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Natural Resource Stewardship and Science

Assessment of Natural Resource Condition in and Adjacent to the Dry Tortugas National Park

Natural Resource Report NPS/DRTO/NRR—2012/558

ON THE COVER
Sergeant majors (*Abudefduf saxatilis*) in Dry Tortugas National Park.
Photograph by NOAA/NOS/NCCOS/CCMA Biogeography Branch

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Christopher F. G. Jeffrey[1,2] ,Sarah D. Hile[1,2], Christine Addison[3], Jerald S. Ault[4], Carolyn Currin[3], Don Field[3], Nicole Fogarty[5], Jiangang Luo[4], Vanessa McDonough[6], Doug Morrison[7], Greg Piniak[1], Varis Ransibrahmanakul[1], Steve G. Smith[4], Shay Viehman[3]

Editor: Christopher F. G. Jeffrey[1,2]

[1]National Oceanic and Atmospheric Administration
National Ocean Service, National Centers for Coastal Ocean Science
Center for Coastal Monitoring and Assessment, Biogeography Branch
1305 East West Highway, SSMC4, N/SCI-1
Silver Spring, MD 20910

[2]Consolidated Safety Services, Inc.
10301 Democracy Lane, Suite 300
Fairfax, VA 22030

[3]National Oceanic and Atmospheric Administration
National Ocean Service, National Centers for Coastal Ocean Science
Center for Coastal Fisheries and Habitat Research
101 Pivers Island Rd
Beaufort NC 28516-9722

[4]University of Miami
Rosenstiel School of Marine and Atmospheric Science
4600 Rickenbacker Causeway
Miami, FL 33149-1098

[5]Nova Southeastern University
Oceanographic Center
8000 N. Ocean Drive
Dania Beach, Florida

[6]National Park Service
Biscayne National Park
9700 SW 328 Street
Homestead, Florida 33033

[7]National Park Service
Everglades and Dry Tortugas National Parks
40001 State Road 9336
Homestead, Florida 33034-6733

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Executive Summary

This project characterized and assessed the condition of coastal water resources in the Dry Tortugas National Park (DRTO) located in the Florida Keys. The goal of the assessment was to: (1) identify the state of knowledge of natural resources that exist within the DRTO, (2) summarize the state of knowledge about natural and anthropogenic stressors and threats that affected these resources, and (3) describe strategies being implemented by DRTO managers to meet their resource management goals.

The park, located in the Straits of Florida 113 km (70 miles) west of Key West, is relatively small (269 km^2) with seven small islands and extensive shallow water coral reefs. Significant natural resources within DRTO include coastal and oceanic waters, coral reefs, reef fisheries, seagrass beds, and sea turtle and bird nesting habitats. This report focuses on marine natural resources identified by DRTO resource managers and researchers as being vitally important to the Tortugas region and the wider South Florida ecosystem. Selected marine resources included physical resources (geology, oceanography, and water quality) and biological resources (coral reef and hardbottom benthic assemblages, seagrass and algal communities, reef fishes and macro invertebrates, and wildlife [sea turtles and sea-birds]). In the past few decades, some of these resources have deteriorated because of natural and anthropogenic factors that are local and global in scale. To meet mandated goals (Chapter 1), resource managers need information on: (1) the types and condition of natural and cultural resources that occur within the park and (2) the stressors and threats that can affect those resources. This report synthesizes and summarizes information on: (1) the status of marine natural resources occurring at DRTO; and (2) types of stressors and threats currently affecting those resources at the DRTO.

Based on published information, the assessment suggests that marine resources at DRTO and its surrounding region are affected by several stressors, many of which act synergistically. Of the nine resource components assessed, one resource category – water quality – received an ecological condition ranking of “Good”; two components – the nonliving portion of coral reef and hardbottom and reef fishes – received a rating of “Caution”; and two components – the biotic components of coral reef and hardbottom substrates and sea turtles – received a rating of “Significant concern” (Table E-1). Seagrass and algal communities and seabirds were unrated for ecological condition because the available information was inadequate. The stressor category of tropical storms was the dominant and most prevalent stressor in the Tortugas region; it affected all of the resource components assessed in this report. Commercial and recreational fishing were also dominant stressors and affected 78% of the resource components assessed. The most stressed resource was the biotic component of coral reef and hardbottom resources, which was affected by 76% of the stressors. Water quality was the least affected; it was negatively affected by 12% of stressors. The systematic assessment of marine natural resources and stressors in the Tortugas region pointed to several gaps in the information. For example, of the nine marine resource components reviewed in this report, the living component of coral reefs and hardbottom resources had the best rated information with 25% of stressor categories rated “Good” for information richness. In contrast, the there was a paucity of information for seagrass and algal communities and sea birds resource components.

The history of the DRTO and its legacy of ecological research and monitoring are well known (Chapter 2). Since the 1800s, scientists have been studying and publishing information on natural resources, such as corals, reef fishes, and other marine life that abound in the coral reef ecosystems of the Tortugas region. The area was declared the Dry Tortugas National Monument in 1935; in 1992, DRTO was formally established as a National Park and the National Park Service (NPS) who received jurisdictional and management responsibilities to protect 269 km^2 (104 mi^2) of subtropical marine ecosystems from commercial fishing. The state of Florida however retained the rights to the seabed and associated resources, and in 2007 the state collaborated with NPS to establish a 119 km^2 (74 mi^2) area closed to all extractive use. Since the 1990s, at least 19 research and monitoring studies have been conducted at DRTO. These interdisciplinary studies were funded by multiple state and federal agencies and evaluated the efficacy of existing protected areas on natural resources in the Tortugas region.

The climatology and oceanography of the Tortugas region makes the area unique (Chapter 3). Oceanographic conditions and circulatory patterns near the DRTO are determined primarily by the convergence of several ocean current systems that profoundly affect the region's ecology. This convergence of current systems from the Caribbean and the Gulf of Mexico enables connectivity among reefs in the Florida Keys and along the Florida mainland. Oceanic circulation in the Tortugas region distribute fish and invertebrate larvae to local reefs or those downstream (e.g., in the Florida Keys). Alternatively migrating oceanic eddies episodically bring nutrients from upstream areas, such as Gulf Coast or the west coast of Florida, to the Tortugas region. Unpredictable disturbances, including hurricanes, cold-water and warm-water events, and other extreme weather events have resulted in atypical oceanographic conditions that have negatively affected ecological processes and populations of marine animals in the region. These climatic and oceanographic processes are beyond the control and purview of resource managers, but knowledge of spatial and temporal variability in extents and frequencies of these physical processes is crucial for determining the ecological condition of marine natural resources.

Coral communities are prominent and biologically productive natural resources at DRTO and was the most important "vital sign" for South Florida/Caribbean Network (SFCN) of parks. Historical accounts of the abundance, spatial distribution, and ecological condition of coral reef and hardbottom areas in DRTO and the surrounding region contrast sharply with those of modern times (Chapter 4). Historical reports and maps from the 1800s suggest that live coral was widely distributed and abundant on hardbottom substrates in the Tortugas region. In sharp contrast, monitoring data from Miller *et al*. (2006), Wheaton *et al*. (2007), and SFCN (2009) indicate that live coral is now significantly less abundant and less widely distributed than in previous times. Long-term declines in the spatial extents and abundance of living coral is unexplained, but may be the result of episodic events (e.g., hurricanes and diseases), as well as human-associated stressors. Furthermore, trends in the distribution and abundance of coral reefs in the DRTO, the Tortugas region, and the Florida Keys during the past decade suggest that future declines in coral cover are likely. Managing the living corals of the region sustainably is contingent on resource managers developing achievable goals for protecting reefs, establishing baselines from which to measure trends, and setting targets to which the coral reef ecosystem should be returned. Such baselines and targets will require well-designed sampling regimes that collect data for metrics that (1) describe the spatial and temporal variability in coral reef ecosystems and (2) are suitable for determining biologically-significant long-term changes. Data from park-wide monitoring are being analyzed to provide park managers with a much broader picture of reef condition inside and outside the park. The NPS is collaborating with state, federal, and academic partners to monitor coral ecosystems inside and outside the protected Research Natural Area (Nash *et al*. 2009).

Seagrass and algal communities are extensive and important components of marine ecosystems in the Tortugas region, and their primary productivity contributes substantially to the nutrients and trophic energy circulated within coral reef ecosystems (Chapter 5). "Seagrass and other subaquatic vegetation" ranked as the fourth most important vital sign for SFCN parks. Historical descriptions and maps of seagrass and algal communities from the 1800s are similar to those from more recent monitoring projects and maps (1982, 1998, and 2004). Data from 10 DRTO sites that were randomly selected as part of the Florida Keys national Marine Sanctuary (FKNMS) seagrass monitoring project (conducted by Fourqurean and Escorcia [2006]) indicate that the spatial distribution of seagrass species correlates strongly with depth, and that several species overlapped in their depth ranges. Turtle grass (*Thallasia testudinum*) and manatee grass (*Syringodium filiforme*), the two most common species, range in depth from a minimum of 0.2−0.9 m (0.7−3 ft) down to a maximum of 18 m (59 ft). Paddle grass (*Halophila* spp.) is more common at depths from 2.4−26.5 m (8−87 ft). The only two sites where five seagrass species (*T. testudinum, S. filiforme, Halodule wrightii, Halophila decipiens*[1]*, and Halophila engelmanni*) were observed during one sampling event occurred at DRTO.

Data from DRTO "seagrass communities monitoring and assessment" project, which is led by Douglas Morrison, indicate that there was a combined loss of 49.5 ha (122 ac) (28.9%) of seagrass between 2003−2007. The loss occurred at six permanent sites (three around Loggerhead Key and three around Garden Key) and was attributed to several hurricanes in 2004 and 2005. The declines in seagrass area could reflect park-wide trends and suggest that DRTO has experienced some losses of ecosystem services (e.g., nursery habitats for fishes, improved water quality, and sediment retention). Greater priority should be given to the establishment of additional seagrass monitoring sites, collection of additional data on condition, spatial extent, and recovery, and the development of restoration projects to mitigate the loss of seagrass beds given their importance and connectivity to coral reef ecosystems. Without restoration, natural recovery of seagrass beds to climax conditions is estimated to take 10−60 years (Sargent *et al*. 1995, Fonseca *et al*. 2004).

Fish assemblages are essential and prominent components of coral reef ecosystems at DRTO (Chapter 6) and were was the second most important vital sign for SFCN parks. Reef fish assemblages within the park are not immune from impacts of overfishing. Fishes occurring at DRTO are part of a larger species complex whose home range extends beyond park boundaries to nearby areas that are fished. The Tortugas region's multibillion-dollar commercial and recreational fisheries, which are supported in part by DRTO fish assemblages, are regulated and managed under three distinct regimes that provide varying levels of resource protection. DRTO has been closed to commercial fishing since its implementation in 1935; however, all of the waters inside the park supported recreational fisheries until 2007 when implementation of the RNA prohibited fishing within a 119-km^2 (46 mi^2) area. The Tortugas Ecological Reserve (TER), which was implemented in July 2001, also prohibits commercial and recreational fishing

[1]The taxonomic name for Halodule wrightii has been changed to Halodule beaudettei according to the Integrated Taxonomic Information System (ITIS).

within its boundaries. The remaining areas of the Tortugas region support fisheries that are managed through a complex suite of conventional fishery regulations implemented by state and federal agencies.

Data from existing reef fish monitoring programs suggest that several metrics of reef fish assemblages at DRTO and TER have improved slightly compared with areas in the region that are open to fishing. For example, domain-wide estimates of mean species richness in 2006 were significantly higher compared with baseline estimates in 1999−2000, although species richness of snappers and groupers did not increase over the same period. Larger black grouper (*Mycteroperca bonaci*) and red snapper (*Lutjanus campechanus*) were observed during surveys conducted in 2004 and 2006 compared with surveys from 1999−2000, which suggest a shift towards larger-sized fish. Reef fish (e.g., black grouper, red grouper [*Epinephelus morio*], and mutton snapper [*Lutjanus analis*]) abundance at the sand-reef interface and other hardbottom habitats at DRTO and TER have increased significantly since TER was implemented in 2001. Evidence indicates that mutton snapper may have re-formed spawning aggregations in Tortugas South Ecological Reserve (TSER), suggesting that closed reserves may be protecting and increasing fish abundance in the region. No significant declines in abundance have yet been detected for exploited species in the reserves, although abundances of non-exploited species within protected areas have shown increases and declines over time. The trends in fish assemblages contrast somewhat with those from fished areas, where the annual abundance of exploited species either declined or did not change over time. The implementation of protected areas likely resulted in an early increase in the biomass of exploited species in the Tortugas region as a whole, although full recovery of reef fish populations is expected to take decades. However, observed spatial and temporal trends in reef fish assemblages within DRTO and the Tortugas region might have resulted synergistically from previously implemented management actions, reserve implementation, and natural episodic events such as hurricanes.

Birds and sea turtles are important components of marine ecosystems and their local presence and abundance are indicators of the overall ecological status of nearshore areas (Chapter 8). Historical and current information on temporal trends and spatial patterns of the occurrence and abundance of seabirds and sea turtles indicate that the park functions as an ecosystem that provides support to resident and migratory fauna. Although turtle abundance in the Tortugas region is substantially lower now compared to pre-European times, nesting of loggerhead turtles increased in numbers from 1994−2000, but decreased between 2001−2004. Green sea turtles (*Chelonia mydas*), which have generation times around 20 years, were less abundant and showed no apparent trend in nesting frequency during the same period. Hawksbill (*Eretmochelys imbricata*), leatherback (*Dermochelys coriacea*) and Kemp's ridley (*Lepidochelys kempii*) sea turtles were uncommon and there was not much information available on the nesting activity of these species.

Sea birds continue to forage and breed in the park, which the National Audubon Society lists as one of the important birding areas in Florida. The Tortugas region provides the only breeding sites within the continental U.S. for three species of seabirds and resource managers have been successful in reestablishing nesting by Roseate Terns (*Sterna dougallii*) at the park. Multiple stressors, such as shoreline erosion, coastal vegetation, exotic plants, and increased human visitation, continue to affect turtle nesting and seabird colonies at DRTO. A sampling plan that uses habitat information to guide selection of sites should be developed to characterize the spatial distribution of sea turtles and colonial nesting birds within the park.

Reef ecosystems in the Tortugas region face a number of threats and stressors, many of which act at multiple scales and have a range of effects. The major threats and stressors to marine natural resources at DRTO include climate change (increased sea surface temperature [SST], sea level rise and ocean acidification); extreme events (tropical storms and coral disease epidemics); and resource extraction (recreational overfishing, habitat destruction from fishing gear, and boat groundings and anchor damage) (Table E.2). Few studies have directly assessed the effects of stressors on marine natural resources in the Tortugas region, which makes it difficult for resource managers to differentiate among causes of local resource degradation in the coral reef ecosystem. Natural stressors, such as episodic cyclonic disturbances, bleaching episodes, and anomalous oceanographic and hydrodynamic circulatory patterns, acted synergistically to reduce coral cover and abundance during the last century. Anthropogenic stressors, such as those associated with resource extraction, contributed to loss of live coral cover and declines in species diversity, overall coral reef ecosystem health, and abundance of natural resources. Currently, the most likely anthropogenic stressors to natural resources in the Tortugas region are recreational activities. Most extractive activities are prohibited in the TER and the DRTO. Continued increase in human visitation to the Tortugas region will result in increased levels of recreational activities, such as boating, fishing, and scuba diving. The cumulative impacts of reef-related recreational activities could have profound negative effects on the region’s natural resources.

The following recommendations were developed during the course of this project:

1. There is a long and rich history of research and monitoring studies in and around the DRTO that provide data essential to conservation of ecosystem resources. Despite the prevalence of research and monitoring studies, limited amounts of data on many natural resources are available directly to park staff for planning and decision making. The lack of data available to park staff likely results from ownership and publication rights of researchers to the data that they collect.

❖ **Recommendation:** NPS should request that researchers share data with resource managers, and park managers should develop a repository for monitoring and research data collected inside and outside DRTO boundaries. NPS and FKNMS should collaboratively develop an information system for monitoring and research studies, which could be tracked through research permits issued for the Tortugas region. Such a system – Sanctuary Integrated Monitoring Network (SIMoN) – has been developed for the Monterey Bay National Marine Sanctuary to provide timely and pertinent information to managers, the research community, and the public. The foundations for an integrated information system already exist. The SFCN has been gathering and archiving reef fish and coral data collected by its partners in southeast Florida and Caribbean parks. This process should include data for other natural resources, including seagrasses, seabirds, and sea turtles. Many of the federal and state management agencies with jurisdictional responsibilities for the region have established electronic databases or information portals that describe their monitoring activities.

2. Several federal and state government agencies and academic organizations conduct monitoring and research programs within the park (Chapter 2). In the past, many of these

agencies collected data that were best suited for their own management or research agendas. Although it may seem cost-effective in the short-term to depend on these programs to obtain information on the availability and abundance of natural resources within the park, data collected by these programs may not always match the needs of the resource managers at DRTO, nor are these data always collected at the appropriate spatial and temporal scales that are relevant to management of the park. For example, data from sampling designs that provide precise metrics at the scale of the Florida Keys reef tract may not provide the precision necessary to detect differences among sampling strata at the scale of the park (Chapter 6). Data collected at randomly selected sites are not always suitable or precise enough for detecting temporal trends. Data collected from permanent sites are not suited for characterizing spatial patterns in the availability of resources, especially if the sites were not chosen randomly. DRTO resource managers should continue to develop specific research goals and objectives to guide research and monitoring within the park.

❖ **Recommendation:** NPS staff should evaluate existing monitoring and research programs carefully to determine what data types are best suited to the park's management needs, and they should work with other agencies to increase the sharing of relevant data between researchers and DRTO staff. Monitoring programs should be designed to collect data that meet the goals and objectives of park managers. The strategy recommended here would ensure that the best ecological information available is used to make management decisions and fill existing gaps in the types of data needed for sustainable management of natural resources. A good example of this is the recent RNA science plan that was developed by a multi-agency team of scientists to assess conservation efficacy of the DRTO (SFNRC and FWC 2007). The science plan focuses on assessing the effects of the RNA on reef fish assemblages. A similar process should be invoked to develop monitoring and research plans for other natural marine organisms, including corals, seagrasses, seabirds, and sea turtles, that are important natural resources to the park. A scientific advisory panel could be created and regularly convened to offer recommendations on science-related issues to park managers.

3. Coral reefs' coral cover and colony abundance in the Tortugas region are very different from what they were 100 years ago. Historical reports and maps suggest that live coral was widely distributed and abundant on hardbottom substrates. This historical view contrasts sharply with reports from current monitoring projects indicating that live coral is now significantly less abundant and less widely distributed. Long-term declines in the spatial extent and abundance of living coral may have resulted from the cumulative, synergistic effects of environmental and anthropogenic human stressors. Trends in the trajectory of coral reefs in DRTO, the Tortugas region, and the Florida Keys during the past decade suggest that future declines in coral cover are likely.

❖ **Recommendation**: DRTO resource managers should develop achievable goals for protecting coral reefs from anthropogenic stressors that could increase the susceptibility of reefs to natural stressors that are beyond the control of managers. Coral reef protection goals are dependent on establishing baseline levels of coral cover and colony abundance against which to measure future change. Baselines and future targets require well-designed monitoring programs that collect data that adequately characterize the spatial and temporal variability in coral reef ecosystems. Every effort should be made to obtain and use monitoring data from existing programs to develop a spatially robust and comprehensive resource management program for corals. This program should identify goals, objectives, and metrics to evaluate progress toward improving coral reef resources. Data from existing monitoring programs should be analyzed to determine the metrics that are suitable for detecting improvement or degradation of coral reefs within DRTO.

4. Seagrass beds are the most spatially extensive benthic cover within DRTO; turtle and manatee grasses dominating substrates <10 m (33 ft) deep and paddle grass is more abundant at depths >10 m (33 ft). Algal communities are also spatially extensive, but typically ephemeral and occur on hard (e.g., rubble) and soft (e.g., sand) substrates. Seagrasses are important to coral reefs in the Tortugas region because their primary productivity is the basis of food webs that support reef fish assemblages, provide connectivity among hardbottom habitats through trophic energy flows, and they remove sediments from the water column improving water quality. Currently, two annual monitoring programs sample benthic communities in seagrass and algal beds within DRTO, but data on the status and condition of seagrass and algal beds are not readily available to park managers and are not adequate to determine the current ecological condition of seagrasses.

❖ **Recommendation**: DRTO managers should expand sampling programs that currently monitor ecological condition of seagrass beds. Existing monitoring projects are good, but the number of sites currently monitored is inadequate to quantify and characterize the spatial extent and the ecological condition of seagrass beds within the park. A probabilistic sampling design that includes all types of seagrasses in all management use zones should be developed to characterize seagrasses in the park.

Data that characterize the magnitude and spatial extent of known seagrass stressors, such as prop-scarring from motor boats, should be collected along with biological data (i.e., percent cover, shoot density, and blade length). The information could be used to develop guidelines for motorboat use in the park's cultural and historic zones to minimize the human impacts on shallow seagrass beds.

5. Reef fish assemblages are the most comprehensively sampled and well-characterized natural resource in the Tortugas region. Fish assemblages are prominent components of the marine ecosystems occurring in the Dry Tortugas, but have suffered significant declines in the abundance and size of desirable species because of historical overfishing. Full recovery is expected to take decades, but establishing no-take reserves coupled with management actions that reduced fishing mortality already may be having a net positive effect on previously exploited reef fish populations. Several studies characterized population abundance and size of exploited species and are tracking temporal trends to evaluate the effectiveness of no-take reserves, including the newly established RNA within DRTO. Reef fish assemblages in unconsolidated sediment habitats, however, are poorly characterized. Reef fishes in the Tortugas region use a mosaic of habitat types, including unconsolidated substrates, through daily home range movements and ontogenetic habitat shifts.

❖ **Recommendation**: Existing programs that characterize reef fish assemblages on reef and hardbottom substrates in the various park management zones should continue. Efforts should be made by resource managers to characterize reef fish assemblages occurring in unconsolidated sediment habitats. Existing data on reef fishes should be analyzed to determine baseline levels for various reef fish metrics against which future data could be compared. The recently developed science plan for evaluating the conservation efficacy of the RNA recommends several additional performance goals and measures for reef assemblages that should be followed (SFNRC and FWC 2007).

6. Sea birds and sea turtles are important components of marine ecosystems. Turtle abundance in the Tortugas region is substantially lower now than in pre-European times, but sea turtles continue to nest on beaches in the park. Sea birds forage and breed in the park and the National Audubon Society lists DRTO as one of the important Florida birding areas. The Tortugas region has the only breeding sites within the continental U.S. for three species of seabirds. Resource managers have been successful in getting Roseate Terns to nest at the park as they did historically. Important stressors affecting turtle nesting and seabird colonies at DRTO include shoreline erosion, coastal vegetation, exotic plants, and increased human visitation. There are no monitoring programs for sea turtles in the park and monitoring of seabirds occurs only at a few sites.

❖ **Recommendation**: A well-defined sampling plan that uses habitat information to guide selection of sites should be developed to characterize the spatial distribution of sea turtles and colonial nesting birds within the park.

7. Multiple environmental stressors acting at different spatial scales have affected the condition, abundance, and availability of natural resources in the Tortugas region. During the last century, anthropogenic stressors have contributed to loss of live coral cover and abundance, declining species diversity, declining of coral reef ecosystem health, and a reduction in reef fishes, sea turtles, and seabirds. Few studies have directly assessed the effects of stressors on natural resources in spite of several research and monitoring programs that have monitored and documented temporal and spatial variability in coral reef resources. It is difficult to differentiate between natural and anthropogenic causes of resource degradation in coral reef ecosystems. The most likely source of anthropogenic stress in the Tortugas region is human recreational activities because most other extractive activities are prohibited in the TER and DRTO. Recreational activities, such as boating, fishing, and scuba diving, are associated with increased visitation to the Tortugas and place increased stress on the region’s coral reef ecosystems. The cumulative impacts of reef-related recreational activities could have a profound negative effect on the region’s natural resources in the long term.

❖ **Recommendation**: Park managers should assemble a team of experts to develop monitoring and sampling programs to characterize impacts of stressors on natural resources within DRTO. Park staff should work with recognized experts to develop strategies to mitigate the negative effects of increased visitation and visitor use on natural resources. A team of experts developed a science plan that outlines performance measures and identified monitoring activities to assess the effects of implementing the RNA on ecological and socioeconomic variables. A similar approach is needed for other natural resources addressed in this report.

Table E-1. Summary of the ecological condition of resources in the Tortugas region based on stressor-resource matrix in Table E-2.

	Natural Resource Categories							
		Coral reef and hardbottom		Seagrass and algae				
	Water quality	**Abiotic**	**Biotic**	**Abiotic**	**Biotic**	**Reef fishes**	**Sea turtles**	**Seabirds**
Proportion of stressors affecting resources	12%	59%	76%	41%	41%	47%	35%	41%
Proportion of stressors with good or fair information on effects	24%	59%	59%	12%	12%	29%	41%	12%
Park-desired condition	Intact and Pristine Marine Ecosystem (NPS 2005); for water quality	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for coral reefs	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for coral reefs	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for seagrasses	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for seagrass and algal beds	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for reef fishes	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for sea turtles	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for seabirds
Recommended metrics to determine Park-desired condition	Dissolved oxygen, total nitrogen, turbidity	Spatial extent of reef and hardbottom communities	Coral cover; colony density; disease prevalence and incidence;	Spatial extents of seagrass and algae habitats	Seagrass shoot density; Species composition; productivity indices	Species composition, abundance and size; presence commercially-important species (e.g., black and red grouper)	Aerial extent of nesting beaches; turtle sighting frequency; turtle nesting activity	Nesting activity; aerial extent of nesting habitat; seasonal and annual bird counts; abundance by life-stage.
Overall condition	Good	Caution	Significant concern	Inadequate data	Inadequate data	Caution	Significant concern	Inadequate data
Information score	1.00	0.59	0.59	0.20	0.22	0.56	0.58	0.20
Stressor extent score	0.09	0.47	0.56	0.55	0.60	0.51	0.38	0.34

Table E.1 (continued).

	Water quality	Coral reef and hardbottom: Abiotic	Coral reef and hardbottom: Biotic	Seagrass and algae: Abiotic	Seagrass and algae: Biotic	Reef fishes	Sea turtles	Seabirds
Temporal trends in resources	None reported. Concentrations of dissolved oxygen and nutrients (nitrogen, phosphorus, and organic carbon) were fairly stable between 1995−2005 (Boyer and Briceño 2006, 2007).	Insufficient data to determine temporal trends	Living coral cover has declined drastically. Average coral cover in 2005 is <20% compared with an average cover >50% before 1975 (Agassiz 1883, Davis 1982, Jaap *et al.*, 2008). Prior to the 1970s, Acroporid corals were spatially extensive and very abundant, but now they have virtually disappeared (Davis 1982, Jaap and Sargent 1993, Jaap *et al.*, 2008).	Insufficient data to determine temporal trends	Data specific to the status and condition of seagrass and algal beds are not readily available to DRTO; Repeated sampling at permanent sites monitored by Park staff are spatially limited and inadequate to determine temporal and spatial trends for the park (Chapter 5, this report). A useful data set to obtain is Fourqurean and Escorcia 2006).	Abundance, size, species composition of reef fish assemblages are below historical levels (Bohnsack *et al.* 1994). Several exploited and unexploited fish populations have increased in abundance and size in the reserves since implementation in 2001 (Ault *et al.* 2007); The mutton-snapper aggregation may be reforming (Burton *et al.* 2005). There was an increase in the frequency of exploited black and red groupers in the Tortugas region (Ault *et al.* 2007)	Abundances of sea turtles are substantially lower than in pre-European times. From 1994−2004, nesting activities of loggerhead and green sea turtles was variable between species. Hawksbill, leatherback, and Kemp's ridley are uncommon, with little data on nesting activity (Van Houtan and Pimm 2006). Existing data and trends are spatially and temporally limited and should not be used to infer long-term demographic trends.	Unknown. Existing quantitative data on sea birds in the Tortugas region are dated (1986-1991), and were not collected with appropriate statistical and sampling rigor to determine temporal and spatial trends and the current ecological condition of sea birds at the park (Chapter 7).

Table E.1 (continued).

		Coral reef and hardbottom		Seagrass and algae				
	Water quality	**Abiotic**	**Biotic**	**Abiotic**	**Biotic**	**Reef fishes**	**Sea turtles**	**Seabirds**
Spatial patterns in resource	Concentrations of dissolved nutrients much lower than in the neighboring Florida Keys. Chlorophyll a is much lower in the Tortugas region than on the West Florida Shelf (Boyer and Briceño 2006, 2007).	Coral reef metrics have been used to characterize and map coral reefs and hardbottom based on spatial patchiness (Franklin *et al.* 2003)	Data on spatial density of coral colonies used to optimize sampling designs; but spatial trends have not been analyzed (Miller *et al.* 2006).	Insufficient data to determine spatial trends	Data specific to the status and condition of seagrass and algal beds are not readily available to DRTO; Repeated sampling at permanent sites monitored by Park staff are spatially limited and inadequate to determine temporal and spatial trends for the park (Chapter 5, this report). A useful data set to obtain is Fourqurean and Escorcia 2006).	The abundance of exploited species in fished areas declined or did not change over time compared to areas within marine reserves since 2001	Average annual nest density was highest at East Key, followed by Loggerhead. Annual trends in nest abundance were spatially variable among the Tortugas islands.	Unknown. Existing quantitative data on sea birds in the Tortugas region are dated (1986-1991), and were not collected with appropriate statistical and sampling rigor to determine temporal and spatial trends and the current ecological condition of sea birds at the park (Chapter 7).

Table E-2. Summary of stressors, their effects on natural resources, and the information available in the Tortugas region.

Threat	Stressor	Natural Resources								
		Oceanography and Climate	Water quality	Coral Reef and Hardbottom Communities		Seagrass and Algae Communities		Reef Fishes	Turtles	Seabirds
				Abiotic	Biotic	Abiotic	Biotic			
Climate change	Increased sea surface temperature	G	U	G	G	U	U	U	G	U
	Sea level rise	G	U	Inf	Inf	U	U	U	Inf	Inf
	Ocean acidification	Inf	U	Inf	Inf	U	U	Inf	U	U
Extreme events	Cold / warm fronts	G	U	G	G	U	U	U	F	U
	Tropical storms	G	G	G	G	G	G	G	G	F
	Disease epidemics	U	U	G	G	U	U	U	U	Inf
Resource extraction	Commercial fishing	U	U	Inf	Inf	Inf	Inf	G	G	P
	Recreational fishing	U	U	Inf	Inf	Inf	Inf	G	G	P
	Trade in live species	U	U	Inf	Inf	U	U	F	U	P
	Habitat destruction from fishing gear	U	U	F	F	Inf	Inf	Inf	Inf	U
	Boat groundings & anchor damage	U	U	G	G	Inf	Inf	Inf	Inf	U
	Oil and gas exploration & spills	U	U	F	F	Inf	Inf	U	F	P
Pollution	Sedimentation	U	G	Inf	Inf	Inf	Inf	U	U	U
	Eutrophication (nutrient enrichment)	U	G	G	G	G	G	U	Inf	U
	Marine debris (e.g., derelict fishing gear)	U	U	F	F	Inf	Inf	Inf	Inf	Inf
	Chemical contaminants	U	G	Inf	Inf	U	U	U	U	Inf
Invasive species	Non-native species introductions	U	U	G	G	Inf	U	G	G	F

Key

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Uknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	U = Unknown	

Table E-2 (continued).

Key

EP - Existing problem: Convincing historical (before 1990) or current (1990 to present) evidence that the stressor affects resources at DRTO negatively

HP - Historical problem: Convincing evidence exists that stressor affected resources at DRTO prior to 1990 but is no longer a problem

PP - Potential problem: Stressor is known to affect resources in the Florida Keys negatively, but there is no convincing evidence that it negatively affects resource at DRTO; threat could become a stressor in the near future

OK - Unlikely problem: Stressor has been investigated and no convincing evidence exists that stressor affects resources negatively; Stressor has been alleviated by a management action

UNK - Unknown: There is insufficient data to determine if the stressor has negative effects on natural resources at DRTO; Effects of stressor has not been investigated at DRTO

-- - Not applicable: Stressor is not known to affect the resource or ecosystem component

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Acronyms

CCFHR – Center for Coastal Fisheries and Habitat Research (NOAA)

CCMA-BB – Center for Coastal Monitoring and Assessment, Biogeography Branch (NOAA)

CREMP – Coral Reef Evaluation and Monitoring Project

DRTO – Dry Tortugas National Park (NPS)

EPA – Environmental Protection Agency

ENSO – El Niño-Southern Oscillation

ESA – Endangered Species Act

FIU – Florida International University

FKNMS – Florida Keys National Marine Sanctuary (NOAA)

FMRI – Florida Marine Research Institute (now known as Florida Wildlife Research Institute)

FSS – Fishery Systems Science

FWC – Florida Fish and Wildlife Conservation Commission

FWRI – Florida Wildlife Research Institute

IPCC – Intergovernmental Panel on Climate Change

IUCN – International Union for Conservation of Nature

PCA – Principal Components Analysis

MDS – Multi-dimensional Scaling

MPA – Marine Protected Area

NCCOS − National Centers for Coastal Ocean Science (NOAA)

NMFS – National Marine Fisheries Service (NOAA)

NPS – National Park Service

NOAA – National Oceanic and Atmospheric Administration

NOS – National Ocean Service (NOAA)

NURC/UNCW – National Underwater Research Center, University of North Carolina, Wilmington

RNA – Reserve Natural Area

SFCN – South Florida/Caribbean Network (NPS)

SERC – Southeast Environmental Research Center

SFNRC – South Florida Natural Resources Center

SIMoN – Sanctuary Integrated Monitoring Network

SPA – Sanctuary Preservation Area

TER – Tortugas Ecological Reserve

TNER – Tortugas North Ecological Reserve

TRACTS – Tortugas Reef Atoll Continuing Transect Studies

TSER – Tortugas South Ecological Reserve

UM-RSMAS – University of Miami, Rosenstiel School of Marine and Atmospheric Science

USGS – U.S. Geological Survey

Chapter 1: Introduction

Christopher F. G. Jeffrey

The condition of water resources were assessed in Dry Tortugas National Park (DRTO) located in the Florida Keys (Figure 1.1). The goals of the project were to identify (1) the state of knowledge of natural resources in DRTO; (2) the state of knowledge of natural and anthropogenic stressors and threats that affect these resources; and (3) the current and future strategies to help DRTO managers meet their management objectives.

As stated in the general management plan (NPS 2005), the goals of DRTO are to:

1. protect and interpret a pristine subtropical marine ecosystem, including an intact coral reef community;

2. protect populations of fish and wildlife, including loggerhead (*Caretta caretta*) and green sea turtles (*Chelonia mydas*), Sooty Terns (*Sterna fuscata*), Frigate Birds (*Olfersia spinifera*) and numerous migratory bird species;

3. protect the pristine natural environment of the Dry Tortugas group of islands;

4. protect, stabilize, restore and interpret Fort Jefferson, an outstanding example of 19th century masonry fortification (Figure 1.2);

5. preserve and protect submerged cultural resources; and

6. provide opportunities for scientific research to achieve goals one through five.

The park, which is located 113 km (70 mi) from Key West in the Straits of Florida, is relatively small (269 km^2 [104 mi^2]) and comprises seven small islands and extensive shallow-water coral reefs (NPS 2005) (Figure 1.1). Significant natural resources include ocean, coral reefs, fisheries, seagrass beds, and sea turtle and seabird nesting habitats. Within the past few decades, some of the resources have deteriorated because of natural and anthropogenic factors that range from local to global in scale. For example, despite the remoteness of the park, live coral cover has decreased substantially in recent years because of global impacts from hurricanes (Wheaton et al. 2007) and elevated sea surface temperatures (Andrews *et al.* 2005), while overfishing has altered reef fish assemblages in the wider Tortugas region (Ault *et al.* 2006a). Benthic resources have been damaged by localized activities, such as boating and anchoring, snorkeling and diving, as well as pollution inside and outside the park.

Coastal watershed condition assessments review and synthesize information to determine the status of resources in coastal parks, including water quality, habitat condition, invasive species, extractive uses, coastal development, and other issues affecting resource conditions. The assessments characterize the relative health or status of terrestrial, aquatic, and marine resources based on the best available data, identify actual or potential stressors, and make recommendations for further studies or assessments. Given that DRTO land area is only about 4 km^2 (1.5 mi^2), the condition of park resources is shaped more by oceanic than terrestrial processes.

