U.S. Department
of Commerce

December 2006

NOAA Professional Paper NMFS 5

Emerging Technologies for Reef Fisheries Research and Management

J. Christopher Taylor (editor)

U.S. Department of Commerce
Carlos M. Gutierrez
Secretary

National Oceanic and Atmospheric Administration
Vice Admiral
Conrad C. Lautenbacher Jr., USN (ret.)
Under Secretary for Oceans and Atmosphere

National Marine Fisheries Service
William T. Hogarth
Assistant Administrator for Fisheries

NOAA Professional Papers NMFS

The NOAA Professional Paper NMFS (ISSN 1931-4590) series is published by the Scientific Publications Office, National Marine Fisheries Service, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115.
The Secretary of Commerce has determined that the publication of this series is necessary in the transaction of the public business required by law of this Department. Use of funds for printing of this series has been approved by the Director of the Office of Management and Budget.

The NOAA Professional Paper NMFS series carries peer-reviewed, lengthy original research reports, taxonomic keys, species synopses, flora and fauna studies, and data-intensive reports on investigations in fishery science, engineering, and economics. Copies of the NOAA Professional Paper NMFS series are available free in limited numbers to government agencies, both federal and state. They are also available in exchange for other scientific and technical publications in the marine sciences. Professional Papers are published online in PDF format at http://spo.nmfs.noaa.gov

NOTICE: This series was established in 2003 to replace the NOAA Technical Report NMFS series.

NOAA Professional Paper NMFS 5

Emerging Technologies for Reef Fisheries Research and Management

J. Christopher Taylor (editor)

December 2006

U.S. Department of Commerce
Seattle, Washington

Suggested reference

Full report: Taylor, J. C. 2006. Emerging technologies for reef fisheries research and management. NOAA Professional Paper NMFS 5, 116 p.
Individual papers: [authors.] 2006. [paper title.] *In* Emerging technologies for reef fisheries research and management, J. C. Taylor (ed.), p. [#-#]. NOAA Professional Paper NMFS 5.

Online dissemination

This report is posted online in PDF format at http://spo.nmfs.noaa.gov (click on *Professional Papers* link).

Copyright law

Proprietary products

CONTENTS

Participants at Emerging Technologies for Reef Fisheries Research and Management Symposium, held during the 56th annual meeting of the Gulf and Caribbean Fisheries Institute, Tortola, British Virgin Islands, November 2003.

Abstract—This publication of the NOAA Professional Paper NMFS Series is the product of a special symposium on "Emerging Technologies for Reef Fisheries Research and Management" held during the 56th annual Gulf and Caribbean Fisheries Institute meeting in Tortola, British Virgin Islands, November 2003. The purpose of this collection is to highlight the diversity of questions and issues in reef fisheries management that are benefiting from applications of technology. Topics cover a wide variety of questions and issues from the study of individual behavior, distribution and abundance of groups and populations, and associations between habitats and fish and shellfish species.

Emerging technologies for reef fisheries research and management

J. Christopher Taylor
Center for Marine Science and Technology
North Carolina State University
303 College Circle
Morehead City, NC 28557
E-mail address: Chris_Taylor@ncsu.edu

Introduction

It is now recognized that fisheries activity around the world has reached and most probably exceeded its maximum sustainable yield (Pauly et al., 2002; Myers and Worm, 2003). This is most certainly the case in coral reef systems where significant human impacts such as overexploitation, harmful fishing practices, and habitat destruction have decimated many reef fish populations (Jackson et al., 2001; Pandolfi et al., 2003). Reef ecosystems support some of the most diverse taxa in the aquatic world (Sale, 2002) and therefore degradation of habitats and extirpation of species through fisheries harvest can have unexpected consequences to the functioning of these ecosystems. Artisanal harvest of reef species also contributes significantly to the local economy of many island communities of the Caribbean, Gulf of Mexico, and tropical western Atlantic, and so has also suffered from the decline in reef ecosystems (Russ, 1991).

While we are gaining a better appreciation for the role coral reef habitats and reef fisheries play in coastal ecosystems and tropical economies, the techniques which fisheries managers have used to collect vital statistics on the status of populations lag behind the need for such data. This is not surprising as many of these species are solitary as adults or elusive as sub-adults and juveniles, using the reef structure as refuge from predation, making them difficult to detect and enumerate. Traditional means of surveying for population estimates or community structure, such as diver-visual surveys, have proven costly and sometimes ineffective in assessing abundance and distribution patterns of many of the most important reef fish populations. In addition, the limitations on dive bottom times and underwater characteristics such as light penetration and visibility place a necessary limit on the range, areal coverage, and depth of the study site that can be surveyed using this traditional method. It is critical that we develop methods that will provide extensive and yet rapid and efficient surveys of both reef habitats as well as the fish species that inhabit them. Ideally, such methods would permit rapid coverage of large spatial extents, produce abundance estimates or species distribution movement maps in real-time or with minimal post-processing, and be noninvasive so they do not interfere with the behavior and thus affect the detection of species of interest.

This collection of papers is a product of a special symposium entitled "Emerging technologies for reef fisheries management" that was held at the 56th annual meeting of the Gulf and Caribbean Fisheries Institute in Tortola, British Virgin Islands, in November 2003. The papers presented in this volume encompass a wide diversity of habitats, species, regions, and techniques and also address issues of reef fisheries ecology including the study of individual behavior, distribution and abundance of groups and populations, and associations between habitats and species. They also cover many aspects of fisheries management such as species conservation, marine protected area design and implementation, and stock assessment and management. These papers are meant to serve as examples of ways in which technology has been employed and resulted in significant improvements in our understanding of reef fisheries and ecosystem processes. Readers interested in the foundations of a particular technology described in this collection should consult references in each paper. Moreover, this collection does not cover other applications of technologies in coral reef conservation and management, particularly remote sensing techniques that are being used to map coastal habitats and coral cover (Mumby et al., 2004). However, several papers in this series do attempt to link these habitat-based objectives with applications that include linking habitats with species of commercial or ecological interest.

This collection of papers is divided into two broad categories: 1) population assessments and distribution patterns of single species, and 2) organism-habitat relationships. In many cases, the technology serves as a complimentary tool in each project. Several of the authors also identify advantages and limitations of their respective application and suggest how the limitations may be overcome in the future.

Distribution and abundance

Rand et al. used a diver-operated stereo video system to improve measurements of individual Nassau grouper in a spawning aggregation. The application also provided some of the first measures of small-scale, three-dimensional spatial structure within a reef fish spawning aggregation.

Johnston et al. used mobile split-beam hydroacoustic surveys to assess the spatial distribution and abundance of red hind (*Epinephelus guttatus*) spawning aggregations along the continental shelf of Puerto Rico. Their survey covered several hundred kilometers along the shelf-break on Puerto Rico and identified regions that held large red hind aggregations during the February and March spawning season.

Taylor et al. present results from a high-resolution mobile hydroacoustic sampling of a Nassau grouper (*Epinephelus striatus*) aggregation. They used a two-stage geostatistical model to estimate the abundance of fish and compared these estimates with those made using scuba visual census. The geostatistical model provided an objective measure of the spatial extent of the aggregation. Measures such as these can be difficult to obtain using traditional diver visual surveys.

Habitat-organism relationships

Glazer and Delgado used sonic telemetry coupled with Geographic Information Systems (GIS) to determine movement and home ranges for queen conch (*Strombus gigas*) on a back reef in Florida Keys. Overlapping home ranges of several individuals during spawning and non-spawning seasons were used to make objective and informed decisions on establishing boundaries of a marine fishery reserve to protect conch populations around the Florida Keys.

Gleason et al. used recent advances in bottom habitat classification from single-beam hydroacoustics along with diver-assisted surveys for grouper to make inferences about species-habitat associations. They found a significant relationship between the distribution of grouper and sediment type and a newly derived acoustic property of the bottom. Their work will lead to habitat-based population assessments for near-shore grouper species and improve site selection for fish surveys using divers.

Weaver, Naar, and Donahue and Weaver, Hickerson, and Schmahl used high-resolution bathymetric maps produced from multibeam sonar surveys to direct submersible surveys for reef habitat features in the Tortugas South Ecological Reserve and Northwestern Gulf of Mexico, respectively. Unique and rare coral habitats and deep reef species were identified at both sites using these complimentary surveying techniques.

Rivera et al. used side-scan sonar imaging from habitat surveys to identify acoustic targets in the water column; acoustic targets not associated with bottom features are typically considered as noise in habitat surveys, so current software packages do not permit analyses of such data. The authors manually extracted water column signals and linked them to the habitat maps through synoptic geopositioning data. Using this novel technique, they are able to begin to make connections between fish distribution and habitat types in a shallow, near-shore reef environment.

Mason et al. used several complimentary technologies to establish relationships between reef habitat quality and fish growth. A combination of active hydroacoustics, passive acoustics, video, and advanced biochemical techniques provided insights into the functional linkages between reef attributes (e.g., structural complexity and prey availability) and processes that regulate gag grouper (*Mycteroperca microlepis*) performance.

Acknowledgements

I thank the members of the board at the Gulf and Caribbean Fisheries Institute for welcoming this special symposium and providing the logistical support during the 56th annual GCFI meeting in Tortola, BVI. A special thanks is extended to A. Costa, L. Creswell, and R. Glazer. I also thank participants in the symposium for valuable discussions during the symposium and their patience and persistence during the completion of this collection. This manuscript benefited from discussions with L. Avens and S. Shoffler. Funding during the organization of this symposium and while compiling these papers was provided by grants from NOAA via the University of Miami (P715647 via NA17RJ1226), the NOAA Caribbean Marine Research Center (CMRC-01-NRDE-04-02A; CMRC-01-NRDE-04-03C; CMRC-00-NRDE-03-01C) and US EPA STAR Fellowship (Grant No. U-9155885).

Literature cited

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, and R. R. Warner.
2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293(5530): 629–638.

Mumby, P. J., W. Skirving, A. E. Strong, J. T. Hardy, E. F. LeDrew, E. J. Hochberg, R. P. Stumpf, and L. T. David.
2004. Remote sensing of coral reefs and their physical environment. Mar. Poll. Bull. 48(3–4): 219–228.

Myers, R. A., and B. Worm.
2003. Rapid worldwide depletion of predatory fish communities. Nature 423(6937): 280–283.

Pandolfi, J. M., R. H. Bradbury, E. Sala, T. P. Hughes, K. A. Bjorndal, R. G. Cooke, D. McArdle, L. McClenachan, M. J. H. Newman, G. Paredes, R. R. Warner, and J. B. C. Jackson.
2003. Global trajectories of the long-term decline of coral reef ecosystems. Science 301(5635): 955–958.

Pauly, D., V. Christensen, S. Guenette, T. J. Pitcher, U. R. Sumaila, C. J. Walters, R. Watson & D. Zeller.
2002. Towards sustainability in world fisheries. Nature 418(6898): 689–695.

Russ, G.
1991. Coral reef fisheries: effects and yields. *In* The ecology of fishes on coral reefs (P. F. Sale, ed.), p. 601–635.

Sale, P. F.
2002. Coral reef fishes dynamics and diversity in a complex ecosystem. Academic Press, New York, 500 p.

Abstract—There is a clear need to develop fisheries independent methods to quantify individual sizes, density, and three dimensional characteristics of reef fish spawning aggregations for use in population assessments and to provide critical baseline data on reproductive life history of exploited populations. We designed, constructed, calibrated, and applied an underwater stereo-video system to estimate individual sizes and three dimensional (3D) positions of Nassau grouper (*Epinephelus striatus*) at a spawning aggregation site located on a reef promontory on the western edge of Little Cayman Island, Cayman Islands, BWI, on 23 January 2003. The system consists of two free-running camcorders mounted on a meter-long bar and supported by a SCUBA diver. Paired video "stills" were captured, and nose and tail of individual fish observed in the field of view of both cameras were digitized using image analysis software. Conversion of these two dimensional screen coordinates to 3D coordinates was achieved through a matrix inversion algorithm and calibration data. Our estimate of mean total length (58.5 cm, n = 29) was in close agreement with estimated lengths from a hydroacoustic survey and from direct measures of fish size using visual census techniques. We discovered a possible bias in length measures using the video method, most likely arising from some fish orientations that were not perpendicular with respect to the optical axis of the camera system. We observed 40 individuals occupying a volume of 33.3 m^3, resulting in a concentration of 1.2 individuals m^{-3} with a mean (SD) nearest neighbor distance of 70.0 (29.7) cm. We promote the use of roving diver stereo-videography as a method to assess the size distribution, density, and 3D spatial structure of fish spawning aggregations.

A video method for quantifying size distribution, density, and three-dimensional spatial structure of reef fish spawning aggregations

Peter S. Rand
The Wild Salmon Center
The Natural Capital Center
721 NW 9th Avenue, Suite 280
Portland, OR 97209
E-mail address: prand@wildsalmoncenter.org

J. Christopher Taylor
Center for Marine Science and Technology
North Carolina State University
303 College Circle
Morehead City, NC 28557

David B. Eggleston
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Jordan Hall
Raleigh, NC 27695

Introduction

There has been growing interest in measuring individual sizes of fishes at liberty and capturing three dimensional (3D) attributes of fish schools or aggregations in situ (Parrish and Hamner, 1997), particularly on exploited populations that have not been assessed using fisheries independent methods. There is a relatively long history of using ship-mounted sonar for quantifying attributes of fish schools and, with the recent introduction of split- and multi-beam echosounders, we have improved our capabilities of resolving bathymetry and water column targets in 3D (Simmonds and MacLennan, 1996; MacLennan, 2003). These methods suffer, however, from a lack of certainty in identifying targets. SCUBA divers have been employed to provide observations for species identification and to quantify density and spatial extent of fish schools and aggregations. Unless these surveys are designed to address observer bias, the approach is prone to generating imprecise data and can be difficult to replicate (Harvey et al., 2001). There is a clear need to develop methods that can reliably measure individual sizes, density, and 3D structure of known targets in situ to overcome the limitations of these other methods.

In field situations that permit it, the use of stereo photography and videography offers a straightforward method for generating data on individual sizes, density, and 3D positions of fish. In addition to providing species identification in most cases, it also allows for estimates of size and 3D positions of fish in the water column, measures that are often difficult using SCUBA observations. There has been a relatively short history of using stereo-pairs of underwater cameras in situ to quantify individual lengths and behaviors of fishes, particularly swimming speed. Klimley and Brown (1983) were the first to conduct such a study, relying on 35 mm still cameras to estimate lengths of hammerhead sharks (*Sphyrna* spp.). Since then, there have been a number of studies in freshwater and marine systems involving stereovideography (Boisclair, 1992; Hughes and Kelly, 1996; Hinch and Rand, 2000; Harvey et al., 2001; Cocito et al., 2003; Harvey et al., 2003; Standen et al., 2004). All of these field efforts have focused on quantifying 3D positions and size of individuals, and, in some cases, estimating swimming speed and resolving swimming maneuvers. While some effort has been devoted to quantifying the structure of fish schools under laboratory conditions (Dill et al., 1981), we are not aware of any published work on combining 3D positioning and size estimation with spatial attributes of fish schools or aggregations in situ. Here we report on results of an application of stereo-videography for quantifying 3D positions, sizes, and spatial properties of a spawning aggregation of Nassau grouper (*Epinephelus striatus*).

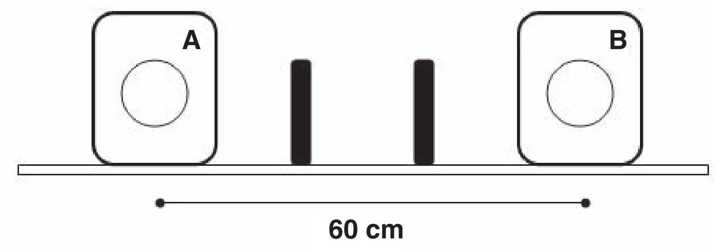


Figure 1

Schematic diagram of a 3D underwater stereo-video system. Two housings containing digital video recorders were fastened on either end of a 1 m steel bar. The cameras were positioned on the bar to achieve a 60 cm optical axis separation. The filled upright bars in the figure are the handles used by diver to support the system during a survey.

Methods

We assembled an underwater stereo-video system for use in resolving 3D attributes of grouper aggregations. The system consisted of two underwater housings (Ikelite Model #6035.36) fitted with dome ports and mounted on opposite ends of a stainless steel bar (see Fig. 1). The weight in air of the bar support was 1.2 kg. This weight was sufficient to achieve slight positive buoyancy of the entire video assembly at the depths where grouper typically aggregate during the spawning period (ca. 30 m depth). The video cameras were SONY Model TRV-11 (single 1.4 type CCD, 680,000 pixel resolution). The cameras were mounted to achieve an optical axis separation of 60 cm (Fig. 1). The zoom lens was fixed at wide angle (3.3 mm focal length), and the cameras were set on auto-focus. Video records were archived on 60 min DV tape format. A single diver operated the camera system and supported the system while underwater using handles placed between the two housings (Fig. 1).

The stereo-video system was calibrated with a 50 cm × 50 cm × 30 cm quadrat consisting of 6.4 mm diameter welded aluminum pipe (Fig. 2). The pipe was welded in a regular grid pattern on each face of the quadrat such that the nodes of adjoining pipe were 10 cm apart. Images of the quadrat were captured in digital format. We conducted the full calibration analysis with the quadrat placed 2 m from the camera assembly (measured from the center point of the steel bar support). The calibration was conducted in approximately 1 m water depth in a swimming pool located at the Southern Cross Club on Little Cayman (see Fig. 2). Still images of the quadrat were captured as JPEG format and analyzed using ImagePro (v. 4.5, Media Cybernetics, Silver Spring, MD). Nodes (n = 36 for each face) were digitized using the Manual Tag method in ImagePro. Pixel coordinates (360 by 270 image resolution) for each node were saved. We used a new program, Mathematica (v. 4.0, Wolfram Research, Champaign, IL), adapted from the approach of Hughes and Kelly (1996), that uses a transformation matrix to convert pixel screen coordinates to view coordinates as a means to estimate 3D positions. This approach can significantly reduce errors in determining positions that are not within the calibration area (Hughes[1]).

We synchronized the two free-running cameras in the field. Frame synchronization was achieved using an underwater laser pointer (Model MBSL, Class IIIA, maximum output <5mW, wavelength 635 nm) directed onto a light background. The diver operating the camera pointed the camera assembly either at another diver or on the reef, and repeatedly illuminated an area with the laser pointer such that both cameras would record the point simultaneously. To assure that we had proper frame synchronization for a particular pair of images captured during a dive, we relied on additional unique visual or auditory clues during playback (e.g. diver movements, taps on housing or sounds from regulator, and recognizable distinct fish behaviors captured in the field of view).

We estimated 3D positions of fish within the spawning aggregation during a dawn dive on 23 January 2003. For all these periods, the anterior- and posterior-most points of each fish clearly identified in both paired camera images were digitized. Pixel coordinates were then read into the transformation matrix program for conversion

---

[1] Hughes, N. 2004. Personal commun. University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, 204 Arctic Health, P.O. Box 757220, Fairbanks, AK 99775-7220.

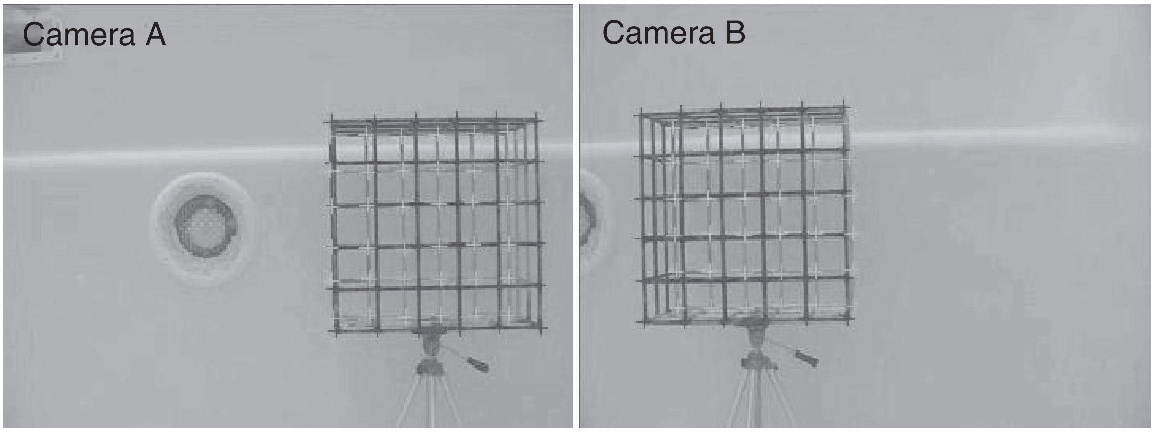


Figure 2

Paired digital images of the calibration quadrat captured with the stereo video system. The calibration was conducted in a swimming pool at the Southern Cross Club, Little Cayman Island, Cayman Islands, BWI. The camera was placed 2 m from the near face of the quadrat. Nodes on the near and far face of the quadrat were digitized.

to a view coordinate system oriented relative to the position of the camera. The origin of the view coordinate system was positioned at 2 m range from the camera system and was located at the point in space occupied by the left bottom corner node of the near face of the calibration quadrat at the time the system was calibrated. In the view coordinate system, the positive x-axis points to the right, the y-axis points away from the camera, and the z-axis points upward.

The resulting 3D positions of each individual fish were plotted as a 3D scatter plot with dropline in SPlus 2000 (Insightful, Inc., Seattle, WA). A convex 3D hull was computed using qhull (Barber et al., 1996). A convex hull of a set of points is the smallest convex set containing the points. The resulting coordinates defining each of the polygons that comprised the hull were uploaded to Mathematica and plotted using the Graphics3D function. This allowed us to define a volume occupied by the fish within the view coordinate system to estimate volumetric density.

We computed a matrix of linear distances separating all members of the fish visible in the image pair. We computed straight line distance between the 3D position of each fish by taking the square root of the sum of the squared distances, using the view coordinates determined for the anterior point on each fish. We computed the mean and standard deviation of the nearest neighbor distances. Finally, we selected a subset of fish that were clear in the image and appeared to be oriented perpendicular to the optical axis of our cameras. We estimated their length by taking the square root of the sum of the squared differences, using the view coordinates of the nose and tail of each fish in the aggregation.

Results

We captured a pair of images of the aggregation at approximately 0725 hr on 23 January 2003 (Fig. 3). Fish were swimming relatively close to the bottom and exhibited polarized swimming behavior. We digitized the nose of 40 individual fish in the field of view and estimated the aggregation in the field of view occupied 33.3 m^3, resulting in a volumetric density of 1.2 grouper m^{-3} (Fig. 4). Nearest neighbor distances ranged from 22.1 to 139.3 cm, with a mean of 70 cm and a standard deviation of 29.7 cm (Fig 5A). This equates to a mean inter-individual spacing within the aggregation of 1.2 body lengths. We digitized the nose and tail of a subset of these individuals and computed an average size of 58.5 cm TL (n = 29), with a range from 32 to 107 cm TL (Fig. 5B). The aggregation was located between 5 and 10 m from the camera system.

Discussion

Our video estimate of fish length is in good agreement with the TL ranges reported on the same aggregation using diver visual methods (45–75 cm TL) and acoustic methods (60–90 cm TL) as reported in Taylor et al. (this volume). Size ranges observed for both of these methods were more constricted than estimated using the

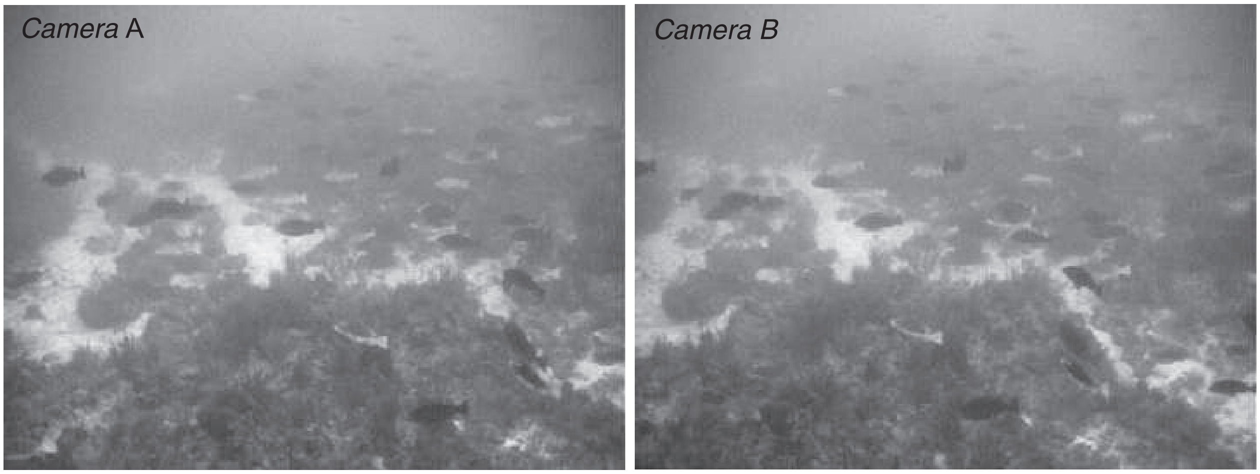


Figure 3

Stereo paired images of a Nassau grouper aggregation. Images were captured on digital video at 0725 hr on 23 January 2003 at Little Cayman Island, Cayman Islands, BWI.

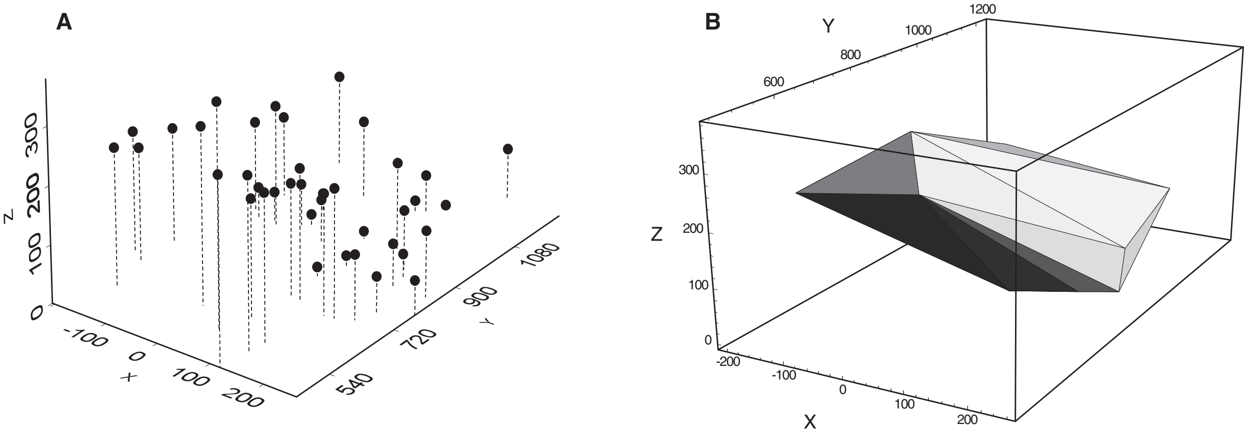


Figure 4

Results of three dimensional analyses depicted as a 3D scatter plot with drop line of individual fish (A) and a 3D rendering of a complex hull surrounding the aggregation (B). A total of 40 individuals were identified in the view of both cameras occupying a total volume of 33.3 m^3 and a volumetric density of 1.2 grouper m^{-3}. Scales on axes in (A) and (B) are in cm.

stereovideography method describe herein. Harvey et al. (2001) reported greater statistical power in resolving changes in mean lengths reported using a stereovideo method, compared to visual surveys performed by divers. We do, however, identify some limitations in estimating total length of grouper using the stereo-video approach described here. The most important source of error likely arises from an alignment of the main axis of the body of the fish that is askew relative to the optical axis of the cameras, resulting in estimated lengths that may be biased low. This is evident in the shape of the distribution of fish lengths generated from images captured during our 23 January 2003 dawn dive. We made an effort to select fish that appeared to be oriented perpendicular to the optical axis of the cameras, but this was relatively difficult to determine, particularly if the fish were at a distance away from the cameras. In past work we have obtained reasonable estimates of fish length by opportunistically targeting small groups of individuals at relatively close range, helping to assure

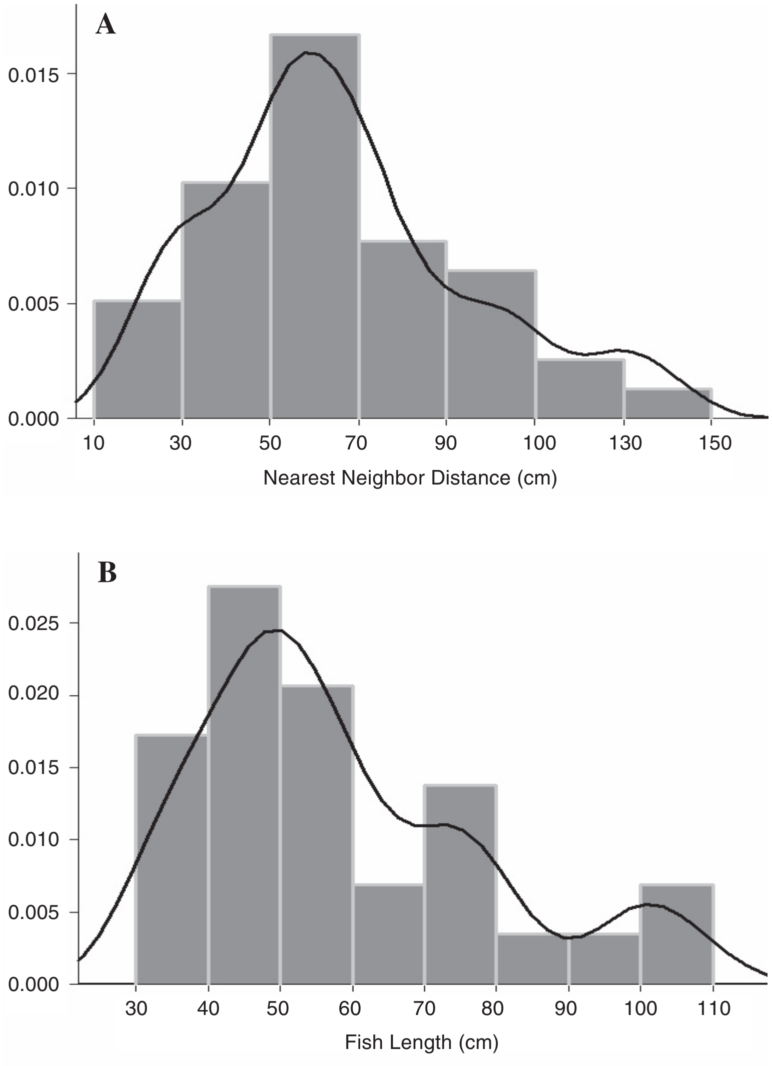


Figure 5

Nearest neighbor distances separating Nassau grouper (A) and size frequency histogram of Nassau grouper (B) measured using stereo-video methods. Average nearest neighbor distance was 70.0 (29.7 SD) cm. Average total length of individuals was 58.5 cm. Measurements were made during 23 January 2003 at a spawning aggregation site off Little Cayman Island, Cayman Islands, BWI. Bold line is density.

that the fish are oriented near perpendicular to the optical axis of the camera (Rand, unpubl. data). The error in estimated size described here is analogous to that introduced from variation in tilt angle exhibited by fish measured using vertical incidence sonar (MacLennan and Simmonds, 1992).

Our stereo-video estimate of volumetric density is within the range reported by Taylor et al. (this volume) on echo-integrated densities. Taylor et al. (this volume) reported maximum volumetric densities of 1.05 and 0.74 grouper m^{-3} during two surveys of the aggregation site, which compare favorably with the estimate of 1.2 grouper m^{-3} reported here. These estimates, however, are not directly comparable because the samples were not collected at the same time of day (stereovideo sampling was conducted during morning of 23 January, and the acoustic sampling was conducted during the afternoon). The stereovideo sampling focused at the center of the main aggregation determined visually during a dive, so it is most appropriate to compare our estimate with that of the maximum recorded during the acoustic sampling. Our average nearest-neighbor estimate of 0.7 m is the first reported for Nassau grouper within a spawning aggregation. Shapiro et al. (1993) reported nearest neighbor distances greater than 3.2 m for a spawning aggregation of red hind *Epinephelus guttatus*. Their visual observations were made from above the aggregation and in two dimensions; therefore, they may not represent true nearest-neighbor distances (Dill et al., 1981).

This effort underscores the need to conduct more rigorous cross-calibration involving independent measures of abundance, density, distribution, and individual sizes of fish within schools or aggregations. As in most cases involving population estimation and biological sampling, there are a variety of approaches that can be applied. It is clear from our work that there is not one clearly superior sampling method to quantify attributes of spawning aggregations of reef fishes; rather, we support a sampling approach involving two or more methods that will likely provide more rigorous and defensible results. Emerging technologies involving acoustic and video techniques will undoubtedly assume a more prominent role in efforts directed toward assessing status and trends of reef fishes in the tropical Atlantic Ocean and Caribbean Sea.

Acknowledgements

We were invited to survey the Little Cayman aggregation site by the Cayman Islands Department of the Environment (CIDoE). We thank P. Bush and K. Luke with CIDoE and L. Whaylen with Reef Environmental Education Foundation (REEF) for their cooperation and collaboration in this effort. Logistical and vessel support was provided by H. Fourier and P. Hillenbrand of the Southern Cross Club. We also thank the Gulf Caribbean Fisheries Institute for hosting this special symposium. Funding was provided by grants from NOAA via the University of Miami (P715647 via NA17RJ1226), NOAA Caribbean Marine Research Center (CMRC-01-NRDE-04-02A; CMRC-01-NRDE-04-03C; CMRC-00-NRDE-03-01C), PADI Project AWARE, and Sigma Xi.

Literature cited

Barber, C. B., D. P. Dobkin, and H. T. Huhdanpaa.
1996. The Quickhull algorithm for convex hulls, ACM Trans. on Mathematical Software 22(4):469–483.

Boisclair, D.
1992. An evaluation of the stereocinematographic method to estimate fish swimming speed. Can. J. Fish. Aquat. Sci. 49:523–531

Cocito, S., S. Sgorbini, A. Peirano, and M. Valle.
2003. 3-D reconstruction of biological objects using underwater video technique and image processing. J. Exp. Mar. Biol. Ecol. 297:57–70.

Dill, L. M., R. L. Dunbrack, and P. F. Major.
1981. A new stereophotographic technique for analyzing the three-dimensional structure of fish schools. Environ. Biol. Fish 6:7–13.

Harvey, E., D. Fletcher, and M. Shortis.
2001. Improving the statistical power of length estimates of reef fish: a comparison of estimates determined visually by divers with estimates produced by a stereo-video system. Fish. Bull. 99:72–80.

Harvey, E., M. Cappo, M. Shortis, S. Robson, J. Buchanan, and P. Speare.
2003. The accuracy and precision of underwater measurements of length and maximum body depth of southern bluefin tuna (*Thunnus maccoyii*) with a stereo-video camera system. Fish. Res. 63:315–326.

Hinch, S. G., and P. S. Rand.
2000. Optimal swimming speeds and forward-assisted propulsion: energy-conserving behaviours of upriver-migrating adult salmon. Can. J. Fish. Aquat. Sci. 57:2470–2478.

Hughes, N. F., and L. H. Kelly.
1996. New techniques for 3-D video tracking of fish swimming movements in still or flowing water. Can. J. Fish. Aquat. Sci. 53:2473–2483.

Klimley, A. P., and S. T. Brown.
1983. Stereophotography for the field biologist: measurement of lengths and three-dimensional positions of free-swimming sharks. Mar. Biol. 74:175–185.

MacLennan, D. N. (ed.).
2003. Acoustics in fisheries and aquatic ecology. Part 1. Proceedings of an ICES Symposium held in Montpellier, France, 10–14 June 2002. ICES Marine Science Symposia, 218,706 p.

MacLennan, D. N., and E. J. Simmonds.
1992. Fisheries acoustics. Fish and Fisheries Series 5. Chapman and Hall, New York, 325 p.

Parrish, J. K., and W. H. Hamner (eds.).
1997. Animal groups in three dimensions. Cambridge University Press, New York, 378 p.

Shapiro, D. Y., Y. Sadovy, and M. A. McGehee.
1993. Size, composition, and spatial structure of the annual spawning aggregation of the red hind, *Epinephelus guttatus*. Copeia 1993(2):399–406.

Simmonds, E. J., and D. N. MacLennan (eds.).
1996. Fisheries and plankton acoustics. Proceedings of an ICES International Symposium held in Aberdeen, Scotland, 12–16 June 1995. ICES Marine Science Symposia, 202.

Standen, E. M., S. G. Hinch, and P. S. Rand.
2004. Influence of river speed on path selection by migrating adult sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 61:905–912.

Taylor, J. C., D. B. Eggleston, and P. S. Rand.
2006. Nassau grouper (*Epinephelus striatus*) spawning aggregations: hydroacoustic surveys and geostatistical analysis. *In* Emerging technologies for reef fisheries research and management (J. C. Taylor, ed.), p. 18–25. NOAA Prof. Paper NMFS 5.

Hydroacoustic evaluation of spawning red hind (*Epinephelus guttatus*) aggregations along the coast of Puerto Rico in 2002 and 2003

Samuel V. Johnston
Hydroacoustic Technology, Inc.
715 NE Northlake Way
Seattle, WA 98105-6429
E-mail: sjohnston@htisonar.com

José A. Rivera
Under contract to:
Biodiversity and Protected Resources Division
Miami Laboratory
National Marine Fisheries Service, NOAA
Box 1736
Boquerón, PR 00622-9704

Aida Rosario
Department of Natural and
Environmental Resources
Commonwealth of Puerto Rico
P.O. Box 9066600
Pta. De Tierra Station
San Juan, PR 00906

Mark A. Timko
Patrick A. Nealson
Kevin K. Kumagai
Hydroacoustic Technology, Inc.
715 NE Northlake Way
Seattle, WA 98105-6429

Abstract—Red hind (*Epinephelus guttatus*) have been overfished in the Caribbean and were included with seven other regional grouper species deemed vulnerable to risk of extinction. The Puerto Rico Department of Natural and Environmental Resources desired to map spawning red hind aggregations within commonwealth waters as part of their resource management program for the species. Mobile hydroacoustic surveys were conducted over 3-day periods in 2002 and 2003, indexed to the full moon phase in February or March when red hind were known to aggregate. Four vessels concurrently sampled the southwest, south, and southeast coasts of Puerto Rico in 2002. In 2003, three vessels conducted complementary surveys of the northwest, north, and northeast coasts of the island, completing a circuit of the coastal shelf-spawning habitat. These surveys indicated that red hind spawning aggregations were prevalent along the south and west coasts, and sparse along the north coast during the survey periods. Highest spawning red hind concentrations were observed in three areas offshore of the west coast of Puerto Rico, around Mona and Desecheo islands (20,443 and 10,559 fish/km^2, respectively) and in the Bajo de Cico seasonal closed area (4,544 fish/km^2). Following both 2002 and 2003 surveys, a series of controlled acoustic measurements of known local fish species in net pens were conducted to assess the mean target strength (acoustic backscatter) of each group. Ten species of fish were measured, including red hind (*E. guttatus*), coney (*E. fulvus*), white grunt (*Haemulon plumieri*), pluma (*Calamus pennatula*), blue tang (*Acanthurus coeruleus*), squirrel fish (*Holocentrus* spp.), black durgeon (*Melichtyhs niger*), ocean file fish (*Canthidermis sufflamen*), ocean surgeon fish (*Acanthurus bahianus*), and butter grouper (*Mycteroperca* spp.). In general, the mean target strength results from the caged fish experiments were in agreement with published target strength length relationships, with the exception of white grunt and pluma.

Introduction

Tropical marine fish species, such as groupers, are generally considered to be overfished across most of their worldwide distribution (Sadovy, 1994; Gascoigne[1]). Over fishing has driven many grouper stocks below sustainable levels and eliminated them from much of their historic range (Sadovy, 1997). Effective management of these fisheries requires innovative approaches, including harvest restrictions, community management systems, and networks of marine protected areas (MPA's). Selection of the most effective management approach requires reliable information as to the distribution, abundance, biology, and harvest of these populations.

Caribbean groupers include a variety of species of the family Serranidae (order *Perciformes*), belonging to either the genera *Epinephelus* or *Mycteroperca*. Common representatives of these genera that are found in Puerto Rican waters include the speckled hind (*E. drummondhayi*), rock hind (*E. adscensionis*) and red hind (*E. guttatus*). The red hind is the most commercially important of the Puerto Rican hinds and has historically supported significant regional fisheries along the west and south coasts of the island (Matos-Caraballo, 2004). However, available information shows that overall grouper landings in the U.S. Caribbean have declined 45% between 1977 and 1985, with an even greater rate of decrease between 1987 and 1989 (Appeldoorn et al., 1992; Sadovy, 1994).

From fishermen it is known that red hind spawn within a specific time period surrounding the full moon in late winter, typically in January, February, or March (Sadovy et al., 1994). They aggregate only at specific locations, where they are present in large numbers (Shapiro, 1993; Sadovy et al., 1994). This stage in the life cycle of the red hind is particularly important since the entire annual reproduction for a region may be concentrated at a few particular locations where aggregations occur for only a few days each year (Nemeth, 2005). In many instances, entire regional stocks have

---

[1] Gascoigne, J. 2002. Nassau grouper and queen conch in the Bahamas: Status and management options. Report by MacAlistair Elliot and Partners, Ltd.. (MEP) to the Bahamas Reef Environment Educational Foundation (B.R.E.E.F.). http://www.macalister-elliott.com/media/reports/1651R02C.pdf [Accessed 25 Sept. 2006.]

been wiped out due to intense fishing pressure on spawning aggregations (Bohnsack[2]).

While the spatial and temporal aggregating behavior of spawning grouper makes them subject to high exploitation, it also provides an annual opportunity to assess population density and distribution. The objective of this paper was to use this localized spawning behavior to identify, map, and quantify red hind aggregations along the entire Puerto Rican shelf using mobile hydroacoustics. The study quantified school aggregations with the characteristic vertical stacking behavior consistent with spawning behavior in red hind and similar grouper species along the continental shelf surrounding Puerto Rico. Due to the limited effort available and the narrow time window for the aggregations, the study objectives were exploratory in nature. Specific project objectives included the following:

1) Employ mobile hydroacoustics to estimate the density and map the location and distribution of red hind/grouper schools across the surveyed coastline.
2) Characterize fish school metrics including school location and mean target strength values.
3) Estimate mean target strength values from caged fish of known species and size to aid in interpretation of the field data and accurate scaling of echo integration density results.
4) Compare the distribution of observed fish aggregations with fishing activity indicated by the distribution of fishing vessels.

Methods

Burczynski (1979) and MacLennan and Simmonds (1992) discuss the principles of mobile hydroacoustic fisheries assessment. Over 1300 km of transects were surveyed during the 2002–2003 Puerto Rico red hind surveys, encompassing the entire 500 km coastline of the island, with the exception of the area between Culebra and Vieques islands.

The areas surveyed during the 2002 hydroacoustic red hind assessment (Johnston et al.[3]) were located along the edge of the continental shelf surrounding the south, southwest, and southeast coasts of Puerto Rico. Four individual geographic survey areas were designated within the overall region of interest, based on the length of transects that could be monitored within a 3-day period of time surrounding the full phase of the moon in February (Fig. 1). The areas were adjacent to one another, providing a coherent sampling record along the southern half of the Island of Puerto Rico. A total of approximately 957 kilometers (517 nautical miles) of transects were surveyed by the four survey vessels between 27 February and 2 March 2002, gathering data for approximately 12 h/d.

1) Area 2002-A: the southern half of the west coast centered around Mayaguez between approximately Rincon and Cabo Rojo. A total of 92 km of transects were surveyed.
2) Area 2002-B: the southern half of the eastern Puerto Rican coast between Arroyo and the eastern end of the Island of Vieques. A total of 182 km of transects were surveyed.
3) Area 2002-C: the southern coast between approximately Cabo Rojo and Ponce, centered around La Perguera. A total of 111 km of transects were surveyed.
4) Area 2002-D: the south central coast of Puerto Rico between approximately Ponce and Arroyo, based out of Salinas. A total of 143 km of transects were surveyed.

The areas surveyed during the 2003 hydroacoustic red hind assessment were located along the edge of the continental shelf surrounding the north, northwest, and western offshore islands of Puerto Rico (Nealson et al.[4]). Three individual geographic survey areas were designated within the overall region of interest, based on the length of transects that could be monitored within a 3-day period of time surrounding the full phase of the moon in March (Fig. 1). The areas were adjacent to one another, providing a coherent sampling record along the northern half of Puerto Rico. A total of approximately 395 kilometers (213 nautical miles) of trackline were surveyed by the three survey vessels between March 18 and March 21, 2003, gathering data for approximately 12 h/d.

1) Area 2003-A: the northeast Puerto Rican coast, from Culebra Island to San Juan. A total of 128 km of transects were surveyed.

---

[2] Bohnsack, J. A. 1989. Protection of grouper spawning aggregations. Coastal Resource Division Contribution CRD-88/89-06. Southeast Fisheries Science Center, NMFS, 75 Virginia Beach Dr., Miami, FL 33149. 8 p.

[3] Johnston, S. V., P. A. Nealson, K. K. Kumagai, M. A. Timko, and G. W. Tritt. 2002. Hydroacoustic evaluation of spawning red hind (*Epinephelus guttatus*) aggregations along the coast of Puerto Rico in February 2002. Report by Hydroacoustic Technology, Inc. (715 NE Northlake Way, Seattle, WA 98105-6429) to Puerto Rico Dept. of Natural Resources, San Juan, PR.

[4] Nealson, P. A., G. W. Tritt, M. A. Timko, K. K. Kumagai, and S. V. Johnston. 2003. Hydroacoustic evaluation of spawning red hind (*Epinephelus guttatus*) aggregations along the coast of Puerto Rico in March 2003. Report by Hydroacoustic Technology, Inc. (715 NE Northlake Way, Seattle, WA 98105-6429) to Puerto Rico Dept. of Natural Resources, San Juan, PR.

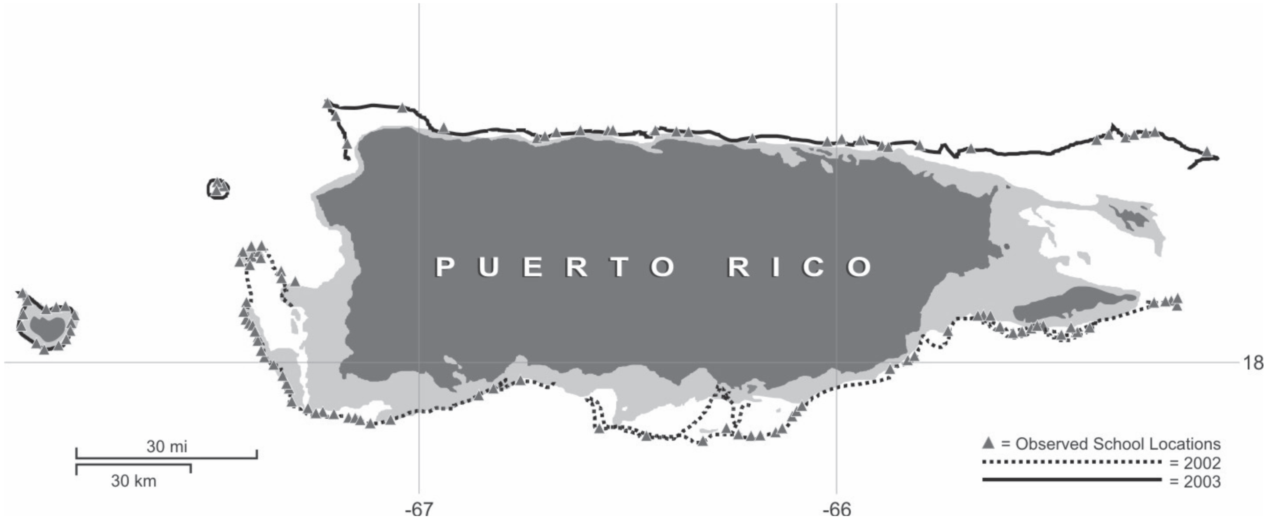


Figure 1

Survey transects and presumed school aggregations for red hind (*Epinephelus guttatus*). Transects in all four designated areas surveyed 27 February to 2 March 2002 are indicated by a dotted line. Transects in all four designated survey areas surveyed 27 February–2 March 2002 are indicated by a solid line.

2) Area 2003-B: the northwest coast of Puerto Rico, from San Juan to Aguadilla. A total of 153 km of transects were surveyed.
3) Area 2003-C: the western coast from Aguadilla to Rincon, Mona, Monita, and Desecheo Islands, and Baja de Cico. A total of 114 km of transects were surveyed.

Six-second echo integration sampling intervals were used to define the minimum spatial areas of resolution over which to estimate school biomass during field data collection. During data analysis, individual school events were identified and processed from the digital samples (DAT tape) data set, to provide finer-scale resolution and editing of these events. GPS data were collected simultaneously, permitting individual schools to be precisely located along the survey transects.

Fishing boat locations were obtained from aerial surveys conducted in 2002 and 2003 by the Puerto Rico Department of Natural and Environmental Resources (DRNA).

Hydroacoustic equipment

Split-beam hydroacoustic systems (Model 243, Hydroacoustic Technology Inc., Seattle, WA) operating at 200 kHz were used for the 2002–2003 Puerto Rico red hind population assessments. Data were recorded to computer and DAT tape during field collection, and later analyzed using EchoScape, an HTI data entry and analysis program.

In 2002, the echo sounders on each survey vessel sampled both 6° and 15° transducers in a fast-multiplexed (simultaneous) mode. The 15° beam width transducers were incorporated to ensure adequate sampling volumes in shallow water. Based on exploratory transects surveyed in shallow waters in 2002, the characteristic red hind spawning aggregations were not observed in shallow water, and it was determined that a single 6° transducer was sufficient for monitoring the relatively deeper areas along the shelf breaks where these schools were observed. This single 6° configuration was used for sampling in 2003. Both transducers were oriented straight down in the water column and mounted on a 1-m long aluminum dead-weight towing vehicle. The maximum sample depth for the hydroacoustic systems was approximately 200 m for the sizes of red hind encountered during the 2002 and 2003 surveys.

Each survey system collected the hydroacoustic data files directly to a laptop computer. All data were also concurrently recorded to DAT tape, providing an ultimate data backup of the unfiltered digital samples for later reprocessing as digital samples. Differential or WAAS-enabled (Wide Area Augmentation System) Global Positioning System (GPS) receivers were interfaced with all hydroacoustic systems to provide position to within approximately 3 m.

Prior to the survey period, the hydroacoustic systems used in this study were calibrated relative to a U.S.

Naval standard transducer of known sensitivity. The 2002–2003 Puerto Rico red hind surveys employed a minimum on-axis target detection threshold of –50 dB. This threshold corresponded to a minimum fish detection length across the full nominal transducer beam width of approximately 55 mm based on Love (1971). To verify the laboratory calibration of the hydroacoustic system, in situ field measurements were made using a 38.1 mm tungsten carbide standard target (MacLennan and Simmonds, 1992) during each individual survey cruise.

Data collection

The 2002 red hind hydroacoustic surveys were conducted between 27 February and 2 March 2002. All school density data were successfully collected within 2 days following the full moon (27 February). The 2003 red hind hydroacoustic surveys were conducted 18–21 March 2003 (the full moon occurred on 18 March). Surveys consisted of a series of predetermined transects following the continental shelf area and the region just inshore of this break. Survey transects generally zigzagged along the edge of the continental shelf approximately 55 m (180 ft) deep. Transects were traversed at a boat speed of approximately 4–5 knots. The overall acoustic repetition (ping) rate of the hydroacoustic system was 2 pings/sec per transducer.

Data analysis

Data were analyzed to provide estimates of fish population and biomass in the survey areas, estimates of fish target strength (related to fish length), and spatial school metrics. Data visualization and editing was performed using the program EchoScape (Version 2.52, Hydroacoustic Technology, Inc., Seattle, WA) to visually identify aggregations from the field computer data file records and mark all single echoes within identified school aggregations as tracked fish. The EchoScape program linked all of the field data records such that, within the tracked fish table, each aggregation was identified with mean target strength, detection time, and a latitude/longitude location.

Raw digital sample files that were collected on the DAT were reintegrated at fine integration intervals of 6 sec in duration and 1 m deep. This provided the ability to isolate the red hind schools from surrounding structure and other targets. These reintegrated files were then read back into EchoScape for final editing. EchoScape was used to manually select the cells that contain aggregations for subsequent estimation of school densities.

In situ target strengths of ten species of coral reef-dwelling fish were measured by using the same split-beam hydroacoustic system described above (Table 1). Measurements were made at La Perguera on 2 March 2002, and Escollo Negro, near Cabo Rojo, on 21 March 2003. Individual fish were placed in a cylindrical, steel-framed cage that was 3 m in diameter, 0.9 m in height, covered with fine mesh monofilament netting. The cage was suspended 7 m below the surface, and fish were placed in the cage individually by divers. One fish of each species was measured at a time. All fish were alive when placed in the cage. The squirrel fish was dead upon retrieval, but all others were alive. The transducer was suspended 5.7 m above the cage, and aimed downward through the fine mesh netting. The ping rate was 10 pings per second. EchoScape was used to summarize the target strength values of red hind and other commonly occurring species measured during the caged fish experiments. These mean backscatter (ó) values were compared to the in situ measures of observed fish target strength collected during the mobile surveys, which were used to scale the integrated relative biomass values to estimates of absolute red hind spawning fish density (fish/m^3).

Table 1

Fish species used in the 2002 and 2003 caged fish measurements, and the average length of each individual.

Fish name	Fish species	Length (cm)
2002		
Red hind	*Epinephelus guttatus*	20.2
Coney	*Epinephelus fulvus*	21.3
White grunt	*Haemulon plumieri*	16.0
Pluma	*Calamus pennatula*	17.9
Blue tang	*Acanthurus coeruleus*	18.0
2003		
Squirrel fish	*Holocentrus* spp.	22.9
Black durgeon	*Melichthys niger*	27.9
Ocean file fish	*Canthidermis sufflamen*	45.7
Ocean surgeon fish	*Acanthurus bahianus*	41.9
Butter grouper	*Mycteroperca* spp.	25.4

Results

Geographic distribution of spawning aggregations

The distribution of the red hind spawning aggregations during the 2002 and 2003 survey periods are presented by regional subarea in Fig. 1. The geographic (latitude/longitude) locations, time of observation, and estimated

Table 2

Mean observed spawning red hind *(Epinephelus guttatus)* density (presumed) in 2002 for each designated survey area. Sequences are defined as the 1-min field echo integration intervals (approximately 150 m long at 5 knots).

Area	Location	Fish/km^2	Sequences surveyed	Sequences w/schools	Percent w/schools	Transect length (km)
A	Cabo Rojo and Mayaguez	1,286	777	67	8.62%	91.5
B	Arroyo and Vieques	1,357	1144	74	6.47%	110.6
C	Cabo Rojo to Cayo Parguera	395	834	85	10.19%	143.1
D	Ponce to Arroyo	962	1073	102	9.51%	182.0

Table 3

Mean observed red hind *(Epinephelus guttatus)* density (presumed) in 2003 for each designated survey area. Sequences are defined as the 1-min field echo integration intervals (approximately 150 m long at 5 knots).

Area	Location	Fish/km^2	Sequences surveyed	Sequences w/schools	Percent w/schools	Transect length (km)
C	Mona	20,443	412	154	37.4%	63.7
C	Desecheo	10,559	82	26	31.7%	9.9
C	Bajo de Cico	4,544	148	82	55.4%	19.9
C	West coast	686	151	3	2.0%	20.3
B	Northwest coast	629	897	47	5.2%	153.3
A	Northeast coast	32	822	24	2.9%	128.2

mean aggregation density (in fish/m^2) are presented for each designated survey area in Table 2 for 2002 and Table 3 for 2003. The acoustic data sets were carefully scrutinized during the analysis process and only coherent, vertically-stacked aggregations of fish were included in the red hind spawning density estimates (Fig. 2). Based on prior knowledge of red hind spawning behavior and the targeted nature of the hydroacoustic surveys, the stacked aggregations were presumed to consist solely of red hind.

Comparison of estimated overall spawning red hind densities in 2002 and 2003

Highest densities were observed associated with either islands or reef areas off of the west coast of the island (Fig. 3). The area surrounding Mona Island had the highest estimated spawning densities (20,443 fish/km^2). Desecheo, in the same general area, had approximately half the spawning density (10,559 fish/km^2) of Mona Island. The Bajo de Cico rise area had estimated spawning densities of 4,544 fish/km^2. The area between Arroyo and Vieques Island had the fourth highest estimated spawning densities (1,357 fish/km^2). Estimated spawning densities along the north and south coasts of Puerto Rico were consistently low, and were lowest off of the northeast coast (32 fish/km^2).

Comparison of acoustic spawning estimates and fishing vessel distribution in 2002

The location of fishing boats targeting red hind, based on Puerto Rico Dept. of Natural and Environmental Resources overflights conducted on 14 February 2002 and 23 January 2003, are shown in Fig. 4, along with the distribution of spawning aggregations observed by the hydroacoustic surveys. The location of fishing vessels was closely associated with the occurrence of schools of red hind, as observed by the hydroacoustic surveys conducted later.

Caged fish target strength experiments

Table 4 presents the mean dorsal aspect target strength and surrounding standard deviation for red hind and nine other species measured during the caged fish target strength experiments. The 2002 experiments revealed mean target strength values of approximately –37 dB for red hind (20 cm in length) and for coney (21 cm in length). White grunt, although physically smaller (16 cm) than the red hind, returned higher target strength values (–32 dB), perhaps due to differing morphology or swim bladder size. The single example of blue tang measured was 18 cm in length and returned a target strength value of –33 dB, also larger than the mea-

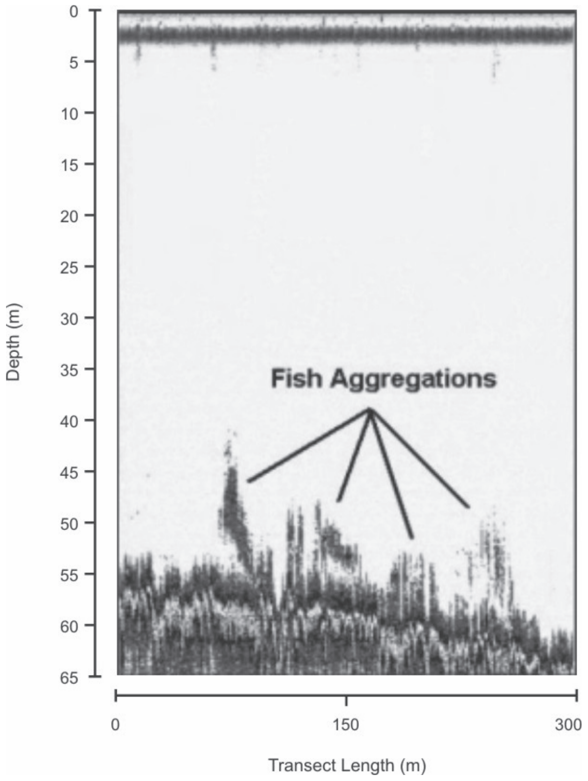


Figure 2

Example hydroacoustic echogram showing identified aggregations near the bottom of the shelf edge. Horizontal scale represents distance (m) along transect line. Vertical axis represents depth (m).

sured grouper species. Eight pluma were acoustically measured during the caged fish experiments, varying in length from 16–24 cm. Pluma returned the smallest mean target strength values, averaging –43 dB, indicating that they reflect less energy from the acoustic signal than the other evaluated species.

The 2003 experiments produced similar target strengths for 23 cm squirrel fish (–35 dB), 28 cm black durgeon (–36 dB), 46 cm ocean file fish (–32 dB), 42 cm ocean surgeon fish (–32 dB), and 25 cm butter grouper (–33 dB).

Discussion

The Puerto Rico 2002–2003 spawning red hind population surveys demonstrated the feasibility of hydroacoustic survey techniques for quantification of schooled spawning aggregations along the continental shelf during the brief full moon spawning period in early spring. The use of fish behavior, specifically the known site fidelity and timing of red hind spawning aggregations, to infer a red hind population in a mixed-species environment was an innovative aspect of the study. However, this inference was also an aspect of the research worthy of additional investigation in future hydroacoustic sampling of red hind and other grouper species exhibiting similar aggregating behavior during spawning. The tight sampling timetable mandated by the requirement to cover large areas of the Puerto Rican coastline within a day of the full moon spawning period did not allow for interruptions to directly sample school aggregations for species identification. The vertically-stacked coherent schools were unique and readily identified from the more frequently observed diffuse and horizontally spread fish aggregations. However, the density estimates obtained may include species other than red hind (Whaylen et al., 2004; Luckhurst[5]). Species-inference of the resulting density estimates based on the vertical schools was solely based on their shape, near-shelf distribution, and timing (proximity to the full-moon). These characteristics, along with the occurrence of fishing vessels targeting red hind, were assumed to uniquely identify spawning red hind schools.

Table 4

Summary of the observed acoustic target strength values of 10 species of caged fish during 2002 and 2003.

Fish species	Length (cm)	Target strength (dB)	Standard dev.	Number echoes
2002				
Red hind	20.2	–36.6	2.95	73
Coney	21.3	–37.1	3.31	440
White grunt	16.0	–31.9	0.59	48
Pluma	17.9	–43.2	2.58	124
Blue tang	18.0	–33.4	1.38	16
2003				
Squirrel fish[1]	22.9	–35.1	2.07	21
Black durgeon	27.9	–35.8	4.39	696
Ocean file fish	45.7	–31.7	4.87	475
Ocean surgeon fish	41.9	–32.0	2.42	549
Butter grouper	25.4	–33.2	2.64	225

[1] Dead upon retrieval from cage.

Recommendations for future quantitative population surveys of this resource include incorporation of additional species identification sampling. Options include

---

[5] Luckhurst, B. 2001. Policies, legislation and management options. Workshop report, Towards sustainable Management of Nassau groupers in Belize, Belize City, 30 July 2001. Marine Resources Divison, Bermuda Dep. of Env. Prot., P.O. Box CRS2, Crawl CRBX, Bermuda.

