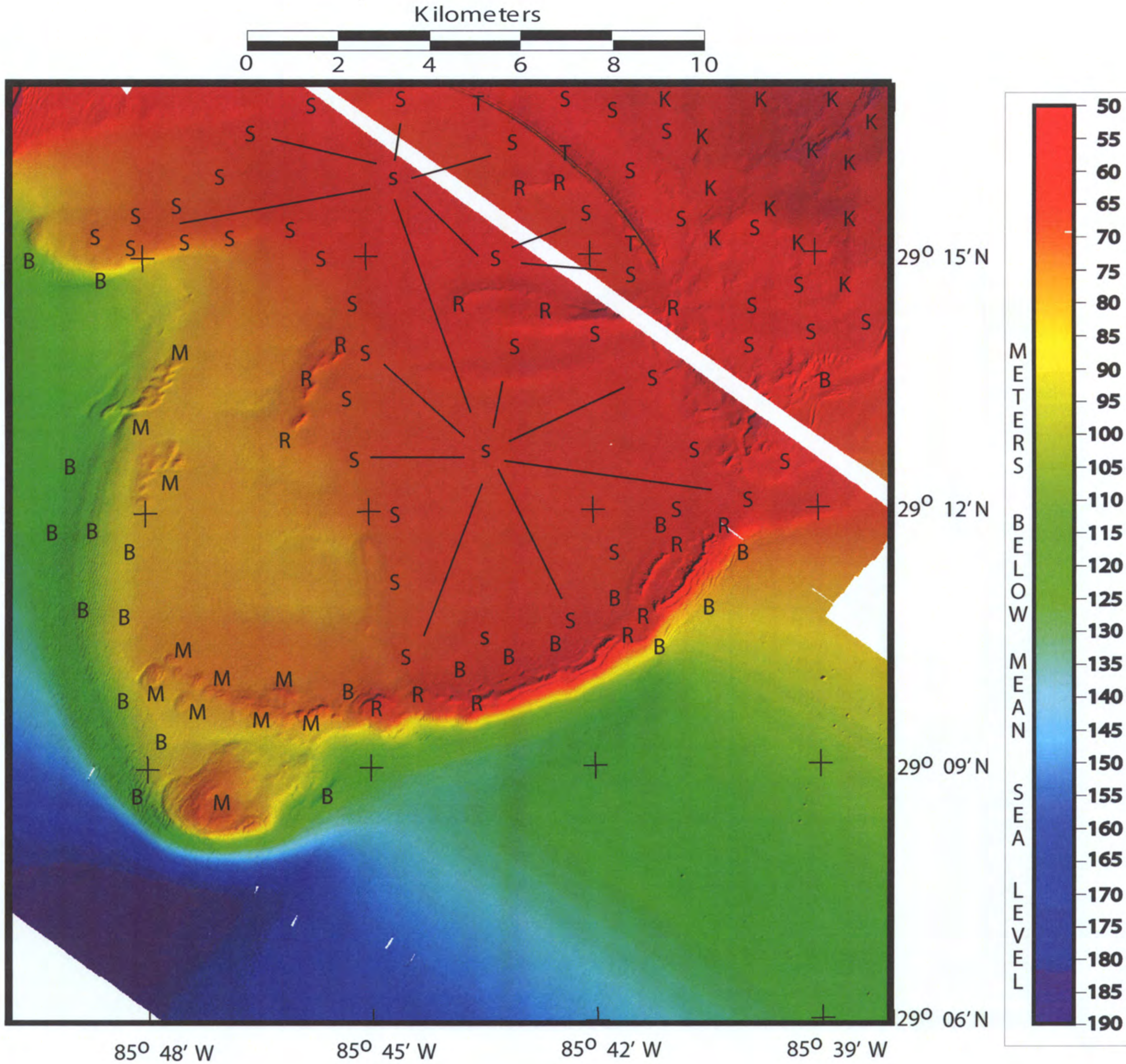
Figure 5. Stationary camera array deployment locations in the Madison-Swanson MPA. The Ridge is in the north, the Pinnacles is the high relief feature in the lower half of the MPA and the Mounds small feature west of the center of the area. Varying numbers of gag seen on each deployment are represented by different symbols and colors.

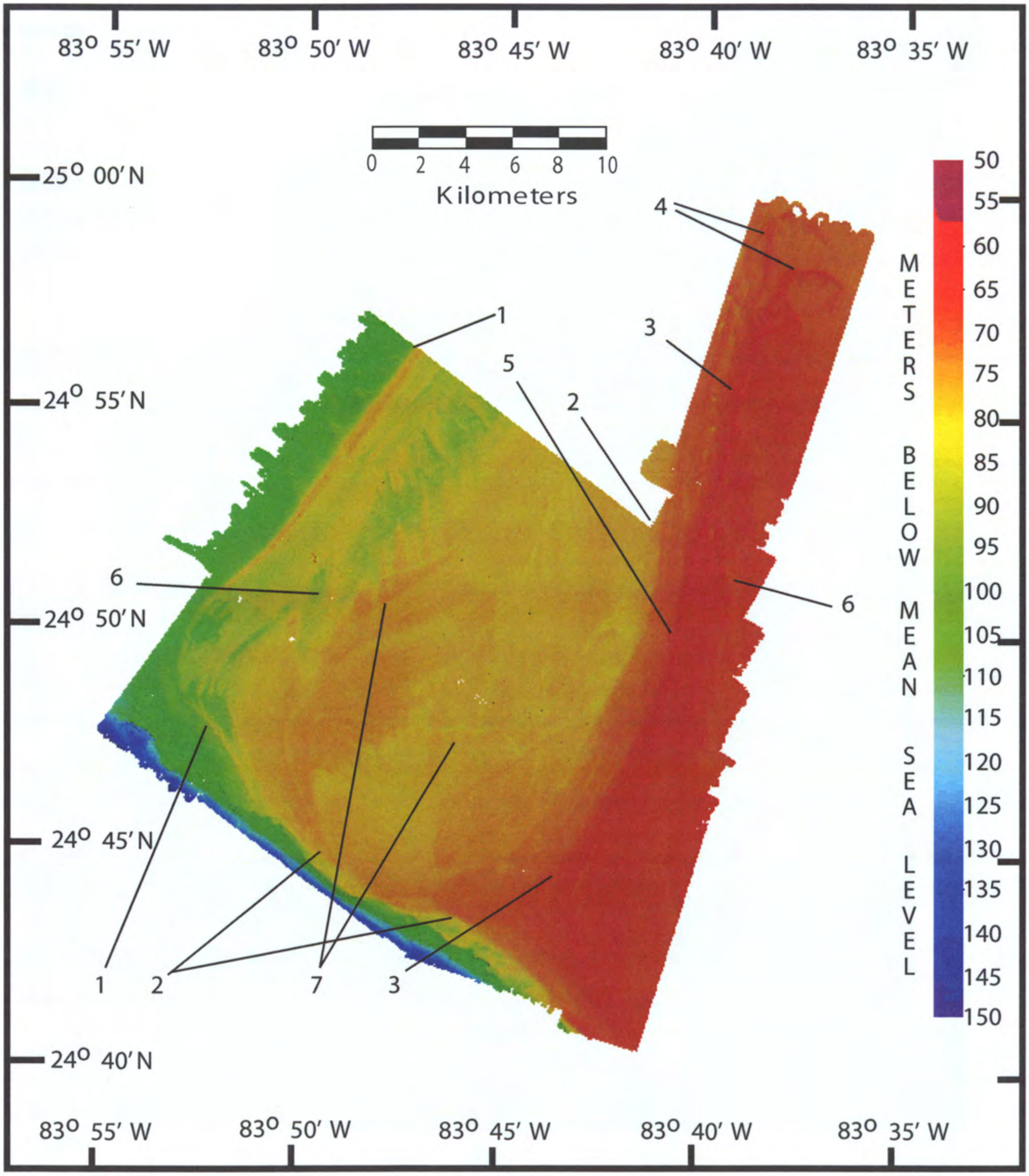
Figure 6. Multibeam bathymetry of the Pulley Ridge HAPC. ROV dive transects are represented by connected lines with different survey years shown in different colors. The HAPC boundary is indicated with the green line.

Figure 7. Canonical Correspondence Analysis of fish species and habitat in the Madison-Swanson MPA. Gag are most closely associated with relict coral reefs and to a lesser degree with greater depth and higher relief.

Figure 8. Grouper abundances by habitat type in the Pulley Ridge HAPC. LRO = low relief outcrops, MRO = moderate relief outcrop, PAV = pavement, and RR = rock rubble. No grouper were observed over sand. LRO, MRO, and PAV habitats were found outside the HAPC. RR was the only habitat observed in the HAPC. Unid grouper=unidentifiable grouper (not able to be identified down to species).


