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Mapping Coral Reef Habitats in Southeast Florida Using a Combined Technique Approach

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ABSTRACT

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To create maps of nearshore benthic habitats of Broward County, Florida, from 0 to 35 m depth, we combined laser bathymetry, acoustic ground discrimination, subbottom profiling, and aerial photography data in a geographic information system (GIS). A mosaic of interpolated, sun-shaded, laser bathymetry data served as the foundation upon which acoustic ground discrimination, limited subbottom profiling and aerial photography, and groundtruthing data aided in interpretation of habitats. Mapping criteria similar to NOAA biogeographic Caribbean mapping were used to allow for a comparable output. Expert-driven visual interpretation outlined geomorphological features at a scale of 1 : 6000 with a minimum mapping unit of 1 acre. Acoustic data were then used to differentiate areas of similar geomorphology by their acoustic diversity into areas of high and low scatter, which could be equated to rugosity created by either the substratum or benthic fauna. Of the approximately 112 km² mapped, 56.62 km² were coral reef and colonized hard bottom (50.42%), 54.78 km² were unconsolidated sediments (46.80%), and 0.43 km² were other categories (2.78%). Three linear reef complexes exist. The outermost linear reef has a mature windward reef morphology including a drowned spur and groove system, which was absent on the other two reef lines. The acoustic ground discrimination and groundtruthing showed different benthic habitats on the outer *vs.* middle and inner reefs. Higher acoustic scatter could be related to taller benthos and more rugose substratum. A considerable amount of colonized pavement (nearshore hard grounds) was found inshore. The map of Broward County yielded a high overall accuracy of 89.6%, only slightly less than the photo-interpreted NOAA Caribbean maps (overall accuracy of 91.1%). User and producer accuracies within each category were also similar. The combined technique approach was effective and accurate, and similar methodology can be used in other areas where photo interpretation is not feasible because of turbidity or depth limitations.

ADDITIONAL INDEX WORDS: *Coral reef, acoustic mapping, aerial photography, bathymetry, Echoplus, Florida, GIS, habitat mapping, LADS, LIDAR, QTC.*

INTRODUCTION

Remote sensing and mapping of coral reefs and essential fish habitat has been a primary objective of resource managers since the Sustainable Fisheries Act outlined its importance in 1996 (SFA, 1996). Consequently, much federal and academic effort focuses on mapping living resources in nearshore estuarine and marine environments such as sea grass meadows, coral reefs, hard bottoms, shellfish beds, and algal communities, including essential fish habitat. Such maps can be useful as proxies for the spatial distribution of organisms (KENDALL *et al.,* 2004; PITTMAN and MCALPINE, 2001), and therefore mapping the extent and content of coastal resources is now considered essential to coastal marine management plans in the United States (NOAA, 1996; NOAA-MIP, 1999).

Mapping areas on such an expansive scale requires the utilization of remote sensing such as satellite and aerial photography, hyperspectral imagery, acoustic analyses, and bathymetric surveys (NOAA-MIP, 1999). Frequently, passive optical sensors, like aerial photography or satellites, are employed that yield moderate- to high-resolution digital images of large areas. Such techniques have been widely used to map coral reef habitat (ANDREFOUET *et al.,* 2003; CHAUVAUD, BOUCHON, and MANIERE, 1999; HOLDEN and LEDREW, 2002; KENDALL *et al.,* 2001; MUMBY and EDWARDS, 2002; SHEPPARD *et al.,* 1995). For visualization of coral reefs, however, useful images are limited to those environments in shallow, clear water less than 10–20 m depth (FINKBEINER, STEVENSON, and SEAMAN, 2001; FINKL, 2005; HOPLEY, 1996; PURKIS, 2005). Other remote sensing tools must be implemented to map turbid and deep reefs (ANDERSON, GREGORY, and COLLINS, 2002; FINKL, BENEDET, and ANDREWS, 2005; GALLOWAY, 2001). Among these devices are high-resolution bathymetry and acoustic ground discrimination (HAMILTON, MULHEARN, and POECKERT, 1999; RIEGL and PURKIS, 2005). High-resolution bathymetric information is usually acquired by multibeam sonar or laser bathymetry (LADS, laser air-

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borne depth sounder); (Banks *et al.,* 2007; Finkl, Benedet, and Andrews, 2005; Lillicrop, 1996; Wells, 1996), providing detailed seafloor topography that facilitates the mapping of submarine geomorphology (Dodge *et al.,* 2002; Finkl, 2005; Finkl, Benedet, and Andrews, 2005; Riegl *et al.,* 2008; Storlazzi, Logan, and Field, 2003) and the analysis of topographic complexity (Blaszczynski, 1997; Brock *et al.,* 2004; Riley, Degloria, and Elliot, 1999; Walker, 2007). The information provided about the benthic community occurring on the surface of the visualized geomorphological structures, however, is still limited.

Acoustic ground discrimination devices like QTC View, Roxanne, Echoplus, and BioSonics are based on single-beam sonar and can provide information about the benthic community occurring on the surface, but their spatial resolution can be limited by survey logistics (line spacing). These systems have been extensively used to remotely map benthic habitats over the past several years (Ellingsen, Gray, and Bjoernbom, 2002; Freitas *et al.,* 2003; Freitas, Rodrigues, and Quintino, 2003; Hamilton, Mulhearn, and Poeckert, 1999; Kenny *et al.,* 2003; Lawrence and Bates, 2001; Moyer *et al.,* 2003). Many of these surveys were conducted in deep North Atlantic waters to detect areas of potential fish habitat, but they are equally valid in detecting changes in benthic cover on coral reefs (Moyer *et al.,* 2003; Riegl and Purkis, 2005). Mapping with these devices in geographic information systems (GISs) involves categorizing sonar wave form returns into classified points, then plotting and interpolating those data into continuous surfaces. The accuracies of such techniques are dependent on the distance between survey lines and can be lower than photogrammetric techniques (Riegl and Purkis, 2005). To obtain greater map accuracies with these systems, other approaches must be explored (Hewitt *et al.,* 2004).

In this paper, mapping areas of poor water clarity is conducted via a bottom-up approach (Hewitt *et al.,* 2004). A habitat map was created for the nearshore benthic habitats along the southeastern Florida coast of Broward County from 0 to 35 m depth. The highest resolution data set, laser bathymetry, was used as the foundation upon which acoustic ground discrimination, aerial photography, and chirp subbottom profiles were overlaid in GIS to obtain a detailed map with high accuracies (>80%). Mapping followed the same constraints as the NOAA biogeographic mapping efforts in Puerto Rico and the U.S. Virgin Islands (Kendall *et al.,* 2001; Kendall and Eschelbach, 2006) to allow for a comparable output. Map accuracies were then compared with the Kendall *et al.* (2001) study, which solely used traditional photogrammetric techniques.