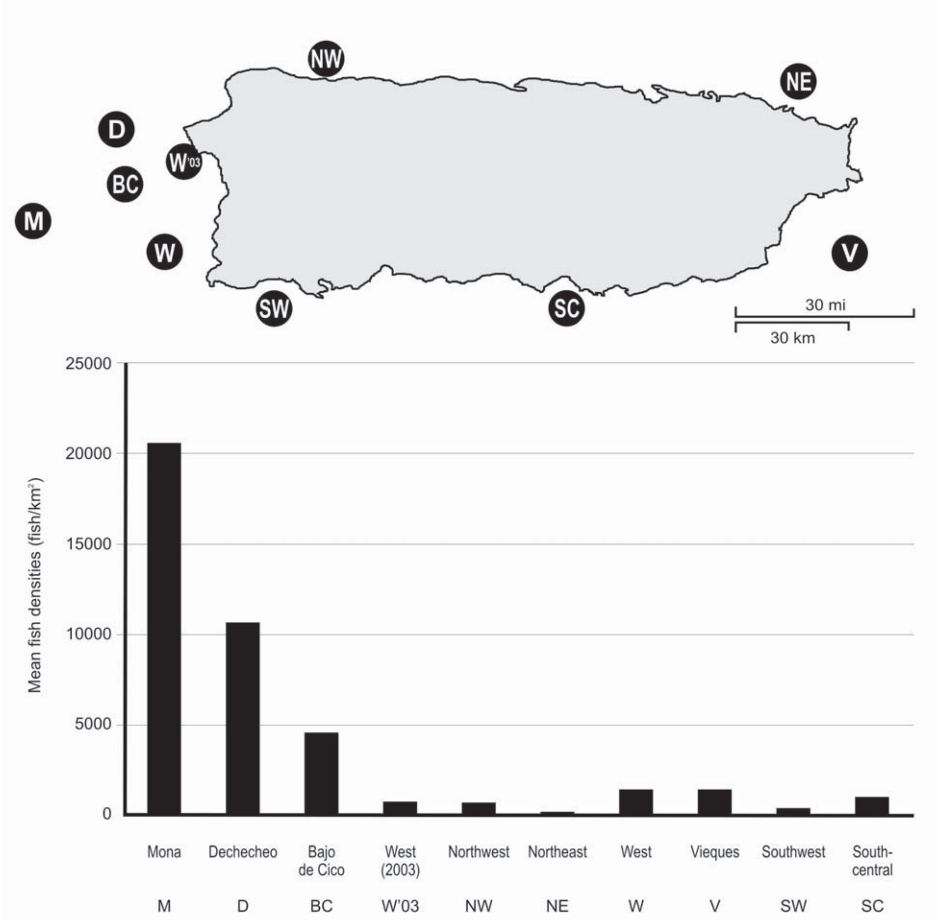


Figure 3

Number of spawning red hind *(Epinephelus guttatus)* per square kilometer by geographic area along the Puerto Rican costal shelf, as estimated by 2002 and 2003 hydroacoustic surveys. Densities on the bar chart are coded and referenced to general geographic location on the map insert.

video, divers, or hook and line sampling. These efforts should be supported by an independent vessel in contact with the hydroacoustic survey boat, which could identify observed school aggregations for investigation.

It would also be worthwhile to investigate spawning aggregation persistence, that is, whether red hind spawn in the same general areas over time. Spawning aggregation persistence could be readily measured within a designated area by a single vessel conducting repetitive survey transects. These longer-term acoustic surveys could also be used to investigate the patchiness of red hind spawning in time over the months of January-March. The fidelity of spawning relative to the full moon phase (number of days over which significant spawning activity occurs) should also be investigated by repetitive acoustic surveys. If spawning activity occurs over a longer time frame than targeted by these acoustic surveys, the overall estimates of spawning biomass could be affected.

Adding hydroacoustic survey transects inshore of the shelf break areas would aid in defining the overall red hind spawning habitat area surrounding Puerto Rico (J. Rivera, pers. observ.). Defining spawning habitat would allow for better identification and delineation of spawning habitats for red hind and potentially other aggregating grouper species around Puerto Rico. In addition, side scan or multi-beam bottom profiling acoustic systems (or geo-referenced data acquired by these systems at an earlier time) could be employed to correlate benthic habitat types with the observed red hind densities. These data may also help to better define spawning habitat for the species.

In general, the mean target strength results of the caged fish experiments for red hind and nine other

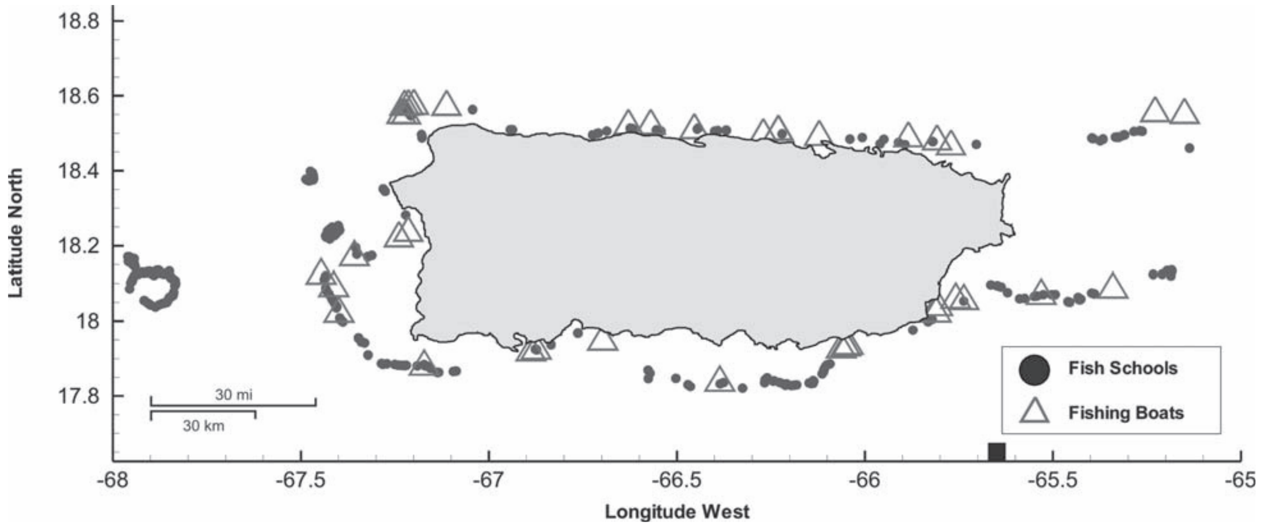


Figure 4

Overview of the entire acoustically-surveyed area in 2002 and 2003 showing the observed school aggregations along the sampled route and the positions of fishing vessels observed targeting red hind *(Epinephelus guttatus)*, based on Puerto Rico Dept. of Natural and Environmental Resources aerial survey data.

species were in agreement with the expected length-to-target strength relationship of Love (1971), with the exception of white grunt and pluma. These two species appeared to have higher backscatter values than would be predicted using this relationship. The observed mean in situ target strength values for the observed vertically-stacked fish aggregations enumerated in 2002–2003 were consistent with the controlled measurements of known red hind, varying between approximately –37 and –42 dB. It would be advisable to conduct additional caged fish target strength experiments on individual red hind specimens over the entire expected length distribution of the species (approximately 10–80 cm). Using these data, a target strength-to-length relationship for the species could be developed. These data would also aid in scaling density estimates and permit examination if unique acoustic descriptors exist that could aid in resolving red hind from other species.

Literature cited

Appledoorn, R., J. Beets, J. Bohnsack, S. Bolden, D. Matos, S. Meyers, A. Rosario, Y. Sadovy, and W. Tobias.
1992. Shallow water reef fish stock assessment for the U.S. Caribbean. NOAA Tech Memo NMFS-SEFSC-304, 70 p.

Burczynski, J. J.
1979. Introduction to the use of sonar systems for estimating fish biomass. Food and Agriculture Organization of the United Nations, Rome, FAO Technical Paper No. 191, 89 p.

Kanciruk, P.
1982. Hydroacoustic biomass estimation techniques. Oak Ridge National Lab., Environ. Sci. Div., Publ. No. 2019.

Love, R. H.
1971. Dorsal-aspect target strength of an individual fish. J. Acoust. Soc. Am. 49:816–823.

Matos-Caraballo, D.
2004. Overview of Puerto Rico's small-scale fisheries statistics, 1998–2004. Proceedings of the Gulf and Carib Fish. Inst. 55:103–118.

MacLennan, D. N., and E. J. Simmonds.
1992. Fisheries Acoustics. Chapman and Hall, London, 325 p.

Nemeth, R. S.
2005. Population characteristics of a recovering U.S. Virgin Islands red hind spawning aggregation following protection. Marine Ecology Prog. Series 286:81–97.

Sadovy, Y.
1994. Grouper stocks of the western central Atlantic: the need for management and management needs. Proceedings of the Gulf and Carib. Fish. Inst. 43:43–64.
1997. The case of the disappearing grouper: *Epinephelus striatus*, the Nassau grouper, in the Caribbean and Western Atlantic. Proceedings of the Gulf and Carib. Fish. Inst. 45:5–22.

Sadovy, Y., A. Rosario, and A. Roman.
1994. Spawning dynamics in an aggregating grouper, the red hind, *Epinephelus guttatus*. Environ. Biol. Fish., 41:269–286.

Shapiro, D. Y.
1993. Size, composition, and spatial structure of the annual spawning aggregation of the red hind, *Epinephelus guttatus* (Pisces: Serranidae). Copeia 1993(2):399–406.

Whaylen, L, C. Pattengill, B. Semmens, P. Bush, and M. Boardman.
2004. Observations of a Nassau grouper, *Epinephelus striatus*, spawning aggregation site in Little Cayman, Cayman Islands, including multi-species spawning information. Environ. Biol. Fish 70:305–313.

Nassau grouper (*Epinephelus striatus*) spawning aggregations: hydroacoustic surveys and geostatistical analysis

J. Christopher Taylor
Department of Zoology
Center for Marine Sciences and Technology
North Carolina State University
303 College Circle
Morehead City, NC 28557
E-mail: chris_taylor@ncsu.edu

David B. Eggleston
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Campus Box 8208
Raleigh, NC 27695-8208

Peter S. Rand
The Wild Salmon Center
The Natural Capital Center
721 NW 9th Avenue, Suite 290
Portland, OR 97209

Abstract—With the near extinction of many spawning aggregations of large grouper and snapper throughout the Caribbean, Gulf of Mexico, and tropical Atlantic, we need to provide baselines for their conservation. Thus, there is a critical need to develop techniques for rapidly assessing the remaining known (and unknown) aggregations. To this end we used mobile hydroacoustic surveys to estimate the density, spatial extent, and total abundance of a Nassau grouper spawning aggregation at Little Cayman Island, Cayman Islands, BWI. Hydroacoustic estimates of abundance, density, and spatial extent were similar on two sampling occasions. The location and approximate spatial extent of the Nassau grouper spawning aggregation near the shelf-break was corroborated by diver visual observations. Hydroacoustic density estimates were, overall, three-times higher than the average density observed by divers; however, we note that in some instances diver-estimated densities in localized areas were similar to hydroacoustic density estimates. The resolution of the hydroacoustic transects and geostatistical interpolation may have resulted in over-estimates in fish abundance, but still provided reasonable estimates of total spatial extent of the aggregation. Limitations in bottom time for scuba and visibility resulted in poor coverage of the entire Nassau grouper aggregation and low estimates of abundance when compared to hydroacoustic estimates. Although the majority of fish in the aggregation were well off bottom, fish that were sometimes in close proximity to the seafloor were not detected by the hydroacoustic survey. We conclude that diver observations of fish spawning aggregations are critical to interpretations of hydroacoustic surveys, and that hydroacoustic surveys provide a more accurate estimate of overall fish abundance and spatial extent than diver observations. Thus, hydroacoustics is an emerging technology that, when coupled with diver observations, provides a comprehensive survey method for monitoring spawning aggregations of fish.

Introduction

Reef fish spawning aggregations have gained distinction in terms of their importance in species conservation and their socio-economic contribution to many Caribbean, tropical western Atlantic, and Gulf of Mexico fishing communities. With the near extinction of many spawning aggregations of large grouper and snapper throughout the Caribbean, Gulf, and tropical western Atlantic, it is essential that we increase our ability to study and document the remaining known (and unknown) aggregations to provide baselines for their conservation (Sadovy, 1994; Sadovy, 1997; Sala et al., 2001; Colin et al., 2003).

The Nassau grouper (*Epinephelus striatus*) is a commercially important tropical reef species that forms discrete spawning aggregations, typically around full moons from December to March (Sadovy and Eklund, 1999). Historically, spawning aggregations of Nassau grouper have occurred throughout the Caribbean, tropical western Atlantic, and Bermuda (Sadovy, 1997; Sadovy and Eklund, 1999). Nassau grouper often migrate great distances (in some cases documented on a scale of 100's of km) to aggregate on reefs at promontories of islands (Colin et al., 1987; Colin, 1992; Bolden, 2000). Long-term monitoring and anecdotal evidence from fisheries have documented use of the same site by some aggregations for as long as 30 years, suggesting high site fidelity by the species (Colin, 1996). Nassau grouper have been the most valuable finfish in the insular Caribbean and the tropical western Atlantic (Sadovy and Eklund, 1999; Sala et al., 2001), and heavy exploitation primarily during spawning seasons has resulted in local extirpation of most aggregations in the Cayman Islands, Bahamas, and Belize (Sadovy, 1997; Sala et al., 2001).

Hydroacoustics has emerged as a valuable tool in fishery population assessments throughout the world. Hydroacoustics provides a method of 1) non-invasively sampling fish

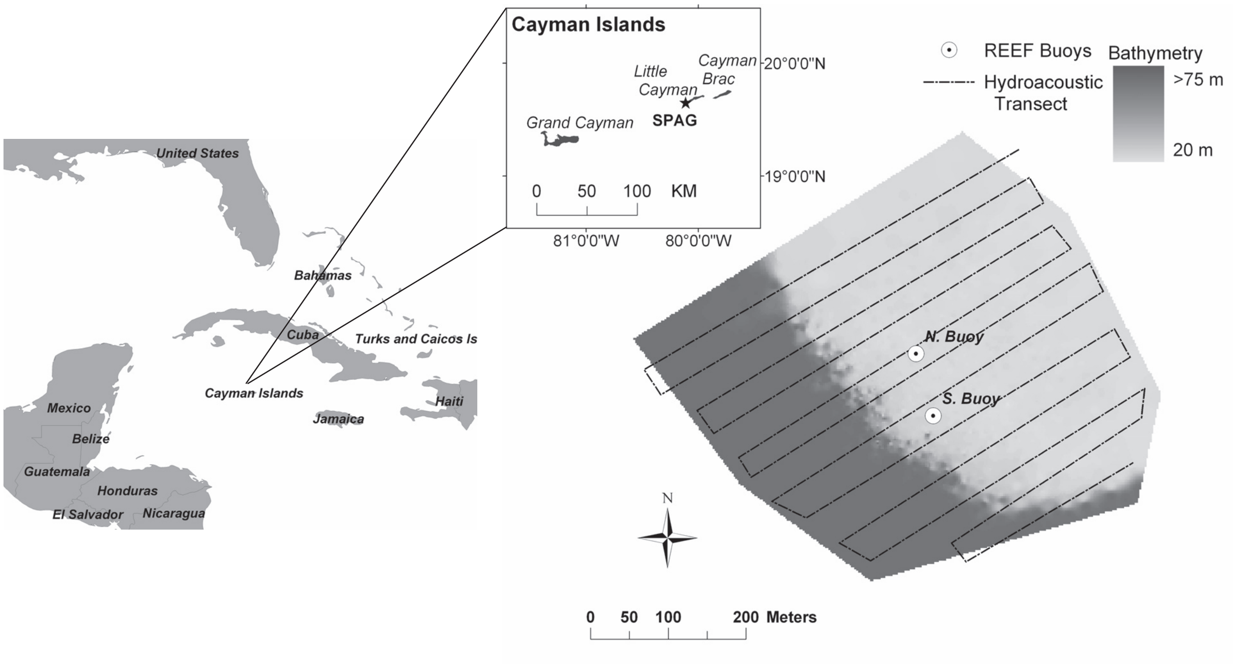


Figure 1

Nassau grouper spawning aggregation survey site at Little Cayman Island, Cayman Islands, BWI, as indicated by star and spawning aggregation (SPAG) in inset. Reef Environmental Education Foundation (REEF) marker buoys (north and south buoys) indicate location of 100-m dive transect line parallel to shelf-break. Idealized rectangular hydroacoustic transect design is overlaid on interpolated bathymetry, which is represented as grayscale shading. The hydroacoustics transect was completely surveyed twice in two segments.

communities, 2) collecting spatially continuous data in three dimensions along transects providing distribution information on sub-meter to kilometer scales, and 3) rapidly assessing fish abundance and distribution over large areas within marine systems. While the technology provides acoustic size of fish targets, supplemental sampling or groundtruthing is still needed to identify species composition and verify size distributions.

Applying fisheries hydroacoustics to assess reef species is rarely done, because it is difficult to verify species and resolve fish targets closely associated with bottom relief. Hydroacoustics may be useful in situations where fish form very large, single species aggregations during spawning, as observed in cod (*Gadus morhua*) (Lawson and Rose, 2000) and orange roughy (*Hoplostethus atlanticus*) (Bull et al., 2001). Formation of very large aggregations (>1000 fish) makes underwater visual censuses by scuba divers and assessments of spatial distributions difficult due to limitations in bottom time (especially at depths exceeding 30 m) and visibility (often reduced due to low water clarity and low light conditions). In such cases, hydroacoustics may provide a suitable means to assess reef fish abundance.

The objectives of this work were to 1) test the applicability of mobile hydroacoustics as a repeatable survey method to rapidly assess a Nassau grouper spawning aggregation, 2) apply geostatistical models to produce objective measures of the spatial extent and total abundance of grouper in an aggregation, and 3) compare distribution, density, and abundance estimates with diver-visual surveys. For this paper, we focus on a survey of a single Nassau grouper spawning aggregation at Little Cayman Island, Cayman Islands, BWI, in January 2003.

Methods

Study sites

Hydroacoustic and diver surveys were conducted near Little Cayman Island, Cayman Islands, BWI, on 23 January 2003 (Fig. 1). The site is located on a promontory on the southwestern end of Little Cayman. The shelf slopes from shore out 0.6 km to a depth of 24–33 m at the shelf edge (Fig. 1). Bottom relief at the site is as much as

5 m and made up of hard and soft corals, sponges, and large expanses of sand. Scientists have observed annual spawning aggregations of Nassau grouper at this site since 2001 (Whaylen et al., 2004).

Underwater visual survey

Scuba divers conducted underwater visual surveys beginning at 1430h on 23 January 2003. Marker buoys were deployed by Reef Environmental Education Foundation (REEF) at the end of a 100-m transect line. The transect line ran parallel to the shelf-break and served as a general marker for the location of the aggregation. It was located approximately 20 m inshore of the main group of aggregating Nassau grouper (Fig. 1). Three divers spent approximately 35 to 50 minutes in the water and either swam on the shoreward side of the 100 m transect line, swam as far as 100 m to the southeast of the line, or maintained position at a point along the transect and documented fish behaviors, color patterns, and estimated total abundance. Divers estimated their area searched using the 100-m transect line as a reference. Divers also used 30-cm measuring poles to estimate fish lengths underwater. The total number of fish at the aggregation site was subsequently estimated by at least one of the divers. Density estimates were calculated by dividing the total counts made by divers by the estimated area searched.

Hydroacoustic equipment deployment

The hydroacoustic survey was conducted during the afternoon immediately following the dive survey. The hydroacoustic survey design consisted of a set of 9 to 16 parallel transects 0.3 to 0.5 km in length and spaced approximately 20- to 30-m apart. Transects ran perpendicular to shore from the 20-m depth contour nearshore to >100-m depths offshore (Fig. 1). The complete set of transects was covered twice in two survey segments. The first segment began at 1550 h, and the second segment began at 1640 h.

We used a HTI Model 241 200 kHz split-beam echosounder (Hydroacoustic Technology Incorporated, Seattle, WA) coupled with a circular (6° nominal beam dimension) transducer. The transducer was mounted to a 1.2-m long towbody towed 0.5- 1.5-m below the water surface rigged from a 1.5-m boom attached mid-ship on the starboard side of a 9-m dive support vessel traveling at about 2 m s^{-1}. Rigging of the towbody included a shock-dampening system that minimized the oscillations due to pitch and roll of the vessel. Ping rate was 5 pulses s^{-1} and the pulse width was 0.18 ms during all transect runs. Target resolution was calculated based on pulse width and sound velocity and found to be approximately 0.2 m; however due to significant bottom relief, fish targets were usually not resolved from reefs at distances less than about 1 m. At the beginning of the cruise we conducted an *in situ* system calibration using a tungsten-carbide reference sphere of known target strength placed greater than 5-m from the transducer (MacLennan and Simmonds, 1992). The data were acquired in real-time for split-beam and echo-integration data processing (HTI DEP v. 3.54, HTI Seattle, WA) and stored as text files on a laptop computer for data analyses.

Hydroacoustic data processing

Hydroacoustic data were post-processed using split-beam and echo-integration analyses. Split-beam analysis was used to determine acoustic size (target strength) of individual fish targets in decibels (dB). Algorithms were used to accumulate several consecutive echoes from individual fish to produce an average acoustic size and 3-dimensional position within the water column (HTI Echoscape v. 2.11, HTI, Seattle, WA). Target strength is proportional to fish size (MacLennan and Simmonds, 1992), and using established equations for reef species encountered during previous studies (Ehrhardt and Deleveaux[1]), target strengths were converted to fish size (cm TL) and verified to species during dive surveys. Only fish target strengths between –50 and –25 dB were used for split-beam analysis, representing the range of fish sizes observed by divers. Split-beam analysis was used to locate and enumerate large targets that likely represented Nassau grouper. On numerous occasions during the surveys of the aggregation site at Little Cayman, fish targets were densely packed, making split-beam analysis difficult due to overlapping echoes. In these instances, individual targets that were on the periphery of the aggregation were used to generate size estimates.

When targets overlapped and individual echoes were not discernable, echo-integration was used to estimate density of fishes present. Echo-integration (EI) is based on the principle that the total sound energy returned from an ensonified volume of water is proportional to the fish density. When scaled to the average fish size observed, volumetric densities (fish m^{-3}) can be estimated. Returning acoustic energy was binned into geo-referenced (latitude/longitude) elementary distance sampling units (EDSU) having dimensions of 20-m along the horizontal axis and 0.25-m on the vertical axis. For each EDSU, the average fish size was determined through split-beam analysis, either from analyses of fish in that cell or mean size of the fish observed along the transect when single targets were not discernable within

---

[1] Ehrhardt, N. M., and V. Deleveaux. 1999. Report on the 1999 Nassau grouper stock assessment in the Bahamas. University of Miami RSMAS/MBF, Miami, FL 33149-1098.

a cell. The total acoustic energy was then standardized by this average fish acoustic size, which allowed for estimates of absolute fish density (fish m^{-3}) for each EDSU. Two-dimensional densities (fish m^{-2}) were then calculated by summing the density estimates for each EDSU in the vertical dimension.

Abundance estimates

Mean fish density, spatial extent, and total fish abundance were calculated for each of the two survey segments. An estimate of total survey coverage was also calculated using the georeferenced transects in a GIS. Total abundance was calculated using arithmetic extrapolation and geostatistical modeling. First, mean fish density, calculated from all EDSUs in the entire sampling region, was extrapolated over the total survey area. Second, we used a two-stage geostatistical modeling procedure to estimate the spatial extent, fish density, and total fish abundance within the aggregation. Echo integration data from each transect was reclassified as a "mark" and scored as a one when fish were present within an EDSU; when they were absent, they were not a "mark" and scored as a zero. The spatial structure of the "marks" was calculated using a classical variogram estimator and a spherical variogram model was fitted with weighted non-linear least squares (Cressie, 1993). The survey area was divided into 20-m square cells and indicator kriging was used to predict the probability of a "mark" occurring in each of the cells based on the variogram and proximity to the sampled locations (Rossi et al., 1992). Cells for which the probability of occurrence was greater than 0.5 were designated as "mark." The number of marked cells and total area were calculated to determine the spatial extent (in m^2) of the aggregation during each segment. The second stage of the modeling procedure used block kriging to determine the average density within the predicted "mark" region (Isaaks and Srivastava, 1989; Cressie, 1993). Block-kriged mean fish density was extrapolated over the estimated spatial extent of the aggregation to produce a global estimate of fish abundance for each sampling segment. All spatial analyses and visualizations were performed in SPLUS (v. 6.1, Insightful Corp., Seattle, WA) and ARCVIEW (v. 8.3, ESRI Corp., Redlands, CA).

Results

Dive survey

Divers counted a total of 450 grouper over approximately 5,400 m^2 searched. Fish were observed in three separate groups, one group south of the south buoy of the 100-m transect (250 fish in approximately 900 m^2), another group on the southern end of the 100-m dive transect (150 fish in approximately 2000 m^2), and a smaller group of fish lying on the bottom to the northeast and closer to shore (50 fish in approximately 2500 m^2). Observations from divers identified and visually estimated lengths of 20 Nassau grouper with an average of 60 cm TL and a range of 35 to 75 cm TL.

Hydroacoustic survey

Dense aggregations of Nassau grouper were observed during both segments of the hydroacoustic survey resulting in occasions where individual echoes were not discernable due to fish target overlap. Statistics on target strengths were limited to tracks that had a minimum of four echoes in a sequence and produced traces indicative of a single fish passing through the acoustic beam. Typically, these targets were located on the outer boundaries (either vertically or horizontally) of the aggregation. Individual fish sizes ranged from –26– –46 dB. Using established conversion equations, these target sizes equate to Nassau grouper of approximately 60–90 cm TL. There was no significant difference between fish sizes observed during the two segments (Kolmogorov-Smirnov test, $P>0.1$), though the number of targets differed between segments. A total of 135 and 90 targets were tracked during the first and second segment, respectively.

The location of the aggregation was restricted to the shelf break on the southern portion of the survey region (Fig. 2). In most cases, the Nassau grouper aggregation was well off the bottom (Fig. 3). Other aggregations of relatively large acoustic targets were observed outside the region typically observed by divers. Because we could not be sure that these targets were Nassau grouper, those marks were not included in estimates of aggregation spatial extent or fish abundance. Fish density estimates for the two segments ranged from 0 to 1.50 fish m^{-2} (0 to 1.05 fish m^{-3}) and 0 to 1.05 fish m^{-2} (0 to 0.74 $fish^{-3}$), respectively. Average estimated fish density over the entire survey region, ignoring spatial correlation in the data, was 0.05 and 0.03 fish m^{-2} for segment 1 and 2, respectively. Total spatial coverage of the survey was approximately 134,266 m^2. Extrapolating these average fish density estimates over the entire sampling region resulted in total fish abundances of 6713 and 4027 fish in segment 1 and 2, respectively.

Both segments produced similar spatial extent maps with fish located from just south of the north buoy to nearly 200 m south of the south buoy (Fig. 2). Estimated spatial extents for the aggregation during the two segments were 6372 m^2 and 9628 m^2, respectively. Average density within the aggregation was 0.32 and 0.21 fish m^{-2} for segments 1 and 2, respectively. Abundance estimates

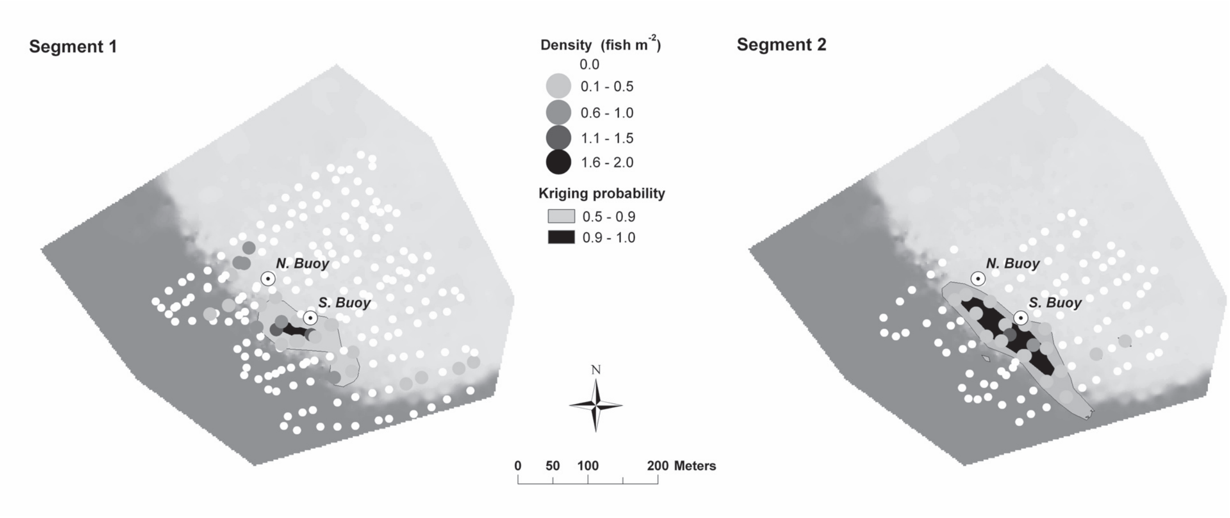


Figure 2

Distribution of Nassau grouper densities from two segments of the hydroacoustic survey of the Little Cayman spawning aggregation site. Bathymetry and REEF marker buoys are shown as in Fig. 1. White circles indicate zero fish observed, positive densities are according to gray scale in legend. Results of indicator kriging of spatial extent of the fish aggregation are noted by outlined grayscale-shaded polygons indicating probability of occurrence.

using the two-stage kriging procedure were 2039 fish for segment 1 and 2022 fish for segment 2.

Discussion

We successfully located the Nassau grouper spawning aggregation off Little Cayman, BWI during both segments of the hydroacoustic survey. In general, the aggregation was observed at or near the shelf-break, although divers observed a smaller group of fish shoreward of the shelf-break that was not observed during the hydroacoustic survey. This may be because the acoustic transects did not cover this area adequately, the fish were too close to the bottom to be detected, or the grouper had moved prior to the hydroacoustic transect coverage. In some cases, other groups of large acoustic targets were located well outside the region observed by the divers. Because previous surveys of Nassau grouper showed that in certain instances target strengths of other species were sometimes quite similar to Nassau grouper, we were reluctant to assign these targets to the Nassau grouper abundance estimate (Taylor, Eggleston, and Rand, unpubl. data). Unfortunately, it was not feasible to use divers to verify the species in these outer groups, so their identity remains unknown. Estimates of the spatial extent and abundance were restricted to those regions that were surveyed by divers.

Other species are known to use the site at Little Cayman as a spawning aggregation site (Whaylen et al., 2004). During our study, the Little Cayman aggregation site did contain a mix of smaller species in close proximity to the Nassau grouper. When smaller fish were mixed in with the Nassau grouper, it was easy to delineate larger targets that were likely grouper from the smaller targets that represented other smaller species. Larger species such as bar jack (*Caranz rubber*) and horse-eye jack (*Caranx latus*) were also present at the aggregation site during our study, but these species were located over deeper water or were distant from the main concentration of Nassau grouper. These marks were excluded from the acoustic analysis.

Average density of Nassau grouper over the entire survey region estimated arithmetically from hydroacoustic data was similar to the average overall grouper density estimated from the dive survey. Grouper densities within the aggregation site estimated using hydroacoustics were on average three times the average density observed by divers; however, densities as high as 0.27 fish m^{-2} were observed by divers in one of the three separate groups. During this survey, it was clear that fish density was not uniform over the aggregation site. Other observations using underwater video provide indications that volumetric densities varied throughout the aggregation and were even twice as high as those observed using hydroacoustics (Rand, unpubl. data). These high fish densities were restricted to a very localized region within the aggregation site and may have been missed by the hydroacoustics or difficult to quantify by divers. Patchy or non-uniform distributions of fishes at spawn-

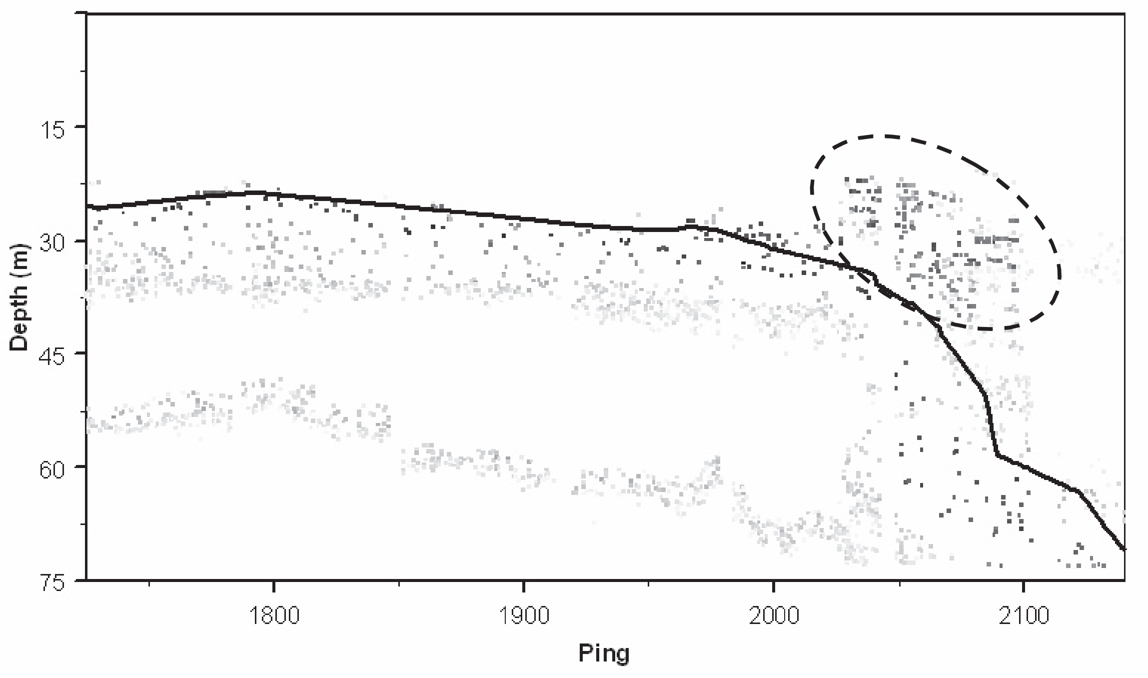


Figure 3

Echogram example for a Nassau grouper spawning aggregation positioned at the shelf break at the Little Cayman site highlighted by hashed oval. Fifty pings along the x-axis represent approximately 20 m linear distance.

ing aggregation sites has been observed in other reef fish species (Shapiro et al., 1993).

Although estimates of average grouper densities over the entire region were similar between divers and hydroacoustics, total abundance estimates were not. The large differences in areas searched by each method may help to explain the discrepancies between the total abundance estimates from the two methods. The divers were only able to survey a total of 5400 m^2 compared to over 134,000 m^2 surveyed using hydroacoustics. Diver observations also may have been confounded by low water clarity and light level, which limits visibility, especially during dusk. In some cases, especially during periods of high grouper densities, it may have been difficult for divers to make accurate counts of fish that were exhibiting rapid movements. Due to limitations in bottom time using scuba, divers were not able to search the entire areal extent of the grouper aggregations as revealed by the hydroacoustics.

The extrapolation of the arithmetic hydroacoustic density estimates over the entire survey region produced abundance estimates that were two to three times higher than the estimates using the geostatistical models. The arithmetic estimates were also an order of magnitude higher than those made by divers. This result comes as no surprise as the presence of spatial correlation in the data, particularly the patchy nature of spawning aggregations, can result in significant biases in global estimates of abundance. Previous efforts to estimate Nassau grouper population abundance using a simple extrapolation method have been criticized for not recognizing such biases (Ehrhardt and Deleveaux[1]; Gascoigne[2]). Abundance estimates calculated using the two-stage kriging method, on the other hand, implicitly incorporate the patchy nature of the distribution pattern and produce a more robust estimate of abundance. Still, there may be some limitations to this two-stage kriging approach. First, abundance estimates using this method are dependent upon accurate estimates of the spatial extent of the aggregation. The hydroacoustic transects were spaced 30 m apart and kriging probability interpolations may have interpolated high densities of fishes between transects, when in fact the groups may have been separated by as much as 30 m. This was likely the case for our estimates of grouper abundance and spatial extent on the mid-day survey of 23 January 2003, since divers reported a disaggregated pattern of distri-

---

[2] Gascoigne, J. 2002. Nassau grouper and queen conch in the Bahamas: State and management options. 44+iv p. http://www.breef.org/groupersummary.pdf [Accessed 20 December 2004.]

bution. A closer examination of the density distributions during segment 1 indicates a possible break in the high-density marks, implying that the Nassau grouper were in separate groups. The region of this separation was not sampled during segment 2 (Fig. 2).

Previous applications of hydroacoustics coupled with geostatistical approaches have worked well on other aggregating species (Rivoirard et al., 2000). For deep-water species such as cod (*Gadus morhua*) and orange roughy (*Hoplostethus atlanticus*), acoustics provide the principal method for fishery independent population estimates during spawning periods (Lawson and Rose, 2000; Bull et al., 2001). The orange roughy typically forms a contiguous group over deep sea mounts (Doonan et al., 2003). Using a star-transect pattern and analyzing the data using a similar two-stage kriging model, Doonan et al. (2003) estimated orange roughy abundance with good precision. However, they do note that accurately positioning the aggregation in the transect pattern can affect the precision of the spatial extent and abundance estimates (Doonan et al., 2003). If fish are not in a contiguous unit, as was the case in our study, abundance estimates may not be as reliable (Doonan et al., 2003).

Despite difficulties making accurate estimates of abundance under patchy fish distributions, mobile hydroacoustic surveys coupled with the geostatistical probability mapping still provides an objective, repeatable measure of the spatial extent of the aggregation. Estimates such as these are valuable when establishing boundaries for reserves or area closures during spawning seasons, and in estimating overall fish abundance (Glazer and Delgado, this issue).

A recognized limitation of the acoustic method is that the fish need to be greater than 1–2 m from the bottom relief to be detected. Large reef species such as snapper and grouper are known to be cryptic and closely associated with the structure of the bottom (Sale and Douglas, 1981). Previous efforts to survey hard-bottom habitats have documented difficulties in detecting fish targets when they are in close proximity (<1-m) to the bottom (Gledhill et al., 1996). Diver observations during our afternoon survey of the Nassau grouper spawning aggregation at Little Cayman found numerous fish on or very close to the bottom. Observations made by divers during surveys of this Nassau grouper spawning aggregation at others times of the day found that most fish were well off bottom during dusk and evening surveys, presumably when fish were exhibiting more spawning behavior. When abundance estimates are desired for Nassau grouper, hydroacoustic surveys may be best suited for dusk or night periods when the fish are well into the water column (Whaylen et al., 2004). In addition to verifying species, observations by divers can provide critical data on the diel behaviors of the species and provide valuable insight into the best approach for conducting mobile hydroacoustic surveys of a known spawning aggregation.

Conclusions

The mobile hydroacoustic method provided a valuable sampling method for surveying Nassau grouper spawning aggregations. Our technique provided a means to rapidly cover large (>100,000 m^2 in less than 1 h) areas when compared to underwater visual surveys using divers (<5500 m^2 in 0.5 h). Analyzing the data using the geostatistical probability mapping provided an objective measure of the spatial extent of the aggregation. In our study, the presence and location of the Nassau grouper aggregation at Little Cayman was well-known. In many cases, however, the location of an aggregation is unknown, or may have moved several hundreds of meters on a promontory (Colin, 1992; Sala et al., 2001). In these cases, hydroacoustics can provide a method to initially survey a relatively large area and locate large targets before using divers for more fine-scale observations of fish distribution and abundance patterns, and species identification. Alternatively, coarse transects could be used to locate patches or aggregations of grouper followed by a finer-scale transect design to characterize the smaller-scale spatial structure of the group. This adaptive sampling approach can have significant advantages over a simple random stratified approach for rare, patchy or aggregating populations (Everson et al., 1996; Hanselman et al., 2003). Other advances in technology such as remotely operated vehicles (Adams et al., 1995; Johnson et al., 2003) may provide additional means to identify large targets prior to using divers to make visual observations. Thus, hydroacoustics is an emerging technology that, when coupled with diver observations, provides a comprehensive survey method for monitoring spawning aggregations of reef fishes.

Acknowledgements

We were invited to survey the Little Cayman aggregation site by the Cayman Islands Department of the Environment (CIDoE). We thank P. Bush and K. Luke with CIDoE and L. Whaylen with Reef Environmental Education Foundation (REEF) for their cooperation and collaboration in this effort. Logistical and vessel support was provided by H. Fourier and P. Hillenbrand of the Southern Cross Club. This manuscript benefited from discussions with L. Avens, S. Searcy, N. Reyns, K. Luke, P. Bush, and L. Whaylen. Funding was provided by grants from NOAA via the University of Miami (P715647 via NA17RJ1226), the NOAA Caribbean Marine Research Center (CMRC-01-NRDE-04-02A; CMRC-01-NRDE-04-03C; CMRC-00-NRDE-03-01C), PADI Project AWARE, and Sigma Xi.

Literature cited

Adams, P. B., J. L. Butler, C. H. Baxter, T. E. Laidig, K. A. Dahlin, and W. W. Wakefield.
1995. Population estimates of Pacific coast groundfishes from video transects and swept-area trawls. Fish. Bull. 93:446–455.

Bolden, S. K.
2000. Long-distance movement of a Nassau grouper (*Epinephelus striatus*) to a spawning aggregation in the Central Bahamas. Fish. Bull. 98:642–645.

Bull, B., I. Doonan, D. Tracey, and A. Hart.
2001. Diel variation in spawning orange roughy (*Hoplostethus atlanticus*, Trachichthyidae) abundance over a seamount feature on the north-west Chatham Rise. N. Z. J. Mar. Freshwat. Res. 35:435–444.

Colin, P. L.
1992. Reproduction of the Nassau grouper, *Epinephelus striatus* (Pisces: Serranidae) and its relationship to environmental conditions. Environ. Biol. Fish. 34:357–377.
1996. Longevity of some coral reef fish spawning aggregations. Copeia 1996:189–192.

Colin, P. L., Y. Sadovy, and M. L. Domeier.
2003. Manual for the study and conservation of reef fish spawning aggregations. Society for the Conservation of Reef Fish Aggregations. Special Publication No. 1, 98 p. http://www.scrfa.org. [Accessed 10 November 2004.]

Colin, P. L., D. Y. Shapiro, and D. Weiler.
1987. Aspects of the reproduction of two groupers, *Epinephelus guttatus* and *E. striatus,* in the West Indies. Bull. Mar. Sci. 40:220–230.

Cressie, N.
1993. Statistics for spatial data. Wiley Interscience, New York, 928 p.

Doonan, I. J., B. Bull, and R. F. Coombs.
2003. Star acoustic surveys of localized fish aggregations. J. Mar. Sci. 60:132–46.

Everson, I., M. Bravington, and C. Goss.
1996. A combined acoustic and trawl survey for efficiently estimating fish abundance. Fish. Res. 26:75–91.

Gledhill, C. T., J. Lyczkowski-Shultz, K. Rademacher, E. Kargard, G. Crist, and M. Grace.
1996. Evaluation of video and acoustic index methods for assessing reef-fish populations. ICES J. Mar. Sci. 53:483–485.

Hanselman, D. H., T. J. Quinn, C. Lunsford, J. Heifetz, and D. Clausen.
2003. Applications in adaptive cluster sampling of Gulf of Alaska rockfish. Fish. Bull. 101:501–513.

Isaaks, E. H., and R. M. Srivastava.
1989. Applied geostatistics. Oxford University Press, New York, 572 p.

Johnson, S. W., M. L. Murphy, and D. J. Csepp.
2003. Distribution, habitat, and behaviour of rockfishes, *Sebastes* spp., in nearshore waters of southeastern Alaska: observations from a remotely operated vehicle. Environ. Biol. Fish. 66:259–270.

Lawson, G. L., and G. A. Rose.
2000. Small-scale spatial and temporal patterns in spawning of Atlantic cod (*Gadus morhua*) in coastal Newfoundland waters. Can. J. Fish. Aq. Sci. 5:1011–1024.

MacLennan, D. N., and E. J. Simmonds.
1992. Fisheries acoustics. Chapman and Hall, New York, 352 p.

Rivoirard, J., J. Simmonds, K. G. Foote, P. Fernandes, and N. Bez.
2000. Geostatistics for estimating fish abundance. Blackwell Science, Oxford; Malden, MA, 216 p.

Rossi, R. E., D. J. Mulla, A. G. Journel, and E. H. Franz.
1992. Geostatistical tools for modeling and interpreting ecological spatial dependence. Ecol. Monogr. 62:277–314.

Sadovy, Y.
1994. Grouper stocks fo the western central Atlantic: the need for management and management needs. Proc. Gulf Car. Fish. Inst. 43:43–64.
1997. The case of the disappearing grouper: Epinephelus striatus, the Nassau grouper, in the Caribbean and Western Atlantic. Proc. Gulf Car. Fish. Inst. 45:5–22.

Sadovy, Y., and A. M. Eklund.
1999. Synopsis of biological data on the Nassau grouper, *Epinephelus striatus* (Bloch, 1792), and the jewfish, *E. itajara* (Lichtenstein, 1822). NOAA Tech. Rep. NMFS 146, 65 p.

Sala, E., E. Ballesteros, and R. M. Starr.
2001. Rapid decline of Nassau grouper spawning aggregations in Belize: Fishery management and conservation needs. Fisheries 26:23–29.

Sale, P. F., and W. A. Douglas.
1981. Precision and accuracy of visual census technique for fish assemblages on coral patch reefs. Environ. Biol. Fish. 6:333–339.

Shapiro, D. Y., Y. Sadovy, and M. A. McGehee.
1993. Size, composition, and spatial structure of the annual spawning aggregation of the red hind, *Epinephelus guttatus* (Pisces: Serranidae). Copeia 1993:399–406.

Whaylen, L., C. V. Pattengill-Semmens, B. X. Semmens, and P. G. Bush.
2004. Observations of a Nassau grouper, *Epinephelus striatus*, spawning aggregation site in Little Cayman, Cayman Islands, including multi-species spawning information. Environ. Biol. Fish. 70:305–313.

Abstract—Marine Fishery Reserves (MFRs) are being adopted, in part, as a strategy to replenish depleted fish stocks and serve as a source for recruits to adjacent fisheries. By necessity, their design must consider the biological parameters of the species under consideration to ensure that the spawning stock is conserved while simultaneously providing propagules for dispersal. We describe how acoustic telemetry can be employed to design effective MFRs by elucidating important life-history parameters of the species under consideration, including home range, and ecological preferences, including habitat utilization. We then designed a reserve based on these parameters using data from two acoustic telemetry studies that examined two closely-linked subpopulations of queen conch (*Strombus gigas*) at Conch Reef in the Florida Keys. The union of the home ranges of the individual conch (aggregation home range: AgHR) within each subpopulation was used to construct a shape delineating the area within which a conch would be located with a high probability. Together with habitat utilization information acquired during both the spawning and non-spawning seasons, as well as landscape features (i.e., corridors), we designed a 66.5 ha MFR to conserve the conch population. Consideration was also given for further expansion of the population into suitable habitats.

Designing marine fishery reserves using passive acoustic telemetry

Robert A. Glazer and Gabriel A. Delgado
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
2796 Overseas Highway, Suite 119
Marathon, FL 33050
e-mail: bob.glazer@myfwc.com

Introduction

Passive acoustic telemetry has been used for many years by fisheries and wildlife biologists to elucidate a number of life-history parameters and to examine the ecological requirements of targeted populations (White and Garrott, 1990). The technology has evolved so that tags are now smaller and battery lives are longer, thus increasing the amount of data acquired and available to the manager or researcher. Coincident with the evolving technology has been the emergence of computer programs using geospatially referenced data (i.e., Geographic Information Systems or GIS). Taken together, these tools provide opportunities for understanding how populations behave and function within the resources available to them.

At the same time, the toolbox of strategies to conserve and manage fish stocks has expanded from traditional management schemes (e.g., limited-entry fisheries, quotas) to include the consideration of no-take marine fishery reserves (MFRs) (Bohnsack, 1994). A growing body of empirical evidence now suggests that in a variety of ways, the no-take approach may enhance commercial and recreational fishers' opportunities to target a population (Lubchenko et al., 2003). In particular, studies have suggested that more and larger individuals may become available to adjacent fisheries by "spillover" from the reserve via emigration (Roberts et al., 2001), the reproductive output of the population may be enhanced by the increased spawning biomass inside the reserve (Côté et al., 2001), and there may be a concomitant enhanced supply of propagules to downstream populations (Kramer and Chapman, 1999; Martel et al., 2000; Meyer et al., 2000; Lowe et al., 2003). However, other, less obvious benefits may also occur including increasing encounters between individuals due to the reduction of Allee effects (Stoner and Ray-Culp, 2000), increased fecundity (Bertelsen and Matthews, 2001), and enhanced or restored biodiversity via cascading trophic effects (Babcock et al., 1999). Furthermore, MFRs may provide opportunities to examine the effects of various fishing strategies in a controlled environment (Bohnsack, 1998). Despite these purported benefits, there are still many unanswered questions related to the optimal design (Boersma and Parrish, 1999), siting (Crowder et al., 2000), and connectivity within MFR networks (Warner and Cowen, 2002).

To design an effective MFR, knowledge of a variety of life-history parameters and ecological requirements of the population are required (Dugan and Davis, 1993). Because the size of an effective reserve will depend in part on the daily, seasonal, and ontogenetic movements of that species (Polacheck, 1990; Lowe et al., 2003), the evaluation of the home range (Kramer and Chapman, 1999), site fidelity (Lembo et al., 1999), and movements and migrations (Zeller et al., 2003) of individuals in the population is critical.

Habitat requirements must also be incorporated into an effective MFR design (Recksiek et al., 2001; Rodwell et al., 2003). Ideally, the high-quality habitats most preferred for forage, reproduction, and refuge will be conserved and protected not only for the existing individuals in the population, but also for providing additional resources as the population expands (Allison et al., 1998; Fogarty, 1999; Murray et al., 1999; Glazer and Kidney, 2004). Ecologically critical landscape features (e.g., corridors) must also be incorporated into the design to ensure that the reserve will protect the targeted population (Recksiek and Appeldoorn, 1998; Recksiek et al., 2001; Glazer and Kidney, 2004).

Despite the widespread recognition of these critical variables, the literature is depauparate with methods that provide guidance on how to incorporate a species' life-history and habitat requirements into an effective MFR design a priori (Recksiek and Appeldoorn, 1998). Rather, there are numerous examples of the evaluation of an MFR's function after it has been established (e.g., Meyer et al., 2000). Additionally, there are comprehensive papers that describe the theoretical considerations in marine reserve design, but few that provide practical guidelines (Botsford et al., 2003).

We present here an approach that links life-history parameters with habitat utilization of the targeted species to define the spatial extent of an optimally designed MFR. The design process incorporates data obtained from acoustic telemetry studies to delineate the area encompassed, the available habitat, and the habitat used by a population targeted for protection. Socioeconomic factors, as well as larval dispersal are beyond the scope of this paper and are therefore not considered in the design criteria. The method is applied to construct an MFR designed to protect a population of queen conch (*Strombus gigas*) in the Florida Keys.

Methods

Designing an MFR

We propose an MFR design process based on the distribution and ecological requirements of the population that is targeted for protection. The data on which the design will be based are acquired using acoustic telemetry.

Initially, two important considerations must be addressed. First, the manager must conclude that an MFR is an appropriate management tool to meet a specific objective based on a variety of social, economic, political, and scientific considerations. Upon embracing this strategy, the proportion of the population targeted for protection must be identified using many of these same criteria. In many cases, the entire population is targeted for conservation; in other cases, the population may be so dispersed that conservation of the entire population is impractical.

After these determinations are made, the design process is fairly straightforward (Fig. 1). First, the distribution of the population is identified in order to preliminarily determine the approximate location of the MFR. In heavily exploited or otherwise affected populations, historical information may be required. In any case, the high-quality habitats associated with reproduction, refuge, and forage should be considered.

In the next step, both the home ranges and the habitats used by individuals in the population are determined. Passive acoustic telemetry presents a versatile and relatively inexpensive method to locate tagged individuals, an important consideration in habitat-utilizations studies. Additionally, with a global positioning system receiver, the geospatial positions of each individual can be easily obtained for home range estimations.

Recognizing that the goal of these studies is to extend the results to a population that includes untagged individuals, an appropriate sample size is required. Ideally, this determination would be made with a power test; however that may be beyond the resources of the researcher or manager. Additionally, an adequate number of individuals must be resighted to ensure sufficient statistical power. However, the number of individuals tagged will also depend upon a variety of factors, including budgetary constraints. In any case, the acoustic tagging study should be conducted at a sufficient temporal scale to ensure that short-term (i.e., diurnal) and/or long-term (i.e., seasonal) movements are captured (Glazer et al., 2003). In our previous work, we determined that conch needed to be tracked for a minimum of eight months in order to ensure that seasonal differences in movements and habitat usage did not influence site fidelity and home range estimations (Glazer et al., 2003). These values may change depending on the species under examination.

The geospatial data acquired from the acoustic telemetry are used to examine how individuals behave in their environment. Computerized methods are making these analyses increasingly accessible within GIS (Hooge et al., 2001). In our process, the location data are used in two ways. First, site fidelity of the tagged individuals is examined. This is a critical step because our process for MFR design requires examination of home ranges, and meaningful home-range estimations require a high degree of site fidelity (Hooge et al., 2001). After site fidelity is validated, the second way the geospatial data are used is to estimate the home range of each tagged individual. We suggest using a probabilistic model (i.e., kernel method) because of its accuracy and robustness (Worton, 1989; Hooge et al., 2001).

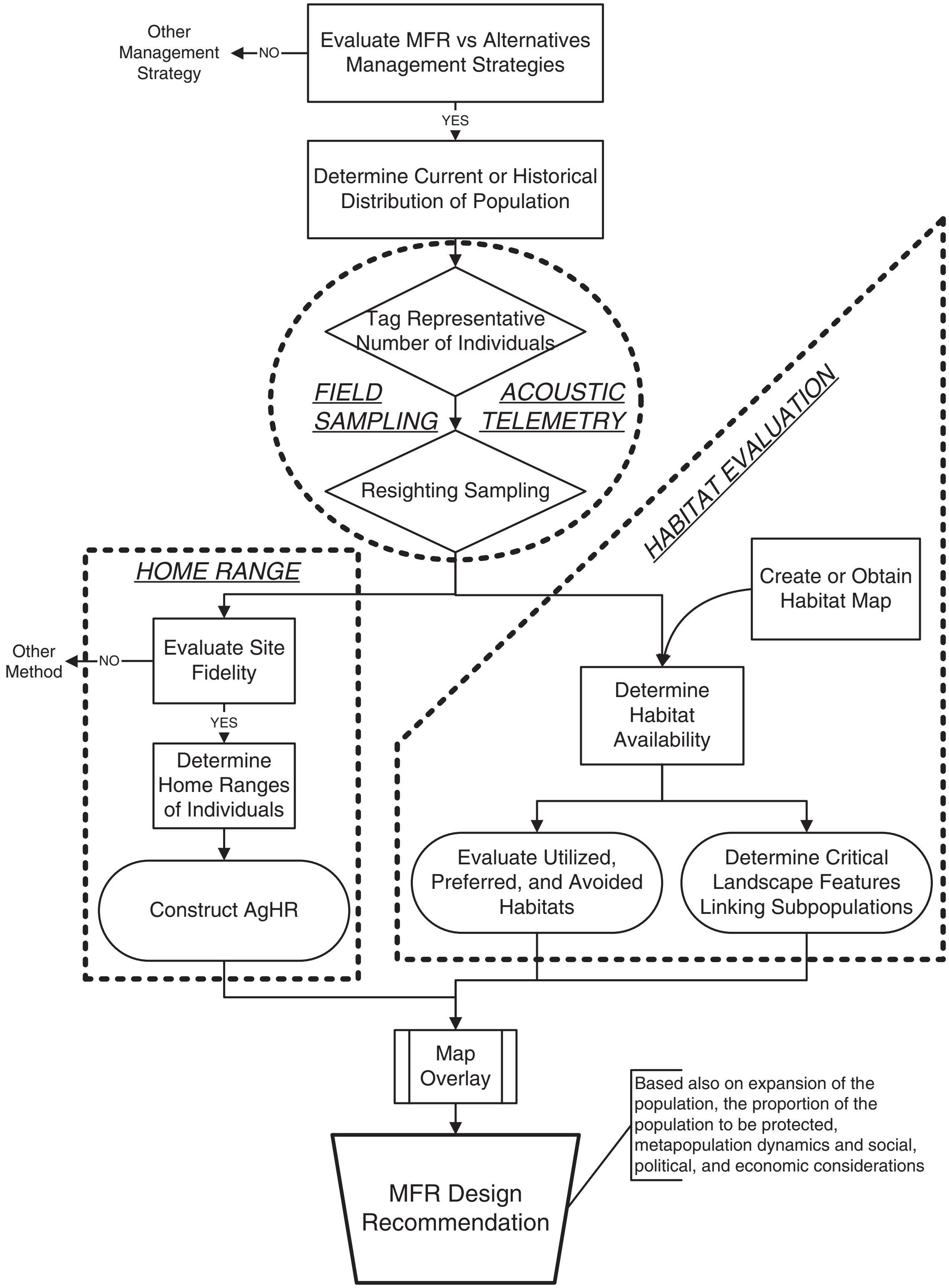


Figure 1

The process for designing a marine fishery reserve. Data acquired from acoustic telemetry studies are used to estimate home ranges of individuals and habitat utilization of the population.

The home range estimation can then be extended to the entire population. In 2003, we introduced a concept we called the aggregation home range (AgHR) to describe an area within which there is a 95% probability that the entire population of tagged individuals will be found (Glazer et al., 2003). The AgHR is represented as an irregular shape that describes the union of the polygons associated with the kernel home ranges of each tagged individual at the 95% probability level (Fig. 2). Given sufficient sample size, this shape approximates, with a high probability, the area occupied by the entire population.

Habitat-use studies provide additional data needed for designing an effective reserve. Because the size and shape of a home range is often dependant on habitat (Kramer and Chapman, 1999), the integration of these parameters into reserve design provides a powerful basis to define the spatial extent of the MFR. Data for these analyses are composed of two components: habitat availability and the habitats occupied by individuals in the population. These analyses then provide statistical representations of the habitats that are utilized, preferred, and avoided by the population (Neu et al., 1974).

Estimating the available habitat requires a map with a suitable spatial scale and appropriate habitat classifications for the targeted species. In many cases, habitat maps may already be available. Alternatively, they can be constructed, and a variety of methods exist to do so (White and Garrot, 1990).

Examining the habitats occupied by individuals requires an efficient method of locating individuals in what may be complex environments, and acoustic telemetry is, in many cases, ideal for this application (for a review, see Eristhee and Oxernford, 2001). The number of observations within each habitat is compared with the percent coverage of each habitat to provide a statistical representation of habitat utilization. Given a habitat map of the area with sufficient scale and resolution, habitats that should be conserved or which the population may colonize may be easily discerned.

Other habitat features should also be considered when designing an MFR. For example, corridors function to permit migration between patches of critical habitat—areas that are essential for reproduction and survival (White and Garrott, 1990). Corridors may also facilitate dispersal between habitat patches in fragmented landscapes (Berggren et al., 2002). If corridors are not protected, individuals may be susceptible to harvest when in transit or they may be unable to migrate into critical habitats (Simpson and Mapleston, 2002). Acoustic telemetry provides an efficient method to locate individuals that are in transit between habitat features and to identify those areas that must be conserved.

Further consideration must be given to habitats in cases where expansion of the population after protection is anticipated and desired. A population expands in one of two ways. First, the population may expand beyond its current boundaries as a result of density-dependent processes. In some cases, animals may even begin to use less desirable habitats (Rowley, 1994). Second, a corridor may be permeable and individuals may immigrate into previously unused adjacent habitats (Acosta, 1999). Both processes reinforce the need to identify corridors.

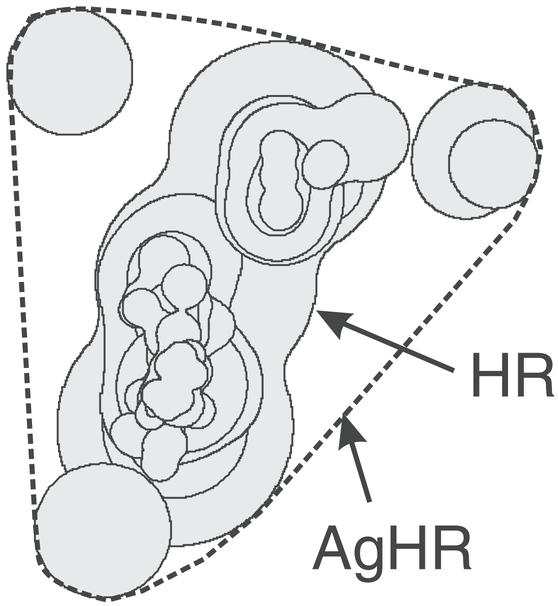


Figure 2

The aggregation home range (AgHR) describing the union of the 95% probability contours of the individual animals (HR). Data are from 23 queen conch (*Strombus gigas*) at French Reef in the Florida Keys (Glazer et al., 2003).

Once the AgHR and the important habitat features are identified, an overlay is constructed to visually interpret the results and to assist in the design of the MFR. This is easily accomplished within a GIS, where boundaries can be identified and manipulated.

An example

To construct an MFR, we used data from two studies of queen conch conducted in 1997 on a Florida Keys back reef (Glazer et al., 2003; Glazer and Kidney, 2004). In those studies, we tagged adult queen conch with acoustic transmitters (Sonotronics, Inc. Tuscon Arixona, USA; Fig. 3) at Conch Reef in the upper Florida Keys. Conch Reef is a shallow-water reef escarpment with two areas delineated for protection: a limited-use Sanctuary

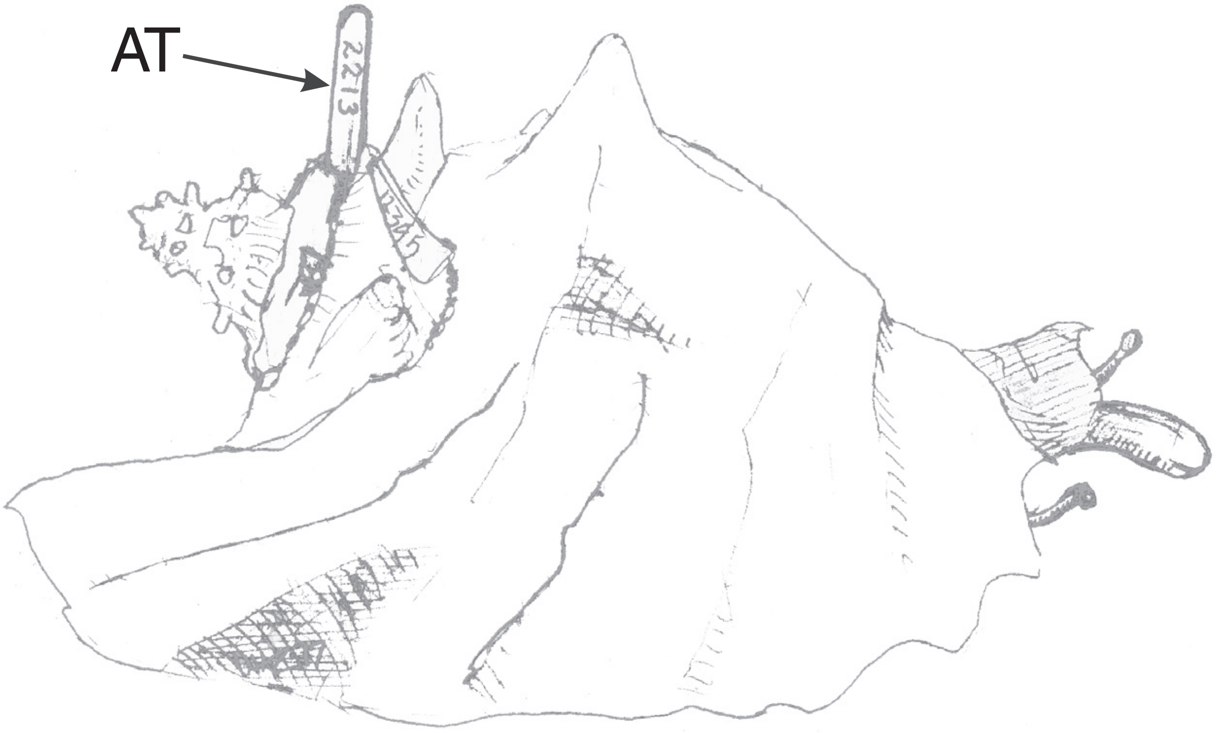


Figure 3

Passive acoustic transmitter (AT) attached to a queen conch (*Strombus gigas*) used in acoustic telemetry studies. A second tag, which was used to identify the conch if the acoustic tag was lost, is shown attached to the spire (for a further discussion, see Glazer et al., 2003).