This report synthesizes information on the status of marine and terrestrial natural resources and the stressors and threats affecting resources at the DRTO. Assessment of the condition of DRTO resources was based on peer-reviewed and non-peer reviewed publications and on unpublished information. Several important sources of information deserve mention.

In 2007, National Park Service (NPS) and the Florida Fish and Wildlife Commission (FWC) developed a collaborative science plan for monitoring and assessing the conservation efficacy of the fully-protected Research Natural Area (RNA) that was implemented at DRTO that year. The RNA science plan summarizes existing information, performance measures and recommended monitoring and research activities for six performance topics, many of which are described in this report. Much of information in the RNA science plan fed into the assessment of ecological condition of resources described herein. In some cases, initial data and other information from the RNA science plan are included in this report. The first report on the implementation of the RNA science plan was released in 2010 and described the progress of 18 projects designed to address the six performance topics (Hallac and Hunt 2010).

The NPS South Florida/Caribbean Network (SFCN) Vital Signs Monitoring Plan (Patterson *et al.* 2008a,b,c) included DRTO. The plan describes a program for monitoring the condition of selected natural resources for early detection of negative trends in resource condition. NPS defines a vital sign as

> …a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values…

Vital signs were ranked in order of importance to park management; 28 of 69 vital signs identified for south Florida and Caribbean parks were deemed important for DRTO. Information on SFCN rankings of vital signs and monitoring strategies are provided for marine natural resources covered in this assessment.

NOAA Biogeography Branch conducted a biogeographic assessment of reef fishes occurring in the wider Tortugas region (http://ccma.nos.noaa.gov/ecosystems/coralreef/tortugas.html). The Tortugas integrated assessment was designed to determine existing or potential biological and human (societal) benefits and impacts resulting from implementation of the Tortugas Ecological Reserve (TER) in the Florida Keys National Marine Sanctuary (FKNMS). The reserve is a 518-km^2 (200 mi^2) no-take marine area consisting of two non-contiguous sections: Tortugas North Ecological Reserve (TNER) and Tortugas South Ecological Reserve (TSER). The TNER is adjacent to DRTO and the TSER is southwest of DRTO (Figure 1.1). The goal of the reserve is to protect large contiguous and diverse habitats to preserve biological diversity, maintain resource quality, and to replenish surrounding areas. The recently enacted DRTO RNA adds 119 km^2 (46 mi^2) of marine habitats to federally protected waters in the Tortugas region.

This report focuses on natural resources identified by researchers and resource managers of the DRTO as vitally important to the Tortugas region and the wider South Florida ecosystem (NPS 2005). Chapter 2 summarizes the history of the DRTO and describes the historical and current research conducted there. Chapter 3 summarizes information on physical resources including geology, oceanography and water quality of the park. Chapters 4–7 describe coral reef and hardbottom benthic assemblages, seagrass and algal communities, reef fishes and macroinvertebrates, sea turtles, and seabirds. Chapter 8 summarizes stressors and threats known to affect natural resources in the park and the Tortugas region. Chapter 8 is a synopsis of the ecological condition of natural resources based on information in the Chapters 3-7. Information on resources and the stressors affecting them was synthesized from several sources, including peer-reviewed journal articles and technical memoranda, unpublished reports, and personal communication with NPS staff. This assessment will aid efforts by resource managers to address threats and issues at a regional oceanographic scale and will help guide development of management actions to reduce and prevent impairment of DRTO marine resources.

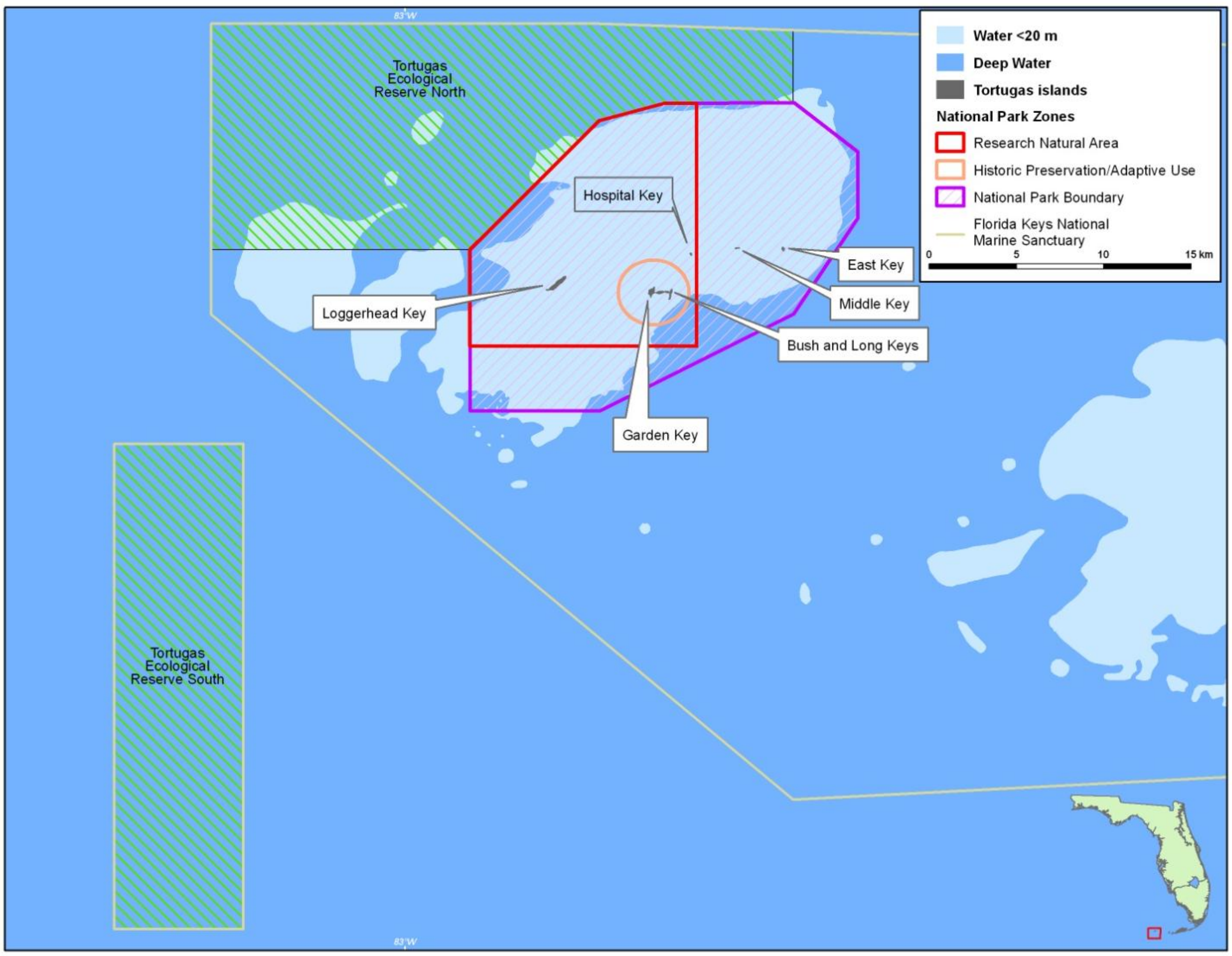

Figure 1.1. Islands and management zones of the Tortugas region, Florida Keys (source: K. Buja).

Figure 1.2. Fort Jefferson on Garden Key in Dry Tortugas National Park (source: NOAA/NOS/NCCOS/CCMA/Biogeography Branch).

Chapter 2: History of Dry Tortugas National Park

Christopher F. G. Jeffrey and Douglas Morrison

Dry Tortugas was given its name by the Ponce de León in the early 1500s because of the abundance of turtles (Davis 1982, NPS 2005, Shinn and Jaap 2005). According to Davis (1982), Gauld mapped and identified 11 sand and coral islands in 1773. Agassiz also mapped the region in 1883 to challenge Darwin's theory on the formation of atolls through the subsidence of volcanoes (Dobbs 2005). In 1904, the Carnegie Institution established a marine laboratory on Loggerhead Key (Davis 1982, Shinn and Jaap 2005; Figure 2.1). President Theodore Roosevelt designated the area as a wildlife refuge in 1908 to protect sea bird rookeries. The Dry Tortugas National Monument was established in 1935 and in 1980, corals and marine life were included for protection. In 1992, the Dry Tortugas National Park (DRTO) was established by the federal government to protect the subtropical marine ecosystem including coral reefs, fish, and wildlife within its boundary (Figure 1.1). The state of Florida retained the rights to the seabed and associated resources (SFNRC and FWC 2007). The park encompasses 269 km^2 (104 mi^2) and its boundary is marked by a series of buoys located beyond the reef margins in about 22 m (72 ft) of water. National Park Service (NPS) regulations prohibit commercial fishing, but allow recreational fishing, boating, snorkeling, scuba-diving, and other recreational activities.

In 2007, NPS and the state of Florida entered into a joint agreement or Memorandum of Understanding (MOU) to establish a Research Natural Area (RNA) within the DRTO (SFNRC and FWC 2007). The RNA is 119 km^2 (46 mi^2), but its regulations exclude an area 1.85 km (1.15 mi) in diameter around Garden Key Lighthouse and the developed areas on Loggerhead Key (Figure 1.1). Aquatic activities permitted within the RNA include boating, swimming, snorkeling, scuba diving, research, and education, but exclude anchoring and recreational fishing. Mooring buoys are provided for snorkeling and scuba diving boat operations during the day. RNA regulations prohibit manipulation of resources within its boundaries, except where needed to achieve restoration (SFNRC and FWC 2007).

The RNA was designed to restore ecological integrity and the capacity for renewal of natural resources within its boundaries and to protect shallow-water marine habitats known to be inhabited by juvenile fishes and benthic communities. Along with the protection to natural resources offered by the adjacent Tortugas North Ecological Reserve (TNER), resource managers hypothesize that the RNA will enhance species diversity, productivity and long-term sustainability of reef fish assemblages in Tortugas region (SFNRC and FWC 2007).

2.1. History of Research, 1852−1990

Research has been conducted at the Dry Tortugas since 1852, some of which has been catalogued in an annotated bibliography by Schmidt and Pikula (1997) and summarized in Davis (1982), Shinn and Jaap (2005), and Wheaton *et al.* (2007). Between 1852−1882, research at the Tortugas described the natural history and mapping the geology of the islands and surrounding marine resources (Davis 1982, Ginsberg 1985, Jaap and Sargent 1993, Wheaton *et al.* 2007). In 1904, the Carnegie Institute of Washington D.C. established the Tortugas Laboratory on Loggerhead Key and, from 1911 until its closing in 1939, research conducted there resulted in several publications on reef geology, animal physiology, chemistry of seawater, taxonomy, and the effects of temperature on growth rates of corals (reviewed by Schmidt and Pikula [1997] and Shinn and Jaap [2005]).

During the late 1970s and 1980s, research at the Tortugas focused on geologic studies *(Shinn et al.* 1977) and interdisciplinary investigations called Tortugas Reef Atoll Continuing Transect Studies (TRACTS) of benthic resources (Davis 1982). The TRACTS program was designed to develop "bench-mark" descriptions of marine resources at the then Fort Jefferson National Monument, which were to be used to define and evaluate long-term change occurring in the Tortugas region (Davis 1982). One highlight from the TRACTS research was an assessment by Davis (1982) that compared the spatial distribution of reef corals in 1979 with their mapped distribution in 1881 described by Agassiz (1882). Davis' findings are critical to understand temporal changes in the distribution of acroporid corals in the Tortugas region and are described in Chapter 3.

2.2. Recent Multi-year Research and Monitoring, 1990−2007

Research on natural resources in the DRTO between 1990−2007 focused mainly on fisheries (reef fish and macro invertebrates), wildlife (seabirds and turtles), benthic communities (corals, algae and seagrass beds), and oceanographic variables (sea surface temperature, ocean color, etc.). Seven established multi-year projects monitored assemblages of reef associated fishes (including sharks) and mobile macroinvertebrates (Table 2.1). Eight multi-year projects monitored benthic communities, including hard and soft corals, algae, and seagrasses (Table 2.2); eight projects have either synthesized data for mapping or conducted mapping activities in the Tortugas region (Table 2.3). Four projects include the Tortugas region in large-scale oceanographic and water quality studies for South Florida (Table 2.4). The interdisciplinary studies are funded by multiple state and federal agencies, and ultimately, aim to evaluate the efficacy of no-take areas on natural resources in the Tortugas region. Anecdotal information, data, and major findings from these monitoring and research programs were reviewed and synthesized in the Chapters 3-7 to determine the status of ecological resources of Tortugas region and the DRTO.

2.3. Current Research and Monitoring, 2007 to Present

In 2007, NPS and Florida Fish and Wildlife Conservation Commission (FWC) developed a RNA science plan to evaluate the effectiveness of the RNA in protecting and enhancing natural resources within its boundaries in six key topical areas of performance (Table 2.5). The RNA science plan is a blueprint for proposed research and monitoring activities; it also defines essential and supplemental activities and performance measures that will quantify the effectiveness of the RNA. Several projects have been implemented to evaluate performance of the RNA and results should be reported to FWC commissioners, NPS managers, and the public every 3-5 years, as stipulated by the MOU between NPS and FWC (Table 2.6).

Table 2.1. Projects that characterize and monitor reef fish assemblages in the Tortugas region (source: D. Morrison, Everglades and Dry Tortugas National Parks, Key Largo, FL).

Project title and description	Activities and data collected	Lead institution	Funding agency	Start year / duration
National Oceanic and Atmospheric Administration (NOAA) / University of Miami Reef Fish Visual Census	Uses the Reef Visual Census Survey method to collect in situ data on reef fishes (species composition, size, and abundance)	University of Miami, Rosenstiel School of Marine and Atmospheric Science (UM-RSMAS)	NOAA National Marine Fisheries Service (NFMS) and National Park Service (NPS)	1994
Reef Environmental Education Foundation (REEF)	REEF's Advanced Assessment Team of Scuba divers collect information on marine fish populations using a Rover Diver Survey method at permanent sites in the DRTO	REEF	NOAA National Ocean Service (NOS) and NPS	2001
SEAMAP Reef Fish Survey	Used video cameras and fish traps to collect data on reef fishes	NMFS	NMFS	2001−2005
Characterization of the Tortugas Ecological Reserve (TER)	Conducts drifter studies for larval transport studies; ichthyoplankton surveys; reef fish visual surveys (fish size and abundance)	NOAA Center for Coastal Fisheries and Habitat Research (CCFHR)	NOS	2002
Reproductive biology and mating behavior of nurse sharks	Observes and tracks sharks during mating and birthing seasons to evaluate growth and local movements; characterizes the social interactions that develop during mating season; determine relationships between mating behavior and essential habitats; uses DNA analysis to assess the composition of social groups	Mote Marine Laboratory		2002−2007

Table 2.2. Multi-year projects that study benthic communities in the Tortugas region (source: D. Morrison, Everglades and Dry Tortugas National Parks, Key Largo, FL).

Project title and description	**Activities and data collected**	**Lead institution**	**Funding agency**	**Start year**
Long-term monitoring of benthic habitats	Collects *in situ* data on sea grasses (species composition, cover, abundance, morphology, growth rate, and isotopic analyses)	Florida International University (FIU)	NOAA NOS	1995
Florida Reef Resilience Program	Collects *in situ* data on algae (species composition and cover), corals (species composition , disease, bleaching, cover, and abundance of colonies) and fishes (species composition and abundance)	Florida Keys National Marine Sanctuary (FKNMS)	NOAA NOS, Environmental Protection Agency (EPA)	1998
Coral Reef Evaluation and Monitoring Project (CREMP)	Uses video transects to conduct a complete station species inventory of benthic organisms and coral diseases.	Florida Fish and Wildlife Research Institute (FWRI)	NOAA NOS / EPA	1999
Coral Reef Benthic Communities Assessment	Monitors long term ecological status and trends of the common and rare coral reef types and effects of hurricanes at seven sites within DRTO	FWC, University of Georgia	NPS	?
Rapid Assessment and Monitoring of Coral Reef Habitats	Collects *in situ* data on benthic composition (percent cover, size, and abundance of corals, algae, gorgonians, and sponges); condition of corals (bleaching and disease)	University of North Carolina National Undersea Research Center (UNC-NURC)	NOAA NMFS and NOS	1999
Distribution and Etiology of Coral Diseases in the Florida Keys	Uses a probabilistic sampling design (based on EPA's EMAP) to select sites and assess the presence or absence of diseased coral colonies at each site	EPA	EPA	2001
Characterization of the TER	Benthic mapping & characterization at permanent sand/reef interface sites (percent cover of algae, gorgonians. Sponges, and coral; sediment cores, stable isotope studies)	NOAA CCFHR	NOAA NOS	2002

Table 2.2 (continued).

Project title and description	Activities and data collected	Lead institution	Funding agency	Start year
South Florida Program Ecological Processes and Coral Reef Recovery Project	Measures coral cover, diversity, herbivory on algae, and mortality rates of juvenile corals; compare juvenile and adult coral assemblages	Florida Institute of Oceanography	NOAA NOS	2002
Monitoring Spiny Lobsters	Collects in situ data on lobsters (size, and abundance)	Florida Fish and Wildlife Conservation Commission (FWC)	FWC	1997
Benthic habitat monitoring of DRTO	Collects *in situ* data on benthic composition (percent cover of algae, gorgonians, sponges, and corals and coral disease)	NPS South Florida / Caribbean Network of Parks (SFCN)	NPS	2004

Table 2.3. Multi-year projects to map and characterize benthic habitats in the Tortugas region (source: D. Morrison, Everglades and Dry Tortugas National Parks, Key Largo, FL).

Project title and description	**Activities and data collected**	**Lead institution**	**Funding agency**	**Start year / duration**
Benthic Habitats of the Florida Keys	Used visual interpretation of aerial photography to identify seafloor features	FWRI	NOAA NOS	1991−1998
Characterization of benthic habitats in the TER	Used a suite of ship-based and remote sensing technologies to map and characterize habitats (towed underwater video, side-scan and multibeam sonar, aerial photography, and satellite imagery)	NOAA CCFHR	NOAA NOS	2001
Benthic habitat mapping in the Tortugas Region, Florida	Synthesized data from a suite of technologies (bathymetric surveys, side scan sonar, imagery, aerial photogrammetry, existing habitat maps, and in situ visual surveys)	UM-RSMAS	NOAA NFMS and NPS	2003-2003
EAARL LIDAR Topography for the Dry Tortugas	Used the National Aeronautics and Space Administration (NASA) Experimental Airborne Advanced Research Lidar (EAARL) to collect data for portions of Florida Keys	U.S. Geological Survey (USGS)	NPS	2004-2006
Benthic Habitat Mapping of Florida Coral Reef Ecosystems	Coordinates efforts among State and Federal agencies to map and characterize coral reef ecosystems of Southern Florida; prioritizes areas for mapping; developed a mapping implementation plan	NOAA Center for Coastal Monitoring and Assessment (NOAA CCMA)	NOAA NOS	2005
Benthic habitat mapping in the Tortugas Region, Florida	Synthesized data from a suite of technologies (bathymetric surveys, side scan sonar, imagery, aerial photogrammetry, existing habitat maps, and in situ visual surveys)	UM-RSMAS	NOAANOS	2005−2007
Bathymetry map of south Florida	Synthesized existing data from various sources to create a single map of the Florida Keys	University of South Florida (USF)		Completed
Dry Tortugas multibeam characterization	Collected multibeam sonar data for the Dry Tortugas region	USF		Completed

Table 2.4. Recently completed or ongoing multi-year projects that study oceanographic conditions and water quality in the Tortugas region (source: D. Morrison, Everglades and Dry Tortugas National Parks, Key Largo, FL).

Project title and description	Activities and data collected	Lead institution	Funding agency	Start year / duration
Southeast Environmental Research Center (SERC) Water Quality Monitoring Network	Collects in situ and grab water samples; measures several water parameters (depth profiles of water temperature, nutrients, salinity, dissolved oxygen, photosynthetically active radiation) chlorophyll a fluorescence, optical back-scatter, turbidity, depth, and density)	FIU	South Florida Water Management District and EPA	1991
Real-time oceanographic observations in the FKNMS	Continuous measurement of oceanographic variables (e.g., salinity, sea height differences, temperature, salinity, chlorophyll a fluorescence, ocean currents, and volume flow from Florida Bay through the Keys passages towards the coral reefs of the FKNMS)	NOAA Office of Oceanic and Atmospheric Research (OAR)	NOAA	2002−2004
Long-term measurement of physical, chemical, and biological water column properties in the south Florida coastal ecosystem	Uses remotely sensed data (SeaWiFs and MODIS satellite ocean color) to estimate water radiance, chlorophyll, and turbidity in Florida Bay	NOAA OAR	NOAA	2004-2007
Regional hydrodynamic model for South Florida coastal seas	Develops a 3-D,"community" hydrodynamic model for Florida Bay and the Florida Keys and conducts simulations to provide boundary conditions for the models	UM-RSMAS	NOAA	2004−2007

Table 2.5. Summary of research topics and performance measures to assess the conservation efficacy of the Dry Tortugas National Park (DRTO) Research Natural Area (RNA) (source: National Park Service and Florida Fish and Wildlife Conservation Commission Science Plan, 2007).

Topic area for evaluating Research Natural Area	Performance measures
1. Quantify changes in the abundance and size structure of exploited species within the RNA relative to adjacent areas	Abundance, sizes, occurrence frequency, and estimates of fisheries stock assessment parameters for groupers, snappers, and grunts inside and outside the RNA. Abundance of reference (non-fishery) reef fishes e.g., parrotfishes)
2. Monitor the immigration and emigration of targeted species in the RNA	Net immigration of select species from the snapper-grouper complex from the RNA to adjacent fished areas inside and outside the DRTO
3. Monitor changes in species composition and catch rates of exploited species throughout the surrounding region	Catch per unit of effort, including released fish, harvested, and population size-structure of targeted reef fishery species, especially grouper and snapper species throughout the region
4. Evaluate the effects of RNA implementation on marine benthic biological communities	Damage to, and loss of, stony and soft corals species, seagrass, benthic community structure, abundance of functional groups, measures of grazing pressure, coral recruitment, spawning, and disease; measures of primary productivity
5. Assess reproductive potential of exploited species by evaluating egg production and larval dispersal	Fecundity and larval production of reef sportfish and movement of reef sportfish from the RNA to spawning aggregation sites. RNA export of targeted reef fishery species, primarily larval groupers and snappers throughout the Tortugas and Florida Keys
6. Incorporate social sciences into the research and monitoring program	Fishing activity scuba and snorkeling activity (total number of scuba divers and snorkelers and duration in water for each designated dive site and reference site), number of boats, anchoring by location, visitor satisfaction, and law enforcement activity

Table 2.6. Summary of research projects implemented after 2007 to assess the conservation efficacy of the Dry Tortugas National Park (DRTO) Research Natural Area (RNA) (source: Hallac and Hunt (2010). UM-RSMAS = University of Miami, Rosenstiel School of Marine Science; FWC = Florida Fish and Wildlife Conservation Commission; USGS = U.S. Geological Survey; SCFN = South Florida / Caribbean Inventory and Monitoring Network.

	RNA topic area	Project title	Lead institution	Project description
1.	Quantify changes in the abundance and size-structure of exploited species within the RNA relative to adjacent areas.	Fishery-independent visual assessment of resource status of the reef fish community in DRTO	UM-RSMAS	Monitor and statistically assess coral reef fish resource status through diver visual surveys to determine efficacy of RNA
		Examining the efficacy of the newly established Research Natural Area for protecting coral reef fishes within DRTO	FWC	Use of baited fish traps, hook and line gear, and tagging studies to evaluate changes in relative abundance, frequency of occurrence, size-age structure, and movements of exploited fishes within the RNA and in adjacent areas
		Characterization of fish assemblages associated with seagrasses within the newly established RNA and adjacent open-use zones at DRTO	FWC	To characterize community structure of seagrass-associated fish within the DRTO RNA and adjacent open-use areas
2.	Monitor the immigration and emigration of targeted species in the RNA	Fine-scale and net migration of selected reef fish species from RNA to adjacent fished areas in DRTO region	FWC	Analysis of reef fish movement and habitat use from acoustic telemetry data to determine patterns and essential spatial range of selected snapper and grouper species
		Reef fish movements and flux around the RNA	UM-RSMAS	A multi-year acoustic telemetry study to determine long-term movement patterns, space requirements, and population flux for exploited fishes in the RNA and to evaluate the contention that reserves are sinks for fisheries production
		Use of protected areas by threatened and endangered marine turtles in the Dry Tortugas	USGS	A turtle capture, tagging, and tracking project to characterize sea turtle populations in DRTO and quantify the proportion of time individuals of each species spend in the RNA compared to other areas of the park.

Table 2.6 (continued).

	RNA topic area	Project title	Lead institution	Project description
3.	Monitor changes in species composition and catch rates of exploited species throughout the surrounding region	Extended creel census development for DRTO	UM-RSMAS	To improve creel census design performance and evaluate fishery-dependent and independent databases as they relate to RNA implementation in DRTO
		DRTO vessel permit system	DRTO	Development of an electronic system to generate permits and maintain statistics and information on park users
4.	Evaluate effects of RNA implementation on marine benthic biological communities	Assessing the effects of scuba and snorkeling use on corals at RNA designated (mooring buoy) dive sites	DRTO	To monitor the effects of diving activity on corals at designated dive sites in the RNA. Performance measures include damage to and loss of stony corals especially *Acropora* spp., which are listed as endangered
		Coral community monitoring ad Bird Key Reef and sites inside and outside RNA at DRTO	SFCN	SFCN is monitoring coral reef communities within DRTO to determine whether the percent cover of stony corals , algae (turf, coralline, macroalgae), octocorals, and sponges; coral species diversity; coral community structure; and rugosity are changing through time at selected coral reef sites and inside and outside RNA
		Trophic relationships on coral reefs of DRTO inside and outside of RNA	USGS	The goals are to examine trophic interactions, to understand better the intricate balance among herbivores, macroalgae, and corals, and to determine if that balance can be restored in protected areas like the RNA. The project conducted detailed baseline species-level surveys of macroalgae, scleractinian corals, gorgonians, herbivorous and exploited fishes, urchins, and substratum rugosity at 18 DRTO sites before RNA was implemented.
		Assessing the effects of creating the RNA no-anchor zone on seagrass meadows	DRTO	The intent of this project is to detect changes in percent cover of seagrass through a fully replicated "Before-After-Reference-Impact" sampling design that measure and compare changes in seagrass cover at RNA and reference sites.

Table 2.6 (continued).

	RNA topic area	Project title	Lead institution	Project description
5.	Assess reproductive potential of exploited species by evaluating egg production and larval dispersal	Reproductive potential of exploited reef fishes within the newly established DRTO RNA and adjacent open-use areas	FWC	To examine gonad tissues and estimate reproductive potential or fecundity of exploited reef fishes. The project examines gonad tissues from 10 snappers and 10 groupers caught within the RNA and in adjacent areas during spring and fall sampling to determine stages of reproductive development. If reproductive development is advanced, a sample of gonad tissue is preserved for further reproductive analysis.
		Immigration and emigration of selected reef fish species from the RNA to Tortugas South Ecological Reserve	FWC	Use an array of acoustic receivers to determine spatial and temporal patterns and rates of movement of acoustically tagged snappers and groupers among the Tortugas North Ecological Reserve, Tortugas South Ecological Reserve, and DRTO including the RNA. Data from the receivers will be used to assess fish habitat utilization patterns, residence times, and migration patterns; the timing of multispecies aggregations; and the importance of habitat linkages between adjacent marine protected areas.
		Larval transport modeling from the Dry Tortugas	UM-RSMAS	To evaluate the expected physical transport and fate of reef fish eggs and larvae spawned in the Dry Tortugas region to the adjacent waters of the south Florida coral reef ecosystem. The study utilizes the Hybrid Miami Isopycnal Coordinate Ocean Model (HYCOM) along with information on spawning and larval life history characteristics of snapper-grouper species.

Table 2.6 (continued).

	RNA topic area	Project title	Lead institution	Project description
6.	Incorporate social sciences into the research and monitoring program	A survey of visitor demographics, attitudes, perceptions, and experiences in DRTO	University of Massachusetts Human Dimensions of Marine And Coastal Ecosystems Program	The project will survey and compare visitors demographics, attitudes, perceptions, and experiences of park resources among visitors who enjoy recreational boating, fishing, SCUBA diving, snorkeling, and other activities. The report will also provide a geospatial assessment of geographic locations of these uses.
		Law enforcement in Dry Tortugas National Park	DRTO	To enhance effectiveness of law enforcement at DRTO. Primary law enforcement goals at DRTO include educating the public and enforce zones that do not permit anchoring and fishing, enforcing fishing limits, in areas where fishing is permitted, and enforcing laws that protect sensitive turtle coral, seagrass habitat, and submerged cultural resources.
		Submerged cultural resource condition assessment project	National Park Service Submerged Resource Center	To conduct baseline documentation, monitoring and condition assessments of known submerged cultural resources in DRTO

Chapter 3: Climate and Oceanography

Christopher F. G. Jeffrey, Jiangang Luo, Jerald S. Ault, Steve G. Smith and Varis Ransibrahmanakul

3.1. Climate

The Dry Tortugas National Park (DRTO) and the surrounding area have a tropical maritime climate that is influenced by the Caribbean Sea, Gulf of Mexico, and the Bermuda/Azores high pressure air system (Schomer and Drew 1982, NOAA 2000) (Figure 3.1). Seasonal variations in position of the "jet stream" and its interactions with other air masses in the upper atmosphere affect temperature, precipitation and wind speed in the region. Two primary climatic seasons are present: a rainy season occurs from about May−October and a drier colder season from November−April caused by northern frontal systems. Winds from the east-southeast typically prevail during the rainy season while warmer winds from the east-northeast predominate during the dry winter season. The wind patterns are disrupted by cyclonic disturbances during the rainy season and by cold fronts associated with strong northwesterly winds during the dry season.

Florida's climate is superimposed on cycles of El Niño-Southern Oscillation (ENSO). El Niño periods result in: (1) warmer, wetter winters with fewer hurricanes and (2) doldrum-like conditions in late summer that are favorable for mass coral bleaching and disease events (Causey 2008, Jaap *et al*. 2008). La Niña periods correlate with drier cooler winters and more frequent storms. Water temperatures typically range from 19^{o}C (66°F) during January to an average high of 32.2^{o}C (90°F) during July and August (Vaughan 1918, Jaap *et al.* 2008). Occasional cold-fronts result in water temperatures as low as 14^{o}C (57°F) in 1978 and have been implicated in the periodic decrease in the cover of live coral in the Florida Keys (Agassiz 1882, Davis 1982, Jaap *et al.* 2008).

The Florida Keys including Dry Tortugas experiences many tropical depressions and hurricanes. In combination with less severe but persistent ecological perturbations, these catastrophic events have shaped the ecology of ecosystems in the southeast Florida region (Precht and Miller 2007, Jaap *et al*. 2008). Precipitation averages 125 cm/yr (49 in/yr), making the Tortugas Islands the driest areas of the Florida Keys. Rainfall is mainly convectional and results from localized storms that occur between June and November and peak during September (Schomer and Drew 1982). Average monthly rainfall ranges from 4.5−14.9 cm (1.8−5.9 in), but precipitation from individual hurricanes ranges typically from 5−15 cm (2−6 in) and can exceed 50 cm (20 in) at times (NOAA National Weather Service Data). Several storms have affected the area in recent decades (Figure 3.1).

3.2. Geologic and Bathymetric Features

Unlike the main reef tract in the Florida Keys, which some regard as being marginal for coral reef growth[2] (Jaap 1984, Shinn *et al.* 1989, Precht and Miller 2007), the Tortugas region boasts

[2]Marginal conditions for coral growth of the modern Florida Reef Tract supposedly is caused by tidally-induced flows from Florida Bay and the Gulf of Mexico over the Florida Reef Tract through tidal passes that create conditions unfavorable to accretion of limestone to reefs (e.g., variable salinity, high nutrient content, temperature extremes and high turbidity [Lidz *et al.* 2008, Ginsburg and Shinn 1964]).

several well developed reef systems with complex benthic features (Agassiz 1882, Davis 1982, Miller *et al.* 2001, Franklin *et al.* 2003). Located on the southwest margin of the Florida Continental Shelf, these carbonate banks are interspersed with sandy islands and form an ellipsoid with a south-west to north-east axis (Figure 3.2). Atoll-like in structure, the rim of the banks consists of 14 m (46 ft) thick Holocene coral reefs (<10,000 years old) that lie above 135,000-year-old rock known as Key Largo Limestone (Shinn *et al.* 1977). The Holocene reefs are comprised of massive heads of *Montastraea* spp. Coral reef and hardbottom substrates on the banks within the park are comprised of nine different habitat types based on bathymetric and geomorphologic features (Franklin *et al.* 2003).

South of the park and within the Tortugas Ecological Reserve[3] (TER) is Riley's Hump – a smaller bank with an area of 12.0 km^2 (4.6 mi^2) (Franklin *et al*. 2003; Figure 3.2). Substrates at Riley's Hump have very low vertical relief (<0.5 m [1.6 ft]) and are predominantly patchy hardbottom and rocky outcrops within a matrix of sand (Franklin *et al*. 2003). To the east of the DRTO is an area of extensive sand (named the quick sands), which is shaped by currents into waves with crests up to 3 m (10 ft). Interestingly, the Tortugas Bank reefs did not keep pace with rising sea levels as did Bird Key Reef that is located in the DRTO (Shinn *et al*. 1977).

To the west of the Tortugas National Park are the Tortugas and Little Banks with a combined area of 137 km^2 (53 mi^2) (Figure 3.3). That area contains fewer hardbottom habitat types compared with the area enclosed within the DRTO and is predominantly low-relief hardbottom and scattered rocky outcrops (94%; Miller *et al.* 2001, Franklin *et al.* 2003). However the remaining 6% of the Tortugas-Little Bank complex consists of terraces and pinnacles that rise from the sand at 33−38 m (108−125 ft) deep to shallower depths at 16−25 m (52−82 ft). Of note is Sherwood Forest, aptly named because of the predominance of massive-mushroom-shaped corals that occur there (Figure 3.3). The topography of Sherwood Forest is very complex with numerous undercuts and caverns and mushroom-shaped and plating corals up to 2 m (6.6 ft) in height (Miller *et al.* 2001). About 50% of the Tortugas-Little Bank area lies within the northern portion of the TER.

3.3. Oceanography and Currents

The oceanography of the Tortugas region is driven by the Gulf Stream Current System, a western boundary current that forms the northward flowing segment of North Atlantic Gyre (Figure 3.4). Equatorial Atlantic surface waters (<1,200 m deep [937 ft]) are transported via the North Equatorial, Brazil, and Guiana currents into the Caribbean Sea through passages between the islands of the Lesser Antilles. The Caribbean Current transports surface waters from the Caribbean Sea through the Yucatan Channel (between the island of Cuba and the Yucatan Peninsula) into the Gulf of Mexico where it becomes the Mexican Current (Sturges and Blaha 1976), Loop Current (Hofmann and Worley 1986), and Florida Current (Lee *et al*. 1994) (Figure 3.1). Just off Florida's east coast, the Florida Current joins the Antillean Current that transports surface water from the near the equator along the eastern boundary of the Lesser Antilles and Greater Antilles to form the Gulf Stream (Figure 3.4).

[3]Tortugas Ecological Reserve (TER) is part of the Florida Keys National Marine Sanctuary, which is under the jurisdiction of NOAA. TER comprises TER North, which abuts the Dry Tortugas National Park and encompasses the Tortugas-Little Bank area, and Tortugas South Ecological Reserve, which includes Riley's Hump.