Madison
Swanson
Pulley
Ridge
25 m
50 m
75 m
3000 m
3200 m
0 30 60 120 180 240
Kilometers
N
S
E
W
93°W 92°W 91°W 90°W 89°W 88°W 87°W 86°W 85°W 84°W 83°W 82°W 81°W 80°W
31°N 30°N 29°N 28°N 27°N 26°N 25°N 24°N


Kilometers
0 2 4 6 8 10
29° 15′N
29° 12′N
29° 09′N
29° 06′N
85° 48′ W
85° 45′ W
85° 42′ W
85° 39′ W
METERS BELOW MEAN SEA LEVEL
50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190



83° 55′ W
83° 50′ W
83° 45′ W
83° 40′ W
83° 35′ W
25° 00′N
24° 55′N
24° 50′N
24° 45′N
24° 40′N
0 2 4 6 8 10
Kilometers
METERS BELOW MEAN SEA LEVEL
50
55
60
65
70
75
80
85
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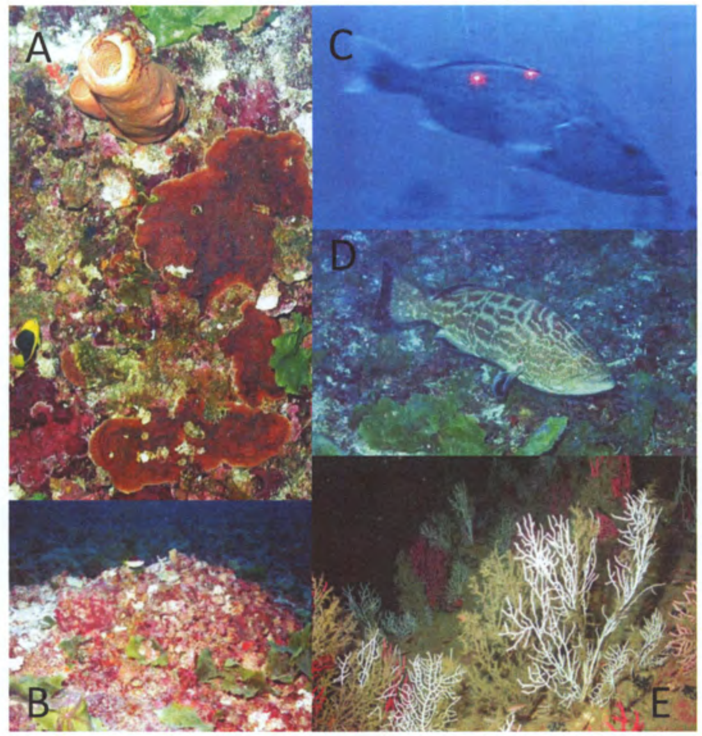
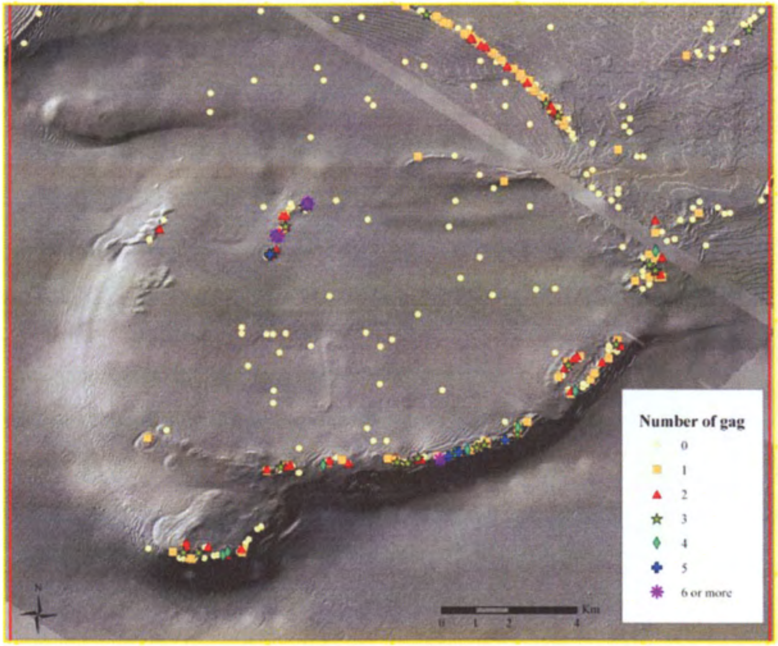
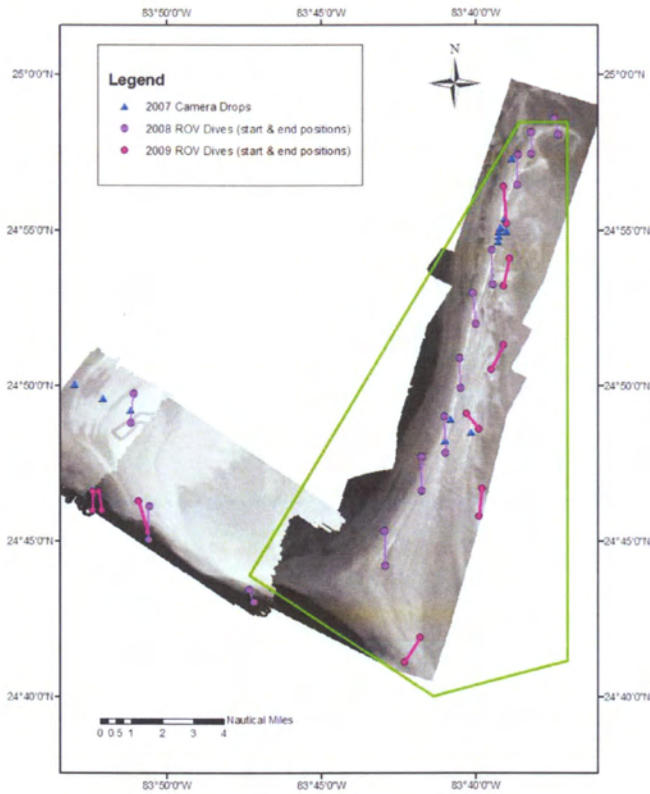
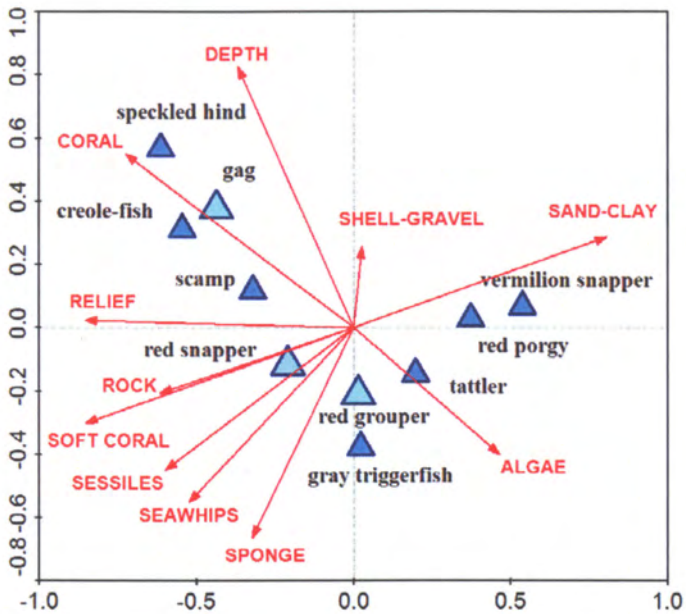
6
7


A
B
C
D
E

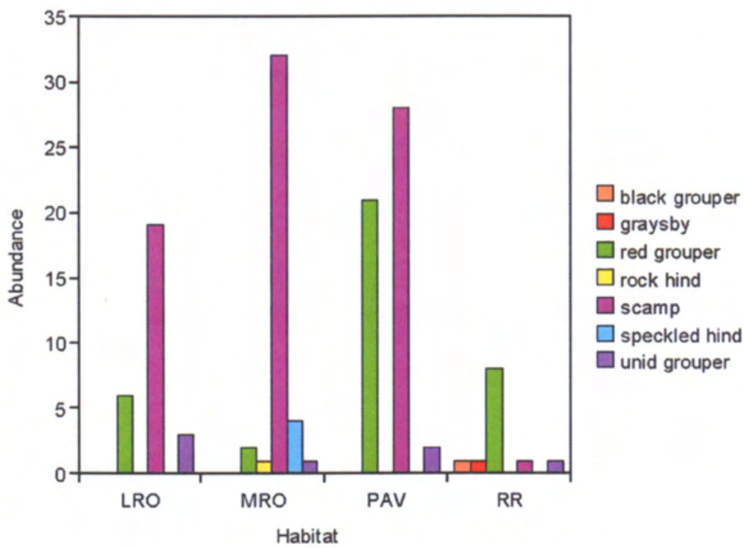


Number of gag
0
1
2
3
4
5
6 or more
N
Km
0
1
2
4


83°50'0"W
83°45'0"W
83°40'0"W
25°0'0"N
24°55'0"N
24°50'0"N
24°45'0"N
24°40'0"N
Legend
2007 Camera Drops
2008 ROV Dives (start & end positions)
2009 ROV Dives (start & end positions)
N
0 0.5 1 2 3 4
Nautical Miles



