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Gulf and Caribbean Research Vol 16(2), 177–184, 2004 Manuscript received May 30, 2004; accepted September 10, 2004

A CHARACTERIZATION OF THE SHALLOW-WATER CORAL REEFS AND ASSOCIATED HABITATS OF PUERTO RICO

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ABSTRACT We mapped bottom types and shelf zones of 1600 km^2 or about one fourth of Puerto Rico's insular shelf from the shoreline to the shelf edge. Overall map accuracy for these bottom types is estimated as 93.6% correct. Maps were produced through visual interpretation of benthic features using orthorectified aerial photographs within a Geographic Information System with customizable software. The maps are one component of an integrated mapping and monitoring program underway by NOAA and its partners in the US Coral Reef Task Force to assess all US reef ecosystems. Maps are currently being used to enhance coastal research and management activities in Puerto Rico such as fisheries assessments and designation of important fish habitats.

Introduction

Coral reef ecosystems present spatial challenges for research and management. The broad scales of ecosystem processes and complex connections among diverse components including seagrass beds, mangroves, algal plains, coral reefs, and other hard bottom substrates are often best understood and managed using ecosystem maps as a spatial framework. The ability to properly stratify sampling programs for research, make informed decisions on defining fish habitats, and place ecologically relevant boundaries for marine protected areas is necessarily limited without accurate benthic maps created using an appropriate classification framework. The National Action Plan for US Coral Reef Protection endorsed by the US Coral Reef Task Force (USCRTF) identified mapping of all US coral reefs as one of the highest priorities for understanding and protecting these important ecosystems (USCRTF 2000, Monaco et al. 2001).

To meet this goal in the US Caribbean (Puerto Rico and the US Virgin Islands), visual interpretation of aerial photography was identified as the most effective approach given the size of the region to be mapped, the well documented and successful applications of photo-interpretation, the desired thematic and spatial resolution of map products, and the desired accuracy of map attributes. The alternatives and tradeoffs among various mapping technologies have been discussed elsewhere in detail (e.g., Holden and LeDrew 1998, Green et al. 2000) and are beyond the scope of this assessment. Furthermore, the specific methods used to create the map products are documented in detail in Kendall et al. (2001), Kendall et al. (in press), and Warner et al. (in review), and so will only be provided in general form here. Rather, the present focus is on the results of a photography-based characterization of reef ecosystems in Puerto Rico.

Previous assessments of marine ecosystems in Puerto Rico have been patchy, focused on single ecosystem characteristics or components (e.g., geology, coral reefs, or mangrove forests respectively), have too coarse a resolution to support most research and management applications, or are simply out of date given the frequency of hurricanes, pace of coastal development, and other vectors of habitat change in the region (e.g., Rodriguez et al. 1977, Morelock 1978, Goenaga and Cintron 1979, Beach and Trumbull 1981, Grove 1983, Pilkey et al. 1987, Trias 1991, Rodriguez et al. 1992, Morelock et al. 1994, Kruer 1995, Reid and Kruer 1998). These historical assessments provide valuable perspective on a subset of ecosystem components, but do not provide the island-wide characterization of the reef ecosystem called for by the USCRTF.

Building on the recently created benthic maps for the Florida Keys (Florida Marine Research Institute 1998) and the US Virgin Islands (Kendall et al. 2001, Kendall et al. in press), the objective of this project was to produce a spatial characterization of the shallow water coral reefs and associated habitats in Puerto Rico, specifically to: 1) map seabed features visible in aerial photography using a hierarchical classification scheme and a minimum mapping unit (MMU; smallest feature mapped) of 4048 m^2 (1 acre); 2) map seabed features with a minimum thematic accuracy of 90% correct for map categories including coral reefs/hard bottom, unconsolidated sediment, and submerged vegetation; 3) identify areas not able to be mapped with this approach to focus future assessments using alternative technologies; 4) quantify the coverage and distribution of mapped features; 5) provide digital habitat maps, images, and other data products to support research and management of coral reef ecosystems.

