

## **Benthic Habitat Mapping in the Tortugas Region, Florida**

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*Concern about declining trends in coral reef habitats and reef fish stocks in the Florida Keys contributed to the implementation of a network of no-take marine protected areas in 1997. In support of the efforts of the Dry Tortugas National Park and Florida Keys National Marine Sanctuary to implement additional no-take areas in the Tortugas region in 2001, we expanded the scale of our fisheries independent monitoring program for coral reef fishes in the region. To provide a foundation for the habitat-based, stratified random*

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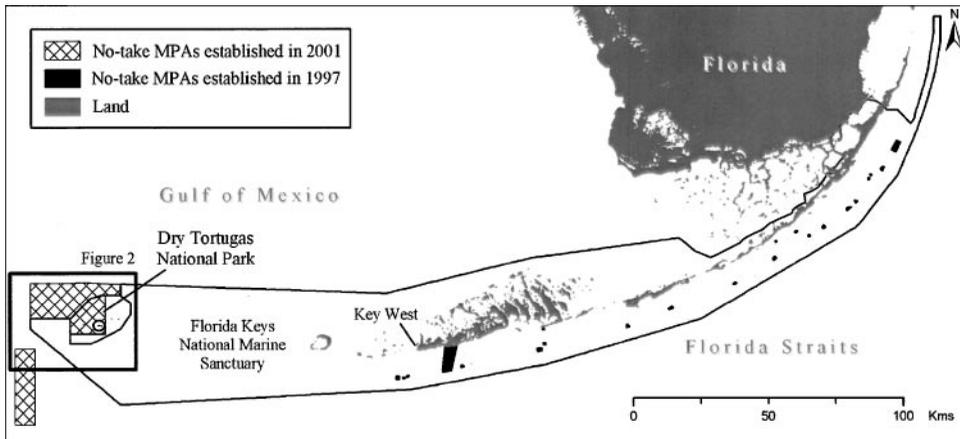
*sampling design of the program, we created a digital benthic habitat map of coral reef and hard-bottom habitats in a geographic information system by synthesizing data from bathymetric surveys, side-scan sonar imagery, aerial photogrammetry, existing habitat maps, and in situ visual surveys. Existing habitat maps prior to 1999 were limited to shallow-water (< 20 m depth) soft-sediment, coral reef, and hard-bottom habitats within Dry Tortugas National Park and did not include deeper areas such as the Tortugas Bank, now partially contained within no-take marine protected area boundaries. From diver observations made during the 1999 survey, we developed a classification scheme based on habitat relief and patchiness to describe nine hard-bottom and coral reef habitats encountered from 1–33 m depth. We provide estimates of area by habitat type for no-take marine protected areas in the Tortugas region. Updated information on the spatial distribution and characteristics of benthic habitats will be used to guide future monitoring, assessment, and management activities in the region. Significant data gaps still exist for the western area of the Florida Keys National Marine Sanctuary and are a priority for future research.*

**Keywords** coral reefs, Dry Tortugas National Park, essential fish habitat, Florida Keys National Marine Sanctuary, geographic information systems, marine protected areas

A network of no-take marine protected areas (MPAs) is recommended as the preferred spatial management tool to protect benthic habitats and enhance fisheries in coral reef ecosystems (Bohnsack and Ault 1996; NRC 2000; PDT 1990). Recognition of ontogenetic habitat requirements for managed species and protection of areas deemed “essential fish habitat” are described as critical steps in rebuilding depleted fish stocks and maintaining marine ecosystem structure and function (Fogarty 1999; NOAA 1996a; Rosenberg et al. 2000). An effective network should contain a biogeographic representation of habitats linked by ocean currents to ensure local persistence of marine populations that can depend heavily on recruitment from other areas (Ballantine 1991; Murray et al. 1999; NRC 2000; Roberts 1997). Studies evaluating the hypothetical effectiveness of reserve networks are often linked to an assumption that the network protects a representative mosaic of habitats for a region (Bohnsack 2000; Dahlgren and Sobel 2000), yet few studies have attempted to map benthic habitats comprehensively to support reserve planning activities (Davidson and Chadderton 1994; Edgar et al. 1997). Habitat mapping in conjunction with fisheries independent surveys can provide empirical evidence of the habitat associations of fishes at different life stages (Rubec et al. 2001), document change or stasis in community structure following spatial closures (NRC 2000), and offer a comparative source of information to fisheries dependent data (Ault et al. 1998; NRC 1999). In addition, mapping activities allow quantification of the area by habitat type protected in no-take zones.

Concern about declining trends in coral reef fish stocks and their associated habitats in the Florida Keys (Ault et al. 1998; Bohnsack et al. 1994) contributed to the implementation of a spatial zoning strategy in 1997 (NOAA 1996b) to augment existing regional marine resource management policies. The network established by the Florida Keys National Marine Sanctuary (FKNMS) consisted of 23 no-take zones that contained approximately 0.5% of the Sanctuary’s total area of 9515.5 Km<sup>2</sup> (Figure 1; NOAA 1996b; Ogden 1997). Due to significant public comments regarding its proposed location, the Sanctuary postponed implementation of an additional and much larger zone in the western region of the Florida Keys until 2001 (NOAA 1996b). The postponed schedule allowed an opportunity for the FKNMS to coordinate their planning efforts with the Dry Tortugas National Park (DTNP), who was also considering the establishment of a no-take MPA in the same region.

