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

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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.

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.

[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.]

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

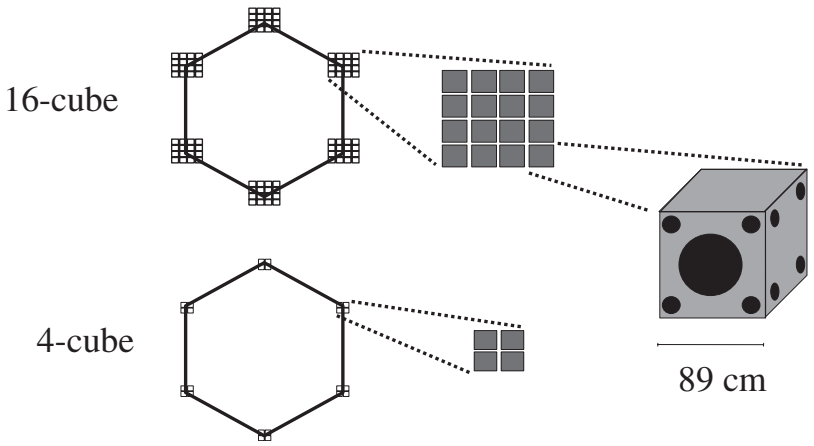

Figure 1

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

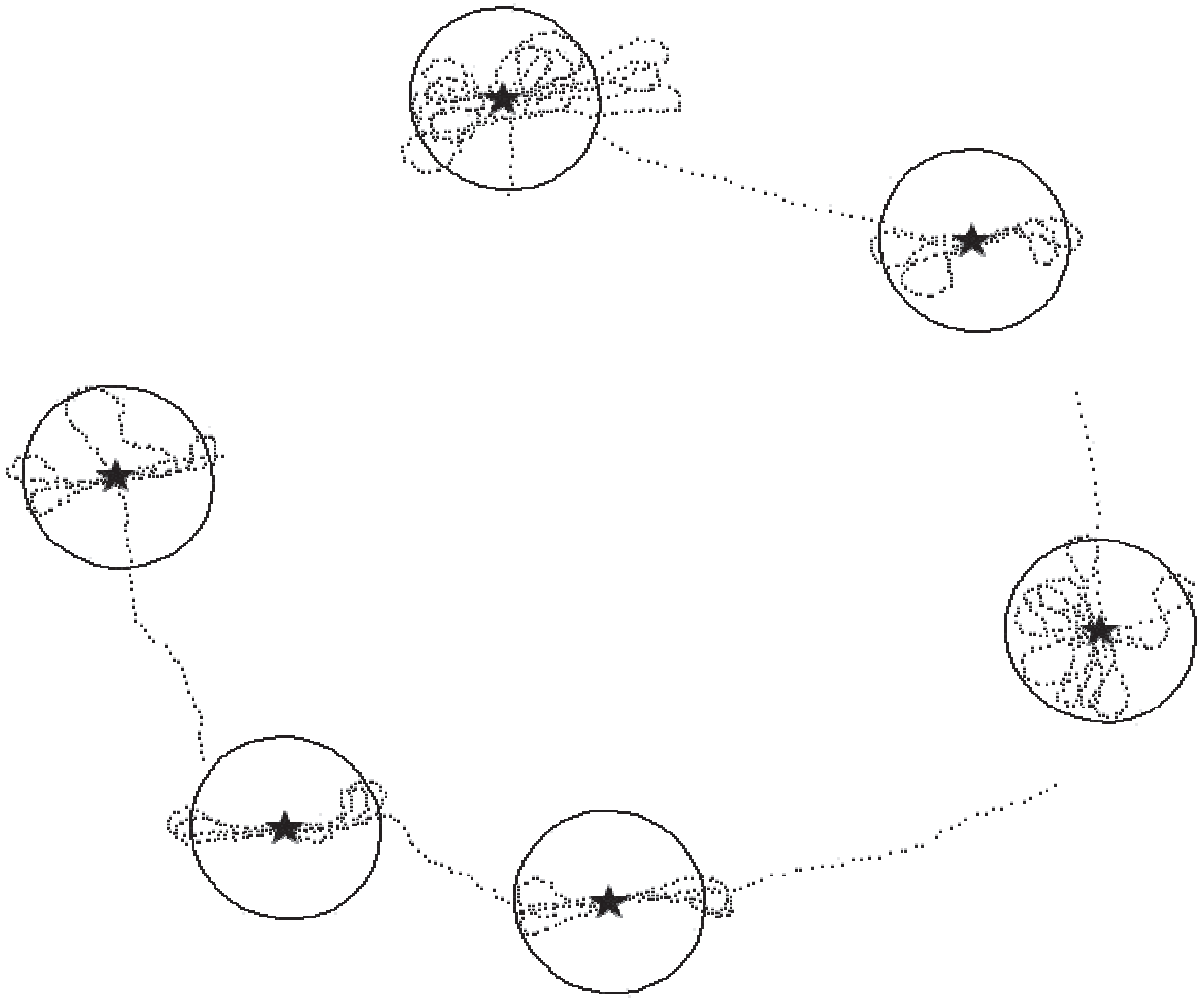

Figure 2

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

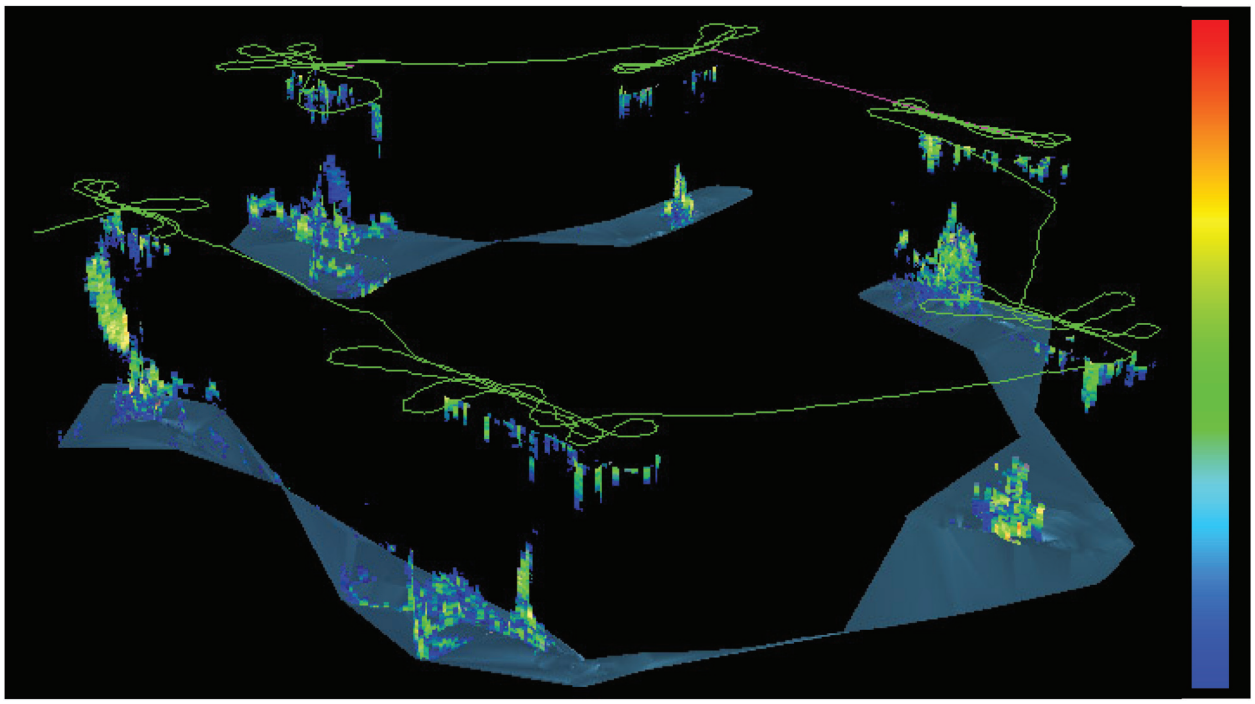

Figure 3

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.