MATERIALS AND METHODS

Location Description

Puerto Rico is located at the intersection of the greater and lesser Antilles on the northern edge of the Caribbean Plate. It shares a volcanic island platform at the edge of the Puerto Rican Trench with several of the US and British Virgin Islands, but has a much larger land area and consequently has a more significant river drainage than the smaller Virgin Islands. The north coast is characterized by a narrow shelf and large amounts of river discharge. The south, southwest, and east coasts of the island have less river output and much broader shelf area. The large area and variable geomorphology of these coastal regions, plus the unique formations of the smaller Puerto Rican islands of Culebra, Vieques, Desecheo, and Mona make comprehensive mapping of benthic resources challenging.

Mapping Methods

Color aerial photographs were acquired in 1999 by NOAA's Aircraft Operation Center and National Geodetic Survey. These 1:48,000 scale photos (except for Desecheo at 1:20,000 and Mona at 1:28,000) were scanned at a resolution of 500 dots per inch resulting in digital images with 2.4 m pixels (Desecheo 1.0 m and Mona 1.5 m). The best images for benthic mapping (least clouds, sun glint, and turbidity) were selected and orthorectified by the NOAA National Geophysical Data Center using ground control points, flightline kinematics, and other image parameters uploaded into Socet Set version 4.2.1 (Warner et al. in review). The coastal regions described above and the individual small islands were batch processed such that 7 separate, orthorectified mosaics were created (Table 1). The positional accuracy of each mosaic was measured using independent ground control points collected with differential GPS. Additional detail on the acquisition parameters and orthorectification process are available in Kendall et al. (2001) and Warner et al. (in review).

Coral reefs and associated benthic habitats such as hard bottom, mangroves, seagrass beds, sand, and algal plains were mapped using GIS software and a hierarchical classification system developed in consultation with local experts and the many schemes classifying Caribbean benthos (e.g., Shepard et al. 1998, Mumby and Harborne 1999). The 3 main habitat categories in the scheme were: coral reef and hard bottom, unconsolidated sediment, and submerged vegetation which encompassed a total of 26 mutually exclusive subcategories. In addition to these bottom types, mapped features were also assigned a location attribute, or zone, to denote their position on the insular shelf. The following zones were identified: shoreline/intertidal, lagoon, backreef, forereef, reef crest, bank/shelf, bank/shelf escarpment, or dredged ("dredged" is included here since this activity eliminates natural zonation). Detailed descriptions as well as under water and aerial imagery for each bottom type and zone are available in Kendall et al. (2001).

Benthic features defined in the classification scheme were visually identified in the orthorectified mosaics and digitized by tracing around their edges using the Habitat Digitizer extension for ArcView 3.2 (Kendall et al. 2001). This software allows users to customize a classification scheme, set a MMU and mapping scale, and facilitates assignment of polygon attributes. Polygons were delineated at a mapping scale of 1:6000 on the computer monitor, which maximized the ability to identify bottom types given the scale and scan resolution of the original imagery. A MMU of 4048 m^2 (1 acre) was selected to meet the spatial

TABLE 1

Mosaic specifications for each island or coastal segment. Positional accuracy is in meters +/- standard deviation.

Location	Photo scale	Pixel width (m)	No. of photos	Mean spatial accuracy (m) latitude	Mean spatial accuracy (m) longitude
Culebra	1:48000	2.4	14	5.51 +/- 20.1	7.04 +/- 18.2
Mona	1:28000	1.5	14	2.76 +/- 9.1	4.06 +/- 4.5
Desecheo	1:20000	1.0	3	4.26 +/- 30.0	9.47 +/- 36.4
Puerto Rico: South	1:48000	2.4	72	0.06 +/- 3.0	0.89 +/- 4.4
Puerto Rico: East	1:48000	2.4	55	0.85 +/- 9.5	2.59 +/- 7.8
Puerto Rico: West	1:48000	2.4	34	1.65 +/- 5.1	1.04 +/- 6.7
Puerto Rico: North	1:48000	2.4	51	4.88 +/- 9.6	4.06 +/- 5.3

resolution requested by the USCRTF and by local natural resource managers. Field surveys conducted with local experts and previous studies of Puerto Rico's benthic habitats were used to guide polygon delineation and labeling whenever possible. Previous studies consulted included geological maps (Beach and Trumbull 1981, Grove 1983, Morelock 1978, Morelock et al. 1994, Pilkey et al. 1987, Rodriguez et al. 1977, Rodriguez et al. 1992, Trias 1991), biological characterizations (Goenaga and Cintron 1979, Kruer 1995, Reid and Kruer 1998), and those that integrate multiple data types (NOAA et al. 2000). Specific field sites that were examined included those with difficult to interpret spectral and textural signatures in the orthorectified mosaics and sites with signatures that were representative of different combinations of bottom type, depth, zone, and water clarity. Draft maps were reviewed by local researchers and managers and further refined.