The western region of the Florida Keys, often called the Dry Tortugas and here referred to as the Tortugas region, is identified as biologically significant for its complex habitats, diverse marine resources, and contribution to the recruitment and productivity of regional

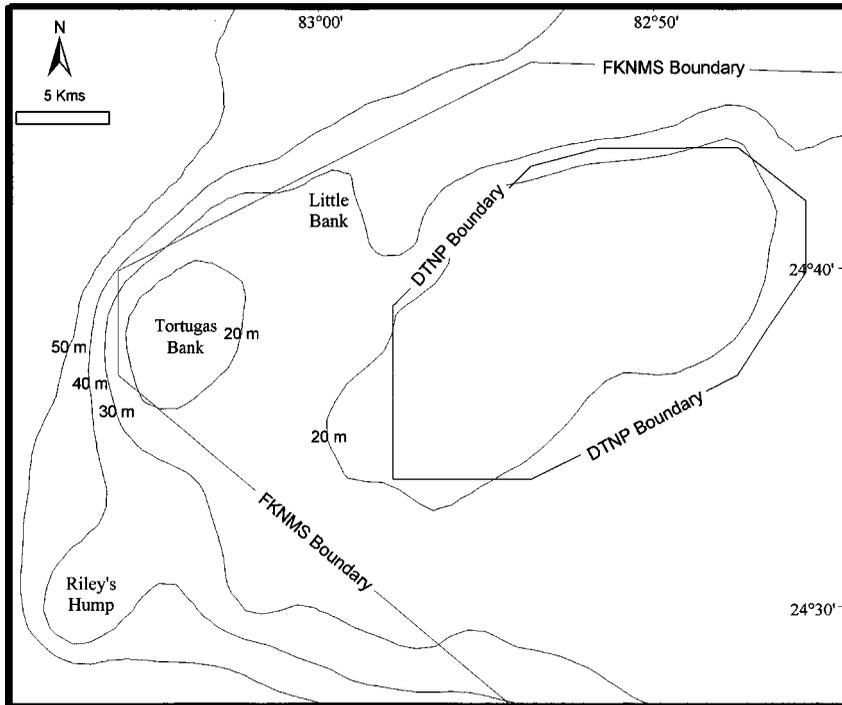


**FIGURE 1** The network of no-take marine protected areas in the Florida Keys. Initial network of no-take zones implemented by the Florida Keys National Marine Sanctuary (FKNMS) in 1997 (solid black areas) and additional no-take MPAs implemented by the FKNMS and the Dry Tortugas National Park in 2001 (cross-hatched areas).

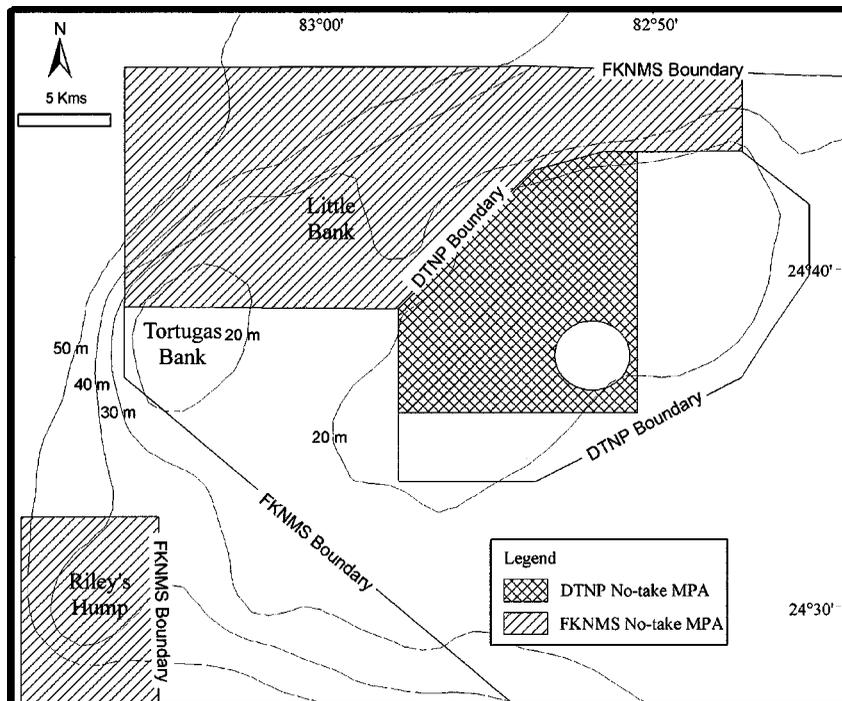
fisheries (Lindeman et al. 2000; NOAA 1996b; Schmidt et al. 1999). Positioned along the southwestern edge of the Florida shelf (Figure 2a), the approximately 1700 Km<sup>2</sup> region is remote from developed areas, supports a limited number of fishers (NOAA 2000), and possesses some of the highest coral cover found in the western Atlantic Ocean (Miller et al. in press). Most importantly, the region benefits from ocean circulation patterns that appear to allow both local retention and regional distribution of larval organisms (Cowen et al. 2000; Lee et al. 1994). Thus, the addition of a no-take zone in the Tortugas would complement the existing MPA network by minimizing the socioeconomic impact of a spatial closure to fisheries and providing a critical mechanism for regional recruitment through larval dispersion to downstream sites (PDT 1990; Roberts 1997).