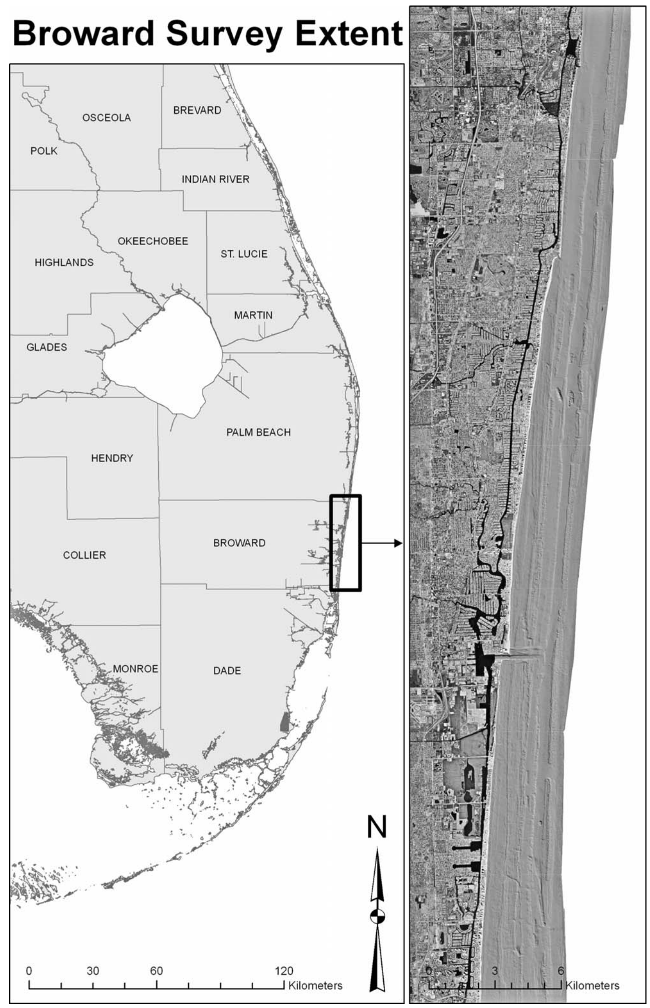


Figure 1. The study area, Broward County, Florida. The extent of this area stretches from Golden Beach in northern Dade County to southern Palm Beach County.

METHODS

Habitat Mapping

The entire subtidal seafloor from 0 to 35 m depth was mapped and classified for Broward County in southeastern Florida (Figure 1). For the production of benthic habitat maps, several data products were integrated including laser bathymetry (LADS), acoustic ground discrimination (QTC, Echoplus), subbottom chirp-sonar data, aerial photography, visual groundtruthing, and ecological data from previous surveys (Moyer *et al.,* 2003). All data were assembled in ArcGIS9. Polygons were drawn to NOAA-mapping criteria of a 1 : 6000 scale and a minimum mapping unit of 1 acre (Kendall *et al.,* 2001). The final map polygons conform to the NOAA hierarchical classification scheme used in Puerto Rico and the U.S. Virgin Islands NOAA Technical Memorandum NOS NCCOS CCMA 152 (Kendall *et al.,* 2001, 2004) with some modification (Figure 2).

The criteria for habitat classification were defined by their location, geomorphologic characteristics, biologic communities, and acoustic characteristics. A high resolution hill-shaded raster image of the LADS bathymetry data, similar to Banks *et al.* (2007) and Finkl, Benedet, and Andrews (2005), was used to map feature location and geomorphology of visible features. A video camera dropped from a boat along with scuba diving in selected areas was used as groundtruthing to characterize habitat types within those features. The

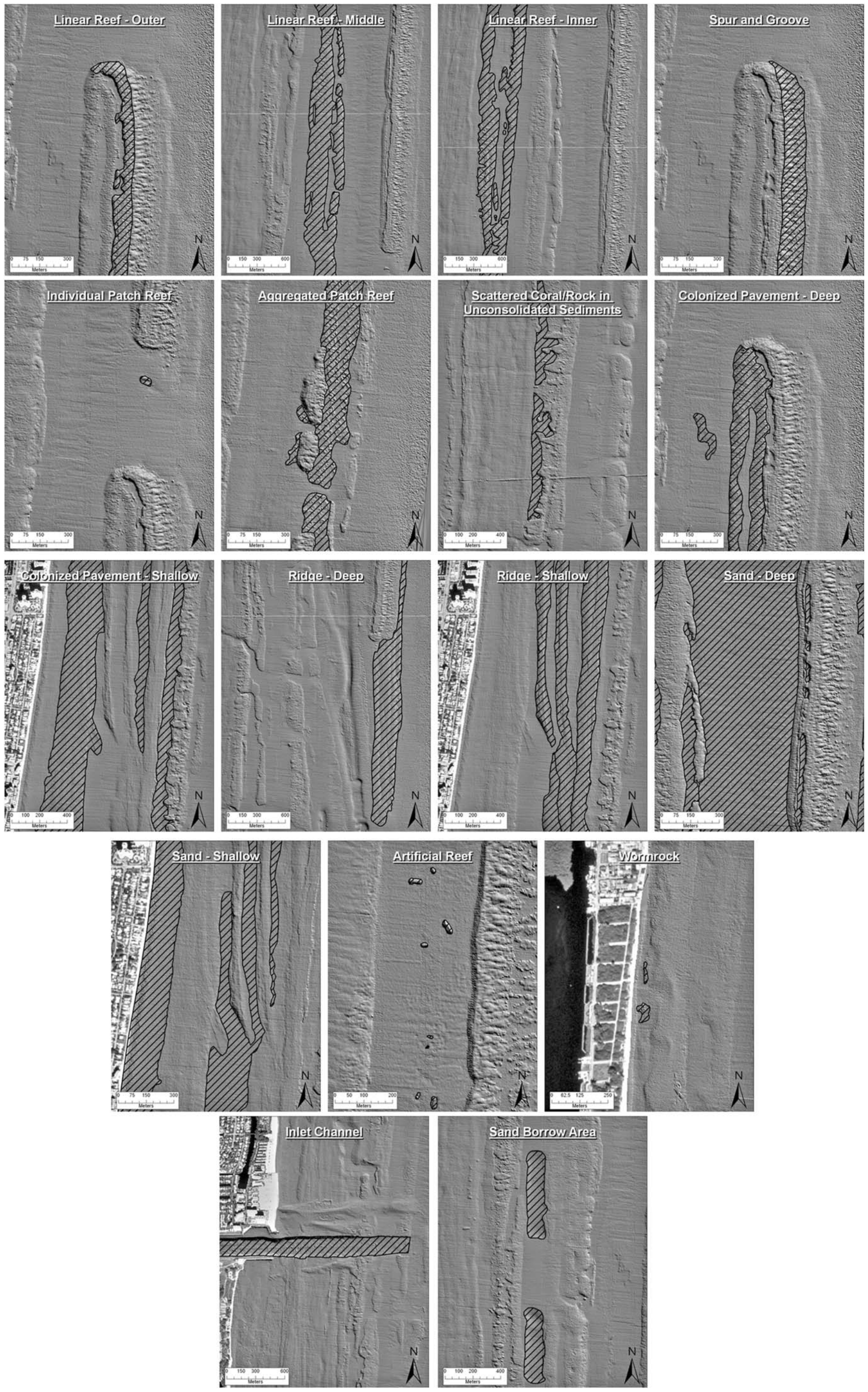


Figure 2. Delineations of the different habitats on the LADS hill-shaded bathymetry. The hashed area demarcates the habitat in the title of each image.

groundtruthing and acoustic data (QTC and Echoplus) were overlain onto the hill-shaded bathymetric map to aid in the definition of the outlined features. Chirp subbottom profiles from an Edgetech 512 X-Star with FM frequency pulse between 0.5 and 8 kHz were used where available to ascertain differences between reef with thin sand veneer and deeper sand areas. Aerial photography was used in shallow water to depict the edges of hard grounds. Conflicts between data types (*e.g.,* QTC and LADS bathymetry) were resolved by expert-driven interpretation based on the agreement of the majority of data types. For example, if an acoustic ground-discrimination point was classified as reef but plotted on what appeared to be sand in the LADS data and at least another data set (such as Echoplus, subbottom profile, and/or aerial photography) also indicated sand, then the polygon was classified as sand.