Preservation Area (SPA) approximately 23.3 ha in area and a restricted access Research Reserve (RR) encompassing approximately 47.5 ha. The conch were located within two spatially distinct sub-populations (Fig. 4), but interchange was possible between them across a rubble field. We estimated that the total number of adult conch in both aggregations was approximately 345 individuals; therefore, about 11% of the population was tagged with acoustic transmitters. We conducted resighting sampling using hydro-acoustic receivers from a research vessel.

Using acoustic telemetry data (i.e., latitudes and longitudes), we determined the 95% probability contours for the home ranges for 21 conch (Glazer et al., 2003). These probabilities were graphically represented in a GIS.

We also examined the habitat requirements of the conch using acoustic telemetry data (Glazer and Kidney, 2004). These data were used in two ways. First we determined the available habitat to the population (Table 1) by constructing the minimum convex polygon of all observations of the 39 conch tagged with acoustic transmitters. Then we examined the habitat utilized and preferred by the conch by comparing the available habitat with the habitats occupied by the conch (Glazer and Kidney, 2004). Based on these analyses, we determined that the conch preferred coarse sand (Cs) and rubble/coarse sand (RbCs) substrates, especially during reproductive season (Table 1). At one site (C2), conch avoided rubble (Rb) relative to its availability; however, the rubble habitat served an important function. Two conch (5% of the tagged population) were observed moving from C1 to C2 across the shallow rubble ridge separating the two sites (Fig. 5). Additionally, observations of untagged conch on this rubble ridge suggest that this habitat serves as an important transit corridor.

These results were used to design an MFR for conch at this site. To design the reserve, we first constructed an AgHR at each subpopulation by drawing a smooth shape around the union of all the individual home range polygons (Fig. 5). We then used the answers from the following questions to further refine the design: 1) is there exchange between the two subpopulations (i.e., is there a migration corridor), 2) what habitats are critical

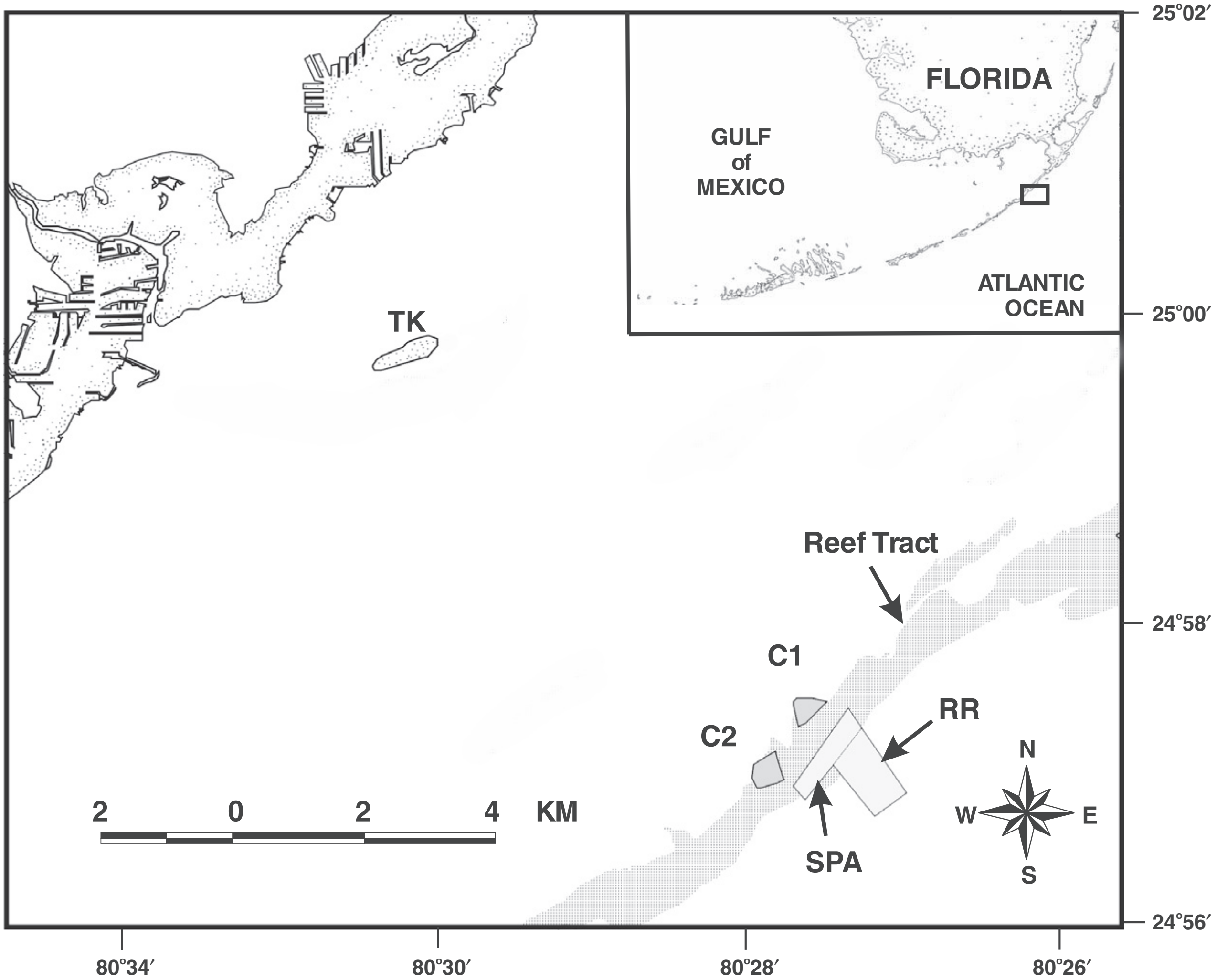


Figure 4

Sample sites for the queen conch (*Strombus gigas*) acoustic telemetry studies in the Florida Keys. All surveys were conducted at Conch Reef; C1 and C2 are subpopulations of queen conch. Two existing marine reserves are shown: a limited-use sanctuary preservation area (SPA) and a restricted-entry research reserve (RR). TK is Tavernier Key.

to conserve, 3) if expansion of the population were to occur in the future, what areas should be conserved relative to the preferred habitats, and 4) what is the simplest design for practical purposes (e.g., enforcement). Furthermore, we decided that this reserve should protect the entire population (i.e., both subpopulations).

The design we chose addressed each of these criteria. We selected a simple shape (i.e., a rectangle) that encompassed the following features: 1) the AgHRs of the two sub-aggregations, 2) the migration corridor between the two sub-aggregations, 3) habitats that were not avoided (except in the case of C2 where the rubble habitat represented the migration corridor), and 4) areas of adjacent habitats that were suitable (i.e., coarse sand, rubble/coarse sand, sparse seagrass/coarse sand, and rubble) but unoccupied and would allow for future expansion. For example, the majority of a deeper area of unoccupied course sand to the southeast of C1 was included in the MFR design (Fig. 5).

One other observation was considered when we designed our reserve. We observed two conch outside the boundaries of the AgHR at C2. We concluded that these animals represented “spillover,” in a management context, from our proposed reserve design; therefore, an effective reserve would not need to encompass this location. The proposed reserve measures approximately 475 m x 1400 m and encompasses approximately 66.5 ha (Fig. 5).

Table 1

Habitat classification and utilization by queen conch tagged with acoustic transmitters at Conch Reef in the Florida Keys. The habitats were defined from high altitude photographs. Asterisks indicate habitats that were occupied by conch during the study. Those habitats that were preferred are indicated with a "P" and those that are avoided are indicated with an "A." N/A is not applicable; "—" indicates those habitats for which there was neither preference nor avoidance. Adapted from Glazer and Kidney (2004).

Code	Habitat	Preferred (P, subsite) or Avoided (A, subsite)	Spawning season—Preferred (P, subsite) or Avoided (A, subsite)
Rf	Reef—continuous barren carbonate substrate	N/A	N/A
Sd	Sand—particles pass through 2-mm sieve, but are retained on 0.5-mm sieve	N/A	N/A
Cs*	Coarse Sand—particles pass through 12-mm sieve, but are retained on 2-mm sieve	P,C2	P,C1
Rb*	Rubble—particles are retained on 12-mm sieve	A,C2	A,C2
RbCs*	Rubble/Coarse Sand—homogenous mix of Rb and Cs	P,C2	P,C2
SgsSd*	Mixed seagrass community (*Thalassia testudinum* and *Syringodium filiforme*), sparse with Sd substrate; seagrass blade density < 1200 • m^{-2} and canopy height < 15 cm	—	—
SgsCs	Mixed seagrass community (*T. testudinum* and *S. filiforme*), sparse with Cs substrate; seagrass blade density < 1200 • m^{-2} and canopy height < 15 cm	N/A	N/A
SgdSd*	Mixed seagrass community (*T. testudinum* and *S. filiforme*), dense with Sd substrate; seagrass blade density > 1200 • m^{-2} and canopy height > 15 cm	—	—
SgdCs*	Mixed seagrass community (*T. testudinum* and *S. filiforme*), dense with Cs substrate; seagrass blade density > 1200 • m^{-2} and canopy height > 15 cm	—	—

Discussion

Passive acoustic telemetry is a method commonly employed in a wide variety of aquatic studies (Zeller, 1998); as of 2003, there were over 320 articles referenced in the literature. In coral reef environments, it is becoming increasingly popular (Zeller, 1997; Eristhee et al., 2001; Beets et al., 2003). Perhaps one of the greatest strengths of this method is that it allows researchers to examine the habits of organisms under conditions that make other sampling strategies difficult. For example, occupied habitats may be examined during times when sampling is problematical (e.g., night: Meyer et al., 2000; Beets et al., 2003; Cartamil et al., 2003) and at sampling frequencies not practical using most other methods (Eristhee and Oxenford, 2001). Additionally, when hydrophones are deployed in situ, passive data collection becomes much simpler than on-site sampling (Lindholm and Auster, 2003) and provides a method to obtain large amounts of highly accurate data (Bolden, 2001). Furthermore, acoustic telemetry circumvents many of the problems associated with traditional mark-recapture technologies including sample size issues (Appeldoorn, 1997). For these reasons, acoustic telemetry has become a popular tool for conducting home range (Zeller, 1997; Eristhee and Oxenford, 2001; Parsons et al., 2003) and habitat preference (Lowe et al., 2003) studies.

In our case, the use of acoustic telemetry allowed us to increase our sample sizes by reducing the amount of labor needed to locate tagged individuals. Had we used traditional tag-recovery methods, it is likely that we would have had a significant reduction in recaptures. As a result, the home range estimations of each individual would likely have been much larger due to the increased variance associated with a reduction in sample size. Likewise, the habitat utilization estimations would probably have suffered from Type 2 errors from the increased variance associated with sample size reduction.

An additional benefit of passive acoustic telemetry is that it is fairly inexpensive. Nevertheless, there are trade-offs. In our studies, we used a single hydrophone deployed from a vessel. This required that at least one researcher was on the vessel for sampling. Using this approach, the up-front investment is fairly modest (approximately $1,500 U.S. for the receiver and hydrophone and $150 for each tag); however, a fairly significant investment in manpower and vessel use was required. On the other hand, labor can be reduced with a significantly greater investment in capital equipment, as in the case where the hydrophones are deployed in an array and the data are acquired passively (Bolden, 2001).

Despite the benefits attributed to acoustic telemetry for the examination of animal movements, the literature is devoid of papers that provide guidance for designing

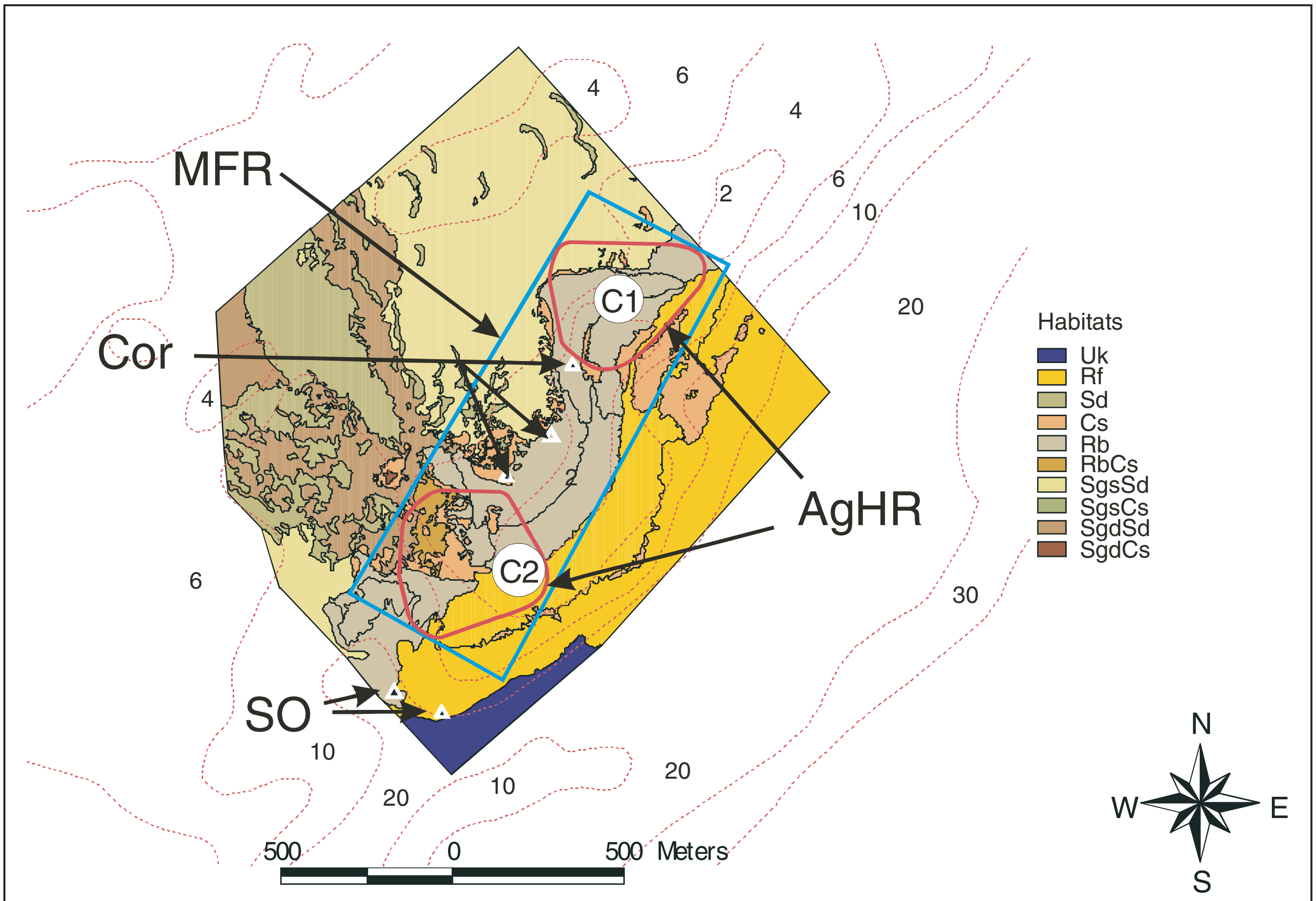


Figure 5

Habitat map derived from high-altitude photogrammetry. The proposed fishery reserve is indicated by MFR. The white triangles represent observations of queen conch (*Strombus gigas*) that are occupying a corridor (Cor) between C1 and C2 or "spillover" conch (SO) that have emigrated from the area defining the proposed reserve. The perimeters of the AgHRs of each sub-population are shown in red. Preferred, utilized, and avoided habitats are described in Table 1. Bathymetric contours (m) are shown for reference.

a reserve using data acquired from this method. In fact, we were only able to locate one paper that used empirical data of the movement of a population to design a reserve (Griffiths and Wilke, 2002) and, even in that study, movements were determined using traditional mark-recapture surveys. They described a method for estimating the minimum reserve size for temperate reef fishes in South Africa based on the radius of movements observed for a population of Sparids. They attached that radius to locations progressively further from the core of the population. In this way, they could predict the proportion of the population that would be protected and concluded that a minimum of three radii and a maximum of five radii would be sufficient to conserve the population.

In contrast to their method, we present a model based not on linear movements, but on the area occupied by individuals with probabilities assigned to that estimation. The use of spatially-explicit, probabilistic home-range models adds a level of security to the determination of what constitutes the area likely to be occupied by an existing or expanding population, especially given that a reserve may not function effectively if the size of the home range is underestimated (Stoner, 1997; Kramer and Chapman, 1999). Our approach has an added advantage in that it includes behavioral and ecological data in the design criteria. For example, by incorporating habitat utilization into the equation, one can make an informed estimation of what areas are likely to be colonized by an expanding population during their foraging and reproductive activities. This approach requires both an objective evaluation of the data and a subjective interpretation of the results.

In our study, we used a species that, in general, exhibits a high degree of site fidelity. However, not all marine animals exhibit this characteristic (i.e., they may be nomadic or highly migratory) and thus may lack fixed home ranges (Colton and Alevizon, 1983; White and Garrott, 1990). Our method may have limited applicability in these cases, especially as it relates to the incorporation of home range into the design of an MFR.

Additionally, queen conch move little and there is a relatively high probability of recapturing tagged individuals relative to more mobile species. For highly mobile species, recapture sitings may be limited due to emigration from the study site. However, probabilistic home range models account for this limitation in the estimation of the home ranges by assigning larger home ranges to individuals with fewer recaptures.

Acoustic telemetry studies may also provide other essential information for effective MFR design. Acosta (2002) studied carrying capacity within reserves in Belize using queen conch and spiny lobsters (*Panuluris argus*) tagged with acoustic transmitters. He predicted the maximum density for spiny lobsters and queen conch for a refuge in Belize by employing a recruitment/diffusion model and, at the end of his study, confirmed that densities of individuals had increased. Because an oft-cited benefit of reserve implementation is the predicted increase in the biomass of the targeted species as a reserve matures (Lubchenko et al., 2003), estimating carrying capacity may provide guidance on expected reproductive output from that reserve as well as functional changes within the ecosystem.

As population densities increase, other changes may occur. Habitat quality, a well-recognized variable that must be addressed for effective marine reserve design (Rowley, 1994; Appeldoorn, 1997; Acosta, 1999; Fogarty, 1999), may be affected. As expansion of the population occurs, less desirable habitats may become occupied in greater frequencies due to depensatory mechanisms (Fretwell and Lucas, 1970). We observed that an unoccupied habitat adjacent to an existing spawning aggregation at Looe Key in the Florida Keys was soon colonized after adult conch were transplanted into the existing aggregation. Additionally, this habitat was positively affected before long as spawning soon began to occur there (Glazer, personal observ.). For these reasons, what are seemingly poor habitats adjacent to an existing population should be carefully considered for inclusion in a reserve before being discounted.

Acoustic telemetry often provides an efficient mechanism to study the complexities associated with examining the movements of individuals and populations in fragmented landscapes (Beets et al., 2003). Because examining these movements is necessary for the conservation of critical habitats (Berggren et al., 2002), these data have now begun to be incorporated into designs of marine reserves (Christensen et al., 2003). However, the holistic approach that uses empirical observation to combine these features with areas occupied by populations is absent from the literature. The conservative approach is to include all habitats connecting distinct patches. This, of course, oversimplifies the question and may result in overprotection if isolated populations are not connected via corridors and are functioning as isolated metapopulations (Dethier et al., 2003). This may then have adverse economic, social, or enforcement consequences. For these reasons, it is essential to determine landscape features that must be conserved even though they are used infrequently. In our proposed reserve, we justified the inclusion of the rubble ridge between C1 and C2 because this feature served an important function as a migration corridor and, if not conserved, the two subpopulations may become isolated. It is unlikely that this area would have been identified as a critical feature without the use of acoustic telemetry given the rapid transit over the rubble ridge by the tagged individuals and the infrequent observations of untagged conch in the area.

When using our criteria to design an MFR, decisions must be founded on information obtained from appropriate temporal scales (Starr et al., 2002). Ontogeny and reproduction may require drastically different resources, and it is critical to design studies or use data that capture habitat requirements during different life stages. Shifts in habitat use during reproduction must be examined (Kramer and Chapman, 1999; Glazer et al., 2003). Because many fish species congregate to spawn, fishermen often target spawning aggregations. If a goal of the reserve is to enhance reproductive output, these aggregations should be identified and their conservation should be considered a high priority (Claro and Lindeman, 2003).

Despite the fairly straightforward approach we described, a good deal of subjectivity will ultimately be required when considering the dimensions of an effective MFR. In our example, we included areas outside of the existing AgHRs in our proposed MFR design to allow for future expansion of the population. We placed added emphasis on including course sand and rubble/coarse sand habitats because conch preferred them during both the reproductive and non-reproductive seasons. Areas of these habitats that were in close proximity to the subpopulations and to the corridor connecting them were included in our design to support increased reproduction in an expanding population. We also included a substantial amount of sparse seagrass/sand habitat that was not currently occupied, despite the fact that there was no preference or avoidance of that habitat (Glazer and Kidney, 2004), because we felt that these were areas that could be rapidly colonized.

It is critical that managers predefine the goals of a prospective MFR. Our approach may be perfectly suitable for enhancing biomass in the reserve and in adjacent fisheries via spillover, if the MFR is well designed. However, guaranteeing that the population is protected and that areas are available for future expansion are not enough to ensure that the reserve functions to meet all the predefined goals. For example, one goal of an MFR may be to provide propagules for dispersal to targeted locations. Therefore, consideration of oceanographic features is critical to ensure proper MFR function (Chiappone and Sullivan Sealey, 2000; Crowder et al., 2000), and the design criteria defined in this study may do little to ensure that this goal is achieved.

Managers must also evaluate the biological, logistical, and/or human resource constraints that may limit the scope of MFR design studies. For example, if the population in the targeted area is too small for telemetry studies, the project may need to be conducted in a different location with similar features. In these instances, home range and habitat utilization information may have to be obtained from the literature, and the researchers and/or managers should recognize that critical site-specific habitat features (e.g., corridors) would not be identified. In other cases, fiscal realities may limit the capacity to effectively evaluate MFR design parameters. In addition to scientific considerations, social, political, and economic factors must be evaluated when designing reserves. Thus, the spatially defined boundaries determined from home range and habitat preference studies are only a few of a suite of variables that must be considered to ensure that an MFR is appropriately designed.

Acknowledgments

This project was supported by a grant from the Florida Fish and Wildlife Conservation Commission's Non-Game grants program (NG97-005). Alejandro Acosta, Rod Bertelsen, Jim Quinn, John Hunt, and three anonymous reviewers provided valuable comments on the manuscript. Judy Leiby and Lynn French assisted in the editorial process. Waz prepared the illustration of the conch. Jim Kidney conducted the field sampling, in some cases with assistance, in others independently. The Nature Conservancy provided volunteer support for assistance with the field sampling.

Literature cited

Acosta, C. A.
1999. Benthic dispersal of Caribbean spiny lobsters among insular habitats: implications for the conservation of exploited marine species. Conserv. Biol. 13:603–612.
2002. Spatially explicit dispersal dynamics and equilibrium population sizes in marine harvest refuges. ICES J. Mar. Sci. 59:458–468.

Allison, G. W., J. Lubchenko, and M. Carr.
1998. Marine reserves are necessary but not sufficient for conservation. Ecol. Appl. 8:79–92.

Appeldoorn, R. S.
1997. Dispersal rates of commercially important coral reef-fishes: what do tagging studies tell us about potential emigration from marine reserves? Proc. Gulf Caribb. Fish Inst. 49:54–63.

Babcock, R. C., S. Kelly, N. T. Shears, J. W. Walker, and T. J. Willis.
1999. Changes in community structure in temperate marine reserves. Mar. Ecol. Prog. Ser. 189:125–134.

Beets, J., L. Muehlstein, K. Haught, and H. Schmitges.
2003. Habitat connectivity in coastal environments: patterns and movements of Caribbean coral reef fishes with emphasis on bluestripe grunt, *Heamulon sciurus*. *In* Caribbean marine protected areas: practical approaches to achieve economic and conservation goals (R. S. Appeldoorn, ed.), p. 29–42. Gulf Caribb. Res. 14(2).

Berggren, Å, B. Birath, and O. Kindvall.
2002. Effect of corridors and habitat edges on dispersal behavior, movement rates, and movement angles of Roesel's bush-cricket (*Metrioptera roeseli*). Conserv. Biol. 16:1562–1569.

Bertelsen, R. D., and T. Matthews.
2001. Fecundity dynamics of female spiny lobster (*Panulirus argus*) in a south Florida fishery and Dry Tortugas National Park lobster sanctuary. Mar. Freshwater Res. 52:1559–1565.

Bohnsack, J. A.
1994. How marine fishery reserves can improve reef fisheries. Proc. Gulf Caribb. Fish. Inst. 43:217–241.
1998. Application of marine reserves to reef fisheries management. Aust. J. Ecol. 23:298–304.

Bolden, S. K.
2001. Nassau grouper (*Epinephalus striatus*, Pisces: Serranidae) movement in the Bahamas, as determined by ultrasonic telemetry. Ph.D. dissert., University of Miami, 172 p.

Boersma, P. D., and J. K. Parrish.
1999. Limiting abuse: marine protected areas, a limited solution. Ecol. Econ. 31:287–304.

Botsford, L. W., F. Micheli, and A. Hastings.
2003. Principles for the design of marine reserves. Ecol. Appl.13: S25–S31.

Cartamil, D. P., J. J. Vaudo, C. G. Lowe, B. M. Wetherbee, and K.N. Holland.
2003. Diel movement patterns of the Hawaiian stingray, *Dasyatis lata*: implications for ecological interactions between sympatric elasmobranch species. Mar. Biol. 142:841–847.

Chiappone, M., and K. M. Sullivan Sealey.
2000. Marine reserve design criteria and measures of success: lessons learned from the Exuma Cays Land and Sea Park. Bull. Mar. Sci. 66:691–705.

Christensen, J. D., C. F. G. Jeffrey, C. Caldow, M. E. Monaco, M. S. Kendall, and R. S. Appeldoorn.
2003. Cross-shelf habitat utilization patterns of reef fishes in southwestern Puerto Rico. *In* Caribbean marine protected areas: practical approaches to achieve economic and conservation goals (R. S. Appeldoorn, ed.), p. 9–27. Gulf Caribb. Res. 14(2).

Claro, R., and K. C. Lindeman.
2003. Spawning aggregation sites of snapper and grouper species (Lutjandae and Serranidae) on the insular shelf of Cuba. *In* Caribbean marine protected areas: practical approaches to achieve economic and conservation goals (R. S. Appeldoorn, ed.), p. 91–106. Gulf Caribb. Res. 14(2).

Colton, D. E., and W. S. Alevizon.
1983. Movement patterns of bonefish, *Albula vulpes*, in Bahamian waters. Fish. Bull. 81:148–154.

Côté, I. M., I. Mosqueira, and J. D. Reynolds.
2001. Effects of marine reserve characteristics on the protection of fish populations: a meta analysis. J. Fish Biol. 59:178–189.

Crowder, L. B., S. J. Lyman, W. F. Figueira, and J. Priddy.
2000. Source-sink population dynamics and the problem of siting marine reserves. Bull. Mar. Sci. 66:799–820.

Dethier, M. N., K. McDonald, and R. R. Strathmann.
2003. Colonization and connectivity of habitat patches for coastal marine species distant from source populations. Conserv. Biol. 17:1024–1035.

Dugan, J. E., and G. E. Davis.
1993. Applications of marine refugia to coastal fisheries management. Can. J. Fish. Aquat. Sci. 50:2029–2042.

Eristhee, N., and H. Oxenford.
2001. Home range size and use of space by Bermuda chub *Kyphosus sectatrix* (L.) in two marine reserves in the Soufriere Marine Mangement Area, St. Lucia, West Indies. J. Fish Biol. 59:129–151.

Eristhee, N., I. Popple, H. Oxenford, and W. Hunte.
2001. Methods and lessons learnt in the application of acoustic telemetry to coral reef fish movement studies. Proc. Gulf Caribb. Fish. Inst. 52:145–159.

Fogarty, M. J.
1999. Essential habitat, marine reserves and fishery management. Trends Ecol. Evol. 14:133–134.

Fretwell, S., and H. Lucas.
1970. On the territorial behavior and other factors influencing habitat distribution in birds. Acta Biotheoretica 19:16–36.

Glazer, R. A., and J. A. Kidney.
2004. Habitat associations of adult queen conch in an unfished Florida Keys back-reef: applications to essential fish habitat. Bull. Mar. Sci. 75:205–224.

Glazer, R. A., G. A. Delgado, and J. A. Kidney.
2003. Estimating queen conch (*Strombus gigas*) home ranges using acoustic telemetry: implications for the design of marine fishery reserves. *In* Caribbean marine protected areas: practical approaches to achieve economic and conservation goals (R. S. Appeldoorn, ed.), p. 79–89. Gulf Caribb. Res. 14(2).

Griffiths, M. H., and C. G. Wilke.
2002. Long-term movement patterns of five temperate-reef fishes (Pisces: Sparidae): implications for marine reserves. Mar. Freshwater Res. 53:233–244.

Hooge, P. N., W. M. Eichenlaub, and E. K. Solomon.
2001. Using GIS to analyze animal movements in the marine environment. *In* Spatial processes and management of marine populations (G.H. Kruse, N. Bez, A. Booth, M.W. Dorn, S. Hills, R.N. Lipcius, D. Pelletier, C. Roy, S.J. Smith, and D. Witherell, eds.), p. 37–51. University of Alaska Sea Grant, AK-SG-01-02, Fairbanks, Alaska.

Kramer, D. L., and M. R. Chapman.
1999. Implications of fish home range size and relocation for marine reserve function. Environ Biol. Fishes 55:65–79.

Lembo, G. I. A. Fleming, F. Økland, P. Carbonara, and M. T. Spedicato.
1999. Site fidelity of the dusky grouper *Epinephelus marginatus* (Lowe, 1834) studied by acoustic telemetry. Mar. Life 9:37–43.

Lindholm, J., and P. Auster.
2003. Site utilization by Atlantic cod (*Gadus morhua*) in offshore gravel habitat as determined by acoustic telemetry: implications for the design of marine protected areas. Mar. Sci. Tech. J. 37:27–34.

Lowe, C. G., D. T. Topping, D. P. Cartamil, and Y. P. Papastamatiou.
2003. Movement patterns, home range, and habitat utilization of adult kelp bass *Paralabrax clathratus* in a temperate no-take reserve. Mar. Ecol. Prog. Ser. 256:205–216.

Lubchenko, J., S. R. Palumbi, S. D. Gaines, and S. Andelman.
2003. Plugging a hole in the ocean: the emerging science of marine reserves. Ecol. Appl. 13:S3–S7.

Martell, S. J. D., C. J. Walters, and S. S. Wallace.
2000. The use of marine protected areas for conservation of lingcod (*Ophiodon elongatus*). Bull. Mar. Sci. 66:729–743.

Meyer, C. G., K. N. Holland, B. M. Wetherbee, and C. G. Love.
2000. Movement patterns, habitat utilization, home range size and site fidelity of whitesaddle goatfish, *Parupeneus porphyreus*, in a marine reserve. Environ. Biol. Fishes 59:235–242.

Murray, S. N., R. F. Ambrose, J. A. Bohnsack, L. W. Botsford, M. H. Carr, G. E. Davis, P. K. Dayton, D. Gotshall, M. A. Hixon, J. Lubchenko, M. Mangel, A. MacCall, D. A. McArdle, J. C. Ogden, J. Roughgarden, R. M. Starr, M. J. Tegner, and M. M. Yoklavich.
1999. No-take reserve networks: sustaining fishery populations and marine ecosystems. Fisheries 24:11–24.

Neu, C. W., C. R. Byers, J. M. Peek, and V. Boy.
1974. A technique for analysis of utilization availability data. J. Wildl. Manage. 38:541–545.

Parsons, D. M., R. C. Babcock, R. K. S. Hankin, T. J. Willis, J. P. Aitken, R. K. O'Dor, and G. D. Jackson.
2003. Snapper *Pagrus auratus* (Sparidae) home range dynamics: acoustic tagging studies in a marine reserve. Mar. Ecol. Prog. Ser. 262:253–265.

Polacheck, T.
1990. Year around closed areas as a management tool. Nat. Res. Modeling 4:327–354.

Recksiek, C. W., and R. A. Appeldoorn.
1998. In pursuit of design criteria for marine fishery reserves. Proc. Gulf and Caribb. Fish Inst. 50:372–384.

Recksiek, C. W., B. R. Murphey, R. S. Appeldoorn, and K. C. Lindeman.
2001. Integrating fish fauna and habitat assessments: a fundamental step in fishery reserve design criteria. Proc. Gulf and Caribb. Fish Inst. 52:654–666.

Roberts, C. M., J. A. Bonsack, F. Gell, J. P. Hawkins, and R. Goodridge.
2001. Effects of marine reserves on adjacent fisheries. Science 294:1920–1923.

Rodwell, L. D., E. B. Barbier, C. M. Roberts, and T. R. McClanahan.
2003. The importance of habitat quality for marine reserve—fishery linkages. Can. J. Fish. Aquat. Sci. 60:171–181.

Rowley, R. J.
1994. Marine reserves in fisheries management. Aquatic Conserv.: Mar. Freshw. Ecosyst. 4:233–254.

Simpson, R. R., and A. J. Mapleston.
2002. Movements and habitat use of the endangered Australian freshwater Mary River cod, *Maccullochella peelii mariensis*. Environ. Biol. Fishes 65:401–410.

Starr, R. M., J. N. Heine, J. M. Felton, and G. M. Cailliet.
2002. Movement of the bocaccio (*Sebastes paucispinis*) and greenspotted rockfishes in a Montery submarine canyon: implications for the design of marine reserves. Fish. Bull. 100:324–337.

Stoner, A.W.
1997. The status of queen conch, *Strombus gigas*, research in the Caribbean. Mar. Fish. Rev. 59:14–22.

Stoner, A.W., and M. Ray-Culp.
2000. Evidence for Allee effects in an over-harvested marine gastropod: density-dependent mating and egg production. Mar. Ecol. Prog. Ser. 202:297–302.

Warner, R. R., and R. K. Cowen.
2002. Local retention of production in marine populations: evidence, mechanisms, and consequences. Bull. Mar. Sci. 70:245–249.

White, G. C., and R. A. Garrott.
1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, 383 p.

Worton, B. J.
1989. Kernel methods for estimating the utilization distribution in home range studies. Ecology 70:164–168.

Zeller, D. C.
1997. Home range and activity patterns of the coral trout *Plectropomus leopardus* (Serranidae). Mar. Ecol. Prog. Ser. 154:65–77.
1998. Ultrasonic telemetry: its application for coral reef fisheries research. Fish. Bull. 97:1058–1065.

Zeller, D., S. L. Stoute, and G. R. Russ.
2003. Movements of reef fishes across marine reserve boundaries: effects of manipulating a density gradient. Mar. Ecol. Prog. Ser. 254:269–280.

Acoustic signatures of the seafloor: tools for predicting grouper habitat

Arthur C. R. Gleason
Division of Marine Geology and Geophysics
Rosenstiel School of Marine and
Atmospheric Science
University of Miami
4600 Rickenbacker Cswy.
Miami, FL 33149
E-mail address: art.gleason@miami.edu

R. Pamela Reid
Division of Marine Geology and Geophysics
Rosenstiel School of Marine and
Atmospheric Science
University of Miami
4600 Rickenbacker Cswy.
Miami, FL 33149

Anne-Marie Eklund
Southeast Fisheries Science Center
National Marine Fisheries Service, NOAA
75 Virginia Beach Dr.
Miami, FL 33149

Veronique Koch
Southeast Fisheries Science Center
National Marine Fisheries Service, NOAA
75 Virginia Beach Dr.
Miami, FL 33149

Abstract—Groupers are important components of commercial and recreational fisheries. Current methods of diver-based grouper census surveys could potentially benefit from development of remotely sensed methods of seabed classification. The goal of the present study was to determine if areas of high grouper abundance have characteristic acoustic signatures.

A commercial acoustic seabed mapping system, QTC View Series V, was used to survey an area near Carysfort Reef, Florida Keys. Acoustic data were clustered using QTC IMPACT software, resulting in three main acoustic classes covering 94% of the area surveyed. Diver-based data indicate that one of the acoustic classes corresponded to hard substrate and the other two represented sediment. A new measurement of seabed heterogeneity, designated acoustic variability, was also computed from the acoustic survey data in order to more fully characterize the acoustic response (i.e., the signature) of the seafloor.

When compared with diver-based grouper census data, both acoustic classification and acoustic variability were significantly different at sites with and without groupers. Sites with groupers were characterized by hard bottom substrate and high acoustic variability. Thus, the acoustic signature of a site, as measured by acoustic classification or acoustic variability, is a potentially useful tool for stratifying diver sampling effort for grouper census.

Introduction

Several species of groupers (family: Serranidae) are important components of recreational and commercial fisheries. These fish also contribute to healthy coral reef ecosystems and are often a focus of recreational diving and photography. As such, preserving healthy populations of groupers is desirable for economic, ecological, and aesthetic reasons.

The life history and behavior of groupers make them especially susceptible to overexploitation (Coleman et al., 1999). Groupers are top predators in the coral reef ecosystem, with long life spans and a low natural mortality rate. When predation by man decreases their abundance, however, groupers are slow to recover because they do not begin to reproduce until late ages (Polovina and Ralston, 1987; Sadovy, 1994). Many species of grouper, such as goliath grouper (*Epinephelus itajara*), Nassau grouper (*E. striatus*), and red grouper (*E. morio*), are unwary of divers and are easily caught in traps or by angling. Furthermore, many groupers form predictable, seasonal, and site specific aggregations, which are easy to eradicate once located by fishermen (Polovina and Ralston, 1987; Sadovy, 1994; Coleman et al., 1999; Sadovy and Eklund, 1999). For these reasons, groupers are a family of fishes that are likely to benefit from marine protected areas (MPAs; areas of no take).

For MPAs to be useful in grouper conservation, they must incorporate appropriate habitat. Currently, however, essential grouper habitat is poorly defined. Like most reef fishes, groupers prefer hard bottom (e.g., coral reef) to unconsolidated substrate (e.g., seagrass or bare sediment). Beyond this, knowledge of grouper habitat is largely anecdotal. The National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) Southeast Fisheries Science Center (SEFSC) has been monitoring grouper density near Carysfort Reef since 1994 (Eklund et al., 2000) and more recently at other reefs of the Florida Keys. Through experience, the NOAA divers have developed a qualitative "feel" for good grouper habitat, which often includes features such as high relief and the presence of caves or crevices, especially on steeply sloping surfaces.

Maps showing the distribution of potential grouper habitat are limited. In the Florida Keys, for example, an aggregation of 70–100 black groupers (*Mycteroperca bonaci*) was observed just 100 m outside the protected area at Carysfort Reef less than a year after the preserve opened (Eklund et al., 2000). Discovery of the first known aggregation of any grouper species in the Florida Keys (Eklund et al., 2000) just outside the largest MPA in the Keys is ironic. Information on the distribution of fish habitat is highly relevant to MPA design, yet often such critical information is unavailable. The experience at Carysfort underscores the need for efficient methods of 1) seabed mapping and 2) prioritizing limited dive time for fish census.

Diver-based grouper census surveys could potentially benefit from improved methods of remotely sensed seabed classification. Optical mapping products, such as the Benthic Habitats of the Florida Keys (FMRI, 1998), are useful in some applications; however, much important grouper habitat, including the area of the large aggregation observed by Eklund et al. (2000) outside the Carysfort MPA, is located in deeper water where optical mapping techniques are not useful. Acoustic mapping systems are a promising technology for mapping areas where the bottom cannot be detected by optical methods.

Acoustic methods have been successfully used to discriminate substrate classes in many areas around the world (e.g., Hamilton et al., 1999; Morrison et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a). To date, however, applications of this methodology in carbonate reefal environments are limited. The overall goal of the present study was to evaluate the potential of a commercial acoustic mapping system, QTC View Series V (QTC-V; Quester Tangent Corporation, Sidney, BC, Canada, 2001), to identify potential grouper habitat and prioritize sites for diver surveys.

Specifically, this project addressed the question: Do areas of high grouper abundance have characteristic acoustic signatures? Results demonstrate two effective predictors of grouper presence or absence: 1) simple acoustic seabed classification, which distinguishes hard bottom from sediment substrate, and 2) a newly developed index of acoustic variability.

Methods

The study focused on Carysfort Reef, Florida Keys (Fig. 1). An acoustic survey was performed and the resulting data processed in two ways. First, clusters of acoustically distinct echoes were segmented using commercially available software. Second, a new index of acoustic variability was developed. This index was designed to measure seabed heterogeneity by quantifying the degree to which the echo at a particular location is similar to other nearby echoes.

The acoustic survey was complemented with diver surveys, which collected "ground truth" data on bottom type and grouper abundance. Correlations between acoustic and diver surveys were conducted to test the value of using acoustic signatures for identifying potential sites for grouper habitat and prioritizing sites for diver surveys. Details of the methods are presented below.

Acoustic survey

Data collection and seabed classification The acoustic survey at Carysfort Reef (Fig. 1) was conducted using a QTC-V acoustic mapping system. Acoustic data were recorded using a Suzuki 50 kHz echo sounder (model 2025). A wide area augmentation system (WAAS) enabled global positioning system (GPS), mounted with its antenna directly over the acoustic transducer, provided vessel positioning. The survey, conducted on 14 March, 28 March, and 4 April 2002, consisted of transects spaced 100 m apart running perpendicular to the reef crest from an inshore depth of 3 m to a maximum offshore depth of 42 m.

Data processing for seabed classification involved four steps (Fig. 2). Processing was done using IMPACT (version 3.4, QTC, Sidney, BC, 2004), the processing software provided with QTC-V. During the first step, the data acquisition phase, the signal generated by an echo sounder is passed to a head amplifier that applies both time-varying gain, to compensate for beam spreading and water depth, and auto gain control, to compensate for variable bottom reflectance. Individual echoes are then digitized using a 5 MHz analog to digital card and recorded by a computer.

In the second step, the data reduction phase, the raw bi-polar waveforms are converted to echo "envelopes" (essentially echo amplitude only). The echo envelopes are stacked (averaged) in groups of five to reduce ping-to-ping variability. The stacked echoes are characterized by a number of algorithms that respond to features of the echo shape. The ensemble of features is reduced using principal components analysis (PCA) to the first three principal components. The end result is that each stacked echo is represented by a single point in three-dimensions ("Q-space"; QTC, 2004). The shape of the stacked echo determines the coordinates of this point.

In the third step, the clustering phase, the "cloud" of points in Q-space is partitioned into clusters using a simulated annealing clustering procedure. The statistical descriptions (mean, covariance) of these clusters comprise a "catalog" (QTC, 2004).

Finally, in the classification stage, a catalog is used to assign a class to all points in a dataset. The catalog can be applied to the original data used to create the catalog (via clustering) or it can be applied to another data set acquired with the same hardware configuration.

The four steps of acquisition, reduction, clustering, and classification are fundamental to the IMPACT

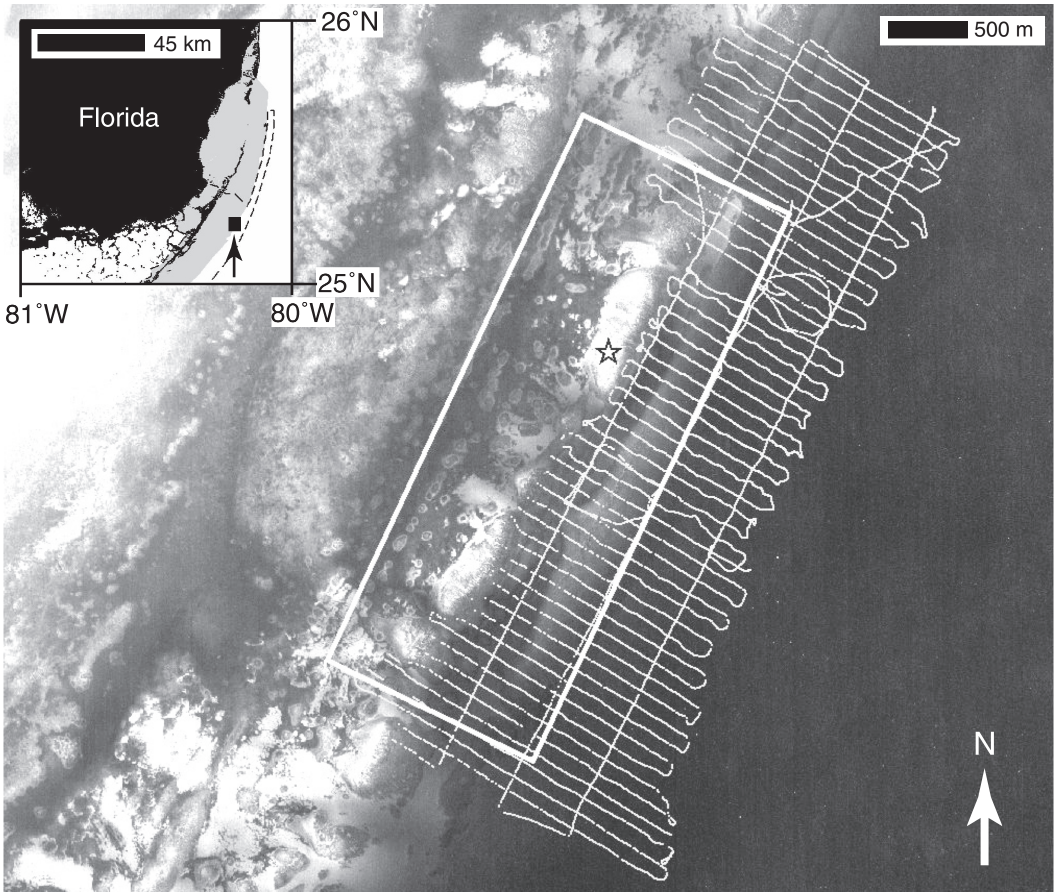


Figure 1

Track lines from the acoustic survey superimposed on an IKONOS satellite image of Carysfort Reef and surroundings. The Carysfort lighthouse (star) and protected area (bold rectangular box) are also shown. The arrow in the inset shows the location of the IKONOS image in the wider context of South Florida (solid black), the Florida Keys National Marine Sanctuary (dashed line), and the area that has been mapped by FMRI (1998) from aerial photography (grey). The track lines extend from near the reef crest to deeper water where the bottom is no longer visible.

processing procedure. The overview above is similar to previous descriptions of data processing using QTC View Series IV and older versions of the IMPACT software (e.g. Hamilton et al., 1999; Morrison et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a). A series of conference papers (e.g. Preston[1]) provide more detailed descriptions of each of the four steps.

Acoustic variability index Standard QTC analysis, as described above, characterizes the acoustic response of a position on the seafloor relative to all others in the survey area based solely on echo shape. The geographic location of the echo is irrelevant in the clustering process; location is used only to plot the classification results. An additional way to characterize acoustic response at a point is to quantify the degree to which a particular echo is similar in shape to its geographic neighbors (as opposed to its neighbors in Q-space). Such a measure, designated acoustic variability, was developed as part of this study (Fig. 3). The computation of acoustic variability, described below, complements the standard QTC classification to more fully characterize the acoustic signature of any given location on the seafloor.

---

[1] Preston, J. M., A. C. Christney, L. S. Beran, and W. T. Collins. 2004. Statistical Seabed Segmentation - From Images and Echoes to Objective Clustering. 7th European Conference on Underwater Acoustics, Delft, Netherlands, 5–8 July 2004. 6 p. is available, along with other papers describing the details of processing QTC View data, from the QTC Web site: http://www.questertangent.com [Accessed on 21 Dec 2004]

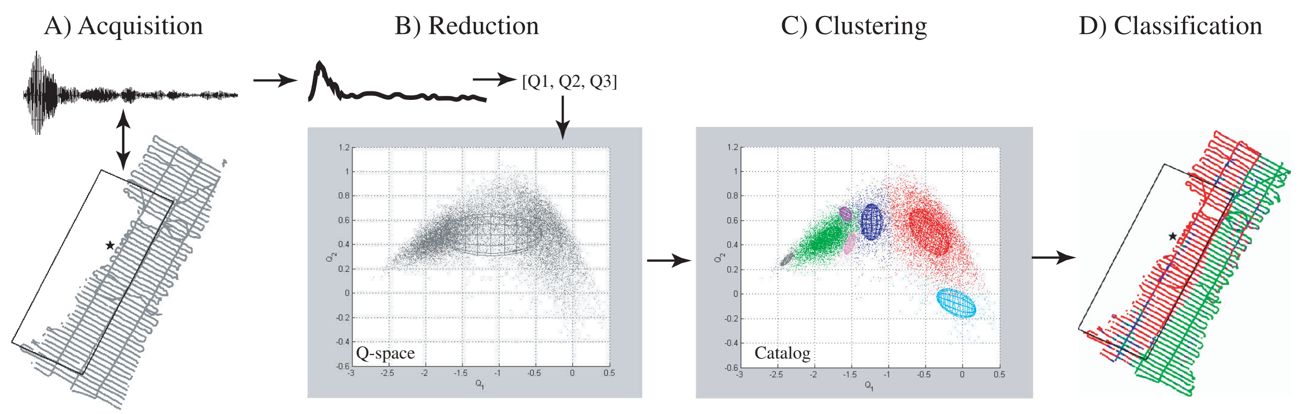


Figure 2

Overview of acoustic processing. A) The full waveform for each point is acquired, georeferenced, and recorded. B) Each echo is converted to three coordinates in "Q-space" based on the shape of the echo "envelope" (echo amplitude). C) Q-space is partitioned into distinct groups defined by their means and covariances. D) Each point is assigned a class based on its location in Q-space.

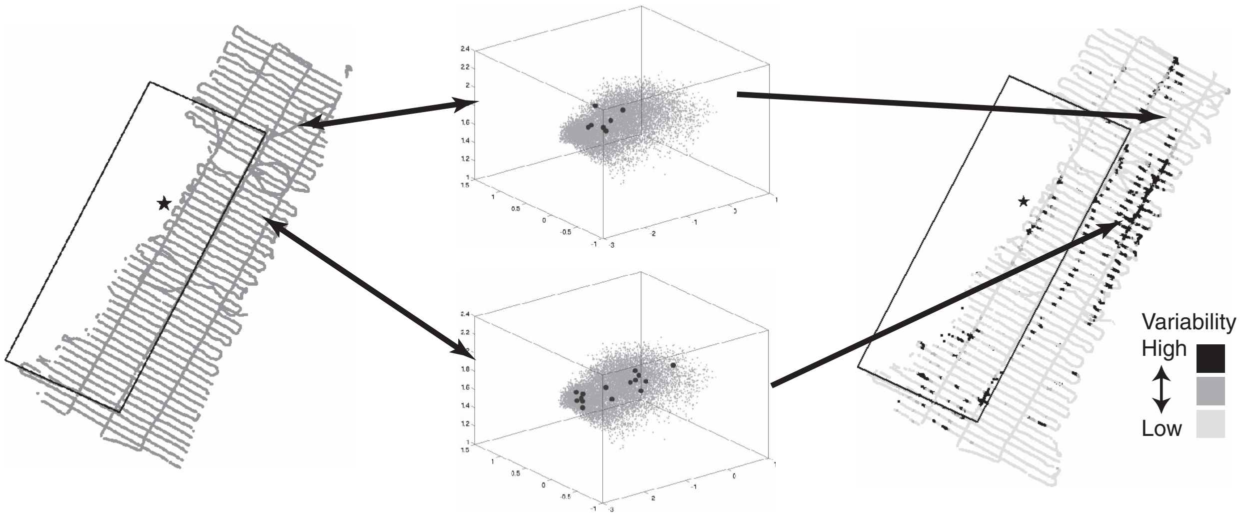


Figure 3

Computation of acoustic variability. A moving window sliding over the geographic dataset (left plot) selects neighboring points. Variability is the sum of the lengths of the principal axes of the cloud formed by the selected points in Q-space. If these points have low acoustic variability, they will cluster close together in Q-space (upper center plot). If they have high acoustic variability, they will form a scattered cloud in Q-space (lower center plot). The spatial pattern of variability is apparent when displayed using the geographic location of each echo (right plot).

Acoustic variability was computed point-by-point across the data set by considering a small moving window applied around each echo in the survey (Fig. 3). For each point, all the echoes within 40 m of that point were identified. In Q-space this subset of the data produces a small cloud of points (typically between 10–20 points, depending on vessel speed). Variability was defined as the sum of the standard deviations along the three principal axes of this cloud of points and was computed by taking the square root of the trace of the covariance matrix computed for each subset of data (Davis, 1986). A window of data that includes echoes that are all very similar will have points very close to one another in Q-space and will therefore have low acoustic variability.

Conversely, a window of data containing echoes that are all very dissimilar will have points spread across Q-space and will have high acoustic variability.

Diver survey

Twenty-two dives were conducted near Carysfort during August of 2002 and October of 2003 to acquire "ground truth" for the acoustic measurements. The locations of the dives were chosen based on the maps of seafloor classification and acoustic variability. Since only a limited number of dives were possible, the sites were chosen to ensure that multiple dives were placed in 1) homogenous areas of each acoustic class, and 2) areas of high and low acoustic variability.

Diver surveys followed NOAA/SEFSC procedures for conducting fish census (Bohnsack and Bannerot, 1986) and benthic habitat assessment (Franklin et al., 2003), as described by McClellan and Miller (2003). At every site, two divers each surveyed non-overlapping, 7.5 m radius cylinders; results from the two divers were averaged to produce a single set of values for each dive site. Diver collected data that were compared with the acoustics were: 1) the number of groupers (*Epinephelus* and *Mycteroperca* spp.) observed in a five minute interval, and 2) estimated percent cover of three substrate classes (sediment, hard bottom, and rubble).

Comparison of acoustic and diver surveys

Results from acoustic and diver surveys were compared to 1) assess the accuracy of the acoustic classification, and 2) correlate grouper abundance with acoustic classification and variability. The general strategy in both cases was to compare a diver-estimated parameter with the closest acoustically derived values.

Acoustic classification accuracy assessment Assessing the accuracy of acoustic classification involved two steps. First, diver-estimated bottom cover was overlain on the acoustic classification map to visually determine which acoustic classes corresponded with which bottom types. Second, the accuracy of the classification was assessed using an error matrix.

The error matrix is a common method of quantifying the accuracy of a thematic map by comparing "ground truth" for a sample of points on the map with the predictions made by the map (Congalton and Green, 1999). Ground truth is often acquired by visiting sites and visually determining what is there (e.g., by divers). A matrix can then be constructed with one column per ground truth class, one row per map class, and entries in the appropriate row and column for each ground truth point visited. The sum of all the elements in the matrix equals the total number of ground truth points, and the sum of the elements in the matrix for which the ground truth class is the same as the map class is the total number of "correct" points visited on the map. The overall accuracy is the latter divided by the former. This technique was used here with one modification. Usually each point visited is assigned one ground truth class and one map class. In this study, however, each ground truth site (a single dive) was assigned a mixture of three classes (sediment, hard bottom, and rubble), but an echo had only one acoustic class. To accommodate mixed bottom types, the entry in the error matrix for the closest echo to a particular dive site was divided among the columns of the matrix in proportion to the diver-estimated bottom cover for that site.

Grouper abundance vs. acoustic classification and variability Acoustic classes and variability were compared with grouper abundance using analysis of variance (ANOVA) and multiple comparison tests to determine the significance of any correlation. Dive sites were grouped into treatments by the number of groupers at the site, and two ANOVA procedures were run. The first tested the null hypothesis that the mean percent of a given acoustic class was the same for sites with different number of groupers. The second tested the null hypothesis that mean variability was the same for sites with different numbers of groupers.

The MATLAB statistics toolbox (Version 4.0:R13; The MathWorks, Inc., Natick, MA 2002) was used to perform the tests. First, the null hypothesis that the variables being compared followed a normal distribution was evaluated using a Lilliefors test ("lillietest" command; see also Conover, 1980). Based on the output of the Lilliefors test, the parametric ("anova1") or non-parametric ("kruskalwallis") MATLAB implementations of ANOVA were used to test the significance of differences between the group means. Finally, if the null hypothesis that all group means were equal was rejected by the ANOVA, the "multcompare" function (based on procedures from Hochberg and Tamhane, 1987) was used to determine which pairs of means were significantly different from one another. A 95% confidence interval ($P < 0.05$) was used for all statistical tests.

Results

Acoustic survey

Clustering the acoustic survey data discriminated seven acoustic classes. The three major classes, which comprised 94% of the echoes in the survey area, are plotted in Figure 4. The four minor classes were dispersed widely across the study area. Due to limited dive time,

Figure 4

The three main acoustic classes, which comprise 94% of echoes in the survey, and diver-estimated substrate at 22 sites. Visual observation of this figure suggests that Acoustic Class 1 corresponds to hard bottom and Acoustic Classes 2 and 3 both correspond to sediment.

the sites chosen for ground truth focused on the three largest classes.

Diver survey

Diver estimates of substrate at the twenty-two sites selected to ground truth the three major acoustic classes are shown in Figure 4. All sites were dominated by sand or hard bottom substrate. Seven sites had small amounts of rubble substrate, with only one site having >10% rubble (Fig. 4).

Grouper abundance at each of the dive sites is shown in Figure 5. At ten sites, no groupers were observed. Groupers were observed at 12 sites, with higher numbers corresponding to decreasing frequency of sites. The maximum number of groupers observed at any site was six (*n*=1).

Acoustic classification accuracy assessment

Bottom types were assigned to acoustic classes based on visual observation of diver survey results overlain on the acoustic classification map (Fig. 4). Visually, Acoustic Class 1 corresponds with the dive sites dominated by hard bottom and Acoustic Classes 2 and 3 both correspond with the dive sites dominated by sediment (Fig. 4).

The overall accuracy of the acoustic classification considering only hard bottom and sand classes was 86% (Table 1), which is comparable to the accuracy of optical

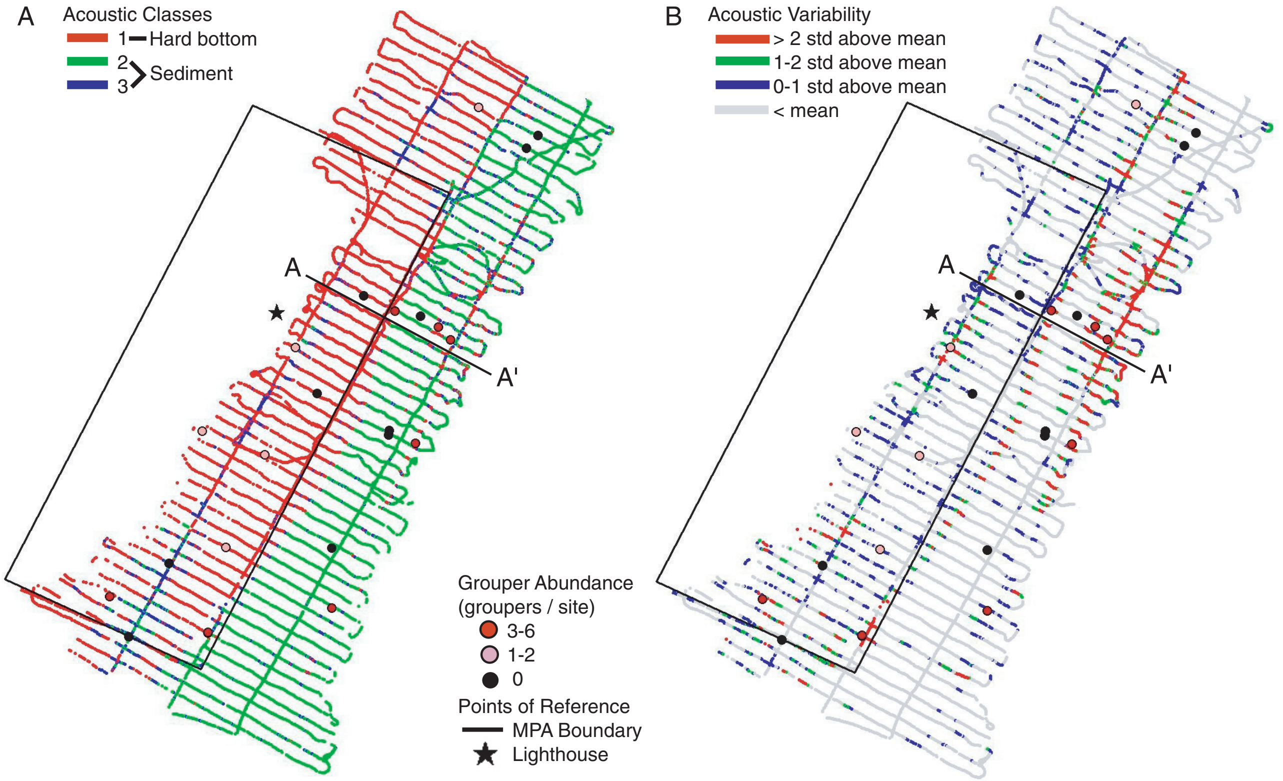


Figure 5

Grouper (*Epinephelus* and *Mycteroperca* spp.) abundance at each of the dive sites relative to (A) acoustic classification and (B) acoustic variability. Groupers were found primarily in areas with hard bottom substrate and high acoustic variability. Note that the area of high variability is much smaller than the area of hard bottom. Transect A-A′ is plotted in Figure 7.

sensors for mapping coarse bottom types (Mumby and Edwards, 2002).

Grouper abundance vs. acoustic classification and variability

Visual inspection of the grouper abundance data in Figure 5 suggests that sites with high grouper abundance were associated with hard bottom and had higher acoustic variability than sites with fewer groupers. The differences between group means were not, however, statistically significant when the data were tested with ANOVA using seven categories (one each for sites with number of groupers from zero to six); this negative result may be due to the small number of sites in most categories. The ANOVA analysis was repeated with sites grouped into only two categories based on the presence (n=12) or absence (n=10) of groupers. Sites with groupers had both a significantly higher percentage of hard bottom relative to sand ($P = 0.006$) and significantly higher acoustic variability ($P < 0.001$) than sites without groupers (Fig. 6).

Discussion

Results from this study demonstrate that acoustic signatures consisting of a simple substrate classification and an index of local heterogeneity were different for dive sites with and without groupers at Carysfort Reef. In general, sites where groupers were present had hard substrate with high local heterogeneity, and sites without groupers had sediment substrate with low local heterogeneity.

QTC systems have previously distinguished outcropping rock from sediment (e.g. Anderson et al., 2002); most of these studies, however, have focused on siliciclastic environments. Moreover, previous work with an older QTC-IV system suggested that rough terrain could adversely affect system accuracy (Hamilton et al., 1999). It is therefore noteworthy that results from this study show that acoustics can be used to distinguish hard bottom and sediment with high accuracy in a high relief, carbonate reef environment.