Prior to MPA planning and implementation in the Tortugas, information on the classification, distribution, and condition of benthic habitats and associated reef fish communities was needed to help optimize the placement of the no-take zones (Ault et al. 2001; NOAA 2000; Schmidt et al. 1999). Unfortunately, the existing information concerning habitat distribution in the Tortugas had not been adequately synthesized to assess the status of the resources for the planning process. Even though benthic habitats within the DTNP were progressively classified and mapped over a century (Agassiz 1883; Davis 1982; FMRI 1998), the broader Tortugas region received little scientific attention. Divers and fishers knew of the area's luxuriant coral reefs and productive fisheries for decades, yet the remote location and depth of the submerged banks limited research activities west of the Dry Tortugas islands (Miller et al. 2001; Shinn et al. 1989).

In support of the MPA planning and evaluation efforts, we dramatically expanded the scale of our fisheries independent monitoring program for coral reef fishes in the Tortugas region. To provide a foundation for the habitat-based stratified random sampling design of the program (Ault et al. 1999), we created a digital benthic habitat map of coral reef and hard-bottom habitats for the Tortugas region in a geographic information system (GIS) by synthesizing data from bathymetric surveys, side-scan sonar imagery, aerial photogrammetry, existing habitat maps, and in situ visual surveys from 1994–1998. The map was the primary instrument utilized to allocate sample surveys for the fisheries and benthic habitat monitoring program (Ault et al. 2001; Miller et al. in press) and guide the placement of



(a)



(b)

**FIGURE 2** The Tortugas region with management boundaries for the Florida Keys National Marine Sanctuary and Dry Tortugas National Park before (a) and after (b) the implementation of no-take marine protected areas in 2001.

no-take MPAs by the FKNMS and DTNP in the Tortugas (Figure 2b; NOAA 2000; NPS 2000). Following the planning process and prior to MPA implementation, we conducted additional expeditions to the Tortugas region in 1999 and 2000 to refine the benthic habitat map and augment the baseline data necessary to evaluate the impact of the zones on reef fish assemblages and their associated habitats (Ault et al. 2001; Miller et al. in press). In this article, we describe the methodology used to create and refine the benthic habitat map, provide updated estimates of area by habitat type for no-take MPAs in the Tortugas region, and discuss the role that habitat mapping has in the monitoring of the Florida Keys reef fish fishery.

## **Methods**

We created, integrated, and manipulated data for the digital benthic habitat map of the Tortugas region using either ESRI Arcview<sup>®</sup> 3.2, Arc/INFO<sup>®</sup> 7.2, or RSI Interactive Data Language<sup>®</sup> 4.0 (IDL) within our PC and UNIX GIS. Data types used were bathymetric soundings, thematic coverages interpreted from aerial photogrammetry, single-beam side-scan sonar imagery, and in situ visual surveys. The data sets represented the best available information for the region and were mostly nonoverlapping in time or space. Although the data sets were collected over a period of about 10 years, coral reef formations can persist for decades or centuries and remain fairly stable in position over time. Area estimates of habitats were made in the GIS using an Albers Equal Area projection (datum NAD83) with latitude of origin of 24.0, standard parallels of 24.0 and 31.5, central meridian of  $-84.0$ , false easting of 400,000.0 and false northing of 0.0 (Snyder 1987). Coverage files for boundary features of no-take MPAs and management areas were provided by FKNMS and DTNP.

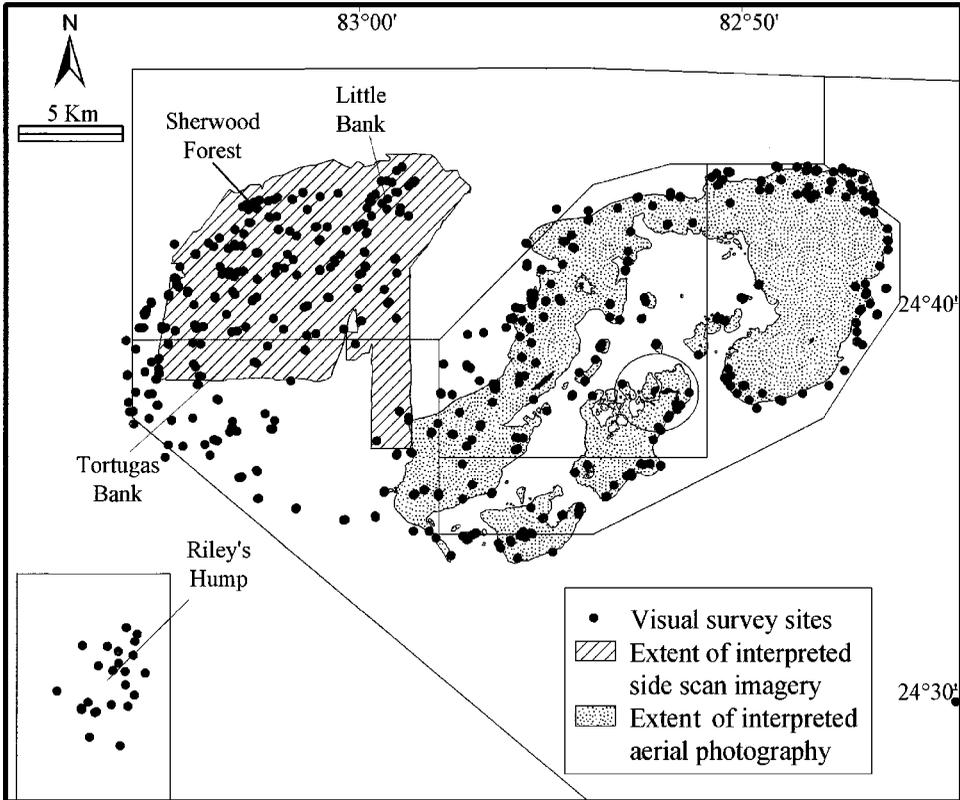
For the MPA planning process, we created a habitat map of polygons derived from (1) a bathymetric grid developed from soundings and geo-tracklines (NGDC 1998), (2) a mosaic of geo-referenced bottom topography for Tortugas Bank and Little Bank obtained from National Ocean Service (NOS) hydrographic surveys that utilized single beam side-scan sonar systems to assess benthic substrates, and (3) a thematic layer of benthic habitats within DTNP previously created from the interpretation of aerial photographic surveys performed between December 1991 and April 1992 (Figure 3). A more detailed description of each data source follows.