Thematic accuracy of the final benthic maps was measured through intensive field sampling within a small but representative region of the project area due to the logistical constraints of collecting a widespread accuracy assessment dataset around all of the islands mapped. For this purpose, the La Parguera area in southwestern Puerto Rico was chosen because of the wide variety of water depth, turbidity, and habitat types present at this site. The accuracy measured at La Parguera is assumed to be similar to the accuracy of maps elsewhere in the project area. Data for accuracy assessment were collected from 200 sites. Sites were selected using a random stratified approach based on the 3 main habitat types in the classification scheme and 2 depth strata (0–15 and 15–30 m). This ensured that comparison points were spread throughout the assessment area and that estimated accuracy would be representative of the wide variety of habitat types and water depths present. Bottom type was recorded at each field site and then compared to the attributes assigned to that location in the habitat map. An error matrix that displays errors of inclusion and exclusion for only the 3 main habitat categories was produced due to the logistical constraints of collecting the recommended minimum range of 20–50 accuracy check points for each of the 26 classifications at the detailed level of the hierarchy (Congalton 1991).

RESULTS

Positional accuracy for orthorectified mosaics varied depending on the data available for georeferencing and the quality of the imagery (Table 1). In general, pixel position in the mosaics was estimated to be within a few pixel widths (~ 10 m) of their true location. An exception to this was the mosaic of Desecheo Island, northwest of Puerto Rico, which was not as accurately geopositioned as the other islands due to the difficulty in identifying coordinates of corresponding land and image features on its barren landscape. Because benthic habitats were digitized directly in a GIS using the georeferenced imagery, the positional accuracy of the habitat maps for each island or island segment is assumed to be the same as that reported for the mosaiced photography (Table 1).

Thematic accuracy of the general level of habitat classification in the La Parguera area was determined to be 93.6 percent overall (Table 2). Maps were 100 percent accurate for the unconsolidated sediment category and 99 percent for the submerged vegetation category. A small

TABLE 2

Error matrix for habitat classification at La Parguera. Numbers in the matrix indicate class coincidence, (I) indicates accuracy based on inclusion errors, and (E) indicates accuracy based on exclusion errors calculated from analysis of 200 ground truth points.

	Actual habitat type		
	Coral reef/ hardbottom	**Submerged vegetation**	**Unconsolidated sediment**
Mapped habitat type			
Coral Reef/Hardbottom	76 91.6% (I) 98.7% (E)	7	0
Submerged Vegetation	1	92 98.9% (I) 92.9% (E)	0
Unconsolidated Sediment	0	0	24 100% (I) 100% (E)

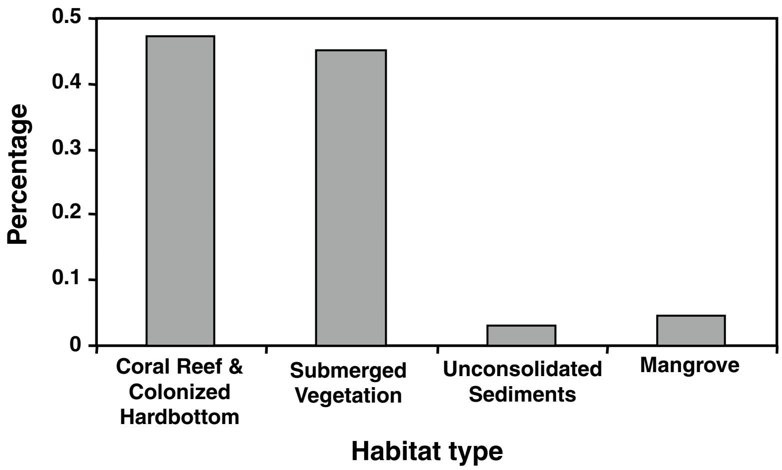

Figure 1: Mapped habitat types in Puerto Rico near shore waters (percent of area excluding polygons with "unknown" bottom type). Only the 3 most general classification categories plus mangroves are displayed.

percentage of coral reef/hardbottom sites were misclassified as submerged vegetation.