The Loop Current is dynamic current pathway that exerts a strong influence on current flow around the Tortugas region. Sometimes the Loop Current is nonexistent as water flows in an almost direct path to the Florida Current south of the Tortugas region through the Florida Straits. This current pattern results in a strong eastward flow over the slope off the Dry Tortugas and lower Florida Keys (Lee *et al.* 1994). At other times, the Loop Current intrudes into the Gulf of Mexico to a mean position of 27.5^{o} N ±100 km (62 mi) north or south of that position (Vukovich 1988, Zavala-Hidalgo *et al.* 2003). When it is prominent, cold, cyclonic gyres or eddies form and evolve from the Loop Current in the southern Straits of Florida (Lee *et al.* 1994). One such eddy is a large counter-clockwise rotating gyre that forms just south of the Tortugas and is known as the Tortugas Gyre (Figure 3.5). The Tortugas Gyre can attain a size of 200 km (124 mi) in diameter and may persist for up to 100 days (Lee *et al.* 1994). The gyre travels eastward toward the Florida Keys at an average speed of 5 km/d (3 mi/d) but reduces to half its original size off Big Pine and Marathon Keys; it eventually becomes unobservable off the northern keys (Lee *et al.* 1994).

The Tortugas Gyre contributes significantly to the uniqueness of the region. The formation of the gyre enhances food supply and retains and transports locally spawned larvae of invertebrates (e.g., conch and lobster) and fishes (e.g., snapper and grouper) eastward toward coastal reefs in the Florida Keys. In fact the Loop current, Tortugas Gyre and Florida current could provide a recruitment pathway for lobsters in the Florida Keys (Lee *et al.* 1994, Yeung *et al.* 2000, Yeung and Lee 2002, Sponaugle *et al.* 2005). For example, passive drifters released at Riley’s Hump became entrained in the Loop Current and transited once around the Tortugas gyre before rapidly exiting the area with the Florida Current (Johns 2003). Drifters released at Riley’s Hump in 2000 became entrained and either drifted eastward along the Florida Keys toward the east coast of Florida or northward toward the West Florida Shelf (Burke *et al.* 2003) (Figure 3.6).

Burke *et al.* (2004) estimated that within approximately 30 days of larval life stage for fishes spawning at Riley’s Hump, larvae could reach as far downstream as Tampa Bay on the west Florida coast and Cape Canaveral on the east coast. This pattern of flow occurs often and has been observed in similar studies (Lee and Williams 1999, Sponaugle *et al.* 2005). Passive transport of fish and invertebrate larvae by these ocean currents and their associated frontal eddies could mean that the Tortugas region may be receiving larvae from reefs in the Yucatan Peninsula or the Caribbean that may be upstream if circulatory patterns match planktonic larval duration (Yeung *et al.* 2000, Yeung and Lee 2002, Sponaugle *et al.* 2005). Likewise, passive oceanic transport could be outsourcing larvae from the Tortugas region eastward toward the rest of the Florida Keys. However, the export of larvae from the Tortugas to the remainder of the Keys is counteracted sometimes by a westward counter-current flow of water that also could be transporting larvae and recruits to the Tortugas region from reefs in the Florida Keys. The westward countercurrent tends to occur during the fall season from Key Largo to the Dry Tortugas when persistent northeasterly winds prevail, and when the Florida Current is further offshore (Lee *et al.* 1994, Lee and Williams 1999).

Several other oceanic conditions could also affect larval transport to or from the Tortugas region. The transport processes in the Florida Keys coastal zone are spatially variable (Yeung and Lee 2002). Semidiurnal internal tides can cause upwelling of colder oligotrophic continental slope waters during periods when the Florida Current meanders closer toward shore. Transport of fish larvae by the movement of these frontal eddies will not occur if fish and invertebrates do not spawn during the passage of these eddies (Sponaugle *et al.* 2005) or if the planktonic larval duration times are shorter or longer than the transit times of the eddies (Yeung and Lee 2002). Although some of the mechanisms, timings, and patterns of flows remain to be understood, the general pattern of oceanic circulation observed in the Tortugas region tends to aid the retention and ultimate recruitment of locally- and distantly-spawned larvae (Lee and Williams 1999, Yeung and Lee 2002, Sponaugle *et al.* 2005).

3.4. Climate Change versus Variability in Ocean Temperature

3.3.1. Sea Surface Temperature

Climate change is now considered a global threat to coral reef ecosystems (Glynn 1983, Hoegh-Guldberg 1999, Kleypas *et al.* 1999). Stressors associated with the threat of climate change include increased SST, sea level rise and ocean acidification. In the Tortugas region, the degradation in coral reef ecosystems has been linked to climate change as well as extreme variability in oceanographic conditions (NPS 2005, Jaap *et al*. 2008). Increasing sea surface temperature (SST) is a stress to corals and has been one of the more devastating problems facing reefs in the Tortugas region. Continued increase in mean ocean temperature will reduce oxygen levels, which could result in respiratory stress to marine animals. In the past 28 years, extremely warm sea surface temperatures (30−32^{o}C [86−90°F]) have resulted in bleaching events followed by disease outbreaks that contributed to a decline in coral cover in the Florida Keys, and the same may have occurred in the Tortugas region (Causey 2001, 2005, Precht and Miller 2007, Jaap *et al.* 2008).

Increased sea surface temperatures have been correlated with bleaching or the loss of zooxanthellae from hard and soft corals, zoanthids, and other zooxanthellate organisms. Several massive bleaching episodes have resulted in widespread decline in coral cover in the Florida Keys and the wider Caribbean in the past 28 years (Causey 2008). Concurrently, the incidence and prevalence of coral diseases increased during the past three decades (Causey 2008). The most recent Caribbean-wide bleaching event occurred in 2005 when unusually warm waters were also detected in Tortugas region. Miller *et al.*, (2006) observed signs of a severe bleaching event in the Florida Keys associated with high surface and bottom seawater temperature (31.1−32.2^{o}C [88−90°F]), but found little evidence of bleaching in the Tortugas region. Coral bleaching may have been minimal in the Tortugas region because the reefs occur in deeper waters than reefs of the Caribbean (Miller *et al.* 2006). The 2005 hurricane season may have mitigated the effect of elevated seawater temperatures on corals and prevented massive bleaching such as occurred in the wider Caribbean.

Episodic passages of cold and warm fronts have also affected coral reefs. Scleractinian coral reef ecosystems in the Tortugas region are at the northern latitudinal and temperature limits of extensive reef growth in the Atlantic (Vaughan 1914, Precht and Miller 2007). The location coupled with the convergence of several ocean current systems makes the area susceptible to extreme variability in oceanographic and climatic conditions that is stressful to reef systems. Periodically, cold and warm fronts travel through the Tortugas region, which results in extreme variability in local oceanographic conditions. For example, episodic cold fronts periodically have resulted in extremely cold-water temperatures (14−18^{o}C [57-64°F]) that obliterated acroporid corals and decimated coral reefs in the Tortugas region in the late 1800s (Vaughan 1918) and 1970s (Davis 1982). Anecdotal information suggests that coral reefs in the Tortugas region may have recovered after episodic events in the past (Davis 1982) (Chapter 4), but relatively rapid changes in global ocean climate in recent times may be slowing or preventing the recovery of corals to historic levels.

There are several examples of the effects of anomalous sea temperature on coral populations in the Tortugas region. Coral bleaching due to exceptionally high water temperatures has been reported in the Tortugas since the early 20^{th} century (Vaughan 1911, Mayer 1918). Jaap (1979, 1984) also reported coral bleaching events in the Lower Keys following late summer doldrums when water temperatures exceeded 31ºC (88°F). Other significant and severe bleaching events on reefs throughout Florida occurred in 1987, 1990, and 1997−1998 (Causey 2001). Bleaching events have caused moderate mortality of the more sensitive stony corals, such as *Millepora complanata* and *Agaricia agaricites*. Declines in populations of other corals, such as *Acropora palmata* (elkhorn coral), *Acropora cervicornis* (staghorn coral), and *Acropora prolifera*, in the Tortugas region have also been associated with hypothermic stress (Roberts *et al*. 1982) (Figure 3.2), virulent diseases, such as white and black band (Peters *et al.* 1983, Voss and Richardson 2006), and cyclonic storms (Jaap *et al*. 2008). Acroporid populations at Bird Key Reef, DRTO for example, experienced significant decline in coral cover from as high as 47% in 1977 to 12% in 2004 (Jaap *et al*. 2008). The decline was caused by the cumulative and synergistic effects of winter cold fronts, bleaching, coral diseases, and hurricanes (Roberts *et al*. 1982, Davis 1982, Jaap *et al*. 2008).

3.3.2. Sea Level Rise

Sea level rise is a predicted outcome of global and long-term climate change. Mean global sea height increased 18 cm (7.1 in) during the 20^{th} century (Douglas 1997) and is expected to increase between 11−17 cm (4.3−6.7 in) during the 21^{st} century (Houghton *et al.* 2001)[4]. Sea level rise results from thermal expansion of sea water and from increased melting of polar ice caps, which would contribute additional quantities of water to the ocean as global temperature increases. Predicted effects of sea level rise are increased erosion, inundation, and flooding of coastal areas, which would lead to a retreat of coastal beaches. Such effects should have minimal negative impacts on submerged marine resources like seagrasses and coral reef ecosystems, but severe negative consequences could result for seabirds and sea turtles populations that nest on the sandy beaches of the low-lying islands of the Tortugas region. Corals in deeper water, such as those occurring in Sherwood Forest and Riley's Hump reef systems, may be at the edge of their photo-adaptive capacity. The predicted increase in sea level height could result in decreased light reaching these corals, which could reduce rates of reef calcification necessary for those reefs to remain within the depth zone needed for reef growth and to keep up with sea level rise (Macintyre 2007).

3.3.3. Ocean Acidification

Ocean acidification is another expected consequence of climate change. The world's oceans are expected to become more acidified in response to an increase in carbon dioxide (CO_2) in seawater driven primarily by an increase in atmospheric CO_2 concentration. The concentration of atmospheric CO_2 is projected to double pre-industrial levels by the 2065 and increase to 720 parts per million (ppm) by the year 2100 (Solomon *et al.* 2007). In response to increases in CO_2 levels, rates of coral growth and calcification are expected to decrease significantly and the

[4]Intergovernmental Panel on Climate Change (IPCC) predicts global mean sea level rise to be 48cm by 2100 (Houghton *et al.* 2001).

dissolution rates of carbonates (e.g., reef structure) are expected to increase significantly (see review in Kleypas *et al.* 2006). Kleypas *et al.* (1999) estimated that average calcification rates on coral reefs might have already declined by 6−14% since pre-industrial times and will continue to decline by as much as 60% during the 21st century (Kleypas *et al.* 2006).

Ocean acidification and its proximate consequences (reduced calcification and increased carbonate dissolution) could impact reefs in the Tortugas region over the long term. Sceleractinian corals and calcareous algae are major builders of carbonate reefs that provide important habitats for reef organisms. Decreases in rates of reef calcification may result in decreases in rates of coral growth and reef extension (Lough and Barnes 2000, Albright *et al*. 2008), reduced abundance of crustose coralline algae (CCA; Kuffner *et al*. 2008, Jokiel *et al*. 2008), and reduced densities of coral colonies. Increased dissolution of carbonates will result in the weakening and loss of carbonate structure over time. The ultimate effects of ocean acidification on the population dynamics of most coral reef organisms and the ecosystem as a whole remain unknown. It is impossible to reliably predict the future ecological condition of reefs under scenarios of increased acidification. However, hypothesized outcomes include reduced reef-building and growth that results in the failure of reefs to keep up with sea level rise (Kleypas *et al.* 2006), reduced recruitment and settlement of larvae that depend on habitat cues for settlement (Munday *et al.* 2008, 2009), increased dissolution and bioerosion of reefs (Kleypas *et al.* 2006), and reduced biodiversity (Munday *et al.* 2009).

3.3.4. Cyclonic Storms

Storms play an active role in shaping coral reef ecosystems in the Dry Tortugas, the Florida Keys, and other areas of South Florida because of the proximity of Florida to the Caribbean Basin where intense hurricanes develop each year. Several studies (see review by Precht and Miller 2007) have concluded that prior to the 1970s, reefs in South Florida, including the Tortugas, exemplified a generalized pattern of zonation and consisted of *A. palmata*, *A. cervicornis*, and *Montastraea annularis*. These three species were the most abundant corals on reefs and were considered frame-builders. Several tropical storms have affected the Tortugas region in the past four decades (1970 to present) and have restructured coral reef communities through direct physical impact, increased terrestrial runoff, sedimentation, and pollution (Table 8.2, Figure 8.1). For example, Hurricane Georges (1998) decimated elkhorn and staghorn corals that were already weakened by disease (USGS 1998, AOML 1999). Likewise, Hurricane Charley fragmented *Acropora* colonies on coral reefs on the northeast side of Loggerhead Key and dislodged several coral formations on Bird Key (W.C. Japp, pers. comm.).

Infrequent storms could have positive effects on coral reefs and coral abundance. Lirman (2003) found that the abundance of *A. palmata* correlated positively with an increase in storm frequency from one storm every 15 years to one storm every 2 years, but declined with a further increase in storm frequency. Successful survivorship, reattachment and growth of coral fragments after storm events may be the only means of propagation for *A. palmata* when sexual recruitment is limited. However, the synergistic effects of multiple stressors (e.g., disease, coastal pollution, and overgrowth by algae) could be preventing normal patterns of recovery in corals after storm events (USGS 1998).

Seventy-four tropical storms have affected the Dry Tortugas region since 1970 (Table 8.2); 31 storms hit the region during the 1990s and 17 storms passed through the area in the 2000s.

During the record breaking hurricane season for the Atlantic Ocean, 28 named tropical storms occurred, of which 15 attained hurricane strength, throughout the Atlantic, Caribbean Sea, and Gulf of Mexico. Five of the tropical cyclones directly affected the Florida Keys; a frequency of one storm per month. Tropical Cyclone Arlene – the first storm in 2005 – passed west of Dry Tortugas, but Hurricane Dennis passed directly over Dry Tortugas approximately one month later and caused severe beach erosion there. Many marine habitats in the Dry Tortugas region suffered obvious physical damage, such as overturned coral colonies and scouring from the storms (Donahue *et al.* 2008). Many areas that were previously gorgonian-dominated hardbottom habitats in 1999−2000 and 2002, especially in the southern portion of DRTO, became devoid of most gorgonians and sponges. Concurrent reef fish surveys documented a marked decline in the abundance of juveniles of some species (e.g., *Mycteroperca bonaci* [black grouper]) that were previously relatively abundant in these habitats (Ault *et al.* 2005, Donahue *et al.* 2008). Reef terraces on Little Tortugas Bank and the northwestern Tortugas Bank (Sherwood Forest) remained in relatively good condition in terms of coral abundance, but coral cover declined from about 50% to about 35% in some areas. In the same sites, scientists noticed an increased prevalence of the brown alga *Lobophora variegata*, which now occupies space once covered by live coral (Donahue *et al.* 2008). A few sites had a relatively high prevalence of coral disease, especially by what is thought to be white plague. in particular. Approximately 25% of the corals were afflicted with this condition at one site (Donahue *et al.* 2008).

3.4. Water Quality

Maintaining water quality that promotes and sustains ecosystem integrity is essential for healthy coral reefs. Poor water quality (defined as waters not meeting established water quality standards) resulting from land-based sources of pollution is a major contributor to the observed deterioration of nearshore ecosystems (degradation of reefs, seagrasses, and mangroves); declining species diversity; and reduced abundance of organisms in many areas around the world (Wilson *et al.* 2006, Halpern *et al.* 2008b, Waddell *et al.* 2008). A few studies suggest that coral reefs ultimately become algae-dominated when ambient nutrient levels increase over time (reviewed in Szmant 2002 and Pandolfi *et al*., 2005). Reefs adjacent to densely populated areas sometimes are in worse condition than reefs located farther away; this difference is intuitively attributed to anthropogenic degradation (Fabricius 2005, Fabricius *et al*. 2005, but see Lirman and Fong 2007). Some studies suggest that chronic nutrient enrichment and sewage inputs from cesspits and septic systems, storm water runoff, and altered hydrology have resulted in poor water quality, elevated incidence of coral diseases, and declines in coral cover in nearshore waters of the Florida Keys (Patterson *et al*. 2002, Brand 2002, Pandolfi *et al*. 2005) and in the Tortugas region (Lollar 2004). Throughout the Florida Keys, groundwater is closely connected to nearshore waters that bathe coral reefs and represents a pathway for the transport of terrestrial pollutants to nearshore reefs (Shinn *et al*. 1994, Brand 2002, Nelson *et al*. 2002). Nutrient enrichment of nearshore waters in the Florida Keys is well documented (Boyer and Briceño 2007), but sources of nutrients and proximal causes of declining water quality is hotly debated (Brand 2002, Pandolfi *et al*. 2005, Grigg *et al*. 2005, FKNMS 2005).

Rapid increases in human population and uncontrolled economic development within the Florida Keys coastal zone are threats to water quality. Florida's human population has grown from 1.5 million in 1930 to about 18 million in 2007 (U.S. Census Bureau 2007). Five million of Florida residents live in the four most densely populated counties (Miami-Dade, Monroe, Broward, and Palm Beach), which are adjacent to Florida's coral reef ecosystems. In 2003, 74 million visitors participated in reef-related recreation in Florida (Visit Florida Year-in-Brief 2003). Recreational activities included snorkeling, scuba diving, fishing, boat tours and rentals, and dive training generated as much as $18 million in revenue in the Florida Keys (Johns *et al.* 2001, Visit Florida Year-in-Brief 2003). In the Florida Keys, residents and visitors spent about 3.9 million person-days diving, fishing, and viewing coral from 2000−2001 (Johns *et al.* 2001). Recreational fishing as measured by the number of registered recreational boats in Florida increased by more than 500% from approximately 40,000 in 1964 to approximately 190,000 in 2002 (Ault *et al.* 2001, 2002). This shift in humans toward the coast along with increased interest in reef recreation has brought more humans in contact with South Florida's nearshore natural resources and may have negative impacts on nearshore water quality.

The influx of humans residing and recreating in the Florida Keys might have increased recreational activities in the Dry Tortugas region and increased anthropogenic stress on DRTO coral reef ecosystems. Visitation to DRTO occurs via commercial ferries, private boats, and sea planes and has been increasing in recent years. The cumulative impacts of visitors and residents engaging in reef-related recreational activities could have a profound negative effect on natural resources in the region. Divers and snorkelers can cause significant physical damage to coral reefs and lower their aesthetic appeal (Hawkins and Roberts 1993, Hawkins *et al.* 1999). Increased human use and contact could further diminish the quality and productivity of nearshore ecosystems and limit their contribution to regional resources. Other anthropogenic stressors likely to affect resources in DRTO are recreational fishing and boating; most other extractive activities are prohibited within DRTO boundaries.

Some experts consider the evidence linking land-derived pollutants to coral decline in the Florida Keys equivocal. For example, some experts contend that there is no compelling evidence that coral decline in the Florida Keys was caused primarily by pollution, or that improvements in water quality will necessarily lead to coral recovery unless global-scale stressors such as diseases and climate change are curtailed (Grigg *et al*. 2005). They attribute observed declines of corals in the Florida Keys to diseases, cold fronts, hurricanes, and coral bleaching. Szmant (2002) concluded that nutrient enrichment appears to play a secondary role in coral reef decline compared to sedimentation, overfishing, and global warming. Lirman and Fong (2007) observed that corals on inshore patch reefs with poor ambient water quality (i.e., high levels of dissolved nitrogen, phosphorus, organic carbon, turbidity, and light attenuation) had significantly higher coral cover and growth rates, but lower partial mortality than corals on offshore patch reefs with significantly higher ambient water quality. FKNMS managers assert that injection of treated wastewater via 914-m (3,000-ft) wells into the ground in Key West, creation of no-pollution discharge zones for vessels throughout the sanctuary, upgrades to existing and construction of advanced sewage and wastewater treatment plants, local ordinances, and increased federal and state project funding have improved wastewater management and water quality in the Florida Keys (Grigg *et al.* 2005, FKNMS 2005).

Housing facilities at DRTO support 12 personnel that oversee park operations (Kimball and Lopez 2004). Most park employees live on Garden Key in houses attached to Fort Jefferson. Two single-family residences on Loggerhead Key provide housing for researchers, volunteers, and work crews (NPS 2005). DRTO has campgrounds for visitors; the main camp ground has eight sites, each of which accommodates up to six campers. There is also a group site that can hold up to 40 campers and an overflow area that houses additional campers during periods of heavy use (http://www.nps.gov/drto/planyourvisit/upload/campingdrto.pdf accessed September 15, 2010).

Fecal and other organic waste from resident NPS personnel, campers, and other visitors are handled by wastewater and septic systems with tanks that feed into leach fields on Garden Key and Loggerhead Key (NPS 2005). These septic systems were inadequate to support existing annual levels of visitation (NPS 2005), and the leach fields did not meet Environmental Protection Agency (EPA) and state regulations because their field pipes emptied into tidally-influenced groundwater (NPS 2005). The campground's waste disposal is a composting system made up of toilets that do not require water or chemicals. In 2002, heavy rains destroyed the septic system at the Garden Key campground, but it was reinstalled in 2004. The campground was closed for about a year because of the damage from heavy rains. Wastewater and septic systems were replaced in 2004 and composting toilets were installed at the campground (Kimball and Lopez 2004). Griffin *et al.* 2006 suggested that septic systems at DRTO were not a significant source of nutrients or microorganisms to the surrounding surface waters.

Information on the condition of water quality of the Tortugas region was obtained from the Water Quality Monitoring Project of the Southeast Environmental Research Center (SERC) at Florida International University (FIU), which has been monitoring several variables since 1995 (Boyer and Briceño 2006, 2007). Between March 1995 and January 2007, the project collected quarterly data at 154 fixed stations within the Florida Keys National Marine Sanctuary (FKNMS) and DRTO (Figure 3.7). Parameters measured at each station included salinity (practical salinity scale), temperature (ºC), dissolved oxygen (DO, mg/l), turbidity (NTU), relative fluorescence, and light attenuation (Kd/m). Water chemistry variables included the dissolved nutrients nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN), and soluble reactive phosphate (SRP). Total unfiltered concentrations of nitrogen (TN), organic nitrogen (TON), organic carbon (TOC), phosphorus (TP), and silicate (SiO_2) were also measured. The biological parameters included chlorophyll *a* (CHLA, µg/L) and alkaline phosphatase activity (APA, µM/h). Detailed descriptions of the water quality monitoring project and its results are provided in Boyer and Briceño (2006, 2007); a summary of the data is provided here (Table 3.1 and Figure 3.8).

Descriptive statistics (median, minimum, maximum, and number of samples) for several water quality parameters obtained from 15 stations during 47 sampling events in the Tortugas region are provided in Table 3.1. In general, the Tortugas region was warm and euhaline. Median surface temperatures were 26.2°C (79.2°F) and median bottom temperatures were 25.4°C (77.7°F). Median salinity ranged from 36.20 parts per thousand (ppt) at the surface to 36.25 ppt at the bottom, indicating very little vertical stratification. CHLA concentrations were also very low (0.21 µg/L) and ranged from 0.00−2.38 µg/L. The median light attenuation coefficient (Kd) was also very low (0.12/m), which reflected low median surface and bottom turbidity (Table 3.1).

In comparison to the wider FKNMS, the waters of the Tortugas region exhibited much better water quality with relatively very low concentrations of nitrogen, phosphorus, and organic carbon (Figure 3.9). Low nutrient concentrations in the Tortugas region most likely reflect the low level of human impacts to water quality. Since 1995, significant and consistent nearshore to offshore gradients of nitrate and total organic carbon concentrations have been observed in the

Florida Keys where human population levels are high (Boyer and Briceño 2006, 2007). An inshore-offshore gradient of reduced variability in salinity has been observed in the Florida Keys (Boyer and Briceño 2007). The gradients most likely reflect land-based sources of nutrients and freshwater inputs near coastal areas in the Florida Keys mixing with Atlantic oceanic waters farther offshore. The gradients, however, have not been observed on inshore-offshore transects in the Tortugas region where the level of human population is low.

Monitoring by SERC identified a strong north-south gradient of CHLA concentration from the west Florida continental shelf toward the Marquesas and Tortugas region, with highest concentrations occurring near the shelf and the lowest concentrations occurring in the Marquesas and Tortugas (Boyer and Jones 2002, Boyer and Briceño 2007). Higher phosphorus concentrations on the west Florida shelf may have resulted from southward advection of Gulf of Mexico waters along the coast continental coupled with entrainment of coastal rivers and runoff toward the Tortugas region (Boyer and Briceño 2007). It is also possible that freshwater plumes, with elevated levels of nutrients from the Mississippi River, were entrained by current eddies associated with the Loop Current in the Gulf of Mexico (Johns 2003, Kourafalou *et al.* 2005, Jaap *et al.* 2008). Satellite derived data on sea surface temperature documented the presence of the Loop Current near the Louisiana coastline, which could transport nutrient-laden, low-salinity water from the Mississippi estuary toward the west Florida shelf, southward to the Dry Tortugas region and eastward to the Florida Keys (Nelson *et al.* 2007).

In 2004, concentrations of nutrients (i.e., nitrate, nitrite, orthophosphate, and iron), fecal coliform bacteria, and human enteric viruses in groundwater and surface water samples collected from the grounds and mote of Fort Jefferson, the visitor’s dock, and nearby camping beach were not different from ambient background levels.

3.5. Summary

The geographic location of the Tortugas region bestows unique qualities on the area. The climatology and oceanography of the region, which are shaped by the convergence of several ocean current systems, have a profound effect on the ecology of marine life. The confluence of major current systems from the Caribbean and the Gulf of Mexico suggests small-scale connectivity among reefs in the Florida Keys and along the Florida mainland as well as broader-scale connectivity among major oceanic bodies such the Caribbean Sea, the Gulf of Mexico, and the Western Atlantic Ocean. Patterns of oceanic circulation are highly variable, but often make the Tortugas region an important source of fish and invertebrate larvae for downstream areas of the Florida Keys, or entrain larvae and food supply to local reefs. At other times, different circulatory patterns (e.g., countercurrent eddies and westward flows) can episodically deliver nutrients from upstream areas (Gulf Coast states or the Florida mainland) to the Tortugas region. Unpredictable disturbances, such as hurricanes, cold-water and warm-water events, and other extreme weather events, result in atypical oceanographic conditions that adversely affect ecological and biological processes and ultimately the demography of organisms in the Tortugas region. Climatic and oceanographic processes are beyond the control of natural resource managers, but understanding the spatial and temporal variability in physical processes is crucial to determine the ecological status and condition of the natural resources they affect.

Table 3.1. Values for water quality parameters in and around Dry Tortugas National Park. Samples (N) were collected from 15 stations during 47 sampling events between May 1995 and December 2006 (source: Boyer and Briceño 2006) (http://serc.fiu.edu/wqmnetwork/FKNMS-CD/2001FKNMS.pdf).

Variable	Symbol	Depth	Median	Min	Max	N
Total Nitrogen (μM)	TN	Surface	0.11	0.01	0.66	692
		Bottom	0.11	0.01	0.62	689
Dissolved Inorganic Nitrogen (μM)	DIN	Surface	0.01	0.00	0.05	687
[NO_3^- + NO_2^- + NH_4^+]		Bottom	0.01	0.00	0.09	689
Total Organic Nitrogen (μM)	TON	Surface	0.11	0.01	0.66	689
		Bottom	0.10	0.01	0.62	686
Total Phosphorus (μM)	TP	Surface	0.01	0.00	0.04	692
		Bottom	0.01	0.00	0.03	691
Soluble Reactive Phosphorus(μM)	SRP	Surface	0.00	0.00	0.01	615
		Bottom	0.00	0.00	0.01	527
Alkaline Phosphatase (μM)	APA	Surface	0.03	0.01	0.79	617
		Bottom	0.03	0.01	0.28	616
Total Organic Carbon (μM)	TOC	Surface	1.63	0.67	12.66	690
		Bottom	1.60	0.65	10.60	689
Silicate (μM)	SiO	Surface	0.01	0.00	0.28	584
		Bottom	0.01	0.00	0.25	613
Turbidity (NTU)	TURB	Surface	0.40	0.00	4.63	674
		Bottom	0.52	0.00	4.59	674
Salinity (ppt)	SAL	Surface	36.20	26.70	36.70	684
		Bottom	36.25	34.00	37.00	685
Temperature (°C)	TEMP	Surface	26.23	20.50	31.10	686
		Bottom	25.40	18.2	30.60	686
Dissolved Oxygen (mg/L)	DO	Surface	5.88	2.14	14.80	679
		Bottom	5.90	3.30	9.00	666
Chlorophyll α (μM/L)	CHLA	Surface	0.21	0.00	2.38	686
Light Attenuation Coefficient (Kd/m)	Kd		0.12	0.00	0.83	516

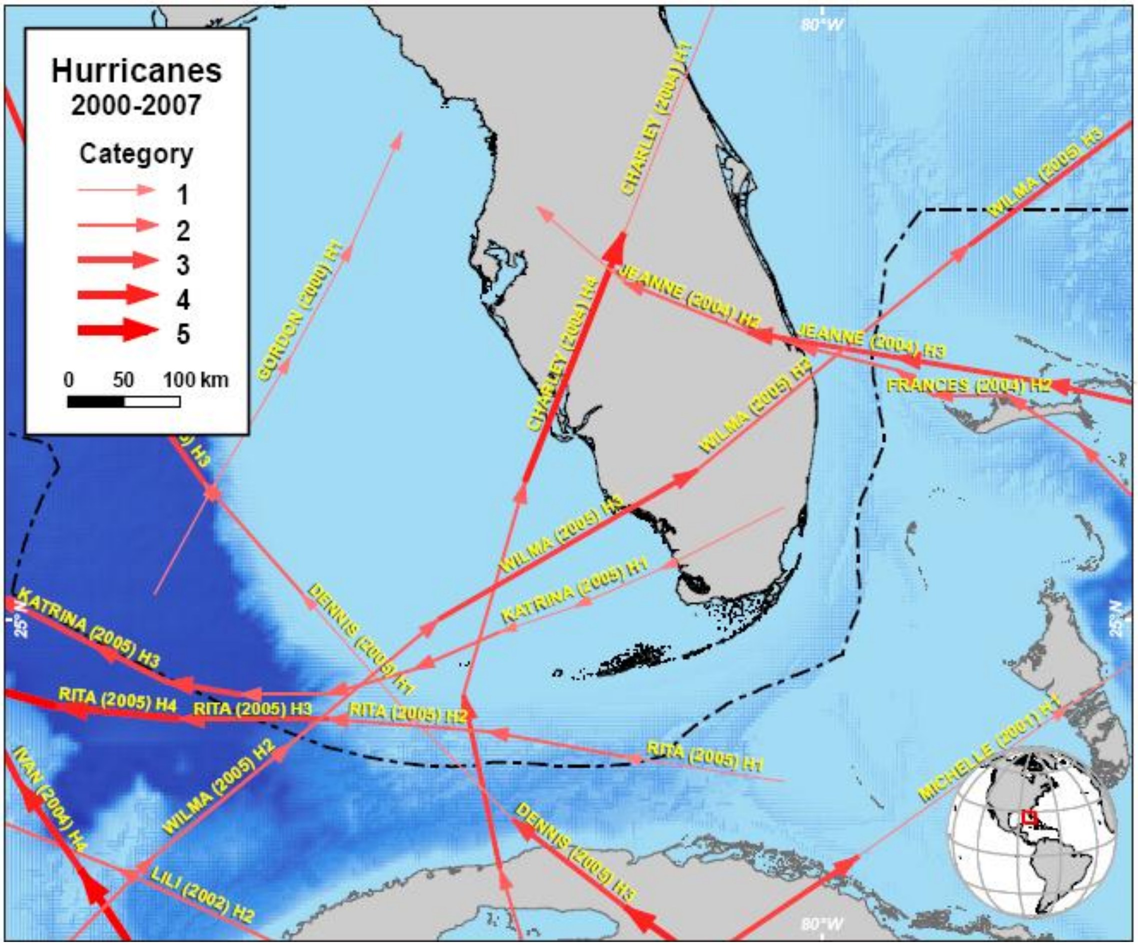

Figure 3.1. Path and intensity of tropical storms affecting the Florida Keys, 2000–2007. The name, year of occurrence, and category of each storm are indicated along each storm track (map: K. Buja adapted from Donahue *et al.* 2008).

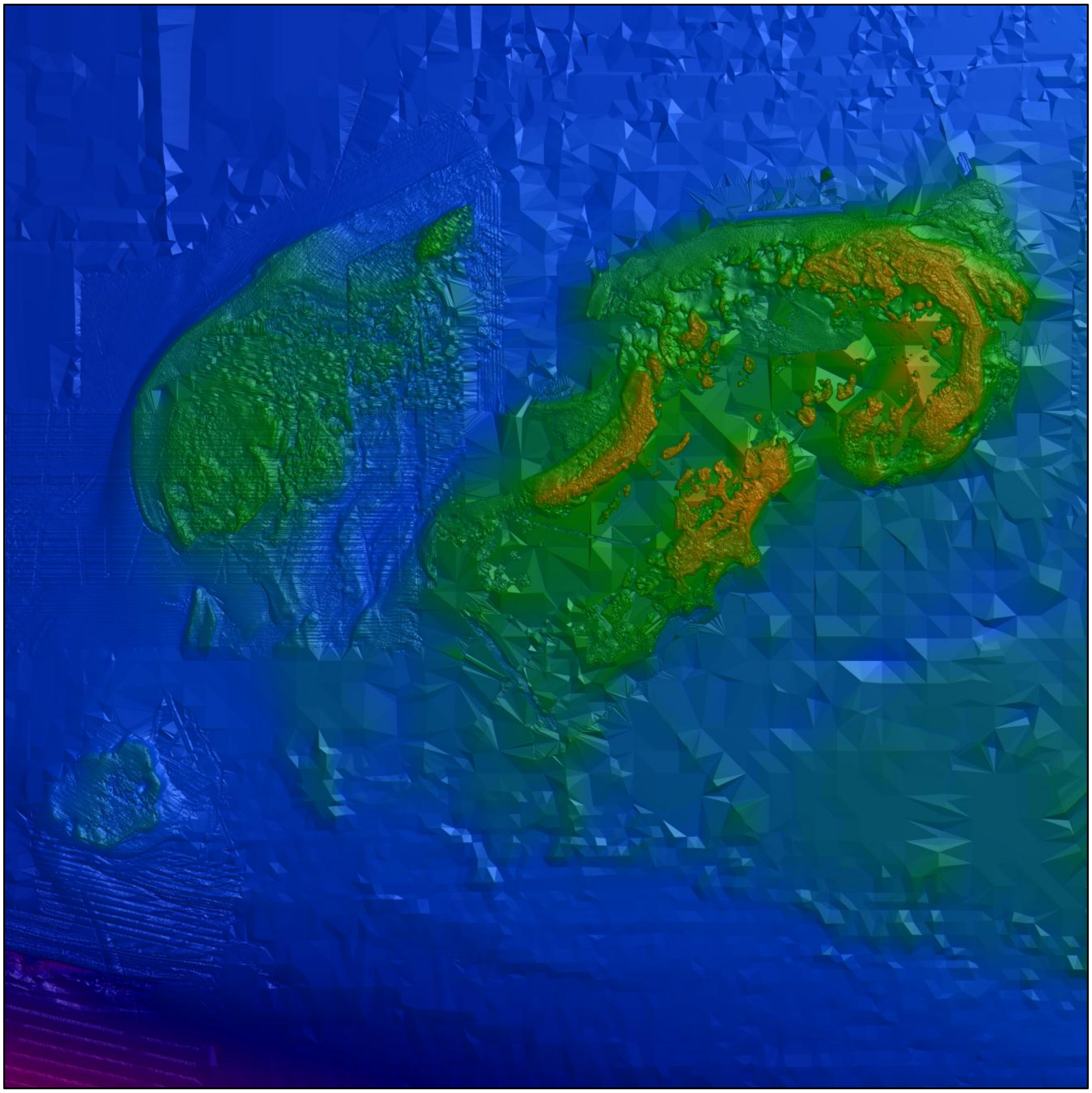

Figure 3.2. Bathymetry of the islands and coral reef banks of the Dry Tortugas region. Yellow-orange colors indicate islands and shallow areas less than 2 m (6.6 ft) deep (source: Ault *et al.* 2006a).