The reason that sediment in the Carysfort Reef area maps as two distinct acoustic classes (Fig 4) is uncertain,

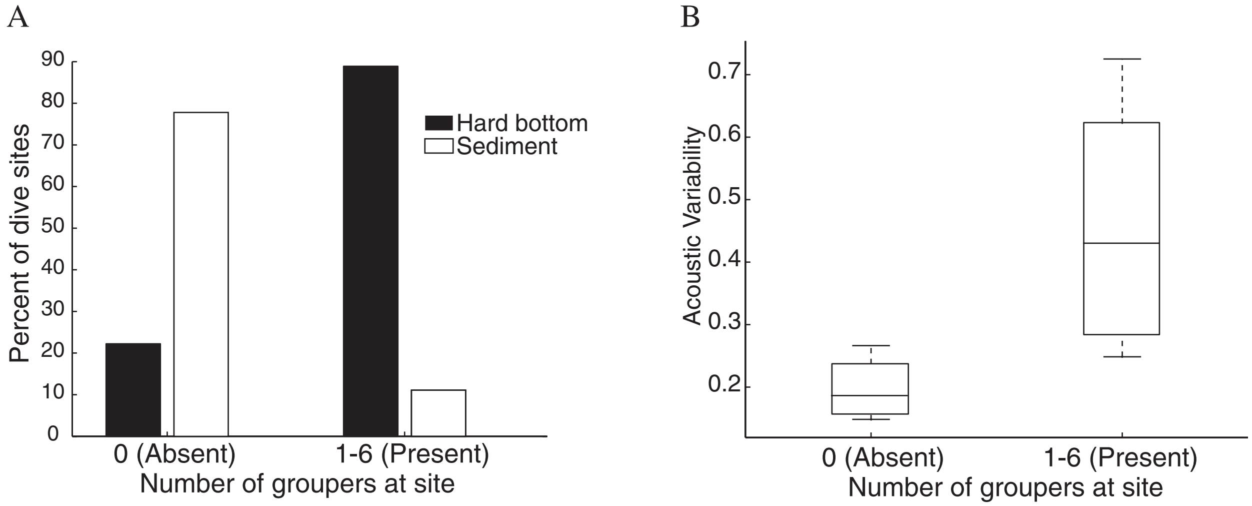


Figure 6

Acoustic classification and acoustic variability computed from the echoes closest to each dive site and grouped by the presence/absence of groupers (*Epinephelus* and *Mycteroperca* spp.). A) Bars indicate the percent of dive sites for which the closest echo classified as hard bottom (Acoustic Class 1) or sediment (Acoustic Classes 2 or 3). B) Box plots of acoustic variability near dive sites. Horizontal lines mark the lower quartile, median, and upper quartile values. The lines extending from each end of the box show the range of all data. Note that grouper presence correlates with hard bottom and high acoustic variability.

but is likely related to differences in physical properties, such as sediment grain size. Clustering of sediment with different grain sizes as distinct acoustic classes would be consistent with previous QTC-derived classification schemes (Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a; Freitas et al., 2003b).

The acoustic classification results at Carysfort Reef demonstrate that the location of a point in Q-space is related to physical characteristics of the bottom. A set of points that are spread out in Q-space are therefore more likely to represent different bottom types than a set of points that are tightly clustered in Q-space. Areas where different bottom types are located close together, such as patchy environments or along edges, have high acoustic variability, and areas where the bottom does not change rapidly have low acoustic variability (Fig. 7). Like the Berger-Parker index (Morrison et al., 2001), acoustic variability highlights transitions between classes (edges) and heterogeneous areas with mixed classes. Acoustic variability, however, is computed directly from the reduced acoustic echo features (Q-space) as opposed to operating on classified data. Operating directly on the Q-values may be advantageous because differences between echoes are measured continuously, rather than in discrete classes, and because the results are not dependent on the classification scheme used.

Table 1

Error matrix comparing acoustic classification with diver-based "ground truth." Acoustic Class 1 was interpreted as a hard bottom class, and Acoustic Classes 2 and 3 were combined to form a single sediment substrate class. Fractional values are possible because the entry for each point was divided proportionally by the diver-estimated substrate at that site. The sum of all entries is 18, indicating that the closest echoes to 18 of the 22 dive sites were classified as Acoustic Classes 1, 2, or 3.

	Diver-estimated substrate			
Acoustic classes	Hard bottom	Sediment	Rubble	Overall accuracy
Class 1 (hard bottom)	8.2	1.1	0.7	0.86
Class 2+3 (sediment)	0.7	7.3	0.0	

Observations by NMFS divers that groupers are often found over "complex" bottoms (caves, crevices, ledges) led to the idea of testing acoustic variability. It should be noted, however, that topographic complexity as observed by divers is not the same as acoustic variability as defined in this study. Topographic complexity occurs on

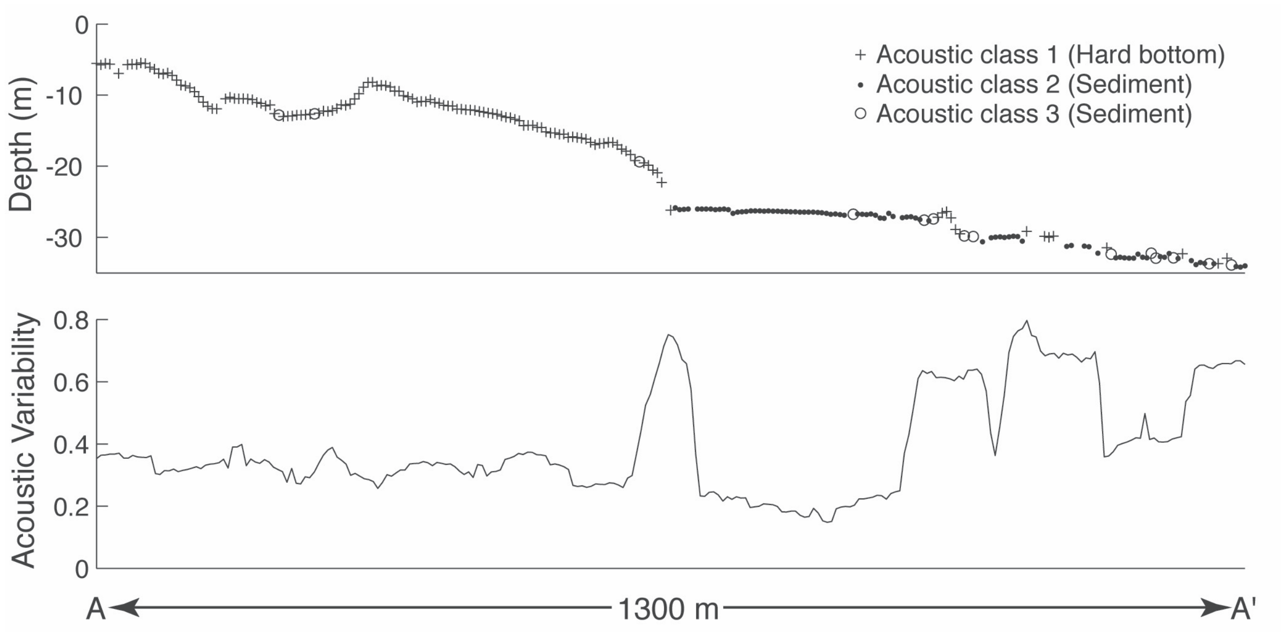


Figure 7

Depth, acoustic class, and acoustic variability along transect A-A′, shown in Figure 5. Acoustic variability within large areas of a single class ranges from high to low, but the highest variability is found at the transitions between classes. Patchy areas, such as the deep outcropping hard bottom, can form extended regions of high acoustic variability.

the scale of meters and might be thought of as a rough or steep bottom. Acoustic variability, on the other hand, is measured on the scale of tens of meters and reflects the proximity of acoustically distinct bottom types.

The observation that sites with groupers had higher acoustic variability than sites without groupers does not mean that acoustic variability is a measure of essential grouper habitat. Acoustic variability does not measure what a diver might perceive as important variables for grouper habitat. Acoustic variability could, however, help prioritize diving effort for grouper population surveys. Acoustic variability might also contribute to a better understanding of grouper habitat. For example, it is not clear why aggregations are so site-specific. From a diver's point of view, the bottom at the site of an aggregation can appear very similar to the bottom just a few hundred meters away. Measurements of acoustic variability may help to interpret diver observations by providing context on a larger spatial scale.

The distinct differences in acoustic signatures of sites with and without groupers (Fig. 6) suggest that acoustic classification and acoustic variability are potentially useful tools for stratifying diver sampling effort for grouper census. A simple map distinguishing hard bottom from sediment, which can be easily produced with acoustics, is a substantial improvement over a lack of any bottom type information in optically deep water. A map of acoustic variability may further refine the location of potential grouper habitat, thereby increasing the efficiency of divers to conduct fish census surveys.

Conclusions

The results of this study showed:

1. A commercial acoustic seafloor classification system (QTC View V) was successfully used to discriminate hard bottom from sediment in a carbonate reef environment.
2. A simple map of hard bottom versus sediment was a useful first step in discriminating potential grouper habitat.
3. An index of acoustic variability, which measures heterogeneity of bottom types, complemented the simple bottom classification map to further target areas of potential grouper habitat.

Therefore, the acoustic signature of the seafloor, as measured with acoustic classification and acoustic diversity, is a useful tool for stratifying sampling effort for diver-based grouper census surveys. Both acoustic classification and acoustic variability can be rapidly and inexpensively acquired when needed by fisheries and park managers around the world because they are easily measured with a single beam echo sounder.

Acknowledgments

Funding for this project was provided by a grant from the NOAA-NMFS Coral Reef Initiative (A.M.E.) and ONR grant N000140110671 (R.P.R.). Small boat and SCUBA diving operations were conducted with the invaluable help of D. McClellan, D. Harper, G.M. Miller, J. Contillo, H. Balchowsky, J. Schull, S. Cimilluca, J. Javech, and N. Baertlein. The authors appreciate insight provided by W. Collins and J. Preston, Quester Tangent Corporation, during the analysis of the acoustic data. Two anonymous reviewers provided detailed and helpful comments on the manuscript.

Literature cited

Anderson, J. T., R. S. Gregory, and W. T. Collins.
2002. Acoustic classification of marine habitats in coastal Newfoundland. ICES J. Mar. Sci. 59:156–167.

Bohnsack, J. A., and S. P. Bannerot.
1986. A stationary visual census technique for quantitatively assessing community structure of coral reef fishes. NOAA Tech. Rep. NMFS 41, 15 p.

Coleman, F. C., C. C. Koenig, A.-M. Eklund, and C. B. Grimes.
1999. Management and conservation of temperate reef fish in the southeastern United States. *In* Life in the slow lane— ecology and conservation of long-lived marine animals (J. A. Musick, ed.), p. 233–242. American Fisheries Society Bethesda, Maryland.

Congalton, R. G., and K. Green.
1999. Assessing the accuracy of remotely sensed data: Principles and practices. Lewis Publishers, Boca Raton, 137 p.

Conover, W. J.
1980. Practical nonparametric statistics. Wiley, New York, 493 p.

Davis, J. C.
1986. Statistics and data analysis in geology. John Wiley & Sons, New York, 646 p.

Eklund, A.-M., D. B. McClellan, and D. E. Harper.
2000. Black grouper aggregations in relation to protected areas within the Florida Keys National Marine Sanctuary. Bull. Mar. Sci. 66(3):721–728.

Ellingsen, K. E., J. S. Gray, and E. Bjornbom.
2002. Acoustic classification of seabed habitats using the QTC VIEW system. ICES J. Mar. Sci.(59):825–835.

Florida Marine Research Institute (FMRI).
1998. Benthic habitats of the Florida Keys. FMRI Technical Report TR-4, 53 p.

Franklin, E. C., J. S. Ault, S. G. Smith, J. Luo, G. A. Meester, G. A. Diaz, M. Chiappone, D. W. Swanson, S. L. Miller, and J. A. Bohnsack.
2003. Benthic habitat mapping in the Tortugas Region, Florida. Mar. Geod. 26:19–34.

Freitas, R., A. M. Rodrigues, and V. Quintino.
2003a. Benthic biotopes remote sensing using acoustics. J. Exp. Mar. Biol. Ecol. 285–286:339–353.

Freitas, R., S. Silva, V. Quintino, A. M. Rodrigues, K. Rhynas, and W. T. Collins.
2003b. Acoustic seabed classification of marine habitats: studies in the western coastal-shelf area of Portugal. ICES J. Mar. Sci. 60:599–608.

Hamilton, L. J., P. J. Mulhearn, and R. Poeckert.
1999. Comparison of RoxAnn and QTC-View acoustic bottom classification system performance for the Cairns area, Great Barrier Reef, Australia. Cont. Shelf. Res. 19:1577–1597.

Hochberg, Y., and A. C. Tamhane.
1987. Multiple comparison procedures, Wiley, 450 p.

McClellan, D. B., and G. M. Miller.
2003. Reef fish abundance, biomass, species composition, and habitat characterization of Navassa Island. *In* Status of reef resources of Navassa Island: Nov. 2002 (M. W. Miller, ed.), p. 24–42. NOAA Tech. Memo. NMFS-SEFSC-501.

Morrison, M. A., S. F. Thrush, and R. Budd.
2001. Detection of acoustic class boundaries in soft sediment systems using the seafloor acoustic discrimination system QTC VIEW. J. Sea Res. 46:233–243.

Mumby, P. J., and A. J. Edwards.
2002. Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy. Remote Sens. Environ. 82:248–257.

Polovina, J. J., and S. Ralston.
1987. Tropical snappers and groupers: biology and fisheries management. Westview Press, Boulder, CO, 659 p.

Quester Tangent Corporation (QTC).
2004. QTC IMPACT User Guide Version 3.40, Sidney, BC, Canada, 126 p.

Sadovy, Y.
1994. Grouper stocks of the western central Atlantic: the need for management and management needs. Proc. Gulf Carib. Fish. Inst. 43:43–64.

Sadovy, Y., and A.-M. Eklund.
1999. Synopsis of biological data on the Nassau grouper, *Epinephelus striatus* (Bloch, 1792), and the jewfish *E. itajara* (Lichtenstein, 1822). NOAA Tech. Rep. NMFS 146, 65 p.

Abstract—The Tortugas South Ecological Reserve, located along the margin of the southwest Florida carbonate platform, is part of the largest no-take marine reserve in the U.S. Established in July 2001, the reserve is approximately 206 km^2 in area, and ranges in depths from 30 m at Riley's Hump to over 600 m at the southern edge of the reserve. Geological and biological information for the Tortugas South Reserve is lacking, and critical for management of the area. Bathymetric surveys were conducted with a Simrad EM 3000 multibeam echosounder at Riley's Hump and Miller's Ledge, located in the northern and central part of the reserve. Resulting data were used to produce basemaps to obtain geological ground truth and visual surveys of biological communities, including reef fishes. Visual surveys were conducted using SCUBA and the Phantom S2 Remotely Operated Vehicle (ROV) at Riley's Hump. Visual surveys were conducted using the ROV and the Deepworker 2000 research submersible along Miller's Ledge, within and outside of the reserve. A total of 108 fishes were recorded during SCUBA, ROV, and submersible observations. Replicate survey transects resulted in over 50 fishes documented at Miller's Ledge, and eight of the top ten most abundant species were planktivores. Many species of groupers, including scamp (*Mycteroperca phenax*), red grouper (*Epinephelus morio*), snowy grouper (*E. niveatus*), speckled hind (*E. drummondhayi*), and Warsaw grouper (*E. nigritus*), are present in the sanctuary. Numerous aggregations of scamp and a bicolor phase of the Warsaw grouper were observed, indicating the importance of Miller's Ledge as a potential spawning location for both commercially important and rare deep reef species, and as a potential source of larval recruits for the Florida Keys and other deep reef ecosystems of Florida.

Deepwater reef fishes and multibeam bathymetry of the Tortugas South Ecological Reserve, Florida Keys National Marine Sanctuary, Florida

Douglas C. Weaver
Flower Garden Banks National Marine Sanctuary, NOAA
4700 Avenue U, Building 216
Galveston, TX 77551
Email: doug.weaver@noaa.gov

David F. Naar
Brian T. Donahue
College of Marine Science
University of South Florida
140 7th Avenue S.
St. Petersberg, FL 33701

Introduction

The Tortugas Ecological Reserve is located 225 km west of Key West, Florida, at the western terminus of the Florida Keys island chain (Fig. 1). The reserve was implemented in July 2001, and consists of two sections: Tortugas North (312 km^2) and Tortugas South (206 km^2), with a total area of 518 km^2 (Cowie-Haskell and Delaney, 2003). Tortugas North protects relatively deep (30–50 m) coral reef banks known as Tortugas Bank, while Tortugas South protects Riley's Hump, a known spawning aggregation site for many species of snappers (family Lutjanidae), and a range of deepwater habitats (50–600 m) (Dahlgren et al., 2001; Cowie-Haskell and Delaney, 2003). The Tortugas South Preserve is part of the largest fully protected marine reserve in the United States (Cowie-Haskell and Delaney, 2003).

Despite the widespread distribution of deep reef ecosystems in the southeastern United States (Avent et al., 1977; Barans and Henry, 1984), our knowledge of deep reef fish diversity, distribution, and ecology is extremely limited. Numerous large predators, including commercially important scamp, gag, red snapper, snowy grouper, Warsaw grouper, and wreckfish, reach abundant population numbers at water depths between 100 and 500 m along the southeastern U.S. and Gulf of Mexico. Smaller species of western Atlantic deep reef fishes are taxonomically and ecologically diverse, and may reach great abundances in these deepwater ecosystems.

Hard bottom reef communities at the shelf-slope break, formed by the consolidation of post-glacial paleoshorelines and formation of relict reef communities following sea level lowstands some 18,000 years ago, provide extensive shelf edge fish habitat worldwide (Mallinson et al., 2003). Holocene reefs of the Dry Tortugas and Riley's Hump actively developed on Pleistocene reef rock between 6 and 10 kbp, but coral growth rates diminished at Riley's Hump at approximately 4 kbp due to rising sea levels, resulting in a "give up" condition of low reef growth (Mallinson et al., 2003). To the south of Riley's Hump, hard bottom habitats are formed from Pleistocene paleoshoreline rock and erosional features, forming a dramatic scarp known as "Miller's Ledge."

Water depths in TSER range from approximately 30 m at Riley's Hump to over 600 m at the southern edge. However, previous research has focused on the coral reef and reef fish assemblage of Riley's Hump, and few studies have been conducted below

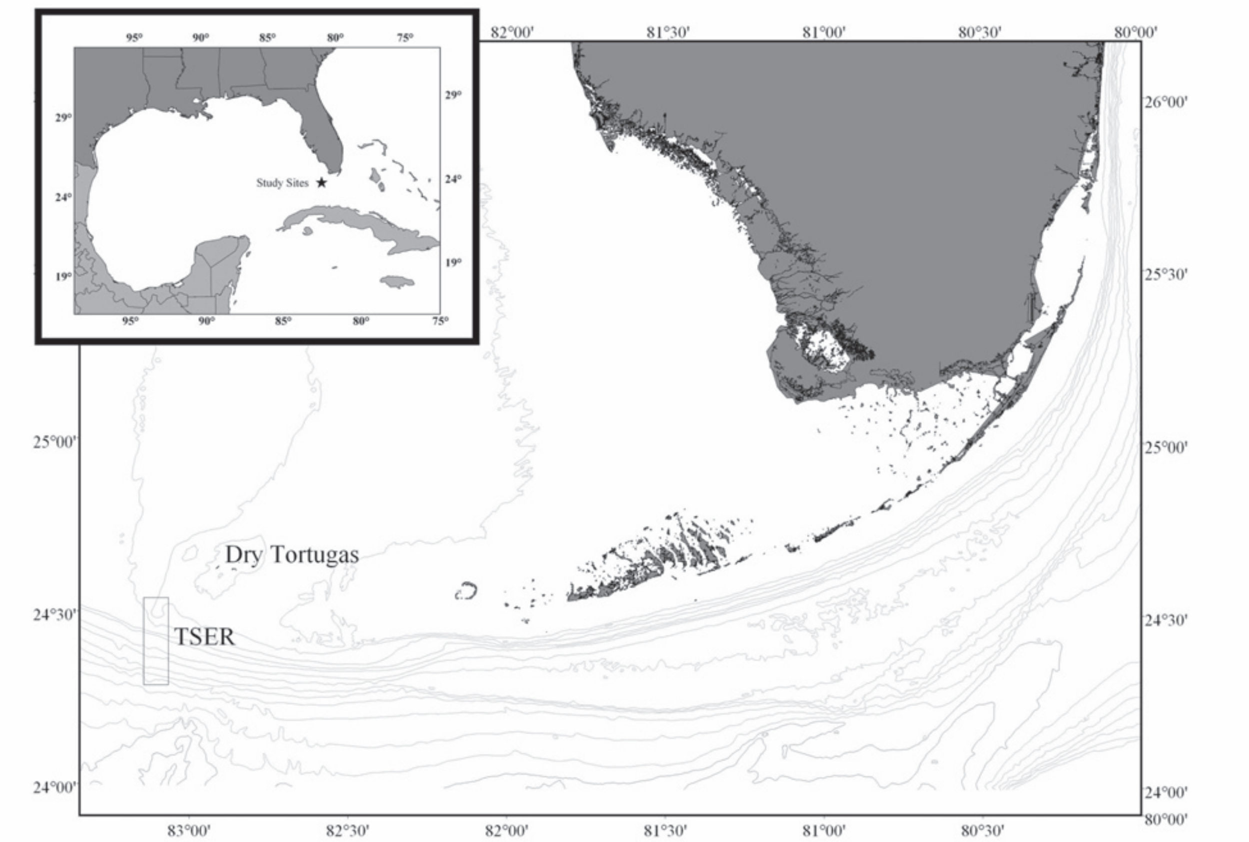


Figure 1

Location of Tortugas South Ecological Reserve, at the western terminus of the Florida Keys tract.

50 m in the reserve (Dahlgren et al., 2001, Franklin et al., 2003). To assist with biological characterization, geological characterization, and habitat mapping within the reserve, we provide bathymetry and information on surface geology between 40 and 150 m within the reserve. To provide comparative ecological data for other deep reef communities and assist with management decisions concerning the TSER, we provide a preliminary list of fishes occurring at the reserve as a representative shelf-edge reef community of the Gulf of Mexico and Caribbean.

Materials and methods

Two additional research cruises were conducted to document reef fish communities within the reserve using SCUBA, remotely operated vehicle (ROV), and manned submersibles. Multibeam bathymetric surveys were conducted using a pole mounted Kongsberg Simrad EM3000 multibeam echo sounder aboard the RV *Suncoaster* (operated by the Florida Institute of Oceanography). During data collection, survey speeds reached a maximum of 9 knots. Sound velocity casts were limited to twice a day because of the relative stability of sound velocity in this area. Sound velocity data were collected using a SBE-19 Seabird CTD, from which the speed of sound was calculated using the Chen-Millero equation. The largest change in sound velocity normally occurs at sea level, which was monitored using an AML sound velocity smart sensor sending data directly to the acquisition computer once per second. The data were post-processed using Neptune software (Kongsberg Maritime, Kongsberg, Norway). Navigation data were cleaned by flagging out positions where the distance between points was greater than 5 m and survey speed was above 9 knots. For data cleaning, the cell size was set to 4 m. Points were rejected if they exceeded a noise limit that was two times the standard deviation of the average mean value of the cell. Final processing was the correction for tidal variation, using a tidal estimating program developed by Ruoying He and Robert Weisberg at the University of South Florida (Ruoying He, pers. commun.). The data were then exported in an ASCII x,y,z

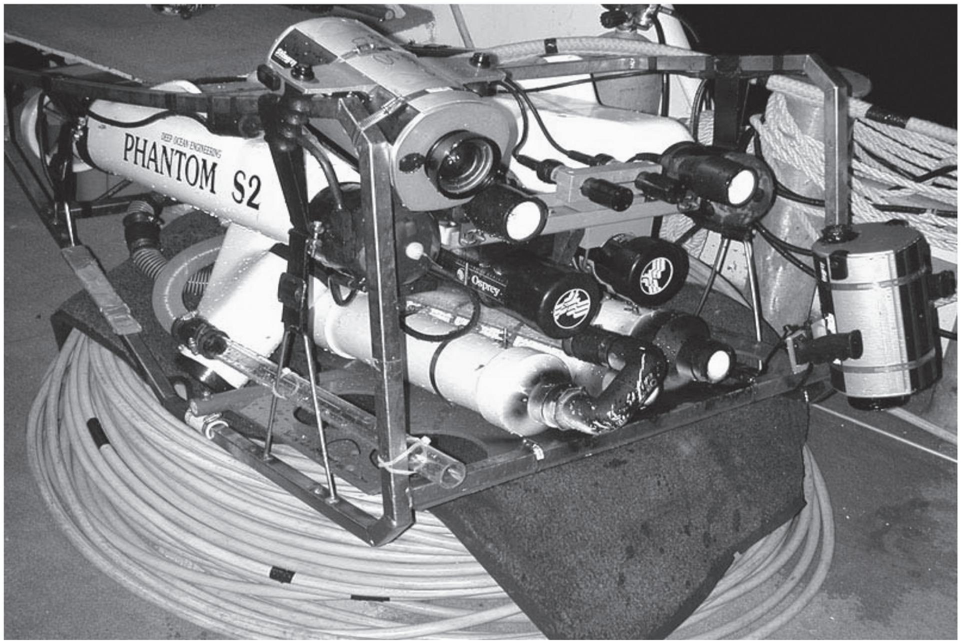


Figure 2
The Phantom S2 Remotely Operated Vehicle (ROV), provided by the National Undersea Research Center at the University of North Carolina, Wilmington. Surveys were conducted to characterize benthic habitat and reef fish communities of Tortugas South Ecological Reserve.

format and imported into Fledermaus software (Interactive Visualization Systems, Fredericton, NB, Canada). The Fledermaus software provided the base maps in this article and a guide to the subsequent fish surveys. Attitude and position of the sonar head were calculated using the Applanix PosMV 320 (previously called TSS POS/MV), which uses dual GPS antennas and an Inertial Motion Unit, which provided Roll and Pitch within 0.2 degrees accuracy and heading within 0.3 degrees accuracy. Positions accuracy is 1 m or better.

Reef fish surveys were conducted using a Phantom S2 ROV provided by the National Undersea Research Center at the University of North Carolina, Wilmington (NURC-UNCW) to document geological formations and associated reef fish community structure throughout the reserve (Fig. 2). Digital video cameras in underwater housings were attached to the ROV to improve resolution of the digital videotapes for taxonomic identification of reef fishes. Fishes were identified to the lowest possible taxon following Humann and DeLoach (2002), based on the taxonomic nomenclature of Robins et al. (1991). Trophic categories were assigned based on dietary information from Randall (1967), Smith-Vaniz et al. (1999), or Bullock and Smith (1991) for individual species or closely related taxa.

Multiple transects were conducted along Miller's Ledge, both within the no-take reserve, and the unprotected areas to the west of the sanctuary. The third research cruise was conducted as part of the Sustainable Seas Expeditions (SSE) using the Deepworker 2000 research submersible, equipped with digital videocamera and sampling arm (Fig. 3). A single submersible transect, 5 km in length, was conducted on 19 July 2002 within the reserve to survey geological features identified in the multibeam basemap and further document reef fish community structure. The first author conducted an additional visual survey on 20 July 2002, using SCUBA and a housed video camera at Riley's Hump to document representative reef fishes occurring on the feature.

Results

Multibeam bathymetry surveys of Riley's Hump reveal a relatively flat crest with an elevated rim along the southwestern and SSE margins (Fig. 4, Fig. 5). A shallow depression is present in the center of the feature, with numerous regions of variable topography along the eastern-central half of the feature. The southern margin of the bank is characterized by a steep (~20 m

Figure 3

The first author in the Deepworker 2000 Research submersible. This one-person submarine is rated to a depth of 2000 fsw (610 m) and equipped with a digital video camera, manipulator arm, and sampling basket. The submersible was used to survey Miller's Ledge at Tortugas South Ecological Reserve. Photograph provided by Kip Evans, National Geographic Society, in association with the Sustainable Seas Expeditions, 2002 (Sylvia Earle, Chief Scientist).

in relief) escarpment, ranging in depth from 30 m at the top of the bank to 50+ m at the base, where a well-developed trough surrounds the southern margin and extends eastward. Reported aggregation sites of the mutton snapper (*Lutjanus analis)* are associated with this steep southern scarp (Fig. 5). The slope is less steep to the east of the bank, suggesting a debris field generated by the prominent easterly flow of the Gulf Loop/Florida Current in this region. A detailed review of geology of Riley's Hump is presented in Mallinson et al. (2003).

Hard bottom communities observed at Riley's Hump are dominated by scleractinian coral assemblages, gorgonians, assorted sponges, and leafy algae (Fig. 6). ROV surveys revealed isolated reef communities interspersed with sand channels and carbonate debris. Dominant scleractinians were *Montastraea cavernosa*, *M. annularis*, and *Siderastrea siderea*. Individual colonies of *Montastrea* sp. were typically small, ranging from 10 to 50 cm in diameter. Occasional large colonies were observed to 2 m in height. Massive sponges, including vase sponges (*Callyspongia* sp.) and giant barrel sponges (*Xestospongia muta*), were abundant on the reef surface. Sea plumes (*Pseudopterogorgia* sp.) and assorted octocorals were abundant on patch reef communities, and extended out onto the carbonate debris fields surrounding the reef platform. At deeper water depths, the benthic community was dominated by rope sponges (*Aplysina cauliformis*) and calcareous algae including *Halimeda* and *Penicillus* sp. Dense algal mats of *Dictyota* sp. and *Lobophora* were observed during SCUBA and ROV surveys on the shallower patch reef communities.

Multibeam bathymetry surveys at Miller's Ledge provide a detailed view of the ~40 m (in relief) escarpment occurring through the center of the TSER (Figs 7–9). Water depths at Miller's Ledge range from approximately 84 m at the crest to 124 m at the base of the feature, where a distinct trough and moat has formed (Fig. 7).

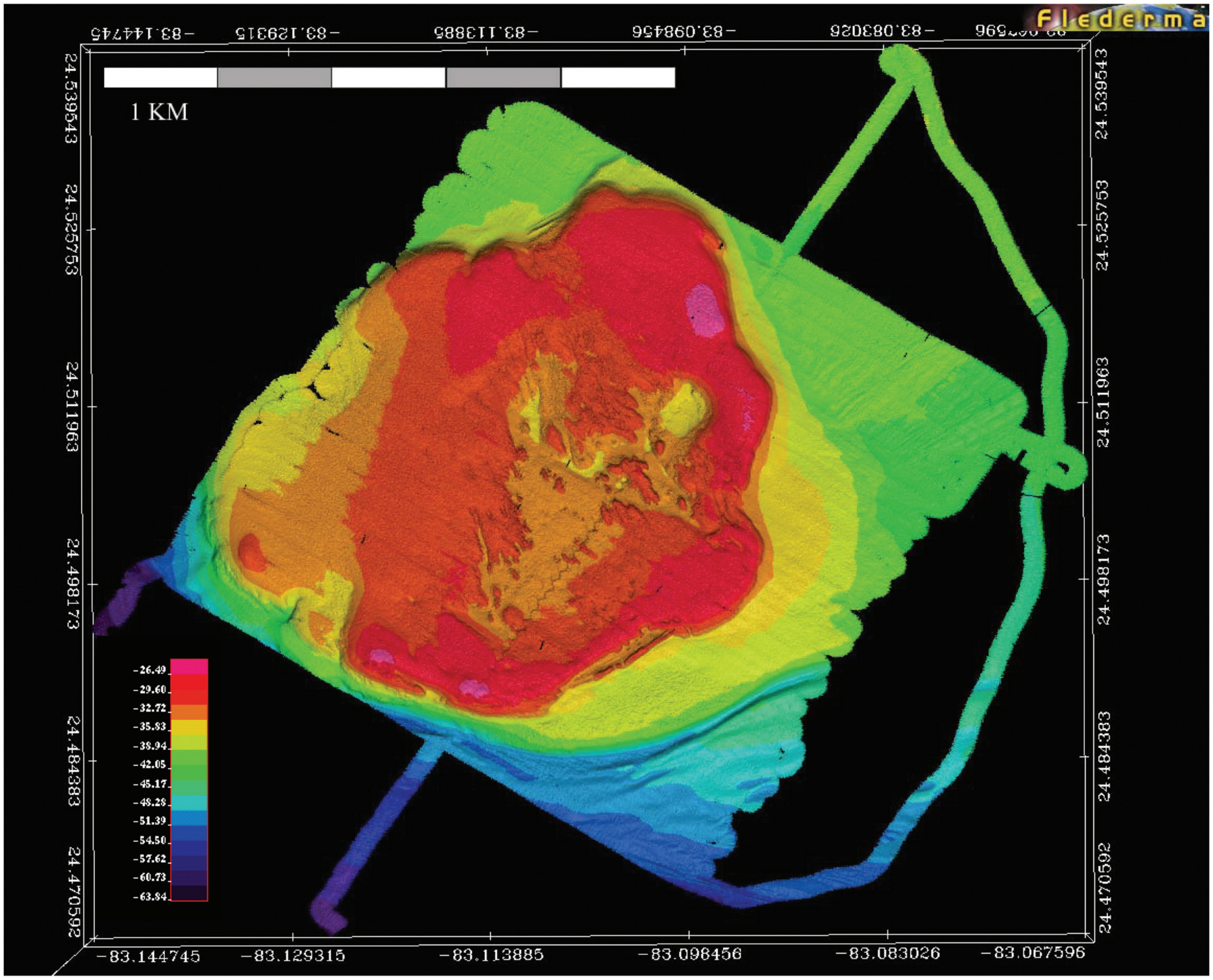


Figure 4

Plan view of color-shaded bathymetry of Riley's Hump. Vertical exaggeration=4X. Depth in meters.

The escarpment is steep, with an estimated rise of approximately 20–30 degrees. There are numerous areas of rock outcrops at the base of the feature (Fig 8A). The escarpment begins along the eastern boundary of TSER and extends 11 km to the western edge of the survey area. Bathymetric charts indicate that it may extend an additional 40 km to the southern extent of Pulley Ridge along the SW corner of the shelf. The western half of the study area is characterized by abrupt topography and many isolated mounds and peaks (Fig. 8A). In contrast, the eastern half of the survey area is characterized by a gradual decrease in the height of the scarp, a reduced number of solitary mounds at the base of the feature, and its eventual burial under shelf sediments (Fig 8C). North of the escarpment, distinct linear ridges are present parallel to the crest of the feature. These ridges most likely represent consolidated paleoshorelines formed during sea level lowstands, and were observed as linear belts of low profile rock outcrops during ROV and submersible dives.

In contrast to the deep coral reef communities of Riley's Hump, benthic assemblages of Miller's Ledge are dominated by small sponges, bryozoans, small solitary corals, and the corkscrew sea whip, *Cirrhipathes* sp. Rocky outcrops associated with paleoshorelines and high profile outcrops at the crest of the ledge had relatively low levels of encrusting invertebrate growth. Consolidated rock cobbles, boulders, and larger blocks were scattered along the face of Miller's Ledge, and colonized by bryozoans, hydrozoans, and solitary corals. This encrusting assemblage was observed on all hard surfaces below 90 m. During submersible dive A20-

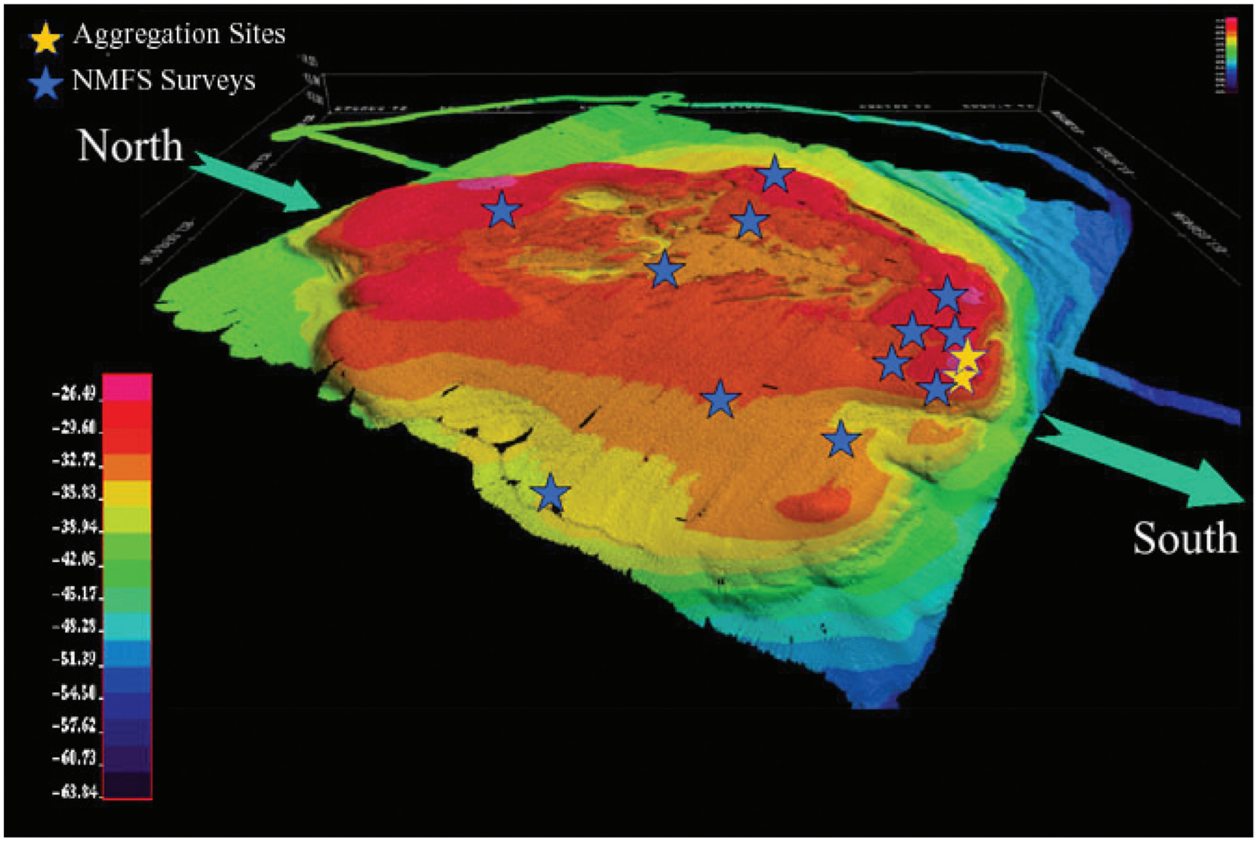


Figure 5

Oblique view of color-shaded bathymetry of Riley's Hump, looking east. Vertical exaggeration=4X. Depth in meters. National Marine Fisheries Service study locations depicted by blue stars, mutton snapper aggregation sites represented by yellow stars (locations courtesy M. Burton, NMFS Beaufort). See Figure 4 for scale.

164, extensive expanses of coarse sediments and fields of carbonate debris were observed along the eastern extent of the feature. This area appears to be buried by coarse sediments and carbonate material carried to the southeast from the shallower regions of the shelf, including Riley's Hump (Fig. 8B). Few hard bottom communities were observed in this area, with occasional low profile rock outcrops and scattered rock fragments. At three separate locations along the submersible track, large aggregations of pencil urchins, *Eucidaris* sp., were observed evenly distributed across the coarse sediment fields. These urchin aggregations were not observed during ROV operations.

Also during the submersible dive, an abandoned set of traps was observed to form an artificial reef (Figs. 10A–C). Seven individual traps were tightly bundled together by a length of trapline (Fig 10A). The surface of the trap mesh was covered with colonial oysters, forming a high profile oyster reef. This artificial reef was densely colonized by small reef fishes, primarily the red barbier (*Hemanthias vivanus*), and attracted numerous species of grouper and snapper, including a pair of speckled hind (*Epinephelus drummondhayi*) and a large aggregation of scamp (*Mycteroperca phenax*) (Fig 10B). A large hogfish (*Lachnolaimus maximus*) was observed foraging on the surface of the artificial reef (Fig 10C).

During ROV surveys at Miller's Ledge, we observed a large Warsaw grouper (*Epinephelus nigritus*) in a distinct bicolor phase, with dark brown grey dorsum, head and caudal fin coloration clearly demarcated from a bright white lateral surface. The black anal fin spot was clearly visible in this individual (Fig. 11).

During ROV surveys at the central and western portion of the survey area, extensive areas of deep rocky reefs were observed at the base of the feature (Fig. 12). The rectilinear fracture pattern observed on these blocks suggest transport of a large section from the rocky layers forming the crest of the escarpment. At other areas of the base of the scarp and trough, extensive regions of

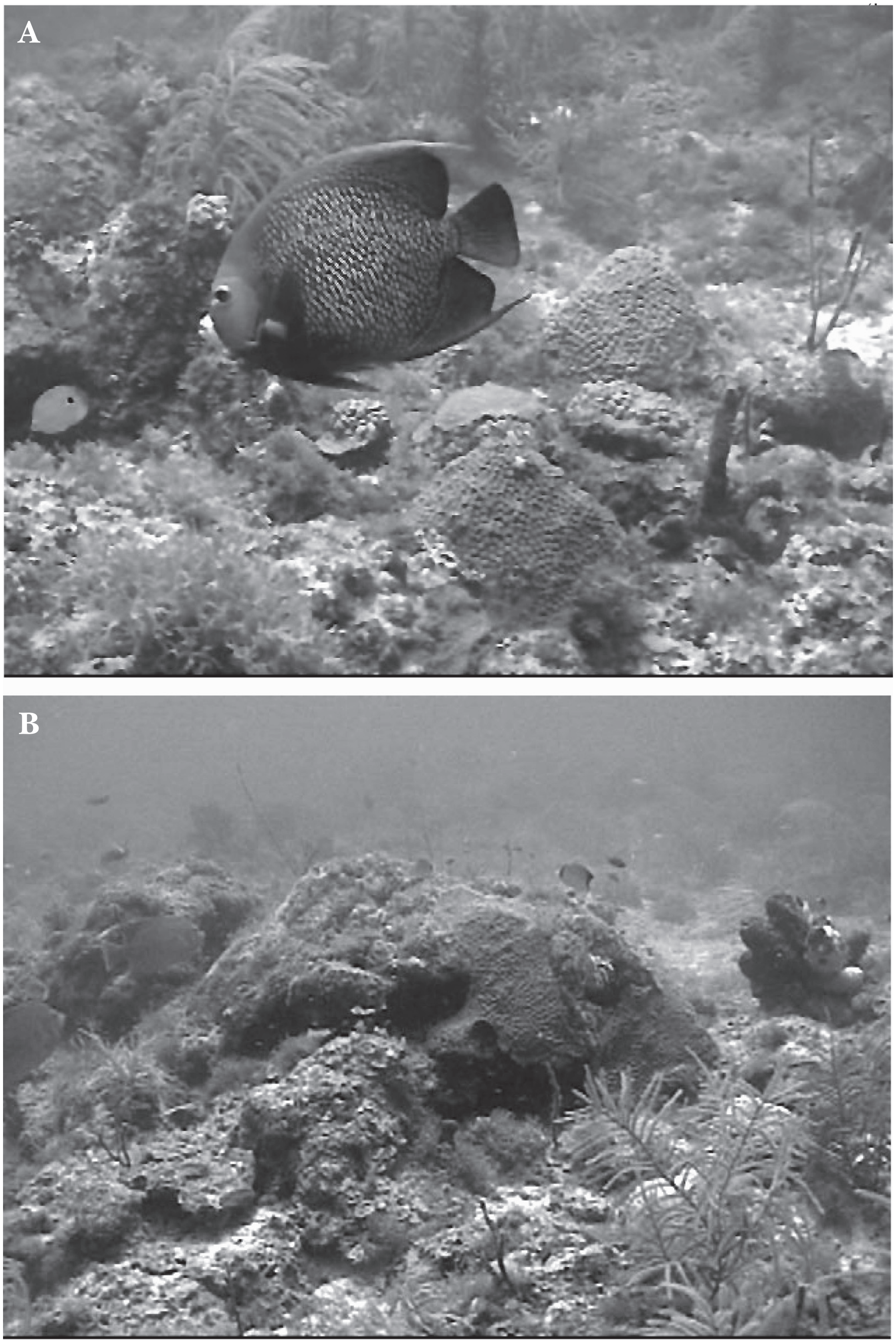


Figure 6

Biological communities of Riley's Hump. A) French angelfish (*Pomacanthus paru*) above scattered small hard coral heads and sea plumes. B) Larger colonies of *Montastrea cavernosa*, sea plumes, and sponges.

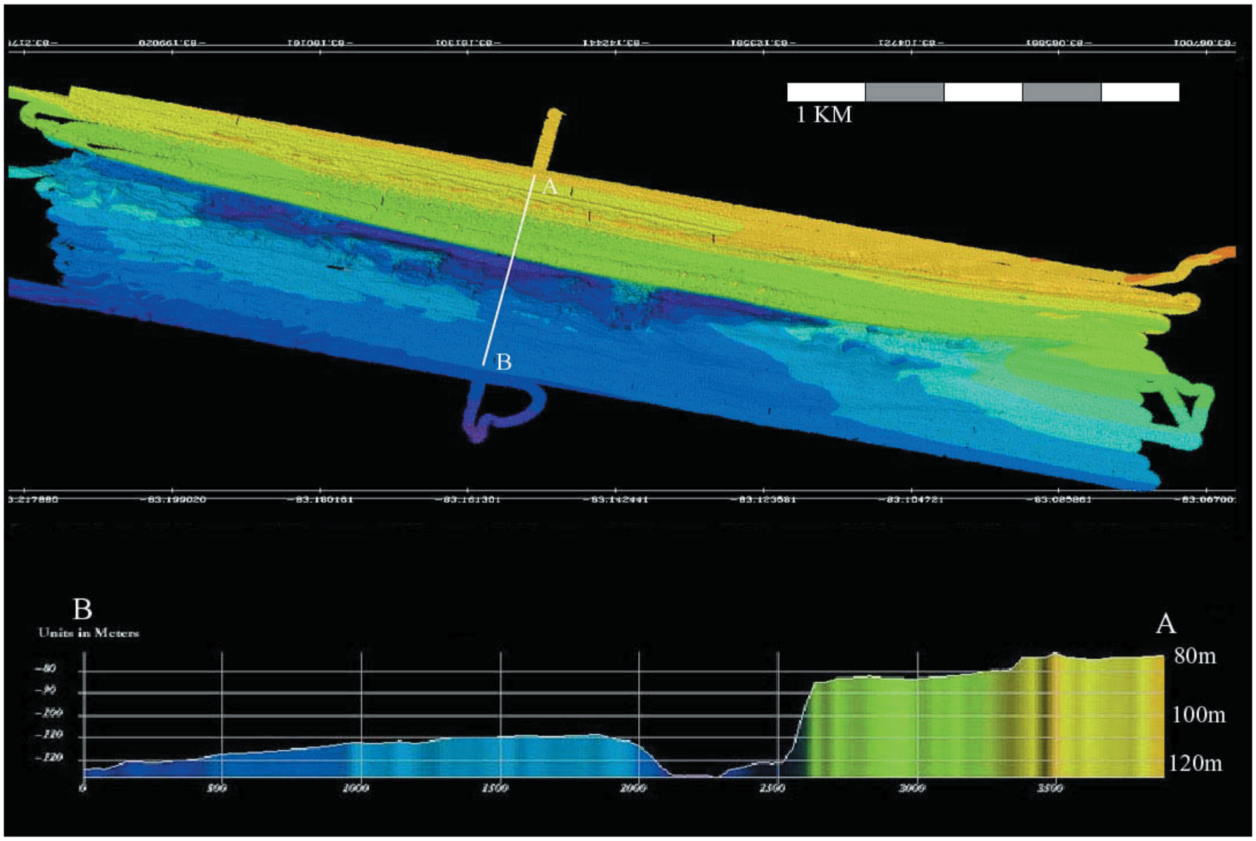


Figure 7

Top) Plan view of color-shaded bathymetry for Miller's Ledge of the Tortugas South Ecological Reserve. Bottom) Cross-section (A–B) of Miller's Ledge revealing steep escarpment. Depth range from 80 m (red) to 150 m (purple). This feature provides extensive habitat for a variety of groupers, including scamp, speckled hind, Warsaw, and snowy grouper.

white clay substratum and scattered rock cobbles and boulders were observed (Fig. 13). This formation was termed "cookie dough" reef due to the rough surface of the rock structures and the presence of small solitary coral colonies scattered about the surface. Dredge samples taken along the west-central region of the study area reveal these reef structures to be biogenic, formed by sessile molluscs, bryozoans, tube worms, and solitary corals (Fig 13, bottom). These small reef structures attracted numerous species of reef fishes, and a variety of groupers were observed on the larger rocky outcrops at the base of the feature.

One hundred and six (106) species of reef fishes and a total of 13,766 individuals were observed at both Riley's Hump and Miller's Ledge via all survey methods (Appendix A). Comparisons of reef fish assemblages at Riley's Hump and Miller's Ledge reveals distinct differences in the reef fish communities (Table 1). Reef fish surveys conducted at Riley's Hump revealed a diverse shallow water coral reef assemblage, dominated by labrids, pomacentrids, and scarids, making up over 70% of the fish population by number. The bluehead (*Thallasoma bifasciatum*), bicolor damsel (*Stegastes partitus*), yellowhead wrasse (*Halichoeres garnoti*), and greenblotch parrotfish (*Sparisoma atomarium*) were the dominant reef fish taxa observed by ROV surveys. In addition to these taxa, the masked goby (*Coryphopterus personatus*) and striped grunts (*Haemulon striatum*) were abundant during SCUBA surveys. Other families of fishes represented were serranids, tetraodontids, acanthurids, and chaetodontids. In contrast, fishes of Miller's Ledge are overwhelmingly dominated by schooling serranids, including the roughtongue bass (*Pronotogrammus martinicensis*), red barbier (*Hemanthias vivanus*), and creole-fish (*Paranthias furcifer*). Other serranids, including tattler (*Serranus phoebe*) and scamp (*Mycteroperca phenax*), are abundant along the ledge and associated habitats. Other dominant taxa at Miller's Ledge include the yellowtail reeffish (*Chromis enchrysura*) and striped grunts. Of the top 15 fish

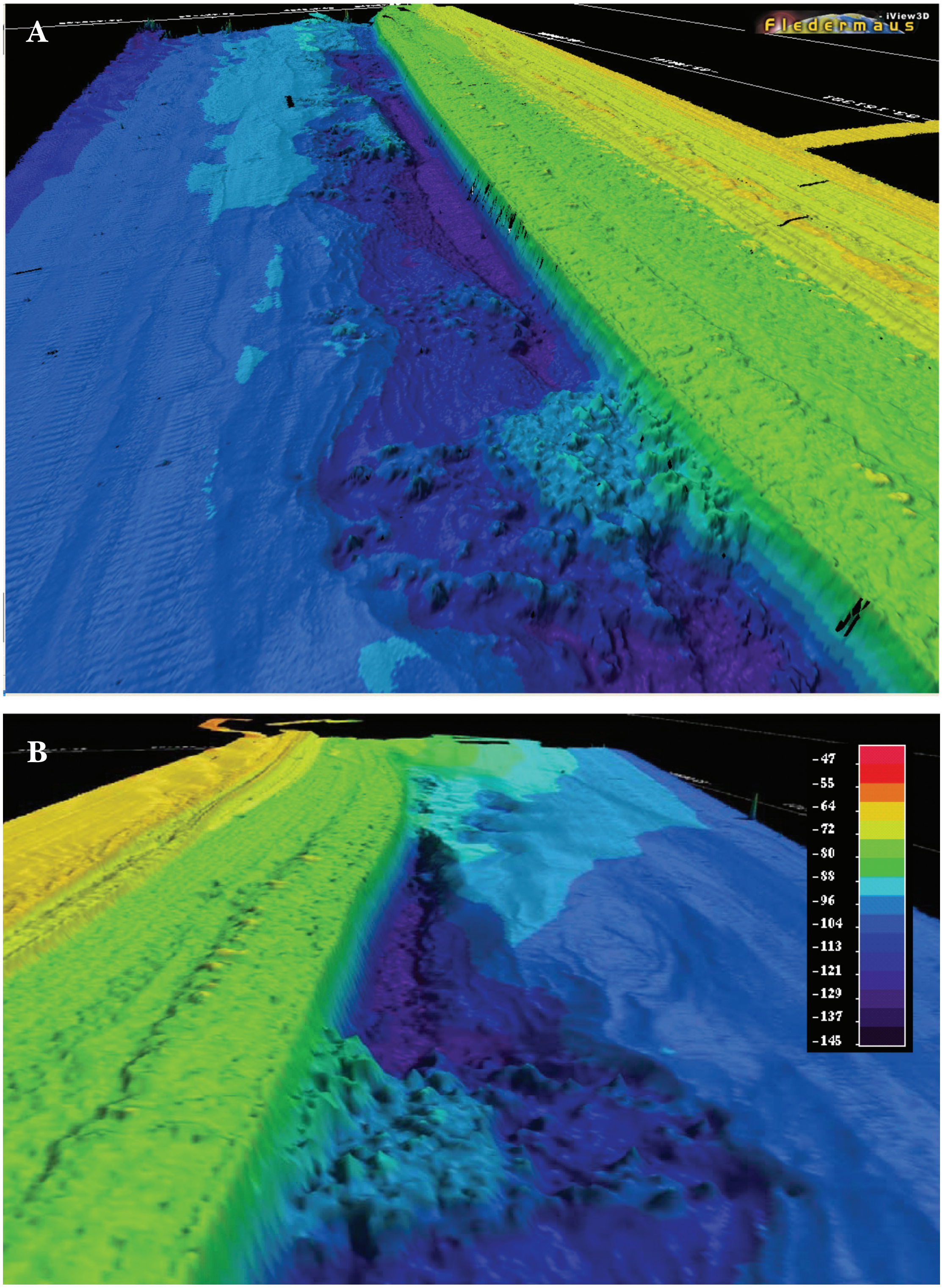


Figure 8

A) Oblique view of color-shaded bathymetry of Miller's Ledge, looking west. B) Oblique view of color-shaded bathymetry of Miller's Ledge, looking east. Vertical exaggeration=4X. Depth in meters. See Fig. 7 for scale.

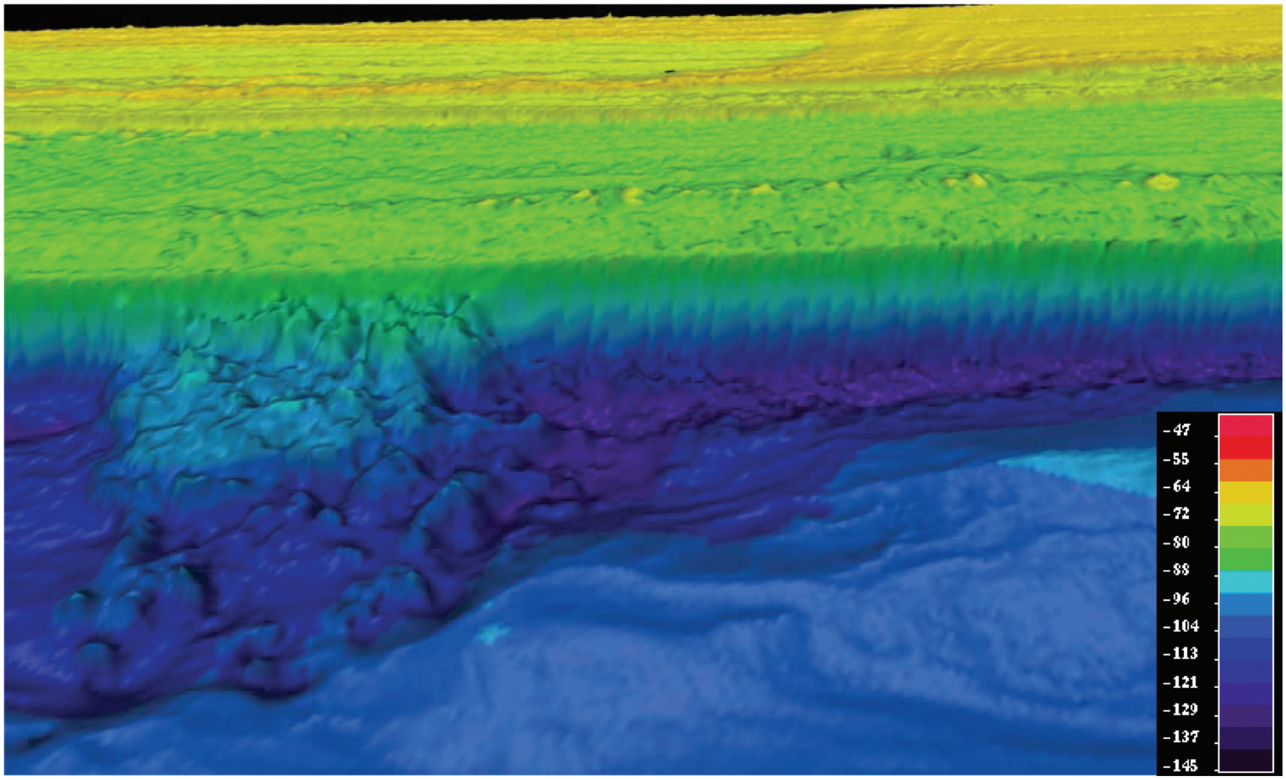


Figure 9

Oblique view of color-shaded bathymetry of Miller's Ledge, looking north. Vertical exaggeration=4X. Depth in meters. See Fig. 7 for scale.

taxa observed at each location, only sharpnose puffer (*Canthigaster rostrata*) and yellowtail reef fish were represented in the 15 most abundant fish taxa observed at both locations (Table 1).

Reef fishes documented at Riley's Hump were ecologically diverse, and dominated by planktivores (three of the top four most abundant species—Table 1). Herbivores, benthic carnivores, and epibenthic browsers were also common in the deep coral reef community. In contrast, the fish community at Miller's Ledge was overwhelmingly dominated by planktivores, with over 95% of the individuals observed by ROV and submersible belonging to this feeding guild. The top five most abundant species observed by ROV, and top four observed by submersible, were planktivores. Piscivores, represented primarily by scamp, and generalized carnivores, represented by tattler, were the next most abundant groups on the submersible transect and ROV transects, respectively. Other groups observed included benthic carnivores (greenband wrasse, *Halichoeres bathyphilus* and red hogfish, *Decodon puellaris*). Epibenthic browsers were represented by the reef butterflyfish (*Chaetodon sedentarius*) and the goldface toby (*Canthigaster jamestyleri*).

Discussion

Reef fish communities observed at the TSER are distinctly divided between the deep coral reef fish assemblage of Riley's Hump, and the outer shelf/upper slope deep reef assemblage associated with drowned/fossil reef formations at Miller's Ledge. Common reef fish taxa of the drowned reef assemblages also dominate hard bottom reefs and banks of the northwestern Gulf of Mexico (Rezak et al., 1985, 1990; Dennis and Bright, 1988). Reef fish assemblages follow similar patterns to benthic invertebrate assemblages, where distance from shore, water turbidity, seasonal temperatures, and water depth determines benthic assemblages and the associated reef fish assemblages (Dennis and Bright, 1988).

While the northwestern Gulf of Mexico is characterized by a diversity of deep reef habitats, including coralgal reefs (partly drowned reefs) and algal nodule-sponge communities, these communities, and many of their associated reef fishes, are absent at the crest of Miller's Ledge. Elevated turbidity levels and swift currents associated with the persistent flow of the Loop Current/Florida Current likely increases suspended sediment levels in this region, and lead to the burial of

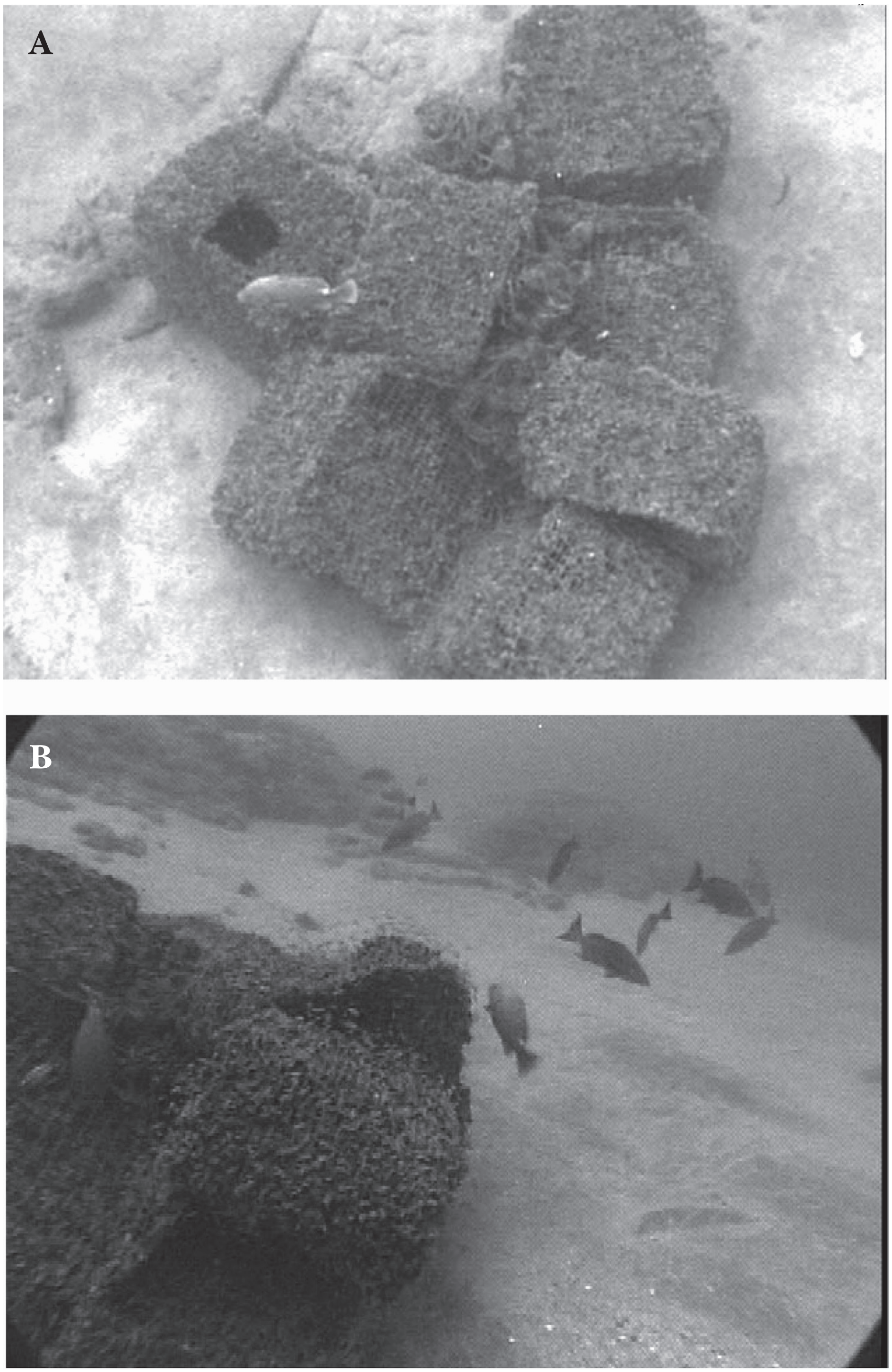


Figure 10

A) Seven ghost fish traps forming an artificial reef, colonized by oysters, at the eastern terminus of Miller's Ledge. A speckled hind (*Epinephelus drummondhayi*) swims above the reef. B) A large group of scamp (*Mycteroperca phenax*) aggregating around the artificial reef. Natural rock outcrops of Miller's Ledge visible in background. C) A large male hogfish (*Lachnolaimus maximus*) foraging on the reef surface. Stills taken from video footage courtesy the Sustainable Seas Expedition.