DEPTH
speckled hind
CORAL
gag
creole-fish
SHELL-GRAVEL
SAND-CLAY
scamp
vermilion snapper
RELIEF
red porgy
red snapper
ROCK
tattler
SOFT CORAL
red grouper
SESSILES
gray triggerfish
ALGAE
SEAWHIPS
SPONGE
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-0.5
0.0
0.5
1.0



35
30
25
20
15
10
5
0
Abundance
LRO
MRO
PAV
RR
Habitat
black grouper
graysby
red grouper
rock hind
scamp
speckled hind
unid grouper

Appendix B

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Spatial and temporal variability of red grouper holes within Steamboat Lumps Marine Reserve, Gulf of Mexico

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ABSTRACT: Red grouper *Epinephelus morio* act as ecosystem engineers by excavating depressions (or holes) in areas of flat sandy bottom, which provide suitable habitat for themselves and numerous other species. To understand the spatial extent of the holes, which serve as spawning habitat, and determine how that habitat changes, high-resolution multibeam sonar data were collected in overlapping areas in 2006 and 2009 within Steamboat Lumps Marine Reserve. This marine reserve was established in 2000 and is located in the eastern Gulf of Mexico. Vertical profiles of the holes visually identified from the multibeam data were extracted to characterize hole shape and determine changes in the height, width, and slope of each hole over time and space. Results from this analysis indicated an increase in hole density from 110 to 141 holes km^{-2} from 2006 to 2009, respectively, with 181 holes detected in 2006 and 231 holes detected in 2009. Height and slope also increased between 2006 and 2009. The shape changes present in the 151 holes identified in the same location between the 2 survey years suggest that while hole shape varies due to red grouper maintenance, holes are constructed and maintained over time. The communication network determined from calculating a 70 m limit to red grouper acoustic communication showed an increase in communication overlap from 2006 to 2009, with over 95% of holes located within 70 m of their nearest neighbor. The increase in number and density of holes from 2006 to 2009 demonstrates that multiyear habitat mapping using active acoustic sonar is an effective method to monitor the presence and extent of red grouper spawning populations.

KEY WORDS: Red grouper · *Epinephelus* · Multibeam sonar · Marine reserves · Holes · Habitat engineer · Gulf of Mexico

INTRODUCTION

Like all grouper species, red grouper *Epinephelus morio* are slow-growing, late-maturing, relatively stationary, and long lived fish. Red grouper are protogynous hermaphrodites that change sex from female to male between 5 and 10 yr of age (Moe 1969, Jory & Iversen 1989, Heemstra & Randall 1993, Musick 1999, Coleman et al. 2000, Sadovy 2001). These life history characteristics should make them vulnerable to overexploitation, especially in the Gulf of Mexico where a sizeable fishery exists. However, red grouper may be relatively resilient to fishing pressure because this species forms small polygamous spawning groups dispersed over large areas, unlike the large spawning aggregations typical in other grouper species (Coleman et al. 1996). Still, red grouper have experienced a truncated age structure and are currently considered Near Threatened by the International Union for Conservation of Nature (IUCN) (SEDAR 2009, Coleman & Koenig 2010, IUCN 2010).

Red grouper spawn offshore (~70 m depth) during the late winter to early spring for ~4 mo, with peaks in April and May (Jory & Iversen 1989, Koenig et al. 2000). During this time, females approach males, which exhibit high site fidelity to an area of the seabed known as their 'home territories' (Coleman et al. 2010). If a male then successfully courts a female, they ascend up into the water column to spawn.

Such offshore spawning habitat is likely to experience increased human disturbances as intense fishing in shallow areas drives fish population sizes down and

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fisheries move offshore (Koslow et al. 2000, Coleman & Koenig 2010). Thus, locating both mature fish populations and spawning habitats essential to population stability are critical considerations for fisheries management (Coleman et al. 1996, Crowder et al. 2000). To alleviate fishing pressure on grouper aggregations during spawning, 2 marine reserves covering 200 n miles^2 were established in June 2000 on the shelf break (50–120 m deep) of the northeastern Gulf of Mexico (Fig. 1): Madison Swanson (29° 06′ N to 29° 17′ N, 85° 38′ W to 85° 50′ W) and Steamboat Lumps (28° 03′ N to 28° 14′ N, 84° 37′ W to 84° 48′ W) Marine Reserves (Coleman et al. 2004).

Two important red grouper behaviors have been documented recently in these marine reserves: (1) sediment excavation (Scanlon et al. 2005, Coleman et al. 2010) and (2) sound production (Montie et al. 2011). In the present study, we focused on sediment excavation in Steamboat Lumps Marine Reserve and the potential for the 2-dimensional spacing of the holes to be within the known acoustic communication range of red grouper.

In continental shelf areas with a sedimentary bottom, red grouper excavate large (5 to 25 m diameter) depressions (or holes) that they use as home territories (Scanlon et al. 2005). Red grouper excavate by carrying mouthfuls of sediment from within a depression to a short distance away and then depositing the sediment by flushing it through their opercles (Scanlon et al. 2005, Coleman et al. 2010). In Steamboat Lumps Marine Reserve, holes are mainly observed to be dug and maintained by males who use this habitat as their home territory where they will spawn. Further inshore, juvenile (female) red grouper also exhibit this behavior (Coleman et al. 2010). Hole excavation is mainly found in areas where relief such as rock outcroppings is not present (Coleman et al. 2010). Excavation uncovers loose rocks such as cemented carbonate nodules, which provide an important source of substrate and refuge for organisms in areas where it was not previously available (Scanlon et al. 2005). Habitat preferences based on substrate composition influence the distribution of many marine organisms, especially benthic species (Day et al. 1989, Coleman & Koenig 2010). Additionally, the probability of observing other species is higher at holes where red grouper are present (active sites) compared to those where red grouper are not present (inactive sites) (Coleman et al. 2010).

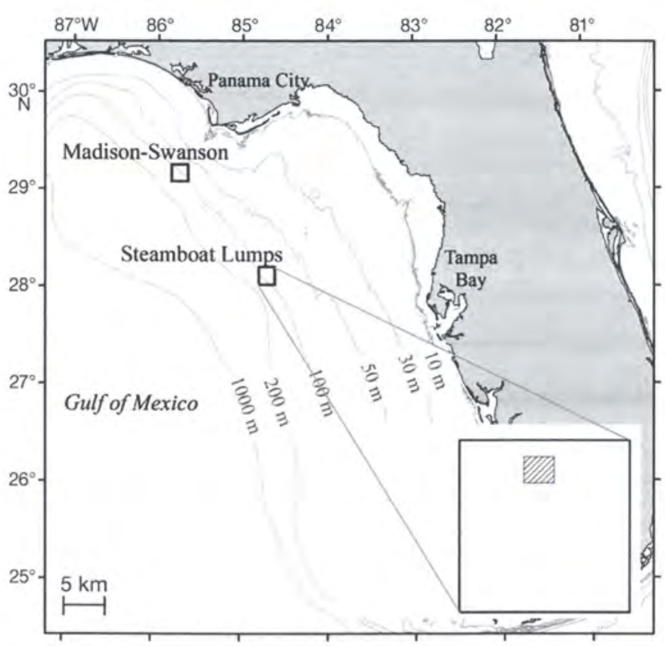

Fig. 1. Madison-Swanson and Steamboat Lumps Marine Reserves located in the eastern Gulf of Mexico. Inset: 2006 and 2009 multibeam data overlapped in the hatched square within Steamboat Lumps Marine Reserve (black box)

Holes can be observed using high-resolution acoustic sonar (e.g. side-scan or multibeam sonar) (Scanlon et al. 2005, Allee et al. in press; Fig. 2). In addition, the swim bladder in fish, including red grouper, can be detected with sonar because acoustic reflections result from the difference in density of the gas-filled swim bladder and the surrounding seawater (Misund 1997). Therefore, the application of active acoustic technology can provide high-resolution information on changes in bathymetry, including holes, and the presence of fish.

The goals of this project were to study the distribution and dynamics of red grouper holes using 2 multibeam sonar surveys conducted 3 yr apart. Additionally, we aimed to quantify the percentage of holes potentially occupied by red grouper and estimate grouper acoustic communication ranges as a means to indicate marine reserve success and understand the groupers' social system.