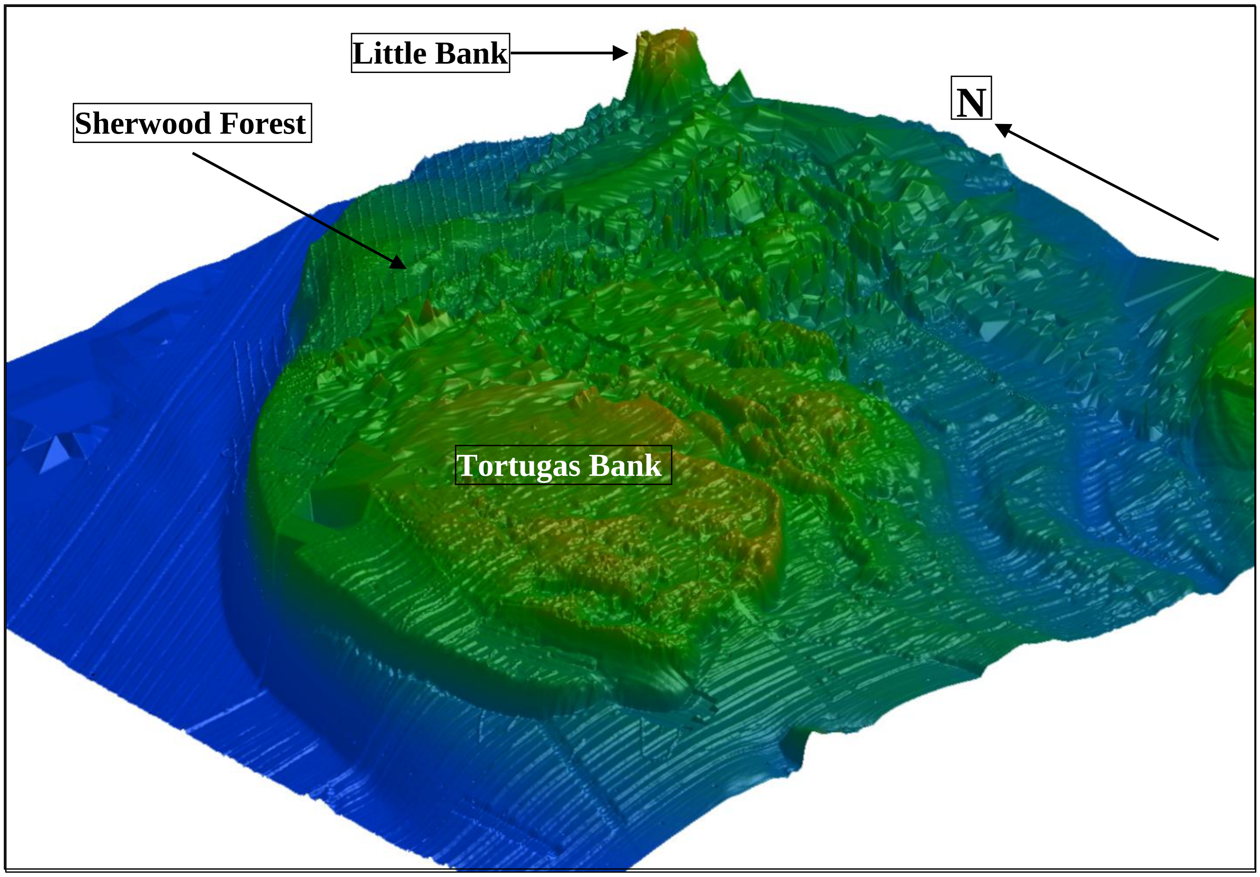

Figure 3.3. Bathymetry of the Tortugas Bank west of the Tortugas National Park. Yellow-orange colors indicate areas less than 16 m (52 ft) deep (source: Ault *et al.* 2006a, Franklin *et al.* 2003).

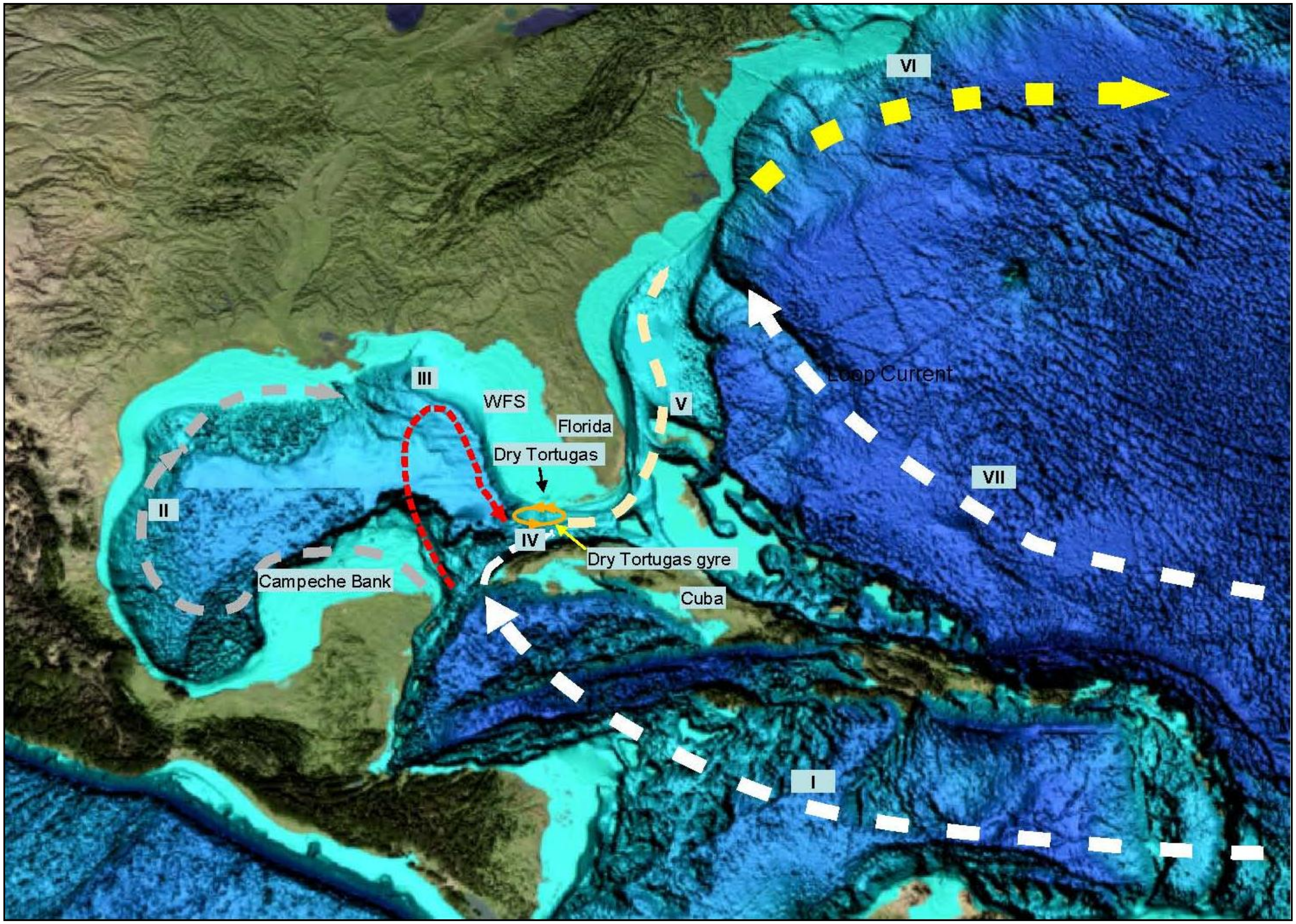

Figure 3.4. Boundary currents affecting the Caribbean Sea, Gulf of Mexico, and Western Atlantic Ocean showing hydrodynamic connectivity among these bodies of water. Key: I – Caribbean Current, II – Mexican Current, III – Loop Current, IV -- Tortugas gyre, V – Florida Current, VI – Gulf Stream, and VII – Antilles Current (source: University of Miami, Rosenstiel School of Marine and Atmospheric Science).

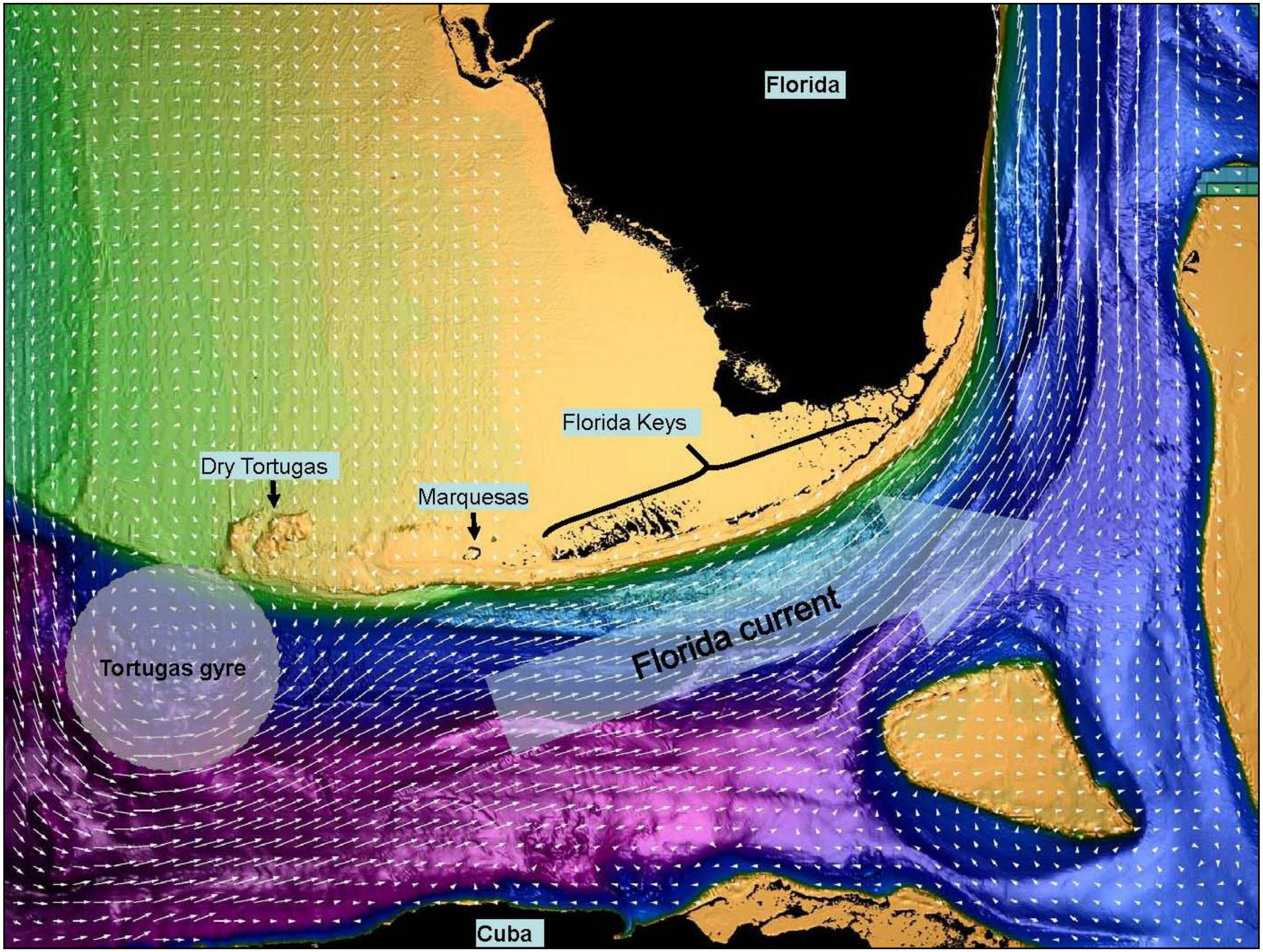

Figure 3.5. Topography of the Dry Tortugas region showing direction of net current flow through the Straits of Florida (source: University of Miami, Rosenstiel School of Marine and Atmospheric Science).

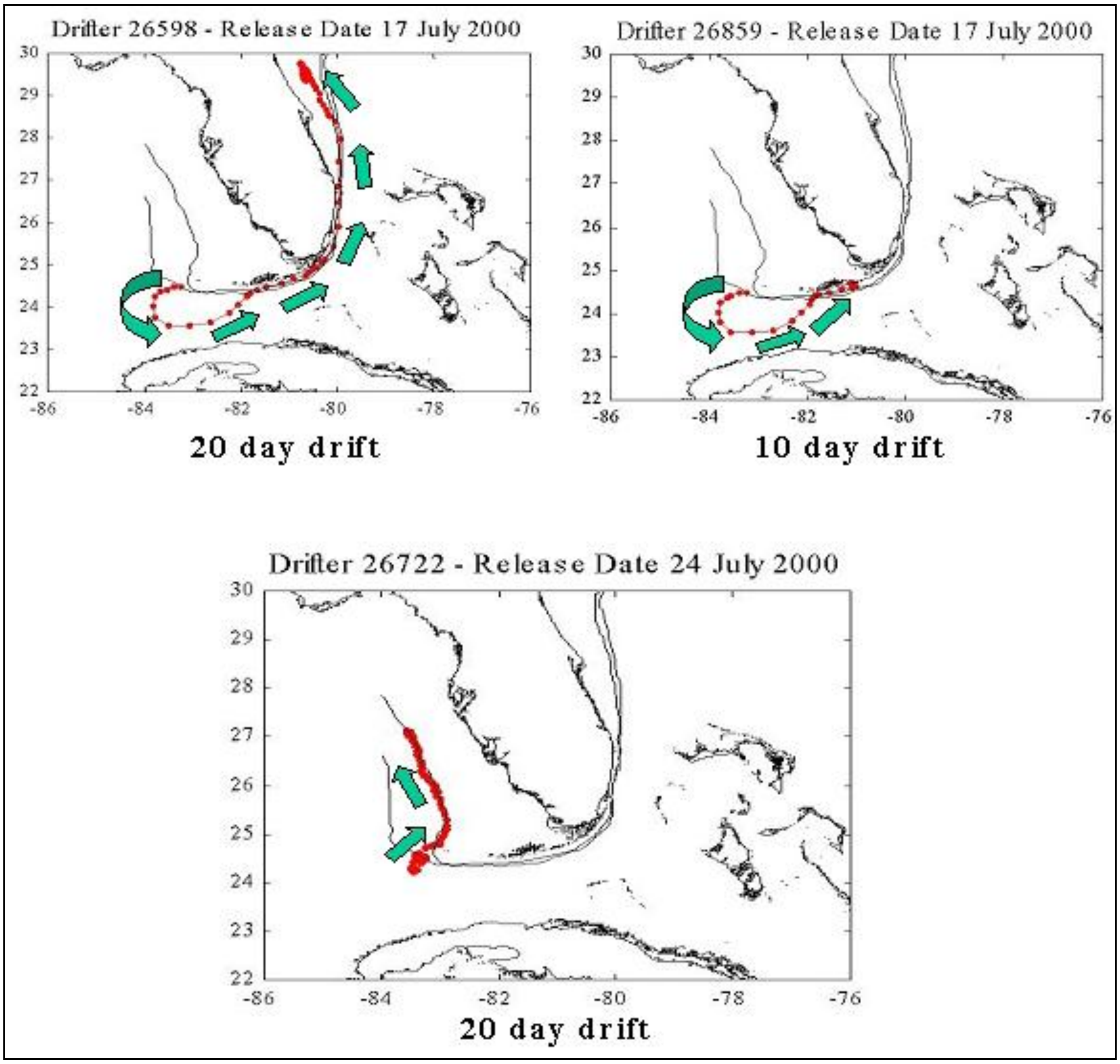

Figure 3.6. Argos (WOCE/SVP) tracks of drifters released by NOAA Center for Fisheries and Habitat Research at Riley's Hump, Tortugas Ecological Reserve, during July 2000. The scale along the x axis is degrees of longitude; scale along the y axis is degrees of latitude (adapted from Burke *et al.* 2004).

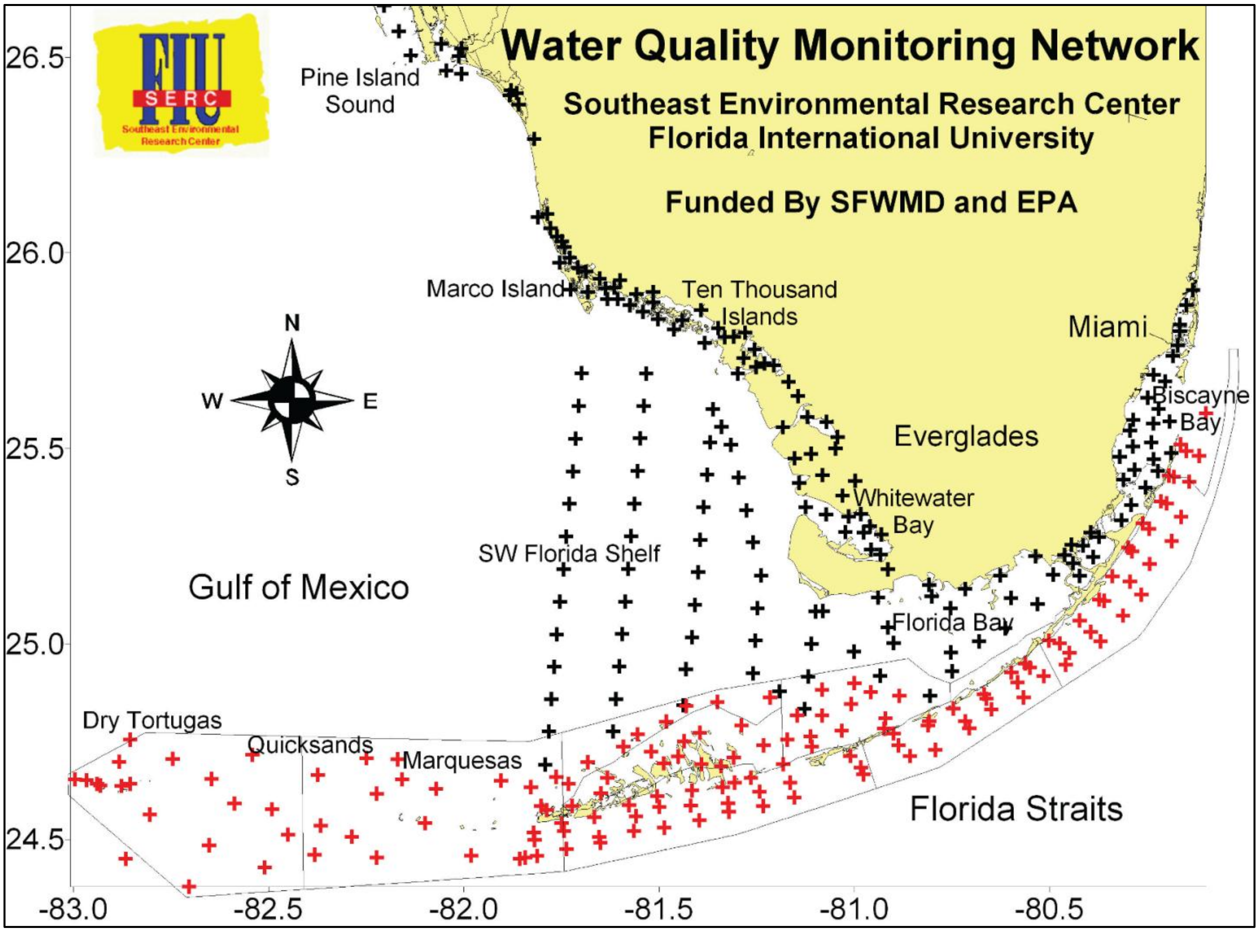

Figure 3.7. Spatial distribution of fixed stations (+) in the Southeast Environmental Research Center Water Quality Monitoring Network within the Florida Keys National Marine Sanctuary including Dry Tortugas National Park, Florida Bay, Biscayne Bay, Whitewater Bay, Ten Thousand Islands and Southwest Florida Shelf. SFWMD=South Florida Water Management District (source: Boyer and Briceño 2006).

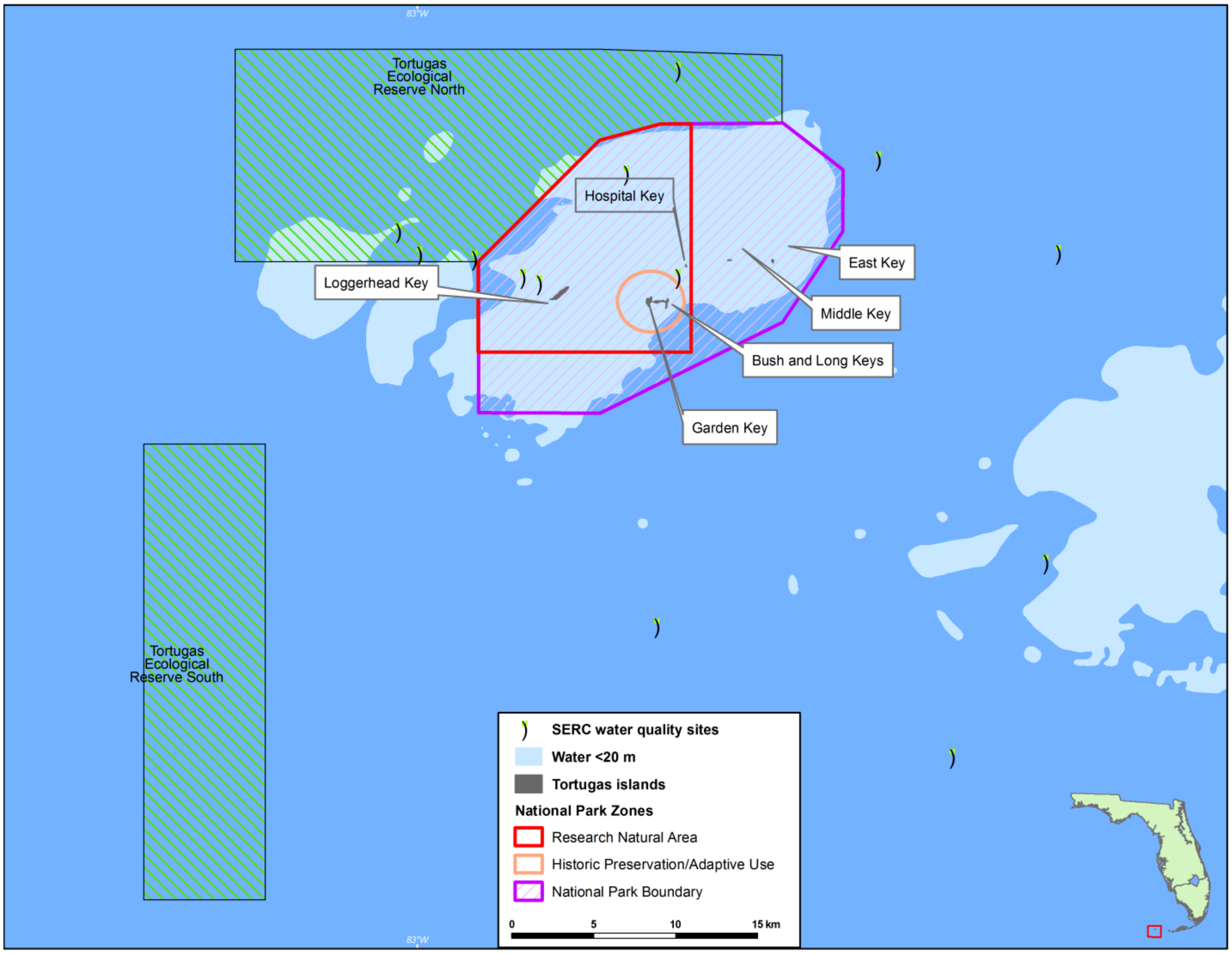

Figure 3.8. Spatial distribution of fixed stations in the Southeast Environmental Research Center Water Quality Monitoring Network in and around the Dry Tortugas (source: Boyer and Briceño 2006).

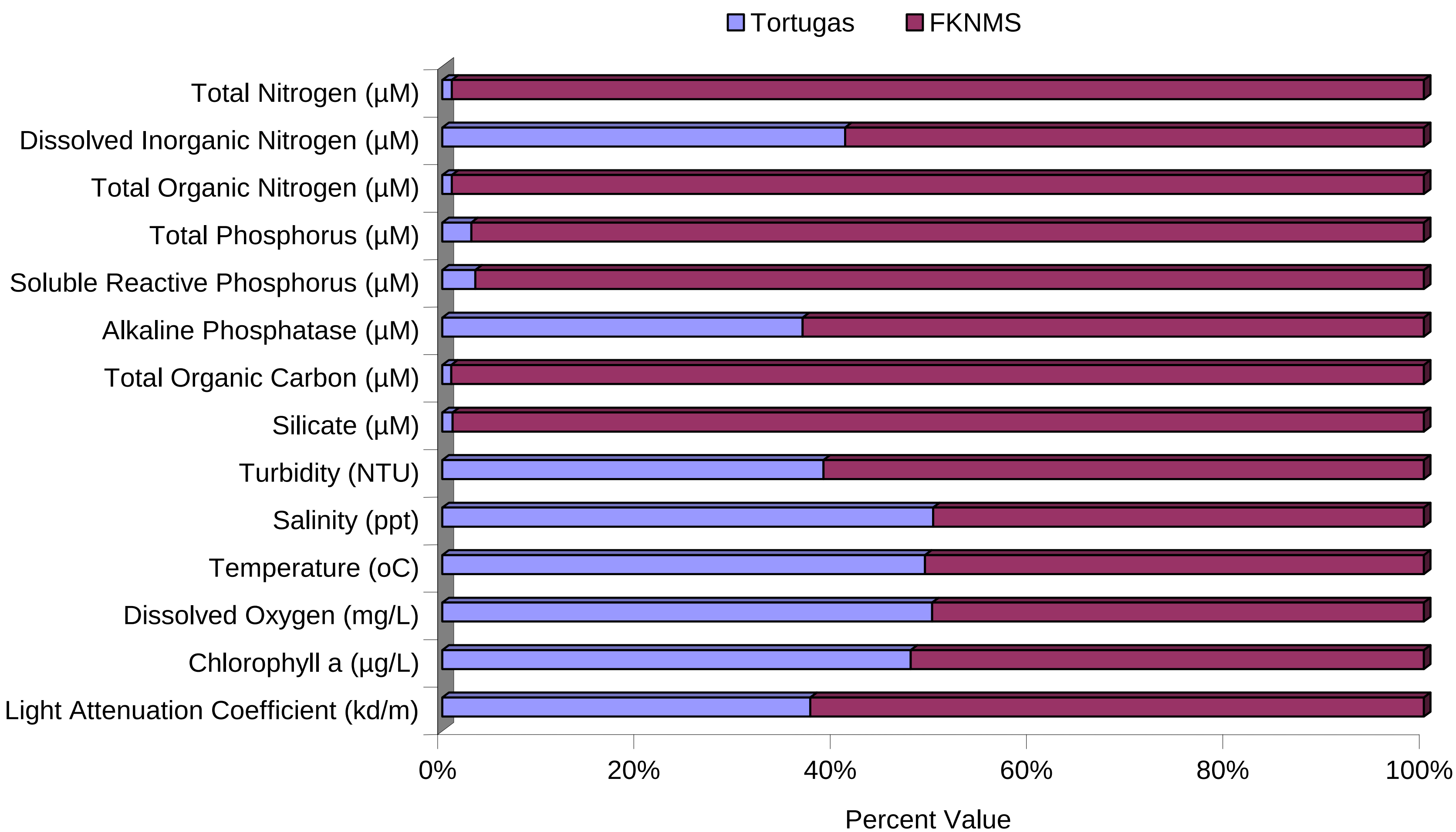

Figure 3.9. Comparison of surface water quality in the Tortugas region with those from the wider Florida Keys National Marine Sanctuary for data collected between May 1995 and December 2006 (source: Boyer and Briceño 2005, 2006) (http://serc.fiu.edu/wqmnetwork/FKNMS-CD/index.htm).

Chapter 4: Distribution and Condition of Coral Reef and Benthic Communities

Greg Piniak, Shay Viehman, Christine Addison, and Nicole Fogarty

4.1. Spatial Distribution of Coral Reefs, 1882−1990s

Live coral was widely distributed and relatively abundant in the Tortugas region about 100 years ago. Populations of *Madrepora*[5] (hereafter *Acropora* spp.) were spatially extensive on hardbottom at depth less than 18 m (59 ft) throughout the Dry Tortugas region, although colonies *Acropora palmata* (elkhorn coral) were concentrated around Bird and Long Key (Figure 4.1). Areas south of Fort Jefferson on Garden Key also contained large corals (presumably *A. palmata*) that were limited in their upward growth only by low tides. Large masses of calcareous algae, including *Udotea and Halimeda*, grew atop elkhorn coral branches that died from exposure to air. "Luxuriant and extensive growth of *Acropora cervicornis* (staghorn coral) also existed on both sides of channels that separated Bird Key, Garden Key, and Long Key, and gave Tortugas reefs a distinctive appearance (Agassiz 1882). Agassiz theorized that the channels were at one time much deeper, but were being filled with sand and sediments because of reduced tidal flow. Agassiz described several clusters of *Porites furcata* and *Porites clavaria* that covered shallow tracts of coarse sand, and *Meandrina areolata* that was growing in between marine lawns of *Thallasia* sea grass. Sea cucumbers (Holothuroidea) were scattered about the reef, and large sea urchins (Diadematidae) filled "pockets" of the reefs in deeper water. Based on vivid descriptions, reefs in the Tortugas appeared to be in better condition than in more recent times.

In a letter advocating the establishment of a research laboratory in the Tortugas however, Mayer (1903) indicated that the "*Madreporaria"* (i.e., acroporid corals) were poorly represented in the Tortugas in 1903 compared with their distribution in 1878. Apparently, "dark-colored" water drifted from the mainland of Florida in 1878 and killed almost all of the stocks of (*A. palmata*[6]) and other marine organisms. Other corals (e.g., *Porites* and *Meandrina*) survived in considerable numbers, because Mayer observed corals that were too large to have been formed since 1878. Colonies of *A. palmata* must also have survived the dark-colored-water event because Agassiz (1882) observed abundant "madreporid" corals three years after the event occurred and in 1902, a "few stocks" remained at depths greater than 2 m (6.6 ft) (Mayer 1903, 1914). *A. cervicornis* occupied about 417 ha (1,030 ac) (24%) and *A. palmata* occupied about 44 ha (109 ac) (3%) of the total coral reef and hardbottom areas mapped by Agassiz in 1882 (Table 4.1). Anecdotal information indicated that *A. palmata* distribution was restricted to a 366 m-long (1,200-ft) area of hardbottom at depths of 2−3 m (6.6−9.8 ft) along seaward of Bird Key reef (Wells 1932, Jaap and Sargent 1994) (Figure 4.1). Wells however did not quantify the areal coverage of corals, but described the coral community as dominated by *Diploria clivosa* and *A. palmata* up to depths of 6 m (20 ft) (Jaap and Sargent 1993).

During the late 1970s and 1980s, research at the Tortugas focused on geologic studies (Shinn *et al.* 1977) and interdisciplinary investigations (TRACTS) of benthic resources (Davis 1982). The TRACTS research program was designed to develop "bench-mark" descriptions of marine

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[5]The genus *Acropora* was formerly classified as *Madrepora* Agassiz (1882).

[6]Referred to as *Madreporia murciata* by Mayer (1903).

resources at the then Fort Jefferson National Monument, which were to be used to define and evaluate long-term change occurring in the Tortugas region (Davis 1982). One highlight from the TRACTS research was an assessment (Davis 1982) that compared the spatial distribution of reef corals in 1979 with their mapped distribution in 1881 as described by (Agassiz 1882).

By 1976, the composition and spatial distribution of coral reef and hardbottom areas had changed drastically from that observed by Agassiz in 1882. A band of elkhorn coral that covered 44 ha (109 ac) or 3% of mapped coral reef and hardbottom areas in 1882 only occupied about 0.06 ha (1.48 ac) or <0.01% of coral reef and hardbottom areas that were mapped by Davis in 1976 (Table 4.1). Davis (1977) noted the appearance of an extensive staghorn reef (approximately 200 ha [494 ac]) in an area that was previously mapped by Agassiz as linear ridges of gorgonians (octocorals) interspersed with sand (Figure 4.2). However, the overall spatial abundance of staghorn coral decreased from 25% of total hardbottom area mapped by Agassiz in 1882 to 10% mapped by Davis in 1976 (Table 4.1). Octocoral coverage increased from 61% of mapped coral and hardbottom areas in 1882 to 80% of coral reef and hardbottom areas mapped in 1976 (Table 4.1).

Some of the changes in spatial abundance of corals between 1882−1976 undoubtedly resulted from differences in technology and units used for mapping (Davis 1977). Some temporal changes in coral distribution may have resulted from episodic natural events. Davis speculated that the staghorn reef that occupied the area formerly colonized by gorgonians in the Agassiz map may have existed prior to 1882, but were killed by the dark-colored water event of 1878 and were not observed by Agassiz (1882). The virtual absence of elkhorn coral from the Davis 1976 map likely resulted from episodic events rather than from differences in mapping techniques because elkhorn corals were vividly described by Agassiz in 1882 and their presence was confirmed by Wells in 1932.

Subsequent episodic events resulted in even more drastic changes in the spatial distribution and coverage of corals in the Dry Tortugas. Cold fronts in 1977−1978 reduced water temperatures in the Dry Tortugas to 14−16°C (57-61°F), which killed 91% of staghorn corals that were mapped in 1976 and 60−70% of two remnant patches of elkhorn corals in Five Foot Channel near Long Key (Davis 1982). Other corals, including *Montastraea annularis* and *Porites porites*, were killed, but the spatial extent of mortality was not estimated. A resurgence of corals followed the cold-water stress, but in 1981, an epidemic disease severely reduced coral populations throughout the Florida Keys (Jaap 1998).

Jaap and Sargent (1993) further assessed changes in the spatial distribution and abundance of *A. palmata* at the Dry Tortugas National Park (DRTO) by mapping the spatial extent of the densest aggregations of *A. palmata* in Five Foot Channel in 1993 (Figure 4.3). They compared their findings with historical reports and maps (Agassiz 1882, Davis 1977) and with aerial photographs taken between 1960−1991 by several federal agencies. Jaap and Sargent (1993) mapped an area of 0.14 ha (0.35 ac) of *A. palmata* reef, with the densest area occupying 0.073 ha (0.18 ac). The *A. palmata* reef was located in the same position as remnant patches mapped by Davis in 1976 (Figure 4.2), and they concluded that the *A. palmata* patch was the population that recovered from the 1977 cold-water event. If true, then the recovery rate was high. Only about 30% (180 m^2 [1,938 ft^2]) of 600 m^2 (6,458 ft^2) of *A. palmata* survived the 1977 cold-water event and increased to an area of 1,400 m^2 (15,070 ft^2) by 1993, a 777% increase over 17 years Jaap and Sargent did not indicate the total area mapped in their study, thus the proportion of coral reef and hardbottom occupied by the *A. palmata* reef is unknown.

Since 1990, eight multi-year projects have been monitoring benthic communities in the Tortugas region (Table 2.3). These studies employed various methods and characterized benthic communities at different locales in the Tortugas region (Figure 4.4). In general, results from these projects indicate that benthic communities in the Tortugas region are very different today compared with 100 or more years ago. The following sections summarize the results of these projects separately and the final section summarizes the overall conclusions about the effects of protection on benthic communities in the Tortugas region.

4.2. Characterization of Benthic Communities at the Sand-reef Interface

In 2001, the NOAA Center for Coastal Fisheries and Habitat Research (CCFHR) began a suite of studies in the Tortugas region to examine the effects of the Tortugas Ecological Reserve (TER) on reef fish assemblages and benthic organisms (Burke *et al*. 2004). A major premise of the studies was that energy flow across reef-sand boundaries is critical to understanding reef function. For example, reef fish may import significant amounts of nutrients onto the reef after foraging in sand, algae, and seagrass flats adjacent to the reef (Meyer *et al*. 1983). Previous work by CCFHR on the west Florida shelf suggested that benthic primary production is the major energetic source supporting fish biomass (Currin *et al*. 2000). Given that the majority of the Tortugas region is not coral reefs, the structure and composition of fish communities near the reef interface would be an area to detect a reserve effect (Burke *et al*. 2004). Fine-scale (meters) surveys of benthic composition were added to complement annual fish surveys and to provide additional covariates for explaining spatial patterns in fish assemblages at sand-reef interface (cf. Chapter 7).

4.2.1. Data Collection and Statistical Analyses

A stratified “before and after reserve implementation” sampling design (Underwood 1991) was used to test for the effects of management on natural resources. Thirty permanent monitoring sites (Figure 4.4) were randomly selected along the reef-sand interface in 2001 (depth 15−32 m [49−105 ft]), using the procedures outlined by Burke *et al.* (2004). Ten sites were established in each of three strata: reserve (in TER), park (in DRTO), and unprotected (areas outside the reserve and park). Several of the park sites were located within the Research Natural Area (RNA) that was designated within DRTO. Sites in each stratum were allocated equally on either side of the predominant direction of current flow across the banks resulting in six strata: park north (PN), park south (PS), reserve north (RN), reserve south (RS), out north (ON) and out south (OS).