About 1600 km^2 of benthic features were mapped. The habitat type with the largest area, excluding areas labeled unknown due to water depth or turbidity, was coral reef/hardbottom which accounted for nearly half of the mapped area (Figure 1). Submerged aquatic vegetation accounted for over 40 percent of the area mapped although this includes patchy seagrass and algae which may include considerable areas of bare sand. Mangrove forests covered about 5 percent of the area mapped. The bank/shelf zone included 85% of the area mapped (Figure 2). Combinations of habitat and zone that covered large areas included seagrass and colonized pavement with sand channels on the bank shelf which together accounted for more than half of the total area mapped (Table 3). Notable sites with extensive coverage of seagrass include the region between Vieques and the east end of Puerto Rico (240 km^2) and the southwestern corner of Puerto Rico around Cabo Rojo (80 km^2) (Figure 3). A large, continuous mangrove forest was mapped east of San Juan (15.5 km^2). Areas with discontinuous mangrove forests that covered large areas included the eastern tip of Puerto Rico around Roosevelt Roads Naval Base (9.1 km^2) and the Parguera area (4.1 km^2) (Figure 3). The largest reef areas mapped were located primarily along the southern and southwestern edge of the island where the shelf is broad and flat.

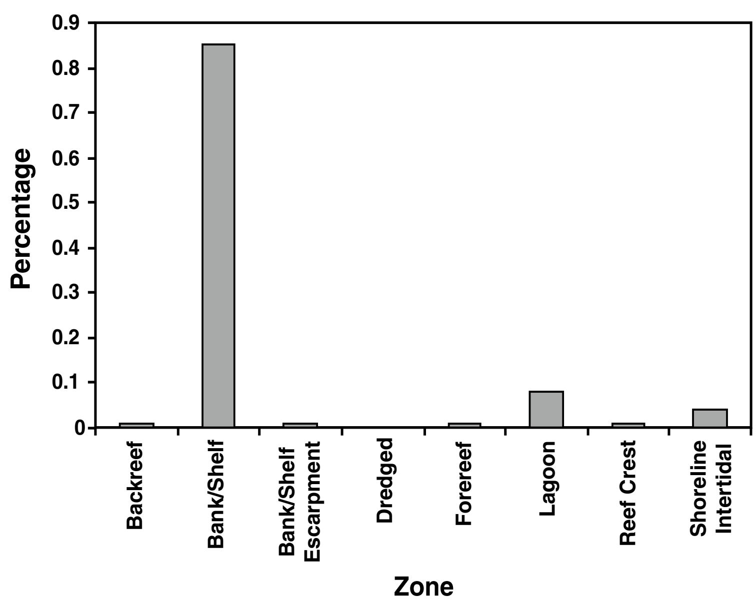

Figure 2: Mapped geomorphic zones in Puerto Rico near shore waters (percent of area excluding polygons with "unknown" zone).

TABLE 3

Matrix of area and percent of total area mapped the unique zone/habitat combinations. Some of the very similar habitat subcategories were grouped to save journal space (such as all 8 categories of seagrass and macroalgal patchiness). Polygons with either zone or habitat type labeled as "unknown" were excluded (this results in small differences between row and column totals between this table and values in Figures 1 and 2). The upper value in each cell denotes the area mapped in km^2 for each zone/habitat combination. The lower value in each cell is the percentage of the total area mapped that is covered by each zone/habitat combination. Blank cells indicate that no polygons were mapped that met those zone and habitat criteria. All table values are rounded to 2 decimal places and therefore may result in some zero values for very small features as well as slight apparent discrepancies in presentation of row and column totals.