Laser Bathymetry

A bathymetric survey was conducted during April 2001 by Tenix LADS Corporation of Australia, using the LADS system with a sounding rate of 900 Hz (3.24 million soundings per hour), a position accuracy of 95% at 5-m circular error probable, a horizontal sounding density of 4 m × 4 m, a swath width of 240 m, area coverage of 64 km^2/h, and a depth range of 70 m, depending on water clarity. This survey encompassed all of Broward County, approximately 43 km of shoreline length, and from the shore eastward to depths of 40 m, approximately 2.5–3.5 km offshore (Figure 1). The entire survey area covered approximately 110 km^2 of marine habitat. The bathymetric data were gridded by triangulation with linear interpolation, sun shaded at a 45° angle and azimuth, and fused with aerial photography of the land. This final image was used as the foundation for mapping.

Acoustic Ground Discrimination

The principles of acoustic ground discrimination based on single-beam echo sounders employed by the QTCView Series 5 and Echoplus systems are reviewed in Bates and Whitehead (2001); Chivers, Emerson, and Burns (1990); Freitas, Rodrigues, and Quintino (2003); Freitas *et al.* (2003); Hamilton, Mulhearn, and Poeckert (1999); Lawrence and Bates (2001); Preston *et al.* (2000); and Riegl and Purkis (2005). We used the QTCView Series 5 and Echoplus turn-key survey systems, which performed acoustic ground discrimination based on the shape of sonar returns (Hamilton, Mulhearn, and Poeckert, 1999; Quester Tangent Corporation, 2002). The two systems are based on similar assumptions and record the characteristics of reflected waveforms to generate habitat classifications based on the acoustic diversity of collected echoes, which encode scattering and penetration properties of different types of seafloor (Chivers, Emerson, and Burns, 1990; Hamilton, Mulhearn, and Poeckert, 1999; Preston *et al.,* 1999). It is known that surface scatter from a statistically rough surface is inversely dependent on transducer opening angle (Clay and Sandness, 1971; Medwin and Clay, 1998). A 200-kHz transducer with 12° opening angle provided a small-enough footprint, allowing for "ecological" precision. The high-frequency pulse was easily scattered by surface structures, such as gorgonians, sponges, or sand ripples, and could therefore be used as a proxy for the detection of benthic fauna (Riegl and Purkis, 2005; Riegl *et al.,* 2005).

QTC

The typical process of data acquisition involved a hydrographic survey during which acoustic data were collected. In QTC Impact software, only the first return of each acoustic echo was digitized and all other multipath echoes were time-gated out. QTC considers only the first echo to carry information relevant for ground discrimination (Quester Tangent Corporation, 2002). The signal envelope of the digitized echoes was then subjected to Fourier and wavelet analyses, and analyzed for area under the curve, spectral moments, and other variables by the acquisition software (Legendre *et al.,* 2002). After being normalized to a range between 0 and 1, they were subjected to principal components analysis (PCA) for data reduction. The first three principal components of each echo were retained (called Q values), according to the assumption that these components explain the majority of variability in the data set (Quester Tangent Corporation, 2002). Data points were then projected into pseudo–three-dimensional space along these three components, and subjected to cluster analysis using a Bayesian approach (Quester Tangent Corporation, 2002). The number of desirable clusters and modality of cluster splitting were user defined and guided by three statistics called cluster performance index (CPI), Chi^2, and total score. Total score decreases to an inflection point that is "a strong indication of best split level" (Quester Tangent Corporation, 2002). CPI increases with increased cluster split (Freitas *et al.,* 2003), while Chi^2 decreases, reaching maximum/minimum values at optimal split level (Quester Tangent Corporation, 2002).

Reviews of the functioning of the QTC system and critiques can be found in Ellingsen, Gray, and Bjoernbom (2002); Freitas, Rodrigues, and Quintino (2003); Freitas *et al.* (2003); Hamilton, Mulhearn, and Poeckert (1999); Legendre (2002); Legendre *et al.* (2002); Preston and Kirlin (2002); Riegl and Purkis (2005); and von Szalay and McConnaughey (2002). The QTC data set was reduced to a three-column matrix consisting of a single *x, y* georeferenced class variable category *z* that was obtained from the cluster analysis. The outputs from each survey were imported into GIS and displayed as classes to aid in the habitat mapping process.

Echoplus

The Echoplus is similar to RoxAnn, which was extensively tested by Hamilton, Mulhearn, and Poeckert (1999). Echoplus is entirely self-contained and, according to the manufacturers, internally compensates for frequency, depth, power level, and pulse length, and can therefore be used with any depth sounder. Pulse amplitude and length were measured for every transmission, the outputs scaled accordingly, and absorption corrections factored in. Echoplus processes the tail of the first return echo plus the entire second echo. The second half of the first echo consists of scattered energy that returns after the surface and subsurface reverberation components. It is therefore a good indicator of bottom roughness. The second echo is considered a good hardness indicator because a hard substratum will reflect more energy and thus lead to a stronger multipath return (Chivers, Emerson, and Burns, 1990). The first echo was digitized and time-gated in a way that only its tail (backscatter component) was used for analysis along with the entire second echo. The measurements from first and second echo were collapsed into two indices, E1 and E2, for the first and second echo, respectively.

The user had no influence on the formation of these indices and collects a georeferenced string of variables (latitude, longitude, E1, E2). All data above the 95th and below the 5th percentile were rejected as outliers and all data were normalized to the 95th percentile, resulting in a range between 0 and 1. Like the QTC data, Echoplus point data were imported into GIS to aid in habitat discrimination.

Groundtruthing

Groundtruthing was performed with 383 video-camera drops recording the nature of the seafloor to help decide how data classes should be interpreted during the mapping process. An underwater video drop camera was used to identify the habitat at the target locations. The benthic cover was described at each location by characterizing the substrate (pavement, sand, rubble, and coral) and biological cover. Biological categories of the major functional groups (algae, gorgonians, sponge, and coral) were estimated on a rating scale from 0 to 5, with each rating corresponding to a percentage cover of the category on the seafloor. Each rating was as follows: 0 = 0% cover, 1 = 1%–20% cover, 2 = 21%–40% covers, 3 = 41%–60% cover, 4 = 61%–80% cover, 5 = 81%–100% cover. This yielded global positioning system (GPS) locations with characterized substrate type and estimated percentage cover of the main functional groups. Each point was imported into a GIS to aid in habitat identification. The habitat polygons were adjusted to match the groundtruthing data.

Accuracy Assessment

A total of 300 independent target points, arranged on a grid over much of Broward County, were chosen for accuracy assessment by the confusion matrix approach (CONGALTON, 1991; MA and REDMOND, 1995). Points were arranged over a regular grid that ignored the underlying substratum to minimize sampling bias. Accuracy assessment data were collected in a similar manner as the groundtruthing points. After the map polygons were drawn and classified using the acoustic discrimination systems, groundtruth points, and LADS bathymetry, 278 actual accuracy assessment point locations were used to compare actual *vs.* mapped habitats in the GIS.