MATERIALS AND METHODS

Study area. The West Florida Shelf (WFS) extends over 200 miles from the Florida coast between the Florida Keys and the Mississippi River delta, creating a wide, gently sloping shelf. The inner WFS consists of a nearly flat, drowned and partially dissolved lithified carbonate (karst) platform covered by a thin layer of carbonate-siliciclastic sediment (Hine 1997, Brooks et al. 2003b). Five Holocene facies, or sediment veneers, have been identified overlying the bedrock of the central WFS: organic-rich mud, muddy sand, shelly sand, mixed siliciclastic/carbonate, and fine quartz sand (Edwards et al. 2003, Robbins et al. 2008). The distribution of each sediment type is highly varied along the inner central WFS and reflects both low accumulation rates and the lack of a single dominating source, all of which come from within or along the perimeter of the catchment (Brooks et al. 2003a). Scarped hard bottom systems are the only natural relief (<4 m) (Obrochta et al. 2003). The lack of active coral reefs in this region is attributed to the effects of the high-nutrient, low-salinity Mississippi River discharge entrained in the Loop Current (Hallock 1988, Gilbert et al. 1996). Detailed descriptions of the WFS geology are provided in Randazzo & Jones (1997) and Jarrett (2003).

Bathymetry mapping. Red grouper spawning habitat was mapped using a Kongsberg EM3000 multibeam swath sonar. The EM3000 operates at 300 kHz with 127 overlapping beams. Beam width is 1.5 × 1.5° with beam spacing of 0.9°, producing a 130 m swath transverse to ship heading. The vertical uncertainty of the EM3000 in a water depth of 100 m is 10 cm RMS with a 20 cm accuracy and 1 m positioning accuracy using an Applanix POSMV 320 system upgraded to a L1/L2 band that provides 0.02° RMS roll, pitch, and heading accuracy. Heave accuracy is 5 cm or 5% of the heave amplitude. Tide data were used to normalize sea level to a mean low low water (MLLW) chart datum.

Multibeam data were collected in overlapping portions of Steamboat Lumps Marine Reserve on 27 July 2006 and 23 April 2009 (Fig. 1). The survey tracks were retraced to replicate the data collection process (Fig. 2). The specific site chosen here corresponded to the study site of another project that focused on passive acoustic monitoring of red grouper sound production. Therefore, this site was a location of opportunity where, from previous work, red grouper were known to be present. Due to the high cost of ship time and the lack of funding, only one small portion of the reserve was monitored as a pilot study. While analysis of multiple areas in Steamboat Lumps over time would have allowed for the detection of red grouper habitat usage throughout the reserve, we were not capable of such a study chosen for this pilot proof-of-concept program.

The multibeam data were displayed and calibrated using CARIS HIPS and SIPS 7.0 software. Corrections for roll, pitch, heave, and tide were applied. Since tide data were not available for 2009, a static offset of 0.53 m, which was the mean difference between the 2 data sets at 100 randomly selected locations, was applied to allow direct comparison to the 2006 data. The short survey period, 103 min, allowed the offset to be static and did not need to account for any significant tidal ebb or flow (see 'Hole profiles' for further details). Depth thresholds were applied to remove data that were out of the range of depths encountered during the survey. Data were further filtered using a threshold of 3 standard deviations away from the moving mean depth. A vertical exaggeration of 5 and sun angle of 45° were applied to visualize the bathymetric features (Fig. 2).

Hole profiles. Two-dimensional vertical profiles of data points that crossed each hole visually identified from the multibeam data were extracted for both years. The profiles best represent the characteristics of the hole including the deepest point (Fig. 3). These data were used to determine the location (latitude and longitude), depth (distance from the tide-corrected surface to the bottom of the hole), height (vertical distance

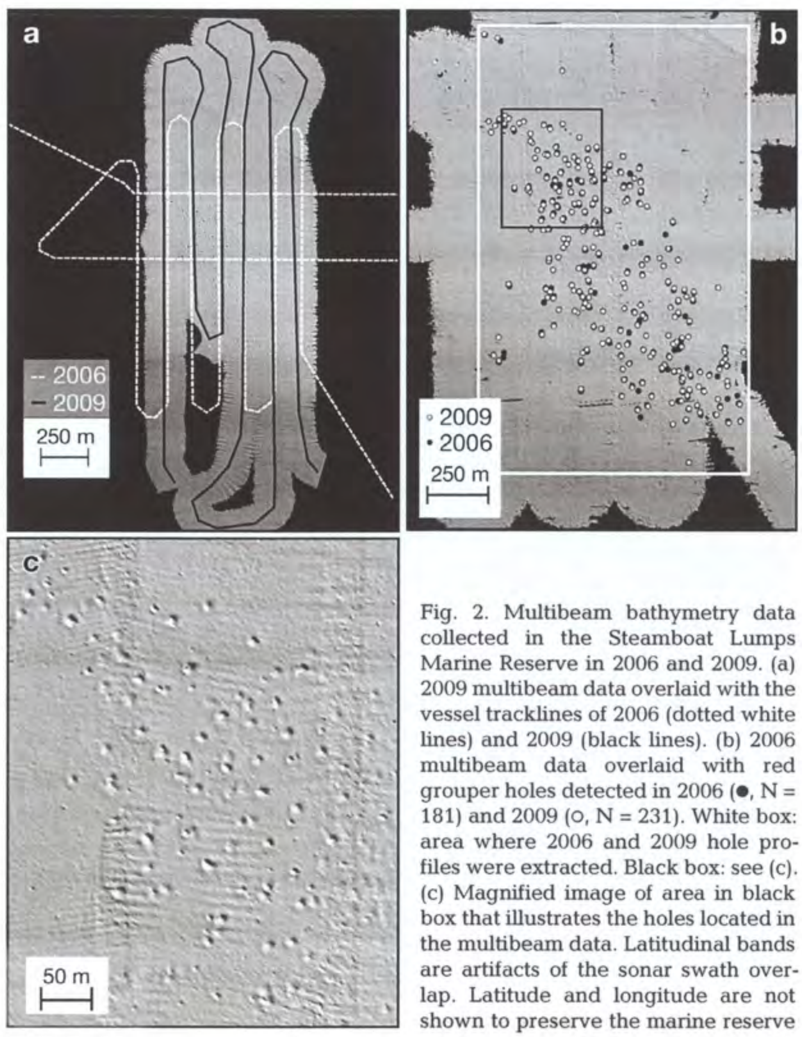

Fig. 2. Multibeam bathymetry data collected in the Steamboat Lumps Marine Reserve in 2006 and 2009. (a) 2009 multibeam data overlaid with the vessel tracklines of 2006 (dotted white lines) and 2009 (black lines). (b) 2006 multibeam data overlaid with red grouper holes detected in 2006 (●, N = 181) and 2009 (○, N = 231). White box: area where 2006 and 2009 hole profiles were extracted. Black box: see (c). (c) Magnified image of area in black box that illustrates the holes located in the multibeam data. Latitudinal bands are artifacts of the sonar swath overlap. Latitude and longitude are not shown to preserve the marine reserve

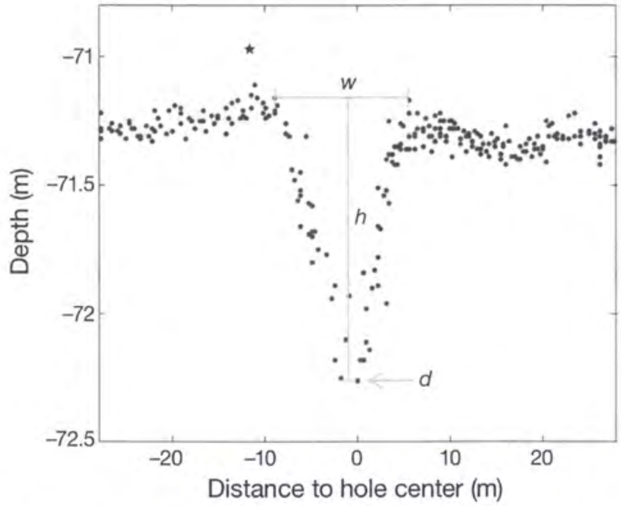

Fig. 3. Example hole profile created from data points (•) showing the shape characteristics that were measured (grey lines). Data points represent individual pulses of high-frequency sound (pings) from the multibeam sonar, from which measurements of depth (d), the distance from tide-corrected surface to hole bottom, height (h), the distance from the top of the hole to the bottom of the hole, and width (w) were made. (★) Data point suspected to be caused by fish presence. Note the exaggeration in the vertical scale

from the depth of the hole edge to the depth of the hole center), width (distance across the hole), and slope (height divided by half the width) of each hole. The above-hole depth (hole height plus hole bottom depth) was calculated to determine an offset in the depth calibration between the 2 data sets. Although the static offset applied to the 2009 data greatly improved its alignment with the 2006 data set, any error in the actual absolute depth measurement will not affect the hole characteristics that were measured (height, slope and width) as they were determined by the difference of very precise (not necessarily accurate) depth measurements. For further discussion and analysis of this type of approach, see Wolfson et al. (2007).