General habitat types	Detailed habitat types	Shoreline intertidal	Lagoon backreef	Reef crest	Forereef	Bank/Shelf	Bank/Shelf	Escarpment	Dredged	ROW TOTALS
Unconsolidated sediment	Mud	11.5	6.2				4.0			21.7
		1.0	0.0			0.0				1.0
	Sand	0.3	2.2	0.1		24.5	0.0			27.1
		0.0	0.0	0.0		2.0	0.0			2.0
Coral reef and hardbottom	Colonized Bedrock	0.9	2.0	0.1	0.2	0.0	23.7			26.9
		0.0	0.0	0.0	0.0	0.0	1.0			2.0
	Colonized Pavement	0.1	1.7	0.1	0.0	0.7	176.3	3.5		182.4
		0.0	0.0	0.0	0.0	0.0	11.0	0.0		11.0
	Colonized Pavement with Sand Channels		2.8	0.7		1.0	305.9	5.8		316.2
			0.0	0.0		0.0	19.0	0.0		20.0
	Linear Reef	0.1	1.1	1.0	19.6	14.3	33.2	5.7		75.0
		0.0	0.0	0.0	1.0	1.0	2.0	0.0		5.0
	Patch Reef (Aggregated)		3.5	0.1			63.2			66.8
			0.0	0.0			4.0			4.0
	Patch Reef (Individual)	0.0	0.3	0.1	0.1	0.1	14.1			14.7
		0.0	0.0	0.0	0.0	0.0	1.0			1.0
	Reef Rubble			0.1	0.3		0.2			0.6
				0.0	0.0		0.0			0.0
	Scattered Coral/Rock in Unconsolidated Sed.		9.0	0.5	1.3	0.1	61.3	0.1		72.4
			1.0	0.0	0.0	0.0	4.0	0.0		5.0
	Spur and Groove Reef					0.1	1.8	0.1		1.9
						0.0	0.0	0.0		0.0
	Uncolonized Bedrock	0.1								
		0.0								
Submerged vegetation	Macroalgae (continuous and patchy)	1.0	6.8	0.2			88.4	0.2	0.0	96.7
		0.0	0.0	0.0			6.0	0.0	0.0	6.0
	Seagrass (continuous and patchy)	3.4	51.9	16.9	1.8	0.3	550.0			624.3
		0.0	3.0	1.0	0.0	0.0	34.0			39.0
Other	Mangrove	72.4			0.2					72.6
		5.0			0.0					5.0
	Artificial						0.1			0.1
							0.0			0.0
	COLUMN TOTALS	90.0	87.0	20.0	24.0	16.0	1347.0	15.0	0.0	1599.0
		6.0	5.0	1.0	1.0	1.0	84.0	1.0	0.0	100.0