### ***Bathymetry***

We developed a bathymetric grid from soundings and geo-tracklines for the region (NGDC 1998). Using the soundings data in IDL, Delaunay triangulation of the combined planar set of points from these data sets provided a surface of bathymetric contours (RSI 1995). After the irregular gridded data points were triangulated, we interpolated surface values to a regular grid of 1 km<sup>2</sup> cells. The bathymetric grid was then matched to a geographic coordinate system within the GIS.

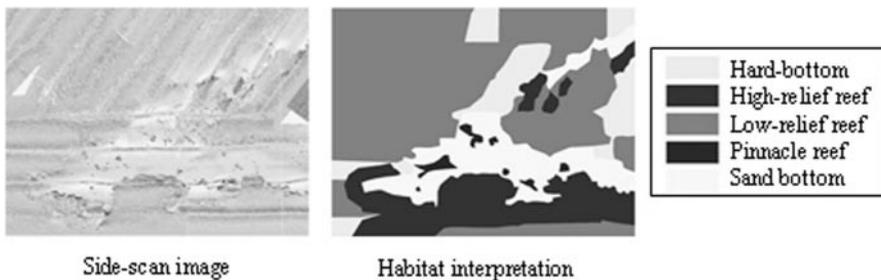
### ***Side-Scan Imagery***

The side-scan imagery for the bank habitats was collected from NOS surveys performed between 1997 and 2000. The 1997 hydrographic survey performed 48 transects of 5 km long and 220 m wide with 60% overlap. The 1998 survey performed 54 transects of 4 km to 5 km long and 220 m wide with 60% overlap. The 2000 survey performed 45 transects of 15 km long and 200 m wide with 50% overlap. From a mosaic of geo-referenced side-scan imagery, we interpreted five categories for the deeper habitats based on the image contrast



**FIGURE 3** Spatial extent of thematic habitat layer from interpreted aerial photogrammetry and side-scan sonar images overlain with visual survey sites from 1994–2000 expeditions to the Tortugas region.

and density that reflected the apparent relief and complexity of benthic features: (1) pinnacle reefs, (2) high-relief reefs, (3) low-relief reefs, (4) hard-bottom, and (5) sand bottom. Using this classification scheme, we created a map by tracing a polygon overlay that defined habitat boundaries and partitioned the imagery between the five categories (Figure 4). In situ visual surveys conducted between 1994–1998 (see Field Surveys section) were used to ground-truth image interpretation of the habitat categories (Figure 3).



**FIGURE 4** Habitat interpretation of side-scan sonar imagery used to prepare preliminary five category habitat map of the Tortugas region.

**TABLE 1** A Comparison of Benthic Habitat Categories Described by FMRI (1998) and This Study for Dry Tortugas National Park, Florida

Habitat categories	
FMRI (1998)	This study
Land	Land
Unknown/unmapped bottom	Unknown/unmapped bottom
Bare substrate	Sand
Seagrass	Seagrass
Hard-bottom	Low-relief hard-bottom
Patch Reef—Coral or rock patches in bare sand	Low-relief hard-bottom
Platform Margin Reef—Remnant—low profile	Low-relief hard-bottom
Platform Margin Reef—Shallow spur and groove	High-relief spur and groove
Platform Margin Reef—Drowned spur and groove	Low-relief spur and groove
Platform Margin Reef—Drowned spur and groove	Medium-profile reef
Platform Margin Reef—Reef rubble	Reef Rubble
Patch Reef—Individual patch reef	Patch reef
Patch Reef—Aggregation of patch reefs	Patch reef
Patch Reef—Halo	Patch reef
Patch Reef—Aggregation of patch reefs with halo	Patch reef

### *Aerial Photogrammetry*

For the shallow habitats of the DTNP, a thematic layer and classification scheme was previously created by the Florida Marine Research Institute from the interpretation of aerial photographic surveys performed between December 1991 and April 1992 (FMRI 1998). The FMRI classification includes 22 categories describing coral reef, seagrass beds, hard bottom, and sand/rock benthic substrates, generally limited to depths of less than 10 m. Using an updated habitat class scheme (see Habitat Classification section), we redescribed a subset of the FMRI categories for this study (Table 1). The nominal photo scale of the source photography was 1:48,000 (FMRI 1998). The vertical and horizontal accuracy of identifiable objects in the photographs were within 2 m and between 5 m to 10 m, respectively.