Due to differences in survey geographic coverage between the 2 yr (e.g. data were collected further south in 2009 than in 2006), only profiles within overlapping data sets were used. Areas in the data where sonar swaths overlap interfere with an accurate representation of the bathymetry and inhibit proper detection and hole characterization. Therefore, only areas with adequate bathymetry data coverage were used to detect holes.

To identify corresponding holes in 2006 and 2009, holes detected in 2006 that were within 10 m of those detected in 2009 were assumed to be potentially the same hole and were inspected visually. As a conservative estimate, 10 m was chosen and encompassed the vast majority of holes coinciding between the years. This analysis was completed using ESRI (Environmental Systems Research Institute) ArcGIS 10 software and was used to account for any georeferencing inconsistencies between the 2 data sets. The height, width, and slope of these holes were compared to determine changes in hole shape from 2006 and 2009. Significant changes in these parameters over the 3 yr period were tested using a paired t-test.

Profiles were also analyzed to determine if a hole had been abandoned or was less defined (inactive) from 2006 to 2009, or if a hole had been created or was better defined (active) in 2009 compared to 2006.

As the multibeam data consist of discrete data points (or pings), a 10-term polynomial was fitted to each hole profile to create a continuous cross-section. This analysis was done to mathematically characterize the general shape of the holes. Unfiltered (raw data) pings floating at least 10 cm above the seafloor along the hole profile were assumed to result from the presence of fish because they are distinct from the underlying seafloor (Fig. 3). To determine if a hole was active or inactive and to characterize the shape of active and inactive holes, we quantified the number of non-seafloor associated pings per profile and compared this count to the hole's polynomial-derived shape and slope. The slope that characterized the steepness of the hole was calculated from each polynomial by subtracting the hole depth at 5 m to the left of the hole center (a placement always located within the hole) from the hole depth at the center and then dividing by 5 m (the horizontal distance from the hole depth to the hole center). We then determined if the hole slopes differed significantly as a result of height or number of non-seafloor associated pings.

Hole distance and red grouper source level. The distance from the deepest point of each profile to the deepest point of the nearest profile was calculated in ArcGIS for 2006 and 2009. Histograms of between-hole distances for both years were created in MATLAB (Mathworks). Male red grouper produce sound during courtship and territorial behavior (Montie et al. 2011). To determine the potential communication network within the study area, the relationship between estimated grouper communication ranges and distances between the holes was analyzed. The intensity of sound produced by red grouper from 1 m away, also known as source level (SL), was assumed to be equal to the most intense received level recorded of a sound produced by a red grouper over many hours of recordings (Montie et al. 2011). Although red grouper are a benthic species and the substrate will interact with the propagation of sound, a cylindrical model (Urick 1983) is not practical due to the depth of the water column (~100 m) where red grouper produce sound without constraint from an air-water interface. Therefore, we applied a spherical spreading model as a conservative estimate of transmission loss ($TL_{spherical}$):

$$TL_{spherical} = -20 \log(R) \quad (1)$$

where R is range in m. With this model, we calculated the maximum acoustic communication range given SL and noise floor level (NL):

$$R = 10^{(SL-NL)/20} \quad (2)$$

where distance is in m and SL–NL represents the signal-to-noise ratio (SNR).

RESULTS

Hole profiles

There were 219 profiles extracted from the 2006 data (1.88 km^2 surveyed) and 278 profiles from the 2009 data (2.81 km^2 surveyed). Thus, the grouper hole density over the areas surveyed was 116 holes km^{-2} in 2006 and 98 grouper holes km^{-2} in 2009. After restricting the study area to that which overlapped in the 2 data sets and removing profiles that were potentially undetectable in the other data set, there were 181 holes in 2006 and 231 holes in 2009, covering ~1.64 km^2. These constraints resulted in a density of 110 and 141 grouper holes km^{-2}, respectively. Height and slope of the holes increased significantly from 2006 to 2009 (Fig. 4).

The 10 m buffer analysis found 151 profiles to be directly comparable between the 2 data sets. After comparing the height, width and slope of corresponding holes, only height and slope were significantly different over the 3 yr (Table 1, Fig. 5). Regression of the above-hole depth of the directly comparable 2006 and 2009 holes identified a close fit between the data sets ($R^2 = 0.9$). Additionally, the mean of the absolute value of the residuals was 0.1 m.

The number of new holes detected in 2009 was greater than the number abandoned after 2006 (Fig. 6). Out of 181 holes, 23 (13%) were identified in 2006 and not in 2009 (Fig. 7a,b). Conversely, 77 out of 231 holes (33%) were identified in 2009 and not in 2006 (Fig. 7c,d). There were 158 total non-seafloor associated pings found among the 23 inactive holes, which resulted in a median of 5 non-seafloor associated pings per hole (SD = 6). In comparison, 473 total non-seafloor associated pings were recorded among the 77 active holes, which equated to a median of 6 non-seafloor associated pings per hole (SD = 4).

The mean of the hole polynomials calculated for each year showed an overall increase in the height and slope of the hole from 2006 to 2009 (Fig. 8a). However, the shape of the polynomials was variable (Fig. 8b). To

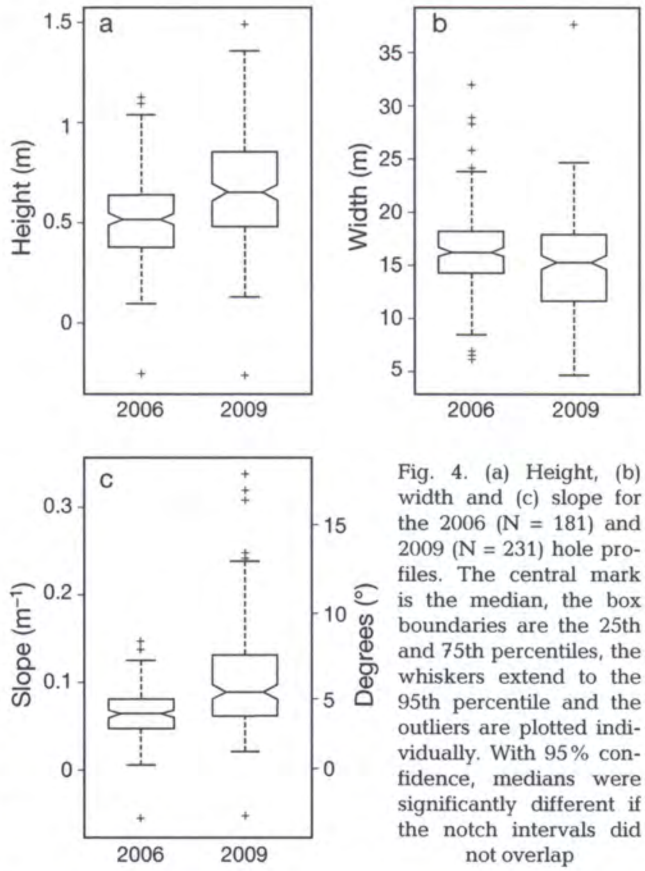

Fig. 4. (a) Height, (b) width and (c) slope for the 2006 (N = 181) and 2009 (N = 231) hole profiles. The central mark is the median, the box boundaries are the 25th and 75th percentiles, the whiskers extend to the 95th percentile and the outliers are plotted individually. With 95% confidence, medians were significantly different if the notch intervals did not overlap

Table 1. Shape parameters for holes (mean ±SD, N = 151) directly comparable between 2006 and 2009 surveys and results of the paired t-test analysis

	Height (m)	Width (m)	Slope (m^{-1})
2006	0.6 ± 0.2	16.4 ± 3.7	0.07 ± 0.04
2009	0.7 ± 0.2	16.3 ± 3.7	0.09 ± 0.04
p	<0.001	0.8	<0.001

reduce this variability, the polynomials were separated into 3 categories of height: <0.35, 0.35–0.70 and >0.70 m (Fig. 9a,b) and 4 categories of non-seafloor associated pings: 0, 1–9, 10–19, and 20–29 pings (Fig. 9c,d). The mean polynomial of each group was calculated. Holes with greater height had a steeper slope. However, hole shape did not appear to be correlated with the number of non-seafloor associated pings, which was a proxy for potential fish presence.