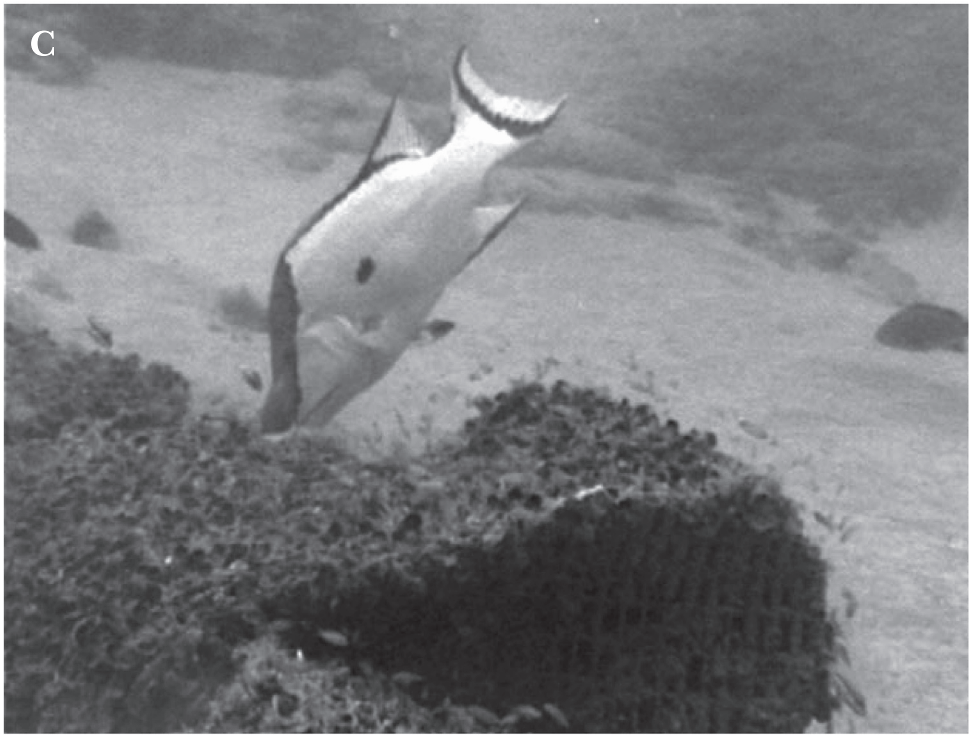


Figure 10 (continued)

the scarp at the eastern boundary of TSER. The formation of the steep vertical scarp of Miller's Ledge along its central and western portion, the associated trough and moat at the base of the formation, and the sweeping of sediments from Riley's Hump and the surrounding shelf eastward all appear to be linked to the prominent flow of the Florida Current. Turbulent water flow and upwelling was observed at the surface during our research cruises, and appear to be caused by the impact of this major current on this steep scarp.

The dominance of planktivores in deep reef fish assemblages has been observed in other studies of community structure in the Gulf of Mexico (Pattengill-Semmens et al., 1997) and the Pacific (Hamner et al., 1988; Thresher and Colin, 1986). Pettengill Semmens et al. (1997) and Hamner et al. (1988) consistently observed high numbers in the reef fish communities of the northwestern Gulf of Mexico (Flower Garden Banks and Stetson Banks) and the Great Barrier Reef, Australia, respectively. Results of the Riley's Hump reef fish surveys show parallel trends at assemblages, with over 50% of the individuals represented by planktivores. Plantivores and piscivores also appear to dominate deeper reef communities worldwide and form the primary trophic pathways between 90 and 300 m (Thresher and Colin, 1986). Roughtongue bass and red barbier were the dominant species observed at Miller's Ledge, and are the most abundant reef fish by number on most drowned reef areas throughout the southeastern U.S. and Gulf of Mexico. Roughtongue bass, red barbier, and threadnose bass form dense schools over high relief rocky structures throughout the Gulf of Mexico, and provide a forage base for many deep reef predators. The high profile rock face of Miller's Ledge provides feeding grounds for large groupers and snappers, and their prey. Numerous scamp were observed along the ledge, and the bicolor phase of the Warsaw grouper indicates a dominant male of the species and potential for spawning activity, as has been observed for other groupers (Gilmore and Jones, 1992).

While small prey fishes often reach great abundances at shelf edge reef structures, upper and middle slope regions are often food poor (Weaver and Sedberry, 2001). With greater depths (150–250 m), the main trophic pathways for dominant predators include benthic invertebrates (snowy grouper, *Epinephelus niveatus,* and tilefish, *Caulolatilus* spp.) and plankton for large schools of yellowtail bass (*Anthias nicholsi*) associated with isolated rock outcrops (Weaver and Sedberry, 2001). While few reef fishes were observed along the eastern (leeward) extent of Miller's Ledge, the persistent currents and abundant hard bottom structures observed along the scarp and base present high profile structures for reef fishes to aggregate. This abrupt change in topography

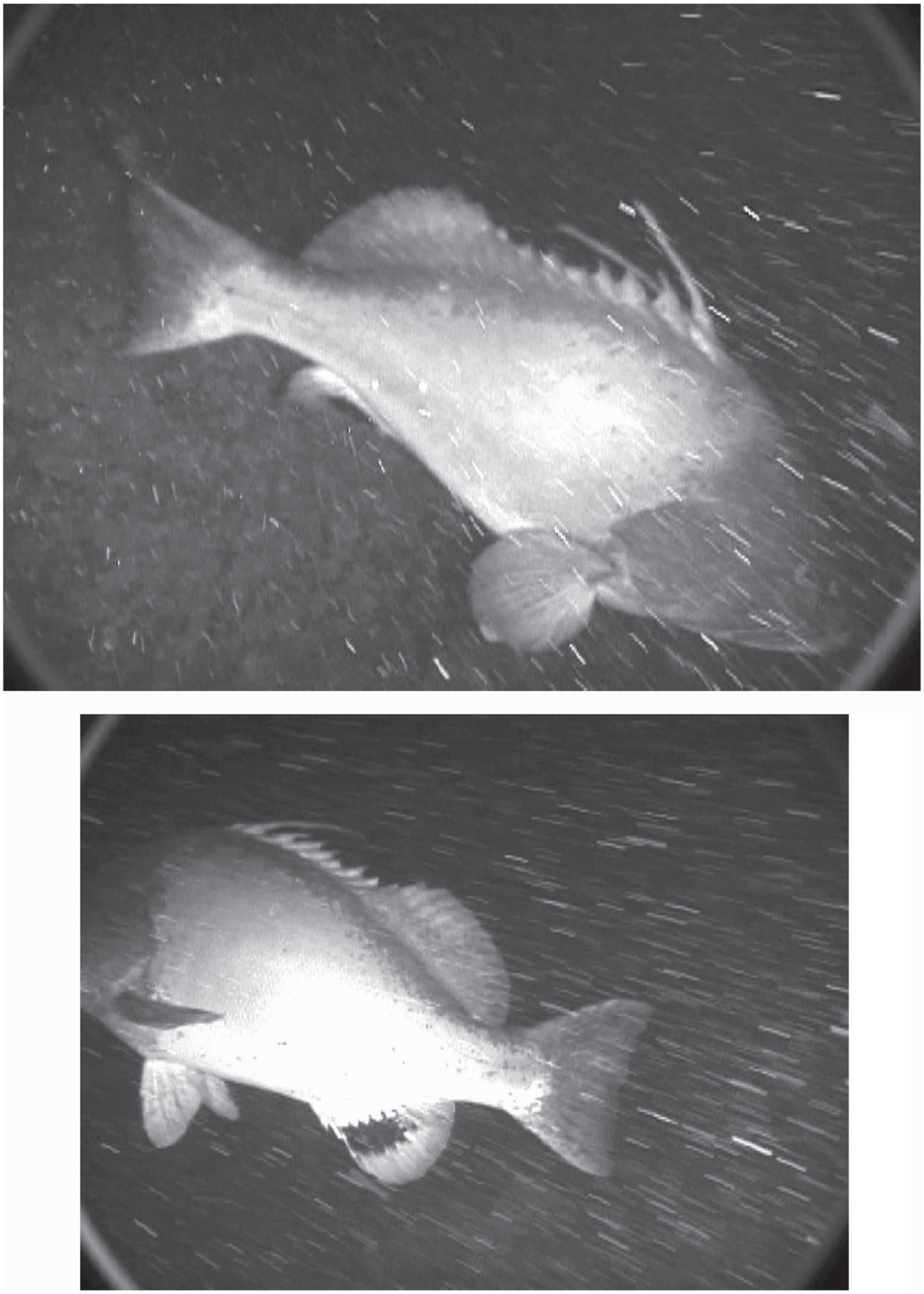


Figure 11

A large Warsaw grouper (*Epinephelus nigritus*) occurring at Tortugas South Ecological Reserve. This individual displays a "bicolor" phase typical of dominant males in spawning condition, and indicates a potential spawning area for this species. The Warsaw grouper is a rare species that is of management concern. Digital still frame provided by NURC-UNCW.

Table 1

Top 15 fishes observed at the Tortugas South Ecological Reserve via SCUBA, ROV, and submersible. Trophic categories follow Randall (1967) and Bullock and Smith (1991).

			TSER0801 Riley's ROV			SSE2002 Riley's SCUBA			TSER0801 Miller's ROV			SSE2002-164 Miller's submersible		
Species	Common name	Diet[1]	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent
Thallasoma bifasciatum	bluehead	PL	1	424	25.48	3	127	11.27	—	—	—	—	—	—
Stegastes partitus	bicolor damselfish	PL	2	270	16.23	4	102	9.05	—	—	—	—	—	—
Halichoeres garnoti	yellowhead wrasse	BC	3	233	14.00	7	35	3.11	—	—	—	—	—	—
Chromis scotti	purple reeffish	PL	4	173	10.40	1	306	27.15	—	—	—	—	—	—
Sparisoma atomarium	greenblotch parrotfish	H	5	104	6.25	18	9	0.80	—	—	—	—	—	—
Inermia vittata	boga	PL	6	100	6.01	—	—	—	—	—	—	—	—	—
Clepticus parrae	creole wrasse	PL	7	44	2.64	15	13	1.15	—	—	—	—	—	—
Sparisoma aurofrenatum	redband parrotfish	H	8	26	1.56	14	14	1.24	—	—	—	—	—	—
Serranus tortugarum	chalk bass	PL	9	24	1.44	—	—	—	—	—	—	—	—	—
Canthigaster rostrata	sharpnose puffer	EB	10	21	1.26	21	4	0.35	25	3	0.04	—	—	—
Chromis cyanea	blue chromis	PL	11	19	1.14	6	45	3.99	—	—	—			
Acanthurus coeruleus	blue tang	H	12	17	1.02	17	11	0.98	—	—	—	—	—	—
Scarus iserti	striped parrotfish	H	13	16	0.96	8	25	2.22	—	—	—	—	—	—
Chromis enchrysura	yellowtail reeffish	PL	14	14	0.84	—	—	—	4	69	0.96	3	104	2.67
Coryphopterus personatus	masked goby	PL	15	12	0.72	2	201	17.83	—	—	—	—	—	—
Acanthurus chirurgus	doctorfish	H	18	11	0.66	9	22	1.95	—	—	—	—	—	—
Pseudopeneus maculatus	spotted goatfish	BC	20	9	0.54	12	16	1.42	45	1	0.01	—	—	—
Chaetodon sedentarius	reef butterflyfish	EB	21	8	0.48	13	14	1.24	9	36	0.50	11	12	0.31
Chromis insolata	sunshinefish	PL	23	7	0.42	11	16	1.42	—	—	—	—	—	—
Chaetodon capistrata	foureye butterflyfish	EB	28	4	0.24	10	19	1.69	—	—	—			
Priacanthus arenatus	bigeye	PL	30	4	0.24	—	—	—	15	16	0.22	28	1	0.03
Mycteroperca phenax	scamp	PI	62	1	0.06	—	—	—	7	44	0.61	5	33	0.85
Pronotogrammus martinicensis	roughtongue bass	PL	—	—	—	—	—	—	1	5663	79.03	2	804	20.66
Hemanthias vivanus	red barbier	PL	—	—	—	—	—	—	2	602	8.40	1	2709	69.62
Paranthias furcifer	creole-fish	PL	—	—	—	—	—	—	5	61	0.85	8	19	0.49
Serranus phoebe	tattler	GC	—	—	—	—	—	—	6	60	0.84	6	26	0.67
Halichoeres bathyphilus	greenband wrasse	BC	—	—	—	—	—	—	8	43	0.60	9	17	0.44
Sargocentron bullisi	deepwater squirrelfish	PL	—	—	—	—	—	—	10	24	0.33	12	7	0.18
Decodon puellaris	red hogfish	BC	—	—	—	—	—	—	11	23	0.32	14	4	0.10
Chaetodon aya	bank butterflyfish	PL	—	—	—	—	—	—	12	21	0.29	7	19	0.49
Seriola rivoliana	almaco jack	PI	—	—	—	—	—	—	13	20	0.28	—	—	—
Canthigaster jamestyleri	goldface toby	EB	—	—	—	—	—	—	14	19	0.27	13	6	0.15
Bodianus pulchellus	spotfin hogfish	GC	—	—	—	—	—	—	19	7	0.10	10	12	0.31
Haemulon striatum	striped grunts	PL	—	—	—	5	76	6.74	3	361	5.01	4	104	2.67
Epinephelus drummondhayi	speckled hind	GC	—	—	—	—	—	—	36	1	0.01	15	4	0.10

[1] BC=benthic carnivores (benthic crustaceans and infauna), EB=epibenthic browsers (sessile invertebrates), GC=general carnivore (mobile invertebrates and fishes), H=herbivore, PI=piscivore, PL=planktivore.

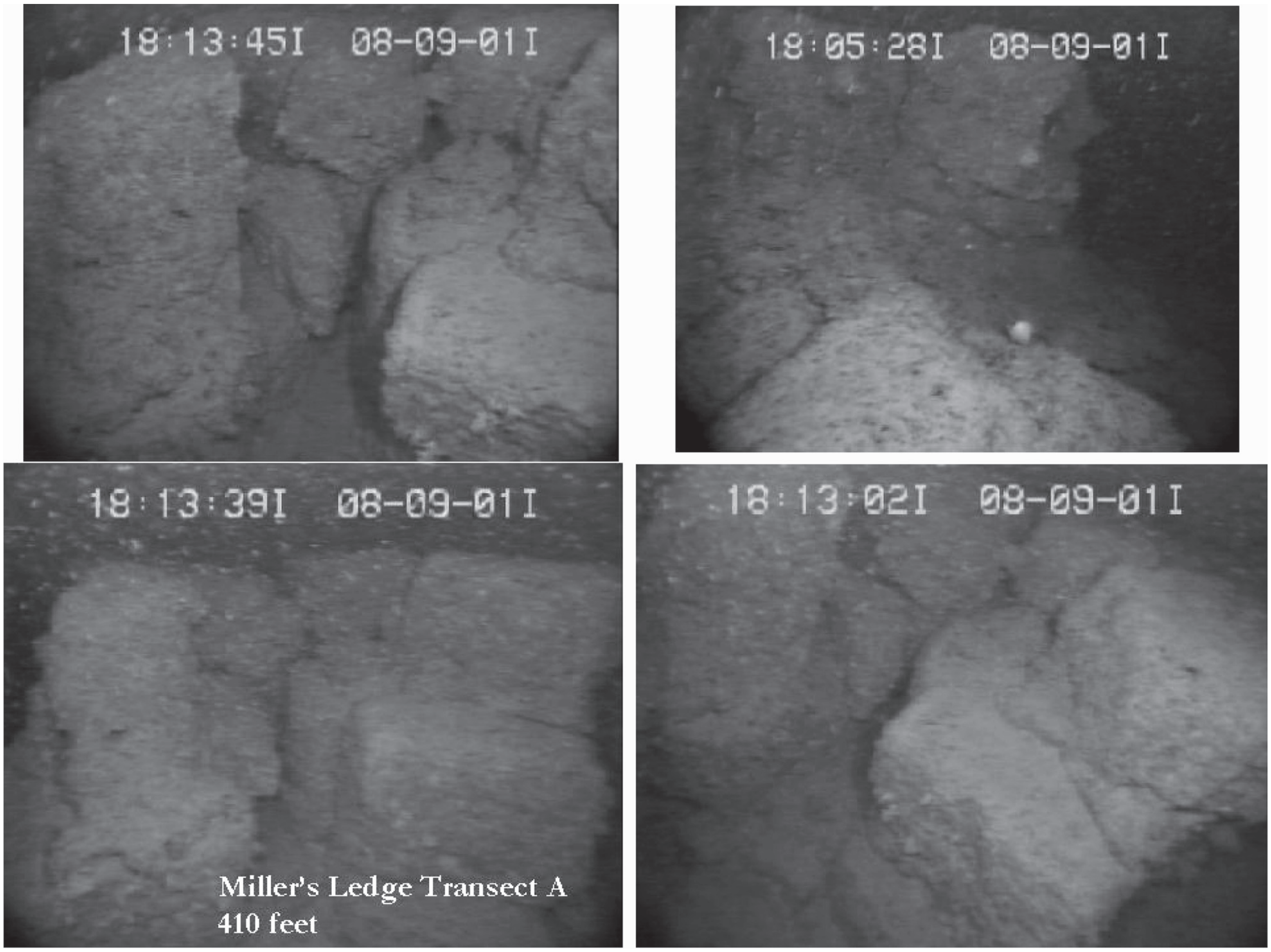


Figure 12

Large natural reef blocks located at the base of Miller's Ledge. Extensive areas of reef at the base of the ledge offer shelter for speckled hind, snowy grouper, scamp, and Warsaw grouper.

associated with rocky outcrops has been shown to support high numbers of fishes in other oceans (Yoklavich et al., 2000). Elevated structures provide shelter and access to plankton brought by impinging water currents (Hamner et al., 1988; Weaver and Sedberry, 2001). In addition to increases in local productivity and prey availability, reef fishes also appear to select areas of elevated topography based on behavioral preferences (Bohnsack, 1989). Further submersible and ROV operations within the reserve should target hard bottom communities in deeper waters to identify additional shifts in fish assemblages.

While the deep coral reef assemblage and underlying geology at Riley's Hump has been well documented (Franklin et al., 2003; Mallinson et al., 2003), the underlying processes leading to the formation of Miller's Ledge remain unresolved. The benthic assemblage leading to the formation of biogenic hard bottom reef structures, and the geologic processes that form rocky outcrops along the northern margin and crest of the scarp, are unknown. Further studies should be conducted to determine the origin and structure of the feature, the interaction between the Loop/Florida Current and the abrupt change in reef topography, and the transport and suspension of sediments from Riley's Hump and the surrounding shelf, so that impacts on the benthic invertebrate assemblages and associated reef fishes can be determined.

Acknowledgements

The Sustainable Seas Expedition (SSE) was a five-year collaborative effort between NOAA and the National

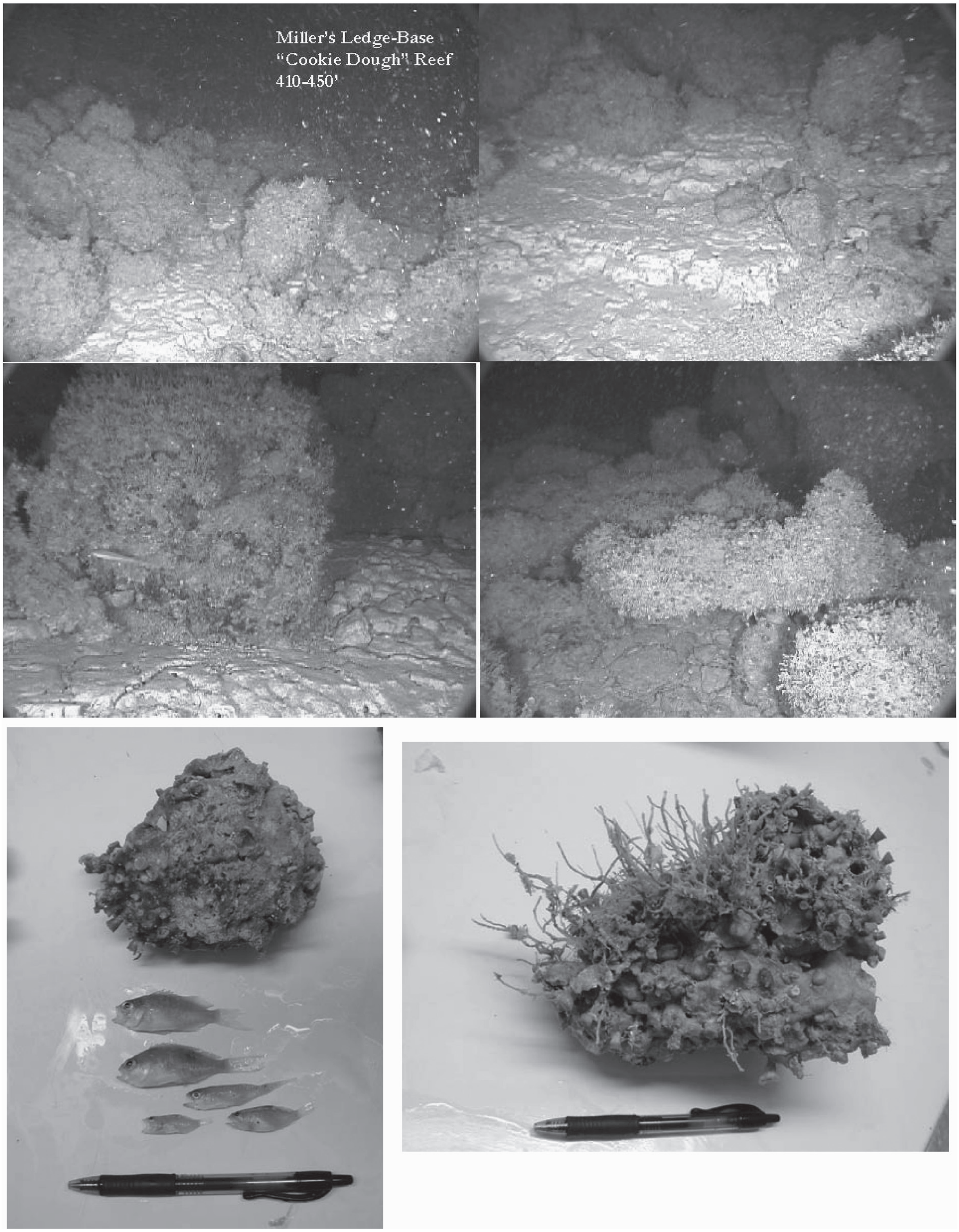


Figure 13

Top) "Cookie dough" reef cobbles and boulders located on a clay substratum along the base of Miller's Ledge. Bottom) These bioherms are built from oysters, bryozoans, and solitary corals, and form extensive hard bottom habitat for small reef fishes along the base of Miller's Ledge.

Geographic Society (NGS) to explore important marine ecosystems with special emphasis on the nation's National Marine Sanctuaries. The first author thanks Sylvia Earle for the opportunity to be part of the SSE missions, train as a pilot, and for the use of the DW2000 submersible during the research cruise to the TSER. We also thank the NGS assistants and Nuytco Research Ltd. personnel for logistical and technical support during cruises in the Dry Tortugas. We thank the captain and crew of the R/V *Suncoaster* of the Florida Institute of Oceanography for hospitality and support during two research cruises. Lance Horn and Tom Potts provided expert operation of the NURC-UNCW *Phantom* ROV during transect surveys. Funding for ship time and ROV surveys were provided by the National Fish and Wildlife Foundation and the Walt Disney Wildlife Conservation Fund, and NURC-Wilmington Grant No. 9911. Multibeam surveys were supported by USGS, USF, ONR, and NOAA. Generous technical and equipment assistance was provided by the Naval Oceanographic Office (NAVO). The authors thank Barbara Reed and others in NAVO for their rapid response, assistance, and data sharing.

Literature cited

Avent, R. M., M. E. King, and R. H. Gore.
1977. Topographic and faunal studies of shelf-edge prominences off the central eastern Florida Coast. In. Rev. Hydrobiol. 62(2):185–208.

Barans, C. A., and V. J. Henry Jr.
1984. A description of the shelf edge groundfish habitat along the southeastern United States. NE Gulf Sci. 7(1):77–96.

Bohnsack, J. A.
1989. Are the high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? Bull. Mar. Sci. 44:631–645.

Bullock, L. H., and G. B. Smith.
1991. Seabasses (Pisces:Serranidae). Memoirs of the *Hourglass* cruise. Florida Marine Research Institute. Dept. Nat. Res., St. Petersburg, FL, Vol. 8, 243 p.

Cowie-Haskell, B. D., and J. M. Delaney.
2003. Integrating science into the design of the Tortugas Ecological Reserve. Mar.Techn. Soc. J. 37(1): 68–79.

Dahlgren, C. P., J. A. Sobel, and D. E. Harper.
2001. Assessment of the reef fish community, habitat, and potential for larval dispersal from the proposed Tortugas South Ecological Reserve. Proc. Gulf Caribb. Fish. Inst. 52:700–712.

Dennis, G. D., and T. J. Bright.
1988a. Reef fish assemblages on hard banks in the northwestern Gulf of Mexico. Bull. Mar. Sci. 43(2):280–307.

Franklin, E. C., J. S. Ault, S. G. Smith, J. Luo, G. A. Meester, G. A. Diaz, M. Chiappone, D. W. Swanson, S. L. Miller, and J. A. Bohnsack.
2003. Benthic habitat mapping in the Tortugas Region, Florida. Mar. Geod. 26:19–34.

Gilmore, R. G., and R. S. Jones.
1992. Color variation and associated behavior in the epinepheline groupers, *Mycteroperca microlepis* (Goode and Bean) and *M. phenax* Jordan and Swain. Bull. Mar. Sci. 51(1):83–103.

Hamner, W. M., M. S. Jones, J. H. Carleton, I. R. Hauri, and D. McB. Williams.
1988. Zooplankton, piscivorous fish, and water currents on a windward reef face: Great Barrier Reef, Australia. Bull. Mar. Sci. 42(3):459–479.

Humann, P., and N. DeLoach.
2002. Reef fish identification (3rd ed.). New World Publications, Jacksonville, FL, 481 p.

Mallinson, D., A. Hine, P. Hallock, S. Locker, E. Shinn, D. Naar, B. Donahue, and D. Weaver.
2003. Development of small carbonate banks on the south Florida platform margin: response to sea level and climate change. Mar. Geol. 3333: 1–19.

Pattengill-Semmens, B. X. Semmens, and S. R. Gittings.
1997. Reef fish trophic structure at the Flower Gardens and Stetson Bank, NW Gulf of Mexico. Proc. 8th Int. Coral Reef Symp. 1:1023–1028.

Randall, J. E.
1967. Food habits of reef fishes of the West Indies. Stud. Trop. Ocean. 5:665–847.

Rezak, R., T. J. Bright, and D. W. McGrail.
1985. Reefs and banks of the Northwestern Gulf of Mexico: Their geological, biological, and physical dynamics. John Wiley and Sons, New York, 259 p.

Rezak, R., S. R. Gittings, and T. R. Bright.
1990. Biotic assemblages and ecological controls on reefs and banks of the northwest Gulf of Mexico. Amer. Zool. 30:23–35.

Robins, C. R., R. M. Bailey, C. E. Bond, J. R. Brooker, E. A. Lachner, R. N. Lea, and W. B. Scott.
1991. Common and scientific names of fishes from the United States and Canada (5th ed.). Am. Fish. Soc. Spec. Publ. 20, 183 p.

Smith-Vaniz, W. F., B. B. Collette, and B. E. Luckhurst.
1999. The Fishes of Bermuda. Amer. Soc. Ichthy. Herpet. Spec. Publ. 4, 424 p.

Thresher, R. E., and P. L. Colin.
1986. Trophic structure, diversity and abundance of fishes of the deep reef (30–300 m) at Enewetak, Marshall Islands. Bull. Mar. Sci. 38:253–272.

Weaver, D. C., and G. R. Sedberry.
2001. Trophic subsidies in the twilight zone: food web structure of reef fishes on the continental slope of the southeastern United States. *In* Islands in the Stream: oceanography and fisheries of the Charleston Bump (G. R. Sedberry, ed.), p. 137–152. American Fisheries Society, Symposium 25, Bethesda, Maryland.

Yoklavich, M. M., H. G. Greene, G. M. Caillet, D. E. Sullivan, R. N. Lea, and M. S. Love.
2000. Habitat association of deep-water rockfishes in a submarine canyon: an example of a natural refuge. Fish. Bull. 98:625–641.

Appendix A

Fishes observed at the Tortugas South Ecological Reserve via SCUBA, ROV, and submersible.

Family Species	Common name	Diet[1]	TSER0801 Riley's ROV Rank	No.	Percent	SSE2002 Riley's SCUBA Rank	No.	Percent	TSER0801 Miller's ROV Rank	No.	Percent	SSE2002-164 Miller's submersible Rank	No.	Percent
Acanthuridae														
Acanthurus bahianus	ocean surgeonfish	H	19	10	0.60	—	—	—	—	—	—	—	—	—
Acanthurus chirurgus	doctorfish	H	18	11	0.66	9	22	1.95	—	—	—	—	—	—
Acanthurus coeruleus	blue tang	H	12	17	1.02	17	11	0.98	—	—	—	—	—	—
Apogonidae														
Apogon pseudomaculatus	twospot cardinalfish	PL	44	1	0.06	—	—	—	—	—	—	—	—	—
Blenniidae														
Parablennius marmoreus	seaweed blenny	H	—	—	—	—	—	—	—	—	—	19	3	0.08
Carangidae														
Caranx ruber	bar jack	PI	46	1	0.06	—	—	—	—	—	—	—	—	—
Seriola dumerili	greater amberjack	PI	17	12	0.72	—	—	—	—	—	—	24	2	0.05
Seriola rivoliana	almaco jack	PI	—	—	—	—	—	—	13	20	0.28	—	—	—
Carcharhinidae														
Carcharhinus sp.		PI	47	1	0.06	—	—	—	—	—	—	—	—	—
Negaprion brevirostis	lemon shark	PI	63	1	0.06	—	—	—	—	—	—	—	—	—
Chaetodontidae														
Chaetodon aya	bank butterflyfish	PL	12	21	0.29	7	19	0.49	—	—	—	—	—	—
Chaetodon capistrata	foureye butterflyfish	EB	28	4	0.24	10	19	1.69	—	—	—	—	—	—
Chaetodon ocellatus	spotfin butterflyfish	EB	27	5	0.30	22	4	0.35	23	4	0.06	—	—	—
Chaetodon sedentarius	reef butterflyfish	EB	21	8	0.48	13	14	1.24	9	36	0.50	11	12	0.31
Chaetodon striata	banded butterflyfish	EB	51	1	0.06	27	2	0.18		—	—	—		
Cirrhitidae														
Ambylocirrhus pinos	redspotted hawkfish	GC	—	—	—	34	1	0.09	—	—	—	—	—	—
Diodontidae														
Diodon holocanthus	balloonfish	GC	52	1	0.06	—	—	—	—	—	—	—	—	—
Echeneidae														
Echineus naucrates	sharksucker	GC	53	1	0.06	28	2	0.18	35	1	0.01	—	—	—
Gobiidae														
Coryphopterus personatus	masked goby	PL	15	12	0.72	2	201	17.83	—	—	—	—	—	—
Gnatholepis thompsoni	goldspot goby	EB	—	—	—	41	1	0.09	32	2	0.03	—	—	—
Ptereleotris calliurus	blue goby	PL	34	3	0.18	—	—	—	—	—	—	—	—	—
Haemulidae														
Haemulon plumieri	white grunt	BC	57	1	0.06	23	4	0.35	—	—	—	—	—	—
Haemulon striatum	striped grunt	PL	—	—	—	5	76	6.74	33	361	5.01	4	104	2.67
Holocentridae														
Corniger spinosus	spinycheek soldierfish	GC	—	—	—	—	—	—	17	12	0.17	—	—	—
Holocentrus adscensionus	squirrelfish	PL	24	9	0.54	—	—	—	21	5	0.07	—	—	—
Holocentrus rufus	longspine squirrelfish	P	16	12	0.72	16	12	1.06	—	—	—	—	—	—
Sargocentron bullisi	deepwater squirrelfish	PL	—	—	—	—	—	—	10	24	0.33	12	7	0.18

continued

Appendix A (continued)

Family Species	Common name	Diet[1]	TSER0801 Riley's ROV			SSE2002 Riley's SCUBA			TSER0801 Miller's ROV			SSE2002-164 Miller's submersible		
			Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent
Inermiidae														
Inermia vittata	boga	PL	6	100	6.01	—	—	—	—	—	—	—	—	—
Labridae														
Bodianus pulchellus	spotfin hogfish	GC	—	—	—	19	7	0.10	10	12	0.31	—	—	—
Clepticus parrae	creole wrasse	PL	7	44	2.64	15	13	1.15	—	—	—	—	—	—
Decodon puellaris	red hogfish	BC	—	—	—	—	—	—	11	23	0.32	14	4	0.10
Halichoeres bathyphilus	greenband wrasse	BC	—	—	—	—	—	—	8	43	0.60	—	—	—
Halichoeres bivittatum	slippery dick	BC	32	3	0.18	29	2	0.18	—	—	—	9	17	0.44
Halichoeres cyanocephalus	yellowcheek wrasse	BC	58	1	0.06	—	—	—	—	—	—	—	—	—
Halichoeres garnoti	yellowhead wrasse	BC	3	233	14.00	7	35	3.11	—	—	—	—	—	—
Halichoeres maculipinna	clown wrasse	BC	25	6	0.36	19	7	0.62	—	—	—	—	—	—
Halichoeres radiatus	puddingwife	BC	—	—	—	42	1	0.09	—	—	—	—	—	—
Lachnolaimus maximus	hogfish	BC	39	2	0.12	24	4	0.35	—	—	—	26	1	0.03
Thallasoma bifasciatum	bluehead	PL	1	424	25.48	3	127	11.27	—	—	—	—	—	—
Lutjanidae														
Lutjanus analis	mutton snapper	GC	40	2	0.12	—	—	—	21	2	0.05	—	—	—
Lutjanus campechanus	red snapper	GC	61	1	0.06	—	—	—	40	1	0.01	27	1	0.03
Lutjanus griseus	gray snapper	GC	33	3	0.18	—	—	—	—	—	—	—	—	—
Lutjanus synagris	lane snapper	GC	—	—	—	—	—	—	—	—	—	17	4	0.10
Ocyurus chrysurus	yellowtail snapper	PL	64	1	0.06	—	—	—	—	—	—	—	—	—
Monacanthidae														
Cantherhines macroceros	whitespotted filefish	EB	45	1	0.06	—	—	—	—	—	—	—	—	—
Canthidermis sufflamen	ocean triggerfish	PL	22	7	0.42	36	1	0.09	—	—	—	—	—	—
Mullidae														
Psuedopeneus maculatus	spotted goatfish	BC	20	9	0.54	12	16	1.42	45	1	0.01	—	—	—
Muraenidae														
Gymnothorax moringa	spotted moray	GC	—	—	—	—	—	—	38	1	0.01	—	—	—
Gymnothorax sp.		GC	—	—	—	—	—	—	39	1	0.01	—	—	—
Opistognathidae														
Opstognathus aurifrons	yellowhead jawfish	PL	41	2	0.12	—	—	—	—	—	—	—	—	—
Ostraciidae														
Acanthostacion polygonia	honeycomb cowfish	EB	35	2	0.12	—	—	—	—	—	—	—	—	—
Lactophrys triqueter	smooth trunkfish	EB	60	1	0.06	—	—	—	—	—	—	—	—	—
Pomacanthidae														
Centropyge argi	cherubfish	EB	48	1	0.06	—	—	—	—	—	—	—	—	—
Holacanthus bermudensis	blue angelfish	EB	29	4	0.24	20	7	0.62	27	3	0.04	—	—	—
Holacanthus ciliaris	queen angelfish	EB	—	—	—	43	1	0.09	—	—	—	—	—	—
Holacanthus tricolor	rock beauty	EB	36	2	0.12	44	1	0.09	28	3	0.04	—	—	—
Pomacanthus paru	French angelfish	EB	65	1	0.06	45	1	0.09	—	—	—	—	—	—
Chromis cyanea	blue chromis	PL	11	19	1.14	6	45	3.99	—	—	—	—	—	—

continued

Appendix A (continued)

Family Species	Common name	Diet1	TSER0801 Riley's ROV Rank	 No.	 Percent	SSE2002 Riley's SCUBA Rank	 No.	 Percent	TSER0801 Miller's ROV Rank	 No.	 Percent	SSE2002-164 Miller's submersible Rank	 No.	 Percent
Chromis enchrysura	yellowtail reeffish	PL	14	14	0.84	—	—	—	4	69	0.96	3	104	2.67
Chromis insolata	sunshinefish	PL	23	7	0.42	11	16	1.42	—	—	—	—	—	—
Chromis multilineata	brown chromis	PL	—	—	—	26	3	0.27	—	—	—	—	—	—
Chromis scotti	purple reeffish	PL	4	173	10.40	1	306	27.15	—	—	—	—	—	—
Stegastes partitus	bicolor damselfish	PL	2	270	16.23	4	102	9.05	—	—	—	—	—	—
Stegastes variabilis	cocoa damselfish	H	68	1	0.06	33	2	0.18	—	—	—	—	—	—
Priacanthus arenatus	bigeye	PL	30	4	0.24	—	—	—	15	16	0.22	28	1	0.03
Pristigenys alta	short bigeye	PL	—	—	—	—	—	—	44	1	0.01	—	—	—
Rhincodontidae														
Ginglyostoma cirratum	nurse shark	GC	56	1	0.06	40	1	0.09	—	—	—	—	—	—
Scaridae														
Scarus iserti	striped parrotfish	H	13	16	0.96	8	25	2.22	—	—	—	—	—	—
Scarus taeniopterus	princess parrotfish	H	66	1	0.06	—	—	—	—	—	—	—	—	—
Sparisoma atomarium	greenblotch parrotfish	H	5	104	6.25	18	9	0.80	—	—	—	—	—	—
Sparisoma aurofrenatum	redband parrotfish	H	8	26	1.56	14	14	1.24	—	—	—	—	—	—
Sparisoma viride	stoplight parrotfish	H	43	2	0.12	46	1	0.09	—	—	—	—	—	—
Sciaenidae														
Equetus lanceolatus	high-hat	BC	—	—	—	—	—	—	—	—	—	20	2	0.05
Pareques iwamotoi	blackbar drum	BC	—	—	—	—	—	—	16	15	0.21	—	—	—
Scorpaenidae														
Scorpaena dispar	hunchback scorpionfish	GC	—	—	—	—	—	—	46	1	0.01	—	—	—
Scorpaena sp.		GC	—	—	—	—	—	—	20	12	0.17	—	—	—
Serranidae														
Centropristis fuscula	twospot seabass	GC	34	1	0.01	—	—	—	—	—	—	—	—	—
Cephalopholis cruentata	graysby	GC	49	1	0.06	37	1	0.09	22	4	0.06	25	1	0.03
Cephalopholis fulva	coney	GC	50	1	0.06	—	—	—	—	—	—	—	—	—
Epinephelus drummondhayi	speckled hind	GC	—	—	—	—	—	—	36	1	0.01	15	4	0.10
Epinephelus guttatus	red hind	GC	54	1	0.06	—	—	—	—	—	—	—	—	—
Epinephelus morio	red grouper	GC	55	1	0.06	39	1	0.09	30	2	0.03	18	3	0.08
Epinephelus nigritus	Warsaw grouper	GC	—	—	—	—	—	—	31	2	0.03	—	—	—
Epinephelus niveatus	snowy grouper	GC	—	—	—	—	—	—	37	1	0.01	—	—	—
Gonioplectrus hispanus	Spanish flag	GC	—	—	—	—	—	—	26	3	0.04	—	—	—
Hemanthias vivanus	red barbier	PL	—	—	—	—	—	—	2	602	8.40	1	2709	69.62
Hypoplectrus gemma	blue hamlet	GC	59	1	0.06	30	2	0.18	—	—	—	—	—	—
Hypoplectrus unicolor	butter hamlet	GC	38	2	0.12	31	2	0.18	—	—	—	—	—	—
Liopropoma eukrines	wrasse bass	GC	—	—	—	—	—	—	18	12	0.17	16	4	0.10
Mycteroperca bonaci	black grouper	PI	—	—	—	—	—	—	41	1	0.01	22	2	0.05
Mycteroperca phenax	scamp	PI	62	1	0.06	—	—	—	7	44	0.61	5	33	0.85
Paranthias furcifer	creole-fish	PL	—	—	—	—	—	—	5	61	0.85	8	19	0.49
Plectranthias garrupellus	apricot bass	GC	—	—	—	—	—	—	43	1	0.01	—	—	—

continued

Appendix A (continued)

Family			TSER0801 Riley's ROV			SSE2002 Riley's SCUBA			TSER0801 Miller's ROV			SSE2002-164 Miller's submersible		
Species	Common name	Diet[1]	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent
Pronotogrammus martinicensis	roughtongue bass	PL	—	—	—	—	—	—	1	5663	79.03	2	804	20.66
Serranus annularis	orangeback bass	GC	42	2	0.12	—	—	—	—	—	—	—	—	—
Serranus phoebe	tattler	GC	—	—	—	—	—	—	6	60	0.84	6	26	0.67
Serranus tabacarius	tabaccofish	GC	—	—	—	25	4	0.35	—	—	—	—	—	—
Serranus tigrinus	harlequin bass	GC	31	4	0.24	32	2	0.18	—	—	—	—	—	—
Serranus tortugarum	chalk bass	PL	9	24	1.44	—	—	—	—	—	—	—	—	—
Sparidae														
Calamus nodosus	knobbed porgy	BC	26	5	0.30	35	1	0.09	—	—	—	—	—	—
Pagrus pagrus	red porgy	BC	—	—	—	—	—	—	42	1	0.01	23	2	0.05
Sphyraenidae														
Sphyraena barracuda	great barracuda	PI	67	1	0.06	—	—	—	—	—	—	—	—	—
Synodontidae														
Synodus intermedius	sand diver	PI	—	—	—	—	—	—	24	4	0.06	—	—	—
Synodus synodus	red lizardfish	PI	—	—	—	—	—	—	47	1	0.01	—	—	—
Tetraodontidae														
Canthigaster rostrata	sharpnose puffer	EB	10	21	1.26	21	4	0.35	25	3	0.04	—	—	—
Canthigaster jamestyleri	goldface toby	EB	14	19	0.27	13	6	0.15	—	—	—	—	—	—
Total				1664			1145			7169			3888	

[1] BC=benthic carnivores (benthic crustaceans and infauna), EB=epibenthic browsers (sessile invertebrates), GC=general carnivore (mobile invertebrates and fishes), H=herbivore, PI=piscivore, PL=planktivore.

Deep reef fish surveys by submersible on Alderdice, McGrail, and Sonnier Banks in the Northwestern Gulf of Mexico

Douglas C. Weaver
Emma L. Hickerson
George P. Schmahl
Flower Garden Banks National Marine Sanctuary, NOAA
4700 Avenue U, Building 216
Galveston, TX 77551
Email (for Weaver): doug.weaver@noaa.gov

Abstract—Submersible surveys at numerous reefs and banks in the northwestern Gulf of Mexico (NWGOM) were conducted as part of the Sustainable Seas Expedition (SSE) during July/August 2002 to identify reef fish communities, characterize benthic habitats, and identify deep coral reef ecosystems. To identify the spatial extent of hard bottom reef communities, the Flower Garden Banks National Marine Sanctuary (FGBNMS) and the U.S. Geological Survey (USGS) mapped approximately 2000 km^2 of the Northwestern Gulf of Mexico (NWGOM) continental shelf during June 2002 with high-resolution multibeam bathymetry. Previous investigations conducted on the features of interest (with the exceptions of East and West Flower Garden and Sonnier Banks, accessible by SCUBA) had not been conducted since the 1970s and 1980s, and did not have the use of high-resolution maps to target survey sites. The base maps were instrumental in navigating submersibles to specific features at each study site during the Sustainable Seas Expedition (SSE)—a submersible effort culminating from a partnership between the National Atmospheric and Oceanic Administration (NOAA) and the National Geographic Society (NGS). We report the initial findings of our submersible surveys, including habitat and reef fish diversity at McGrail, Alderdice, and Sonnier Banks. A total of 120 species and 40,724 individuals were identified from video surveys at the three banks. Planktivorous fishes constituted over 87% by number for the three banks, ranging from 81.4% at Sonnier Banks to 94.3% at Alderdice Bank, indicating a direct link to pelagic prey communities, particularly in the deep reef zones. High numbers of groupers, snappers, jacks, and other fishery species were observed on all three features. These sites were nominated as Habitat Areas of Particular Concern (HAPC) by the Gulf of Mexico Fishery Council in March 2004. Data obtained during this project will contribute to benthic habitat characterization and assessment of the associated fish communities through future SCUBA, ROV, and submersible missions, and allow comparisons to other deep reef ecosystems found throughout the Gulf of Mexico and western Atlantic Ocean.

Introduction

The northwestern Gulf of Mexico (NWGOM) reefs and banks are associated with the surface expression of salt domes, and have been identified as unique biological features warranting protection by Minerals Management Service (MMS) from oil and gas activities. The most recent investigations of reef fishes on the shelf-edge features in the northwestern Gulf (with the exceptions of East and West Flower Garden, Stetson and Sonnier Banks) were conducted during the 1970s and 1980s (Rezak et al., 1985; Dennis and Bright, 1988a, 1988b), without the use of high-resolution multibeam bathymetry or high-resolution camera systems.

The Sustainable Seas Expedition (SSE) was a five-year collaborative effort between NOAA and the National Geographic Society (NGS) to explore important marine ecosystems with special emphasis on the nation's National Marine Sanctuaries. Led by Sylvia Earle, Explorer-in-Residence of the NGS, the SSE program utilized both manned and unmanned submersible technologies to explore the NWGOM in 1999, 2001, and 2002. The use of the submersibles allowed the Flower Garden Banks National Marine Sanctuary (FGBNMS) team to visit several of the reefs and banks of the NWGOM and conduct exploratory dives to investigate reef fish and benthic communities in July 2002.

The reefs and banks of the northwestern Gulf have been afforded some protection since the early 1970s. The MMS recognized early on that these sensitive areas should not be subjected to the direct impacts of offshore oil and gas development, and defined them as "no activity" zones (Fig. 1). However, these features are subject to a variety of other potential impacts unrelated to offshore development, which may not be regulated sufficiently. These impacts include those of commercial shipping (predominantly anchoring), fishing, cultural resource recovery and recreational activities. There is recent emphasis on the increased use of marine protected areas (MPA's) in many ocean regions as a method to consolidate management under a coordinated mechanism. Accurately identifying the resources in the northwestern Gulf will contribute greatly to this effort.

Background

The Department of Oceanography at Texas A&M University (TAMU) conducted studies on "topographic features"—Outer Continental Shelf (OCS) reefs and banks—during the 1970s and 1980s. Funding was provided by the U.S. Department of the Interior (DOI), Bureau of Land Management (BLM), out of which MMS later emerged through reorganization. The purpose of the TAMU study

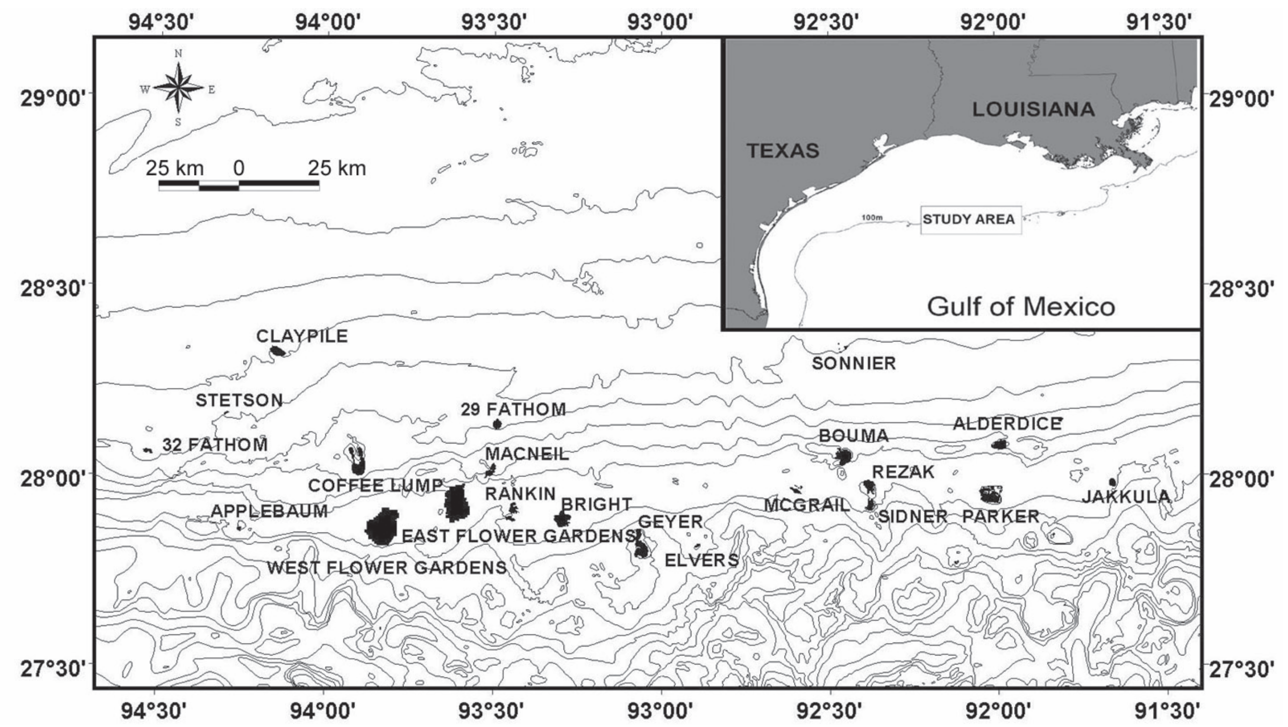


Figure 1

Location of outer shelf banks in the northwestern Gulf of Mexico.

was to provide the MMS with data on the geologic, biologic, hydrologic, and chemical characteristics of the reefs and banks, to be used as a basis for management decisions on tracts nominated for oil and gas leasing (Rezak et al., 1985).

As a comparison, the technology used for the historic surveys conducted by Rezak et al. (1985) included bathymetric mapping using a LORAN-C positioning system for navigation, a 3.5kHz subbottom profiler, EG&G Uniboom seismic system for subbottom information, and EG&G side-scan sonar systems for bottom characterization. Direct observations of the sea floor were made using the Texas A&M submersible DRV *Diaphus* (Rezak and Tieh, 1984; Dennis and Bright, 1988a).

Each of the survey sites has a distinct biological zonation associated with base depths and water turbidity, and the following zones (when present), described during the early TAMU/MMS studies (Rezak et al., 1985; 1990). The *Stephanocoenia-Millepora* Zone is inhabited by a low-diversity coral assemblage of 12 hermatypic coral species and can be found at the FGBNMS, McGrail Bank, and Bright Bank to depths of 50 m. On midshelf banks, such as Stetson and Sonnier Banks, the *Millepora*-Sponge Zone occupies depths less than 36 m. Crusts of the hydrozoan coral, *Millepora,* sponges, and other epifauna occupy the tops of siltstone, claystone, or sandstone outcrops on the crests of these features. The Algal-Sponge Zone covers the largest area among the reef-building zones on shelf-edge banks. The dominant organisms of the zone are the coralline algae, which are the most important carbonate producers through algal nodules and algal reefs (Minnery et al., 1985). The nodules range from 1 to 20 cm in size, cover up to 80 percent of the bottom, and generally occur between 55 and 85 m. Partly Drowned Reefs are also a major biotope occurring at similar depths to the Algal-Sponge Zone, and are defined as massive reefal structures covered with living crusts of coralline algae. With increased water depth, the assemblages of the zone become less diverse, characterized by antipatharians, comatulid crinoids, diminished leafy or coralline algae, and limited fish. High turbidity, sedimentation, and re-suspension occur in the Nepheloid Zone, where exposed rocks lack encrusting coralline algal crusts. Drowned Reefs occurring in this zone are often covered with a thin veneer of sediment, and epifauna are scarce. This zone occurs on all banks, but its depth differs at each bank and extends to the surrounding soft bottom.

The Sonnier Bank complex (historically referred to as Three Hickey Rock and Candy Mountain) is a mid-shelf bank, defined by Rezak et al. (1985, 1990) as salt dome structures rising from depths of 80 m or less and having a relief of about 4 to 50 m. The banks are located 135 km south of the Louisiana border, at position 28°20′N/92°27′W. As noted by Rezak et al. (1985) the Sonnier Bank complex consists of eight separate banks or peaks associated with a single salt dome. The peaks are nearly conical features with a maximum relief of about 30 m. Observations made by SCUBA and submersible have characterized the reef habitat on the peaks as entirely encrusted with fire coral (*Millepora* sp.) and sponges (primarily *Neofibularia nolitangere* and *Ircinia* sp.) (Rezak et al., 1985). This is the basis for the zonation name of Millepora-Sponge Zone. Rezak et al. (1985) reported three species of coral from the crests at Sonnier Banks: *Stephanocoenia* sp., *Millepora* sp., and *Agaricia* sp. In 1997, SCUBA surveys conducted by MMS and FGBNMS representatives compiled coral observations on the two shallowest peaks (24 m and 18 m) of Sonnier Banks. Other hermatypic coral species added by MMS diver surveys include *Madracis decactis, M. mirabilis, M. pharensis, Siderastrea radians, Montastraea cavernosa,* and *Agaricia fragilis.*

McGrail Bank (formerly referred to as 18 Fathom Bank) is located 180 km south of the coast of Louisiana, at 27°58′N/92°36′W. As described by Rezak et al. (1985), the McGrail Bank is an arcuate pair of northeast-southwest trending ridges separated by a valley. McGrail Bank is one of the few banks in the northwestern Gulf of Mexico that has extensive growth of reef-building corals, in addition to East and West Flower Garden Banks. The original BLM OCS surveys documented four species of coral: the blushing star coral (*Stephanocoenia intersepta;* formerly *S. michilini),* fire coral (*Millepora* sp.), the great star coral (*Montastraea cavernosa*), and *Agaricia* sp.

Alderdice Bank is unique among the offshore banks in that it bears outcrops of basalt associated with the underlying salt dome (Rezak and Tieh, 1984). Alderdice Bank is located about 160 km south of Marsh Island, LA at 92°00′W/28°05′N. The bank is an oval, elongate in an east-west direction, and covers an area of approximately 9.8 km^2. Rezak and Tieh (1984) states that the bank is a classic example of the surface expression of a salt dome. A single basalt outcropping, described by Rezak and Tieh (1984), was discovered during a submersible dive during the BLM OCS studies. Potassium-argon age determination anaysis indicated an age of $76.8 \pm 3.3 \times 10^6$ years (late Cretaceous-Campanian).

As a result of these investigations, MMS initiated regulatory zones around the majority of the hard bottom habitat in the NWGOM, regulating oil and gas activity. Regulations placed on the oil and gas industry included the mandatory shunting of discharges to within 10 m of the sea floor.

During 8–28 June 2002, a multibeam mapping cruise was conducted to survey approximately 2000 km^2 of the northwestern Gulf of Mexico continental shelf[1]. Multibeam bathymetry data sets were used as base maps to guide submersible surveys of select topographic features during the 2002 Sustainable Seas Expedition to the northern Gulf of Mexico, conducted by the FGBNMS in conjunction with the NGS.

The SSE missions initiated an ongoing multidisciplinary project led by the FGBNMS to revisit the reefs and banks of the NWGOM and build on the description and characterization effort conducted during past research programs.

During the SSE missions, submersible dives were conducted on the East Flower Garden (EFGB), West Flower Garden (WFGB), Jakkula, Sidner, Alderdice, Bright, McGrail, and Sonnier Banks. Results from the SSE submersible surveys at Alderdice, McGrail, and Sonnier Banks are reported herein, due to the more extensive surveys conducted at these features.

Materials and methods

The SSE dives were conducted using Nuytco Research Ltd's Deepworker 2000 (DW2000) and Deep Rover (DR) submersibles (Fig. 2). Both systems are single-person submersibles—the DW2000 rated to 610 m and DR rated to 1000 m. One of the benefits of these two submersibles is the nearly 360° observation capability afforded to the pilot. Other technology that enhanced the capabilities of the submersibles during the SSE missions included accurate underwater tracking using the ORE International 4410C Track Point II with the Winfrog integrated navigation package, underwater communication, and high resolution digital video and still camera.

Submersible surveys were conducted along selected waypoints based on reef topography to survey as much hard bottom habitat as possible during each dive. Reef fishes and macroinvertebrates were only counted during segments where the field of view was illuminated and the submersible maintained close contact to the bottom. Numbers of individuals for schooling species were estimated based on paused still frames and extrapolated to the entire school. Fishes were identified to the lowest possible taxon following Humann and DeLoach (2002), based on the taxonomic nomenclature of Robins et al. (1991). Trophic categories were assigned based on dietary information from Randall (1967), Smith-Vaniz et al. (1999), or Bullock and Smith (1991) for individual species or closely related taxa.

---

[1] USGS (United States Geological Survey). 2002. Multibeam Bathymetry Mapping of the Northwestern Gulf of Mexico. http://walrus.wr.usgs.gov/pacmaps/wg-index.html. [Accessed 14 August 2005].

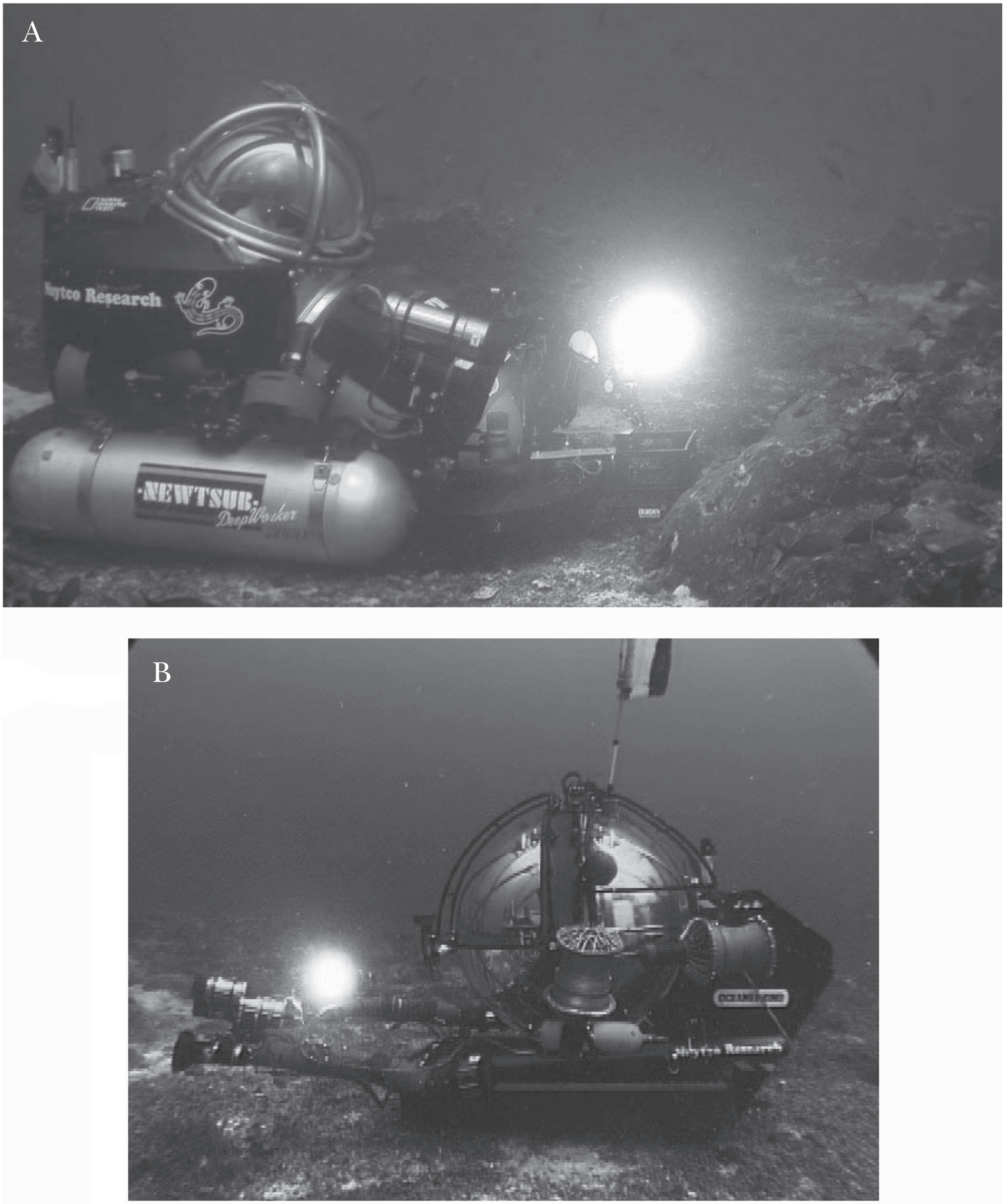


Figure 2

Submersibles used during SSE2002. A) Deepworker 2000, piloted by G.P. Schmahl during SSE Dive A20-185 at McGrail Bank. B) Deep Rover, piloted by Kip Evans, during SSE Dive A20-186 at McGrail Bank. Photograph and still image by Kip Evans, NGS, and G. P. Schmahl, FGBNMS.

Table 1

Submersible dives conducted at Sonnier, McGrail, and Alderdice Banks.

SSE dive no.	Bank	Submersible	Pilot	Depth range (m)	Survey duration	Track length (km)	Habitats observed
A20-179	Alderdice	Deep Worker	D. Weaver	62–73	5.6 hours	1.1	basalt spires, drowned reef zone
A20-180	Alderdice	Deep Worker	G. Schmahl	62–90	4.2 hours	0.9	basalt spires, algal nodule-sponge zone
A20-181	Alderdice	Deep Worker	E. Hickerson	68–85	4.3 hours	1.3	Algal nodule sponge zone
A20-184	McGrail	Deep Worker	G. Schmahl	45–78	5.2 hours	1.7	Coral cap, algal nodule-sponge zone
A20-185	McGrail	Deep Rover	K. Evans	45–85	5.5 hours	2.5	Coral cap, algal nodule-sponge zone
A20-186	Sonnier	Deep Worker	D. Weaver	19–60	3.2 hours	2.1	*Millepora*-sponge zone, drowned reef zone

The submersible dives were facilitated by the availability of detailed multibeam bathymetry collected during June 2002. A Konsberg Simrad EM1000 high resolution multibeam echosounder was used to map the seafloor at specific features, following hydrographic standards.[1] The multibeam surveys were conducted and data analyzed by James Gardner (Univ. of New Hampshire, formerly of USGS, Menlo Park). Resulting data were gridded at 5 m resolution and used to produce georeferenced images and 3D visualizations. Discussion of the earlier bathymetric surveys conducted within the FGBNMS is presented in Gardner et al. (1998), and data from those surveys are also available[1].

Base maps were used to guide submersible operations as part of the SSE mission to the northern Gulf of Mexico during 24 July–6 August 2002, co-sponsored by NGS and NOAA. Submersible dives were conducted using the Deepworker 2000 and Deep Rover submersibles aboard the Oceaneering International, Inc. M/V OCEAN PROJECT.

Bathymetry maps were geo-referenced in ArcView GIS (Version 3.2, Environmental Research Systems Institute, Redlands, CA), and used to plot waypoints for submersible transects. Submersible position was continuously logged during dives, and dive tracks were later superimposed on bathymetry to identify location of video surveys.

Results

Six submersible dives were conducted at the three study sites, focusing on hard bottom communities and high profile reef structures. Three submersible dives were made on the basalt spire features and large mound of Alderdice Bank (Table 1). Two dives were conducted around the coral cap region of McGrail Bank, while a single submersible transect was conducted at Sonnier Bank (Fig. 3). Depths surveyed at Sonnier Banks ranged from 19 to 60 m, McGrail Bank 45–85 m, and Alderdice Bank 62–90 m. Sonnier Banks were characterized by *Millepora*-sponge and drowned reef habitats, while McGrail and Alderdice transects were dominated by algal nodule-sponge communities (Table 1).

One hundred and twenty (120) fishes were observed in association with the deep reef communities of the three banks (Appendix A). McGrail Bank had the highest observed species richness (78 species), followed by Sonnier Banks (77), and Alderdice Bank (68). A total of 40,724 fishes were counted from submersible videotape from submersible dives (Table 2).