### *Field Surveys*

Quantitative surveys of reef fish and hard-bottom and coral reef invertebrate communities were conducted in the Tortugas region during exploratory cruises between 1994–1998 and more intensively in 1999 and 2000 (Figure 3; Ault et al. 2001). Between 1994–1998, we sampled 25 sites in the DTNP and deeper bank habitats. For 1999 and 2000 surveys, we allocated sampling effort and determined survey sites based on the distribution of reef fish densities by benthic habitat types collected during prior surveys. The polygon overlay created from side-scan imagery, together with the bathymetric grid, provided the fundamental base map for the Tortugas Bank and Little Bank region that was used to allocate field surveys conducted in 1999 and 2000. During June–July 1999, we surveyed 194 sites at Tortugas Bank, Little Bank, Riley’s Hump, and the DTNP (Figure 3). During May–June 2000, we surveyed 207 sites that mostly included the DTNP, especially deeper, unmapped areas on the periphery of the National Park (Figure 3). Biological data were collected using standard, nondestructive, in situ visual monitoring methods using open-circuit SCUBA (Ault

et al. 2001; Bohnsack and Bannerot 1986; Miller et al. in press). Video surveys were also carried out to provide an archival record of survey locations (Aronson et al. 1994, Miller et al. in press). As part of the survey protocol, each sampling site was qualitatively assessed according to a habitat classification scheme (see next section). Safety constraints limited the depth range of survey sites to 33 m. Survey sites were located with a differential GPS unit onboard the survey vessel and marked with a surface buoy. NOS Navigational Chart 11434 served as a guide for navigating the region outside DTNP and mapping the Tortugas

**TABLE 2** Distribution and Characteristics of Nine Coral Reef and Hard-Bottom Habitat Types Sampled in the Tortugas Region

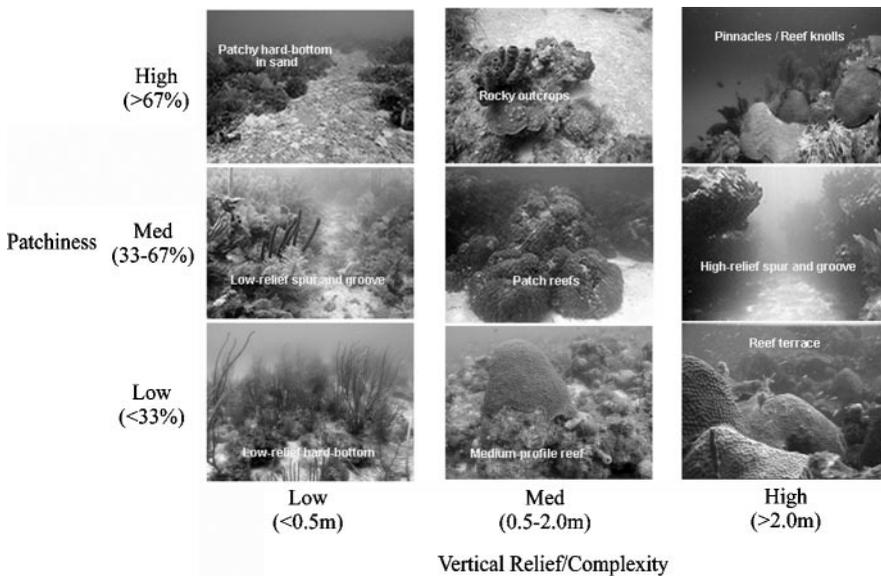
Habitat distribution	Habitat type	Characteristics
Region-wide	Patchy hard-bottom in sand	<ul style="list-style-type: none"> <li>• Sand plains with patches of hard-bottom</li> <li>• Low vertical relief (&lt; 0.5 m) and complexity</li> </ul>
	Low-relief hard-bottom	<ul style="list-style-type: none"> <li>• Contiguous hard-bottom substrate</li> <li>• Low structural complexity and relief</li> <li>• Usually dominated by gorgonians</li> </ul>
	Rocky outcrop	<ul style="list-style-type: none"> <li>• Hard-bottom aggregations bounded by sand</li> <li>• Moderate vertical relief (0.5–2.0 m)</li> </ul>
	Pinnacle reef	<ul style="list-style-type: none"> <li>• High-complexity patches rising to 15 m depth</li> <li>• Surrounded by sand plains</li> </ul>
	Reef terrace	<ul style="list-style-type: none"> <li>• High-relief (&gt;2 m), contiguous reef habitat</li> <li>• Abundant and large mushroom and platy corals</li> <li>• primarily located on western sides of banks</li> </ul>
DTNP only	Patch reef	<ul style="list-style-type: none"> <li>• Aggregate or clusters of dome-shaped reefs</li> <li>• Interspersed with sand</li> <li>• Moderate vertical relief and substrate complexity</li> <li>• Similar to patch reefs in the Florida Keys</li> </ul>
	Medium-profile reef	<ul style="list-style-type: none"> <li>• Contiguous reef substrate</li> <li>• Moderate vertical relief and complexity</li> </ul>
	Low-relief spur and groove	<ul style="list-style-type: none"> <li>• Low-profile coralline spurs separated by sand grooves</li> <li>• Broad spurs up to 5 m wide with low vertical relief</li> </ul>
	High-relief spur and groove	<ul style="list-style-type: none"> <li>• High-profile coralline spurs separated by sand grooves</li> <li>• High vertical relief (&gt;2 m) and complexity</li> <li>• Diverse assemblage of reef benthos</li> </ul>