Accuracy assessment was performed by the confusion matrix approach in two separate analyses using the same reference data. One confusion matrix analyzed the map accuracy by a two-category approach: unconsolidated sediments and coral reef or hardbottom. The second analysis was a three-category approach to look at the effectiveness of mapping unconsolidated sediments, linear coral reef, and colonized pavement. Users, producers, and total map accuracies were calculated as described in CONGALTON (1991). The tau coefficient was calculated as described in MA and REDMOND (1995). The tau coefficient is considered a better measure of overall classification accuracy than other methods (KEPNER *et al.,* 2002; MA and REDMOND, 1995).

RESULTS

Application of NOAA Classification Scheme to the Broward Subtidal

The classification scheme was adapted from KENDALL *et al.* (2001, 2004). Our inability to detect sea grass and macroalgae required the omission of submerged vegetation categories. Added categories were ridge, sand borrow area, and wormrock. Acoustic ground discrimination results provided additional information that required other modifications to the classification scheme. A depth component was added to the colonized pavement and sand classes to indicate that the benthic assemblages on these features vary with depth. Furthermore, a clear acoustic distinction (see following discussion) enabled us to split the NOAA class "linear reef" into the following three subclasses: inner linear reef, middle linear reef, and outer linear reef.

Here we list all habitats identified during this study. Definitions are only supplied where they deviate from the standard NOAA terminology. For definition of all other terms see KENDALL *et al.* (2001).

- Coral reef and colonized hard bottom
  - Linear reef
    - Linear reef—outer: Consists of the reef crest of the outer reef.
    - Linear reef—middle: Because the middle reef exhibited much less clear morphological differentiation than the outer reef, it was not practical to subdivide it into several units. It is therefore encompassed in one single category, "linear reef." This category is given a unique color identifier because the acoustic roughness measures suggest a community structure that is largely distinct from hard grounds, shallow reef, and outer reef.
    - Linear reef—inner: The inner reef is an immature reef, best described as linear reef lacking clearly defined zonation. It has a unique color identifier because acoustic and biological data indicate that it harbors a distinct benthic community from the middle and outer reefs.
  - Spur and groove (drowned): Habitat having alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment.
  - Patch reef
    - Individual patch reef
    - Aggregated patch reef
  - Scattered coral or rock in unconsolidated sediment
  - Colonized pavement
    - Colonized pavement—deep: This category includes a transition zone from colonized pavement to colonized rubble on the deep reefs. Because much of the rubble in the lee of the outer reef is at least partly consolidated, the differentiation between colonized pavement and rubble would be somewhat artificial.
    - Colonized pavement—shallow: This category includes rubble in many areas; however, consolidated rubble fields are a less frequent feature in shallow water. Especially inshore of the ridge complexes, limited

rubble is found and a wide, contiguous area of pavement is encountered. This area can have variable sand cover, which shifts according to wave energy in response to weather. Thus, some of the colonized pavement will always be covered by shifting sand and the density of colonization will be highly variable.

Ridge: Linear, shore-parallel, low-relief features that appear to be submerged cemented ancient shoreline deposits. Presumably, they are the foundation upon which the linear reefs grew and consist of early Holocene shoreline deposits; however, verification is needed. The biological cover is similar to that of colonized pavement with macroalgae, scleractinians, gorgonians, and other sessile invertebrates that are dense enough to partially obscure the underlying carbonate rock.

Ridge—deep: While the geological provenance of the structure is not clear, its morphology suggests it to be a shoreline deposit of older age than the outer reef, possibly the structure on which the outer reef initiated. It consists of hard ground with variable and shifting sand cover and sparse benthic communities.

Ridge—shallow: Ridges found in shallow water near shore that are geomorphologically distinct, yet their benthic cover remains similar to the shallow colonized pavement communities on the surrounding hard grounds. They presumably consist of early Holocene shoreline deposits with possibly some *Acropora* framestones. However, verification is needed.

Unconsolidated sediments

Sand

Sand—shallow: Shallow water sediment exposed to a higher energy environment. Large, mobile sand pockets are found on the areas of consolidated hardgrounds. It is believed that the sand movement is a deciding factor in the generation of benthic patterns.

Sand–deep: Deep water sediment exposed to a lower energy environment. This is finer grained sediment primarily encountered between the middle and outer reefs and deeper.

Other delineations

Artificial: Manmade habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil.

Wormrock: This category is only encountered in the immediate nearshore areas, where the polychaete worms *Phragmatopoma caudata* (Sabeleriidae) build small bioherms consisting of their collated tubes. Wormrock is generally more ephemeral than the surrounding limestones. They persist on the very nearshore shallow pavement, jetties, and piers throughout the county.

Inlet channel: All inlet channels in the survey area are maintained artificially and are characterized by dredged bottom and spoil ridges on the flanks.

Sand borrow areas: Several borrow pits from previous dredging projects are found throughout the survey area. While they are all found in sandy areas at the bottom, many of them expose limestone, and thus small ridges or patch reefs are formed that can harbor a strongly localized and patchy, but sometimes dense, benthic fauna.

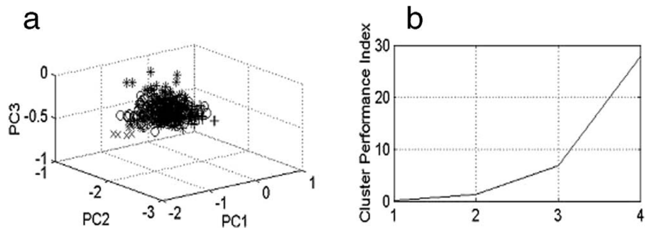


Figure 3. (a) Ordination of all data points along the first three principal components (left). Data within the point cloud are coded according to class. (b) The cluster performance index (CPI) is a measure indicating whether a splitting decision was correct, which is indicated by an increase in value (right). The CPI graph indicates that the splitting decisions to four clusters were correct.

Acoustic Results

Over 2300 km of survey lines were conducted on inshore habitat for acoustic ground discrimination. The entire marine area of Broward County from the 6-m depth contour to the 35-m depth contour was surveyed at a line spacing of 50 m. Surveys were organized into "tiles" of approximately 5 km × 1 km area. A total of 44 such survey tiles were produced.

QTC View

The acoustic data were merged into three groups, each encompassing about a third of the survey area. The merge was necessary because not all survey tiles contained all habitats and depth zones. In the merged files, signals from all possible habitats were included. Differences in waveform characteristics between the three reefs were evaluated. Data points arranged along the first three principal components were tightly clustered (Figure 3a). The cluster performance index, a measure indicating correctness of splitting decisions, showed a marked increase after four splits (Figure 3b), which suggests that this was the optimal number of classes. The depth distribution of all the split classes indicated that depth contamination did not affect the clustering process because all classes occurred over all depths within a survey. But depth distribution of classed points also indicated depth preference in some classes (Figure 4). Four classes showed clear distributional preferences and a fifth ubiquitous class (omitted from display) was randomly distributed over the entire depth. The four preferentially distributed classes (and their color codes used in Figure 4) were concentrated:

In the deeper areas on the outer reef (white) and beyond (light gray)
On the middle reef (dark gray)
On the nearshore ridges and hardgrounds (black)

These classes were coherent between the three merged tile groups and were therefore considered to encode the same substrata in each of the three regions of Broward County.