Every year between 2001−2005, divers concurrently surveyed fishes and collected data on benthic communities along two 30-m (98-ft) transects perpendicular to the interface − one into the sand, and one onto the reef. However, transects in the sand had scant biological cover and reliable identification of benthic microalgae found on this substrate was difficult. Only data obtained from transects on reef and hardbottom substrates are presented here. Data on benthic communities were collected with an analog video or digital-still camera and used to determine percent cover and taxonomic richness and diversity. In 2001, continuous video data of benthic communities were collected along each transect with a camera positioned approximately 1 m (3.3 ft) above the bottom. Between 2002−2004, the camera height was decreased to 0.4 m (1.3 ft) to improve image resolution and identification of benthic organisms. Non-overlapping frames from the videos were selected with Sony DVGate software for processing and identifying benthic organisms. In 2005, continuous video was discontinued. Instead, digital still photos were taken at every meter along each 30-m (98-ft) transect at a fixed height of 0.4 m (1.3 ft) above the sea floor. Still photography improved image resolution and eliminated the need to select image frames from video. For each site, percent cover, diversity, and richness of benthic organisms were determined from either digital still photos or analog video frames through point-count analysis with Coral Point Count (CPCe) software (Kohler and Gill 2006)[7]. Benthic organisms were categorized into the following functional groups: scleractinian coral, fire coral, macroalgae, sponge, octocoral, crustose coralline algae (CCA), hard substrate, seagrass, microalgae and soft substrate, other invertebrates, and unknown/manmade substrate (Figure 4.2).

Statistical tests were conducted to determine differences in benthic composition among management strata and among sites within strata. It was not possible to determine temporal change in benthic composition because among-year differences in benthic cover due to differences in photographic techniques would confound differences caused by temporal variability. Data from years with similar methodologies were pooled for analysis (e.g., 2001, 2002-2003, and 2005). For data that met parametric assumptions[8], one-way Analysis of Variance (ANOVA) was used to determine if the percent cover of benthic organisms were different among management strata for data collected during 2001 and 2005. A two-way ANOVA was used to determine if percent cover of benthic organisms differed among management strata and between years for data collected during 2002 and 2003. When significant differences were found among management strata or between years, post-hoc comparisons among strata and years were made using Tukey's honestly significant difference (HSD) test if variance among strata was homogeneous or Dunnett's test if variance was not homogeneous. Data that did not meet parametric assumptions after arcsine square root transformation were tested with nonparametric Kruskal-Wallis ANOVA or the Scheirer-Ray-Hare nonparametric two-way ANOVA to determine differences among management strata and year.

Multivariate analyses were conducted in Primer 6.0 to explore the similarity in the percent cover of benthic functional groups among sites and strata within a given year. Data on percent cover were arcsine-square-root transformed and principal components analysis (PCA) was conducted to examine which benthic categories accounted for the most variability observed among sites. Non-metric multi-dimensional scaling (MDS) ordination was applied to identify similarity among sites. MDS results were confirmed by hierarchical cluster analysis based on group averages and Bray-Curtis similarity indices for functional groups.

4.2.2. Results and Discussion

Benthic cover by management stratum

All eight benthic functional groups were observed at reef-sand interfaces in all management strata and in all years (Figure 4.5). Primary producers (macroalgae, CCA, and seagrasses) and

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[7]Preliminary comparisons of the video and still photo techniques at a small subset of sites in 2005 suggested the two methods provide comparable results. CCFHR re-surveyed the 30 permanent transects using the still photos in August 2007 with concurrent video transects for additional method calibration.

[8]Percent cover data were tested for normality using Kolmogorov-Smirnov test and for homogeneity of variance using Levene's test.

sand with microalgae accounted for the most benthic cover in all strata for all years. Scleractinian corals, octocorals, and sponges were relatively low in cover compared with the other benthic functional groups. Reef rubble was the next most abundant substrate, except at park reef-sand interface surveyed in 2005.

Relatively few statistically significant differences in the cover of benthic functional groups were observed among management strata and differences were inconsistent across years. For example, in 2001, the percent cover of rock/rubble was significantly higher at reef-sand interfaces in the park ($F_{2,27}$=6.617, p=0.005) than at comparable sites in the TER (Tukey's HSD p=0.017) and in unprotected areas (p=0.005) in 2001. Octocoral cover was usually lowest at DRTO reef-sand interfaces compared with reserve and unprotected sites, but only the difference between the TER and DRTO sites in 2002−2003 was significant ($F_{2,54}$=3.398, p=0.041, Tukey's HSD p=0.033). The only significant temporal difference observed was an increase in percent cover of primary producers during 2003 compared with 2002 ($F_{1,54}$=7.743, p=0.007), which correlated with a concomitant decrease in the percent cover of rock rubble ($F_{1,54}$=4.101, p=0.048). Percent cover of corals at reserve sites was typically twice as high as that in park or unprotected sites, but only differences observed during 2002−2003 were significant ($F_{2,54}$=6.688, p=0.003).

In general, coral cover in all strata primarily consisted of *Montastraea cavernosa* and the *Montastraea annularis* complex (mostly *M. faveolata*), which were present at most sites. *Siderastrea siderea* and *Colpophyllia natans* form a secondary group of framework-building species at these sites, whereas *Diploria* spp. was relatively uncommon. Historically, acroporids were major framework builders on the shallow Tortugas (Davis 1982), but were rare at surveyed sites, which may have been below the lower depth limit of these corals. Among non-framework builders, the most common species were *Mycetophyllia* spp. and *Agaricia* spp., with occasional *Meandrina meandrites*, *Porites astreoides*, *Stephanocoenia intersepts*, and *Siderastrea radians*. Rare species included *Dichocoenia stokesii*, *Scolymia* spp., *Solenastrea bournoni*, and *Eusmilia fastigiata*. These interface sites are relatively deep (15−32 m [50–105 ft]) so branching corals are present, but not abundant. *Oculina diffusa*, *Madracis decactis*, *Madracis mirabilis*, and *P. porites* were occasionally observed, while *A. cervicornis* was rare.

Richness and diversity of scleractinian coral species in 2002−2003 tended to be higher at TER reef-sand interfaces than at sites in the park or unprotected areas, but was not significant. Although increased photographic resolution in 2005 resulted in better identification of coral species, there were no significant differences among strata in coral richness ($F_{2,27}$=0.138, p=0.872) or diversity ($F_{2,27}$=1.180, p=0.323) (Figure 4.6). Diversity correlated positively with depth (r=0.386, p=0.035), but richness did not (r=0.214, p=0.256). Greater photographic resolution in 2005 also improved taxonomic identification of macroalgae; the predominant genera were *Dictyota*, *Halimeda*, and *Lobophora*. *Codium* was moderately abundant at park reef-sand interface.

The few statistically significant differences among strata could imply that management strategies have had little effect on benthic resources, but methodological differences make temporal comparisons difficult. Differences between sites may have swamped variability among strata. The experimental design emphasized replication at the stratum level rather than the site level, but additional transects at each site may have helped reduce variability among sites. Given that the TER was established only in 2000 and that global stressors, such as climate change and coral diseases, act at spatial scales much larger than the Tortugas region, it could be too early to observe differences in benthic composition that result from protection.

Benthic cover by site and year

In 2001, coral cover was variable among reef-sand interface sites within management strata (Figure 4.7). Three sites in the park and four in the reserve had greater than 10% live coral, whereas only one unprotected reef-sand interface had 10% or more live coral. Relative percent coral cover was highest (approximately 24%) at reserve site RS10262 and park site PN3120. The highest observed coral cover at unprotected reef-sand sites was about 10% and occurred at OS7675. Percent coral was greater than 2% at all 10 unprotected sites, but was less than 1% at two sites in the park and in the reserve. TER had the most reef-sand interface sites with fire coral, though its overall cover did not differ among strata ($F_{2,27}$=2.068, p=0.146). The unprotected stratum had sites with the highest octocoral cover (ON6772 and OS7675). Sponge cover was relatively consistent among sites. Macroalgal cover at reef-sand interfaces in the park appeared more variable than that of reserve or unprotected sites, and the park stratum included sites with the highest and lowest algal cover. Video resolution in 2001 was not sufficient to identify seagrass or CCA reliably, so the cover of these organisms is unknown. Site PN632 was sparsely colonized and had 76% cover of sand and less than 5% cover of any benthic functional group (Figure 4.7).

Principal components analysis (PCA) explained 59.7% of the variation in PC1 with the three dominant functional groups of soft substrate, macroalgae, and coral. With the addition of hard substrate, PC2 increased the cumulative percent variation explained to 80.0%. Several distinct groups were seen in the MDS plot and supported by group-averaged cluster analysis from Bray-Curtis similarities (Figure 4.8). Reef-sand interface sites, however, did not cluster by management strata, which further confirmed that benthic composition was not significantly different among the strata. Instead clusters were comprosed of sites from different strata that were similar in benthic composition. Cluster C contained sites with the highest proportion of sand. Within that group, sites with the highest octocoral cover (OS7265 and RS8233) clustered together, as did the only sites with macroalgal cover >20% (OS6731 and RN9498). Cluster B contained the two sites with the highest coverage of rock/rubble (54.4% at PN1136, 45.7% at PN690). Site ON94, an outlier, shared less than 80% similarity with other sites and was the only site with <1% cover of octocorals. The remaining sites were grouped in Cluster A and did not have a single defining characteristic. Three of the six groups in this cluster had high (>33%) macroalgae, but were separated by other categories. RN9807 and PS2780 had low cover of corals and octocorals, ON5842 and OS12379 had moderate coral cover and high octocoral cover. RN10105 and RN8924 had high coral and octocoral cover but contained very little bare sand. Among the other three groups, PS6108 and PS6493 had high cover of corals but had more rock than macroalgae. ON11460 and OS1864 had virtually identical coverage for every benthic category except coral cover, whereas PN3275 was closely grouped, but had slightly less sponge cover. The final group contained the four sites in this cluster with the highest sand cover (ON5527, RN1915, RS10529, OS7675).

2002−2003

Coral cover was greater at many TER sites than at DRTO and unprotected sites in 2002 (Figure 4.9); in 2003, all TER sites had higher coral cover than sites in other strata (Figure 4.10). Similar to 2001, RS10262 had the highest coral cover in 2002 (17.1%) and 2003 (23.5%). ON11460 was an outlier in the unprotected stratum with coral cover at 0.1% in 2002 and 0.3% in 2003. Fire coral was commonly observed at the reserve sites (eight and six sites in 2002 and 2003, respectively), but at only two sites did fire coral cover exceed 1% (RN9807 in 2002 and PS2780 in 2003). Black coral (Antipathidae) was observed at two sites in 2002, both of which were in DRTO. In contrast to 2001, reserve sites generally had the highest octocoral cover in 2002 and 2003. Macroalgal cover was highly variable. The unprotected stratum had the site with the lowest macroalgal cover in 2002, but that stratum had sites with the highest and lowest macroalgal cover in 2003. CCA was present at every TER site surveyed in 2002, but occurred at only seven sites in 2003. Seagrass (*Halophila decipiens*) was present at two DTNP sites in 2002, PN3120 and PS4671, but only at OS1864 in 2003. PS3926 again appeared to be the outlier among all sites – macroalgal cover was 14.6% in 2002 and 10.6% in 2003, but no other biological category had cover >1.5%.

PCA of data collected in 2002 explained 52.9% of the variation in PC1 and identified three dominant functional groups: microalgae and soft substrate, hard substrate, and coral. With the addition of macroalgae, PC2 increased the cumulative percent variation explained to 73.9%. PCA of data from 2003 accounted for 49.3% of variation in PC1 with microalgae and soft substrate, macroalgae, and coral accounting for most of that variability. The addition of hard substrate increased this to a total of 79.3% variance explained. MDS ordination plots (Figures 4.11 and 4.12) show PS3926 and RS10529 as outliers in both 2002 and 2003, as they have <80% similarity to the other sites. PS3926 was again characterized by very high sand cover and virtually no living biological cover, while RS10529 stands out because it had the highest coverage of zoanthids in each year (5.2% in 2002, 6.1% in 2003). The other two outliers in 2002 were the sites with the highest rock/rubble cover; PS6108 had high coral cover (10%) and moderate macroalgae, while ON5527 had high sponge cover (7.5%). The other 2003 outlier, RS9042, had the highest macroalgal cover that year (63%).

In 2002, reef-sand interface sites were grouped into two main clusters based on 80% similarity. Cluster A contained sites with low coral cover (0.1−2.6%) and high sand cover (30.5−58%), whereas cluster B contained sites with relatively high cover (3.1−17%; Figure 4.11). Furthermore, sites within cluster A were divided into three sub-groups based on 90% similarity. One group was characterized by low sponge cover (OS7265 and ON11460), the second had mainly rock/rubble substrates (OS1864 and PN3275), and the third group had high octocoral cover (PS4671 and RN9498). Cluster B had five sub-groups based on 90% similarity: 3% coral (ON5842, OS12379), low sponge (ON6772, RS9162), high rock (PN1136, OS12379, RS8233), high sand (PS6493, PN3120) and high coral/octocoral (RN10105, RN8924). Two sites occurred in both clusters − OS1864 has the highest coral cover cluster A, whereas and RN1915 had the highest sand cover cluster B.

Clustering patterns in 2003 were different from those observed in 2002. MDS of sites surveyed in 2003 resulted in the formation of three main clusters based on 80% similarity between sites (Figure 4.12). Cluster A contained sites with low cover (<11.5%) of rock/rubble substrate, whereas cluster C was comprised of sites that had very little sand (<5.3%), but high cover of sponges (7.6−10.3%). In cluster C, the two sites with the lowest coral and highest rock cover (PS 6493 and ON5842) formed a subgroup based on 90% similarity. The three other sites in cluster C had the highest cover of coral observed in 2003, but they did not form a separate subgroup. Cluster B had no distinctive characteristics and contained the remaining sites organized into four subgroups based on 90% similarity. A pair of sites (PS4671 and PN1136) was distinguished by high cover of rock, a second pair (RN1915 and RS8233) had the highest cover (<1%) of CCA within cluster B, and a third pair of sites (OS12379 and OS1864) had similar cover in nearly every category including the highest amount of unidentified data points (3.2 and 1.8%, respectively). The last subgroup of cluster B (PS6108, RS9162, PS2780 and ON6772) contained sites with coral cover ranging between 6.1−8.9% and macroalgae cover of 27.1−36.7%.

2005

Use of digital still photography instead of videography for benthic images resulted in a slightly smaller field of view, but the average coral cover for all sites in 2005 (5.5%) was comparable to that observed in previous years (6.0% in 2003, 5.0% in 2002, 6.3% in 2001). Six of the seven sites with the highest coral cover in 2005 occurred in the TER (Figure 4.13). In all previous years coral was most abundant at RS10262, but in 2005, RN8924 had the highest coral cover (24.5%) observed in any year of the study. Seven of the TER sites had fire coral, including the highest coverage observed in this study (3.7% at RS10529). Black coral was observed in DTNP (site PN1136), but was rare in the TER (<0.25% cover at RS10529 and RS8233). There was no apparent pattern in octocoral or sponge cover among sites. Half of the sites had macroalgal cover greater than the highest observed coral cover, compared to 22 sites in each of 2002 and 2003 and 19 sites in 2001. Seagrass (*H. decipiens*) was observed at two park sites (PN1136, PS2780) and one TER site (RN1915). CCA were again most commonly observed at TER sites, although the unprotected and DTNP strata each had more sites with CCA than in previous years.

PCA of the 2005 data resulted in 76.2% of the variability in functional groups among sites being explained by the first two principal components. The first principal component (PC1) explained 48.0% of the variation and identified three dominant functional groups (microalgae and soft substrate, macroalgae, and coral). PC2 accounted for an additional 28.2% of the variation and identified hard substrate as an additional dominant factor. The MDS plot of the 2005 data indicated that RS10529 was an outlier, as it was in 2002 and 2003 (Figure 4.14). However, in this case the site was an outlier because it contained far more fire coral than any other site (Figure 4.12). Site PS2780 was identified as an outlier by MDS because the cover of zooanthids was unusually high at that site.

The MDS ordination of data showed three main clusters in 2005 (Figure 4.14). The left cluster contains sites with moderate to high macroalgae (23.5−52.3%). Groups within this cluster include sites with low coral cover (RN9807, ON11460) and low rock/rubble (OS12379, OS7265, OS7675). Sites with high sand cover (54.3−75.7%) form the cluster on the right, with sites grouped by low coral cover (PN1136, RN9498), high coral cover (PN3275, RN10105, RX10262) and high rock/moderate macroalgae (PN632, PS3926). The cluster at the bottom is intermediate, with low macroalgae (5.2−18%) and moderate sand cover (39.4−58.1%). The two sites with the highest macroalgal cover in this cluster (OS1864, RN1915) were grouped together.

The intent of the CCFHR study was to characterize resources at the reef-sand interface in the Tortugas and to monitor the effects of implementing the TER. Interface sites were randomly selected using a rigorous statistical approach, but the resultant spatial variability among sites made detection of management effects or temporal trends difficult. On average, one half of each reef transect was non-living substrate (rock and sand). Macroalgae were the most common biological component, with an average cover of 25−33%. Coral cover was 5−6%, but it was highly variable among sites and ranged from 0−24.5%. Relationships among sites were not consistent over time.

4.3. Multi-scale Mapping, Benthic Cover, and Fish Surveys

A large-scale assessment of the community structure and condition of hardbottom and coral reef habitats, coral population structure, and potential habitat change at multiple spatial scales has been conducted since 1999 by NOAA's Underwater Research Center/University of North Carolina, Wilmington (NURC/UNCW). The study provides complementary habitat information for fishery-independent reef fish surveys and modeling efforts for evaluating essential fish habitat (NOAA National Marine Fisheries Service [NMFS] and University of Miami, Rosenstiel School of Marine and Atmospheric Science [UM-RSMAS]). The survey design is scaled at three management zones: Tortugas Bank Fished (commercial and recreational fishing), DRTO (recreational hook and line only), and TNER (closed to all fishing since 2001; Ault *et al.* 2006a) as well as by reef, habitat type, and regions of the South Florida shelf (Miller *et al.* 2006).

Independent sample sites were selected randomly from a digital benthic habitat map stratified by nine categories of hardbottom and coral reef habitat types (Franklin *et al.* 2003). Each site has four random transects. Surveys use the linear point-intercept method and strip transects to measure coverage, octocoral abundance, species richness, coral size and condition, juvenile coral abundance and size, urchin abundance and size, anemone and corallimorph abundance, and algae coverage by functional group (Miller *et al.* 2000, Miller *et al.* 2006).

Habitat surveys included 24 sites in 1999, 36 in 2000, 24 in 2002, and 46 in 2006; sites ranged from 5−27 m (16−89 ft) depth (Miller *et al.* 2000, Miller *et al.* 2006). Physical damage from the 2005 storms was patchy and more apparent on the south side of the park. Prior to 2006, gorgonians and sponges were dominant, but after 2006, their cover and abundance were reduced. In some high cover areas, coral cover has declined from nearly 50% in 2004 to approximately 35% in 2006 due to coral disease and has been replaced with *Lobophora variegata* (Miller *et al.* 2006). Mean stony coral cover ranged from 0.25−31% among 42 of the 46 sites. Sponge species richness was greater than or equal to stony corals and gorgonian species richness. Combined juvenile coral colonies ranged from $0.16-5.77/m^2$ ($0.015-0.536/ft^2$), with higher densities within DRTO high-relief habitats. These results are similar to the 1999−2000 Tortugas surveys as well as other Florida Keys surveys. Disease prevalence was relatively low (<5%), but some medium-profile reefs and patchy hardbottom habitat sites on the northern and northeastern areas had higher incidence of disease (15−37%). No bleaching was observed in 2006 (Miller *et al.* 2006).

4.4. Long-term Monitoring of Coral Cover

The state of Florida has conducted research in the Dry Tortugas since 1975. The goal of the Coral Reef Evaluation and Monitoring Project (CREMP) is to assess the ecological status and annual trends in coral reefs. Monitoring occurs through repetitive surveys with underwater video transects and station species inventories that includes information on species richness, distribution, and mean percent cover of stony corals and selected functional groups.

Three Dry Tortugas sites (12 stations) were established in 1999, of which two are inside DRTO and one is now within the Florida Keys National Marine Sanctuary (FKNMS) TER. Four additional park sites were added in 2004 (Wheaton *et al*. 2006). Sites range in depth from 2−12.5 m (6.6−41 ft), and each site has two to four stations with permanent markers at start and end points for 22-m (72-ft) transects. Repeated video transects and species inventories are used to estimate the biodiversity, distribution, coverage, and species richness of stony corals and octocorals, clionid sponge assessment, selected disease conditions, benthic algae coverage, and incidence of long-spined sea urchins (*Diadema antillarum*) (Beaver *et al*. 2006, Wheaton *et al*. 2006). Similarities between sites and stations were analyzed using MDS of Bray-Curtis similarity indices for functional groups, including coral species.

Coral colonies at the CREMP sites have been influenced by disease, bleaching, tropical storm and hurricane activity, and other unknown factors (Figure 4.3). In 2005, 29 stony coral species (Milleporina and Scleractinia) were identified at 23 Tortugas stations; mean coral cover ranged from 1.6−13.8% (Beaver *et al.* 2006). Stony coral cover averaged 7.2% in 2004, but decreased to 6.7% in 2005; the reduction was not statistically significant. Coral species richness decreased significantly at two sites from when the site was established (1999 or 2001) and 2005, which was attributed to tropical storm activity 2003−2005 (Beaver *et al.* 2006, Wheaton *et al.* 2006). Shallow reefs formerly dominated by acroporids have shown a dramatic decline, for example at one *A. cervicornis* dominated site, coral cover declined from 17.4% in 1990 to 9.5% by 1999 (Beaver *et al.* 2006). However, *Acropora* populations fluctuated historically in the Dry Tortugas due to hurricanes, cold water and other factors (Jaap *et al.* 1989). CREMP data showed a decline in *M. annularis* and *C. natans* coral cover from 2003 to 2005, which was attributed to an unknown coral disease (Beaver *et al.* 2006, Wheaton *et al.* 2006). In 2005, 18 of 23 stations showed signs of coral disease or bleaching and 18 of 29 inventoried coral species showed bleaching. *A. cervicornis* had a “white” disease at two stations, and an unknown disease affected *M. annularis* spp. complex and *S. siderea* (Beaver *et al.* 2006, Wheaton *et al.* 2006). Octocoral cover varied inversely with coral cover (Shinn and Jaap 2005). Macroalgae cover was relatively low, <10.4%, for all sites in 2004 and 2005 (Wheaton *et al.* 2006).

4.5. Long-term Monitoring of Coral Disease and Bleaching

Monitoring of coral disease and bleaching prevalence in the Dry Tortugas has been conducted by the Environmental Protection Agency (EPA). Three permanent sites were established in the Dry Tortugas (two at Bird Key and one at Loggerhead Key) as part of larger study with 30 sites throughout the Florida Keys to characterize coral community composition, abundance, age class structure and species survival. Sites were selected randomly from a spatially-balanced grid. A radial arc transect was used for disease and bleaching surveys and coral colony counts (Santavy *et al.* 2005). In 2005, five stations in the Dry Tortugas were surveyed and estimates of total coral surface area and percent living coral tissue were added to the methodology (Fisher *et al.* 2006, Fisher *et al.* 2007).

In 2000, survey sites throughout the Florida Keys, including the Dry Tortugas, had less than 13% disease prevalence, while approximately 80% of the reef area had lower than 5% disease prevalence (Fisher *et al*. 2006). Dry Tortugas stations had a higher total coral surface area than Key West stations, in addition to differences in size distribution, species diversity and the contribution of different species to total coral surface area. In Key West and the Dry Tortugas, *D. clivosa*, *P. astreoides*, and *P. porites* had a high percentage of live coral, but *C. natans* and *M. faveolata* had a low percentage of live coral (Figure 4.4). High numbers of small corals were surveyed and an inverse relationship between abundance and size was found (Santavy *et al*. 2005). Each colony encountered at the five stations had 76.4−84.1% live coral calculated. At each station, estimates of total coral surface area ranged from 29.0−42.4 m^2 (312−456 ft^2) and estimates of living coral surface area ranged from 22.7−32.4 m^2 (244−349 ft^2). At 35.7% *D. clivosa* had the greatest total surface area per species and composed 33.9% of total coral colonies.

4.6. South Florida/Caribbean Inventory and Monitoring Network

In 2004, the NPS South Florida/Caribbean Network (SFCN) began monitoring benthic habitats in DRTO. Originally planned for June, the trip was rescheduled for October because of Hurricane Charlie. This first cruise was a collaborative effort between SFCN and Florida Fish and Wildlife Research Institute (FWRI)[9]. The scientists established one permanent index site at Bird Key Reef (also called Long Reef) and allowed for exploration of two others coinciding with FWRI's monitoring. The Bird Key Reef site perimeter was identified using the AquaMap™ underwater sonar navigation system delineating an area of 19,765 m^2 (4.9 ac) with an average stony coral cover value of 12.2%.

In June 2005, SFCN chartered the M/V *Winning Ticket*, which allowed four SFCN scientists to monitor DRTO and Biscayne National Park (BISC) in a single trip. The DRTO Bird Key reef site was monitored and an adjoining site named Bird Key North was established. The new site has an area of 24,944 m^2 (6.2 ac) with an average coral cover of 11%.

In June of 2006, SFCN scientists worked alongside resource management staff from BISC aboard the *R/V Tiburon* to assist on monitoring in DRTO and BISC. Partnering with U.S. Geological Survey (USGS) and the BISC dive team, the team added to the standard coral video monitoring with stony coral disease monitoring and collected samples with swabs of diseased and healthy stony corals. A new method of relocating transects using ranges, compass bearings, and photos was evaluated. The results were very successful.

In 2007, the SFCN team worked from aboard the M/V *Fort Jefferson*, a 33.5-m (110 ft) NPS vessel built in 2003 used primarily for logistical support between DRTO and Key West. This was the first year the ship was used to support scientific research and was much more cost effective than contracting a private dive boat. The SFCN team conducted a pilot project that examined the potential for more long-term coral reef community monitoring sites around the park. A generalized random tessellation stratified survey (GRTS) procedure developed by EPA to ensure a random, spatially balanced placement of sampling sites was used to choose random 40-m^2 (431-ft^2) grid cells created within a stratum of depths ranging from 2−20 m (6.6−66 ft). Benthic communities including coral reefs and hardbottom habitats, as well as unknown habitats based on the NOAA Benthic Habitats of the Florida Keys (FMRI[10] and NOAA 1998). Unknown habitat classification accounts for approximately 25% of the park's mapped submerged resources. The SFCN team evaluated 158 grid cells for potential inclusion for additional long term monitoring sites. At each site, habitat characteristics were collected, including depth, general vertical relief for the cell, habitat classification, percent cover of biotic and abiotic features, presence of *D. antillarum* and rough estimates of fish abundance.

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[9]The Florida Marine Research Institute (FMRI) was renamed Florida Fish and Wildlife Research Institute (FWRI) on July 1, 2004.

[10]cf. footnote 9.

In June 2008, the SFCN team monitored 40 transects at Bird Key and Bird Key North index sites, and began the installation of permanent transects at sites defined from the 2007 exploratory work. This extensive design will help park management track changes in the coral community over time, as well as examine differences in managed areas in the park, inside and outside the RNA, which prohibits fishing and anchoring within its 119 km^2 (46 mi^2) area.

4.7. Summary

Despite differences in methodologies and spatial scales surveyed by current coral monitoring projects (Table 2.5), estimates of the average and range of percent coral cover are fairly similar among the current studies (Figure 4.15) and significantly less than those from historical reports (Figure 4.16). Current trends in the trajectory of coral reefs in the Tortugas region and the Florida Keys suggest that further declines in coral cover will occur in the region. The differences between historical and current coral species composition and cover have sparked a debate among reef scientists about the likely causes of the decline in coral cover in the Tortugas and Florida Keys. One side believes that pressures from human activities (recreational use, coastal development, and over extraction of fish and invertebrates) and global climate change resulting from greenhouse gases are the likely causes of coral reef decline (Porter *et al.* 2001, Hughes *et al.* 2003, Pandolfi *et al.* 2003, Precht *et al.* 2005). Alternatively, episodic natural disturbances, such as cold-water events, coral disease outbreaks, and tropical storms, have periodically reduced the abundance of scleractinian corals in the Tortugas and Florida Keys (Precht and Miller 2007, Shinn 2004, Precht *et al.* 2005, Jaap *et al.* 2008). The debate has relevance to the management of coral reefs in the Tortugas region because the outcome ultimately determines the strategies DRTO resource managers will use to achieve their management goals. For example, if coral reef decline in the Tortugas region results primarily from local human activities, then reversal of the decline in coral reef resources will only occur if the human stressors are reduced. If episodic natural disasters beyond human control are causing the decline of coral resources, then management actions that reduce known human stressors may do little to reverse the decline in scleractinian corals.

Coral reefs in the Tortugas region appear very different today from what they were a century ago. The data reviewed here support the contention that episodic events have resulted in boom and bust cycles of coral abundance in the Tortugas region since the 1800s. However, the data also support an overall declining trend in the abundance of coral through time. One explanation suggests that pressures from human activities may have slowed or prevented the recovery of corals to previous “boom” levels after each “bust cycle” resulting in the long-term decline in the abundance of corals.

The NPS General Management Plan for DRTO outlines several goals that include protection of an intact and pristine subtropical marine ecosystem and the populations of fish and wildlife that live there (NPS 2005). To achieve this goal, the concept of an “intact” and “pristine” marine ecosystem must be defined for the Tortugas region. Most of the extant monitoring programs in the Tortugas list ecosystem characterization and the determination of baselines for corals as major goals. Although these programs provide baseline characterizations of coral reef ecosystems, resource managers must decide if the baselines reported represent the “pristine” condition of coral reef ecosystems that they are mandated to maintain and protect. The park was established in 1935, but corals and marine life were included for protection only in 1980 (NPS 2005). Should the condition of coral reefs in the 1980s be considered the baseline from which to measure the amount of coral loss in Tortugas region? Should it be the target to which the ecosystem must be returned to be considered pristine?

In the Tortugas, the phenomenon of shifting baselines (Knowlton and Jackson 2008) is confounded further by the historical boom and bust cycles of corals there, and begs the question of how much investment should made by resource managers in attempting to return the coral reef ecosystem to a more pristine state (i.e., return coral abundance, structure, and cover to some previous level). For example, large-scale restoration of coral reef structure is possible via available technologies, such as the reattachment and transplantation of corals to an injured area or the use of preformed man-made modules as substrates for coral settlement (Symons *et al.* 2006). However, these technologies are very expensive, time consuming to implement, and require long periods to show positive ecosystem-wide results. Gains from coral reef restoration efforts could easily be wiped out by natural episodic disturbances.

Ultimately, park resource managers must set achievable goals for protecting coral resources, determine the true costs of protection, and whether the ultimate gains from protection are worth the costs. The determination of appropriate metrics and baselines against which to measure coral decline, and to set targets to which the coral reef ecosystem should be returned, requires well-designed sampling regimes that adequately describe the spatial and temporal variability in coral reef ecosystems of the Tortugas region. A few of the monitoring programs reviewed here collect spatially-explicit data that could be used to address this issue (Table 2.2). Park managers should increase their efforts to obtain these data to develop a resource management program to help the park meet its natural resource goals.

Figure 4.1. Map showing the distribution of corals in the southwestern Tortugas region developed by Agassiz in 1882 (source: Agassiz 1882). The red line demarcates an area colonized by gorgonians (octocorals) in 1882, which was later identified by Davis (1977) to be staghorn coral (*Acropora cervicornis*).

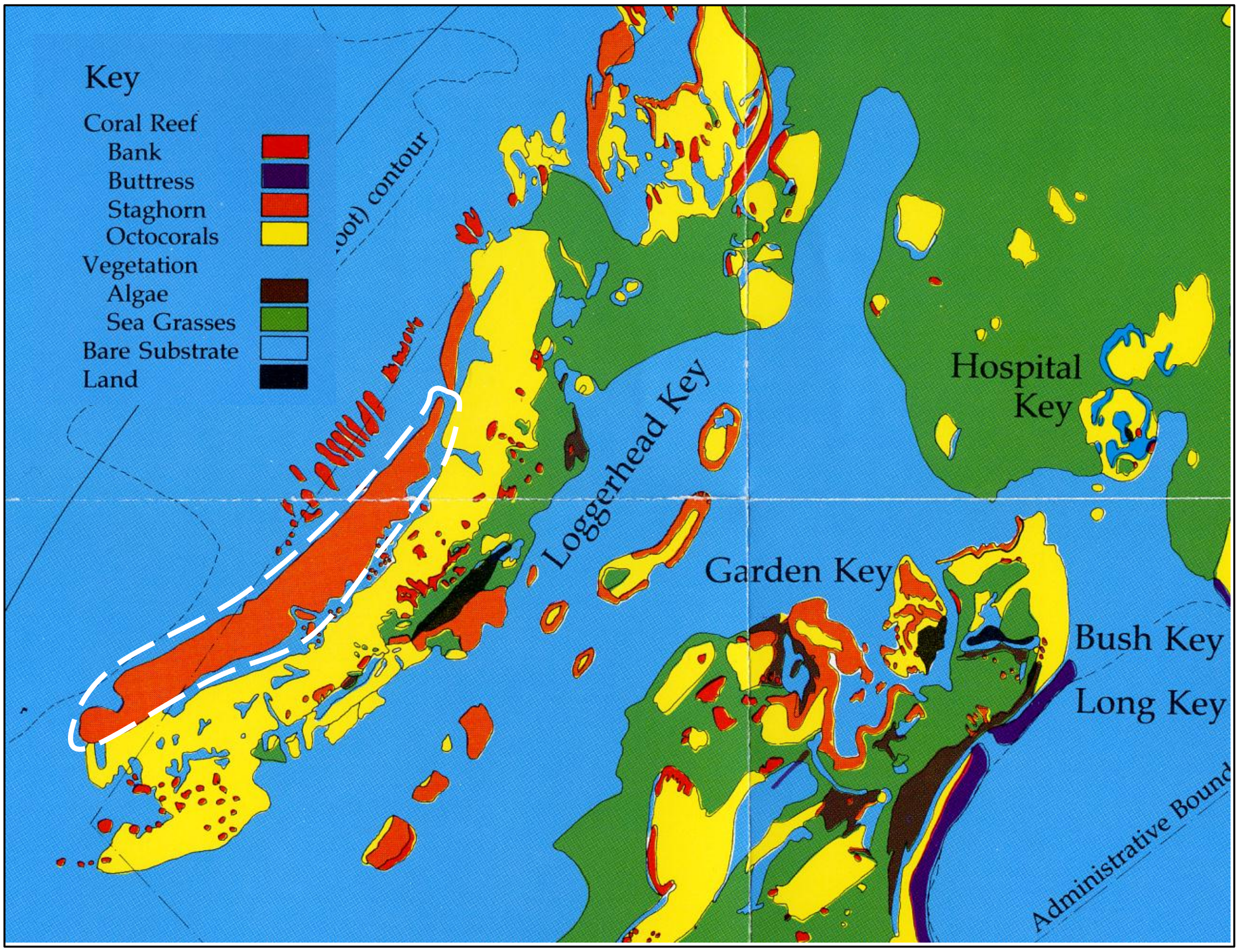


Figure 4.2. Map showing the distribution of benthic habitats in the Tortugas region in 1979 developed by Davis (1982). The white broken polygon west of loggerhead Key shows an *Acropora cervicornis* reef (staghorn coral) that was previously colonized by octocorals in 1882 (cf. Figure 4.1).