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.

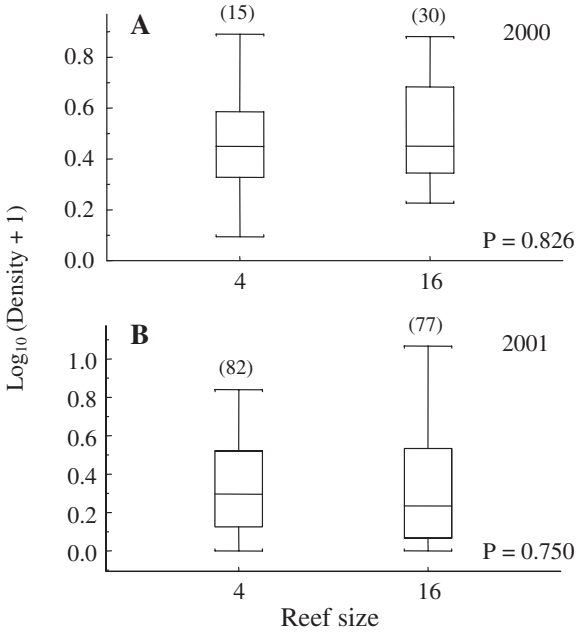

Figure 4

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).

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

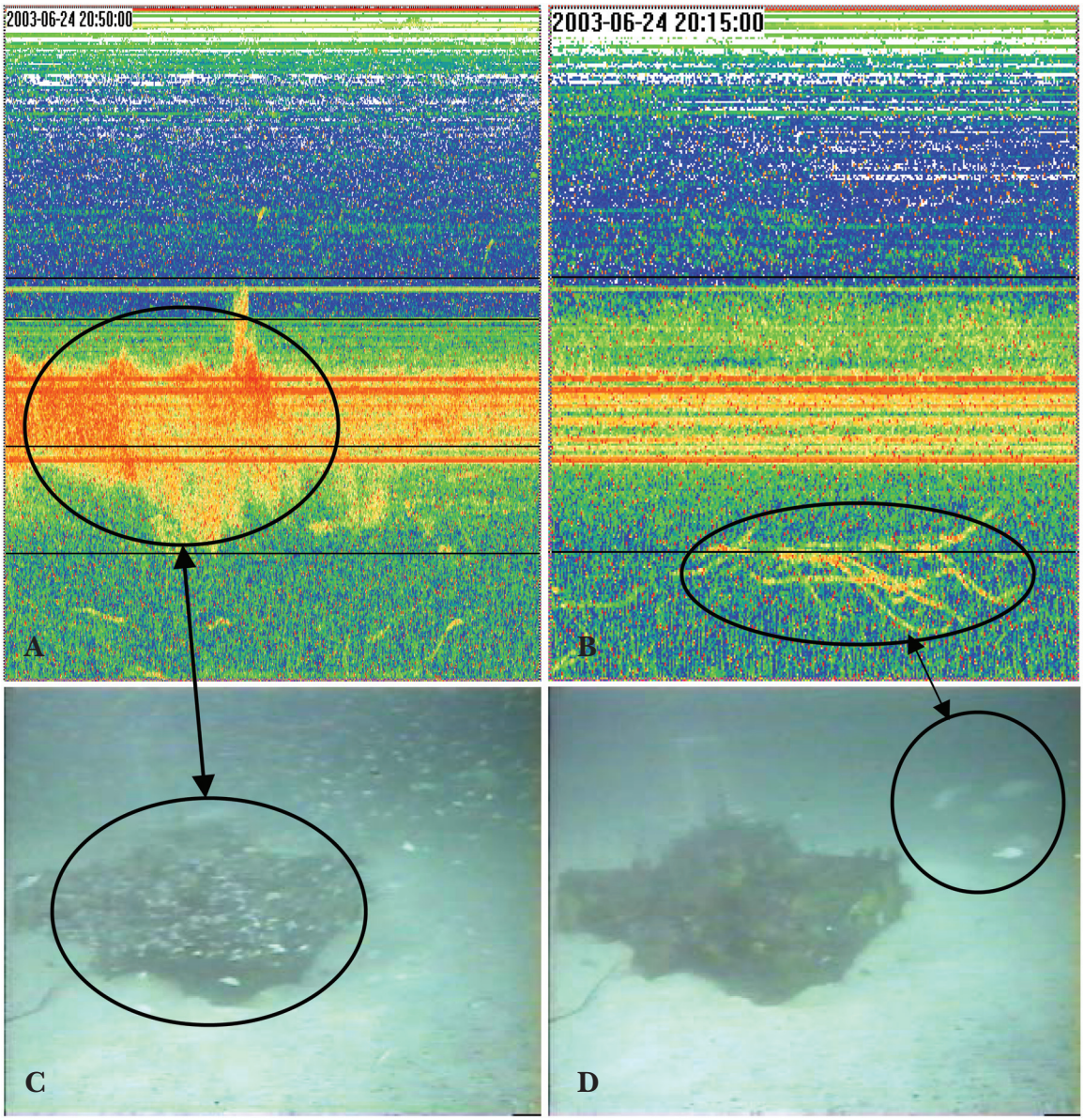

Figure 5