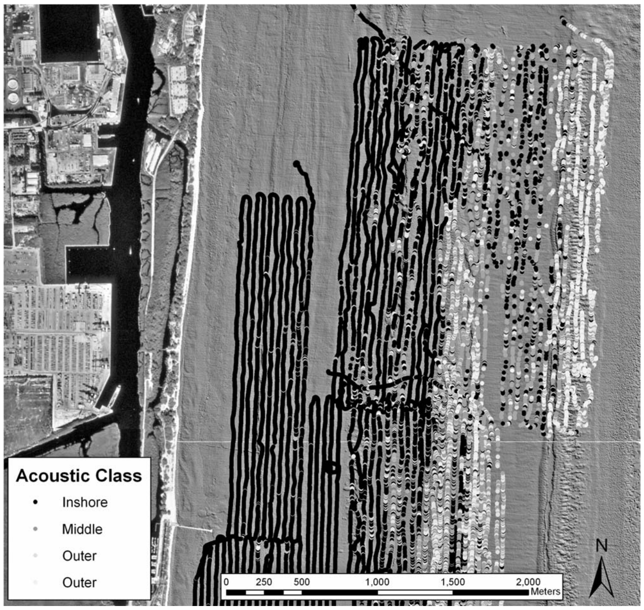


Figure 4. Merged QTC surveys for South Broward. The merged surveys were classified by PCA analysis in QTC view for optimal splits and imported into GIS for analysis. The merged data show clear trends evident when displayed on the hill-shaded LADS bathymetric surface as reference. Four of the five classes were associated with specific areas. The black class was found most frequently inshore while the dark gray concentrated on the middle reef and the light gray and white on the outer.

Echoplus

The Echoplus data set consisted of 1,270,061 individual data points. A total of 39 survey tiles were used. The digital number return encoded different categories than the QTC survey. In QTC, some clear differences were found between the reefs and the shallow and deep areas; however, the within-reef spatial patterns were not very clear. In Echoplus, a very clear differentiation between low-scatter areas on reefs and sand, and high-scatter areas was found. The Echoplus surveys allowed a clear delineation of the reefs and rubble areas as high-scatter areas (Figure 5). Also within the reefs, areas of relatively higher and lower scatter were detected.

Data distribution of the E1 parameter was normal, while that of the E2 parameter was strongly nonnormal (Figure 6). From survey geometry and the relative distribution of hardgrounds *vs.* softgrounds in Broward County, a more normal distribution was expected. It is unclear why the E2 parameter was so strongly skewed to small values. This problem has been previously reported by other authors (Hamilton, Mulhearn, and Poeckert, 1999) and remains unresolved but could represent some depth pollution of the signal. Therefore, the E1 parameter was favored in further analyses over the E2 parameter.

Area of Mapped Habitat

Areas of the mapped classes were tabulated in ArcGIS9. Approximately 112 km^2 were mapped in the top tier (habitat) of which 56.62 km^2 consisted of coral reef and colonized hard

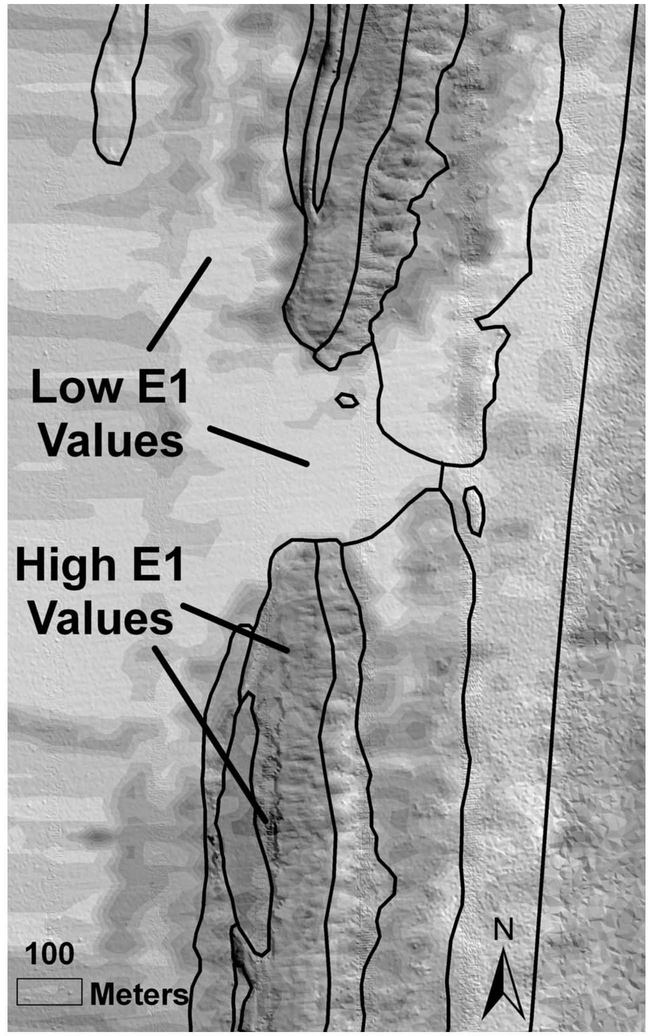


Figure 5. Inverse distance weighted interpolation map of E1 values from a single Echoplus survey tile on the outer reef. The black lines are the mapped polygons and the IDW layer is partially transparent to see the bathymetric surface. High E1 values (dark) correspond to the linear outer reef while low E1 values (light) correspond to the sand surrounding the reefs. The gradient of E1 values within the reef is believed to correspond to changing faunal densities.

bottom (50.42%), 52.56 km^2 of unconsolidated sediments (46.80%), and 3.12 km^2 was classified as other (2.78%) (Table 1). These categories were further refined in a middle tier (type) into 12 groups giving the following areas: 52.56 km^2 of sand (46.80%), 19.42 km^2 of colonized pavement (17.29%), 18.38 km^2 of linear reef (16.37%), 10.76 km^2 of ridge (9.58%), 4.82 km^2 of aggregated patch reef (4.29%), 2.90 km^2 of spur and groove (2.58%), 2.22 km^2 of sand borrow area (1.98%), 0.48 km^2 of inlet channel (0.42%), 0.42 km^2 of artificial (0.38%), 0.31 km^2 of scattered coral and rock in sand (0.27%), 0.03 km^2 of patch reef (0.03%), and 0.004 km^2 of wormrock (0.004%). The third classification tier, modifier, subdivided certain classes by a depth component. This division is illustrated in Table 1.

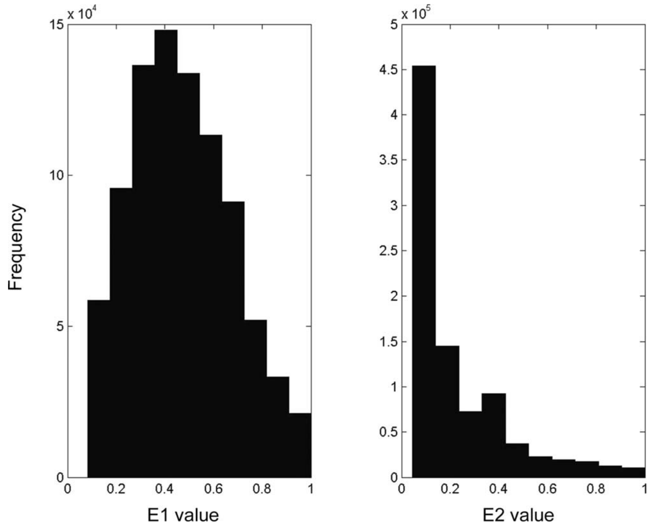


Figure 6. Distribution of E1 (left) and E2 (right) parameters from Echoplus survey. Data were grouped into 10 bins. Larger numbers of bins did not significantly alter the distribution pattern.