Bank and Little Bank (NOAA 1998). Within DTNP, NOS Navigational Chart 11438 was used for navigation and site selection (NOAA 1997).

### *Habitat Classification*

We developed and refined a classification scheme based primarily on geomorphological characteristics of benthic habitats for the Tortugas region during the 1999 and 2000 surveys (Table 2). Previous classification schemes (Agassiz 1883; Davis 1982; FMRI 1998; Jaap 1984; Shinn et al. 1989) for the Florida Keys were reviewed during development of the new classification. Revisions to the nomenclature of the FMRI benthic categories (1998) for the DTNP were made based upon diver observations of the habitats during the 1999 surveys. Several of the deeper bank habitat types such as reef terrace and pinnacle reefs were previously undescribed for the Florida Keys (Miller et al. 2001). Based on the visual surveys and literature review, we described 12 habitat types encountered in the Tortugas region. Coral reef and hard-bottom habitats were distinguished by two main features: (1) the degree of “patchiness” (i.e., contiguous hard substrate vs. reef patches interspersed with sand), and (2) hard substrate vertical relief and complexity. The degree of habitat patchiness is determined by observing a low (< 30%), medium (33–66%), or high (> 67%) ratio of consolidated hard-bottom to sand bottom. Habitat relief is distinguished by low (< 0.5 m), medium (0.5–2.0 m), or high (> 2.0 m) levels of vertical relief and associated complexity (Figure 5a). Nine coral reef and hard-bottom habitat types were encountered: (1) patchy hard-bottom in sand, (2) low-relief hard-bottom, (3) low-relief spur and groove, (4) rocky outcrops, (5) patch reefs, (6) medium profile reef, (7) high-relief spur and groove, (8) reef terrace, and (9) pinnacle reefs (Figure 5b). We also encountered sand bottom, seagrass, and rubble.

Using the updated classification scheme, further refinement of the regional map included the translation of existing habitat polygons and the addition of newly described



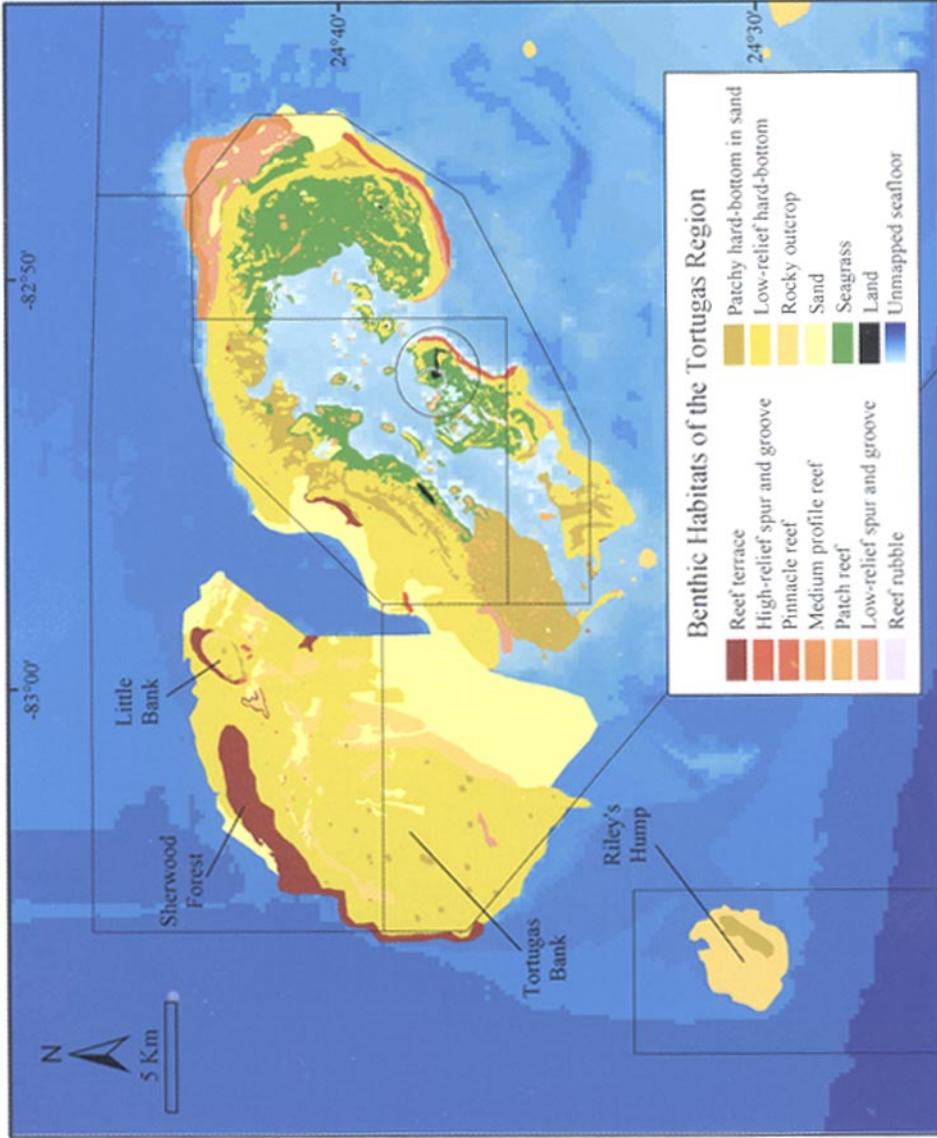
**FIGURE 5** Diagram of vertical relief characteristics and degree of patchiness for coral reef and hard-bottom habitat types in the Tortugas region with representative images for each habitat.