The top 25 species observed on each bank are presented in Table 3. Planktivorous fishes dominated the reef communities of all three banks, but different taxa were numerically abundant at each location. Sonnier Bank reef fish populations are dominated by the yellowtail reeffish (*Chromis enchrysura)*, creole-fish (*Paranthias furcifer)*, and brown chromis (*Chromis mulilineata)*. McGrail Bank reef fish populations are dominated by *P. furcifer*, the threadnose bass (*Anthias tenuis*), and the yellow goatfish (*Mulloidichthys martinicis*). In contrast, Alderdice Bank is dominated by the roughtongue bass (*Pronotogrammus martinicensis*), *C. enchrysura*, and *P. furcifer.*

Planktivorous fishes constituted over 81.4% by number at each bank, ranging from 81.6% at Sonnier Banks to 94.3% at Alderdice Bank. The remaining categories comprised less than 10%, with the exception of benthic carnivores at Sonnier Banks and McGrail Bank, represented by large populations of tomtate (*Haemulon aurolineatum*) and yellow goatfish, respectively. Benthic carnivores represented the second most abundant trophic guild on each bank. Epibenthic browsers, including invertebrate browsers such as pomacanthids and chaetodontids, declined in number from Sonnier Banks (4.5%) to McGrail (1.6%) to Alderdice (0.5%). Herbivores also decreased in this order, and herbivores such as scarids and acanthurids made up 0.6% at Sonnier, 0.3% at McGrail, and 0.1% at Alderdice. Generalized carnivores also followed this general pattern. In contrast, piscivores exhibited a slight increase from 0.9% at Sonnier Banks to 1.6% at McGrail Bank to 1.9% at Alderdice Bank.

Sonnier Banks

High-resolution multibeam bathymetry of the Sonnier Banks reveals up to at least a dozen additional lower

Table 2

Reef fishes by trophic category at Sonnier, McGrail, and Alderdice Banks. Numbers of individuals observed during video surveys are given.

	Sonnier Banks		McGrail Bank		Alderdice Bank		Totals	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Planktivores	6284	81.4	12,465	81.6	16,717	94.3	35,466	87.1
Piscivores	68	0.9	249	1.6	335	1.9	652	1.6
General carnivores	351	4.5	218	1.4	226	1.3	795	2.0
Herbivores	49	0.6	39	0.3	11	0.1	99	0.2
Epibenthic browsers	350	4.5	237	1.6	97	0.5	783	1.9
Benthic carnivores	615	8.0	2067	13.5	346	2.0	3028	7.4
Totals	7717	100.0	15,275	100.0	17,732	100.0	40,724	100.0

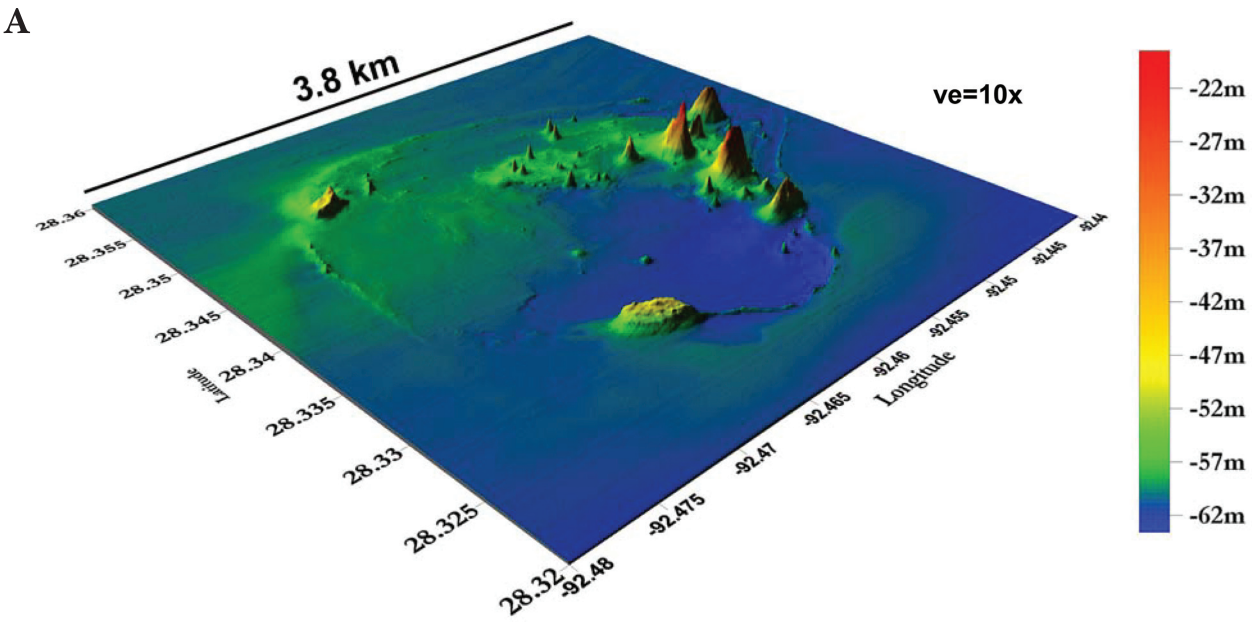


Figure 3

A) Multibeam bathymetry map of Sonnier Banks, oblique view (bathymetry data courtesy James Gardner, University of New Hampshire, Center for Coastal and Ocean Mapping, 24 Colovos Road, Durham, NH 03824). Submersible surveys were conducted on *Millepora*-sponge zones and drowned reef areas as part of the Sustainable Seas Expeditions during July–August 2002. B) Plan view (ve=vertical exaggeration) of Sonnier Banks (bathymetry data courtesy James Gardner). C) A still video frame of the Millepora-Sponge cap at Sonnier Banks, with a queen angelfish, *Holacanthus ciliaris*. Assorted sponges and *Millepora* (tan in color) are present.

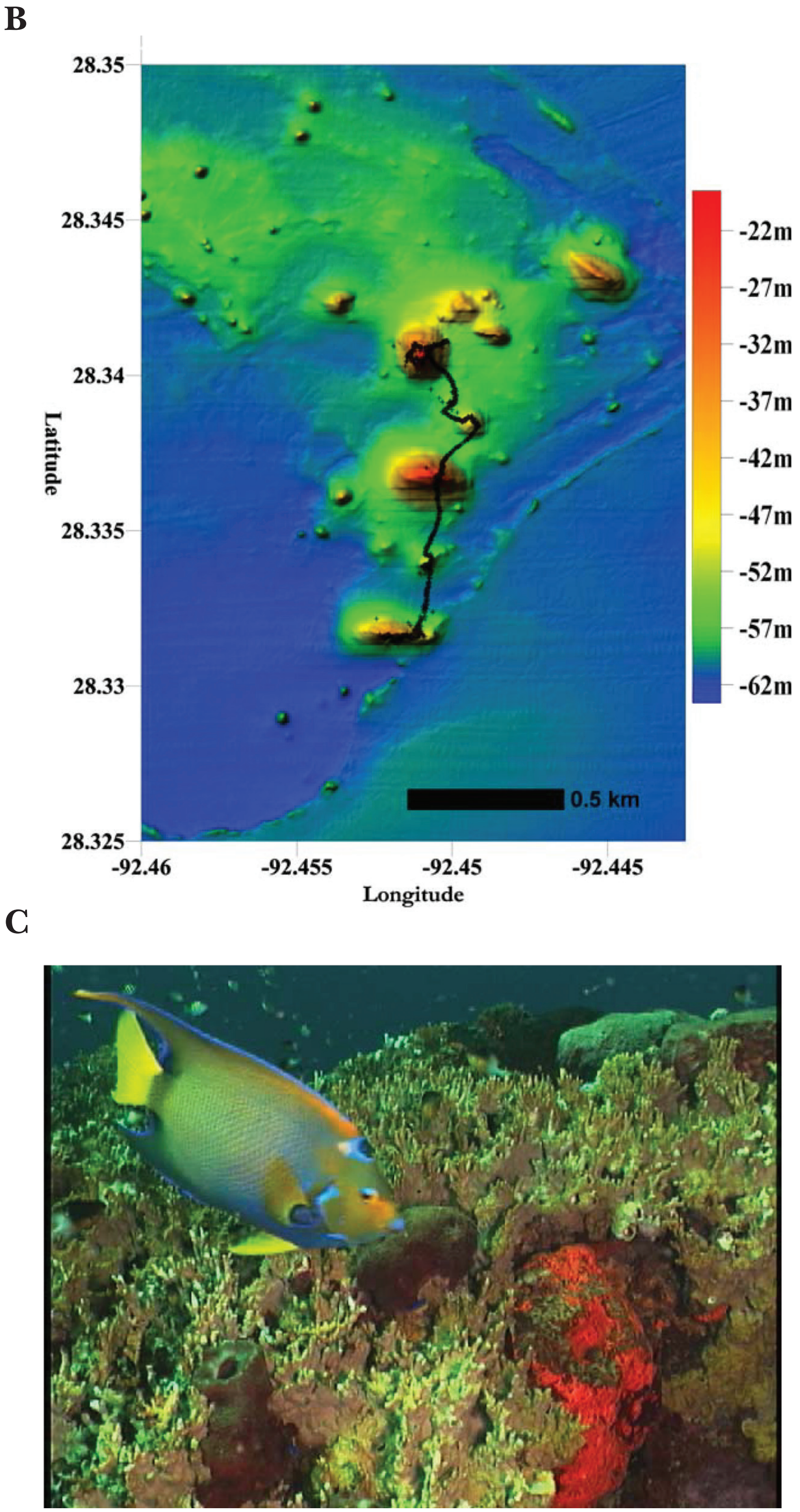


Figure 3 (continued)

Table 3

Top 25 fish species observed during submersible surveys of Sonnier, McGrail, and Alderdice Banks during SSE2002. Dominance rank is based on numerical abundance from videotaped ROV surveys. Trophic categories are based on dietary studies of Randall (1967) or Bullock and Smith (1991).

			Sonnier Banks		McGrail Bank		Alderdice Bank	
Species ID	Common name	Trophic guild[1]	Rank	Percent	Rank	Percent	Rank	Percent
Chromis enchrysura	yellowtail reeffish	PL	1	23.1	5	6.19	2	24.61
Paranthias furcifer	creole-fish	PL	2	17.7	1	43.3	3	18.49
Chromis multilineatus	brown chromis	PL	3	13.6	12	0.58	—	—
Chromis insolata	sunshine fish	PL	4	6.36	4	7.64	5	5.67
Thallasoma bifasciatum	bluehead	PL	5	5.73	18	0.22	24	0.07
Haemulon aurolineatum	tomtate	GC	6	5.55	—	—	—	—
Chromis scotti	purple reeffish	PL	7	5.34	10	0.69	8	0.97
Stegastes variabilis	cocoa damselfish	H	8	2.80	—	—	—	—
Clepticus parrae	creole wrasse	PL	9	2.34	15	0.48	14	0.19
Stegastes partitus	bicolor damselfish	FL	10	2.03	7	1.04	—	—
Kyphosus sp.	Bermuda/yellow chub	PL	11	1.80	—	—	—	—
Rhomboplites aurorubens	vermilion snapper	PL	12	1.42	—	—	6	3.29
Balistes capriscus	gray triggerfish	BC	13	1.03	—	—	—	—
Lutjanus griseus	gray snapper	GC	14	1.03	9	0.73	9	0.52
Lutjanus campechanus	red snapper	GC	15	0.90	—	—	—	—
Bodianus pulchellus	spotfin hogfish	GC	16	0.66	21	0.18	10	0.42
Bodianus rufus	Spanish hogfish	GC	17	0.58	24	0.14	—	—
Lutjanus buccanella	blackfin snapper	GC	18	0.55	—	—	—	—
Abudefduf saxatalis	sergeant major	PL	19	0.53	—	—	—	—
Myripristis jacobus	blackbar soldierfish	PL	20	0.40	—	—	—	—
Chaetodon sedentarius	reef butterflyfish	EB	21	0.32	13	0.54	13	0.28
Ptereleotris calliurus	blue goby	PL	22	0.28	—	—	—	—
Epinephelus adscensionis	rock hind	GC	23	0.27	—	—	—	—
Canthigaster rostrata	sharpnose puffer	EB	24	0.25	—	—	—	—
Holacanthus tricolor	rock beauty	EB	25	0.25	—	—	22	0.08
Mulloidichthys martinicus	yellow goatfish	BC	26	0.25	3	13.0	7	1.60
Halichoeres bathyphilus	greenband wrasse	BC	28	0.24	—	—	25	0.06
Holacanthus bermudensis	blue angelfish	EB	29	0.23	—	—	23	0.07
Mycteroperca interstitialis	yellowmouth grouper	PI	33	0.18	20	0.19	15	0.17
Caranx latus	horse-eye jack	PI	34	0.16	14	0.53	—	—
Pareques umbrosus	cubbyu	BC	36	0.16	—	—	18	0.10
Chromis cyanea	blue chromis	PL	38	0.15	8	0.93	—	—
Pseudupeneus maculates	spotted goatfish	BC	39	0.15	—	—	20	0.09
Sparisoma atomarium	greenblotch parrotfish	H	42	0.14	23	0.15	—	—
Seriola dumerili	greater amberjack	PI	44	0.12	—	—	11	0.30
Holocentrus rufus	longfin squirrelfish	PL	45	0.11	22	0.18	—	—
Anthias tenuis	threadnose bass	PL	—	—	2	17.9	4	13.13
Apogon affinis	bigtooth cardinalfish	PL	—	—	—	—	12	0.29
Aulostomus maculates	trumpetfish	PI	—	—	—	—	16	0.14
Caranx bartholomaei	yellow jack	PI	—	—	17	0.24	—	—
Caranx hippos	crevalle jack	PI	—	—	19	0.19	—	—
Centropyge argi	pygmy angelfish	EB	—	—	11	0.62	—	—
Chaetodon aya	bank butterflyfish	PL	—	—	—	—	17	0.10
Gonioplectrus hispanus	Spanish flag	PI	—	—	—	—	19	0.09
Pronotogrammus martinicensis	roughtongue bass	PL	—	—	16	0.48	1	28.45
Schultzea beta	school bass	PL	—	—	6	1.43	—	—
Seriola rivoliana	almaco jack	PI	—	—	—	—	21	0.09

[1] BC-Benthic carnivores (benthic crustaceans and infauma), EB-Epibenthic browsers (sessile invertebrates), GC-General carnivore (mobile invertebrates and fishes), H-Herbivore, PL-Planktivore, PI-Piscivore (fishes and cephalopods).

relief peaks associated with the feature, ranging in depth from 18 to 55 m (Fig. 3). Deeper peaks surveyed during the SSE mission had reduced coverage of fire coral and a more extensive and diverse community of encrusting and massive sponges.

The 2002 SSE submersible dive covered three of the major peaks and two of the lower relief peaks. No additional species of hermatypic coral were observed during these surveys. *Astropyga magnifica*, a deep water echinoid, was observed in crevices along the rocky reef slopes in 2002. Submersible investigations revealed a diverse assemblage of fishes and invertebrates, from the species-rich reef fish assemblages on the *Millepora* sponge zones associated with the two shallowest banks, to species-depauperate drowned reef assemblages on the smaller features within the region (Fig. 3). Results of our surveys indicate unique biological assemblages associated with each bank within the region, related to the depth of the bank crest and the extent of the turbid Nepheloid Zone, which was encountered over surrounding soft bottom areas at each peak during submersible surveys.

Reef fishes observed at Sonnier were numerically dominated by planktivores, representing the top five species, eight of the top ten numerically abundant species. In addition to *C. enchrysura*, *P. furcifer*, and *C. multilineatus*, the sunshinefish (*Chromis insolata*) and bluehead (*Thallasoma bifasciata*) were next most abundant. Dense schools of planktivores, including *P. furcifer*, *C. multilineata*, *T. bifasciata*, and creole wrasse (*Clepticus parrae*), characterize the shallow crest areas of the larger peaks. Deeper reef communities were characterized by an assemblage of *H. aurolineatum*, red snapper (*L. campechanus*), greater amberjack (*Seriola dumerili*), and gray triggerfish (*Balistes capriscus*). Soft bottom regions surrounding the main peaks had few fishes, with the exception of the blue goby (*Ptereleotris calliurus*), living in burrows in the circum-reef talus zones, and tattler (*Serranus phoebe*), associated with talus zones and carbonate debris surrounding hard bottom features.

McGrail Bank

Submersible surveys conducted during SSE on McGrail Bank revealed extensive growth of a hard coral community dominated by *S. intersepta*, large brain corals (*Diploria strigosa*), *M. cavernosa*, and a species of *Agaricia*. Estimated coral coverage reached 30% in some areas, at a depth range of 45 m–60 m, while the base of the bank is approximately 85 m (Fig. 4A). Two SSE 2002 submersible dives targeted the crest of the southernmost ridge to identify the extent of the deep coral reef community. In addition to these four previously documented species of hermatypic corals, a 2 m tall colony of *Diploria strigosa* was noted, as was a more extensive *S. intersepta* reef than previously described. One reef site (45–60 m depth range)—a crest approximately 0.07 km^2 (0.40 km × 0.28 km), was documented to be populated by up to 30% coverage of *S. intersepta* coral heads, averaging 1m width × 0.75 m tall (Fig. 4B). Numerous heads reached upwards of 2 m in height. In addition to the *S. intersepta* colonies, numerous 1–2 m tall *M. cavernosa* colonies were encountered.

Reef fishes observed at McGrail Bank were overwhelmingly dominated by *P. furcifer*, which made up almost half of the individuals observed (43%). Threadnose bass comprised 18% of fishes observed, followed by the yellow goatfish. The occurrence of a large school of goatfish has not been previously reported in the literature. While this species was observed on all three banks, they were in much lower abundance at Alderdice and Sonnier Banks. Sunshinefish (*C. insolata*), school bass (*Schultzea beta*), bicolor damselfish (*Stegastes partitus*), and the blue chromis (*Chromis cyanea*), were the next most dominant reef fish taxa, and all are planktivorous. McGrail Bank lacked many of the species associated with the turbid drowned reef areas of Sonnier Bank, including *H. aurolineatum* and *L. campechanus*.

A notable observation made during the submersible surveys is that up to five aggregations of longspine urchins (*Astropyga magnifica*) were encountered in the sandy valley between the ridges of McGrail Bank. These aggregations were made up of at least 100 individuals. Associated with each aggregation were upwards of six juvenile marbled grouper (*Dermatolepis inermis*) individuals to each *A. magnifica* aggregation (Fig. 4A).

Alderdice Bank

While previous bathymetric surveys of the area identified a single "spire" at Alderdice Bank, the multibeam data set resolved two distinct spires with associated talus fields (Fig. 5). The second basalt spire is located approximately 220 m NNE of the outcropping described by Rezak and Tieh (1984). Both spires provide high profile structure that attracts large schools of creole-fish, vermilion snapper (*Rhomboplites aurorubens*), and several species of grouper, snapper, and jacks. In 2002, the original basalt feature was surveyed and characterized by a similar biota as originally described by Rezak et al. (1985). Through direction from a topside navigation technician, the submersible pilot was able to navigate both of the spires, confirming that the second feature was indeed an additional basalt outcrop (Figs. 5A, B).

Reef fishes observed at Alderdice Bank were overwhelmingly dominated by roughtongue bass, with yellowtail reeffish and creole-fish also dominating the reef fish community. These three species made up over 71% of the individual fishes observed. A notable observation during the SSE mission is the occurrence of the rare marbled grouper (*Dermatolepis inermis*), both at

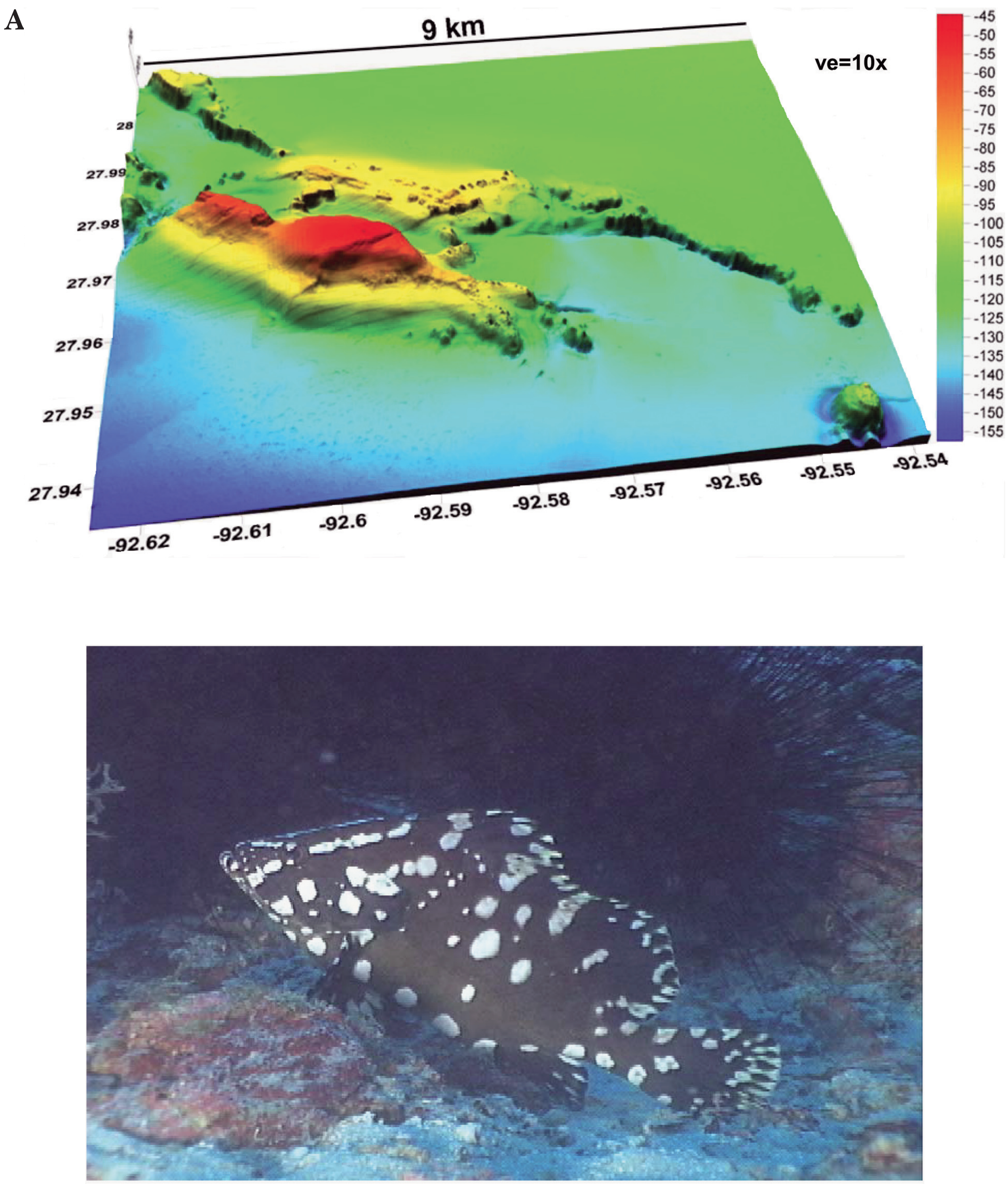


Figure 4

A) Top: Multibeam bathymetry map of McGrail Banks, oblique view (bathymetry data courtesy James Gardner; see Fig. 3 for contact info.). Bottom: Marble grouper, *Dermatolepis inermis*, resting at the base of sea urchin aggregation. B) Extensive growth of hard corals, including *Stephanocoenia, Montastraea*, and *Diploria* spp., on the summits of the bank were documented during submersible surveys during the Sustainable Seas Expedition during summer 2002. Video still courtesy SSE.

Figure 4 (continued)

the basalt outcroppings and the eastern algal/sponge mound.

Discussion

Reef fishes of the northwestern Gulf of Mexico, as previous authors have noted, are represented by a tropical assemblage on mid to outer shelf banks where suitable habitat occurs (Rezak et al., 1985, 1990; Dennis and Bright, 1988a). Results of this survey provide the first detailed look at reef fish communities associated with the chosen features using modern submersibles, and identify differences among the fish communities associated with their unique benthic assemblages. The number of reef-associated species at each bank was very similar, ranging from 68 at Sonnier Banks to 78 at McGrail Bank. While total species richness was similar, the numerically dominant taxa vary between sites and reflect the distribution of habitat at each of the chosen study sites. Sonnier Banks are comprised of steep sided, relatively flat-topped features that have limited talus aprons and shallow peaks. The predominance of *Millepora*-sponge zones on the shallow peaks of the main features is reflected in the abundance of creole-fish, creole wrasse, brown chromis, and other planktivores that typically associate with the shallow crests of other reefs and banks in the Gulf of Mexico, such at East Flower Garden Bank, West Flower Garden Bank, and Stetson Bank (Rezak et al., 1985; Pattengill-Semmens et al., 1997). Sonnier Banks also have limited deep reef habitat, due to the dominance of a nepheloid layer at the deeper areas surrounding the main peaks (Rezak et al., 1990). This results in extensive soft bottom communities around the banks, a lack of algal nodule-sponge zones, and limited distribution of partly drowned and drowned reef structures and associated reef fish communities.

In addition to general comments on the reef fish community at McGrail Bank, Rezak et al. (1985) noted significant populations of common black sea urchins (*Diadema* sp.) and spiny lobsters (*Panulirus* sp.) occurring on the ledges and along the slopes of many of the shelf edge banks. These observations are inconsistent with the 2002 observations. This can be accounted in part by the well-documented Caribbean-wide mass die-

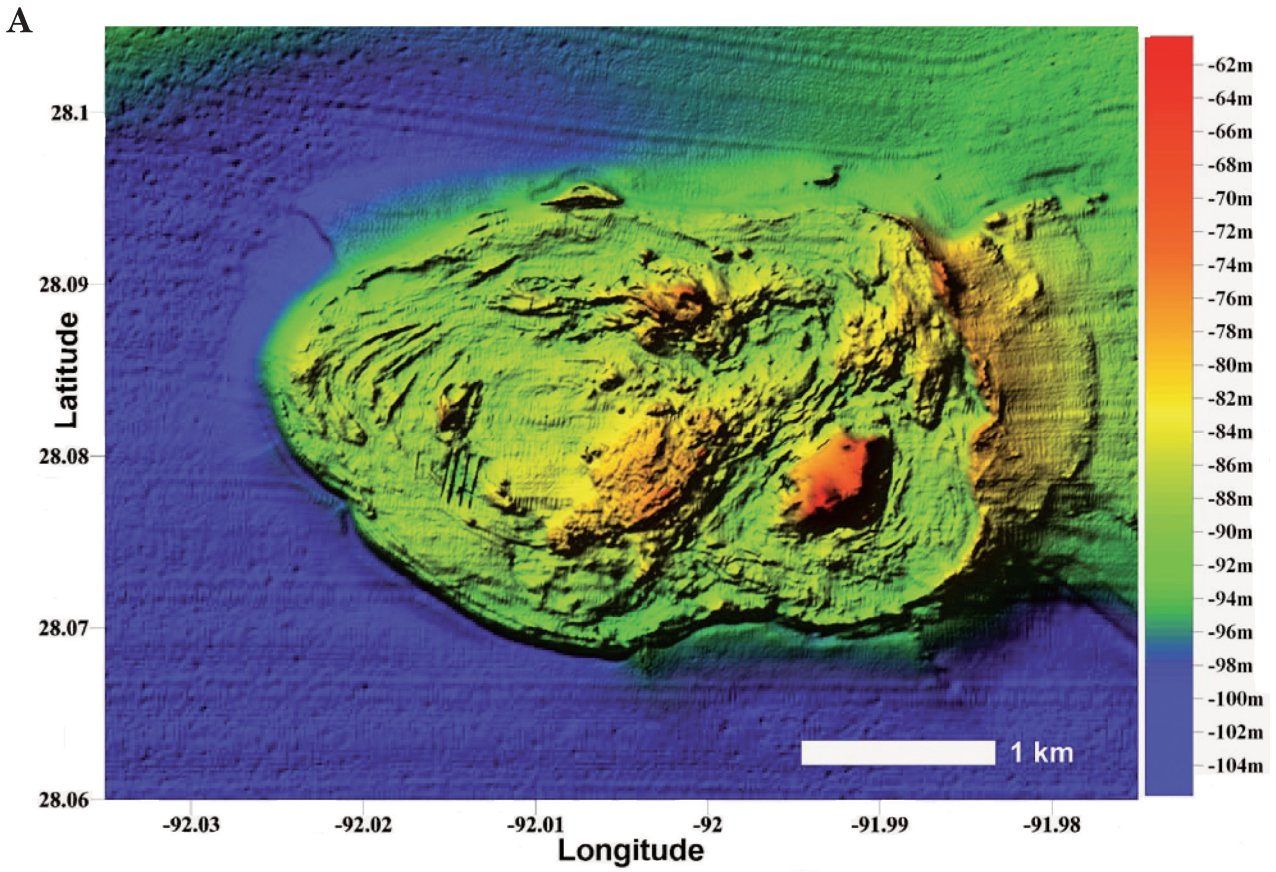


Figure 5

A) Multibeam bathymetry map of Alderdice Bank, plan view. B) Multibeam bathymetry, oblique view (ve=vertical exaggeration) of basalt spires and isolated mound (bathymetry data courtesy James Gardner, see Fig. 3 for contact info.). C) A school of roughtongue bass, *Pronotogrammus martinicensis*, the most abundant species observed at Alderdice Bank. This small, planktivorous sea bass is one of the most common members of the deep reef fish community, and a common prey species of groupers and snappers. Photograph courtesy FGBNMS/NURC-UNCW.

off of *D. antillarum* in the early 1980s (Lessios et al., 1984). This die-off was reported at the Flower Garden Banks NMS in 1984 (Gittings and Hickerson, 1998). Spiny lobster observations were rare in 2002, with a total of three individuals observed on all three banks during submersible dives.

Observations of biological communities at Alderdice Bank were very similar to those reported in the earlier studies. Both basalt spires appear abruptly out of the soft bottom sediments, and the rock surfaces are clearly visible. Rezak and Tieh (1984) speculated that the uplifting of the basalt is a geologically recent occurrence, based on the lack of growth on the basalt blocks. The 2002 observations of the basalt spires gave no indication that growth on the blocks had increased significantly in the 25 years since the last observations. Additional dives on the eastern algal/sponge mound revealed comparable biological assemblages as reported by Rezak et al. (1985). Rezak et al. (1985) report encountering an exceptionally large number of yellowtail reeffish (*Chromis enchrysura*) on the basalt peak—this is consistent with observations made on the eastern algal/sponge mound in 2002

The domination of planktivores in the deep reef fish community is both a regional and worldwide pattern (Thresher and Colin, 1986; Hamner et al., 1988). Pattengill-Semmens et al. (1997) reported planktivores to be the dominant trophic guild on Stetson Bank and the East and West Flower Garden Banks. Percentages of planktivores were lower in their study (36 to 73%), reflecting the shallower depths surveyed by SCUBA, limited to the shallow crests of each bank. Deep-water reef fishes at Enewetak, Marshall Islands (Thresher and Colin, 1986), became dominated by planktivores and piscivores

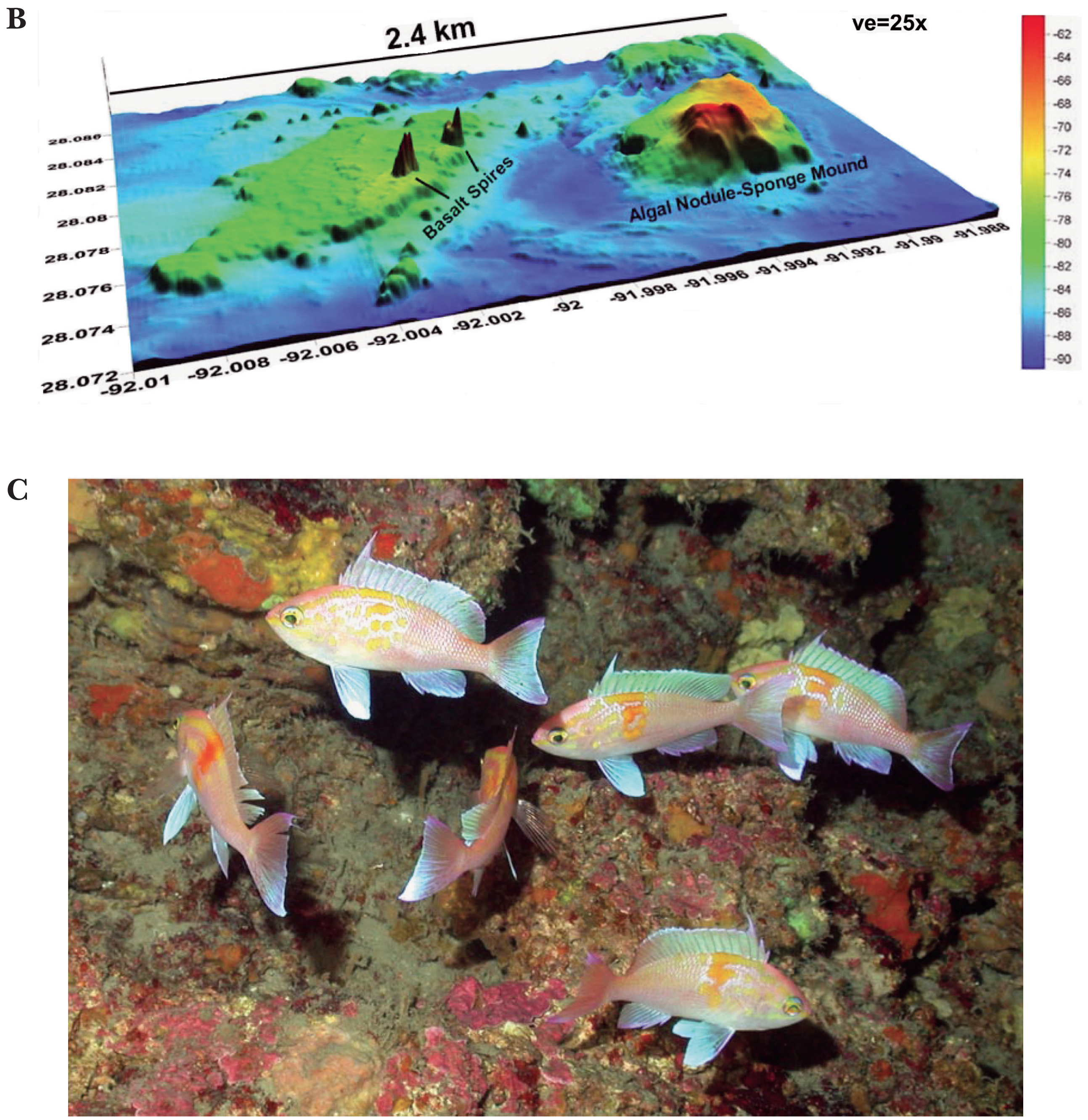


Figure 5 (continued)

with increasing depths between 90 and 120 m, and were numerically dominated by anthiine serranids (streamer basses), and the pomacentrids (*Chromis* spp.). The results of our study directly parallel this pattern, as planktivores became increasingly abundant on the deeper reef site (Alderdice), and were also numerically dominated by anthiine serranids (*A. tenuis* and *P. martinicensis*) and planktivorous damselfishes (*Chromis* spp.). Planktivores abundant on the shallower peaks of Sonnier Bank, T. *bifasciata*, *C. multilineata*, and *S. partitus*, decreased in abundance at Alderdice Bank, and were replaced by *P. martinicensis* and *A. tenuis*, two species that dominate other deepwater areas of the Flower Garden Banks National Marine Sanctuary (Dennis and Bright, 1988a).

Dennis and Bright (1988a) reported three distinct reef fish assemblages based on cluster analysis, a *Millepora*-sponge community associated with the crest of midshelf banks, an algal nodule-sponge fish assemblage, and a drowned reef fish assemblage. These categories are the dominant habitats characterizing Sonnier, McGrail, and Alderdice Banks, respectively, and results of this study parallel those observed by these authors on previous submersible dives. While Dennis and Bright (1988a) did not provide an extensive species list for each of the banks surveyed, their observations of reef fish/habitat associations remain valid. Increased resolution of video cameras, including zoom capabilities and clarity of digital videotape, allows for identification of a larger component of the reef fish fauna, including smaller cryptic species such as juvenile anthiines, blennies, and gobies. Many of the species observed here, including the roughtongue bass (*P. martinicensis*), have only recently been reported to occur in the NWGOM, and the threadnose bass (*A. tenuis*) has not previously been reported to occur in our area (Dennis and Bright, 1988a, b). Recent deepwater surveys at the Flower Garden Banks NMS have indicated that it is one of the most abundant species in the deep reef community between 50 and 100 m.

Rezak et al. (1990) comment on the similarity of geology and biological communities of Sonnier and Stetson Banks. Submersible observations conducted during 2002 SSE surveys support this observation, and provides data on habitat distribution and fish community structure to compare to ongoing surveys being conducted by FGBNMS staff at Stetson Bank. Dennis and Bright (1988a) reported the unique reef fish assemblage associated with the bank crests of the *Millepora* sponge zone. On the Pacific Coast, Yoklavich et al. (2000) found higher numbers of rockfishes associated with abrupt, steep sided rock features surrounded by mud and sand habitats. Both Sonnier Banks and Alderdice Bank are characterized by steep sided rocky features surrounded by relatively flat soft bottom communities. Bohnsack (1989) commented on the behavioral attraction that many fishes have for high profile rocky structure, and that as a result they aggregate in large numbers. High numbers of reef fishes, both small and large species, were observed at the crests of all three banks.

In general, the observations made between the historical surveys and the 2002 SSE mission are similar. The fish assemblages in 2002 appear to be similar to those observed in earlier surveys, although large schools of yellow goatfish that were documented in the 2002 surveys were not listed as representative assemblages in the earlier surveys at any of the shelf edge features. Variations are noted, but do not indicate deterioration of habitat or major shift in associated biological communities. The three banks under discussion were identified as areas warranting regulatory action through MMS, in regards to oil and gas development. These areas are potential ecological and biological significance, harboring juvenile populations of grouper, recovering populations of the longspine urchins, and hermatypic deep coral reefs. These reefs and banks have also been adopted by the Gulf of Mexico Fisheries Management Council as Habitat Areas of Particular Concern (HAPC). No regulations are currently in place to protect Sonnier and Alderice from over-fishing, anchoring, or excavation. Designation of McGrail Bank as a Coral HAPC zone prohibits trawling, bottom longlines, deployment of fish traps, and bottom anchoring.

The availability of accurate, high-resolution bathymetric base maps has allowed the development of comprehensive datasets that can be integrated via a GIS database. The FGBNMS multidisciplinary effort to characterize the reefs and banks of the NWGOM continues to benefit through partnerships such as SSE, and through the advancement of the available technology. While our studies were exploratory in nature, the basic patterns of habitat distribution and reef fish assemblages will allow more rigorous, quantitative surveys of reef fish densities and habitat association during future studies. Information on habitat distribution and associated biological assemblages is also being used to revise the current benthic habitat scheme for the reefs and banks of the NWGOM, including the Flower Garden Banks National Marine Sanctuary. The data acquired will be used to make well-informed management decisions regarding the diverse biological resources of the Northwestern Gulf of Mexico.

Acknowledgments

The authors would like to particularly thank Sylvia Earle for the opportunity to be part of the SSE missions, to train as pilots, and the use of submersible during the research cruises. The SSE program was funded by grants from the Richard and Rhoda Goldman Foundation and NOAA. We also thank the NGS assistants and Nuytco Research Ltd. personnel for logistical and technical support during cruises in the Northwestern Gulf of Mexico. We thank the captain and crew of the M/V OCEAN PROJECT for hospitality and support during the extended research cruise. Multibeam surveys were funded by NOAA's Office of Ocean Exploration and the Minerals Management Service (MMS). We acknowledge the dedication and cooperation of James Gardner of UNH, in his efforts to expediate the extensive multibeam surveys prior to our submersible mission and to accelerate the processing of the data for use during our research cruises.

Literature cited

Bohnsack, J. A.
1989. Are the high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? Bull. Mar. Sci. 44:631–645.

Bullock, L. H., and G. B. Smith.
1991. Seabasses (Pisces:Serranidae). Memoirs of the *Hourglass* cruise. Florida Marine Research Institute. Dept. Nat. Res., St. Petersburg, FL. Vol. 8, 243 p.

Dennis, G. D., and T. J. Bright.
1988a. Reef fish assemblages on hard banks in the northwestern Gulf of Mexico. Bull. Mar. Sci. 43(2): 280–307.
1988b. New records of fishes in the northwestern Gulf of Mexico, with notes on some rare species. Northeast Gulf Sci. 10(1):1–18.

Gardner, J. V., L. A. Mayer, J. E. Hughes Clarke, and A. Kleiner.
1998. High-resolution multibeam bathymetry of East and West Flower Gardens and Stetson Banks, Gulf of Mexico. Gulf of Mexico Sci. 16(2):131–143.

Gittings, S. R., and E. L. Hickerson.
1998. Introduction, Flower Garden Banks National Marine Sanctuary dedicated issue. Gulf of Mexico Sci. 16(2):128–130.

Hamner, W. M., M. S. Jones, J. H. Carleton, I. R. Hauri, and D. McB. Williams.
1988. Zooplankton, piscivorous fish, and water currents on a windward reef face: Great Barrier Reef, Australia. Bull. Mar. Sci. 42(3):459–479.

Humann, P., and N. DeLoach.
2002. Reef fish identification (3rd ed.). New World Publications, Jacksonville, FL. 481 p.

Lessios, H. A., D. R. Robertson, and J. D. Cubit.
1984. Spread of *Diadema* mass mortality through the Caribbean. Science 226:335–337.

Minnery, G. A., R. Rezak, and T. J. Bright.
1985. Depth zonation and growth form of crustose coralline algae: Flower Garden Banks, Northwestern Gulf of Mexico. *In* Paleoalgology: Contemporary Research and Applications (D.F. Toomey and M. H. Nitecki, eds.), p. 237–246. Springer-Verlag, Berlin.

Pattengill-Semmens, B. X. Semmens, and S. R. Gittings.
1997. Reef fish trophic structure at the Flower Gardens and Stetson Bank, NW Gulf of Mexico. Proc. 8th Int. Coral Reef Symp. 1:1023–1028.

Randall, J. E.
1967. Food habits of reef fishes of the West Indies. Stud. Trop. Ocean. 5:665–847.

Rezak, R., and T. T. Tieh.
1984. Basalt from Louisiana Continental Shelf. Geo-Marine Letters 4:69–76.

Rezak, R., T. J. Bright, and D.W. McGrail.
1985. Reefs and banks of the Northwestern Gulf of Mexico: Their geological, biological, and physical dynamics. John Wiley and Sons, New York, 259 p.

Rezak, R., S. R. Gittings, and T. R. Bright.
1990. Biotic assemblages and ecological controls on reefs and banks of the northwest Gulf of Mexico. Amer. Zool. 30:23–35.

Robins, C. R., R. M. Bailey, C. E. Bond, J. R. Brooker, E. A. Lachner, R. N. Lea, and W. B. Scott.
1991. Common and scientific names of fishes from the United States and Canada (5th ed.). Am. Fish. Soc. Spec. Publ. 20, 183 p.

Smith-Vaniz, W. F., B. B. Collette, and B. E. Luckhurst.
1999. The Fishes of Bermuda. Amer. Soc. Ichthy. Herpet. Spec. Publ. 4, 424 p.

Thresher, R. E., and P. L. Colin.
1986. Trophic structure, diversity and abundance of fishes of the deep reef (30–300m) at Enewetak, Marshall Islands. Bull. Mar. Sci. 38:253–272.

Yoklavich, M. M., H. G. Greene, G. M. Caillet, D. E. Sullivan, R. N. Lea, and M. S. Love.
2000. Habitat association of deep-water rockfishes in a submarine canyon: an example of a natural refuge. Fish. Bull. 98:625–641.

Appendix A

Fishes observed during SSE2002 Submersible Dives at Sonnier, McGrail, and Alderdice Banks.

Family		Trophic	Sonnier Banks			McGrail Bank			Alderdice Bank		
Species	Common name	guild[1]	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent
Acanthuridae											
Acanthurus chirurgus	doctorfish	EB	27	19	0.25	36	9	0.06	31	8	0.05
Acanthurus coeruleus	blue tang	EB	52	5	0.06	—	2	—	—	—	—
Apogonidae											
Apogon affinis	bigtooth cardinalfish	PL	—	—	—	—	—	—	13	50	0.29
Apogon maculatus	flamefish	PL	57	3	0.04	54	3	0.02	—	—	—
Apogon psuedomaculatus	twospot cardinalfish	PL	60	2	0.03	—	—	—	—	—	—
Aulostomidae											
Aulostomus maculatus	trumpetfish	PI	—	—	—	—	—	—	17	25	0.14
Balistidae											
Balistes capriscus	gray triggerfish	BC	13	80	1.04	27	19	0.12	28	10	0.06
Balistes vetula	queen triggerfish	BC	—	—	—	44	6	0.04			
Cantherhines macrocerus	whitespotted filefish	EB	—	—	—	38	8	0.05	56	1	0.01
Cantherhines pullus	orangespotted filefish	EB	—	—	—	—	—	—	55	1	0.01
Canthidermis sufflamen	ocean triggerfish	PL	—	—	—	29	18	0.12	—	—	—
Xanthichtys ringens	sargassum triggerfish	PL	42	7	0.05	—	—	—	—	—	—
Blenniidae											
Parablennius marmoreus	seaweed blenny	EB	59	3	0.04	—	—	—	—	—	—
Carangidae											
Alectis ciliaris	African pompano	PI	53	5	0.06	—	—	—	—	—	—
Caranx bartholomaei	yellow jack	PI	—	—	—	17	38	0.25	39	4	0.02
Caranx chrysos	blue runner	PL	54	4	0.05	—	—	—	—	—	—
Caranx hippos	crevalle jack	PI	—	—	—	19	30	0.20	—	—	—
Caranx latus	horse-eye jack	PI	34	13	0.17	14	81	0.53	—	—	—
Caranx lugubris	black jack	PI	—	—	—	39	8	0.05	—	—	—
Caranx ruber	bar jack	PI	40	11	0.14	30	17	0.11	—	—	—
Selene vomer	lookdown	GC	56	4	0.05	—	—	—	—	—	—
Seriola dumerili	greater amberjack	PI	44	10	0.13	35	10	0.07	12	53	0.30
Seriola rivoliana	almaco jack	PI	—	—	—	34	11	0.07	22	16	0.09
Carcharhinidae											
Carcharhinus plumbeus	sandbar shark	PI	50	6	0.08	59	2	0.01	58	1	0.01
Carcharhinus sp.		PI	—	—	—	64	1	0.01	—	—	—
Chaetodontidae											
Chaetodon aculeatus	longsnout butterflyfish	EB	—	—	—	45	6	0.04	59	1	0.10
Chaetodon aya	bank butterflyfish	PL	—	—	—	—	—	—	18	18	0.10
Chaetodon ocellatus	spotfin butterflyfish	EB	61	2	0.03	66	1	0.01	60	1	0.01
Chaetodon sedentarius	reef butterflyfish	EB	21	25	0.32	13	84	0.55	14	49	0.28
Clinidae											
Starksia sp.	unidentified blenny	BC	77	1	0.01	—	—	—	—	—	—

continued

Appendix A (continued)

Family Species	Common name	Trophic guild[1]	Sonnier Banks			McGrail Bank			Alderdice Bank		
			Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent
Congridae											
Conger oceanicus	conger eel	GC	—	—	—	—	—	—	61	1	0.01
Dasyatidae											
Dasyatis americana	southern stingray	GC	—	—	—	—	—	—	62	1	0.01
Echeneidae											
Echeneis naucrates	sharksucker	GC	69	1	0.01	—	—	—	—	—	—
Gobiidae											
Gnatholepis thompsoni	goldspot goby	BC	63	2	0.03	49	5	0.03	—	—	—
Gobiidae	unidentified gobies	BC	32	16	0.21	—	—	—	—	—	—
Gobiosoma xanthiprora	prownose goby	BC	47	7	0.09	68	1	0.01	—	—	—
Ptereleotris calliurus	blue goby	PL	22	22	0.29	—	—	—	—	—	—
Haemulidae											
Haemulon aurolineatum	tomtate	GC	6	428	5.55	—	—	—	—	—	—
Holocentridae											
Corniger spinosus	spinycheek soldierfish	GC	—	—	—	—	—	—	44	2	0.01
Holocentrus adscensionis	squirrelfish	PL	43	10	0.13	46	6	0.04	49	2	0.01
Holocentrus rufus	longfin squirrelfish	PL	45	9	0.12	22	28	0.18	65	1	0.01
Myripristis jacobus	blackbar soldierfish	PL	20	31	0.40	28	19	0.12	33	8	0.05
Sargocentron bullisi	deepwater squirrelfish	PL	66	2	0.03	75	1	0.01	38	5	0.03
Kyphosidae											
Kyphosus sp.	Bermuda/yellow chub	PL	11	139	1.80	—	—	—	—	—	—
Labridae											
Bodianus pulchellus	spotfin hogfish	GC	16	51	0.66	21	28	0.18	11	73	0.42
Bodianus rufus	Spanish hogfish	GC	17	45	0.58	24	22	0.14	54	1	0.01
Clepticus parrae	creole wrasse	PL	9	181	2.35	15	74	0.48	15	34	0.19
Decodon puellaris	red hogfish	BC	—	—	—	—	—	—	45	2	0.01
Halichoeres bathyphilus	greenband wrasse	BC	28	19	0.25	—	—	—	26	11	0.06
Halichoeres bivitattus	slippery dick	BC	41	11	0.14	—	—	—	—	—	—
Halichoeres garnoti	yellowhead wrasse	BC	—	—	—	37	9	0.06	47	2	0.01
Halichoeres maculipinna	clown wrasse	BC	—	—	—	56	3	0.02	—	—	—
Thallasoma bifasciatum	bluehead	PL	5	442	5.73	18	35	0.23	25	12	0.07
Lutjanidae											
Lutjanus buccanella	blackfin snapper	GC	18	43	0.56	—	—	—	41	3	0.02
Lutjanus campechanus	red snapper	GC	15	70	0.91	—	—	—	29	10	0.06
Lutjanus cyanopterus	cubera snapper	PI	—	—	—	71	1	0.01	—	—	—
Lutjanus griseus	gray snapper	GC	14	80	1.04	9	112	0.73	10	91	0.52
Lutjanus jocu	dog snapper	GC	48	7	0.09	26	20	0.13	30	10	0.06
Lutjanus synagris	lane snapper	GC	55	4	0.05	—	—	—	—	—	—
Ocyurus chrysurus	yellowtail snapper	PL	72	1	0.01	73	1	0.01	—	—	—
Rhomboplites aurorubens	vermilion snapper	PL	12	110	1.43	—	—	—	6	576	3.29

continued

Appendix A (continued)

Family		Trophic	Sonnier Banks			McGrail Bank			Alderdice Bank		
Species	Common name	guild[1]	Rank	No.	Percent	Rank	No.	Percent	Rank	No.	Percent
Malacanthidae											
Malacanthus plumieri	sand tilefish	BC	—	—	—	57	3	0.02	66	1	0.01
Mullidae											
Mulloidichthys martinicus	yellow goatfish	BC	26	20	0.26	3	2000	13.09	7	280	1.60
Pseudupeneus maculatus	spotted goatfish	BC	39	12	0.16	31	15	0.10	21	16	0.09
Muraenidae											
Gymnothorax moringa	spotted moray	GC	64	2	0.03	69	1	0.01	—	—	—
Ophichthidae											
Myrichthys breviceps	sharptail eel	GC	—	—	—	—	1	—	—	—	—
Opistognathidae											
Opistognathus aurifrons	yellowhead jawfish	PL	—	—	—	62	2	0.01	—	—	—
Ostraciidae											
Lactophrys triqueter	smooth trunkfish	BC	58	3	0.04	70	1	0.01	—	—	—
Pomacanthidae											
Centropyge argi	pygmy angelfish	EB	—	—	—	11	96	0.63	34	6	0.03
Holacanthus bermudensis	blue angelfish	EB	29	18	0.23	40	8	0.05	24	13	0.07
Holacanthus ciliaris	queen angelfish	EB	35	13	0.17	52	4	0.03	48	2	0.01
Holacanthus tricolor	rock beauty	EB	25	20	0.26	25	22	0.14	23	14	0.08
Pomacanthus paru	French angelfish	EB	30	18	0.23	53	4	0.03	—	—	—
Pomacentridae											
Abudefduf saxatalis	sargeant major	PL	19	41	0.53	—	—	—	—	—	—
Chromis cyanea	blue chromis	PL	38	12	0.16	8	143	0.94	40	3	0.02
Chromis enchrysura	yellowtail reeffish	PL	1	1782	23.11	5	947	6.20	2	4311	24.61
Chromis insolata	sunshinefish	PL	4	491	6.37	4	1168	7.64	5	993	5.67
Chromis multilineatus	brown chromis	PL	3	1055	13.68	12	90	0.59	—	—	—
Chromis scotti	purple reeffish	PL	7	412	5.34	10	106	0.69	9	170	0.97
Stegastes partitus	bicolor damselfish	PL	10	157	2.04	7	159	1.04	—	—	—
Stegastes planifrons	threespot damselfish	EB	31	18	0.23	—	—	—	—	—	—
Stegastes variabilis	cocoa damselfish	EB	8	216	2.80	62	2	0.01	—	—	—
Priacanthidae											
Priacanthus arenatus	bigeye	PL	74	1	0.01	—	—	—	27	11	0.06
Rachycentridae											
Rachycentron canadum	cobia	GC	65	2	0.03	—	—	—	—	—	—
Rhincodontidae											
Ginglymostoma cirratum	nurse shark	GC	70	1	0.01	—	—	—	64	1	0.01
Scaridae											
Cryptotomus roseus	bluelip parrotfish	EB	68	1	0.01	—	—	—	—	—	—
Scaridae	unidentified parrotfish	EB	75	1	0.01	—	—	—	—	—	—
Scarus taeniopterus	princess parrotfish	EB	67	2	0.03	—	—	—	—	—	—
Sparisoma atomarium	greenblotch parrotfish	EB	42	11	0.14	23	23	0.15	42	3	0.02
Sparisoma aurofrenatum	redband parrotfish	EB	49	7	0.09	51	5	0.03	—	—	—

continued

Appendix A (continued)

Family Species	Common name	Trophic guild[1]	Sonnier Banks Rank	Sonnier Banks No.	Sonnier Banks Percent	McGrail Bank Rank	McGrail Bank No.	McGrail Bank Percent	Alderdice Bank Rank	Alderdice Bank No.	Alderdice Bank Percent
Sciaenidae											
Equetus punctatus	spotted drum	BC	62	2	0.03	—	—	—	—	—	—
Pareques iwamotoi	blackbar drum	BC	—	—	—	—	—	—	37	5	0.03
Pareques umbrosus	cubbyu	BC	36	13	0.17	—	—	—	19	17	0.10
Scombridae											
Scomberomorus cavalla	king mackerel	PI	—	—	—	—	—	—	8	200	1.14
Serranidae											
Anthias tenuis	threadnose bass	PL	—	—	—	2	2745	17.96	4	2300	13.13
Cephalopholis cruentata	graysby	GC	37	12	0.16	48	5	0.03	—	—	—
Cephalopholis fulva	coney	GC	—	—	—	65	1	0.01	—	—	—
Dermatolepis inermis	Marble grouper	GC	—	—	—	41	7	0.05	46	2	0.01
Epinephelus adscensionis	rock hind	GC	23	21	0.27	67	1	0.01	—	1	0.01
Epinephelus guttatus	red hind	GC	—	—	—	55	3	0.02	—	—	—
Gonioplectrus hispanus	Spanish flag	GC	—	—	—	—	—	—	20	16	0.09
Liopropoma eukrines	wrasse bass	GC	71	1	0.01	—	—	—	36	5	0.03
Mycteroperca bonaci	black grouper	PI	—	—	—	33	11	0.07	50	2	0.01
Mycteroperca interstitialis	yellowmouth grouper	PI	33	14	0.18	20	30	0.20	16	29	0.17
Mycteroperca microlepis	gag	PI	—	—	—	—	—	—	51	2	0.01
Mycteroperca phenax	scamp	PI	46	9	0.12	61	2	0.01	52	2	0.01
Mycteroperca venenosa	yellowfin grouper	PI	—	—	—	50	5	0.03	—	—	—
Paranthias furcifer	creole-fish	PL	2	1370	17.77	1	6625	43.35	3	3239	18.49
Pronotogrammus martinicensis	roughtongue bass	PL	—	—	—	16	74	0.48	1	4984	28.45
Schultzea beta	school bass	PL	—	—	—	6	220	1.44	—	—	—
Serranus annularis	orangeback bass	GC	—	—	—	32	15	0.10	34	6	0.03
Serranus notospilus	saddle bass	GC	76	1	0.01	76	1	0.01	68	1	0.01
Serranus phoebe	tattler	GC	51	6	0.08	77	1	0.01	53	2	0.01
Sparidae											
Calamus sp.		BC	—	—	—	47	5	0.03	43	2	0.01
Pagrus pagrus	red porgy	BC	73	1	0.01	—	—	—	—	—	—
Sphyraenidae											
Sphyraena barracuda	great barracuda	PI	—	—	—	78	1	0.01	—	—	—
Synodontidae											
Synodus intermedius	sand diver	PI	—	—	—	—	—	—	69	1	0.01
Synodus synodus	red lizardfish	PI	—	—	—	79	1	0.01	—	—	—
Tetraodontidae											
Canthigaster jamestyleri	goldface toby	EB	—	—	—	—	—	—	57	1	0.01
Canthigaster rostrata	sharpnose puffer	EB	24	20	0.26	59	2	0.01	32	8	0.05
			No. Sp. 77	Total N 7,717		No. Sp. 79	Total N 15,288		No. Sp. 69	Total N 17,519	

---

[1] PL-Planktivore, PI-Piscivore, GC-General carnivore (mobile invertebrates and fishes), H-Herbivore, EB-Epibenthic browsers (sessile invertebrates), BC-Benthic carnivores (benthic crustaceans and infauna).

Detecting fish aggregations from reef habitats mapped with high resolution side scan sonar imagery

José A. Rivera
Under contract to:
Miami Laboratory-Biodiversity and Protected Resources Division
NOAA, NMFS
HC-01, Box 1736
Cabo Rojo, PR 00622-9704
Email: jarivera@msn.com

Martha C. Prada
P.O. Box 2048
San Andres Isla, Colombia

Jean-Luc Arsenault
Gary Moody
Nicolas Benoit
Geophysique GPR International, Inc.
2545 Rue Delorimier
Longueuil (Quebec), Canada J4K 3P7

Abstract—As part of a multibeam and side scan sonar (SSS) benthic survey of the Marine Conservation District (MCD) south of St. Thomas, USVI and the seasonal closed areas in St. Croix—Lang Bank (LB) for red hind (*Epinephelus guttatus*) and the Mutton Snapper (MS) (*Lutjanus analis*) area—we extracted signals from water column targets that represent individual and aggregated fish over various benthic habitats encountered in the SSS imagery. The survey covered a total of 18 km^2 throughout the federal jurisdiction fishery management areas. The complementary set of 28 habitat classification digital maps covered a total of 5,462.3 ha; MCDW (West) accounted for 45% of that area, and MCDE (East) 26%, LB 17%, and MS the remaining 13%. With the exception of MS, corals and gorgonians on consolidated habitats were significantly more abundant than submerged aquatic vegetation (SAV) on unconsolidated sediments or unconsolidated sediments. Continuous coral habitat was the most abundant consolidated habitat for both MCDW and MCDE (41% and 43% respectively). Consolidated habitats in LB and MS predominantly consisted of gorgonian plain habitat with 95% and 83% respectively. Coral limestone habitat was more abundant than coral patch habitat; it was found near the shelf break in MS, MCDW, and MCDE. Coral limestone and coral patch habitats only covered LB minimally. The high spatial resolution (0.15 m) of the acquired imagery allowed the detection of differing fish aggregation (FA) types. The largest FA densities were located at MCDW and MCDE over coral communities that occupy up to 70% of the bottom cover. Counts of unidentified swimming objects (USOs), likely representing individual fish, were similar among locations and occurred primarily over sand and shelf edge areas. Fish aggregation school sizes were significantly smaller at MS than the other three locations (MCDW, MCDE, and LB). This study shows the advantages of utilizing SSS in determining fish distributions and density.

Introduction

Ideally, fishery biologists dream of a sensor that, when placed in a water body, provides all density and meristic information of the fishes present in the water body. Even better, the sensor would also identify the fish species. In addition, all this information would be available synoptically for a large water area. In reality, such a sensor exists taking the shape of a single beam fish finder with a very narrow search cone extending from the surface to the bottom of the water body. Availability of acoustic sensors such as side scan sonar (SSS) and multibeam bottom sounders incorporating very fast processor capabilities are beginning to actualize the fishery biologist's dream (Fish and Carr, 1990).

Remote sensing techniques offer a viable option for mapping marine habitats, determining not only the location and amount of distinct benthic habitats, but also how these habitats are distributed and their degree of connectivity. In tropical regions, specifically in coastal waters, the use of traditional passive sensors (Ikonos or Landsat 7 satellites, aerial photographic camera) is restricted because light is exponentially absorbed by the water column, phytoplankton minimize remote benthic reflectance, and colored dissolved organic matter alters measured wavelengths (Roesler and Perry, 1989; Gordon and Wang, 1994; Lee et al., 1994; Arono and Gould, 1998). Even in clear water, the bottom signature can be inconclusive because it is the result of mixed spectra, which becomes more complicated with depth (Mumby et al., 1998). Existing passive sensors are also limited by low spatial resolution and lack of information from deep or turbid areas with high cloud cover. Additional problems result from back scattering from inorganic suspended particles, which add noise and may modify the bottom signal reaching the sensor. To avoid confusion between water and bottom signatures, bathymetry measurements and knowledge of water attenuation is required. Elevation models for reef areas, when available, are often inaccurate because they do not include a complete coverage of depth and they lack precise positioning. Lizenga (1978, 1981) developed the depth-invariant bottom index, which is widely applied when mapping benthic habitats regardless of algorithm limitations. Despite the above limitations, passive sensors are currently the preferred mapping tool.

An alternative to passive sensors is the use of active remote sensors. Active sensors emit a signal and detect the intensity of the signal reflected from an object. Active remote sensing in the oceanic environment is feasible using acoustic or optical techniques. An optical sensor (using a laser) can have excellent spatial resolution (cm or mm, depending on the altitude of the sensor), but accuracy falls off rapidly with increasing range; therefore its use is limited to a swath of 3–5 m (Klepsvik et al., 1994). At this time, laser sensors are too expensive and time-consuming to be an option for mapping large areas (10s km^2 or larger).

The remaining alternative, the use of acoustic technology such as SSS, is a promising approach for mapping coral reefs. By selecting an appropriate SSS system it is possible to obtain images of features as large as seamounts or as small as sand ripples. SSS images can be combined to generate mosaics over large areas, showing all structures and their position in a planimetric manner. To solve this limitation, SSS data can be combined with high resolution multibeam echo sounder, which adds depth data as a third dimension to the SSS images. The merging of these technologies has rapidly become the preferred mapping tool for accurate positioning and navigation.

SSS technology was used for the first time in 1963 in England and has been routinely used by hydrographers to help determine the characteristics of the ocean bottom in the making of nautical charts. SSS is especially valuable in identifying bottom objects in turbid waters. Historically, SSS has been used to map seabed configuration and predominant bottom targets for petroleum industry applications, dredging, and mine hunting. Geologists and geophysicists see fish and other water column signals as interference that affects the interpretation of the ocean bottom features. Such signals are eliminated from the sonar record during either acquisition or post processing. The utilization of SSS for environmental and fisheries applications is more recent (Siljestrom et al., 1996; Friedlander et al., 1999; Karl et al., 1994).