Linear regression of the slope and height for 2006 and 2009 showed a positive correlation and relatively good fit (Fig. 10a,b). The regression of slope and number of non-seafloor associated pings had a poor fit and low correlation (Fig. 10d). Over 90% of the profiles for

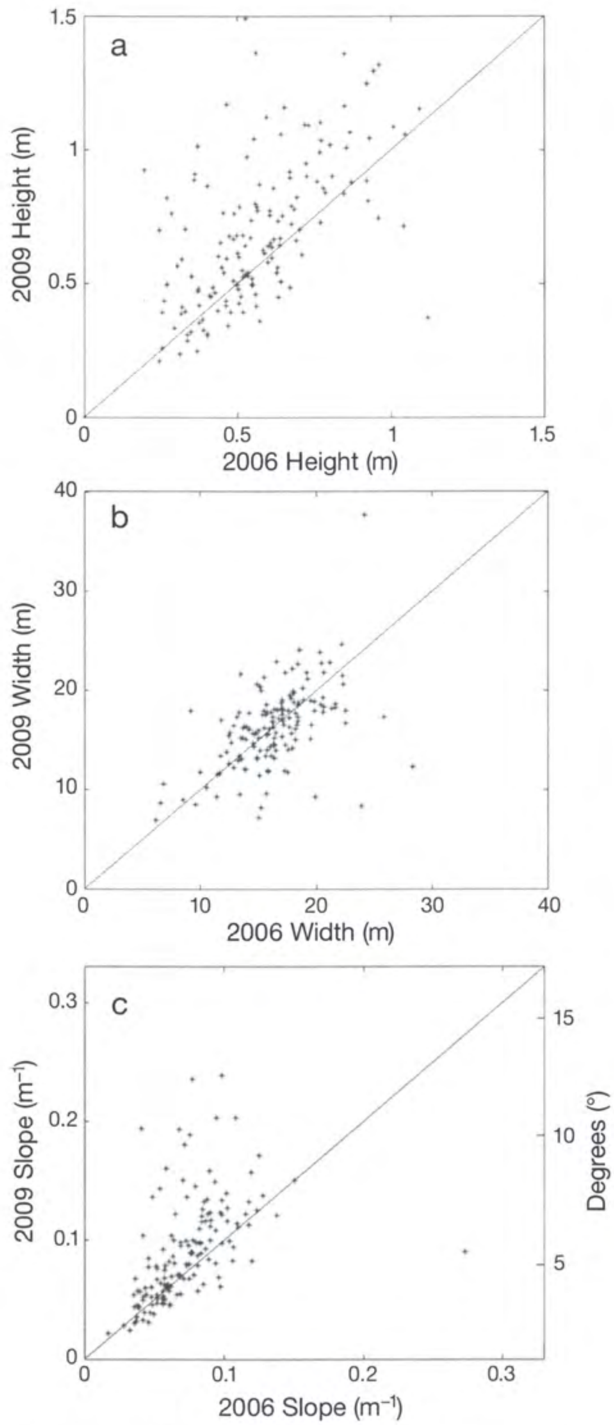

Fig. 5. (a) Height, (b) width and (c) slope for holes that corresponded across the 2006 and 2009 surveys (N = 151). The black line shows a 1:1 ratio. Data points above this line indicate an increase in that parameter from 2006 to 2009

Fig. 6. Multibeam data collected in 2009 overlaid with inactive holes that were filled in (●, N = 23) or active holes that were new or deeper (O, N = 77) between the 2006 and 2009 surveys

2006 (164 out of 181) and 2009 (214 out of 231) contained at least 1 non-seafloor associated ping. Slopes corresponding to holes with 0 non-seafloor associated pings (potentially inactive holes) did not differ from those corresponding to holes with at least 1 non-seafloor associated ping (potentially active holes).

Hole distance and red grouper source level

The sound pressure level (SPL) thresholds of red grouper hearing within the frequency range of red grouper sound production (100 to 300 Hz) are estimated to be 100 dB re 1 µPa based on hearing thresholds of gag grouper *Mycteroperca microlepis* (S. Larsen & D. A. Mann unpubl. data). Therefore, with a median NL of 105 dB re 1 µPa, the noise floor, rather than hearing thresholds, will limit communication distances. With an estimated SL of 142 dB re 1 µPa (Montie et al. 2011), sound produced by one red grouper is

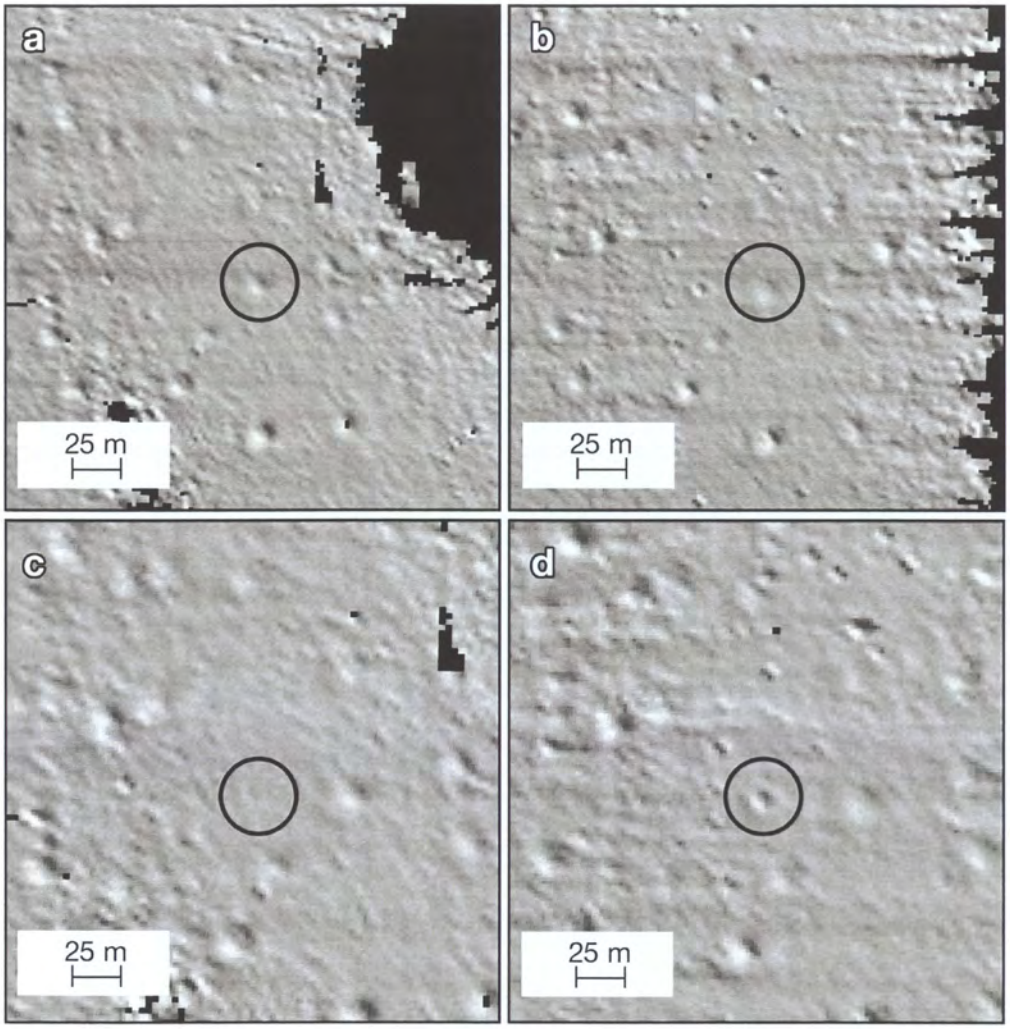

Fig. 7. Example changes in quality of holes (black circle) observed in multibeam data between the 2 surveys. Same hole detected in (a) 2006 and (b) 2009 that became less well-defined and a second hole detected in (c) 2006 and (d) 2009 that became more well-defined

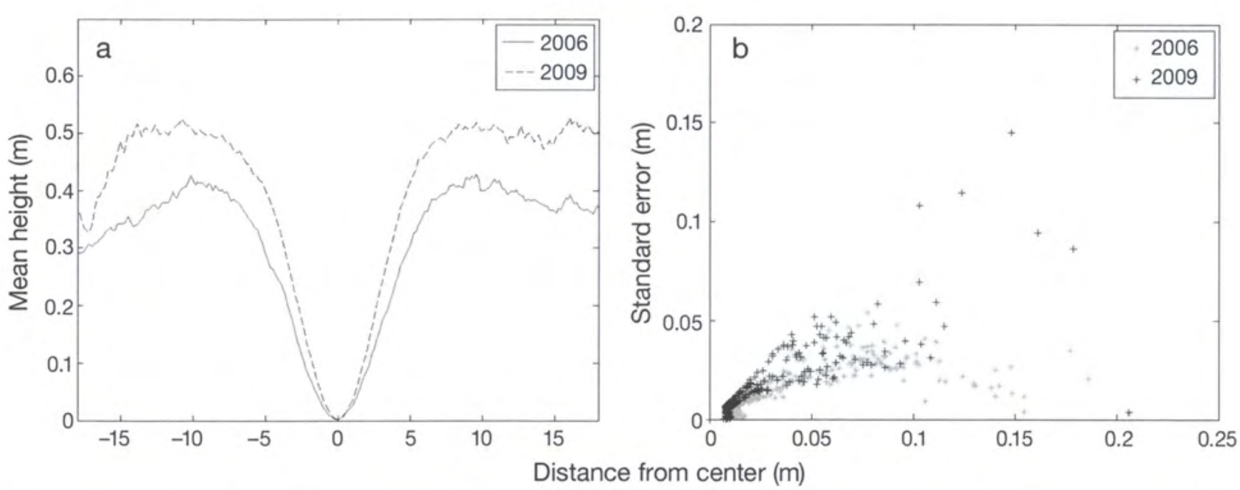

Fig. 8. (a) Mean hole height and (b) standard error by year visualized with a 10-term polynomial applied to each hole profile. Note the exaggeration in the vertical scale