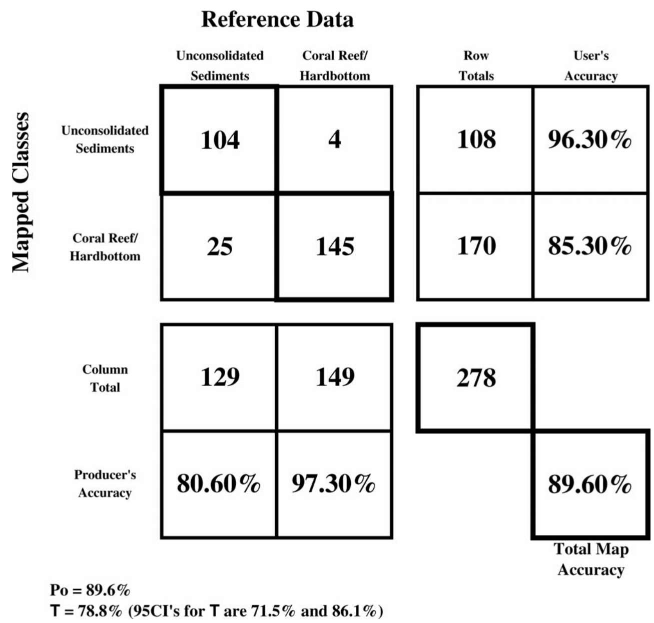


Figure 7. Confusion matrix for two generalized mapped classes: unconsolidated sediment and coral reef–hard bottom.

Accuracy Assessment

The results of the accuracy assessment yielded a high level of accuracy with a total percentage agreement (Po) of 89.6% for the two-category analysis (Figure 7) and 88.1% for the three-category analysis (Figure 8). Combining the linear reef and colonized pavement classes together into one class as coral reef–hard bottom yielded the highest user, producer, and total map accuracies (Figure 7). The two-category approach gave a user's accuracy of 85.3% and a producer's accuracy of 97.3% for coral reef–hard bottom and 96.3% and 80.6% for user's and producer's accuracies for unconsolidated sediments, respectively. The tau coefficient for the two-category analysis was 78.8%.

The three-category analysis (using the same reference data) split the coral reef and colonized hard bottom into two

Table 1. *Areas (km²) of all mapped polygons delineated by three classification scheme tiers; habitat, habitat type, and habitat modifier. Note for habitat, any polygon classified to contain coral or rock (*e.g., *aggregated patch reef) was included in the coral reef and colonized hard bottom class.*

Habitat	Type	Modifier	Area (km²)	% of Total Area
Coral reef and colonized hard bottom	Colonized pavement	Shallow	17.46	15.55%
		Deep	1.96	1.74%
	Patch reef		0.03	0.03%
	Scattered coral or rock in sand		0.31	0.27%
	Linear reef	Inner	6.95	6.18%
		Middle	8.37	7.45%
		Outer	3.07	2.73%
	Spur and groove		2.9	2.58%
	Aggregated patch reef		4.82	4.29%
	Ridge	Shallow	8.45	7.52%
		Deep	2.31	2.06%
Unconsolidated sediments	Sand	Shallow	27.46	24.45%
		Deep	25.1	22.35%
Other delineations	Sand borrow area		2.22	1.98%
	Artificial		0.42	0.38%
	Wormrock		0.004	0.00%
	Inlet channel		0.48	0.42%

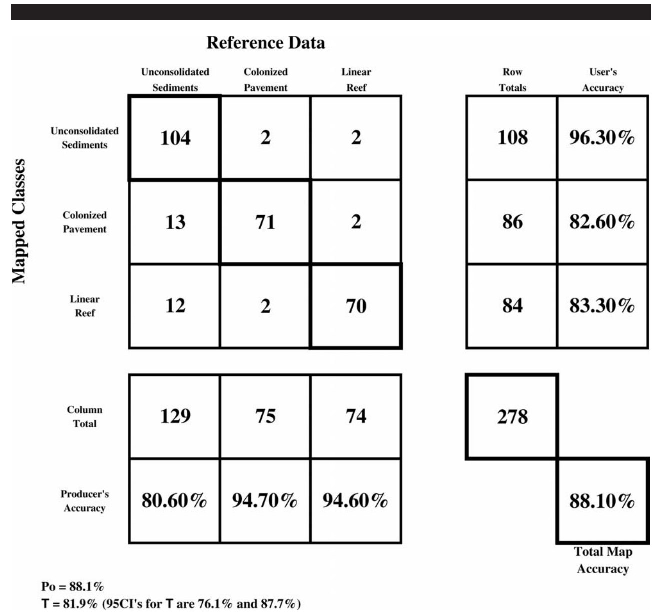
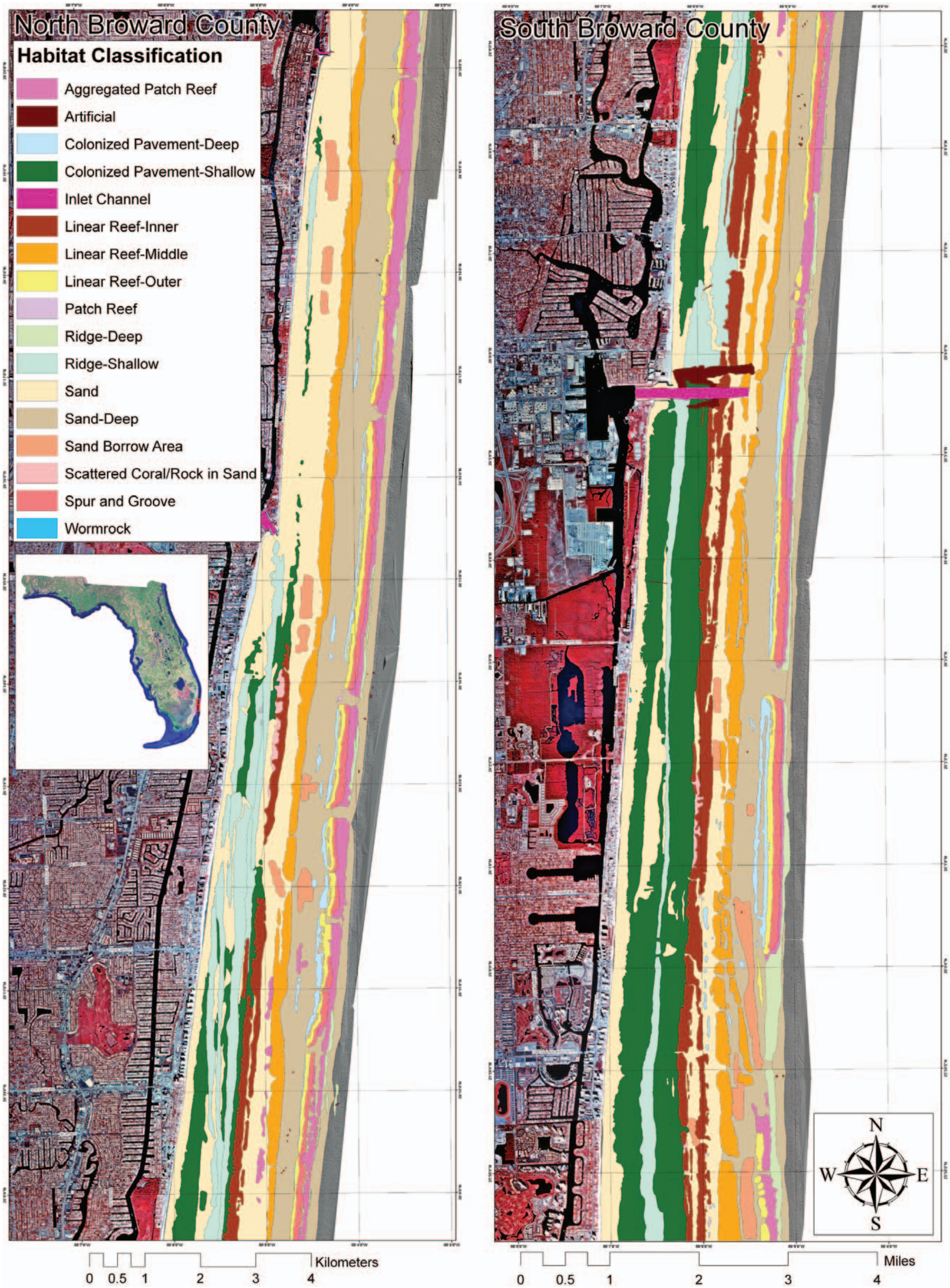