The advantage of using SSS over conventional single beam fish finders to locate fish echoes is the added volume sampled per transducer signal or ping. Typically, SSS can sample out to a range of 10–100 m on each side of a transducer, depending on the range setting and transducer frequency. The single beam transducer sampling area depends on depth and transducer beam geometry. The shallower the depth, the smaller the area sampled. All SSS systems marketed today are designed for working in relatively deep water (>10 m depth). This limitation is primarily due to the mechanical design for transducer deployment and recovery and the undesirable interaction of the transmitted sound wave with the water surface and the propeller wash. In deeper water, this problem is avoided by submerging the SSS transducer to the lower 30% of the water column.

In October 1996, Congress re-authorized the Magnuson-Stevens Fishery Conservation and Management Act (Public Law 94-265) with amendments (Kantor et al., 1996). One amendment in Title III, section 305 mandates Fisheries Management Councils to revise all Fisheries Management Plans (FMP) to include delineation of “essential fish habitat” (EFH) by October 1998. Although some FMPs will benefit from existing information portrayed in map format, other FMPs will not have such information. Information for these FMPs will be collected and relevant maps produced. The main objective of our work was to contribute to the formulation of EFH maps for the Caribbean Fishery Management Council (CFMC) in the United States Virgin Islands Exclusive Economic Zone (EEZ). The aim of the marine surveys was to provide high resolution bathymetry and SSS maps of the seabed and detailed maps of the benthic habitat at three designated conservation areas. The survey areas were designated as follows: Marine Conservation District (MCD, south off St. Thomas), and Lang Bank and Mutton Snapper (LB and MS, east and south west off St. Croix respectively). The work reported concentrates on the fish signals encountered in the SSS mapping of the seabed.

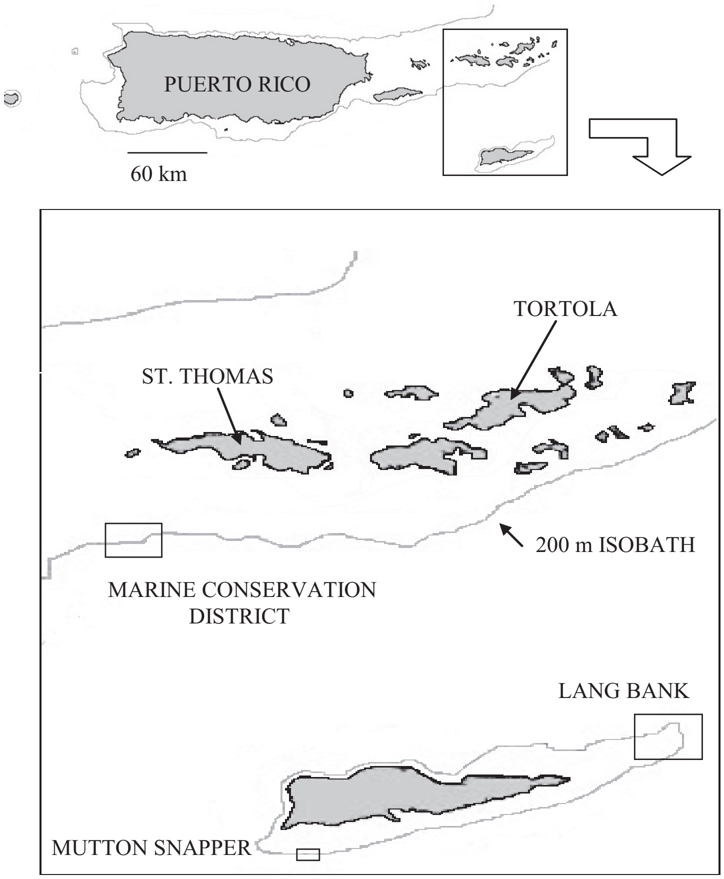
Materials and methods

Survey region and equipment deployment

Surveys were conducted on St. Thomas, USVI in the recently developed Marine Conservation District East (MCDE) and West (MCDW, Fig. 1). The data acquisition was carried out from a chartered 17 m Grand Banks wood cruiser, with dual inboard motors, Onan service generator, Raytheon autopilot, and GPS navigation system. Several remote sensing technologies were deployed from this single vessel for navigation and hydroacoustic surveying (Fig. 2). The vessel cruising speed is 8 knots.

Positioning

The survey extended from 9 April to 31 May 2003. Vessel positioning was achieved using a Trimble Series 5700 Real-time Kinematic Global Positioning System (RTK GPS). The transmission of positional corrections from a base station transmitter on shore allowed horizontal and



MARINE CONSERVATION DISTRICT

1.	18º 13.2í N	65º 06.9í W
2.	18º 13.2í N	64º 59.0í W
3.	18º 11.8í N	64º 59.0í W
4.	18º 10.7í N	65º 06.9í W

LANG BANK

1.	17º 49.3í N	64º 27.9í W
2.	17º 49.3í N	64º 26.8í W
3.	17º 48.3í N	64º 25.9í W
4.	17º 48.3í N	64º 26.8í W
5.	17º 47.3í N	64º 28.0í W
6.	17º 47.3í N	64º 26.8í W

MUTTON SNAPPER

1.	17º 37.8í N	64º 53.0í W
2.	17º 39.0í N	64º 53.0í W
3.	17º 39.0í N	64º 50.5í W
4.	17º 38.1í N	64º 50.5í W
5.	17º 37.8í N	64º 52.5í W

Figure 1

Location of three mapped areas.

vertical accuracy of the order of 5 cm to be achieved. A Pacific Crest PDL radio modem on the survey vessel received the positional corrections.

A laptop computer ran the Hypack Max (version 2.12, Coastal Oceanographics, Inc., Middletown, CT) navigation software aboard the survey vessel. Latitude and longitude measured by the RTK GPS system were stored at the rate of five readings per second on the laptop's hard drive. These were converted into Cartesian (X, Y) coordinates of the local grid used for surveying. The Universal Transverse Mercator (U.T.M.) projection system (Zone 20-N), with the WGS-84 datum was used for horizontal positioning. Current vessel position relative to the local grid was displayed on a screen dedicated for use by the vessel captain. The Sonarwiz (version 1.65, Chesapeake Technology, Inc., Mountain View, CA) SSS data acquisition software system was linked to Hypack Max via multiple RS232 interfaces. During data acquisition, the SSS output data were attached to the (X, Y) grid position and stored on hard disk. The various instrument offsets relative to the GPS antenna were entered into the data acquisition systems, allowing real-time positional corrections to be carried out. The vessel was also equipped with a Meridian Surveyor gyrocompass from S. B. Brown Ltd., which was used to provide precise heading information during surveying.

Swath bathymetry

We use a Geoacoustics, Ltd., Geoswath 250 kHz phase comparison system to conduct the swath bathymetry. Complete equipment specifications can be found in Appendix A. The transducer V-plate was installed in a position directly off the port side of the vessel, 0.91 m from the stern. The V-plate mounting contains a motion reference unit (MRU) and the port and starboard trans-

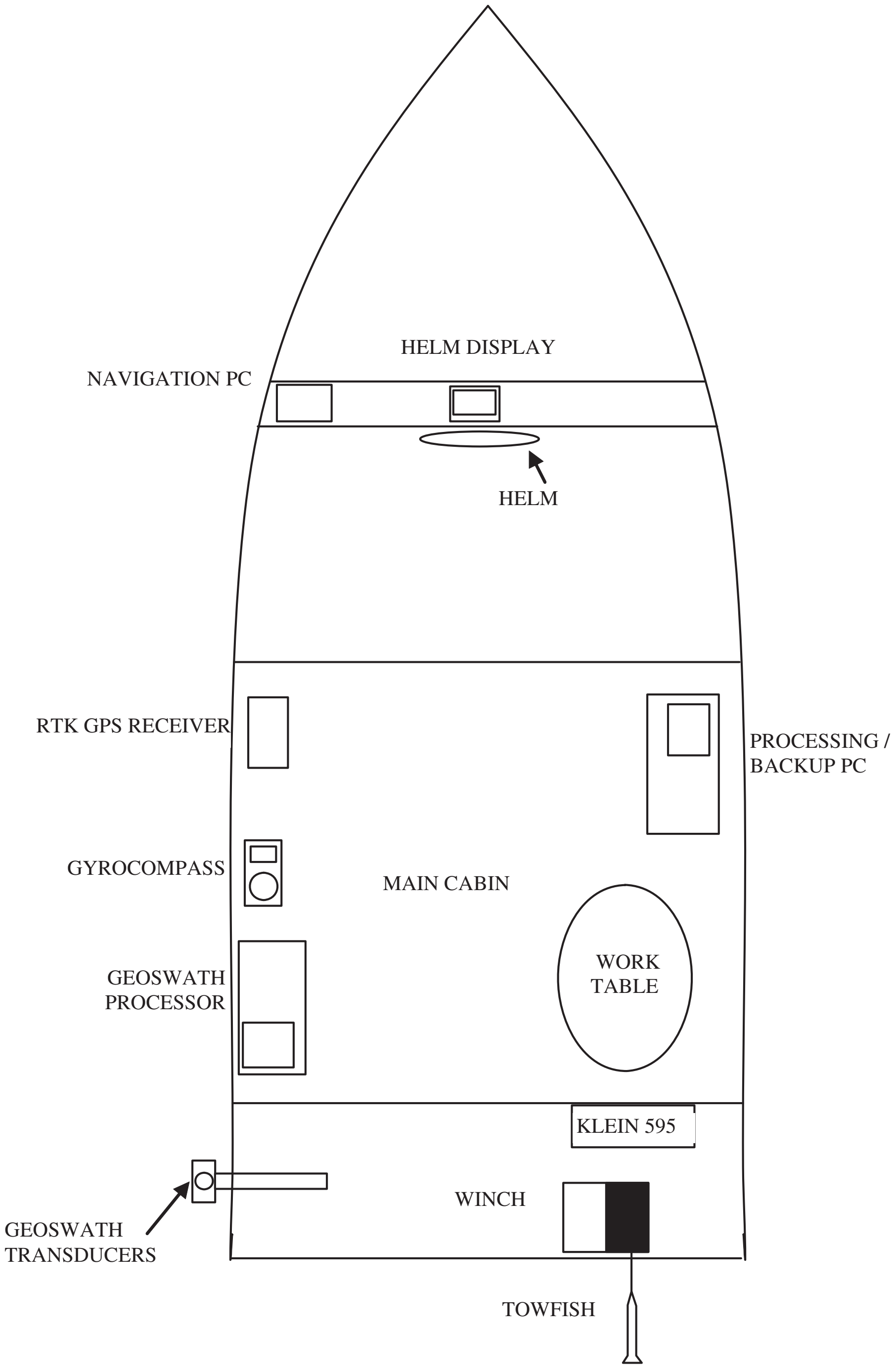


Figure 2

Survey vessel equipment layout diagram.

ducers. The V-plate assembly was fixed at approximately 1.1 m beneath the waterline, and was secured using an anodized aluminum mounting pole attached to a swivel over the side mount. The vertical pole was locked at the top end, and steel guy wires were run from the V-plate to the amidships and the stern of the vessel to ensure the V-plate was stable. Signals from the transducers and MRU were sent to the Geoswath processing unit, located in the main cabin of the vessel. This PC-based system ran proprietary software (version 2.07s, Swath32, Geoacoustics, Ltd., Norfolk, UK) on the Microsoft Windows® 98/Me operating system.

Correction for survey vessel heave, pitch, and roll was performed through the use of a dynamic motion sensor (DMS) from TSS Limited, located in the V-plate assembly between the transducers. The DMS from TSS Limited is the MRU. The DMS was connected to the Geoswath system via an RS-232 connection, enabling correction of the bathymetric data for heave, roll, and pitch in real time.

Sound velocity profiles

For the Geoswath system to accurately survey the seabed, precise information on the water column sound speed profile is required. This information was acquired by lowering a Valeport DigiBar sound velocity probe through the water column at approximately 1 m intervals. The sound speed profile was entered into the Geoswath software to accurately convert the raw data into depths.

Side scan sonar

The side scan sonar system utilized was a Klein Model 595. Data was captured using a Klein 590 Digital Graphic Recorder unit, and subsequently transferred to a PC running Sonarwiz data acquisition software. Although the tow fish was a dual frequency fish, capable of acquiring data at 100 kHz and 500 kHz, only the 500 kHz data was analyzed. The instrument range was set at 50 m on each side of the sonar transducer. During data acquisition, the vessel speed was maintained between 2 and 5 knots, while the tow fish was kept between 5 and 10 m off the seabed. The length of cable out was controlled by an electric winch. This length was entered into the SonarWiz program, which allowed a layback calculation to be applied to the sonar image navigation coordinates. Navigation was supplied to the SonarWiz system through serial communication of the NMEA GLL data string generated by Hypack Max at the rate of two readings per second. The navigation string was corrected for the offset between the vessel reference position and the winch tow-block position.

Side scan sonar data processing

The raw side scan sonar data consisted of a digital file in standard XTF format. SonarWeb software (version 3.15G, Chesapeake Technology, Inc., Mountain View, CA) was used to process the XTF file into mosaic form. Before utilization of SonarWeb, some pre-processing of the side scan data was necessary. This was accomplished using GPR's proprietary dedicated software to smooth the navigation data and correct for the slowly varying amount of cable out. Once the navigation data was corrected, the XTF files were partitioned into separate blocks of 1.86 km^2. This was necessary due to the scale requirements for the maps, and due to file size limitations in creating the mosaics using SonarWeb. Once the XTF files were correctly partitioned, they could be imported into SonarWeb. Each 1.86 km^2 area was processed as a separate project.

The underlying purpose of each project was to produce finished sonar mosaics at high resolution for display and analysis. The most critical and time-consuming task was tracking the return from the seabed (bottom-track) for all the SSS data (Fig. 3). Bottom-tracking had to be carried out by manually digitizing the return since the automated tracker provided in the software was not sufficiently accurate. Bottom-tracking allowed the water column to be accurately measured and its influence removed, so as to provide slant range corrected data. Once all the files in a project were accurately bottom-tracked, the mosaic was generated using a set resolution and color scheme.

No beam angle corrections were made to the mosaic data in order to obtain maximum signal contrast. The mosaics were exported in geotiff format, and then imported into a separate software package for visualization/map preparation. These mosaics were subsequently used to perform habitat mapping.

Delineation of habitat from SSS mosaics

A total of 28-1.86 km^2 mosaics in geotiff format from SSS imagery processed at 0.2 m resolution were used to generate detailed benthic habitat maps through visual interpretation and delineation. Interpretation was aided by the availability of geotiff mosaics from multibeam bathymetry processed at 1 m resolution, which provided a three dimensional perspective when assigning a habitat class to an area. Habitat maps were created using ArcView (version 3.2, Environmental Systems Research Institute, Inc., Redlands, CA) and projected in Universal Transverse Mercator (UTM) coordinates for UTM-83 Zone 20. Digitization utilized the ArcView extension Habitat.avx v 1.2 developed by the NOAA/NOS/Biogeography Team[1].

A modified version of the hierarchical habitat classification scheme developed by Prada (2002) was used to run the Habitat extension, which contained a total of 23 different habitat types (one more than originally defined (Table 1)). The hierarchical classification scheme was developed after qualitative observations were conducted at 107 sites in fifteen 1.86 km^2 areas

---

[1] NOAA/NOS Biogeography Team. 2002. Benthic habitats of Puerto Rico and the U.S. Virgin Islands. CD-ROM, Silver Spring, Md. Available from http://ccmaserver.nos.noaa.gov/products/biogeography/benthic/order.shtml

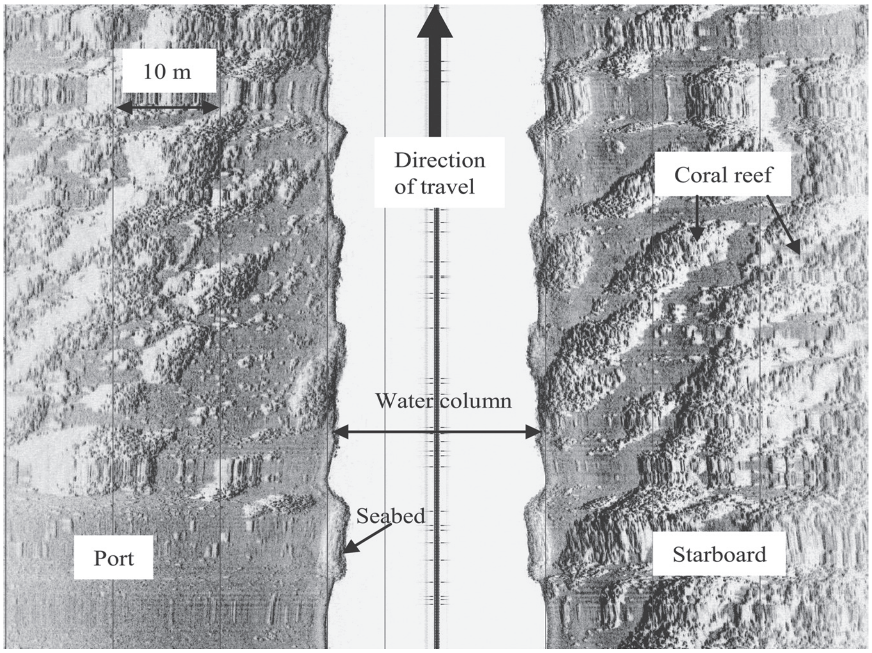


Figure 3

Example side scan sonar record with water column (before slant range correction).

corresponding to their respective SSS mosaics. Each habitat type was visited at least three times within a SSS depicted habitat. Habitat types were based on detailed observations of the SSS mosaics performed at a series of spatial scales (1:500, 1:1000, 1:2500, and 1:5000). The qualitative observations were obtained by videotaping through an underwater drop video camera an average of three minutes per location from a small boat while slowly transiting. Quantitative measurements were conducted at an additional 59 sites. The quantitative data were taken in 5–6 replicates within each sampled habitat type by a team of 4–5 divers. At each location, four quadrants of 1m^2 were randomly placed along a 48 m metric tape. Within each quadrant, divers estimated the percent cover of sand, rubble, live coral, dead coral, gorgonians, sponges, macro algae, sea grass, and Cyanophyta. Number and size (length, height, and width) of each live colony of hard corals, gorgonians, and sponges within the quadrant were also recorded. Additionally, twelve rugosity estimates were taken at each location using a 3 m (2 cm link) chain laid along the metric tape. Percent cover and presence or absence data were then analyzed utilizing the Ochiai Index (Ochiai, 1957) and detrended correspondence analysis (DCA) to ordinate the habitat types by levels of complexity. The scheme was organized into four levels of complexity. The first level grouped habitats in three meta-communities designated: corals and gorgonians on consolidated sediments, submerged aquatic vegetation (SAV) on unconsolidated sediments (algae and sea grasses), and unconsolidated sediments (Fig. 3).

Map colors were similar to the palette defined in Prada (2002) to easily identify habitat types. The new category was included within variations of the color green. Most habitat maps overlap 100–200 m in every direction, with the exception of the MS area that had no overlap. Small areas (hundreds of meters) in the MS area, and a larger (thousands of meters) area at LB had no SSS information, which consequently resulted in gaps in the habitat maps.

Quantitative determination of habitat classification map accuracy at the MCDW and MCDE areas by using existing ground truth video was not performed because available video lacked precise frame specific time or geo-positioning. However, a general idea of habitat classification map accuracy was obtained by comparing underwater benthic pictures obtained from an Autonomous Underwater Vehicle (AUV)[2] and drift transects from a digital video underwater camera with

---

[2] Autonomous Underwater Vehicle Expedition. 2003. Caribbean Fisheries Management Council AUV Expedition to the MCD south of St. Thomas, USVI. Collection of digital photo transects. Caribbean Fisheries Management Council, 268 Muñoz Rivera Ave., Suite 1108, San Juan, PR 00918-2577.

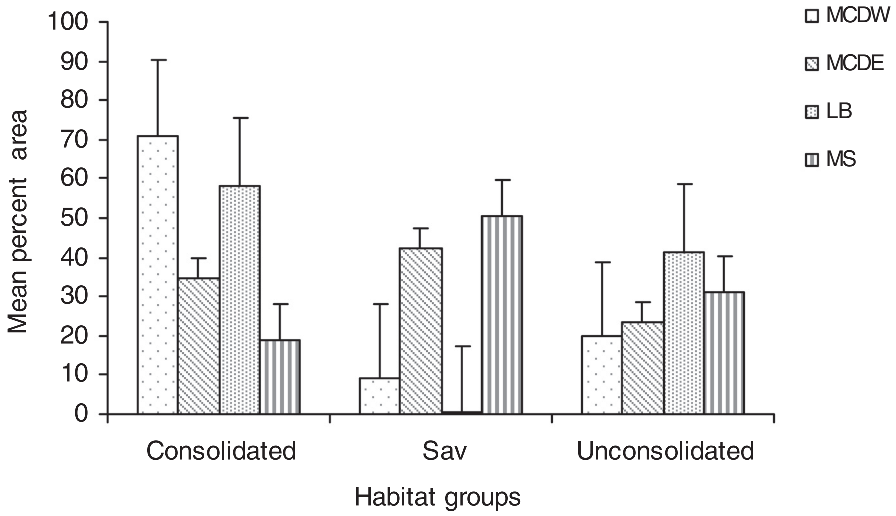


Figure 4

Mean percent area for the three habitat groups in the mapped area. Error bars indicate one standard error.

Table 1

Hierarchical classification scheme of benthic habitats used to generate detailed habitat maps (Modified from Prada, 2002).

Meta-community	Community	Sub-community	Habitat types	Habitat Codes
Coral and gorgonians on consolidated sediments	corals	coral high relief	Continuous Corals	COCO
		coral patch	Coral Patch	COPA
		coral low relief	Coral Limestone	COLI
		gorgonian patch	Gorgonian Patch	GOPA
	gorgonians	Plains	Gorgonian Plains	GOPL
		elevated plains	Elevated Gorgonians	ELGO
Submerged Aquatic Vegetation (SAV) on unconsolidated sediments	seagrass	Seagrass	Dense Grass	DEGR
			Sparse Grass	SPGR
			Grass-Invertebrates	GRIN
			Grass Halo & Coral Patch	HALO
	macro-algae	algae on sand	Dense Algae	DEAL
			Sparse Algae	SPAL
			Algae & Invertebrates	ALIN
		algae on silt	Shallow Algae	SHAL
			Deep Algae	DEEP
Bare or mixed invertebrates on unconsolidated sediments	sand	coarse sand	Sand Invertebrates	SAIN
		Sand no Ripple	SANR	
			Sand Ripple	SARI
		fine sand	Fine Sand	FIMU
	silt	mud	Mud-Invertebrates	MUIN
			Mud Bare	MUBA
			Mud Reef	MURE

habitat classification maps at presumed AUV transect lines. Estimation of habitat classification accuracy for maps for the MS and LB areas could not be conducted, even at the qualitative level, due to lack of ground truth; consequently these maps may need correction.

Habitat polygons were visually delineated from a Viscon FV170, 40.8 cm LCD monitor with high contrast ratio (350:1). Habitat polygon classification is based on the texture, brightness, and shape of the benthic habitat features on the high resolution SSS imagery.

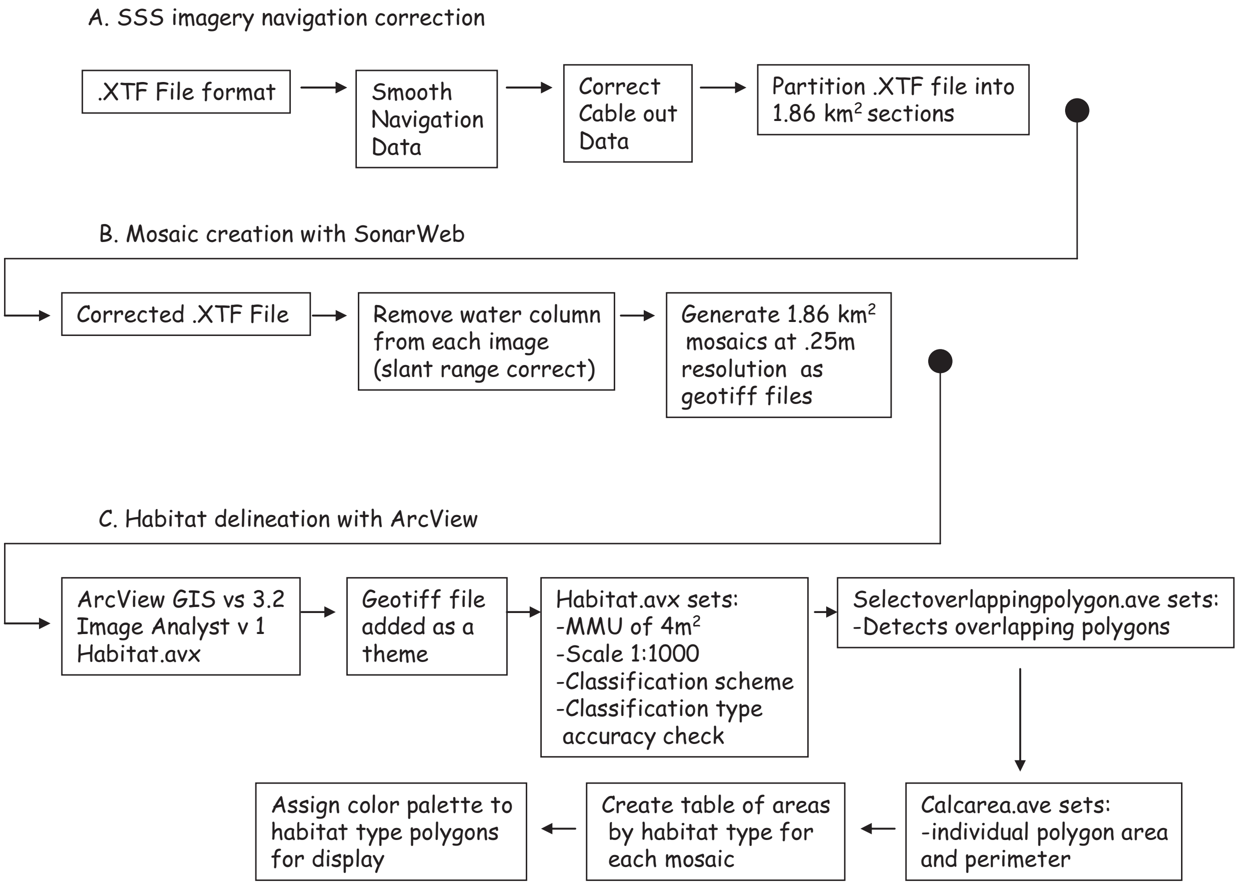


Figure 5

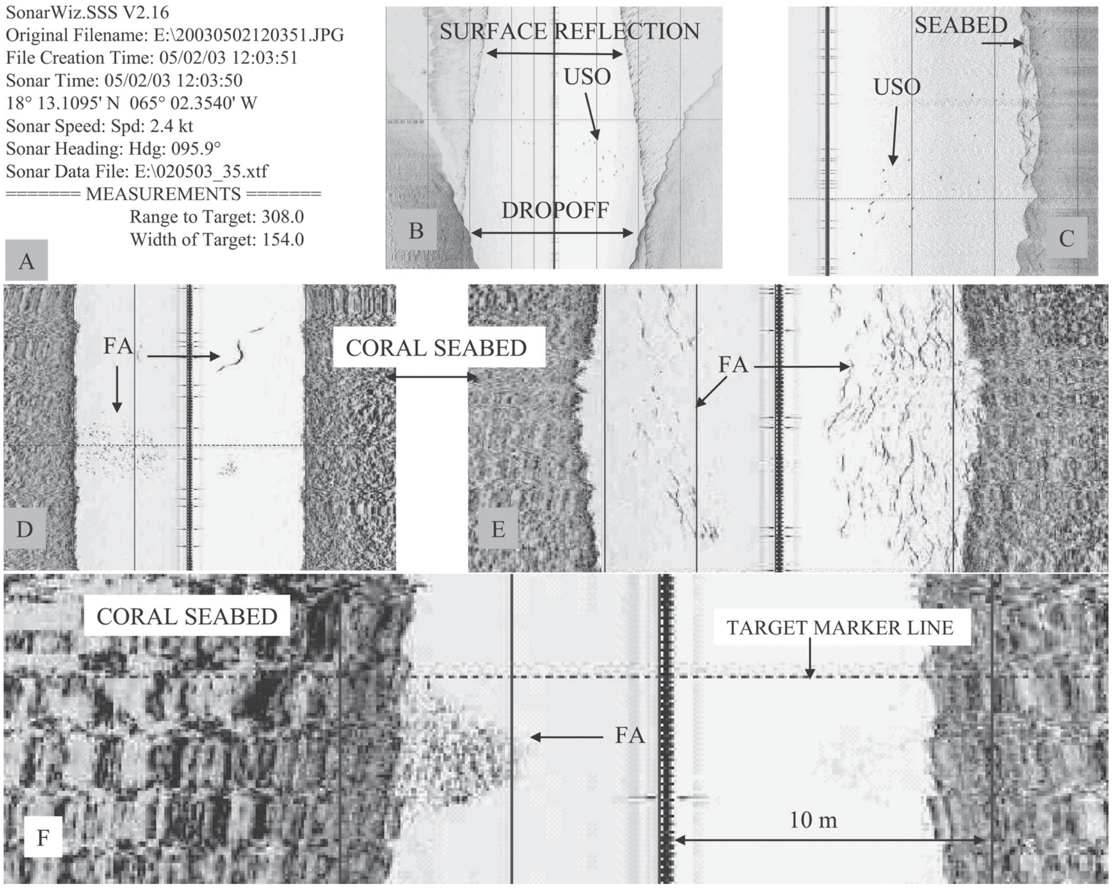
Flow diagram of SSS data processing procedures. A) SSS imagery navigation correction. B) Mosaic creation with SonarWeb. C) Habitat delineation with ArcView.

The interpreter's accumulated experience and ground truth information were also taken into account. Ground truth information consisted of a 1.10 hour digital video available for drift transects for MCDW (mosaics 2, 3, 4, 5, 6) and MCDE (mosaics 2, 3) which covered a total length of approximately 2.3 km. In addition, high resolution underwater pictures (foot print of 2 × 2 m) taken by an AUV were provided by the CFMC for four 1 km transect lines at MCDW (mosaics 1, 2, 10) and MCDE (mosaics 6, 7).

Data processing of the SSS habitat survey data involved a series of events in order to differentiate habitat types according to prescribed classifications and to isolate water column signals that would represent individual fish or aggregations of fish (Fig. 5). Prior to initiating the digitizing process, within the Habitat extension a Minimum Mapping Unit (MMU) of 4 m and an image scale of 1:1000 was defined. At the end of digitization of each image mosaic, resulting small polygons were joined if they shared a boundary and had the same classification type. Habitat type classification accuracy was checked utilizing the Habitat extension routine. Overlapping polygons (generated after polygon junction) were detected by running the ArcView script SelectOverlappingPolygons2.ave. Once detected, overlapping polygons were separated to ensure the correct habitat type classification. The use of the Calcacre.ave ArcView script allowed inclusion of individual polygon area and perimeter into the map's attribute table.

Processing of fish signals

As the SSS data was being displayed and acquired by SonarWiz, two viewers made a visual inspection of all water column echo returns. Every time an echo suggesting fish was detected in the water column, the signal was saved as a target image in "jpg" format. In addition to the raster image, an ancillary text file was also saved simultaneously containing image position, name and saved location information (e.g., Fig. 6).



SonarWiz.SSS V2.16
Original Filename: E:\20030502120351.JPG
File Creation Time: 05/02/03 12:03:51
Sonar Time: 05/02/03 12:03:50
18° 13.1095' N 065° 02.3540' W
Sonar Speed: Spd: 2.4 kt
Sonar Heading: Hdg: 095.9°
Sonar Data File: E:\020503_35.xtf
======= MEASUREMENTS =======
Range to Target: 308.0
Width of Target: 154.0

Figure 6

Example of unidentified swimming objects (USO) and fishing aggregations (FA) target images and ancillary text file with position and reference information. All images are from MCDW and MCDE. A) Ancillary text file with position and reference information. B) Port and starboard transducer SSS image record separated by center black line. USO's are represented by black dots. Image is from MCDW at shelf drop off. C) USO target image from right SSS transducer only to provide more detail. D) FA signal patterns pointed out by arrows. Benthic habitat is primarily flatten coral plate (*Montastrea spp.*). E) Undulating fish signals indicate swimming movement relative to SSS transducer. F) Bell shaped FA pointed out by arrow. Target marker line is correlated with target data file for locating position.

At the end of each data collection day, fish target image files were cataloged by date and survey line number. After cataloging, each target image was visually inspected to verify that the signal saved was a possible fish signal return. The cataloged ancillary target image text files were then transferred into an Excel spreadsheet in preparation for spatial analysis. All geographic positions were converted into UTM 83 Zone 20 northing and easting grid values for plotting in the GIS using the geodetic conversion software Tralaine (version 5.17, Mentor Software, Inc., Golden, Colorado). The coordinates for each target file were then plotted as a point overlay on available habitat maps. Using the Geoprocessing tool in ArcView, information on habitat was introduced into the point attribute table. This allowed estimation of the total number of USOs and fish aggregations (FAs) by habitat type. Some points had no benthic habitat classification because their position placed them on the shelf edge; these were classified as shelf edge (Table 1). Some target files contained more than one FA; therefore number of locations may differ from the number of FAs.

Individual FAs were digitized from georeferenced target files using ArcView. These target files raster images were transformed from .jpg format to .bmp format in order to permit ArcView to process them. A pixel size of 0.15 m was specified for all target files into the final text file containing the georeference. The whole dataset of FAs was then divided into four subsets to match their respective locations: MCDW, MCDE, LB, and MS. Bathymetry and habitat maps were also parsed by location.

Digitizing of each FA signal area was performed at a scale of 1:1000 (same as that generated for habitat maps). It was not possible to estimate FA density based on fish counts within a FA image mainly because resolution was lost in raster transformation and in some cases the fish density was too high to permit discrimination of individual fish signals. Calculation of FA signal area was then obtained by running an ArcView Script (Calcacre.ave) on the delineated and digitized polygon file. The attribute tables of all the polygon files created for the four studied areas were copied into an Excel worksheet for statistical analysis. Georeferencing of the FAs may not be as precise as bathymetry or SSS data, since a target file position is referenced to the first raster line of the image; however, the FA position will be within 10 m of the target file reference position.

Results

Location of mapped areas

In total, more than 800 km (average of 30 km of line per day) of line survey were run to collect the bathymetry and side-scan sonar data. The total area covered by the bathymetric survey was approximately 18 km^2. Slightly less coverage was obtained with the SSS due to the entanglement of SSS transducer with surface buoys from fish traps, affecting collection of imagery for partial areas of LB and MS.

Bathymetry

All three mapped areas were split into a series of 1.86 km^2 sections. This resulted in the generation of 19 sections for the MCD, 6 sections for LB, and 3 sections for MS. The final processed bathymetry data consisted of depth grids at 1 m resolution which, in our opinion, represented the optimal resolution obtainable from the data. The final maps displayed the one-meter grids using a color depth coding scheme and sun-illuminated overlay. Complete details about paper map products can be obtained from a report by Geophysics GPR International, Inc[3]. The color table used is based on a histogram equalization scheme, and therefore was not linear, but the smallest color interval was 0.2 meters. Each of the color maps has a printed color scale bar for interpretation purposes. These maps were produced at a scale of 1:10,000 (Figs. 7 and 8).

Side scan sonar mosaics

The final processed SSS mosaics were produced utilizing the software SonarWeb. Each SSS mosaic represented a 1.86 km^2 section of the seabed which matched the equivalent bathymetric section. The mosaics were exported as geo-referenced geotiff files, and imported into Oasis Montaj (version 5.1.7, Geosoft, Inc., Toronto, Canada) where they could be placed on the background coordinate grid and printed as a final product. The mosaics were re-processed at 1 m resolution for printing. The mosaics were produced using the SonarWeb color scheme "Brown" with a 5% contrast setting. In this scheme, black represents low backscatter strength, and light brown represents high backscatter strength.

Habitat classification

Eleven of the 23 habitat types of the classification scheme used by Prada (2002) were found at the mapped areas. See Table 1 for details of the classification scheme and Table 2 for acreage summary by habitat type. The complementary set of 28 habitat classification digital maps covered a total of 5462.3 ha, with the MCDW accounting for 45% of that area, MCDE for 26%, LB for 17%, and MS the remaining 13%.

With the exception of MS, corals and gorgonians on consolidated habitats were significantly more abundant than submerged aquatic vegetation (SAV) on unconsolidated sediments or unconsolidated sediments alone, as shown in Table 1. Continuous coral habitat was the most abundant consolidated habitat for both MCDW and MCDE (41% and 43% respectively). The LB and MS areas had consolidated habitats predominantly consisting of gorgonian plain habitat (95% and 83% respectively). Coral limestone habitat was more abundant than coral patch habitat and was found near the shelf break in MS, MCDW, and MCDE. At LB, there was minimal coverage for either of those habitat types.

SAV habitats were the second most abundant habitat group in MCDW and MCDE, the most abundant in MS, and almost non existent in LB. Unconsolidated habitats were present in all areas but not dominant anywhere (Table 2, Fig. 9).

Position of fish signals

A total of 671 fish signal target files were saved for the entire mapped areas (Fig. 7 and 8). Within each target

---

[3] Geophysics GPR, International, Inc. 2003, Marine Habitat Mapping Offshore St. Thomas & St. Croix, USVI EEZ. M-03704. Report to the Caribbean Fisheries Management Council, 30 p., maps plus appendixes, 2 volumes. Caribbean Fisheries Management Council, 268 Muñoz Rivera Ave., Suite 1108, San Juan, PR 00918-2577.

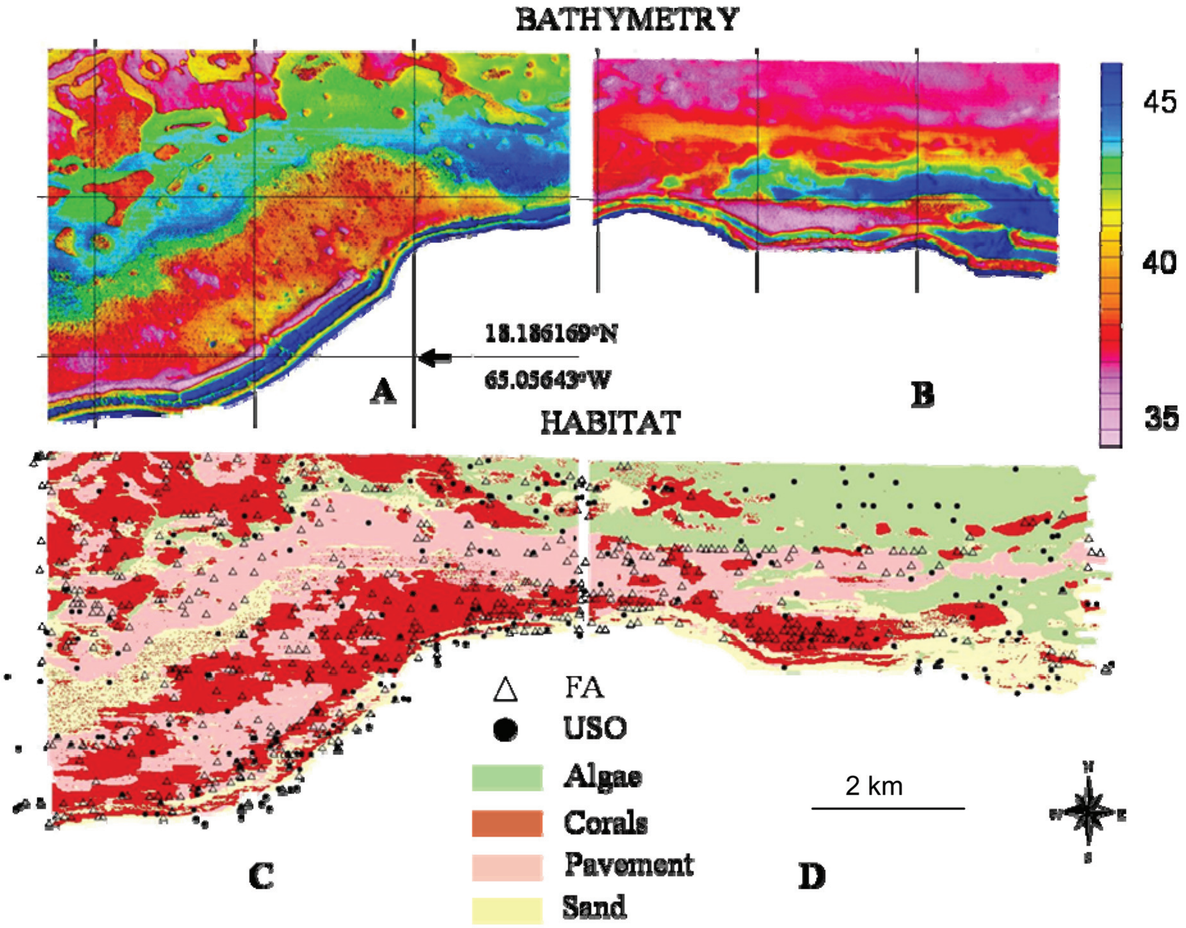


Figure 7

Bathymetry, habitat classification and fish signal positions for the MCDW and MCDE south of St. Thomas. A) MCDW, bathymetry color scale denotes depth in meters. B) MCDE. C) MCDW, habitat types; pavement denotes coral communities and gorgonians. Fish signals classified as fish aggregations (FA) are represented by triangles, black circles represent unidentified swimming objects (USO). D) MCDE. Scale is 1:40,000.

file, fish signals were classified into two categories. If the fish signal was large and isolated, it was identified as a unidentified swimming object (USO). If the fish signal was a pattern of echoes forming an aggregation or school of fish it was identified as a fish aggregation (FA). Most of the identified target files were found in the water column portion of the SSS signal return, usually within the first 20 m of the 50 m SSS channel range. Fish aggregations were either vertically or horizontally oriented. We made no distinction between these patterns of aggregation in this study.

The majority of the FA's positions were located over continuous coral, gorgonian, and sand habitat types (Fig. 9). FAs were also common over the shelf edge or drop off. The majority of USOs were located over sand and shelf edge habitat types, although they were also common over continuous coral and gorgonian habitat types. The highest density of FAs were found in the MCDW and MCDE locations; LB and MS densities were about five times smaller (Fig. 10). USO's densities were similar at all the locations (Fig. 10). The mean FA signal areas were similar between MCDW, MCDE, and LB. However, the mean FA signal area for MS was significantly smaller than the other three locations (Fig. 11).

Discussion

Most single vertical beam sounders used to interpret fish signals have beamwidths of 6–30° and at times undersample the ensonified sea bottom compared to an SSS (Misund et al., 1996). The SSS has a narrow fore-

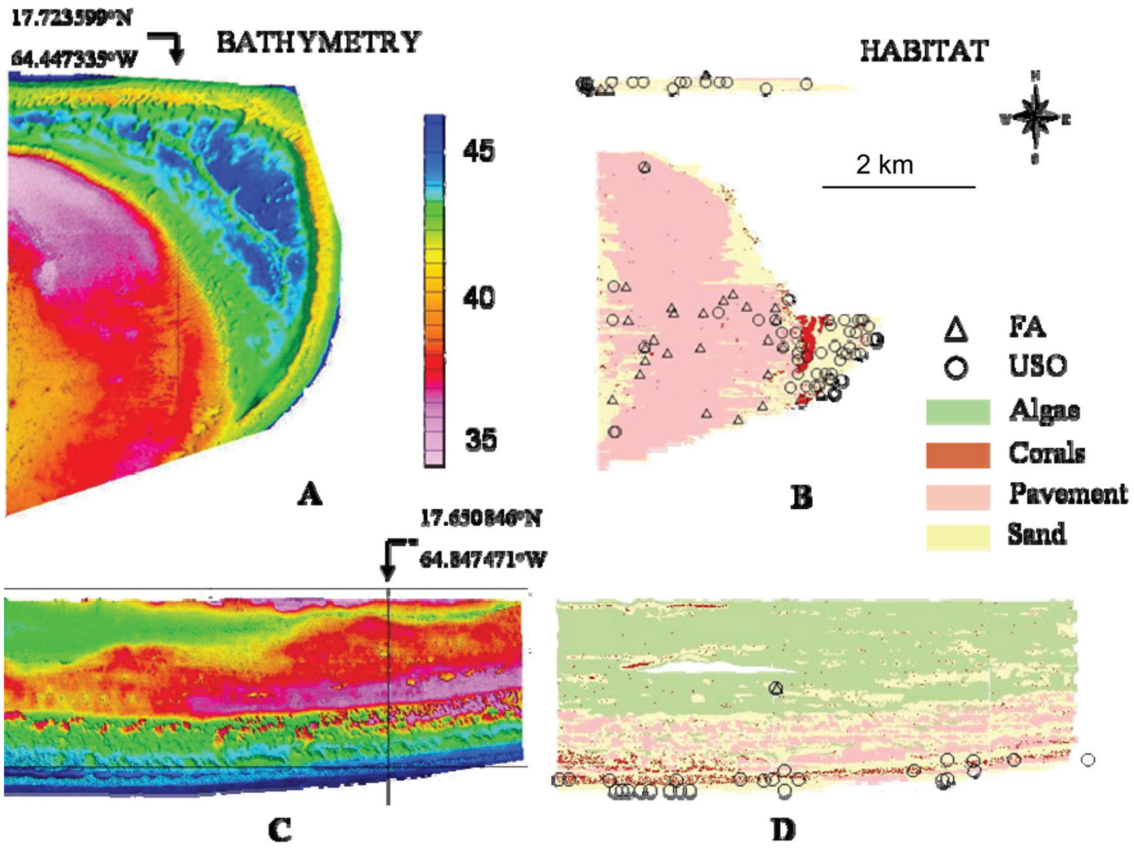


Figure 8

Bathymetry, habitat classification, and fish signal positions for the LB and MS southwest and east of St. Croix respectively. A) LB, bathymetry color scale denotes depth in meters. B) LB, habitat types; pavement denotes coral communities and gorgonians. Fish signals classified as fish aggregations (FA) are represented by triangles, circles represent unidentified swimming objects (USO). C) MS, bathymetry. D) MS, habitat types. White backgrounds within habitat map boundary denote lack of SSS imagery. Scale is 1:40,000.

aft beamwidth of 2° and a wide vertical beam of 20–30° extending to each side of the transducer. These characteristics enable it to resolve short horizontal wavelengths even at long ranges. The backscatter obtained from an SSS facilitates seabed characterization. To effectively use SSS systems, slower sampling vessel speeds (in the order of 3.5 to 5 knots) usually are required to ensure adequate resolution and sampling. Newer models are able to maintain resolution at higher speeds (ca. 5 to 8 knots). The larger sweep area of the SSS also enhances its efficiency in locating water column fish aggregations compared to single vertical beam systems.

A disadvantage of the SSS is that one usually cannot obtain fish species identification from the return acoustic signal, although sometimes one can identify the characteristic shapes of species if the range and resolution of the imagery are appropriate. This is due primarily to the lack of transducer calibrated backscattering strength data (Hammerstad[4]). Also, one normally needs either a vessel platform or an AUV on which to stage a SSS system. Sonar imagery cannot be collected independent of these platforms very easily. Processing SSS imagery requires a minimal amount of expertise and specialized software. Unlike low frequency single beam sounders, high frequency SSS signals cannot penetrate to great ranges in the water column. However, in deep water, one can usually lower the SSS transducer to the required depth by paying out wire from the cable winch aboard the vessel or by programming an AUV for the desired depths. Future research needs to address a more automated quantitative method of correctly classifying SSS acoustic signals to infer habitat designations.

---

[4] Hammerstad, E. 2000. EM technical note: backscattering and seabed image reflectivity. Kongsberg maritime products, hydroacoustics, underwater vehicles and systems, echosounders, multibeam related links at http://www.km.kongsberg.com.

Table 2

Total area (ha) of benthic habitats for MCD, LB and MS. Habitat codes as presented in Table 1.

SITE	COCO	COPA	COLI	GOPA	GOPL	ALIN	DEAL	SPAL	SAIN	SANR	SARI	Total
MCD1W	47.7	3.9	3.1		49.4	60.3	1.1	48.9	28.0	2.3		244.9
MCD2W	37.1	13.0	2.3		125.5	15.4		15.2	39.4	5.9		253.8
MCD3W	37.1	13.0	2.3		125.5	15.4		15.2	39.4	5.9		253.8
MCD4W	47.3	6.1	5.8		95.6	25.0	0.1	44.1	30.1	7.3		261.3
MCD5W	34.4	3.1	6.4		67.9	0.4		6.9	62.2	4.5		185.8
MCD6W	106.3	2.9	8.4		141.2	0.7		2.4	85.2	1.6		348.7
MCD7W	169.4	6.6	0.8		107.7	0.1			26.0	4.7		315.3
MCD8W	82.7	26.7	4.5		36.9	0.0		0.5	18.8	13.8		183.8
MCD9W	60.3	2.4	2.0		41.3	0.0		0.0	21.7	3.8		131.5
MCD10W	84.0	2.6	0.0		103.9	0.1		0.6	25.1	6.4		222.7
MCD11W	21.1	2.6	0.0		18.7	0.0		0.0	14.6	6.8		63.9
Total MCDW	727.5	83.0	35.6		913.4	117.3	1.2	134.0	390.4	63.0		2465.5
MCD1E	47.7	3.9	3.1		49.4	60.3	1.1	48.9	28.0	2.3		244.9
MCD2E	5.2	3.2			45.6	76.0	1.0	103.8	10.8	0.2		245.8
MCD3E	15.9	2.3			29.2	73.9	2.3	112.1	8.8	0.5		245.2
MCD4E	3.2	0.8			8.7	12.5		17.3	2.8	0.1		45.4
MCD5E	35.4	2.0	0.1		58.4	0.2		2.1	20.1	19.6		137.9
MCD6E	84.6	2.1	0.1		52.5	7.0	0.2	11.7	28.4	24.5		211.0
MCD7E	20.6	8.2			7.4	45.5	0.2	28.8	46.7	69.3		226.8
MCD8E	2.2	3.5				4.5		10.5	10.8	13.9		45.5
Total MCDE	214.8	26.1	3.3		251.2	279.9	4.9	335.2	156.4	130.4		1402.4
LB1		0.3	0.6		105.2	0.7			32.7	11.9		151.4
LB2					3.4	0.4			11.9	3.1		18.8
LB3		0.5	0.1	0.6	285.2				49.2	1.3		336.9
LB4	9.5	0.9	10.1		49.4				36.2	24.9		131.0
LB5	0.0	0.3		0.3	163.2				29.0	5.7		198.6
LB6	3.2	0.6	0.3	0.5	22.0				28.7	9.9		65.1
Total LB	12.7	2.7	11.1	1.4	628.4	1.1			187.8	56.8		901.9
MS1		3.3	10.0		35.5	149.8	2.0	3.8	74.3	17.6	0.0	296.3
MS2		1.1	3.8		46.1	144.8	0.7	7.9	66.3	18.8	0.1	289.5
MS3		0.3	1.9		21.2	46.7	0.1	2.0	22.3	11.8	0.3	106.6
Total MS		4.7	15.6		102.9	341.3	2.8	13.6	162.9	48.2	0.4	692.4

This would expedite data processing time, providing an economic incentive to collect SSS data by resource managers that need this type of information.

Development of methods for the identification of fish species needs to be encouraged. Species target strength determinations need be made for as many reef inhabiting species as possible, to provide the acoustic signal strength criteria for unambiguous identification. The use of multiple or broadband frequency sonars have the potential to aid in resolving species identification problems (Fleisher[5]). The integration of video imagery or sonar imagery of near video quality collection synoptically with either SSS or calibrated fish finders when performing surveys can provide dynamic visual information essential to fish species identification not available with static acoustic means alone. More research on fish species daily water column movement patterns can help sort out species identification conflicts by incorporating information about species preferred depth strata behaviors. Tagging known species with acoustic tags could also be used as method of identifying the tracked location of the known species in reference to the fish that surround it. This can help identify similar acoustic or echo signal shapes as same species. Incorporating hydrophone techniques to collocate fish emitted sounds with acoustic tag tracking can also help improve species identification for more cryptic inhabiting species (Berk, 1998; Evans and Norris, 1993) by helping to correlate emitted sound position with tagged fish position.

Future research will focus on elucidating the species identification of USOs and FAs through acoustic target strength characterization with in situ verification by

---

[5] Fleischer, G. W., 2005. Personal commun. NOAA, NMFS, 2725 Montlake Blvd. East, Seattle, WA 98112

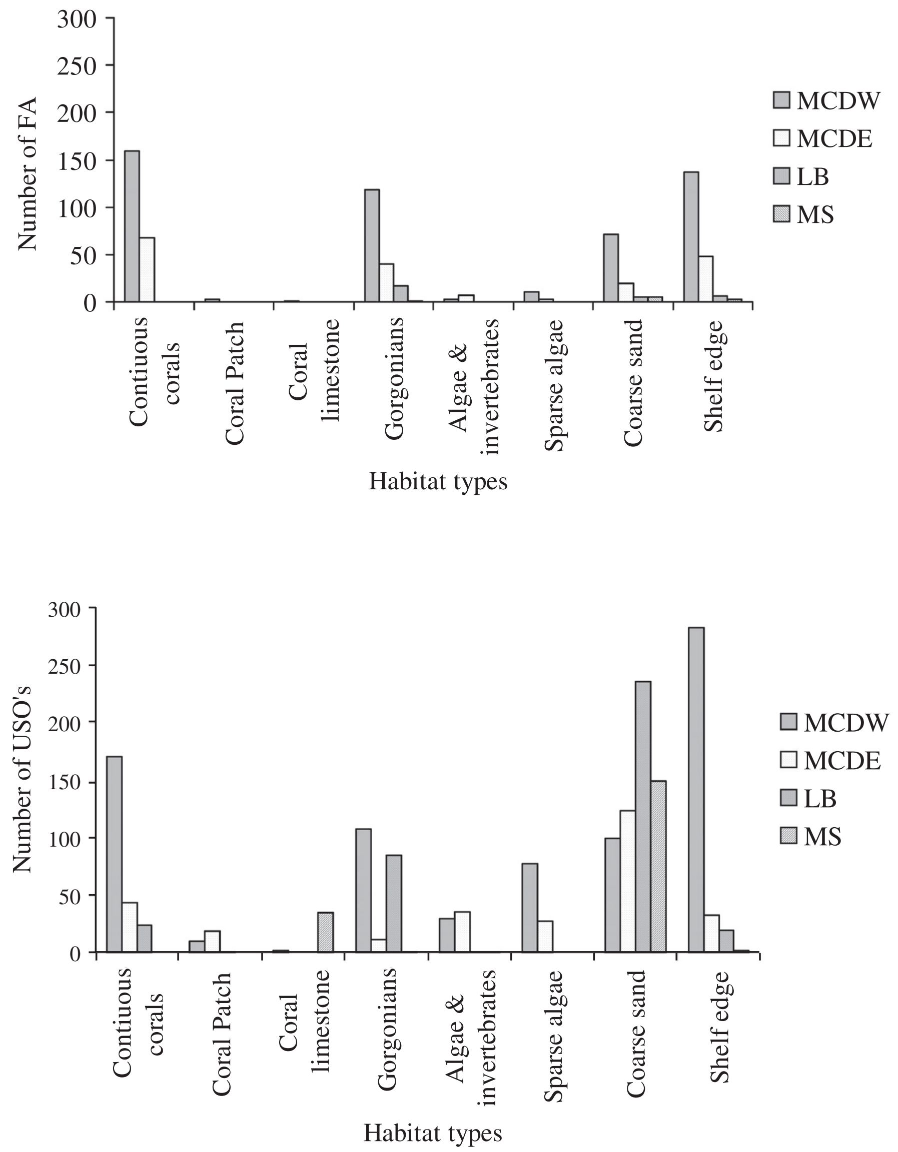


Figure 9

Top: fish aggregations frequency distribution by habitat type for all study areas. Bottom: unidentified swimming object (USO) frequency distribution by habitat type for all study area sites. Only 60% of LB was mapped with SSS.

video observations. We currently suspect that USOs may be echoes from turtles since the sampling period coincides with their nesting season and the intensity of the acoustic signal appears roughly consistent with a turtle body size (Rivera and Arsenault[6]). However, the echoes could also be from Cubera snappers (*Lutjanus cyanopterus*) which have been reported for the MCDW and MCDE locations of the study area by Beets and Friedlander[7]. This same species has been also reported to aggregate for reproduction at the Grammanic Bank just east of the MCDE sampling area at the same sam-

---

[6] Rivera, J. A., and J. Arsenault, 2003. Unpublished data. See author address for data access.

[7] Beets, J., and A. Friedlander, 1997. Evaluation of the Spawning Aggregation for Red Hind (*Epinephelus Guttatus*), St. Thomas, US Virgin Islands. Report to the Caribbean Fisheries Management Council, 268 Munoz Rivera Avenue, Suite 1108, San Juan, Puerto Rico, 00918-2577, 26 p.

[8] Whitman, E., 2004. Personal commun. Center for Marine and Environmental Studies, University of the Virgin Islands, St. Thomas, USVI 00802-9990.

pling period as this study (Whitman[8]). Cubera snapper size (1–1.5 m) also fit the derived length from the echo signal shape.

While producing a benthic habitat map of three federal jurisdiction fishery management areas with SSS technology, we were able to obtain relative fish density indices by habitat. At little incremental cost, these indices provide fishery managers with resource insights not previously available. Specifically, for our survey, the largest FA densities were located at MCDW and MCDE over coral communities that occupied up to 70% of the benthic habitat. USO's densities were similar for the differing locations with highest densities primarily over sand and shelf edge areas. FA's school size was significantly smaller at MS than the other three locations (MCDW, MCDE, and LB).

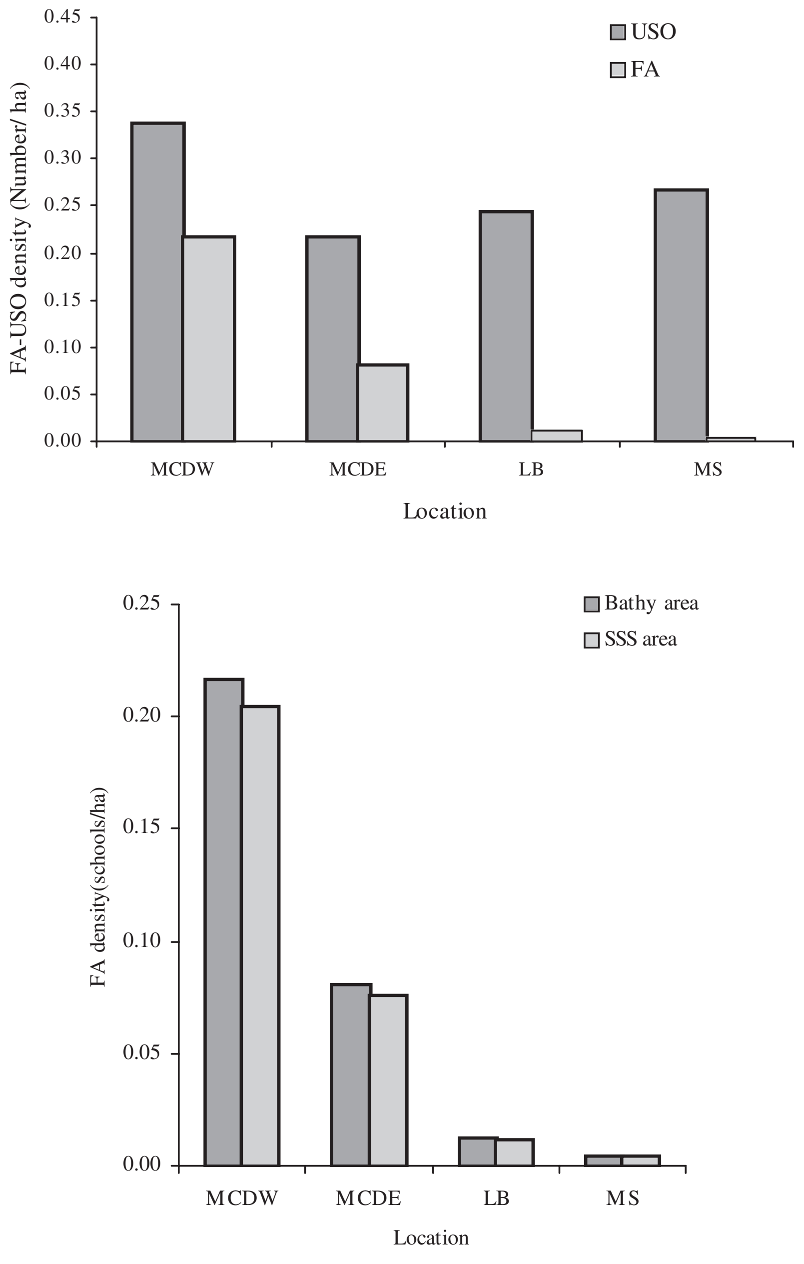


Figure 10

Top: FA's density by location total mapped area. Bottom: unidentified swimming object (USO) density estimates by location. Only 60% of LB was mapped with SSS. Area in hectares (ha).

Acknowledgements

We thank NOAA Fisheries through their Coral Reef Initiative for grant number NA17FC2204 to the Caribbean Fishery Management Council, which funded the habitat mapping study providing data for this paper. This research would not have been possible without the collaboration and able help of Mike and Cindi Clemens, USVI Enforcement Officer Oliver Christian, U.S. Coast Guard Chief Petty Officer Joseph Restle, sonar winch troubleshooter Harry Jacobs, and base station tender Hap Starr. William Tobias from the USVI Department of Planning and Environmental Resources, Division of Fish and Wildlife, provided much appreciated logistics support with winch parts in St. Croix. The St. Croix Yacht Club allowed us use of pier space to help support our logistics. Hanumant Singh, Roy Armstrong, and Graciela Garcia made available the AUV imagery which assisted with ground truthing the SSS imagery. We thank Christopher Taylor for his initiative, patience, and effort in chairing the special session in acoustics during the 56th Annual Meeting of the Gulf and Caribbean Fisheries Institute which resulted in this publication.

Literature cited

Arono, R., and R. Gould.
1998. Coastal monitoring using ocean color, inverting ocean reflectance into water properties, coastal interactions; satellite sensor advances stimulated algorithm, data management development. Sea Technology, September, p. 18–27.

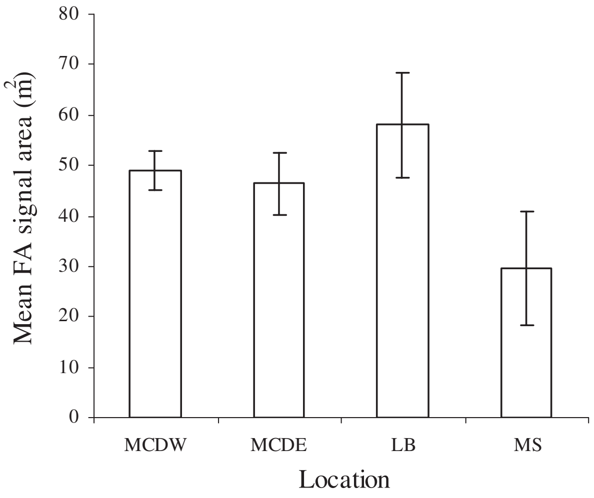


Figure 11

Mean Fish Aggregation (FA) signal area (m^2) for each location. Error bars indicate standard error.