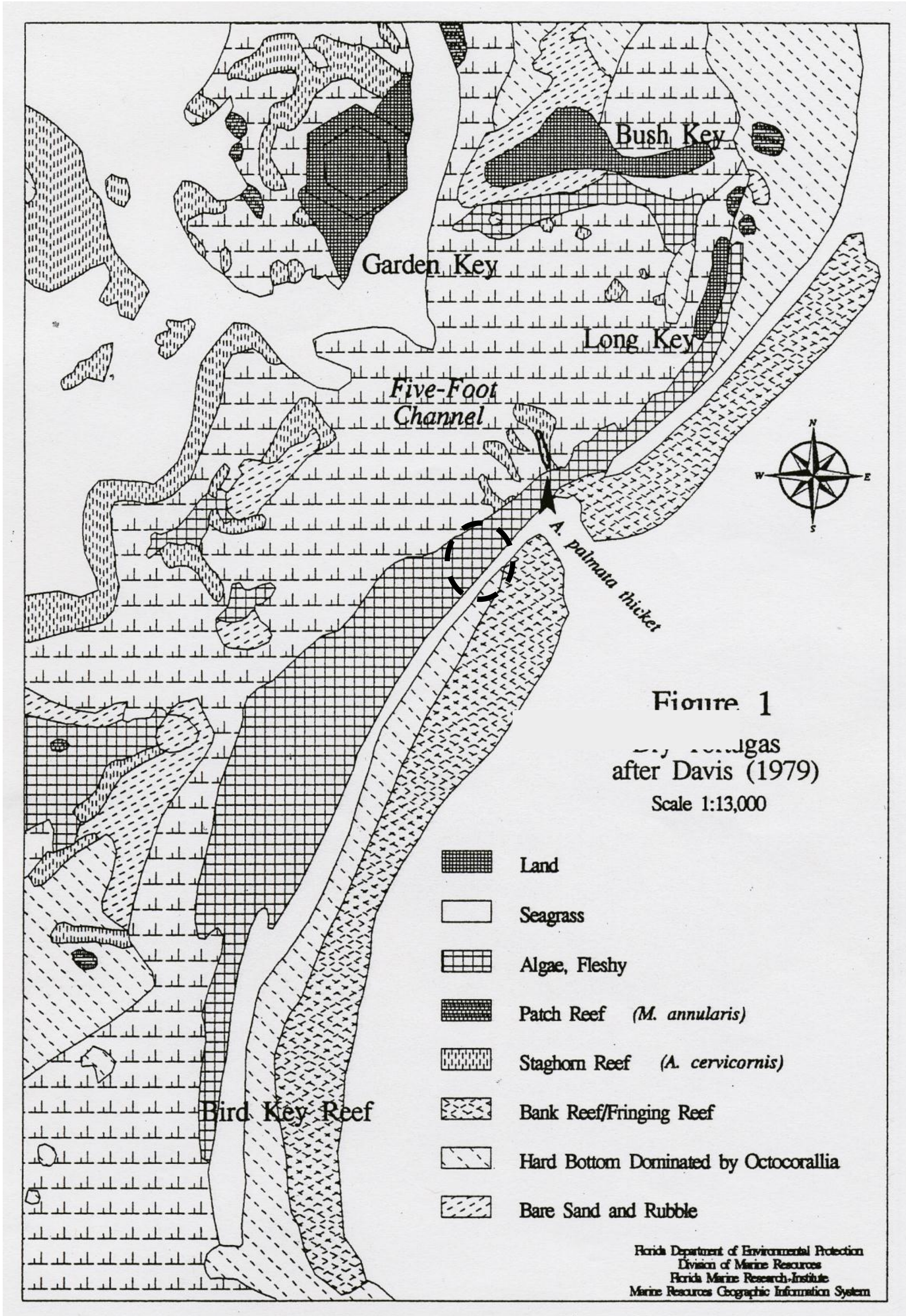


Figure 4.3. Map showing the location of the remnant *Acropora palmata* (elkhorn coral) thicket (broken circle) in the Dry Tortugas in 1993 (adapted from Jaap and Sargent 1993).

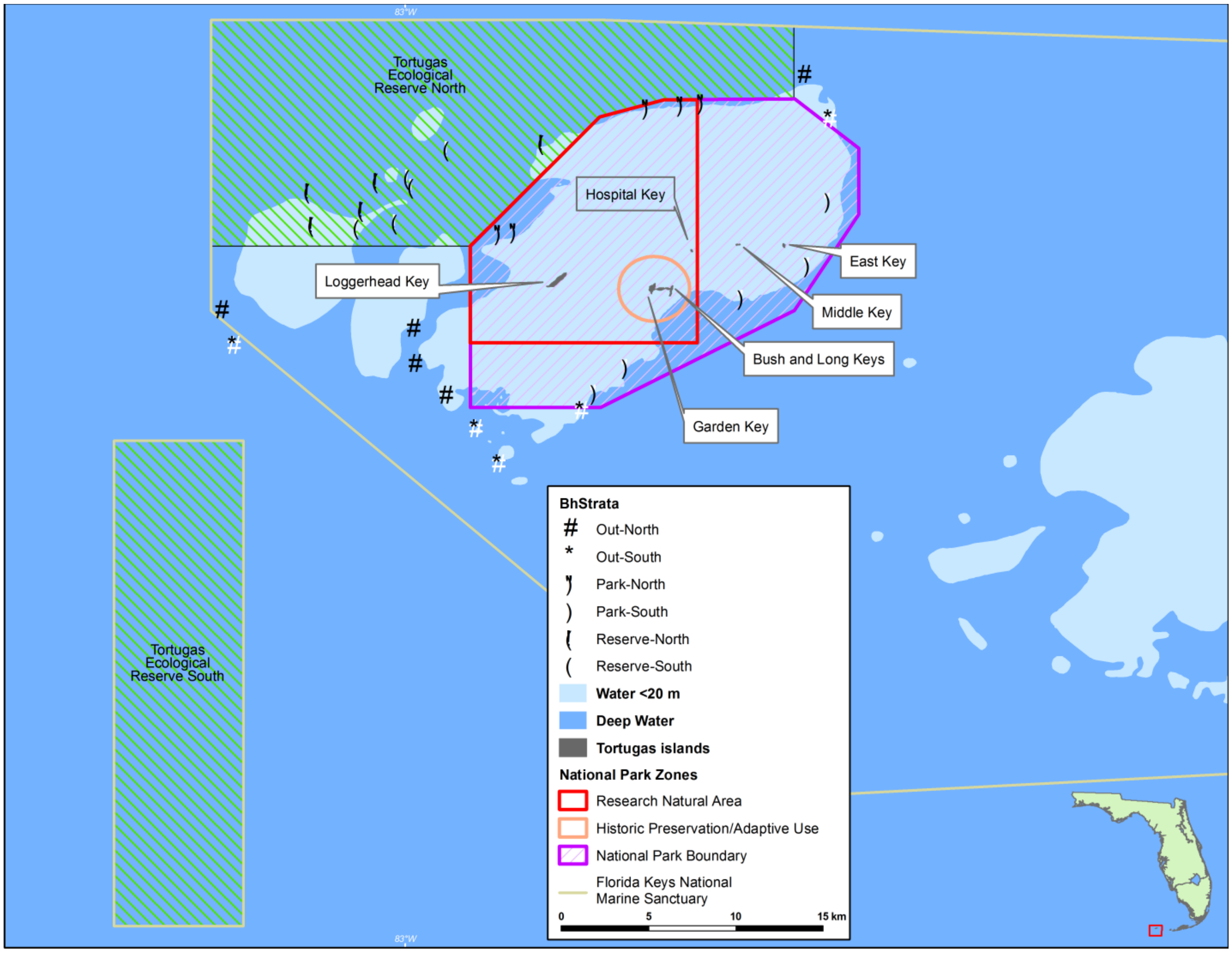


Figure 4.4. Location of permanent reef-sand interface sites in the Dry Tortugas region the Tortugas Ecological Reserve and the Dry Tortugas National Park surveyed by NOAA's Center for Coastal Fisheries and Habitat Research.

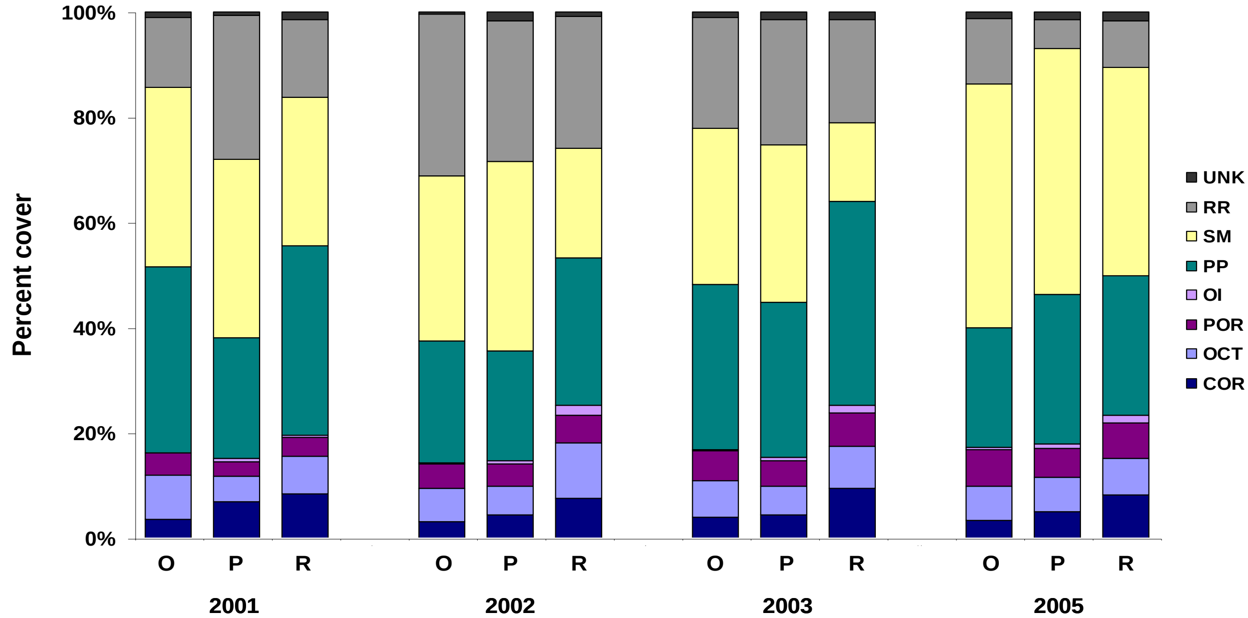


Figure 4.5. Percent cover on benthic reef transects in the Tortugas Ecological Reserve (R), Dry Tortugas National Park (P), and unprotected areas outside the reserve and park (O). COR = coral, OCT = octocoral, POR = sponges, OI = other invertebrates, PP = primary producers, SM = sand and benthic microalgae, RR = rock and rubble, UNK = unknown. Video collected in 2004 has not been analyzed.

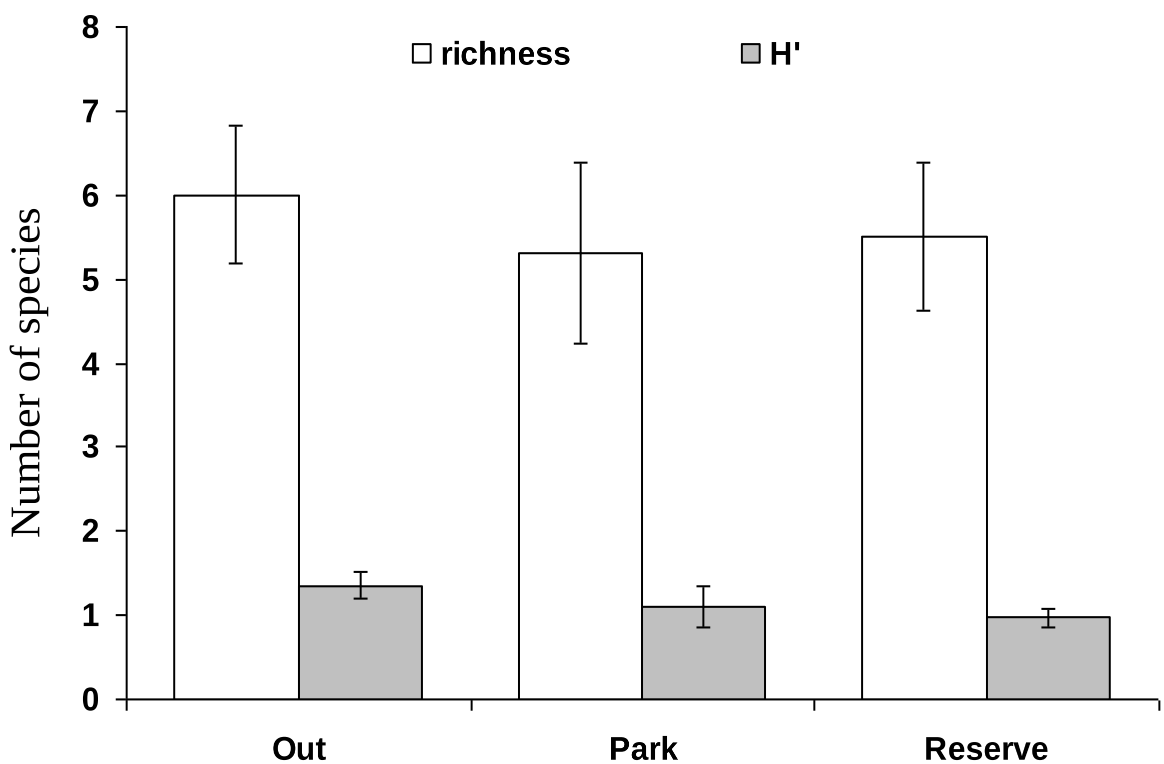


Figure 4.6. Species richness and diversity (H') of scleractinian corals in 2005.

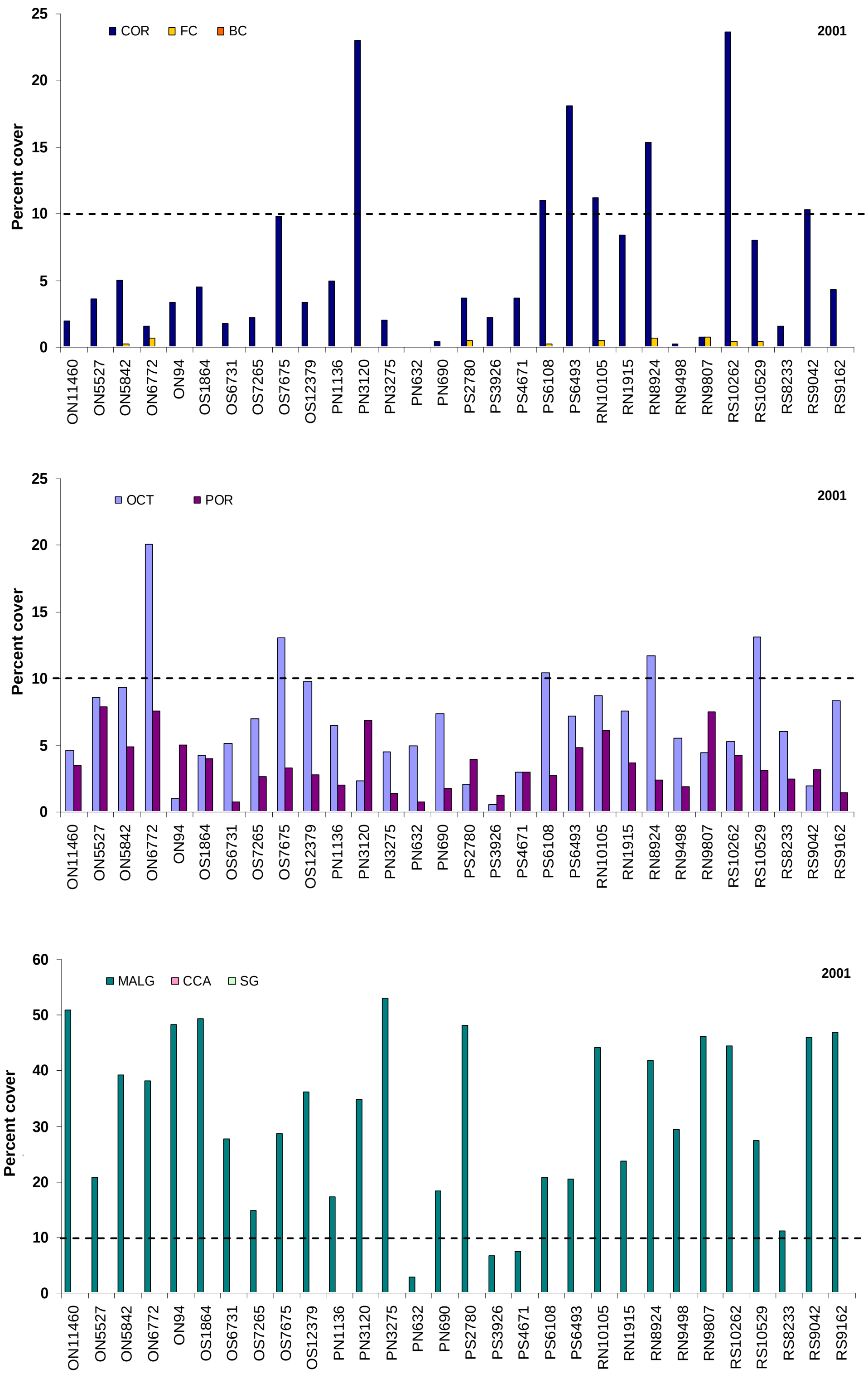


Figure 4.7. Percent cover of benthic biota on reef transects in 2001 in the Tortugas Ecological Reserve (R), Dry Tortugas National Park (P), and unprotected areas outside the reserve and park (O). COR = coral, FC = fire coral, BC = black coral, OCT = octocoral, POR = sponges, MALG = macroalgae, CCA = crustose coralline algae, SG = seagrass. Dashed line is the overall average benthic cover of biota at surveyed sites.

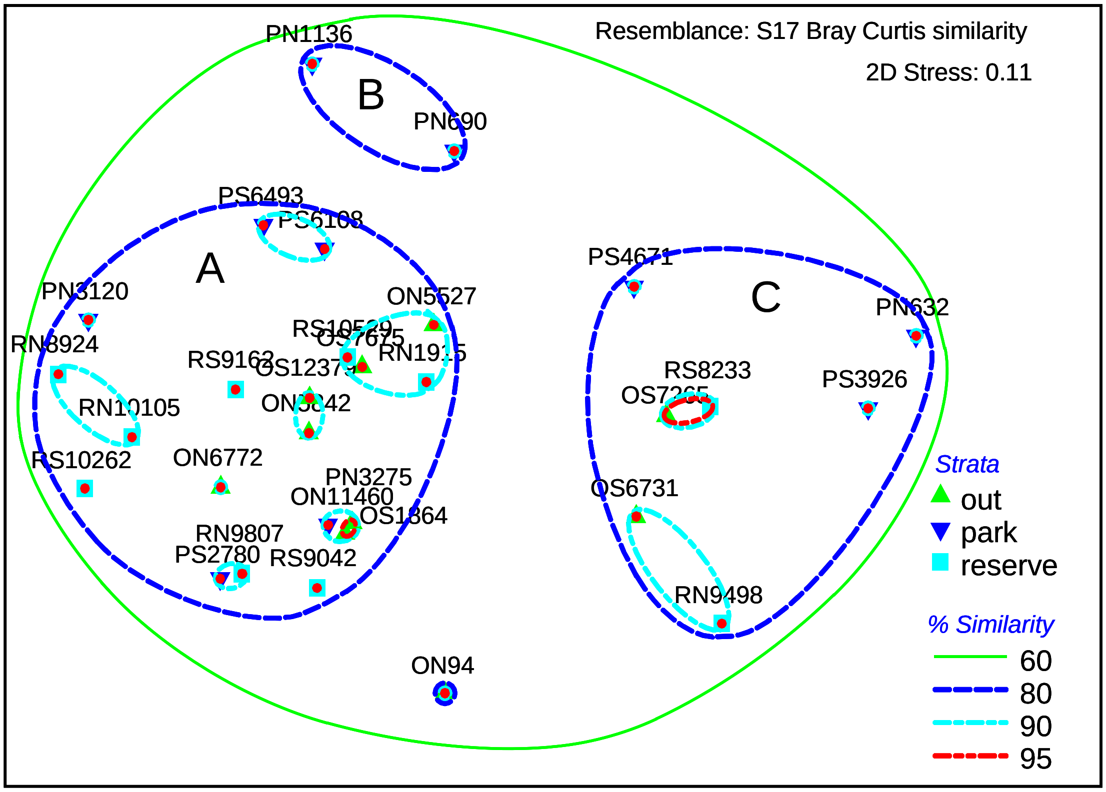


Figure 4.8. Multi-dimensional scaling of Bray-Curtis similarities of 2001 Tortugas coral reef biota functional groups with superimposed group-averaged clustering obtained from the same similarities.

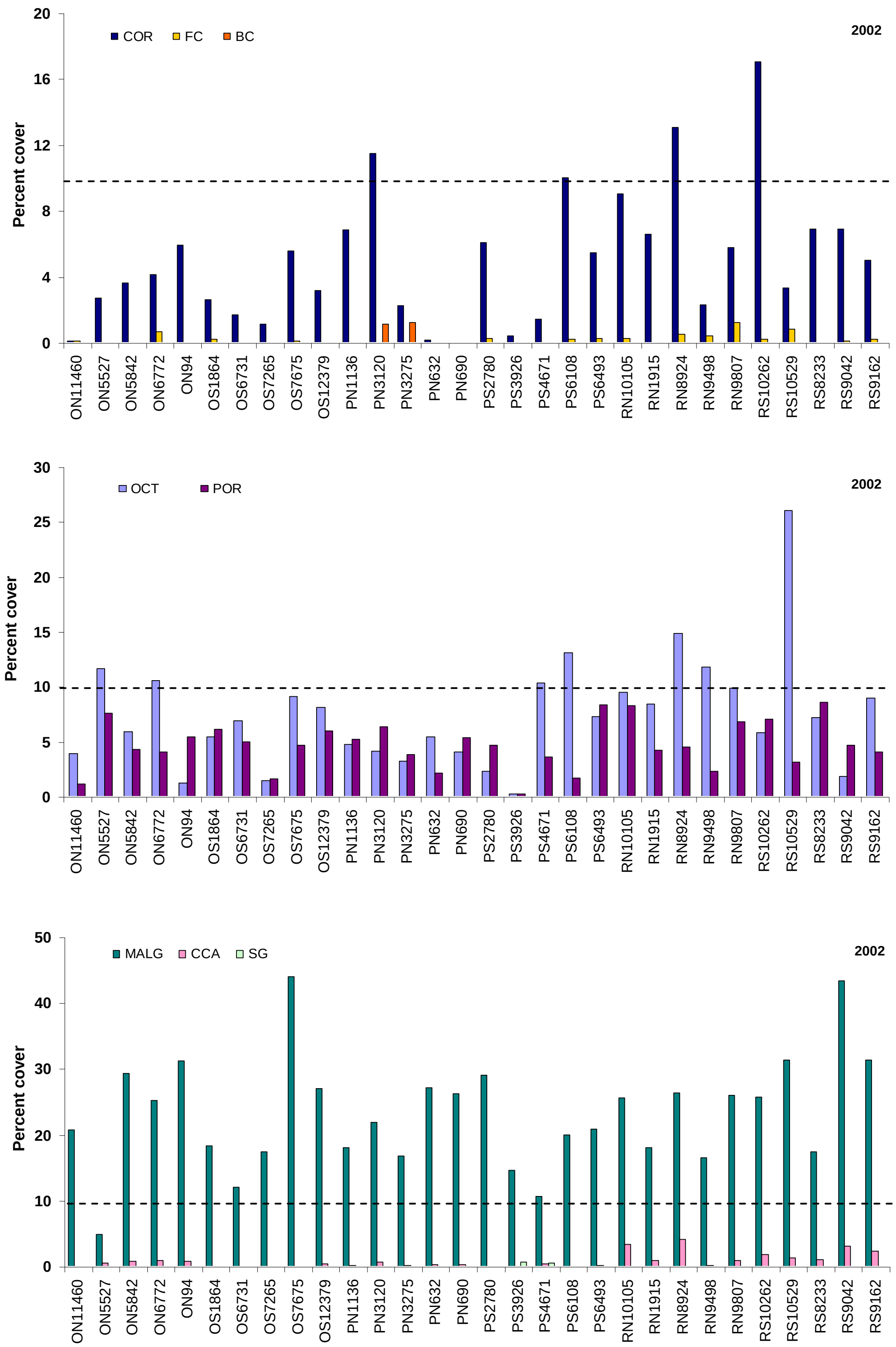


Figure 4.9. Percent cover of benthic biota on reef transects in 2002 in the Tortugas Ecological Reserve (R), Dry Tortugas National Park (P), and unprotected areas outside the reserve and park (O).COR = coral, FC = fire coral, BC = black coral, OCT = octocoral, POR = sponges, MALG = macroalgae, CCA = crustose coralline algae, SG = seagrass. Dashed line indicates overall average benthic cover of biota at surveyed sites.

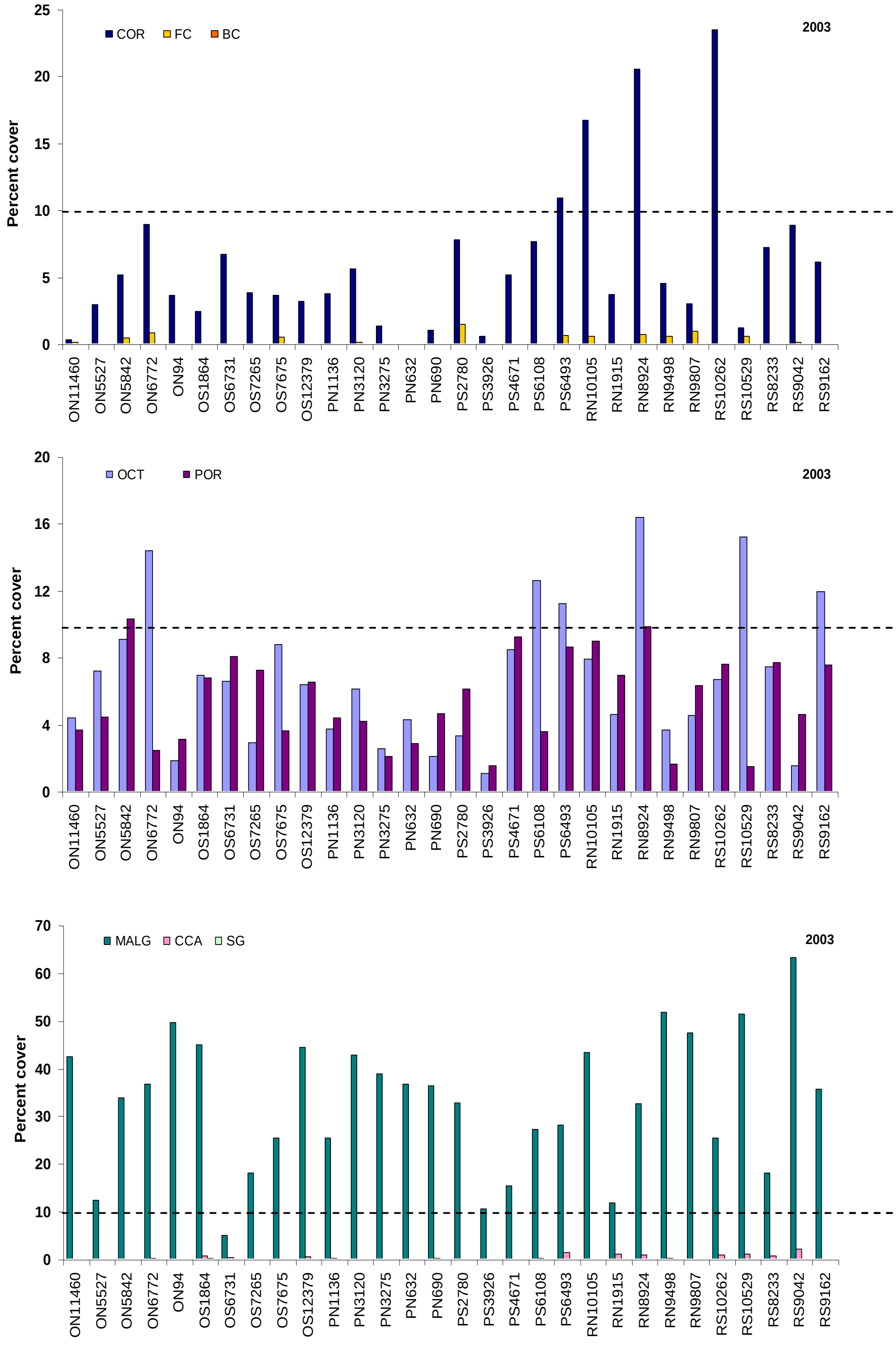


Figure 4.10. Percent cover of benthic biota on reef transects in 2003 in the Tortugas Ecological Reserve (R), Dry Tortugas National Park (P), and unprotected areas outside the reserve and park (O). COR = coral, FC = fire coral, BC = black coral, OCT = octocoral, POR = sponges, MALG = macroalgae, CCA = crustose coralline algae, SG = seagrass. Dashed line indicates overall average benthic cover of biota at surveyed sites.

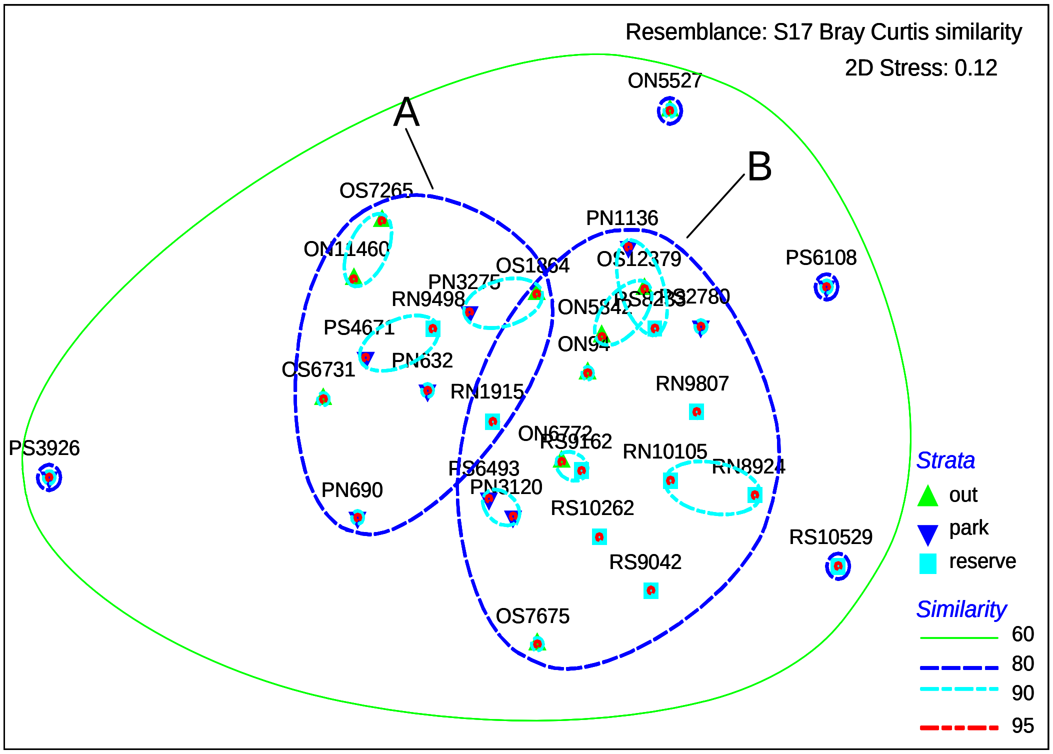


Figure 4.11. Multi-dimensional scaling of Bray-Curtis similarities of 2002 Tortugas coral reef biota functional groups with superimposed group-averaged clustering obtained from the same similarities.

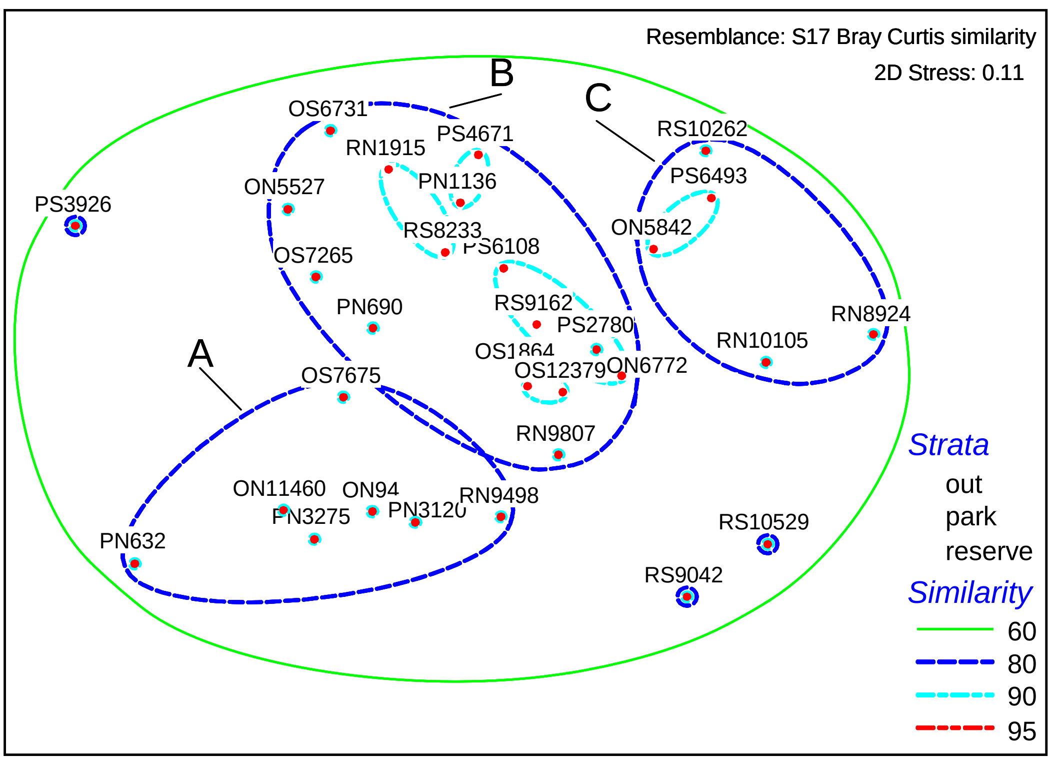


Figure 4.12. Multi-dimensional scaling of Bray-Curtis similarities of 2003 Tortugas coral reef biota functional groups with superimposed group-averaged clustering obtained from the same similarities.

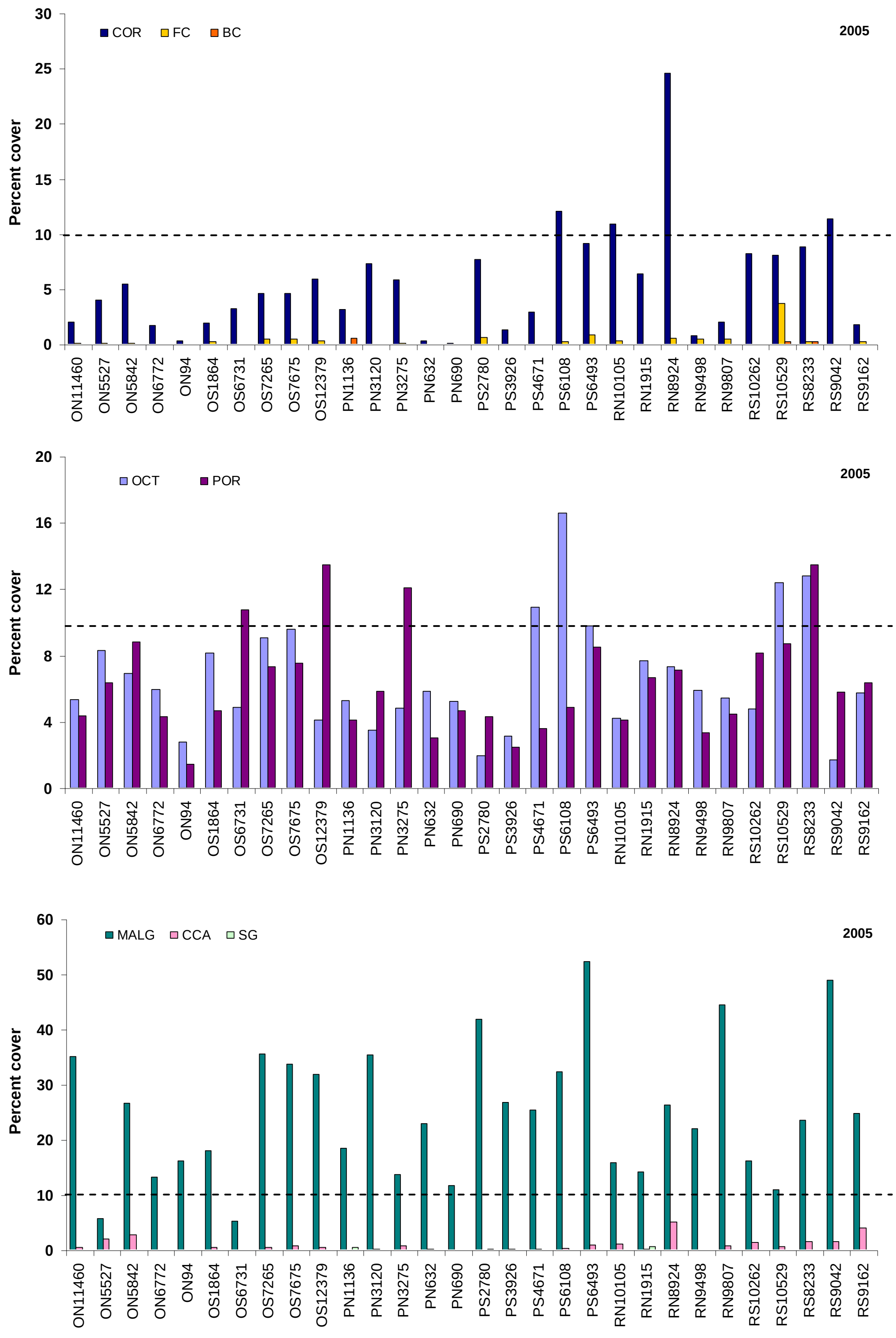


Figure 4.13. Percent cover of benthic biota on reef transects in 2005 in the Tortugas Ecological Reserve (R), Dry Tortugas National Park (P), and unprotected areas outside the reserve and park (O). COR = coral, FC = fire coral, BC = black coral, OCT = octocoral, POR = sponges, MALG = macroalgae, CCA = crustose coralline algae, SG = seagrass. Dashed line indicates overall average benthic cover of biota at surveyed sites.