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.

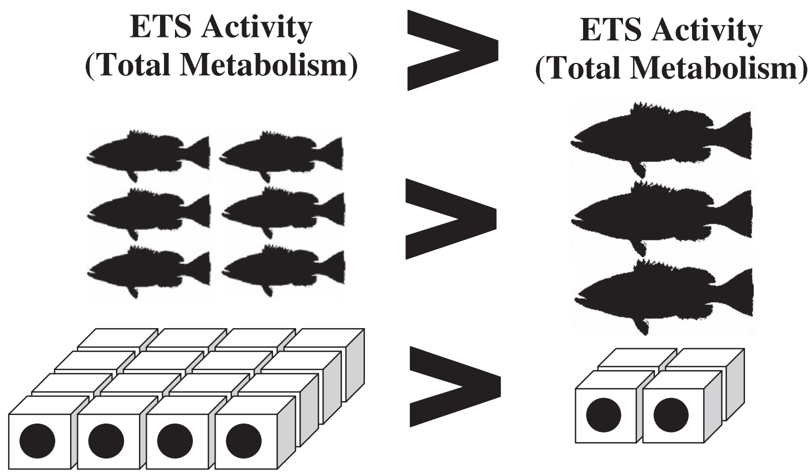

Figure 6

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-

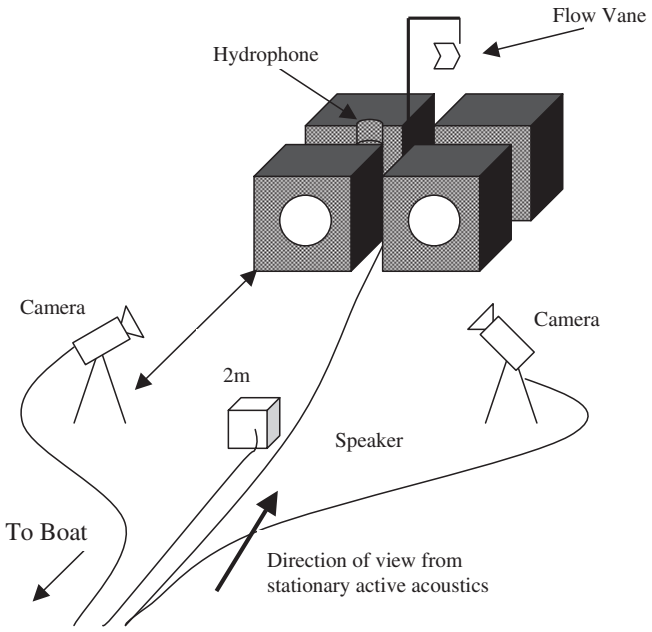

Figure 7

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.

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