Berk, I. M.
1998. Sound production by white shrimp (*Penaeus setiferus*), analysis of another crustacean-like sound from the Gulf of Mexico, and applications for passive sonar in the shrimping industry. J. Shellfish Res., 17(5):1497–5000.

Evans, W. E., and J. C. Norris.
1993. The potential role of passive sonar in fisheries resource evaluation. *In* Recent Advances in Marine Science and Technology, 92, N. Saxena (ed.), p. 423–432. PACON International, Honolulu, HI.

Fish, J. P., and H. A. Carr.
1990. Sound Underwater Images. Lower Cape Publishing, Orleans, MA, 189 pages.

Friedlander, A. M., G. W. Boehlert, M. E. Field, J. E. Mason, J. V. Gardner, and P. Dartnell.
1999. Sidescan-sonar mapping of benthic trawl marks on the shelf and slope off Eureka, California. Fish. Bull. 97(4):786–801.

Gordon, H., and M. Wang.
1994. Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWIFS: a preliminary algorithm. Applied Optics 33:443–452.

Kantor, M., D. J. Baker, and R. A. Schmitten.
1996. Magnuson-Stevens Fishery Conservation and Management Act. NOAA Tech. Memo. NMFS F/SPO-23, 121 p.

Karl, H. A., W. C. Schwab, A. St. C. Wright, D. E. Drake, J. L. Chin, W. W. Danforth, and E. Ueber.
1994. Acoustic Mapping as an Enviromental Management Tool: I. Detection of Barrels of Low-Level Radioactive Waste, Gulf of the Farallones National Marine Sanctuary, California. Ocean and Coastal Management 22:201–227.

Klepsvik, J, M. Bjarnar, P. Broarstad, D. Braend, and H. Westrum.
1994. A novel laser radar system for sub-sea inspection and mapping. Oceans 2:700–704.

Lee, Z., K. Carder, S. Hawes, R. Steward, T. Peacock, and C. Davis.
1994. Model for the interpretation of hyperspectral remote-sensing reflectance. Applied Optics 33:5721–5732.

Lizenga, D.
1978. Passive remote sensing techniques for mapping water depth and bottom features. Applied Optics 17:379–383.
1981. Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. Int. J. Remote Sensing. 2:71–82.

Misund, O. A., A. Aglen, J. Hamre, E. Ona, I. Rottingen, D. Skagen, and J. W. Valdemarsen.
1996. Improved mapping of schooling fish near the surface: comparison of abundance estimates obtained by sonar and echo integration. ICES J. Mar. Sci. 53:383–388.

Mumby, P., C. Clark, E. Green, and A. Edwards.
1998. Benefits of water column correction and contextual editing for mapping coral reef. Int. J. Remote Sensing. 19(1):203–210.

Ochiai, A.
1957. Zoogeographical studies on the soleoid fishes found in Japan and its neighboring region. Bull. Japan Soc. Sci. Fish. 22:526–530.

Prada, M. C.
2002. Mapping Benthic Habitats on the South West of Puerto Rico as determined by Side Scan Sonar. PhD dissert. University of Puerto Rico at Mayaguez, Department of Marine Sciences. 175 p., 5 app., 4 CD-ROMs with map data.

Roesler, C., and M. Perry.
1989. Modeling in situ phytoplankton absorption from total absorption spectra in productive inland marine waters. Limm. Oceanogr. 34:1510–1523.

Siljestrom, P. A., J. Rey, and A. Moreno.
1996. Characterization of phanerogram communities (*Posidonia oceanica* and *Cymodocea nodosa*) using side scan-sonar images. J. Photogramm. Remote Sensing 51:308–315.

Appendix A

Parameter Report

System	Parameter	Value
Geoswath system	Roll offset (positive starboard horizon)	0.98°
	Pitch offset (positive aft horizon)	–0.05°
	Yaw (heading) offset relative to gyrocompass	2.93°
	Time latency (s)	< 0.01
	Transducer draft from static waterline	1.14 m
	System frequency	250 kHz
	Swath width (average)	60 m
	Pings per second (average)	9
RTK GPS system	Main antenna offset (starboard positive))	0.91 m
	Main antenna offset (forward positive)	0.98 m
	Main antenna offset (height above SWL)	5.51 m
	Time latency (s)	0.02
	Position update rate	5 Hz
RTK Radio Modem	Effective baud rate	4800
Side-scan sonar system	Frequency	100/500 kHz
	Horizontal beam width	1°/0.2°
	Slant range	50 m
	Gains: Auto CPU return & offset, Att. STBD & PORT	7,9,A,A
Sonarwiz DAQ	Digitizing rate	66 kHz
	Resolution	16 bit

Survey Equipment List

No.	Item	Manufacturer	Model
1	Swath echo-sounder system	Geoacoustics Ltd. (UK)	Geoswath
2	Side-scan sonar system, 500kHz	Klein Sonar Inc. (USA)	595
3	Sonarwiz data acquisition system	Chesapeake Technology (USA)	N/A
4	Sound velocity probe	Valeport Ltd. (UK)	Soundbar
5	Motion reference unit	TSS Ltd. (UK)	DMS-05
6	Gyrocompass	TSS Ltd. (UK)	Meridian surveyor
7	Electric winch for sonar	Sea Mac Inc. (USA)	EM-302
8	RTK GPS system	Trimble Inc. (USA)	5700
9	Radio modem system for RTK GPS	Pacific Crest Corp. (USA)	RFM96W
10	Navigation software	Coastal Oceanographics (USA)	Hypack Max (v02.12)

Processing Software List

No.	Item	Manufacturer	Name & Version
1	Side-scan sonar data processing	Chesapeake Technology (USA)	SonarWeb Pro (v3.15G)
2	Bathymetry data processing	Geoacoustics Ltd. (UK)	Swath32 (v2.17s)
3	Data presentation software	Geosoft Inc.(Canada)	Oasis Montaj (v5.1.7)

Abstract—Functional linkage between reef habitat quality and fish growth and production has remained elusive. Most current research is focused on correlative relationships between a general habitat type and presence/absence of a species, an index of species abundance, or species diversity. Such descriptive information largely ignores how reef attributes regulate reef fish abundance (density-dependent habitat selection), trophic interactions, and physiological performance (growth and condition). To determine the functional relationship between habitat quality, fish abundance, trophic interactions, and physiological performance, we are using an experimental reef system in the northeastern Gulf of Mexico where we apply advanced sensor and biochemical technologies. Our study site controls for reef attributes (size, cavity space, and reef mosaics) and focuses on the processes that regulate gag grouper (*Mycteroperca microlepis*) abundance, behavior and performance (growth and condition), and the availability of their pelagic prey. We combine mobile and fixed-active (fisheries) acoustics, passive acoustics, video cameras, and advanced biochemical techniques. Fisheries acoustics quantifies the abundance of pelagic prey fishes associated with the reefs and their behavior. Passive acoustics and video allow direct observation of gag and prey fish behavior and the acoustic environment, and provide a direct visual for the interpretation of fixed fisheries acoustics measurements. New application of biochemical techniques, such as Electron Transport System (ETS) assay, allow the in situ measurement of metabolic expenditure of gag and relates this back to reef attributes, gag behavior, and prey fish availability. Here, we provide an overview of our integrated technological approach for understanding and quantifying the functional relationship between reef habitat quality and one element of production – gag grouper growth on shallow coastal reefs.

Integration of technologies for understanding the functional relationship between reef habitat and fish growth and production

Doran M. Mason
NOAA Great Lakes Environmental Research Laboratory
2205 Commonwealth Blvd.
Ann Arbor, MI 48105
email: Doran.Mason@noaa.gov

Brian Nagy
Mark Butler
Stephen Larsen
Debra J. Murie
William J. Lindberg
Department of Fisheries and Aquatic Sciences
University of Florida
7922 NW 71st Street
Gainesville, FL 32653-3071

Introduction

The Sustainable Fisheries Act of 1996 and the amended Magnuson-Stevens Fishery Conservation and Management Act elevated habitat and conservation as priorities in federal fisheries management. In particular, the Essential Fish Habitat (EFH) amendment to the Magnuson-Stevens Fishery Conservation and Management Act establishes guidelines to assist fishery managers in the description and identification of EFH. Essential fish habitat is defined as ". . . those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity. . . . waters include aquatic areas and their associated physical, chemical, and biological properties that are used by fish, and may include areas historically used by fish where appropriate; 'substrate' includes sediment, hard bottom, structures underlying the waters, and associated biological communities; 'necessary' means the habitat required to support a sustainable fishery and a healthy ecosystem; . . ." Moreover, National Marine Fisheries Service (NMFS) guidelines call for analysis of EFH at four levels of detail: **Level 1** – the presence/absence of distributional data for some or all portions of the geographic range of a species; **Level 2** – habitat-related densities of a species; **Level 3** – growth, reproduction, or survival rates within habitats; and **Level 4** – production rates by habitat (see technical guidelines at: http://www.nmfs.noaa.gov/habitat/efh/). That is, the amendment and guidelines highlight a process-oriented framework and provide for using ecosystem concepts in the management of fisheries and aquatic habitats.

Much of the current research is focused on correlative relationships between general categories of habitat (e.g., sand, coral, hard live bottom, temperature, salinity) and the presence or absence of a species, a general index of species abundance, or species diversity (e.g., Minello, 1999; Packard and Hoff, 1999). Such descriptive information is consistent with NMFS EFH Levels 1 and 2, but largely ignores how reef attributes (complexity, size, cavity space) regulate reef fish abundance (e.g., density-dependent habitat selection), trophic interactions, and physiological performance (growth and condition) (Lindberg et al. 2006, Lindberg et al.[1]), that is, NMFS EFH Level 3. Statistical models have been developed using descriptive information as a baseline for managing habitat and fisheries (e.g., Rubec et al., 1999). However, such statistical models lack mechanistic understanding and a theoretical foundation, and as such, may fail unexpectedly and for unknown reasons.

Developing the statistical relationships between general habitat categories and fish presence, relative abundance, and diversity is an excellent start, but lacks the process-based understanding that comes from Levels 3 and 4 that ultimately allows us to fully develop predictive capabilities. Our long-term program goal is to develop this process-based understanding and to develop the capacity to predict fish production from reef habitat attributes. Such a goal is riddled with complexities, but the availability of emerging technologies may help to alleviate the otherwise intractability of those complexities.

Herein, we describe the suite of technologies that we are currently using to develop our quantitative understanding towards achieving our longer-term goal of prediction. In this paper, we focus on growth; other aspects of production (abundance, mortality, emigration, immigration) are also being addressed in our program (Lindberg et al, 2006) but are not the topic of this paper. Some of the techniques (i.e., mobile fisheries acoustics) we use are a part of fisheries assessment programs around the world. Other technologies (e.g., biochemical) have yet to be implemented for quantifying fish performance in response to reef attributes. Moreover, it is the integration of these technologies for understanding the fundamental relationship between reef habitat attributes and fish growth and production that is novel and innovative. Thus, the overall objective of this paper is to describe the technologies (with examples) and the integration of these technologies for gaining NMFS EFH Levels 3 and 4 understanding of reef habitat. First we provide background on our experimental system, and then we describe the suite of technologies being used to understand the habitat-fish production system.

Methods

Approach

Ours is an in situ experimental approach, with a focus on reef architecture and gag grouper (*Mycteroperca microlepis*). We define reef architecture as those physical attributes that characterize habitat quality; for gag these include vertical relief, cavity volume (volume of interstitial spaces), and aerial extent, with a potential secondary characteristic that includes proximity to neighboring reefs (i.e., reef mosaics across the landscape). We focus on gag grouper because of its economic and ecological importance, its dominance in our study region, and because characteristics of its life history, behavior, and ecology simplify testing key habitat relationships that may be of general management consequence for reef fisheries (Lindberg et al., 2006).

Our study site is the Suwannee Regional Reef System (SRRS), located in the northeastern Gulf of Mexico, which controls for reef attributes to evaluate limiting factors and habitat constraints to reef fish production (Lindberg et al., 2006). The SRRS is a unique large-scale experimentally manipulated reef system, consisting of 22 reef sites, with reef sites located about 24–29 km offshore and spaced about 2 km apart along the 12 m depth contour. Each reef site is made up of six patch reefs made of concrete. Patch reef complexity and composition is controlled, while patch reef spacing and size is manipulated (Fig. 1). All reefs within the SRRS have the same representation of environmental characteristics, especially with regard to temperature and salinity regimes. In addition, gag grouper on these reefs are within the same relative range of body size; all are juvenile-to-young-adult females (Lindberg et al., 2006) and show a strong site/reef fidelity (Kiel, 2004; Lindberg et al., 2006). Such an in situ experimental system provides a unique opportunity to quantify the role of habitat architecture in mediating fish performance (condition, physiology) and predator-prey interactions (gag and their pelagic fish prey), and thus gag growth and production.

Our past research has demonstrated an empirical relationship between reef size and total cavity space and the abundance, growth, and condition of gag on these reefs. As the size of the reef and total cavity space (volume) increases, gag numbers increase, but growth and condition declines (Lindberg et al., 2006). Given that growth and condition are bioenergetic processes, we structure our research about those processes that regulate consumption (trophic dynamics) and metabolic expenditures (activity). For growth and condition to decline on the larger reefs, either consumption has to decrease or metabolic expenditures must increase, or some weighted combination of both. This leads to a

---

[1] Lindberg, W. J., D. Mason, and D. Murie. 2002. Habitat-mediated predator-prey interactions: implications for sustainable production of gag grouper. Final Project Report (grant no. R/LR-B-49). Florida Sea Grant College Program. 60 p. http://www.glerl.noaa.gov/res/Task_rpts/Resources/edymason09-3projrpt.pdf [Accessed 1 August 2006.]

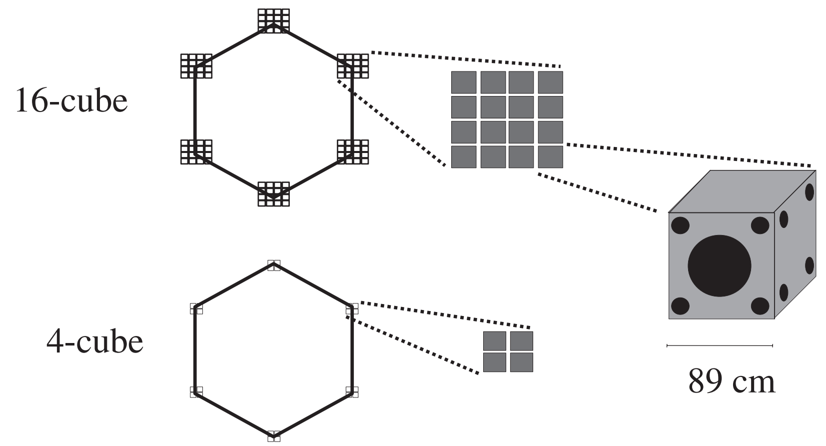


Figure 1

The Suwannee Regional Reef System is comprised of 22 experimental reef sites offshore from Cedar Key, Florida, along Florida's north-central Gulf coast. Hexagonal arrays of patch reefs are located at each reef site. Equal-sized patch reefs at each site are comprised of either 4 or 16 prefabricated concrete cubes, and the spacing between patches is 25 m, 75 m, or 225 m.

series of inter-related hypotheses that we are exploring in our research:

1) Reef architecture determines the abundance of gag and pelagic schooling planktivorous fishes, the principle prey of gag.
2) Abundance of gag and pelagic prey determines prey availability to gag and foraging efficiency of gag, and thus gag daily ration.
3) Abundance of gag and pelagic prey determines the metabolic expenditure of gag, where increased gag numbers may:
    a) Decrease the number of prey per gag, which directly decreases daily ration.
    b) Increase social interaction, which may increase energetic expenditures.
    c) Decrease foraging efficiency through interference causing an increased number of attacks, which may be energetically expensive.

These hypotheses follow a logical progression from how habitat regulates the abundance of gag and availability of pelagic prey fishes, the implications of predator and prey abundances on the bioenergetic efficiencies of foraging and metabolism for gag, and ultimately to growth and production. To address these specific hypotheses, we are simultaneously using several technologies including acoustics, video, and a biochemical technique. In this paper, we focus entirely on the technologies and the integration of these technologies to address the above hypotheses.

Technologies

Our integrated technological approach directly measures abundance, behavior, and physiological performance of gag in relation to reef attributes. We combine mobile and fixed active (fisheries) acoustics, passive acoustics, video cameras, and advanced biochemical techniques. Mobile and fixed fisheries acoustics quantifies the abundance of pelagic forage fishes with respect to reef size, as well as the behavior of pelagic prey fish and gag. Passive acoustics and video allow direct observation of gag and prey fish behavior relative to one another and to pelagic predators, and to the acoustic environment, and provide direct visual observations for the interpretation of fixed fisheries acoustics measurements. New application of biochemical techniques, i.e., Electron Transport System (ETS) assay, allow the direct in situ measurement of total metabolic expenditure of gag and relates this back to reef attributes, gag abundance and behavior, and prey fish availability. Below we provide details of each of the technologies and examples of their use.

Active fisheries acoustics We use mobile hydroacoustic surveys to estimate pelagic planktivorous (prey) fish abundance as a function of patch reef size (4 vs. 16 cube patch reefs) and to quantify inter-annual variability in pelagic prey fish densities. In this section, we provide an example of the application of this technology to address one of the above hypotheses, i.e., reef architecture determines the abundance of pelagic schooling prey

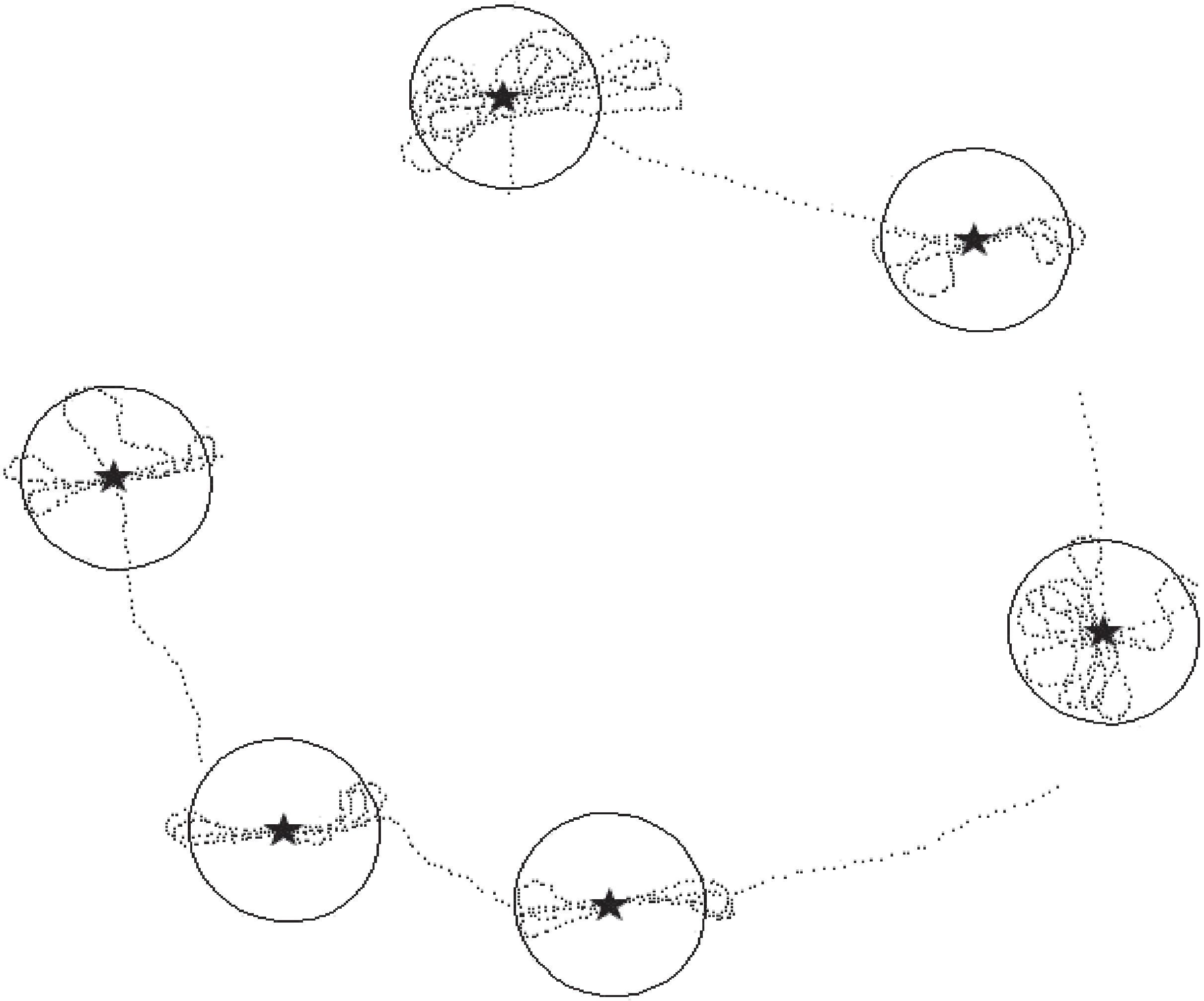


Figure 2

A reef array showing an acoustic transect (dotted line) and the 50-m radius buffers (large circles) over top of individual patch reefs (star) used for data collection and data selection.

fish. We used a 120 kHz split-beam echosounder (Simrad EY500, beam width = 7.2°, power setting = 63 W, pulse duration = 0.3 ms, ping rate = 3 pings s^{-1}), which consisted of a deck unit (echosounder), laptop for data acquisition, power source (12V DC battery), cable, and transducer. The acoustic transducer is mounted on a stable, 1.2 m towbody and towed alongside the research vessel at a depth of about 1 m and at speeds of 2.5–3.5 m s^{-1}. Acoustic transects traversed each patch reef at least five times from different directions to ensure full ensonification of any schools present (Fig. 2). Often times greater than five passes at a single patch reef is required to insure full ensonification above the reef for a minimum of five transects. Equipment performance is monitored in the field using the acquisition software, and raw digitized acoustic signals are time-marked and geocoded using a Global Positioning System (GPS; model: Garmin GPS 48) and saved for later processing. Calibrations are performed either before or after every cruise using a 33 mm diameter tungsten carbide reference sphere (Foote et al., 1987; Foote, 1990).

For our example here, acoustic data were processed using the Digital Echo Visualization and Information System (DEVIS) (Jech and Luo, 2000). DEVIS performs echo-squared integration (Powell and Stanton, 1983; Thorne, 1983) and split-beam analyses (Ehrenberg, 1983) to estimate absolute fish density. Echo-squared integration (vertically integrated from surface to bottom with S_v threshold of –70 dB) provided a quantitative relative measure of fish density that was scaled to

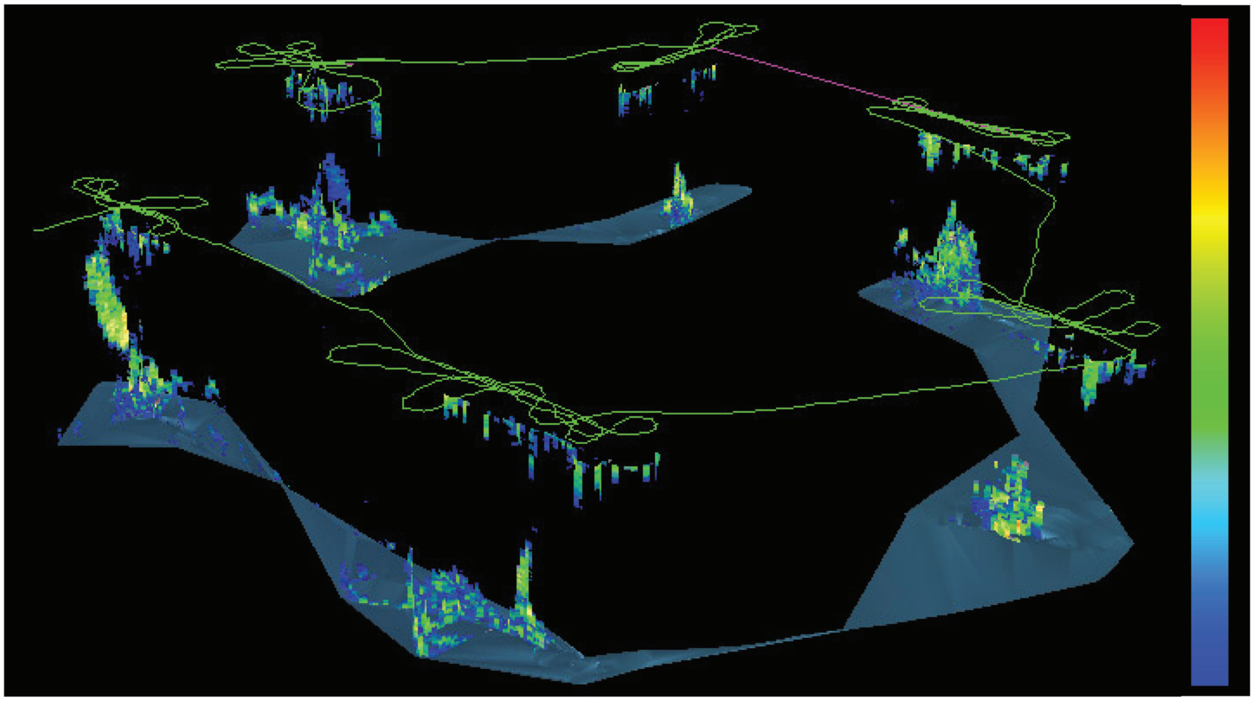


Figure 3

Three-dimensional rendering of a reef site showing acoustic backscatter of pelagic prey fish schools (mostly scaled sardines, *Harengula jaguana*) associated with each patch reef. Color represents intensity of backscatter with red being highest intensity (greatest biomass) and blue being lowest intensity (lowest biomass but not zero). Green line above the acoustic backscatter demarks the actual acoustic transect. Distance from the green line to acoustic backscatter on bottom (grayish) is range, where the distance from surface to bottom is 11 m. Purple line denotes movement between two patch reefs when the echosounder was not collecting data.

absolute fish density with system parameters obtained from equipment calibration and measures of the mean backscattering cross-section of the fish obtained from split-beam analyses. Split-beam analysis was used to determine the depth distribution of fish backscattering coefficients (σ_{bs}) and fish target strengths (TS), i.e., acoustic size. To identify single targets, we used a minimum TS detection threshold of –70 dB, minimum echo length of 0.8, maximum echo length of 1.6, maximum gain composition of 3.0 dB, and maximum phase deviation of 3.0°. Fish density (number m^{-2}) was determined by dividing the corrected sums of squared voltages from the echo-squared integration by σ_{bs}. Acoustic data were inspected for noise and bottom contamination before applying the mean backscattering cross-section to the echo-squared integration. Obvious grouper targets, if present, were removed from the analysis.

Acoustic data in a 50-m radius of any given patch reef were selected for the analyses (Fig. 2). This ensured that only fish associated with the patch reef were included in the analysis. Once the appropriate acoustic data were selected for each patch reef, we estimated fish density for each pass over the reef; the mean of these passes was used as the estimate of pelagic fish density. This provided a density estimate for each patch reef within a given reef array. Density estimates were not normally distributed, so all density values were $\log_{10}$ transformed. We used density estimates to test the hypothesis that pelagic forage fish density was similar between patch reefs of different sizes (4-cube vs. 16-cube reefs).

An example of day transects traversing all six patch reefs at a reef site is displayed in Fig. 3. Note the strong affinity of the fish schools to each patch reef and that for each patch reef there is a pelagic fish school. This pattern is common and consistent across all of our reef sites such that 99% of the patch reef sampled had pelagic schools of forage fishes associated with the reef.

Pelagic fish density was similar between patch reefs of different sizes (Fig. 4A,B). Random direct sampling and direct visual observations suggested that the pelagic prey fish were young of the year sardines (*Harengula jaguana* and *Sardinella aurita*).

Fixed fisheries acoustics Fixed-array acoustics are being used to measure pelagic prey fish schooling behavior and dynamics at patch reefs and to measure movement of gag at the reefs. The fixed array acoustic system consists of two transducers and two frequencies, 200 kHz (beam widths = 8°×14°, source level = 218 dB re μPa @ 1 m, pulse duration = 0.3 ms) and 420 kHz (beam widths = 6.7°×15°, source level = 215 dB re μPa @ 1 m, pulse duration = 0.3 ms) (BioSonics DE6000). Transducers are attached to two tripods, each equipped with a remote control rotator (Remote Ocean Systems PT-10) for fine scale aiming in both the horizontal and vertical dimension, and placed on the sea floor approximately 30 m from a patch and about 0.5 m off the bottom. Given the beam widths for each transducer, this provides an aerial coverage directly over the reef patch of 27 m^2 for the 420 kHz transducers and 30 m^2 for the 200 kHz transducers. This allows almost complete coverage of the water column above the patch reef. All transducers are cabled to a deck unit aboard a vessel anchored approximately 100 m from the reef patch. Echosounder is calibrated using 36-mm tungsten carbide sphere for the 200 kHz and a 21-mm tungsten carbide sphere for the 420 kHz. Data are collected for a 24-hour period, focusing on dawn, day, and dusk so as to capture the morning re-aggregation process over the reefs, the daylight behavior of fish around the reefs, and the nightly dispersion off the reefs.

From these data we are quantifying how pelagic fish schools use the reefs. Such information includes the strength of the affinity of fish schools to the reefs, the residency time of fish schools at the reefs (all day or transient), and the response of the schools to periods in the tidal cycle. In addition, we hope to capture the dynamics of gag and prey fish interactions, such as corroborating the time of day when foraging occurs, determining if there are cues prompting a foraging event, and measuring the attack strategy (attack angle and swimming velocity) and the response of the school to an attack.

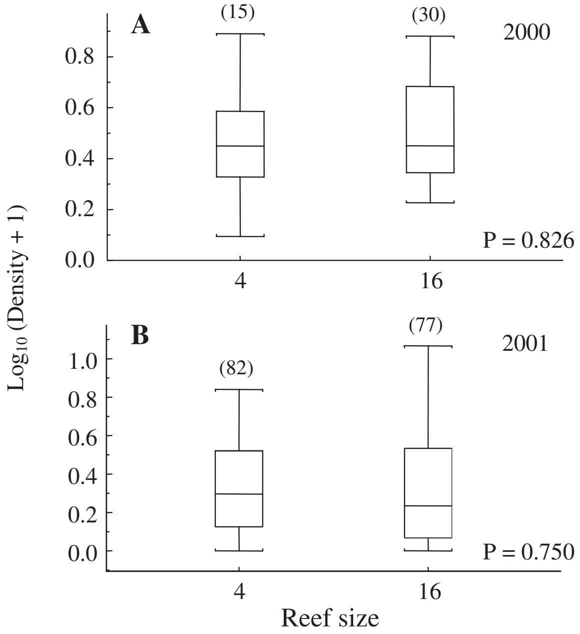


Figure 4

Box and whisker plot (median, 25% quartiles, 75% quartiles, range, and hashed area is the ±95% CL) of the log transformed fish density (fish m^{-2}), LOG_{10} [density+1] estimated for data collected from July–October in (A) 2000 and (B) 2001. No significant difference was detected between 4 and 16-cube reefs for either year (ANOVA, P=0.826 in 2000, P=0.750 in 2001).

Video and passive acoustics Video and passive acoustics are being used to study the daylight behavior of gag and pelagic fish schools in response to one another, potential gag predators, and periods in the tidal cycle. Visual monitoring of the artificial reefs using ambient light is achieved through deployment of a two-camera system (Sony Handycam CCD-TR910 in a Hypertech underwater housing, and the Ocean Systems, Inc. self-contained Splash-cam—Deep Blue Pro Color). Cameras are powered using 12 V marine batteries, and video is recorded on VHS or Hi-8 tapes. The two cameras are set on the same side of the reef, about 2 m from the reef, and 1 m above the bottom. This deployment provides a compromise between invasiveness of the camera array and near total reef coverage. There is only one blind spot with this configuration, the area just behind the reef. Both cameras provide a live feed to the surface for real-time monitoring.

In addition, we are artificially exposing gag to potential predator threats by manipulating and monitoring the acoustic environment to determine how gag use reef habitat in response to a potential predator. To accomplish this, we are using a submersible speaker (30 watt underwater speaker, University Sound UW-30, source level 120 dB re 1 μPa) to broadcast bottlenose dolphin vocalizations (predator) and a combined video and hydrophone (High Tech Inc. model HTI-96-MIN) system to watch and listen for the gag behavioral response. The speaker is positioned 2 m from the reef and centered between the two cameras, with the hydrophone positioned at the center of the reef. The audio feed is digitally recorded as a *.wav file (digital audio file format developed by Microsoft) at a sample rate of 44.1 kHz. Both the visually observed and vocal response of gag is recorded on a video feed and recorded to VHS cassette. An example of the combined video and audio (listening and transmitting) is shown in Fig. 5. In Fig. 5, the hydrophones are not visible; frames C and D are frames extracted from the video showing schooling fish

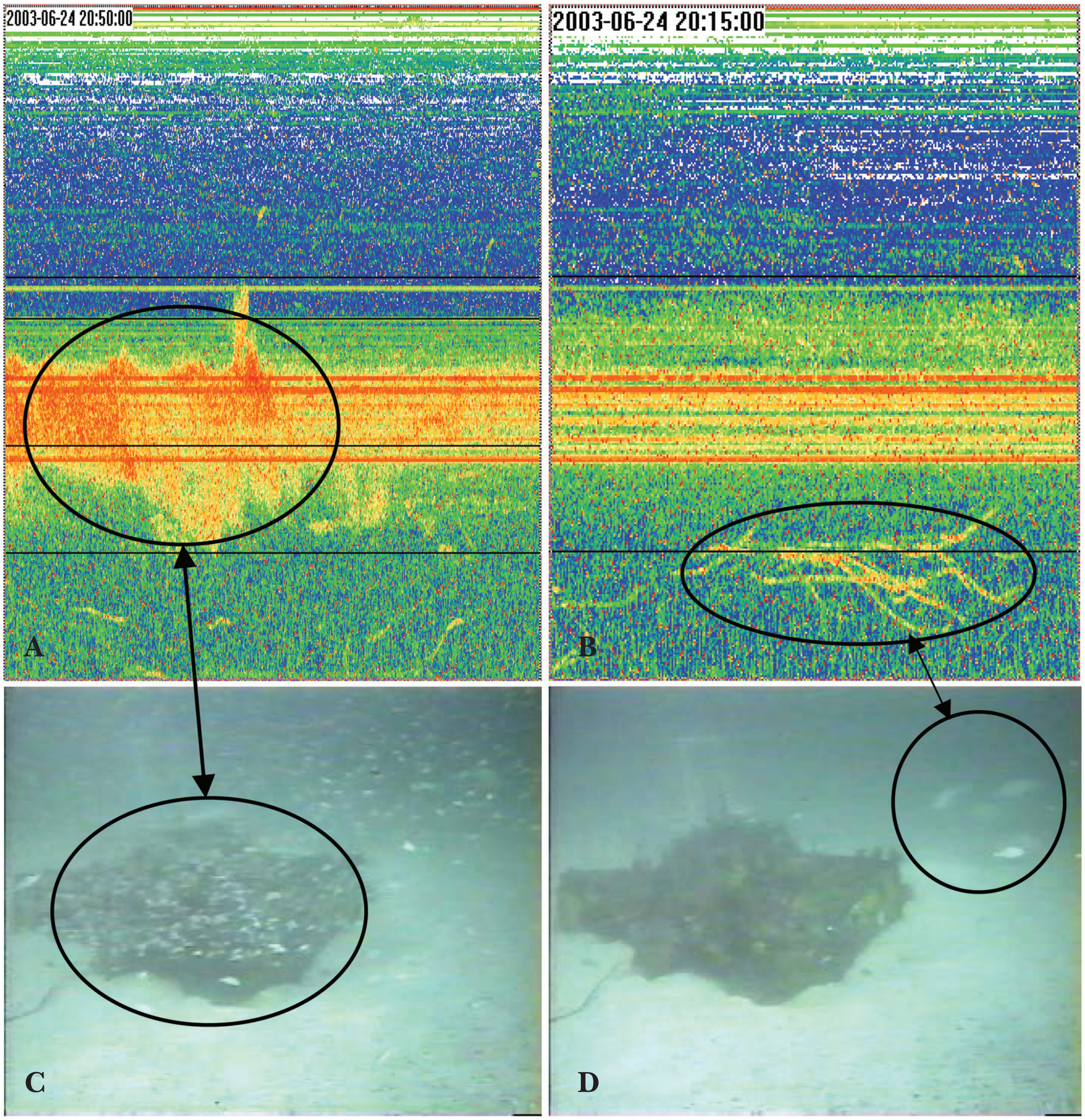


Figure 5

Fixed, side-facing acoustics (A,B) and the time matched frames from the video recording (C,D). For A and B, the transducer is located at the top of the image, vertical dimension is distance from transducer (m), and horizontal dimension is time. The first (upper most) red horizontal line is the leading edge of the reef and the bottom red horizontal line is the far end of the reef. Each of the black horizontal lines denotes 20 m with the entire range displayed at 50 m; the leading edge of the reef is 28 m from the transducer. Circled areas for A–C and B–D match the acoustics data to the video output. A and C show school of fish on the reef. B and D show that the fish school moved off the reef (just out of view of the camera) and gag milling around on the backside of the reef.

over the reef (Fig. 5C) and the response of gag to dolphin vocalizations (Fig. 5D).

Electron transport system assay Electron transport system (ETS) enzyme assay technique provides in situ estimates of fish total metabolic rates (Butler et al.[2]). ETS enzyme assay is a method to estimate the time-averaged potential respiratory capacity (potential oxygen

---

[2] Butler, M. W., D. M. Mason, W. J. Lindberg, D. J. Murie, and D. C. Parkyn. In prep. Non-lethal application of the electron transport system assay for in-situ estimation of relative metabolic rates of large marine fishes.

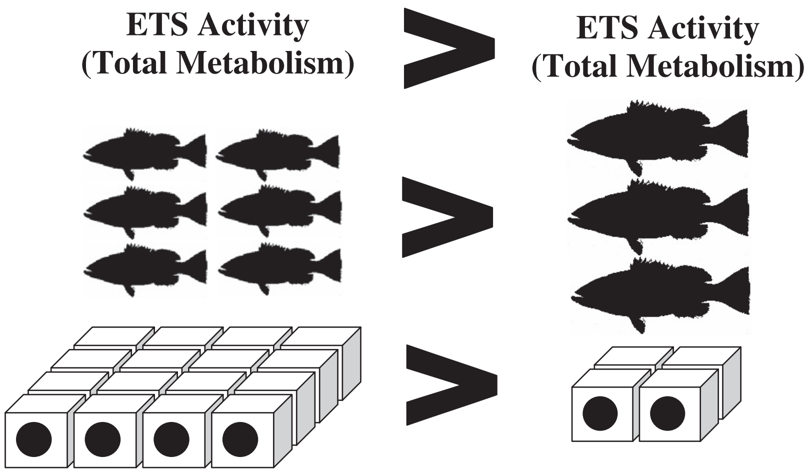


Figure 6

Cubes represent the two associated treatments (4 vs 16) on the Suwannee Regional Reef System. There is an associated increase in the number of gag and decrease in gag size at age with increasing reef size (Lindberg et al., 2006). We hypothesize that total metabolism as determined by ETS assay will follow the same trend.

consumption) of an organism by measuring the enzymatic activity of the rate-limiting step in oxygen use, namely adenosine triphosphate (ATP) production. For ETS, this step is the oxidation of the coenzyme UQ-cytochrome b complex (Broberg, 1985). The advantages in using ETS enzyme assay to measure metabolic rates include: 1) ability to measure metabolism in situ; 2) ETS responds slower to environmental change than respiration, thereby providing an integrated measure of metabolism for about a one week duration (Bämstedt, 1980; Ikeda, 1996), effectively eliminating short-term fluctuations in respiration (noise) and the stress associated with specimen collection; 3) it is a simple and extremely sensitive technique; 4) samples from animals can be collected, quickly frozen until analysis, then later thawed and measured for ETS activity, thereby allowing measurements on a large number of samples.

ETS enzyme assay technique has been used successfully to measure oxygen uptake potential for bacteria (Tan and Ruger, 1989), marine and freshwater plankton (Packard, 1971; King and Packard, 1975; Owens and King, 1975; Devol, 1979; del Giorgio, 1992), benthic polychaetes and amphipods (Cammen et al., 1990), and zebra mussels (*Dreissena polymorpha*) (Madon et al., 1998; Fanslow et al., 2001). ETS has also been used to successfully estimate the metabolic rates of freshwater and marine larval and juvenile fishes including hybrid striped bass (*Morone saxatilis*), yellow perch (*Perca flavescens*), walleye (*Stizostedion vitreum*), largemouth bass (*Micropterus salmoides*), walleye pollock (*Theragra chalcogramma*), and leptocephali (Yamashita and Bailey, 1990; Pfeiler and Govoni, 1993; Gopalan et al., 1996), and small-bodied adult fishes, such as myctophid, gobies, and pomacentrids (Ikeda, 1989), where whole bodies are used. However, ETS assays have not been applied to large fish. Therefore, our current emphasis is on adapting this technique for non-lethal application to larger fish species (Butler et al.[2]). This requires knowledge of where and how to collect a small quantity of muscle tissue from a fish, as well as evaluating the entire analytical procedure for maximizing the signal (enzymatic activity) and minimizing the error in tissue collection and preparation.

We have recently developed the ETS assay protocol for non-lethal application to gag ranging in size from 25 to 90 cm (Butler et al.[2]). Our next step is to apply this technique to our experimental reef system to determine the in situ metabolism of grouper and compare it across differing habitats. With this information, we expect to measure the metabolic demands potentially mediated by reef architecture through changes in gag densities, foraging efficiencies, and social interactions (Fig. 6). This will allow us to make predictions about condition based on habitat structure and quality.

Integration across technologies Each of the discussed technologies are being used to address specific questions related to the above stated hypotheses. However, the integration of these technologies extends the application and data. For example, the combined fixed side-look-

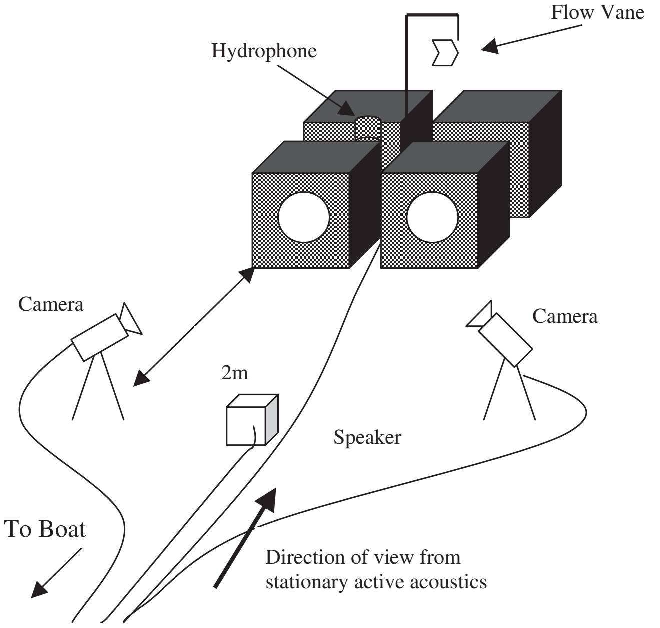


Figure 7

Equipment arrangement for visual observation (cameras), passive acoustics (hydrophone), active acoustics (not pictured), and playback experiments (speaker). Transducers for stationary active acoustics are located about 30 m from the reef in the direction of the boat.

ing acoustical deployment, video, and audio playback (Fig. 7), and listening (all of which were synced based on time) provides information not available if each were used independently. Direct benefits for the application and interpretation of the fixed side-looking acoustics occurs by having direct species identification from the video, as well as the ability to visually track fish schools when they move out of the acoustical beam. Also, changes in current direction (period in the tidal cycle) are captured in the video by virtue of having a visual reference on a flow meter (General Oceanics model 2030) suspended in the center of the patch. All provide additional information to link changes in the observed spatial distribution and dynamics of fish schools relative to the position of the reef. Lastly, the video camera can detect the presence of pelagic predators when present at the patch reef, again providing additional information on the dynamics of the schooling prey fish relative to predator threat.

Data from the fixed side-looking acoustics also provides information necessary for interpreting the behavior of gag observed in the video. For example, information from the fixed active acoustics system can provide distance measures (e.g., distance gag are from the reef and distance moved), swimming speed estimates, and detailed spatial tracking of gag; information that may be difficult to measure directly and accurately from video (although see Taylor and Rand, 2006). Such information can be used to parameterize movement and home range models, as well as to detect subtle changes of gag in response to predation threats. For example, the meandering gag observed in Fig. 4D have a mean swimming velocity of 0.56 m s^{-1} (range: 0.17 to 1.34 m s^{-1}), average about 8.4 m distance from the reef (range: 3.8 to 15.6 m), and have a mean target strength of –25.6 dB (range: –34.1 to –22.4 dB). Moreover, we detected a subtle response of gag to the presence of a diver (disturbance) on the reefs. Prior to a disturbance from a diver, gag averaged a distance of 8.2 m (±0.5 m 95% CI) from the reef and had an average swimming velocity of 0.57 m s^{-1}; upon the diver entering the water and approaching the reef, gag moved to a distance of 10.8 m (±2.2 m 95% CI) from the reef and had an average swimming velocity of 0.54 m s^{-1}. The net change in distance of 2.8 m from the reef was significant (T-test for unequal variances, P=0.027), but the change in swimming velocity was not (T-test for equal variances, P=0.617). Swimming speeds were estimated using the target tracking module available in Echoview© software (SonarData Pty Ltd., Hobart, Tasmania, Australia). Environmental conditions at this time included a well-mixed water column, salinity of 32 ppt, and a water temperature of 20°C. Lastly, observations from the video and hydroacoustics may provide the necessary information to explain any observed differences in metabolic expenditure from the ETS assay through the direct analysis of activity (swimming velocity and frequency of activities) and behavior.

Discussion

We have demonstrated how the integration of various technologies will help in our ability to achieve NMFS EFH Level 3 for understanding the functional relationship between reef architecture and individual somatic growth. Growth is a bioenergetics process that incorporates density-dependence in foraging and energy expenditure, which we are quantifying using the technologies described herein (acoustics, optics, and ETS). To achieve the longer-term goal of obtaining NMFS EFH Level 4 (production rates by habitat), we are combining our integrated technological approach with more traditional techniques. Traditional techniques (visual census of reef fish populations using SCUBA, direct biological sampling to collect aging structures, diet composition, daily ration, and telemetry) provide the other necessary data to complete the bioenergetics mass balance of growth, and to quantify emigration, immigration, mortality, and maximum number of fish sustainable by a reef as a function of reef architecture (Kiel, 2004; Lindberg et al., 2006). Ultimately, it is the combination of technologies and traditional approaches that will provide us with the quantitative understanding of reef architecture and reef fish production to develop our predictive capabilities.

The technologies highlighted here are not necessarily new, having already had applications in science and management. Mobile fisheries acoustics is used in freshwater (Burczynski et al., 1987; Brandt et al., 1991; Mason et al., 2001), estuarine (Lou and Brandt, 1993), and marine (Cushing, 1968; Baily and Simmonds, 1990; MacLennan and Simmonds, 1992) ecosystems throughout the world to estimate abundance of pelagic fishes, as well as for spatial studies of fish distributions for population estimation and for spatial studies of pelagic systems (Brandt and Mason, 1994; Mason et al., 1995). Passive acoustics are used for the detection and evaluation of aggregations of sound-producing fish (Mann and Lobel, 1995; Luczkovich et.al., 1999), monitoring of migrations by sound-producing species (Moore et.al., 1989), as well as general investigations of sound production by fish species (Mann and Lobel, 1998). However, the most novel applications of these technologies come from their integration, to address a series of inter-related hypotheses and competing hypotheses.

Each of the discussed technologies are being used to address specific questions in our process-oriented approach. In brief, some of our objectives include determining the quantitative and qualitative relationships among gag grouper, pelagic prey fish, and reef architecture, and the in situ determination of metabolic expenditure. The mobile fisheries acoustics is providing the quantitative data for determining if pelagic forage fish density may change as a function of contrasting reef architectures. Combined video, audio, and fixed side-looking acoustics are providing the detailed data to explore how reef architecture mediates growth and production of gag through behavioral processes (e.g., the availability of prey fish and the efficiency and timing of feeding by gag). Another example is how gag use reef structure (cavity volume) and proximity to the reef under conditions of predation risk. And lastly, how reef structure may mediate intensity of behavioral interactions and the expenditure of energy. These technologies combined, in the context of our experimental design, are a promising approach for understanding how reef architecture mediates numerical, behavioral, and physiological processes of reef fishes.

Acknowledgements

We thank two anonymous reviewers for helpful comments on the manuscript; Doug Marcinek, Eddie Leonard, Elizabeth Berens, Jackie Debicella, and Rick Kline for help in the field; and David Mann for advice and equipment for the production and recording of underwater sounds. The Suwannee Regional Reef System was constructed with funds from the Florida Artificial Reef Program, Florida Fish and Wildlife Conservation Commission (formerly in the Department of Environmental Protection), under contract numbers C-6051, C-7062 and C-7551, with direct cooperation of the Levy County Board of County Commissioners. We thank Ginnie Vale, Jon Dodrill, and the late State Senator George G. Kirkpatrick Jr. for facilitating development of this study system. This project was supported by the Florida Sea Grant College Program (Grant No. R/LR-B-49 and L/LR-B-53), the D.M. Smith Fellowship Fund, and NOAA Great Lakes Environmental Research Laboratory. This is contribution number 1327 of the NOAA Great Lakes Environmental Research Laboratory.

Literature cited

Baily, R. S., and E. J. Simmonds.
1990. The use of acoustics surveys in the assessment of the North Sea herring stock and a comparison with other methods. Rapp. P-v. Réun. Cons. perm. int. Explor. Mer 189:9–17.

Bämstedt, U.
1980. ETS activity as an estimator of respiratory rate of zooplankton populations: The significance of variations in environmental factors. J. Exp. Mar. Biol. Ecol. 42:267–283.

Brandt, S. B., and D. M. Mason.
1994. Landscape approaches for assessing spatial patterns in fish foraging and growth. *In* Theory and applications in fish feeding ecology (D.J. Stouder, K. L. Fresh, and R. J. Feller, eds.), p. 211–238. University of South Carolina Press, Columbia, SC.

Brandt, S. B., D. M. Mason, E. V. Patrick, R. L. Argyle, L. Wells, P. A. Unger, and D. J. Stewart.
1991. Acoustic measures of abundance and size of pelagic planktivores in Lake Michigan. Can. J. Fish. Aquat. Sci. 48:894–908.

Broberg, A.
1985. A modified method for studies of electron transport system activity in freshwater sediments. Hydrobiol. 120:181–187.

Burczynski, J. J., P. H. Michaletz, and G. M. Marrone.
1987. Hydroacoustic assessment of the abundance and distribution of rainbow smelt in Lake Oahe. N. Amer. J. Fish. Manag. 7:106–116.

Cammen, L. M., S. Corwin, and J. P. Christensen.
1990. Electron transport system (ETS) activity as a measure of benthic macrofaunal metabolism. Mar. Ecol. Prog. Ser. 65:171–182.

Cushing, D. H.
1968. Direct estimation of fish populations acoustically. J. Fish. Res. Bd. Can. 25:2349–2364.

del Giorgio, P. A.
1992. The relationship between ETS (electron transport system) activity and oxygen consumption in lake plankton: a cross system calibration. J. Plank. Res. 14:1723–1741.

Devol, A. H.
1979. Zooplankton respirations and its relationship to plankton dynamics in two lakes of contrasting trophic state. Limno. Oceanog. 24:893–905.

Ehrenberg, J. E.
1983. A review of in situ target strength estimation techniques. *In* Symposium on fisheries acoustics (O. Nakken and S. C. Venema eds.), p. 85–90. FAO Fisheries Report 300, Bergen, Norway.

Fanslow, D. L., T. F. Nalepa, and T. H. Johengen.
2001. Seasonal changes in the respiratory electron transport system (ETS) and respiration of the zebra mussel, *Dreissena polymorpha* in Saginaw Bay, Lake Huron. Hydrobiol. 448:61–70.

Foote, K. G.
1990. Spheres for calibrating an eleven frequency acoustic measurement system. Rapp. P-v. Réun. Cons. perm. int. Explor. Mer 46:284–286.

Foote, K. G., H. P. Knudsen, G. Vestnes, D. N. MacLennan, and E. J. Simmonds.
1987. Calibration of acoustic instruments for fish density estimation: a practical guide. International Council for Exploration of the Sea Cooperative Research Report no. 144, 57 p.

Gopalan, G., S. P. Madon, D. A. Culver, and P. W. Pappas.
1996. Measurement of metabolism in free ranging juvenile fishes using electron transport system (ETS) enzyme asssays. *In* High Performance Fish II Symposium Proceedings, International Congress on the Biology of Fishes (D. MacKinlay and J. Nelson, eds.), p. 21–30. San Francisco State University.

Ikeda, T.
1989. Estimated respiration rate of Myctophid fish from the enzyme activity of the electron transport system. J Oceanogr. Soc. Japan 45:167–173.
1996. Metabolism, body composition, and energy budget of the mesopelagic fish *Mauriculus muelleri* in the Sea of Japan. Fish. Bull. 94:49–58.

Jech, J. M., and J. Luo.
2000. Digital echo visualization and information system (DEVIS) for fisheries acoustics data. J. Fish. Res. 47:115–124.

Kiel, B.L.
2004. Homing and spatial use of gag grouper, *Mycteroperca microlepis*. M.S. Thesis, University of Florida, Gainesville, 89 p.

King, F. D., and T. T. Packard.
1975. Respiration and the activity of the electron transport system in marine zooplankton. Limno. Oceanogr. 20:849–854.

Lindberg, W. J. T. K. Frazer, K. P. Portier, F. Vose, J. Loftin, D. Murie, D. M. Mason, B. Nagy, and M. Hart.
2006. Density-dependent habitat selection and performance by a large mobile reef fish. Ecol. Appl. 16:731–746.

Lou, J., and S. B. Brandt.
1993. Bay anchovy production and consumption in mid-Chesapeake Bay based on a bioenergetics model and acoustics measures of fish abundances. Mar. Ecol. Prog. Ser. 98:223–236.

Luczkovich, J. J., M. W. Sprague, S. E. Johnson, and R. C. Pullinger.
1999. Delimiting spawning areas of weakfish, *Cynoscion regalis*, (Family Sciaenidae), in Pamlico Sound, North Carolina using passive hydroacoustic surveys. Bioacoustics, 10:143–160.

MacLennan, D. N., and E. J. Simmonds.
1992. Fisheries Acoustics, 336 p. Chapman and Hall, London.

Madon, S. P., D. W. Schneider, and J. A. Stoeckel.
1998. In situ estimation of zebra mussel metabolic rates using the electron transport system (ETS) assay. J. Shellfish Res. 17:195–203.

Mann, D. A., and P. S. Lobel.
1995. Passive acoustic detection of fish sound production associated with courtship and spawning. Bull. Mar. Sci. 57:705–706.
1998. Acoustic behavior of the damselfish *Dascyllus albisella*: behavioral and geographic variation. Environ. Biol. Fish. 51:421–428.

Mason, D. M., A. Goyke, and S. B. Brandt.
1995. A spatially-explicit bioenergetics measure of environmental quality for salmonines: a comparison between Lakes Michigan and Ontario. Can. J. Fish. Aquat. Sci. 52:1572–1583.

Mason, D. M., A. P. Goyke, S. B. Brandt, and J. M. Jech.
2001. Acoustic fish stock assessment in the Laurentian Great Lakes. *In* The Great Lakes of the World (GLOW): Food web, health and integrity (M. Munawar and R. E. Hecky, eds), p. 317–339. Ecovision World Monograph Series. Backhuys, Leiden, The Netherlands.

Minello, T. J.
1999. Nekton densities in shallow estuarine habitats of Texas and Louisiana and the identification of essential fish habitat. *In* Fish habitat: essential fish habitat and rehabilitation (L. Benaka, ed.), p. 43–75. Am. Fish. Soc. Symp. 22, Bethesda, Maryland.

Moore, S., J. Bennett, and D. Ljungblad.
1989. Use of passive acoustics in conjunction with aerial surveys to monitor the fall bowhead whale (*Balaena mysticetus*) migration. Rep. Int. Whaling Comm. 39:291–295.

Owens, G., and F. D. King.
1975. The measurement of respiratory electron-transport system activity in marine zooplankton. Mar. Biol. 30:27–36.

Packard, D. B., and T. Hoff.
1999. Life history, habitat parameters, and essential habitat of mid-Atlantic summer flounder. *In* Fish habitat: essential fish habitat and rehabilitation (L. Benaka, ed.), p. 76–92. Am. Fish. Soc. Symp. 22, Bethesda, Maryland.

Packard, T. T.
1971. The measurement of electron transport activity of microplankton. J. Mar. Res. 29:235–244.

Pfeiler, E., and J. J. Govoni.
1993. Metabolic rates in early life history stages of elopomorph fishes. Biol. Bull. 185:277–283.

Powell, L. A. and T. K. Stanton.
1983. A programmable microcomputer-based sonar echo processor for real-time processing. IEEE J. Oceanics Eng. 8:280–287.

Rubec, P. J., J. C. W. Bexley, J. Noris, M. S. Coyne, M. E. Monaco, S. G. Smith, and J. S. Ault.
1999. Suitability modeling to delineate habitat essential to sustainable fisheries. *In* Fish habitat: essential fish habitat and rehabilitation (L. Benaka, ed.), p. 108–133. Am. Fish. Soc. Symp. 22, Bethesda, Maryland.

Tan, T. L., and H. J. Ruger.
1989. Benthic studies of the Northwest African upwelling region: bacteria standing stock and ETS-activity, ATP-biomass and adenylate energy charge. Mar. Ecol. Prog. Ser. 9:171–179.

Taylor, J. C., and P. S. Rand.
2006. A roving diver video method for quantifying size distribution, density and three dimensional spatial structure of Nassau grouper aggregations. *In* Emerging technologies for reef fisheries research and management (J. C. Taylor, ed.), p. 4–9. NOAA Prof. Paper NMFS 5.

Thorne, R.E.
1983. Assessment of population abundance by hydroacoustics. Biol. Oceanogr. 2:253–262.

Yamashita, T. and K. M. Bailey.
1990. Electron transport system (ETS) activity as a possible index of respiration for larval walleye pollock (*Theragra chalcogramma*). Nippon Suisan Gakkaishi (Bull. Jap. Soc. Sci. Fish.) 556:1059–1062.

NOAA Professional Papers NMFS

Guide for Contributors

Manuscript Preparation

Title page should include authors' full names and mailing addresses and the senior author's telephone and FAX number.

Abstract should not exceed one double-spaced typed page. It should state the main scope of the research but emphasize its conclusions andrelevant findings. Because abstracts are circulated by abstracting agencies,it is important that they represent the research clearly and concisely.

Text must be typed double-spaced throughout. A brief introduction should portray the broad significance of the paper; the remainder of the paper should be divided into the following sections: **Materials and methods, Results, Discussion** (or **Conclusions**), and **Acknowledgments**. Headings within each section must be short, reflect a logical sequence, and follow the rules of multiple subdivision (i.e. there can be no subdivision without at least two items). The entire text should be intelligible to interdisciplinary readers; therefore, all acronyms, abbreviations, and technical terms should be spelled out the first time they are mentioned. The scientific names of species must be written out the first time they are mentioned; subsequent mention of scientific names may be abbreviated. Follow the U.S. Government Printing Office Style Manual (1984 ed.) and the CBE Style Manual (5th ed.) for editorial style, and the most current issue of the American Fisheries Society's Common and Scientific Names of Fishes from the United States and Canada for fish nomenclature. Dates should be written as follows: 11 November 1991. Measurements should be expressed in metric units, e.g., metric tons as (t); if other units of measurement are used, please make this fact explicit to the reader. The numeral one (1) should be typed as a one, not as a lower-case el (l).

Text footnotes should be numbered with Arabic numerals and typed on a separate sheet of paper. Footnote all personal communications, unpublished data, and unpublished manuscripts with full address of the communicator or author, or, as in the case of unpublished data, where the data are on file. Authors are advised to avoid references to nonstandard (gray) literature, such as internal, project, processed, or administrative reports, wherever possible. Where these references are used, please include whether they are available from NTIS (National Technical Information Service) or from some other public depository.

Literature cited comprises published works and those accepted for publication in peer-reviewed literature (in press). Follow the name and year system for citation format. In the text, cite Smith and Jones (1977) or (Smith and Jones, 1977). If there is a sequence of citations, list chronologically: Smith, 1932;Green, 1947; Smith and Jones, 1985. Abbreviations of serials should conform to abbreviations given in Serial Sources for the BIOSIS Previews Database. Authors are responsible for the accuracy and completeness of all citations.

Tables should not be excessive in size and must be cited in numerical order in the text. Headings should be short but ample enough to allow the table to be intelligible on its own. All unusual symbols must be explained in the table heading. Other incidental comments may be footnoted with italic numerals. Use asterisks for probability in statistical data. Because tables are typeset, they need only be submitted typed and formatted, with double-spaced legends. Zeros should precede all decimal points for values less than one.

Figures include line illustrations and photographs (or slides) and must be cited in numerical order in the text. Unless photographs are submitted on glossy paper with good contrast, we cannot guarantee a good final printed copy. Figures are to be labeled with author's name and number of figure. Use Times Roman font (upper and lowercase letters) to label within figures. Avoid vertical lettering except for y-axis labels. Zeros should precede all decimal points for values less than one. Figures may be submitted as computer software files (along with laser-printed copies), as photo-mechanical transfers (PMTs), or as high quality photographic prints. Send only xerox copies of figures to the Scientific Editor; original figures will be requested later when the manuscript has been accepted for publication. Figure legends should explain all symbols and abbreviations and should be double-spaced on a separate page at the end of the manuscript.

Copyright law does not cover government publications; they fall within the public domain. If an author reproduces any part of a government publication in his work, reference to source is considered correct form.

Submission

Send printed copies (original and three copies) to the Scientific Editor:

Dr. Adam Moles
Scientific Editor, Prof. Papers
NOAA/NMFS/AFSC
11305 Glacier Hwy.
Juneau, AK 99801-8626

Once the manuscript has been accepted for publication, you will be asked to submit an electronic file of it. The file should be submitted in WordPerfect or Word format and be compatible with either Windows or Macintosh systems.

UNITED STATES
DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC
ADMINISTRATION
NATIONAL MARINE FISHERIES SERVICE
7600 SAND POINT WAY NE
SEATTLE, WA 98115
OFFICIAL BUSINESS

Penalty for Private Use, $300

PRSRT STD
POSTAGE & FEES PAID
U.S. DEPARTMENT OF COMMERCE
PERMIT NO. G-19

NOAA SCIENTIFIC AND TECHNICAL PUBLICATIONS

The National Oceanic and Atmospheric Administration was established as part of the Department of Commerce on October 13, 1970. The mission responsibilities of NOAA are to assess the socioeconomic impact of natural and technological changes in the environment and to monitor and predict the state of the solid Earth, the oceans and their living resources, the atmosphere, and the space environment of the Earth.

The major components of NOAA regularly produce various types of scientific and technical information in the following kinds of publications:

PROFESSIONAL PAPERS: Important definitive research results, major techniques, and special investigations.

CONTRACT AND GRANT REPORTS: Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS: Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions, etc.

TECHNICAL SERVICE PUBLICATIONS: Reports containing data, observations, instructions, etc. A partial listing includes data serials; predictions and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHNICAL REPORTS: Journal quality with extensive details, mathematical development, or data listings.

TECHNICAL MEMORANDUMS: Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

Iinformation on availablity of NOAA publications can be obtained from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
www.ntis.gov