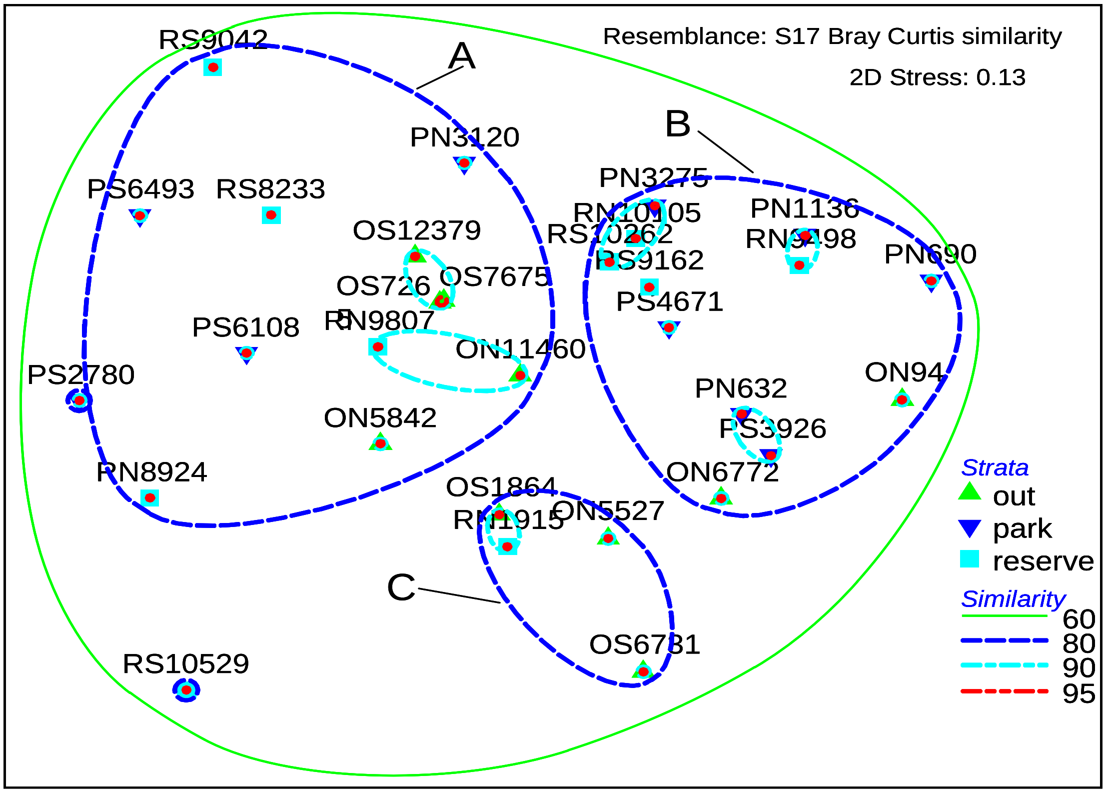


Figure 4.14. Multi-dimensional scaling of Bray-Curtis similarities of 2005 Tortugas coral reef biota functional groups with superimposed group-averaged clustering obtained from the same similarities.

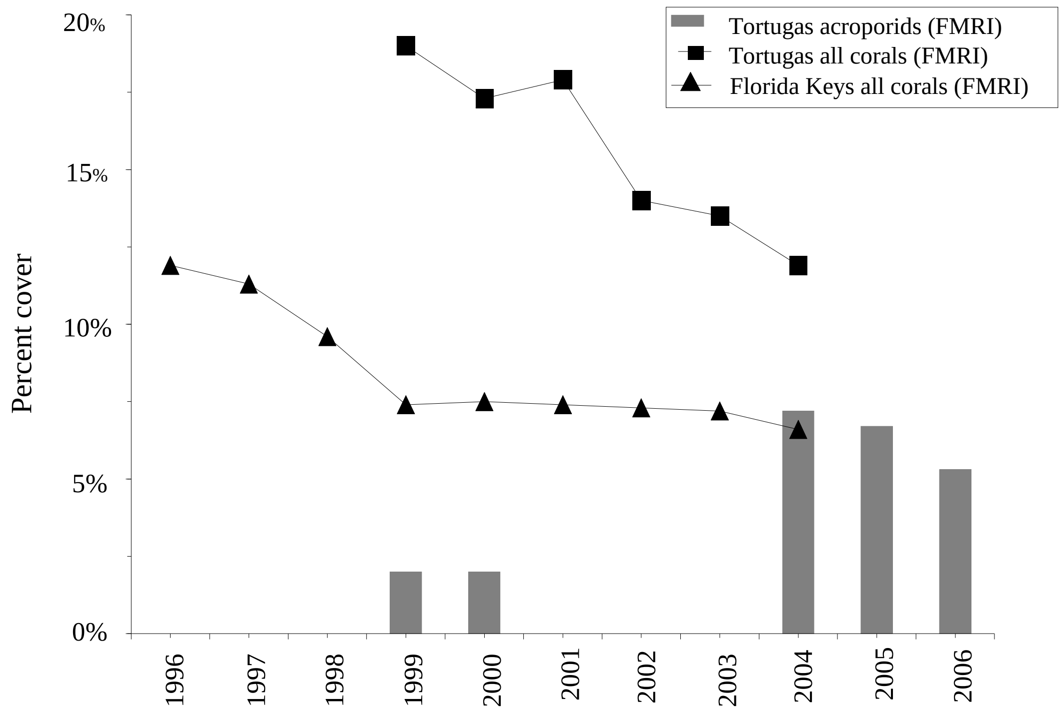


Figure 4.15. Coral cover in Tortugas region and Dry Tortugas between 1996−2007. Data were summarized from studies and projects in Table 2.2.

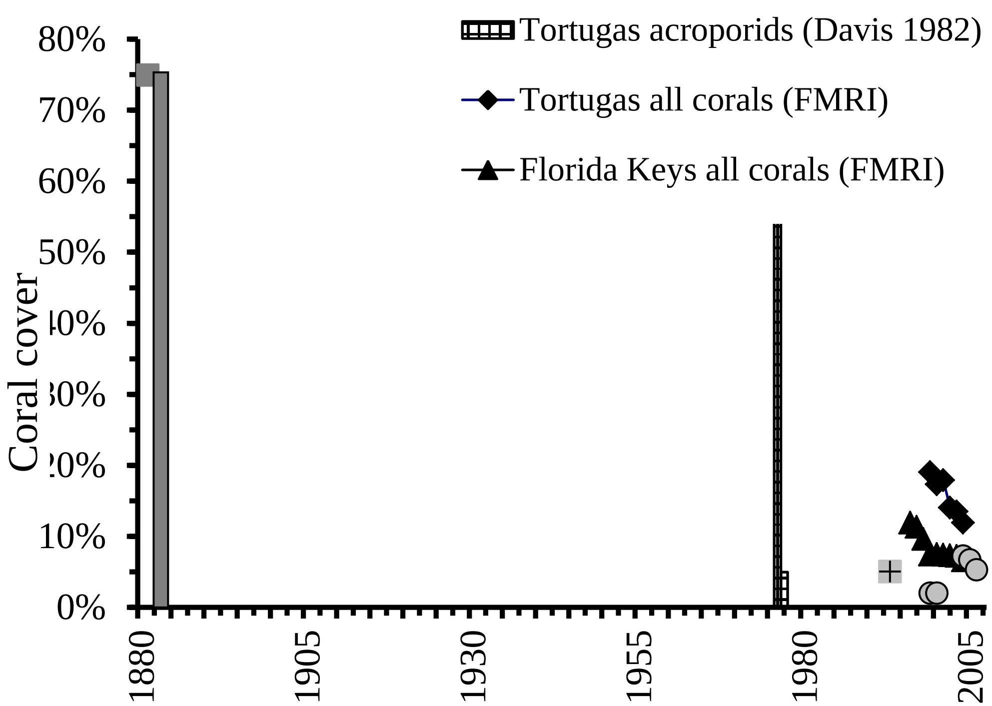


Figure 4.16. Coral cover in Tortugas region and Dry Tortugas between 1880−2007. Data were summarized from studies and projects in Table 2.2.

Chapter 5: Distribution and Condition of Seagrass, Algal, and Sand Communities

Christopher F. G. Jeffrey and Doug Morrison

5.1. Importance of Seagrass and Algal Communities to Coral Reef Ecosystems

Seagrass and algal communities are important components of coral reef ecosystems in the Caribbean. Seagrass beds provide habitat and food for important coral reef fishery species, threatened and endangered species, and many other organisms (Parrish 1989, Sobel and Dahlgren 2004, Adams *et al*. 2006). Calcareous algae (e.g., *Halimeda* spp.) are major contributors of carbonate sediments to the coral reef ecosystems in the Atlantic Ocean (e.g., quick sands areas of the Tortugas region). Reef fishes migrate from reef and hardbottom areas and forage in adjacent habitats (sand, seagrasses, and algal plains) creating a trophic pathway that transfers energy from these habitats to the reefs (McFarland *et al*. 1979, Meyer *et al.* 1983). The presence and abundance of seagrass habitats are correlated with increased fish abundance and species richness in mangrove communities in Puerto Rico (Pittman *et al.* 2007) and higher sighting frequencies of groupers on hardbottom habitats in the Florida Keys (Jeffrey 2004).

Seagrass and algal communities form important components of the nearshore environments of the Florida Keys and the Dry Tortugas region (Figure 5.1). For example, reef-associated and pelagic fish species collected from coral reefs and hardbottom areas on the West Florida Shelf and in the Tortugas region had stable carbon isotope signatures that were similar to the isotope signatures of macroalgae and the seagrass *Halophila decipiens* collected from adjacent sandy substrates. The similarity in carbon signatures suggests that pelagic and hardbottom fish assemblages on the West Florida Shelf are being supported by benthic primary producers in seagrass and algal communities (Burke *et al*. 2004, Fonseca *et al*. 2006). Seagrasses may be driving primary production by exporting defoliated leaf blades to other habitats (Fourqurean *et al.* 2006).

5.2. Types and Spatial Distribution of Submerged Aquatic Vegetation

Seagrass and algal meadows are spatially extensive within the Dry Tortugas National Park (DRTO) and Florida Keys National Marine Sanctuary (FKNMS). Seagrasses account for over 4,440 ha (10,970 ac) (approximately 31%) of mapped areas within the park and about and 288,080 ha (711,900 ac) (approximately 71%) of mapped areas within the FKNMS (FMRI[11] and NOAA 1998). Community composition of seagrasses is determined by several factors including salinity levels, light extinction rates, spatial distribution of hardbottom and soft sediments, nutrient enrichment, water quality, disease, level of disturbance and succession (Duarte 2002). Density of seagrasses in DRTO varies by species but typically most areas are sparsely colonized, with deeper areas (>10 m [33 ft]) of the park being dominated by *H. decipiens* (Fourqurean *et al.* 2002). *Thallasia testudinum* and *Syringodium filiforme* typically abound in shallower waters <10 m (33 ft). Algal communities in the Dry Tortugas tend to be ephemeral and they occur on a variety of bottom types. Algae are commonly found on rocks or rubble in reef flats and areas of

[11]The Florida Marine Research Institute (FMRI) was renamed Florida Fish and Wildlife Research Institute (FWRI) on July 1, 2004.

high wave energy (Davis 1982, Jaap *et al*. 1998). Conspicuous genera include *Laurencia*, *Dictyota*, *Sargassum*, *Cladophora*, and *Padina*; they have more foliose morphologies (Figure 5.2). Algae also occur on soft sedimentary (sandy) deposits, where more calcareous forms, such as *Halimeda*, *Avrainvillea*, *Penicillus*, and *Udotea*, are more abundant. Crustose coralline algae (CCA; Rhodophyceae) form thin-branched or unbranched crusts and typically are attached to hard substrates. In 1928, 377 species of marine algae were described for the Dry Tortugas (Taylor 1928); eight more species were later identified near Pulaski Shoals (Ballantine and Aponte 1995, Ballantine 1996).

Mapping and habitat characterizations have been used several times to estimate the areal extent and spatial distribution of submerged aquatic vegetation in Tortugas region (Agassiz 1882, Davis 1982, FMRI and NOAA 1998). These estimates varied depending on mapping methods used and the spatial extent of the area mapped, but estimates of proportional cover of seagrasses were very similar among the efforts and ranged from 30−32% of mapped area (Table 5.1). Estimates of the spatial extent of non-vegetated areas (bare substrate, sand, and rubble) were much more variable among mapping efforts and ranged from 60% of mapped area in 1882 (Agassiz 1882) to 40% in 1982 (Davis 1982) and 1% in 1992 (FMRI and NOAA 1998; Table 5.1). The differences in estimates result more from differences in the way soft bottom habitats (i.e., non-coral reef and hardbottom areas) were classified than from natural or anthropogenic changes in the spatial extent of these habitats over time. For example, Davis (1982) differentiated between vegetated and non-vegetated soft bottom habitats, whereas Agassiz (1882) mapped all soft bottom areas as sediments. FMRI and NOAA (1998) classified 6,400 ha (15,810 ac) (31%) of DRTO as unknown habitat because those areas were either too deep or too turbid for photo interpretation of the imagery used for mapping and characterization.

Ongoing activities to map and characterize benthic habitats in the Tortugas region have also yielded variable estimates of the spatial extents of soft bottom areas there. Since 2001, NOAA's Center for Coastal Fisheries and Habitat Research (CCFHR) has used side-scan and multibeam sonar and underwater video surveys to map and characterize the sand-coral reef interface (i.e., where coral reefs transition to seagrass/algal plains) in the DRTO and the Tortugas Ecological Reserves (Burke *et al*. 2004b, Fonseca *et al.* 2006). The interface is located along the perimeters of the Tortugas Bank and the Park (Figure 5.3). GIS-based comparisons of CCFHR's benthic characterizations with those by FMRI and NOAA (1998) based on photo interpretation and ground-truthing of 1991 aerial imagery, indicated that FMRI and NOAA underestimated the spatial extents of coral reef habitats by at least 28% and overestimated soft bottom substrates by the same amount (Fonseca *et al.* 2006).

The University of Miami RSMAS synthesized data collected by a variety of technologies to develop a detailed digital map of coral reef and hardbottom habitats for the Tortugas region. The RSMAS map is updated biennially with data from diver surveys, and the area of the Tortugas region mapped as coral reef and hardbottom has increased to 35,560 ha (87,870 ac) from 9,480 ha (23,430 ac) as mapped by FMRI and NOAA (1998). A GIS overlay of the RSMAS map onto the FMRI and NOAA (1998) map showed that 2,568 ha (6,346 ac) (58%) of areas previously classified as seagrass habitats have been reclassified as coral reef and hardbottom habitat (Table 5.2, Figure 5.4). This leaves 1,853 ha (4,579 ac) of seagrass in DRTO, with about 333 ha (823 ac) in the RNA, 155 ha (383 ac) in the Historic Preservation/Adaptive Use Zone (AUZ), and 1,364 ha (3,371 ac) in the rest of the park (Figure 5.5).

5.3. Monitoring of Seagrasses and Algae

5.3.1. South Florida/Caribbean Monitoring Network

The South Florida/Caribbean Network (SFCN) is one of 32 networks across the National Park System created to meet the science needs of the park managers. The networks conduct inventories and monitor natural resources – vertebrates, vascular plants, and species of special management concerns – that occur on lands managed by NPS (http://science.nature.nps.gov/im/units/sfcn/Index.cfm). The SFCN is charged with: (1) selecting "vital signs" for monitoring the health of natural resources, (2) developing new programs or coordinating existing programs to monitor selected "vital signs," and (3) reporting on the status, changes, or trends in the vital signs to assist in the adaptive management of park resources. "Vital signs" are defined as "physical, chemical and biological elements and processes of park ecosystems that represent the overall health or condition of the park; they may also be park resources that are highly valued but not necessarily indicative of general park health" (http://science.nature.nps.gov/im/units/sfcn/docs/SFCN%20VItal%20Signs%20Fact%20Sheet2a.pdf). The SFCN selected 41 "vital signs" to monitor the health and condition of natural resources in the parks within its network, and has been developing monitoring protocols for each of them. "Marine benthic communities," including submerged aquatic vegetation and coral reefs, is the most important "vital sign" (http://science.nature.nps.gov/im/units/sfcn/benthic.cfm). A monitoring protocol was developed for coral reef communities within the network and one for submerged aquatic vegetation is being developed.

5.3.2. Monitoring of Seagrasses

Two monitoring programs collect data on seagrasses and algae within DRTO. Monitoring and assessment of seagrass communities within DRTO began in 2005 by park staff. The goals of the monitoring program are: (1) to evaluate the long term ecological status and trends of seagrass communities in the park and (2) to assess the effects of hurricanes on seagrass meadows and to determine recovery from hurricane damage. Since 2000, 10 named tropical storms and seven hurricanes have affected the Tortugas region, and five hurricanes passed through the region between August 2004 and October 2005 (http://maps.csc.noaa.gov/hurricanes/). DRTO experiences tropical cyclones each year, but the frequency of storms experienced during 2004 and 2005 was unprecedented.

The monitoring program samples seagrass communities at permanently marked sites selected randomly from three depth strata: (<3 m [<10 ft], 3−10 m [10-33 ft], and >10 m [>33 ft]) and replicated across the park's three management zones (Figure 5.6). Replicate sites were initially selected randomly from each depth stratum within each monitoring zone, however, the absence of a certified scuba diving program and insufficient funding in 2005 and 2006, only allowed sites shallower than 3 m (10 ft) in the RNA and Adaptive Use Zone (AUZ) to be being surveyed. A broader scale assessment of hurricane effects and seagrass recovery around the Tortugas islands (Loggerhead, Garden, Bush, and East Keys) by aerial photography was planned, but was not been implemented because of insufficient funding.

DRTO seagrass communities are also monitored by Florida International University's (FUI) Southeast Environmental Research Center (SERC; http://serc.fiu.edu/seagrass/; Figure 5.7). The objectives of SERC seagrass monitoring are to measure the status and trends of seagrass communities and to evaluate progress toward protecting and restoring the living marine resources of the FKNMS (Fourqurean and Escorcia 2006). SERC monitors about 10−15 sites every year within the park, but the sites are in deeper water (>10 m [33 ft]), and new sites are selected at random for every sampling event (Fourqurean and Escorcia 2006). Seagrass data for sites in DRTO are not readily available from SERC, although annual reports and publications for the entire Florida Keys and FKNMS are web accessible.

Seagrass monitoring data collected by park staff at permanently marked sites in shallow areas could provide complementary information on the status of seagrass communities that are not being sampled by SERC, and are the only data on seagrass abundance and occurrence available for this resource condition assessment.

5.3.3. Methods

Three shallow (<3 m [10 ft] deep) randomly selected permanent sites around Loggerhead Key (in the RNA) and three such sites in the AUZ were sampled in 2005 and 2006 (Figure 5.6). All sites were surveyed in June 2005, before Hurricanes Dennis, Katrina and Rita. Two sites (GK-2 and GK-3) were also examined in September after these three hurricanes, but before Hurricane Wilma. All sites were surveyed in July 2006. Randomly located 0.25 m^2 (2.7 ft^2) quadrats subdivided into 5% grids were used to sample each site (N=15−21). The percent cover of each seagrass and macroalgal species observed were recorded in each quadrat to the nearest 5%, and individuals of macroalgae, such as *Penicillus* spp. and *Halimeda incrassate,* were enumerated to determine abundance. Echinoids (sea urchins and sea biscuits) were enumerated in 1 m^2 (10.8 ft^2) quadrats.

A two-way Analysis of Variance (ANOVA), with species and time as main factors, was used on transformed data to determine if significant differences in percent cover were observed among species and between sampling periods (Zar 1996). For site GK-3, where only one species was abundant, a non-parametric one-way ANOVA was used to test if seagrass cover and echinoid density varied significantly among sampling periods. If significant differences were observed, multiple comparison tests were used to determine pair-wise differences among species and between sampling periods (Zar 1996).

5.3.4. Results and Discussion

T. testundinum (turtle grass) was the most abundant benthic macrophyte at all shallow water sites, except at site LK-2 in 2005 where it was co-dominant with the seagrass *S. filiforme* (Figures 5.7 and 5.8). *Syringodium* was the second most plentiful macrophyte at all LK stations and GK-1. *Syringodium* was not observed at GK-2 and GK-3. Macroalgae were abundant (>5% cover) only at GK-2. GK-2 is close to the Bush Key bird rookery, a likely major nutrient source. Macroalgal species frequently associated with relatively higher nutrient conditions were common at GK-2. GK-2 also had the greatest variability (i.e., patchiness) in seagrass percent cover. The most common macroalgal species at the other sites were calcareous greens (e.g., *Halimeda* spp., *Penicillus* spp.) that are indicative of relatively lower nutrient levels (Littler *et al.* 1983).

Seagrass abundance decreased significantly ($p<0.05$) from June 2005 (pre hurricanes) through July 2006 (post hurricanes) at all sites, except GK-2 (Figures 5.7 and 5.8). The change in seagrass cover at GK-2 was marginally significant ($p=0.055$). Site GK-2 was most protected from wave action, and it had the greatest seagrass patchiness of all the sites before the hurricanes. Macroalgal abundance at GK-2 changed significantly among June 2005 (pre-hurricanes), September 2005 (post Hurricanes Dennis, Katrina, and Rita) and July 2006 surveys.

The observed changes in seagrass and macroalgae abundance at sampled sites most likely resulted from the combined effects of four 2005 hurricanes (Dennis, Katrina, Rita, and Wilma) that passed through or near DRTO in four months. GK-3, which is located on the side of Bush Key exposed to the open ocean, was most affected by the hurricanes. The hurricanes, especially Katrina caused substantial amounts of sand erosion from Bush Key, and the eroded sediment smothered much of the seagrass at GK-3. Sites GK-2 and GK-3 were also sampled in September 2005 after Dennis, Katrina, and Rita (Figure 5.9). One can get an idea of short-term recovery by comparing the September 2005 and July 2006 surveys at these sites, even though Wilma occurred in October 2006. Macroalgal and seagrass abundance at GK-2 was significantly lower in September 2005; but there was no significant difference between June 2005 and July 2006, denoting complete recovery. Even at highly impacted GK-3, seagrass abundance was significantly greater in July 2006 than September 2005, indicating some recovery. Aerial photography is needed for a more comprehensive, seascape scale assessment of the effects on seagrass communities of, and recovery from, the 2004−2005 hurricanes. This photography could be compared to that taken by U.S. Geological Society (USGS) in 2004 before the hurricanes. Post-hurricane qualitative aerial photography and in-water surveys found substantial loss of shallow water seagrass around Loggerhead, East, and Bush Keys.

Echinoids (sea urchins and sea biscuits) were observed at several sites. However, the only echinoid species with abundance >0.3 individuals/m^2 (>0.03 individuals/ft^2) was the sea biscuit *Clypeaster,* which occurred only at GK-3 (Figure 5.9). *Clypeaster* density declined significantly ($p=0.004$) after the 2005 hurricanes. No *Clypeaster* were observed at GK-3 in the July 2006 survey. Sea urchins (*Echinometra* and *Diadema*) were recorded at GK-1 in 2006 (0.3 individuals/m^2), but not in 2005. There was no statistically significant difference in total urchin abundance from 2005 to 2006 (Mann-Whitney U test, $p=0.32$). The urchins were on coral rubble and rocks that were deposited at GK-1 by the 2005 hurricanes.

5.4 Summary

Seagrass and algal communities are important components of the natural resources within DRTO. Their primary productivity may form the basis of food webs that support reef fish assemblages in hardbottom habitats. Recent mapping indicates that seagrass and algal communities in DRTO may be less spatially extensive (approximately 58%) than previously estimated; however a large part of DRTO remains unmapped. Given the importance and connectivity of seagrass communities to coral reef ecosystems, additional mapping is needed to determine the full suite and spatial extents of habitats that exist within DRTO.

Currently, two monitoring programs sample benthic communities in seagrass and algal beds within DRTO. The SERC project monitors 10−15 new sites in DRTO annually as part of a larger project to measure the status and trends of seagrass communities within the FKNMS and to evaluate progress toward protecting and restoring the living marine resources in South Florida. However, data specific to status and condition of seagrass and algal beds at DRTO sites are not readily available to local park managers from the SERC project. For example, SERC has developed GIS-based maps of the abundance and distribution of various seagrasses for the FKNMS (Figure 5.10), but similar maps are not available for DRTO. If developed, maps of DRTO seagrass distribution could be used by park managers to prioritize use within management zones to minimize anthropogenic impacts to seagrasses. Additional information on nutrients, water quality, and other factors that affect seagrass beds should be collected to address questions about changes in spatial distribution, spatial extent, and composition of seagrass habitats over time. Monitoring of nutrients and other water quality parameters as done by the SERC program should be implemented for shallow water areas that are not monitored. Efforts should be made by park staff to leverage information relevant to DRTO needs and mission from existing programs.

DRTO staff recently began monitoring shallow (<3 m [10 ft]) seagrass beds within the RNA and Historical Use/AUZ to determine the effects of hurricanes damage and monitor seagrass recovery from such damage. However, only three shallow, permanent sites have been monitored, which is inadequate to address the objectives for which it was designed, namely detecting hurricane damage and measuring seagrass recovery. Analyses of the data identified significant differences in seagrass abundance among sampling periods, which may have resulted from hurricane damage. However, the three sites are not representative of all seagrass beds within DRTO; the results from this monitoring activity should not be generalized for all seagrass beds in DRTO. Prop scarring and anchor damage from small boats are leading causes of the seagrass decline in South Florida (http://research.myfwc.com/features/view_article.asp?id=3142). It is unknown if prop scarring remains a threat to shallow seagrass habitats at DRTO, but damage should be quantified to determine seagrass damage and recovery from hurricanes. Recently created no-anchor zones should reduce the amount of damage caused by small boat anchors, but not necessarily reduce the damage caused by scarring from boat props. The presence of the Historic Preservation Area within the protected RNA may still expose shallow-water seagrass and algal communities to damage from prop scarring. Additional financial resources and increased monitoring capacity are needed to manage successfully the natural resources in the seagrass and algal communities because they are a vital part of coral reef ecosystems within DRTO. Hopefully, these and other concerns will be addressed in the monitoring protocol developed by SFCN as part of its vital signs monitoring program.

Table 5.1. Spatial extents of mapped habitats in Dry Tortugas National Park estimated from Agassiz (1882), Davis (1982), and FMRI and NOAA (1998). 1 ha = 2.5 ac.

	1882		1979		1992	
Bottom Type	Area (ha)	*% of map area*	Area (ha)	*% of map area*	Area (ha)	*% of map area*
Seagrass	7,053	32%	6,904	30%	4,440	31%
Bare substrate, sand, rubble	13,162	60%	10,892	48%	210	1%
Coral reef, hardbottom	1,736	8%	4,945	22%	9,480	67%
Sub-total	**21,951**	**100%**	**22,741**	**100%**	**14,130**	**100%**
Land	44		46		40	
Unknown					6,400	
Total area mapped	**21,995**		**22,787**		**20,570**	

Table 5.2. Variability in estimates of spatial extent of seagrass in Dry Tortugas National Park. 1 ha = 2.5 ac.

	Continuous seagrass (ha)	**Patchy seagrass (ha)**	**Total (ha)**
Area of seagrass estimated by FMRI and NOAA (1998)	1,731	2,708	4,439
Area of mapped seagrass reclassified as hardbottom by Ault *et al*. (2006a)	995	1,591	2,586
Current estimate of seagrass extent [FMRI and NOAA (1998) - Ault *et al*. (2006a)]	736	1,117	1,853

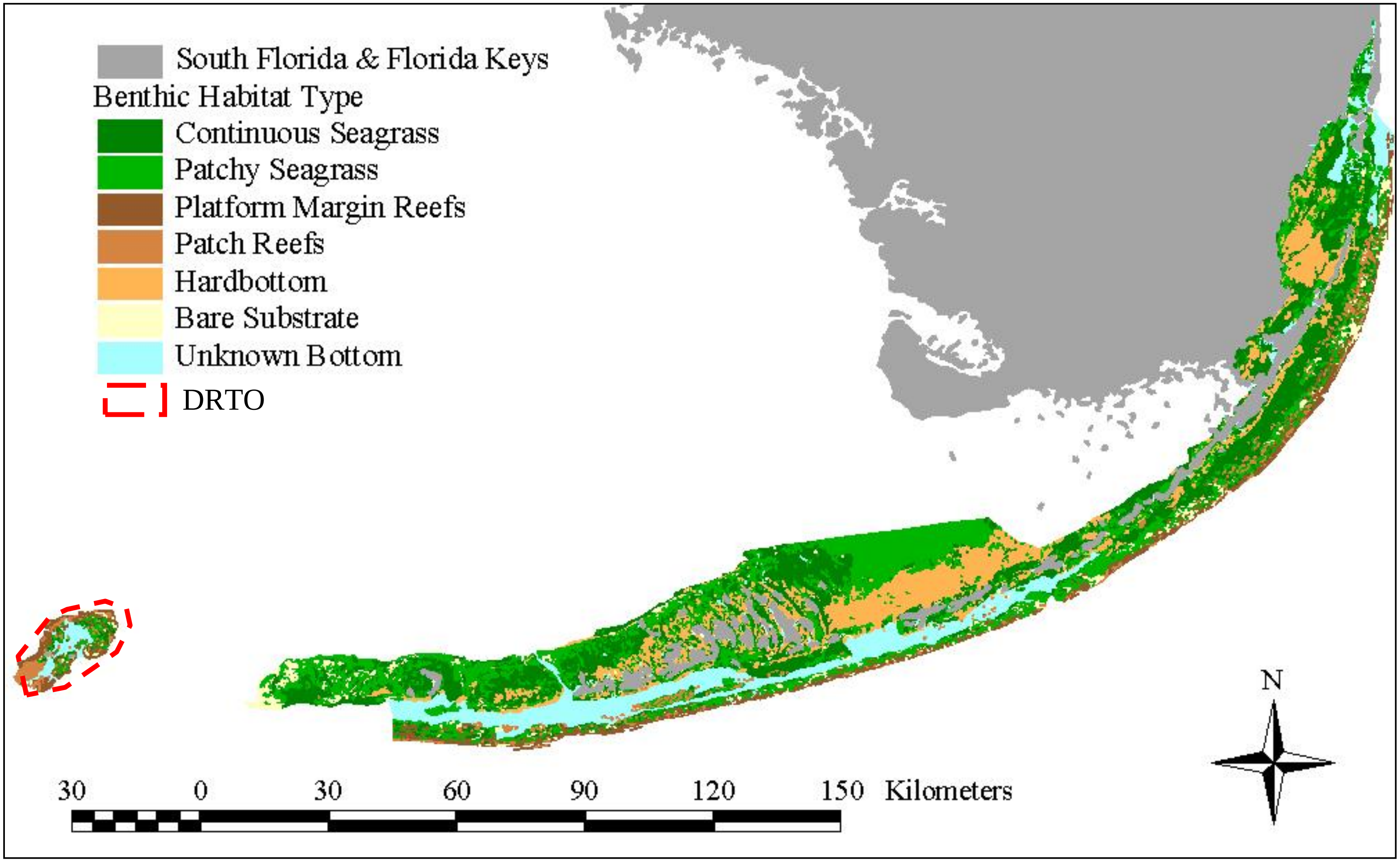


Figure 5.1. Benthic habitats of the Florida Keys and the Dry Tortugas (source: FMRI and NOAA 1998; map: C. Jeffrey).

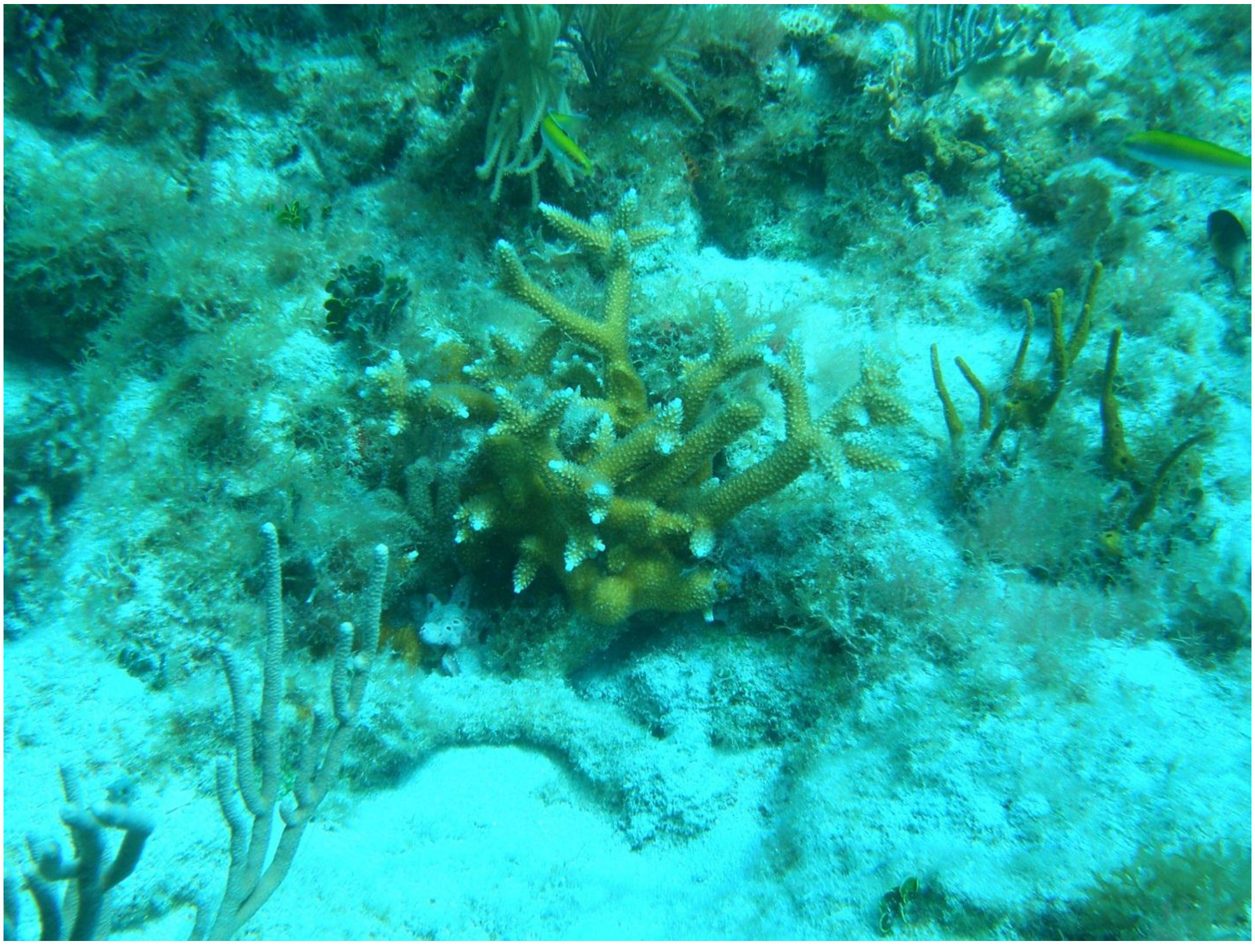


Figure 5.2. Photo of *Dictyota* spp. surrounding staghorn coral (*Acropora cervicornis*) in Dry Tortugas National Park (DRTO) (source: NOAA/NCCOS/CCMA).