Figure 8. Confusion matrix for three generalized mapped classes: unconsolidated sediments, colonized pavement, and linear reef.


North Broward County
Habitat Classification
Aggregated Patch Reef
Artificial
Colonized Pavement-Deep
Colonized Pavement-Shallow
Inlet Channel
Linear Reef-Inner
Linear Reef-Middle
Linear Reef-Outer
Patch Reef
Ridge-Deep
Ridge-Shallow
Sand
Sand-Deep
Sand Borrow Area
Scattered Coral/Rock in Sand
Spur and Groove
Wormrock
0 0.5 1 2 3 4 Kilometers
South Broward County
N
W
E
S
0 0.5 1 2 3 4 Miles

Reference Data

Mapped Classes	Unconsolidated Sediments	Coral Reef/ Hardbottom	Row Totals	User's Accuracy
Unconsolidated Sediments	37	6	43	86.00%
Coral Reef/ Hardbottom	1	35	36	97.20%
Column Total	38	41	79	
Producer's Accuracy	97.40%	85.40%		91.10% (Total Map Accuracy)

Po = 91.1%
T = 82.3% (95CI's for T are 69.8% and 94.8%)

Figure 10. Confusion matrix from photo interpretation of Buck Island, St.Croix, U.S. Virgin Islands, using on-screen digitizing excluding the submerged vegetation class (from Kendall *et al.*, 2004).

classes (colonized pavement and linear reef) based upon the location of the assessment point. This yielded a slightly lower total map accuracy of 88.1%. The user's and producer's accuracies for unconsolidated sediments were the same. The producer's accuracy for colonized pavement and linear reef were 94.7% and 94.6%, respectively. User's accuracies for colonized pavement and linear reef were 82.6% and 83.3%, respectively. The tau coefficient for the three-category analyses was 81.9%.

DISCUSSION

Benthic habitats were made compatible with the NOAA Puerto Rico mapping effort (KENDALL *et al.,* 2001) with slight modification. They were drawn at the same scale using the same minimal mapping unit and a similar classification scheme. The most notable modification was in the mapping of different zones. The NOAA Puerto Rico mapping effort classified the polygons into nine reef zones according to the features' relationship along the shore (*i.e.,* lagoon, back reef, fore reef, bank/shelf, *etc.*). While these categories were useful in Puerto Rico, many of these mapped zones did not apply in south Florida. The absence of an emergent reef in south Florida precluded mapping zones such as lagoon, back reef, and reef crest. Our effort was confined to depths from shore to 35 m, every mapped feature resided in the bank/shelf zone, and the land and shoreline intertidal zones were excluded.

The final map showed three linear reef complexes (outer, middle, and inner), a series of deep and shallow ridges thought to be antecedent shorelines (BANKS *et al.,* 2007; DAVIS, 1997; FINKL, 2005; STAUBLE and MCNEIL, 1985), a large sand area between the middle and outer reefs, and a considerable amount of colonized pavement (Figure 9). The outer linear reef was divided into four habitats: aggregated patch reef, spur and groove, linear reef, and deep colonized pavement. Aggregated patch reefs on the eastern edge of the outer linear reef were interspersed with the deep sand. Patches were more prevalent close to the reef and tapered off eastward, becoming less dense. The drowned spur and groove was evident by mostly continuous reef spurs and sand grooves along the eastern edge of the outer reef. The crest of the outer reef was mapped as the linear reef proper, and the western edge was mapped as colonized pavement. The outer reef was separated from the middle reef by a wide sandy plane (deep sand), which was characterized by a different scattering class in acoustic analyses than the shallow sand found inshore. Likely, this was founded in the more developed ripples on the shallow sand, which created a unique scattering class. The eastern boundary of the middle reef was distinct and easily mapped, whereas acoustic discrimination aided in determining the western boundary. Much of the inner reef is patchy growth atop an inshore ridge and clear zonation is absent. Shoreward of the inner reef, another sand area or a mixture of sand and colonized pavements were found. Several nearshore ridges were mapped that could be classified as linear reef habitat but were thought to be of nonreef origin (BANKS *et al.,* 2007; FINKL, 2005). These structures were mapped separately even though similar habitat comprises the inshore ridges and the shallow colonized pavements. Although present in the mapped area, submerged vegetation and large rubble zones were not detected with sufficient accuracy to allow their mapping.

Acoustic ground discrimination is capable of detecting differences in the density of epibenthic communities such as medium- to large-sized barrel sponges, gorgonians, and/or hard corals (MOYER *et al.,* 2003; RIEGL and PURKIS, 2005; RIEGL *et al.,* 2005) and therefore has the potential of detecting differences in the benthic communities between and within the reef complexes. The high resolution LADS bathymetry and video groundtruthing were the foundation to which the acoustic data were added and primarily used to detect differences in scatter types related to different heights of the fauna, which correlated to different community types (Figure 4). In this study, we used the acoustic data to derive broad-brush differences between the reef types. This between-reef pattern of the acoustic surveys was confirmed by ecological data (GILLIAM, 2006; GILLIAM *et al.,* 2006; MOYER *et al.,* 2003). The acoustic survey also provided additional information to the bathymetry by showing well-defined roughness classes aiding the identification of surface complexity caused by benthic fauna or flora in areas of uniform bathymetry. The combination of these data types yielded a more accurate map than any

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Figure 9. Habitat map for Broward County, Florida.