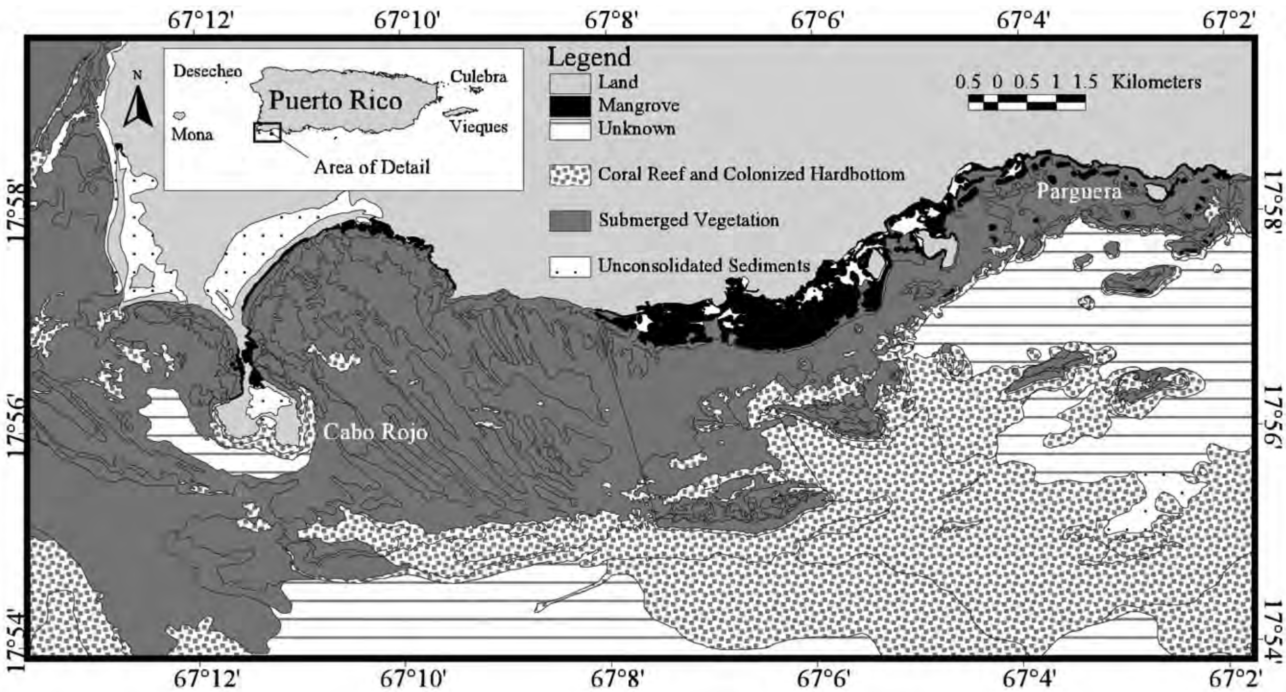

Figure 3: Benthic map of southwestern Puerto Rico from Cabo Rojo to Parguera. To simplify this example map, only "land", "mangrove", "unknown", "coral reef and hardbottom", "submerged vegetation", and "unconsolidated sediments" are shown rather than all of the more detailed thematic classifications.

DISCUSSION

The baseline inventory of Puerto Rico's coral reefs, seagrass beds, mangroves, and associated habitats provided by this assessment offer diverse opportunities for research and management of this ecosystem. Uses of these map products already include a wide range of research, monitoring, and management applications. The GIS data provides a spatial framework within which to stratify sampling for fisheries and habitat research (Christensen et al. 2003). The maps are one component of an integrated monitoring and assessment program underway by NOAA and its partners in the USCRTF to assess reef condition and health trends (Monaco et al. 2001). The spatially articulated inventory of coral reefs and associated habitats is required for identifying Essential Fish Habitat (Rosenberg et al. 2000), identifying locations and appropriate sizes for marine protected areas (National Research Council 2001), and providing coastal management agencies with basic information to conduct change detection following natural or anthropogenic disturbance events.

The large area mapped, small MMU, and large number of detailed classifications prevent inclusion of all but an example map in journal format (Figure 3; only 4 map classes shown). Furthermore, the real value of this assessment goes well beyond the summary statistics of habitat areas reported above. An atlas containing 211 printable maps, digital map data (ArcGIS shapefiles), orthorectified mosaics of aerial photos, unrectified scans of all aerial photographs, ground control points, accuracy assessment points, the Habitat Digitizer extension to ArcView 3.x, and other project components are all freely available from the authors' website (http://biogeo.nos.noaa.gov).

It is important to note that the summary statistics reported above do not include the large area of insular shelf that could not be mapped in this assessment. Due to discharge of turbid rivers, suspended sediment from wave action, water depth, clouds, and other factors that prevent benthic features from being visible, 75% of the Puerto Rican insular shelf (area between the shoreline and the 30 m isobath or shelf edge) could not be mapped using the available aerial photography. Much of the north coast of Puerto Rico could not be mapped due to turbidity associated with the many rivers and heavy surf conditions that characterize this region. The central portion of the west coast had shelf features obscured by sediment laden river discharge from Rio Guanajibo and Rio Grande de Anasco. The very small island of Monito was not photographed. A large area between the islands of Vieques and Culebra extending eastward along the shelf platform to the territorial boundary of the US Virgin Islands was not mapped because bottom depth was beyond the limit of detection by aerial photography (~ 20 m). A widening variety of remote sensing technologies including satellites, airborne hyperspectral scanners, lidar, and shipboard multibeam sonar are rapidly improving and providing ever more detailed, accurate, and cost effective alternatives for benthic mapping in range of depths and water conditions. A combination of these aerial, satellite, and in water technologies will be required to comprehensively and cost effectively map all US reef ecosystems (USCRTF 2000) such as those portions of the Puerto Rican shelf mapped as “unknown” in this assessment.