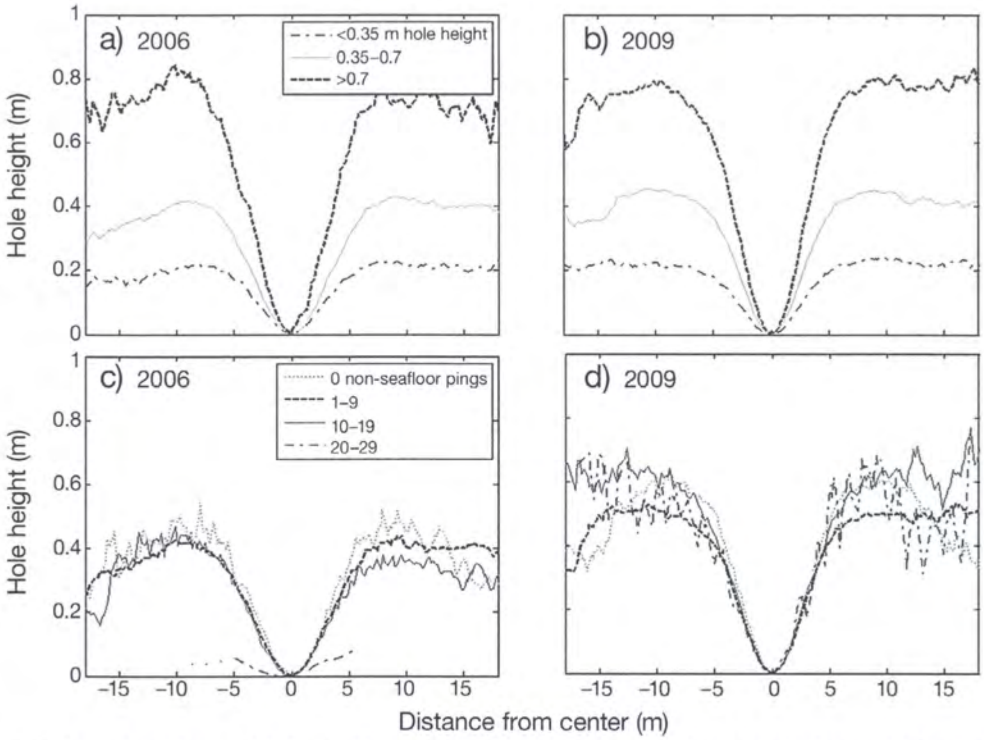

Fig. 9. Mean polynominal shape of hole profiles grouped by (a,b) maximum hole height for (a) 2006 and (b) 2009 and (c,d) non-seafloor associated pings for (c) 2006 and (d) 2009. Note the exaggeration in the vertical scale

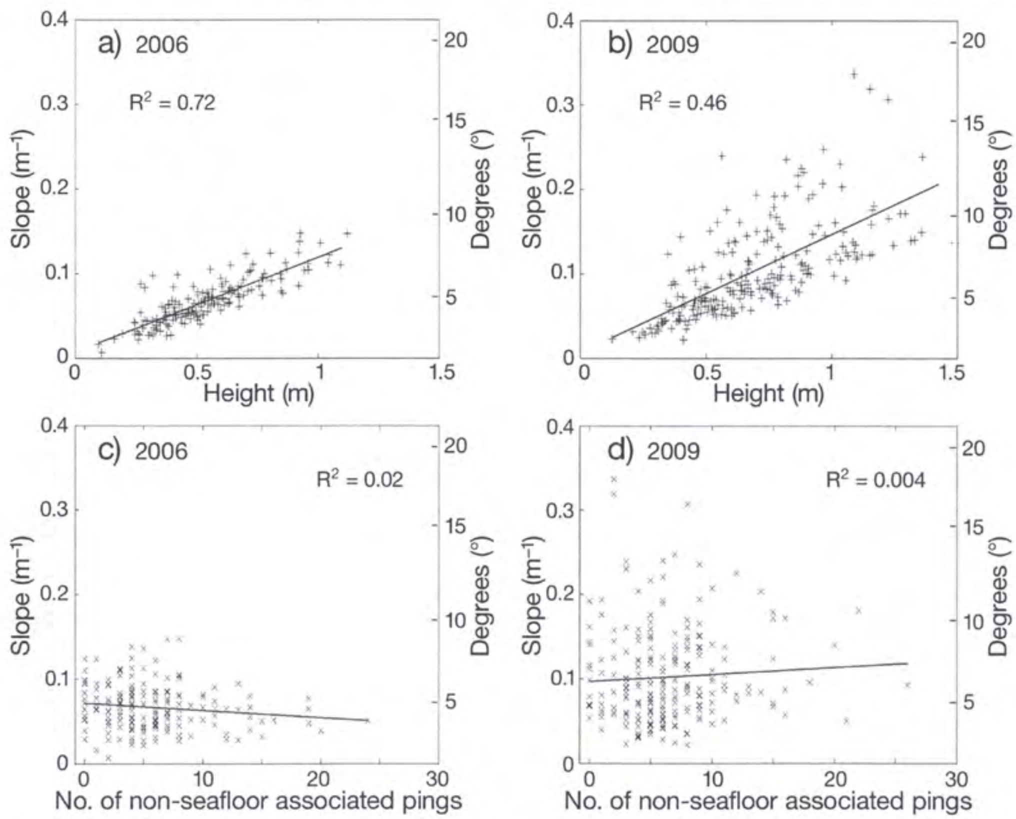

Fig. 10. Linear regression (black line) and fit statistic (R^2) for mean slope and (a,b) mean height of holes measured in (a) 2006 and (b) 2009 and (c,d) mean slope and number of non-seafloor associated pings, which indicate relative fish abundance, for holes measured in (c) 2006 and (d) 2009

calculated to be detectable by another red grouper up to 70 m away. Due to the short transmission distance and low acoustic frequency, acoustic attenuation due to absorption is negligible.

Maps of the distance estimated between the deepest point of the hole profiles in 2006 and 2009 showed that the holes cluster towards the center of the study area (Fig. 11). The effective acoustic communication network between holes, based on the maximum range estimate of 70 m, is illustrated in Fig. 12. Histograms of the between-hole distances show over 95% of holes are located within 70 m of their nearest neighbor (Fig. 13). The median distance between nearest holes is 26 m (SD = 15) and 24 m (SD = 28) for 2006 and 2009, respectively.

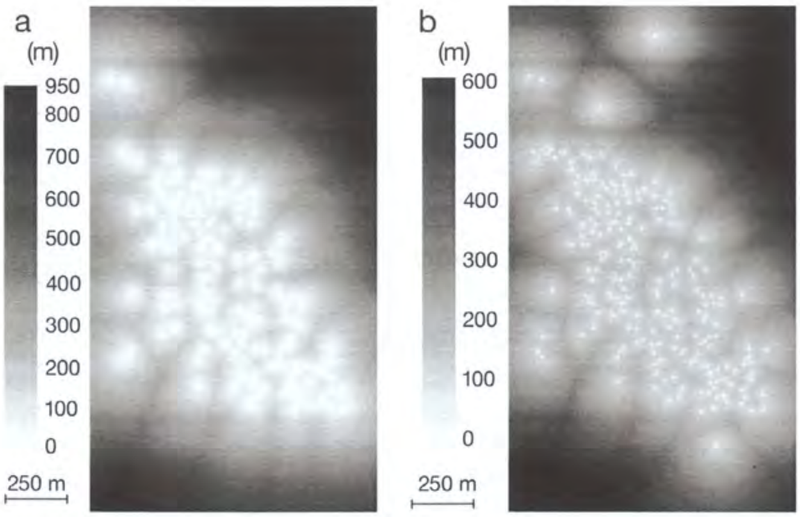

Fig. 11. Nearest neighbor distance (m) between holes detected in (a) 2006 (N = 181) and (b) 2009 (N = 231). Note the difference in greyscale bar