habitat categories. Additionally, polygons were added for the new sites that were visited outside the domain of the mapped area. Feature boundaries delineating habitats have an estimated vertical accuracy of 3 m and horizontal accuracy of 5 m to 10 m, respectively. The horizontal accuracy of easily discernable habitat boundaries such as the transition between a rocky outcrop to a sand bottom is estimated to be 5 m, while the horizontal accuracy of the boundary between low-relief hard bottom and patchy hard-bottom in sand is estimated to be 10 m.

## Results and Discussion

We created and refined a composite digital habitat map for the area encompassing Dry Tortugas National Park, Tortugas Bank, Little Bank, and Riley's Hump (Figure 6). As an integral component of the spatial sampling design of an ongoing reef fish and benthic monitoring program (Ault et al. 2001; Miller et al. in press), the map was the focus of a site characterization for the fisheries and essential habitats of the Tortugas region provided to the FKNMS (Schmidt et al. 1999) and a spatial management decision-making exercise to recommend optimal MPA configurations to the DTNP (Ault et al. 2000; Meester et al. 2001). The map, site characterization, and recommendations were utilized by the planning groups and contributed to the implementation of three no-take MPAs totaling approximately 675 km<sup>2</sup> in the Tortugas region (NOAA 2000; NPS 2000). The new zones significantly increased the proportion of no-take zones in the FKNMS and DTNP from approximately 0.5% to 6.7% of their combined area. Designation of 20% of a region under consideration as no-take has been suggested as the minimum area necessary to realize the potential ecological and fisheries benefits derived from no-take MPAs (Bohnsack 1994, 1996; NRC 2000; PDT 1990). The 20% benchmark is suggested as a conservative standard to decrease the risk of protecting only unproductive, poor quality or "sink" habitats (Crowder et al. 2000; PDT 1990). Although the total area protected in the Florida Keys is still well under 20%, the Tortugas no-take MPAs contain a diverse representation of habitats found throughout the region. The mapping efforts classified approximately 200 km<sup>2</sup> of previously unmapped habitats, especially for the deeper Tortugas Bank and Riley's Hump (Table 3). Of the nine reef and hard-bottom habitats we observed, five were present throughout the entire Tortugas region (i.e., patchy hard-bottom in sand, low-relief hard-bottom, rocky outcrops, pinnacle reefs, and reef terrace). The remaining four habitats were found exclusively within DTNP (i.e., patch reefs, medium profile reefs, high-relief spur and groove, and low-relief spur and groove) (Table 3). Although a habitat map existed for DTNP prior to our research cruises (Davis 1982, FMRI 1998), substantial areas of the National Park, particularly deeper areas on the northern and western rims of the atoll, were not previously mapped. An interesting finding from our efforts is the presence of high-relief and medium-relief reef habitats in these areas of DTNP. Benthic habitats within DTNP also include extensive shallow-water seagrass beds, rubble zones, and sand bottom.

While most of the mapped area (137.5 km<sup>2</sup>) of the Tortugas Bank consists of low-relief hard-bottom (105.5 km<sup>2</sup> or 77%) and scattered, rocky outcrops (16.6 km<sup>2</sup> or 12%), the submerged banks also contain high-relief reef-dominated habitats that extend from a depth of 16–25 m down to the surrounding sand bottom at 33–38 m. Of particular note is the fairly extensive reef terrace habitat (13.9 km<sup>2</sup>) along the northern and western rims of Tortugas Bank and Little Bank. A particularly unique section of this habitat has been nicknamed "Sherwood Forest" for the vertically-elongated coral colonies found there that appear to mimic a miniature forest canopy (Miller et al. 2001). The terrace community is a deeper version (22–27 m) of the reef terraces near Loggerhead Key 15 km to the southeast in DTNP (Davis 1982; Miller et al. 2001). The reef terraces appear to be highly productive habitats that



**FIGURE 6** Benthic habitat map for the Tortugas region.

**TABLE 3** Mapped Area, Percentage of Mapped Area Protected in a No-Take MPA, and Percentage of Mapped Area of the Dry Tortugas National Park (DTNP), Tortugas Bank and Little Bank, Riley's Hump, and Combined Regional Totals for Each Coral Reef and Hard-Bottom Habitat Surveyed