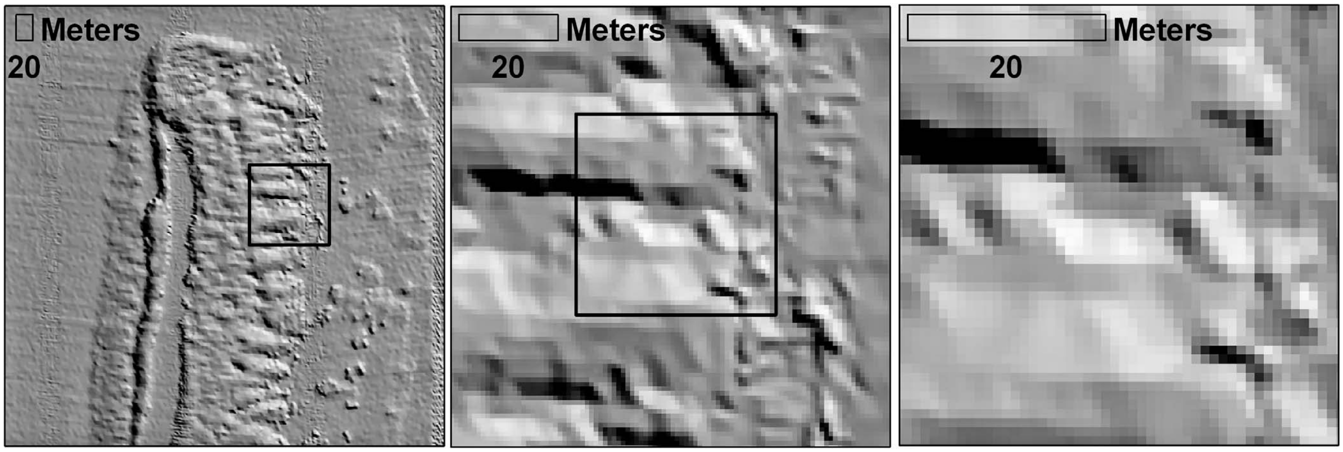

Figure 11. Hillside-shaded images from high-resolution bathymetry at different scales. The left image is the data at 1 : 6000, the center is the same data zoomed to 1 : 1000, and the right image is zoomed to 1 : 500. Scale becomes an issue when increases in mapping resolution are desired.

single method (*e.g.,* laser bathymetry or the acoustic data) separately.

The acoustic surveys may add an additional dimension not incorporated into the map presented herein. Within-reef patterns of acoustic diversity were evident (Figure 5) throughout much of the study area. Although unconfirmed in this study, these patterns may be showing biological density gradients within the reef polygons. If confirmed, these data could be added as a finer classification tier in the hierarchy to show a biological density gradient within features.

The LADS data allowed a geomorphology-driven classification of reef features to be developed that is broadly compatible with NOAA mapping categories. For the interpretation of the geomorphologic features, the QTC View and Echoplus surveys proved primarily important in the discrimination of habitats that were poorly resolved in the bathymetric data sets, such as areas of pavement (flat and largely featureless submarine hard grounds). Since these areas had similar benthic communities as the nearby reefs, they usually showed a "reef-type" acoustic class thus allowing the delineation of flat hard ground from sand. In particular in the sector of Broward County south of Port Everglades, the QTC View and Echoplus data were of crucial importance to understanding the structure of the colonized pavements between the shoreline and the inner reef. From bathymetry data alone, it was not possible to distinguish whether the area was sandy or rocky, but the acoustic surveys indicated that the entire area consisted of consolidated hard grounds variably covered with a generally thin sand veneer. In limited areas, verification via chirp subbottom sonar profiles showed discrimination of clear subsurface reflectors to about 7 m depth inside the substratum, thus facilitating the discrimination between linear reefs and areas of deeper sand. Additionally, aerial photography was used in shallow water areas where it was helpful in distinguishing hard bottom from sand; however, poor water clarity precluded its extensive use.

The habitat maps presented here have similarities to those of FINKL (2005), which were based solely on geomorphology but did not attempt to characterize benthic faunal assemblages. This current study adds biological community information to the knowledge of those same features, encompasses the entire county, and makes the Broward County maps compatible and comparable with other large-scale biogeographic maps by NOAA.

The Broward County benthic habitat maps were accurate to a high degree. At the most basic hierarchical level as in the two-category assessment between unconsolidated sediments and coral reef–hard bottom, the map accuracy was 89.6% and all producer's and user's accuracy statistics were above 80% (Figure 7). The tau coefficient, perhaps the most accurate measure (MA and REDMOND, 1995), yielded an accuracy of 78.8%. A three-category approach where the coral reef–hard bottom was separated into colonized pavement and linear reef yielded a tau coefficient of 81.9% (Figure 8).

The accuracy assessment results reported herein are directly comparable to the NOAA Puerto Rico and Virgin Island mapping effort using photo interpretation and on-screen digitizing in GIS. Both efforts were undertaken using a similar classification scheme of Western Caribbean habitats. The Broward accuracy (Po) of 89.6% was only 4% lower than the NOAA Puerto Rico and Virgin Island accuracy of 93.6% (KENDALL *et al.,* 2004). The NOAA tau was 90.3%, 8.4% better than the Broward effort. Accuracy statistics of the NOAA maps were heavily influenced by the successful mapping of submerged vegetation. NOAA aerial photography interpretation was 100% accurate for this category. When recalculating without this category, NOAA and Broward map accuracies were close (Figure 10): NOAA 91.1%, *i.e.,* 1.5% better than in Broward; tau coefficient of 82.3%, *i.e.,* 3.5% better than in Broward. The accuracy of expert-driven visual interpretation of high-resolution bathymetry supplemented by acoustic ground discrimination and other methods is similar to that of aerial photography alone for mapping coral reef–hard bottom and unconsolidated sediments.

The lowest accuracy in the Broward maps was where the mapped category coral reef–hard ground in groundtruthing turned out to be unconsolidated sediment. Broward reefs contain many small-scale sand patches that are below the minimum mapping unit of 1 acre and were therefore beyond the scope of this effort. Decreasing the minimum mapping unit in the visual interpretation of high-resolution bathymetry is unlikely to yield higher accuracies because of scaling issues. The bathymetric surface was interpolated from points measuring approximately every 4 m, which gives a good perspective of most seafloor features at a larger scale (greater than 1 : 1000). At a scale smaller than 1 : 1000, features become much harder to delineate (Figure 11) and at 1 : 500 the 4 m × 4 m data resolution primarily shows interpolation artifacts rather than true seafloor morphology. Also the difficulty of distinguishing low relief habitats limits visual interpretation of bathymetric data. Low-relief hard-bottom, sand, and submerged vegetation look essentially the same, and sand veneers atop reef structure are nearly impossible to detect solely from bathymetry. With the aid of aerial photography, satellite imagery, or acoustic data these problems can be overcome.

CONCLUSIONS

Accurate maps outlining the entire Broward County subtidal seafloor from 0 to 35 m depth classified into NOAA equivalent habitat classes were created. Production of the maps was based on a variety of data types, including laser bathymetry, QTC View and Echoplus acoustic seafloor discrimination, chirp subbottom profiles, aerial photography, and groundtruthing. The accuracy of the Broward maps is comparable with that achieved by photo interpretation in clear waters and is a good example of how similar mapping products can be attained by different means. The approach employed herein ensured high accuracy by utilizing the data with highest resolution (LADS bathymetry) as the base and supplementing it with the lower resolution data of different information content. Similar methodology can be used in other areas where photo interpretation alone is not feasible.

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