Thematic accuracy measured in the Parguera area was well within acceptable levels for maps of this type. Since the variety of water conditions and habitats in Parguera are representative of most of Puerto Rico, the entire project area is assumed to be mapped with similar success. Areas with poorer water conditions were labeled as unknown. It is important to note, however, that the accuracy assessment applies only to the highest level in the classification hierarchy. This was identified by the local scientific and management groups consulted during map production as the most important level in the scheme to be evaluated using the limited funds and logistical support available for field activities. While categories at this hierarchical level encompass the more detailed classifications, thematic accuracy of the more detailed categories was not quantified and is likely to be lower than the overall accuracy and values for the 3 main categories (Table 2).

Our modifications to an established and proven approach to coral ecosystem mapping have been used in Puerto Rico, the US Virgin Islands (Kendall et al. in press), portions of the Hawaiian Islands (Coyne et al. 2003), and are being further modified to incorporate new technologies for mapping US coral ecosystems elsewhere in the world. The maps and associated products made by this assessment provide a needed characterization of Puerto Rico’s benthic habitats, direct future assessments toward unmapped areas, and enhance coastal research and management capabilities in the region.

ACKNOWLEDGMENTS

NOAA coral mapping activities can only be conducted through a suite of federal, state, territory, commonwealth, academic, and private sector partnerships. We thank all of these entities and especially our colleagues in the National Geodetic Survey who conducted the aerial photography missions and the dozens of participants at local workshops who provided guidance in the development of the classification scheme and in reviewing draft maps. In addition, special thanks to R. Matos, R. Appeldoorn, J. Rivera, J. Morelock, C. Gonzalez, A. Rosario and the many field staff with the PR Department of Natural and Environmental Resources, University of Puerto Rico, and Jobos Bay National Estuarine Research Reserve for devoting their time, facilities, advice, and tremendous assistance during the field work necessary to complete this project. Curtis Kruer deserves special recognition for tirelessly conducting the many hours of digitizing and visual interpretation of imagery needed to complete this project.

LITERATURE CITED

Beach, D.K. and J.V.A. Trumbull. 1981. Marine Geologic map of the Puerto Rico insular shelf, Isla Caja de Muertos area. Miscellaneous Investigations Series I-1265. US Geological Survey, Washington, DC, USA.

Christensen, J.C., 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. Gulf and Caribbean Research 14:9–28.

Congalton, R.G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of the Environment 37:35–46.

Coyne, M.S., T.A. Battista, M. Anderson, J. Waddell, W. Smith, P. Jokiel, M.S. Kendall, and M.E. Monaco. 2003. Benthic Habitats of the Main Hawaiian Islands. NOAA NOS NCCOS CCMA Technical Memorandum (On-line). URL: http://biogeo.nos.noaa.gov/projects/mapping/pacific/. Silver Spring, MD, USA.

Florida Marine Research Institute. 1998. Benthic habitats of the Florida Keys. FMRI Technical Report TR-4, St. Petersburg, FL, USA.

Goenaga, C. and G. Cintron. 1979. Inventory of the Puerto Rican coral reefs. Report submitted to the Coastal Zone Management, Department of Natural Resources, San Juan, PR, USA, p. 123–159.

Green, E.P., P.J. Mumby, A.J. Edwards, and C.D. Clark. 2000. Remote Sensing Handbook for Tropical Coastal Management.UNESCO Publishing, Fontenoy, Paris, France, 316 p.

Grove, K.A. 1983. Marine geologic map of the Puerto Rico insular shelf, Northwestern area: Rio Grande de Anasco to Rio Camuy. Miscellaneous Investigations Series, I-1418. US Geological Survey, Washington, DC, USA.

Holden, H. and E. LeDrew. 1998. The scientific issues surrounding remote detection of submerged coral ecosystems. Progress in Physical Geography 22:190–221.