Habitat	DTNP			Tortugas-Little Bank			Riley's Hump			Total		
	Area <sup>a</sup> (km <sup>2</sup> )	MPA <sup>b</sup> (%)	Area <sup>c</sup> (%)	Area (km <sup>2</sup> )	MPA (%)	Area (%)	Area (km <sup>2</sup> )	MPA (%)	Area (%)	Area (km <sup>2</sup> )	MPA (%)	Area (%)
Patchy hard-bottom in sand	33.6	51.1	18.1	30.5	48.9	22.2	2.6	100.0	21.6	66.7	52.0	19.9
Low-relief hard-bottom	95.7	46.3	51.5	75.0	59.7	54.6	—	—	—	170.8	52.2	50.9
Rocky outcrop	1.8	22.2	1.0	16.6	67.8	12.1	9.4	100.0	78.4	27.9	75.8	8.3
Patch reef	28.1	49.1	15.1	—	—	—	—	—	—	28.1	49.1	15.1
Medium profile reef	7.8	18.6	4.2	—	—	—	—	—	—	7.8	18.6	4.2
Low-relief spur and groove	11.8	2.7	6.4	—	—	—	—	—	—	11.8	2.7	6.4
High-relief spur and groove	5.1	20.5	2.7	—	—	—	—	—	—	5.1	20.5	2.7
Pinnacle reef	0.3	62.5	0.2	0.4	100.0	0.3	—	—	—	0.7	82.4	0.2
Reef terrace	1.5	81.6	0.8	15.0	87.4	10.9	—	—	—	16.5	86.9	4.9
Total	185.7	43.0	100.0	137.5	61.4	100.0	12.0	100.0	100.0	335.3	52.6	100.0

<sup>a</sup> Area of habitat type within subregion determined in Albers Equal Area projection, NAD83 (i.e., DTNP, Tortugas Bank/Little Bank, and Riley's Hump).

<sup>b</sup> Percentage of habitat type protected by a no-take MPA within the subregion.

<sup>c</sup> Percentage of habitat type within subregion (i.e., DTNP, Tortugas Bank/Little Bank, and Riley's Hump).

are found on the Bank's edge on the side of the prevailing seasonal current. The remainder of the area is primarily low-relief hard-bottom and sand interspersed with pinnacle reefs. Although they occupy a minute proportion (0.4 km<sup>2</sup>) of the banks, pinnacle reefs are highly complex structures that appear to support dense aggregations of organisms and may provide critical stepping stones for the ontogenetic migration of fish species throughout the region.

With proper enforcement, the no-take MPAs in the Tortugas should provide protection for natural spawning, nursery, and permanent residence areas and protect the full range of diverse benthic habitats (NOAA 1996b, 2000; NPS 2000). The zones contain a biogeographic representation of benthic habitats to accommodate the shifting ontogenetic habitat requirements of marine organisms. It should be pointed out, however, that approximately 70% of the habitats in the Tortugas no-take MPAs and 40% of the combined total area of the FKNMS and DTNP are yet to be classified and mapped. The unmapped habitats are either deeper areas (> 40 m) assumed to be mostly sand bottom or shallow seagrass and patchy hard-bottom that was uninterpretable from aerial photogrammetry. To address this deficiency, improved habitat maps and bathymetry, especially including the area from the Tortugas region to the reefs offshore of Key West, are clearly needed to effectively monitor benthic and fisheries resources and should be a focus of future research efforts in the region.

Although the spatial distribution and resolution of the data sets were variable, the map presented is the best available attempt at a synthesis of this information. Ideally, the collection of the data types would be overlapping in space and time (Li 2000). Although the benthic structures formed by corals can remain for decades and centuries, an attempt should be made for a synoptic effort to survey the entire region. In addition, the habitat classification is based solely on qualitative observations of geomorphological characteristics and does not yet include quantitative parameters of biological modifiers such as species richness or coral cover that were also collected. Unfortunately, the immense size of the Tortugas region prevented us from performing a comprehensive assessment. This effort is ongoing and future expeditions will continue to visit sites to ground-truth and expand the habitat map. To address some of these concerns, we recommend including airborne remote sensing technologies such as LIDAR and multibeam sonar to provide a near-instantaneous, comprehensive survey of benthic complexity and community composition (Mumby et al. 1995). The steps outlined in this process could be applied to a range of different settings, and although they represent not ideal conditions, could assist other similar efforts.

Efforts to incorporate spatial strategies into fisheries management should begin with the identification of ontogenetic habitat requirements for managed species (Bohnsack and Ault 1996; Nishida and Booth 2001; Rubec et al. 1999). For demersal species like reef fishes, the mapping of benthic habitats and the associated reef fish assemblage is one of the principal steps necessary upon which to build the framework of an effective fishery management system (Ault 1996). The system should include a quantitative monitoring program to assess temporal and spatial fluctuations in the abundance and distribution of organisms, stock assessments for the multispecies reef fish community, and appropriate guidance for marine policy makers. To improve spatially-explicit fisheries management decision-making, the integration of data in a GIS is used to analyze the distribution, abundance, and habitat preference of fishes and fishers (Meester et al. 2001; Rubec et al. 1999). The integration of GIS technology with appropriate sampling design and analysis of region-wide data sets represents an attempt to create a more holistic or ecosystem approach to fisheries management and the investigation of essential fish habitat.

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