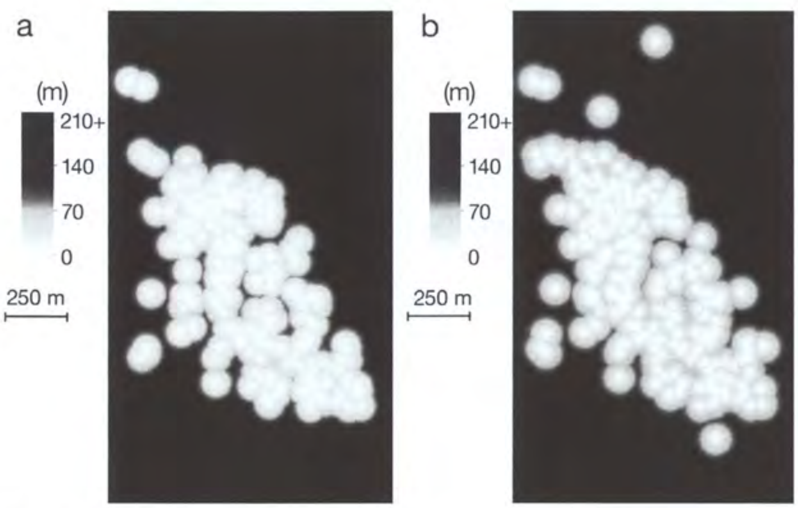

Fig. 12. Red grouper communication network showing the estimated maximum estimated ranges of grouper acoustic signals (white circles), which are estimated to be 70 m away from grouper holes located in (a) 2006 and (b) 2009. Distances >70 m (black) were suspected to be outside of the effective communication range of red grouper

DISCUSSION

High-resolution multibeam bathymetry data collected in 2006 and 2009 in Steamboat Lumps Marine Reserve allowed detailed documentation and characterization of holes excavated by red grouper. Analysis of these data showed a significant increase in number, height and slope of holes over this 3 yr period. Direct comparisons of holes detected in both 2006 and 2009 indicated significant changes in height and slope. The changes in these parameters suggest that hole shape could vary because of maintenance by red groupers and that holes are constructed and maintained over time (Coleman et al. 2010). Low sediment accumulation rates in the Gulf of Mexico also prevent quick infill and shape modification of holes in the absence of red grouper (Brooks et al. 2003a).

Active vents are generally steeper and deeper than inactive vents indicating that increased height in conjunction with slopes greater than the angle of sediment

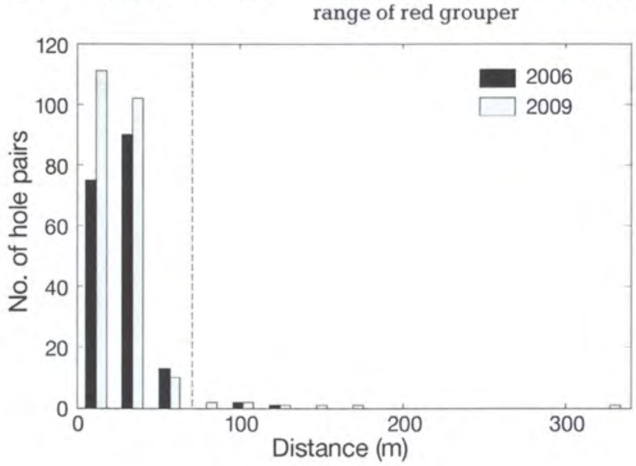

Fig. 13. Number of pairs of red grouper holes found at different nearest neighbor distances between holes identified in 2006 (black) and 2009 (gray) and binned into 20 m intervals. Over 95% of the holes in both years were within 70 m of their nearest neighbor and therefore likely contained individual fish within acoustic contact. Dashed line indicates maximum distance of red grouper communication

repose might signify active hole occupation (Saleem 2007). Although overall hole slope increased significantly from 2006 to 2009, the lack of correlation between hole slope and number of non-seafloor associated pings suggests the shape does not change significantly if unoccupied unless bad pings are poor indicators of fish. Ground-truthed data are needed in concert with simultaneous multibeam data collection to determine if hole occupation can be established based solely on the presence of non-seafloor associated pings.

Despite collecting bathymetry data in depths ranging from 69 to 81 m, the median depth for all holes was 71.2 m with a standard deviation of 0.6 m. The reason for the clustering of holes within this depth range is unknown. Initially, we suspected the clustering to be related to constraints of bottom composition preventing hole excavation since sediment type distribution is highly varied throughout the WFS (Brooks et al. 2003a). Yet, backscatter data, which is useful for identifying bottom type (Dartnell & Gardner 2004), collected concurrently with the bathymetry data indicated uniform sediment distribution in our study area. If more than just social behavior is at hand, additional factors such as water temperature, bottom currents and loop current intrusions may be influencing the location of red grouper holes in this area.

Scanlon et al. (2005) calculated hole density in Steamboat Lumps to be 250 holes km^{-2} from side-scan sonar data collected in 2000, which is roughly double the hole densities measured with multibeam sonar in this study (110 and 141 holes km^{-2} in 2006 and 2009). The specific 0.4 km^2 area that they surveyed may have not directly overlapped with the area surveyed in this study. In addition, the hole density calculated by Scanlon et al. (2005) focused on a subset of data that was heavily populated with holes and then extrapolated the density estimate throughout the study area. We calculated hole density over the entire survey area, which consisted of dense and sparse areas of holes. Scanlon et al. (2005) classified a grouper hole visually from the interpolated raster created from side-scan sonar data. By examining the multibeam data on the data point level, we were able to exclude artifacts and errant pings that appeared to be holes when solely examining the backscatter raster data. Although it aides visually, applying a vertical exaggeration to interpolated bathymetry maps can trick the eye into believing a hole exists when it is actually an artifact of the data. This density discrepancy could be compounded further by the differences in sonar technologies used. Interpreting the backscatter shadows in side-scan sonar data can be difficult due to the angular uncertainty, their dependence on the direction of the boat, and the varying grazing angles, which can change throughout a survey and across the survey track. The backscatter shadows can be misleading because they can result from changes in seafloor geology or biology in addition to relative depth. With multibeam data, shadows can be created in software during post processing and will provide a consistent 'grazing' angle across the track regardless of depth. Side-scan sonar devices offer more refined backscatter data to determine bottom composition and provide higher resolutions when towed close to the bottom compared to hull-mounted multibeam ones.

The increase in number of holes detected from 2006 to 2009 is consistent with increases in hole density and habitat usage, potentially the result of an increased grouper population. We attempted to identify if red grouper or other species were present within or near holes using non-seafloor associated pings. The percentage of potentially inactive holes (0 non-seafloor associated pings) decreased from 9% in 2006 to 5% in 2009, which also supports an increase in active holes. As fish very close to (<10 cm) or on the bottom become indistinguishable from the bottom structure by the multibeam sonar, the estimates determined from this method are likely conservative, and more holes may be occupied than can be identified using non-seafloor associated pings. Inactive holes could possibly still have other fish using the exposed habitat. Ground-truthed data are necessary before concrete conclusions regarding increases in the number of active holes can be made.

The communication network maps created from assuming a 70 m limit to red grouper acoustic communication showed an increase in communication overlap within the cluster of holes found in the center of the study area from 2006 to 2009. The numbers of holes in communication solitude also increased. These results showed that fish have to move to be heard, suggesting that sound production may just be used for short-range communication. Females likely need to travel during mate choice, which is consistent with observations of females swimming towards holes occupied by males.

Red grouper, which are the target species of a large commercial fishery in the Gulf of Mexico, are established ecological engineers whose behavior provides structure and protection for other reef fish and invertebrates (Jones et al. 1994, Coleman & Williams 2002). Sustaining red grouper populations is therefore important at both the species and ecosystem levels (Jones et al. 1994, Wright & Jones 2006). In this study we have identified an increase in spawning habitat usage within a portion of the marine reserve over a 3 yr period. Populations in the reserve are anticipated to increase naturally in the absence of fishing (Claudet et al. 2010). Poaching is known to occur (C. C. Koenig pers. comm.), and the rate of increase in the red grouper population may not be as high as it could be (Russ & Alcala 2004). Regardless, the results of this research provide evidence towards the potential benefit of such reserves (Pauly et al. 2002, Jennings 2009, Lester et al. 2009, Babcock et al. 2010).

Conducting a similar analysis outside of the marine reserve is a necessary next step to understand changes in habitat usage by red grouper populations that are fished. Initial analysis of multibeam data collected across the WFS indicate numerous areas containing putative grouper holes (Coleman et al. 2010, Allee et al. in press, D. F. Naar unpubl. data). Reserve- and shelf-wide mapping of red grouper habitat would be a time and cost intensive endeavor due to the relatively narrow swath width of multibeam sonar in shallow water. However, small subsets of data over time would provide highly informative glimpses into large-scale changes in habitat use.

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