Kendall, M.S., C.R. Kruer, K.R. Buja, J.D. Christensen, M. Finkbeiner, R.A. Warner, and M.E. Monaco. 2001. Methods used to map the benthic habitats of Puerto Rico and the US Virgin Islands. NOAA NOS NCCOS CCMA Technical Report 152. Silver Spring, MD, USA, 45 p.

Kendall, M.S., K.R. Buja, J.D. Christensen, C.R. Kruer, and M.E. Monaco. in press. The seascape approach to coral ecosystem mapping: an integral component of understanding the habitat utilization patterns of reef fish. Bulletin of Marine Science.

Kruer, C.R. 1995. Mapping and characterizing seagrass areas important to manatees in Puerto Rico—Benthic communities mapping and assessment. Report prepared for US Department of Interior, National Biological Survey, Sirenia Project, Order No. 83023-5-0161, 14 p.

Monaco, M.E., J.D. Christensen, and S.O. Rohmann. 2001. Mapping and monitoring of US coral reef ecosystems. Earth System Monitor 12:1–7.

Morelock, J. 1978. Shoreline of Puerto Rico. Coastal Zone Management Program, Department of Natural Resources, San Juan, PR, USA, 45 p.

Morelock, J., E. Winget, and C. Goenaga. 1994. Marine geology of the Parguera-Guanica quadrangles, Puerto Rico. USGS Miscellaneous Investigations Series. US Geological Survey, Washington, DC, USA.

Mumby, P.J. and A.R. Harborne. 1999. Development of a systematic classification scheme of marine habitats to facilitate regional management and mapping of Caribbean coral reefs. Biological Conservation 88:155–163.

NOAA, US Environmental Protection Agency, US Coast Guard, Puerto Rico Departmento de Recursos Naturales y Ambientales, and Department of Interior. 2000. Sensitivity of Coastal and Inland Resources to Spilled Oil—Puerto Rico Atlas. Hazardous Materials Response Division of NOAA. Seattle, WA, USA.

National Research Council. 2001. Marine Protected Areas: Tools for Sustaining Ocean Ecosystems. National Academy Press, Washington, DC, USA, 272 p.

Pilkey, O.H., D.M. Bush, and R.W. Rodriguez. 1987. Bottom sediment types of the northern insular shelf of Puerto Rico: Punta Penon to Punta Salinas. Miscellaneous Investigations Series I-1861. US Geological Survey, Washington, DC, USA.

Sheppard, C.R., K. Matheson, J.C. Bythel, P.Murphy, C.B.Myers, and B.Blake. 1998. Habitat mapping in the Caribbean for management and conservation: Use and Assessment of Aerial Photography. Aquatic Conservation 5:277–298.

Reid, J.P. and C.R. Kruer. 1998. Mapping and characterization of nearshore benthic habitats around Vieques Island, Puerto Rico. Report to US Navy. US Geological Survey/BRD, Sirenia Project, Gainesville, FL, USA, 8 p.

Rodriguez, R.W., J.V.A. Trumbull, and W.P. Dillon. 1977. Marine geologic map of Isla de Mona area, Puerto Rico. Miscellaneous Investigations Series I-1063. US Geological Survey, Washington, DC, USA.

Rodriguez, R.W., R.M.T. Webb, D.M. Bush, and K.M. Scanlon. 1992. Marine geologic map of the north insular shelf of Puerto Rico- Rio de Bayamon to Rio Grande de Loiza. Miscellaneous Investigations Series I-2207. US Geological Survey, Washington, DC, USA.

Rosenberg, A., T.E. Bigford, S. Leathery, R.L. Hill, and K. Bickers. 2000. Ecosystem approaches to fishery management through essential fish habitat. Bulletin of Marine Science 66:535–542.

Trias, J.L. 1991. Marine geologic map of the Puerto Rico insular shelf- Guanica to Ponce area. Miscellaneous Investigations Map I-2263. US Geological Survey, Washington, DC, USA.

USCRTF. 2000. The National Action Plan to Conserve Coral Reefs. (http://coralreef.gov/) Washington, DC, USA, 8 p.

Warner, R.A., J. Dietz, M.S. Kendall, G. Goddard, and C. Elvidge. in review. Operational photogrammetric method used for mapping US Caribbean shallow water coral reefs. Photogrammetric Engineering and Remote Sensing.