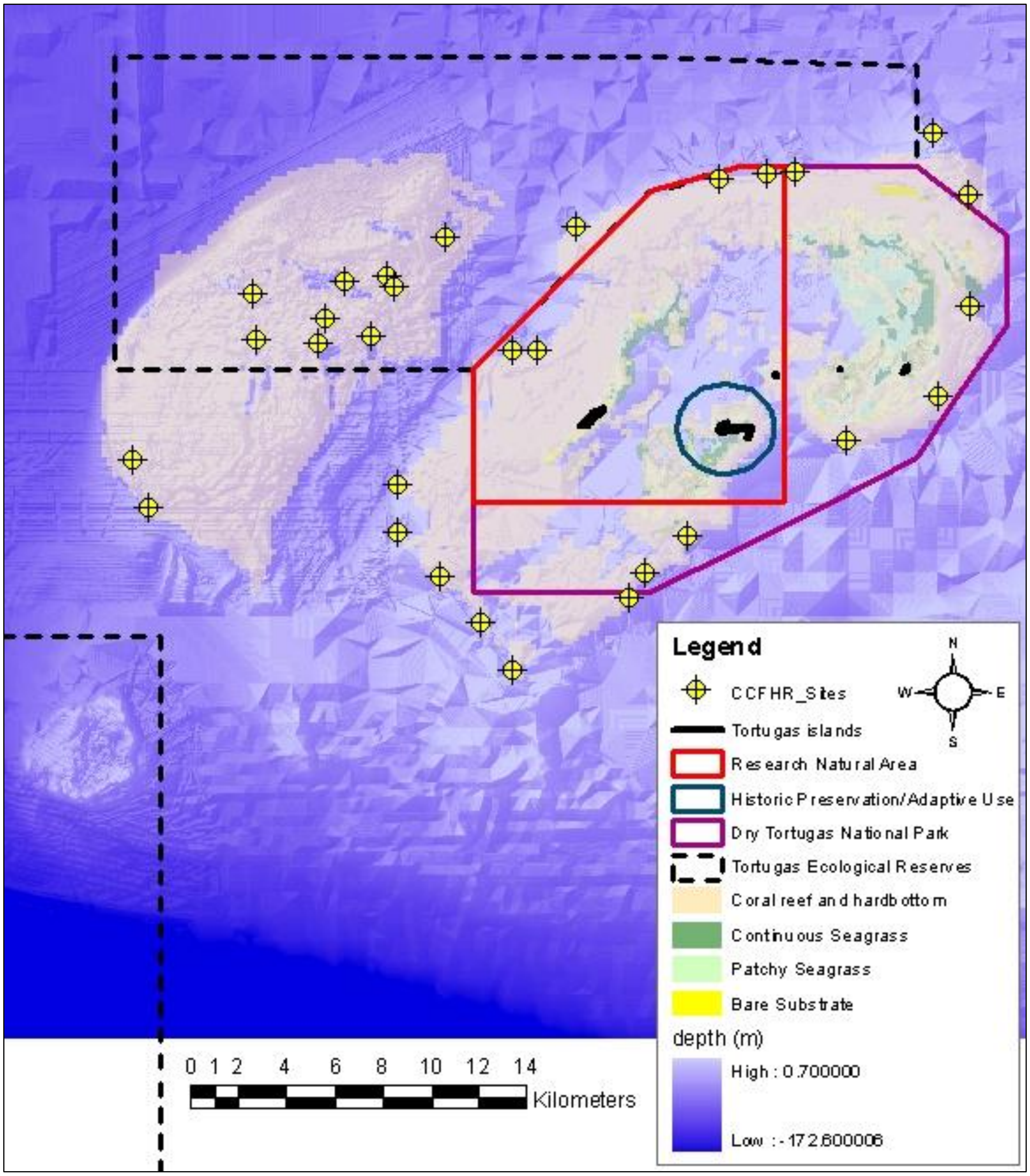


Figure 5.3. Location of Center for Coastal Fisheries and Habitat Research sites along sand- reef interface on Tortugas Bank and along the perimeter of Dry Tortugas National Park (map: C. Jeffrey).

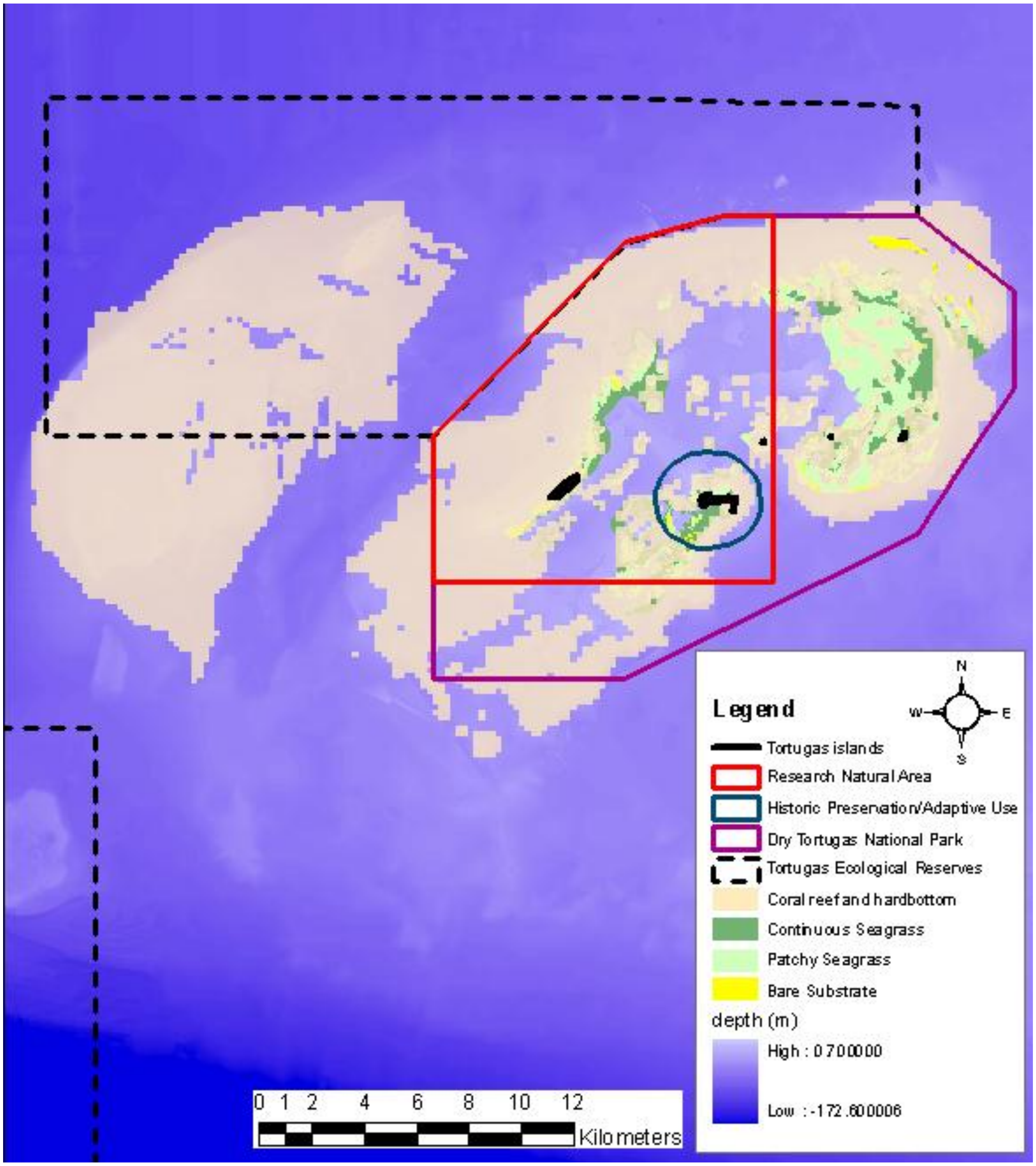


Figure 5.4. Spatial distribution of seagrass beds relative to coral reef and hard bottom areas habitats in the Dry Tortugas National Park (DRTO). Estimated area of seagrass beds in DRTO by zone: Research Natural Area = 333 ha (823 ac); Historic Preservation Area = 155 ha (383 ac); DRTO = 1364 ha (3371 ac); total = 1,853 ha [4,579 ac]) (source: FMRI and NOAA [1998], Ault *et al.* [2006a]).

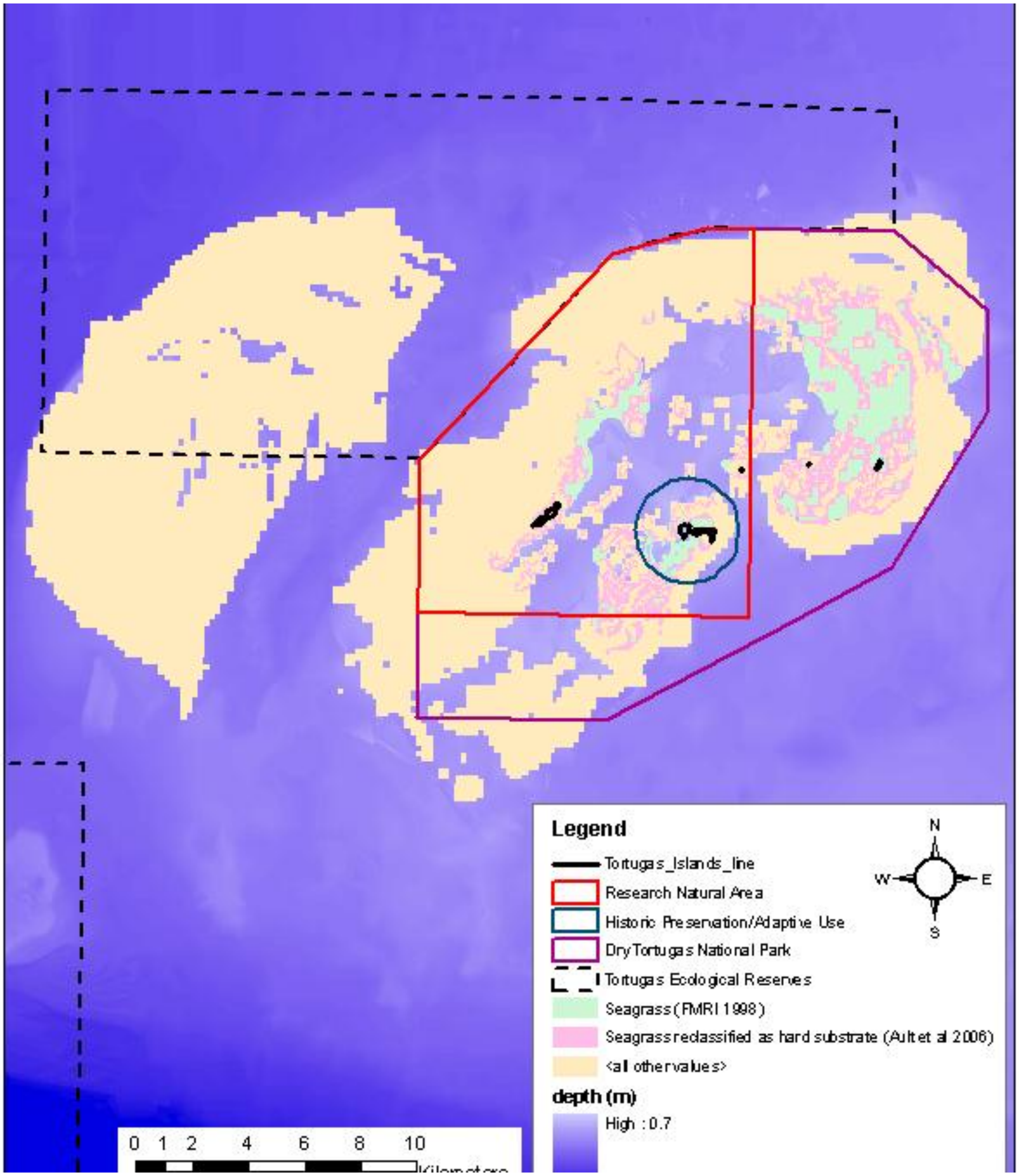
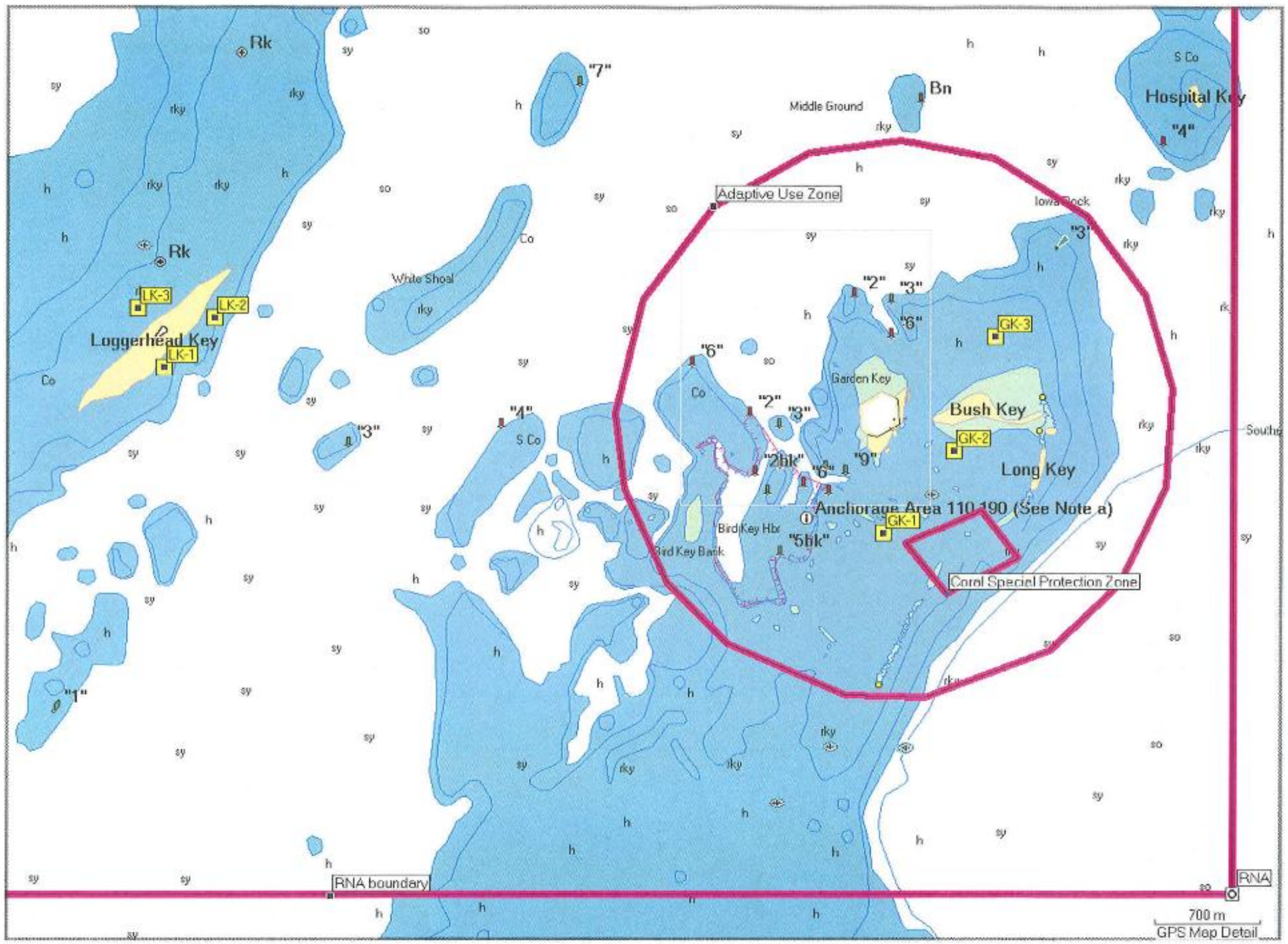


Figure 5.5. Spatial distribution of coral reef and hard bottom, seagrass, and seagrass areas reclassified as coral reef and hard bottom in Dry Tortugas National Park. Estimated area of seagrass beds in the park is 1,853 ha (4,579 ac) (source: FMRI and NOAA [1998], Ault *et al.* [2006a]).



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DRTO Seagrass Assessment Sites

Figure 5.6. Long-term sites (LK 1-3 and GK 1-3) for ecological assessments of seagrass communities at Dry Tortugas National Park (source: D. Morrison).

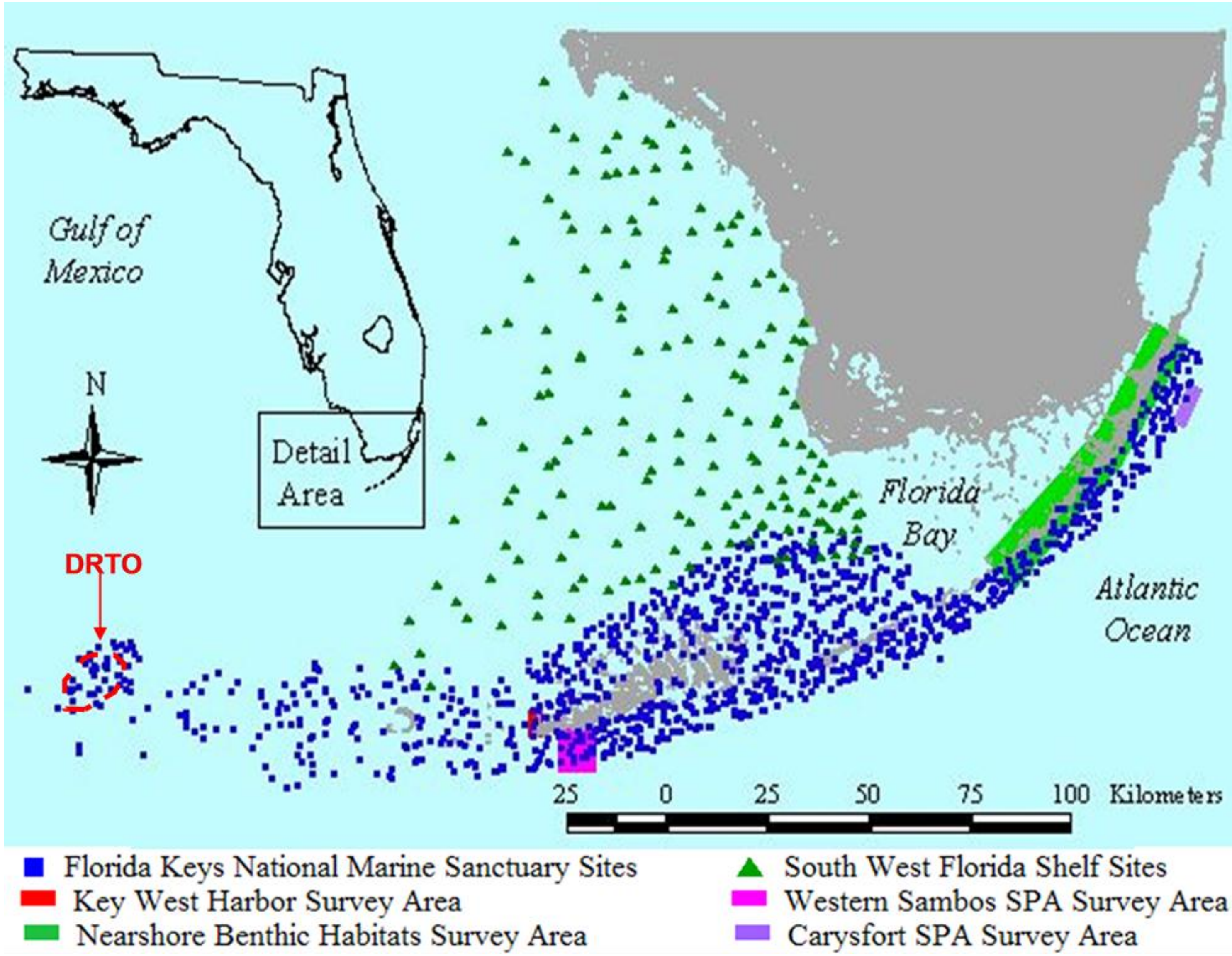
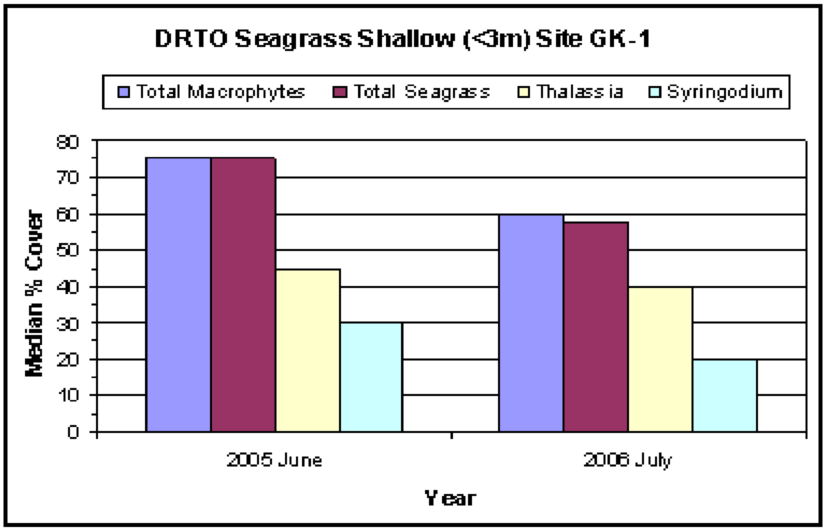
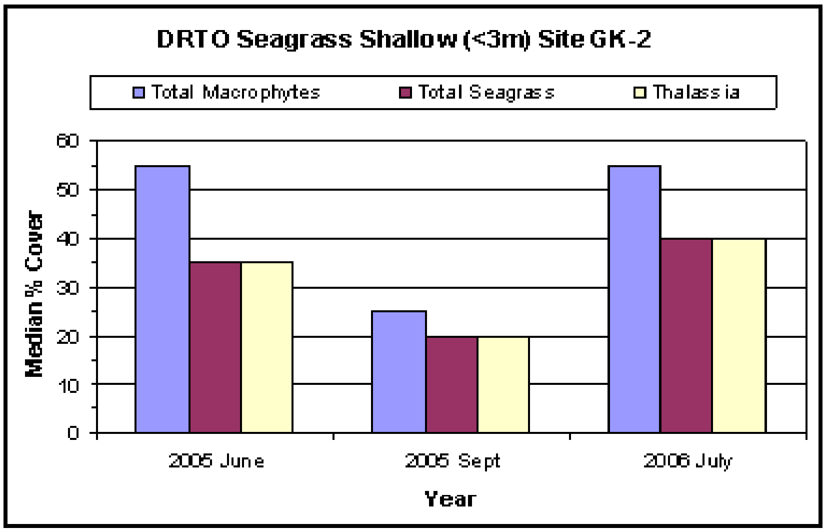


Figure 5.7. Location of sites sampled for seagrasses in the Florida Keys National Marine Sanctuary, 1996−2004 (adapted from Fourqurean and Escorcia 2006; http://serc.fiu.edu/seagrass/!CDreport/DataHome.htm).





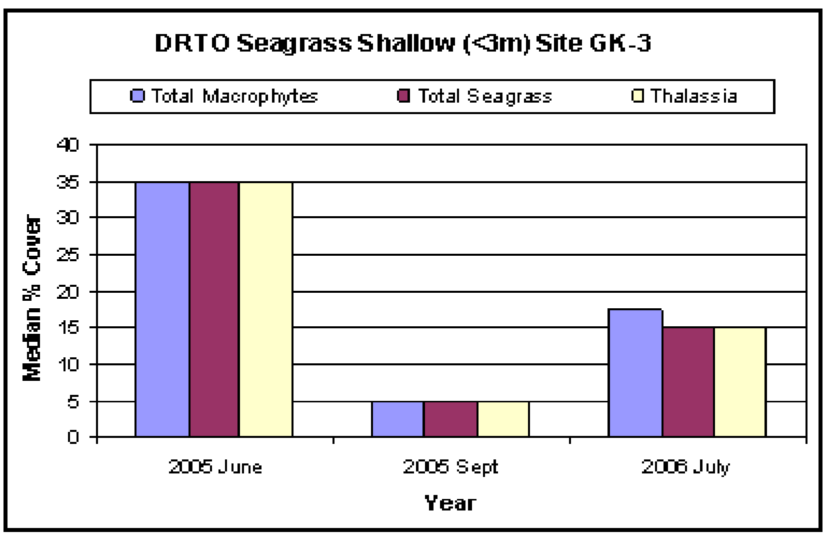
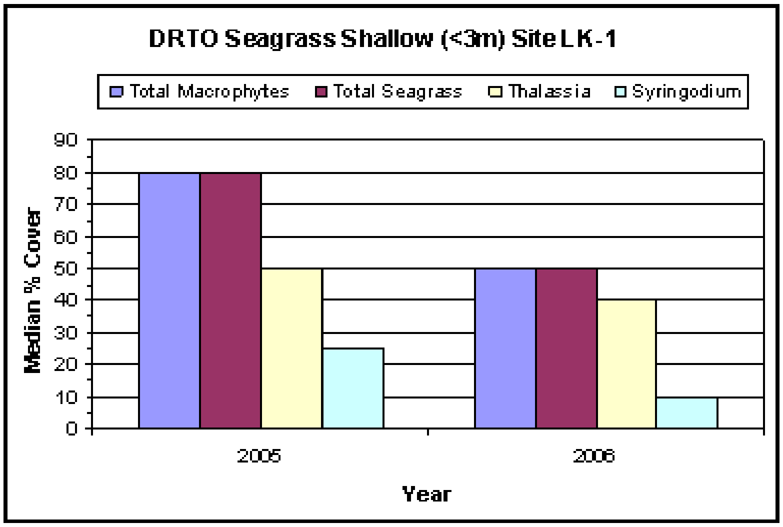
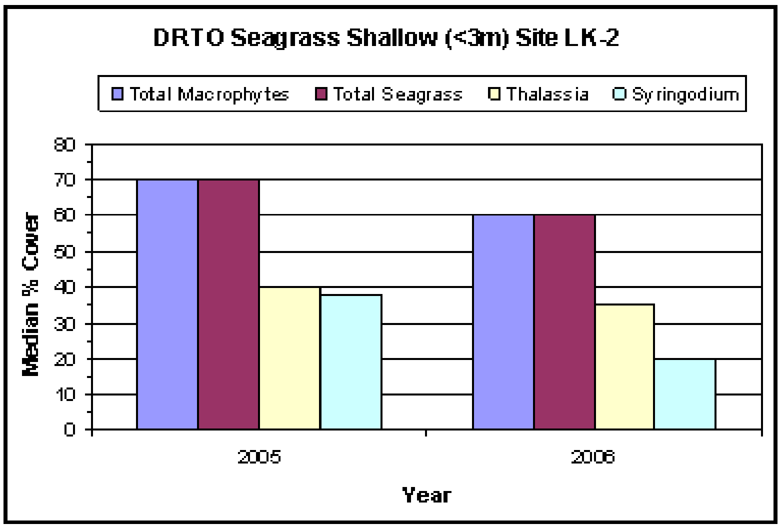


Figure 5.8. Benthic macrophyte abundance (median percent cover) at the shallow (<3 m [10 ft]) seagrass assessments sites near Garden and Bush keys in the Adaptive Use Zone in Dry Tortugas National Park (DRTO).





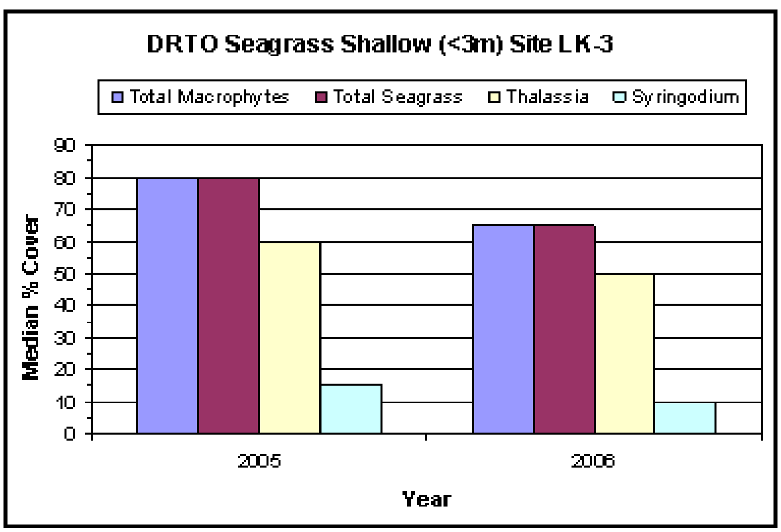


Figure 5.9. Benthic macrophyte abundance (median percent cover) at the shallow (<3 m [10 ft]) seagrass assessments sites around Loggerhead Key in the Research Natural Area in Dry Tortugas National Park (DRTO).

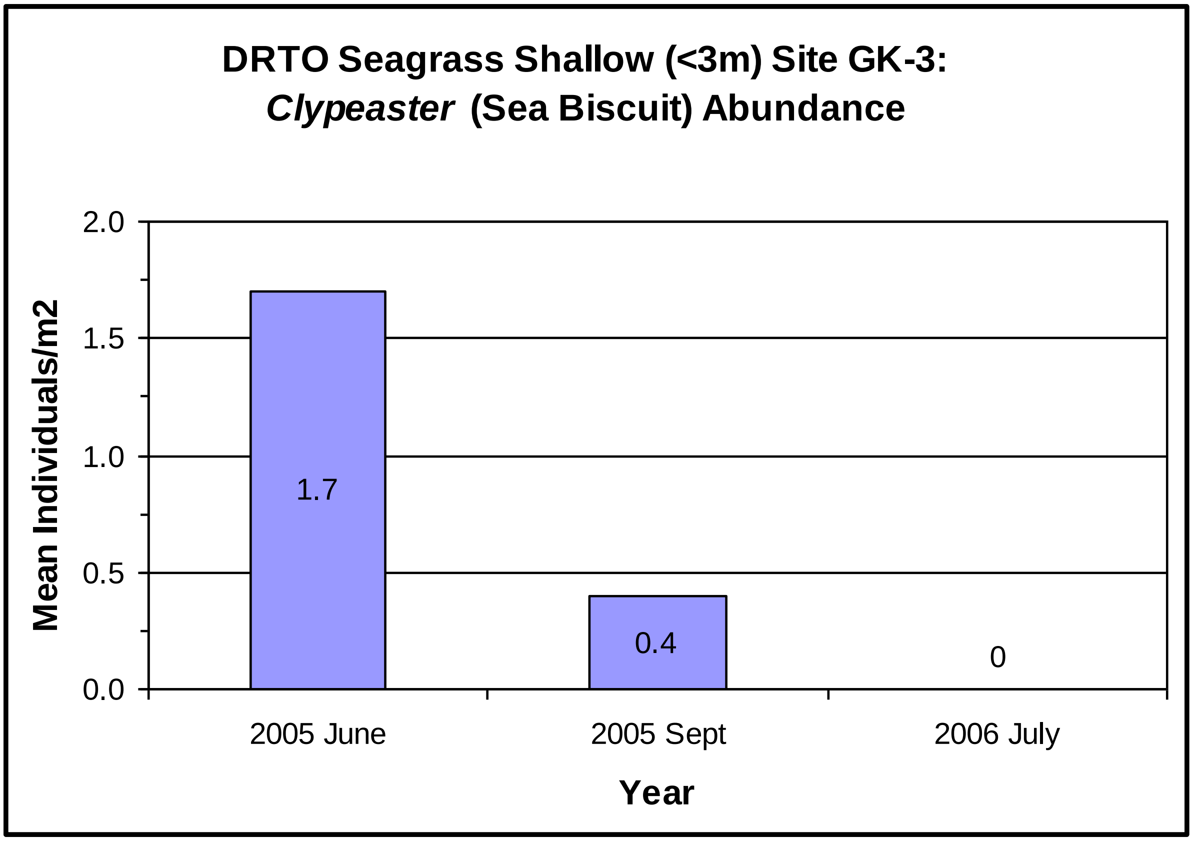


Figure 5.10. *Clypeaster* (sea biscuit) abundance (mean individuals/m^2) at site GK-3 in Dry Tortugas National Park (DRTO). June 2005 before the 2005 hurricanes; September 2005 after hurricanes Dennis, Katrina, and Rita.

Chapter 6: Condition of Reef Fishes and Macroinvertebrates

Christopher F. G. Jeffrey, Vanessa McDonough, Caroline Currin, and Don Field

6.1. Reef Fishes, Fisheries, and Resource Management

Fish assemblages are essential and prominent components of the marine ecosystems in the Dry Tortugas, which contains numerous spawning aggregation sites (Schmidt *et al.* 1999). Fisheries in the Tortugas region include reef fishes (e.g., snapper-grouper complex) (Figure 6.1); invertebrates (conch, lobster, and shrimp); sciaenids (e.g., red drum); and pelagic fish (e.g., Spanish and king mackerels, dolphin fish, and sharks). Of these, reef fish and invertebrate fisheries are the biggest concern to NPS. Fishes are the basis of multibillion dollar fisheries and supply local populations with much needed goods and services, such as food, employment, and recreation (Bannerot 1990, Bohnsack *et al.* 1994, Johns *et al.* 2001). Prior to the establishment of the TERs in 2001, commercial fishing was allowed in the Tortugas region. Back then, 105−110 commercial fishers operated 164 fishing vessels and targeted invertebrates (spiny lobster, shrimp, and stone crabs) that composed 63% of total landings in waters outside the DRTO. Commercial fishers also targeted reef fishes, Spanish and king mackerels (*Scomberomorus maculates* and *S. cavalla* respectively), and sharks. About 85% of commercial fishers in the Tortugas region were full-time fishermen that earned 100% of their income from fishing. However, these commercial fishers also fished elsewhere in the Florida Keys and only earned about 45% of their total income from fishing in the Tortugas region (Leeworthy and Wiley 2000). Although commercial fishing was prohibited within the DRTO in 1935, the activity was a major source of mortality for reef fishes in the Tortugas region until 2001 because many targeted species have home ranges larger than the area protected by the park.

Recreational fishing also occurs in the Tortugas region and is thought to be a major source of mortality for local reef fish assemblages (Ault *et al.* 2005). Recreational fishers include residents of and visitors to the Florida that target mainly reef fish assemblages (Leeworthy and Wiley 2000). Between 1981−1992, reef fishes made up 92% of average total recreational headboat[12] landings in the Tortugas region (Bohnsack *et al.* 1994). Recreational fisheries target about 73 species of reef fish from about six families (groupers and snappers, grunts, jacks, porgies, and hogfish [Ault *et al.* 2005]). Prior to 2001, recreational fishing was permitted throughout the Tortugas region including DRTO. Since 2001, recreational fishing has been disallowed within the TERs, but it has continued within the park and in areas outside the reserves. In 2007, an RNA was established within DRTO that prohibited all fishing within its boundaries. Recreational fishing continues in areas outside the ecological reserves and within the park, but outside the RNAs. The total area of the Tortugas region now closed to all fishing is 685 km^2 (265 mi^2) − 518 km^2 (200 mi^2) in the TERs and 119 km^2 (46 mi^2) in the RNA within DRTO.

The National park Service, Florida Fish and Wildlife Conservation Commission (FWC), and NOAA's National Marine Fisheries Service (NMFS) have jurisdictional responsibilities for managing fishery resources in the Tortugas region. The FWC's Fish and Wildlife Research Institute (FWRI) and NMFS are the primary agencies that compile information on fishery landings in the Tortugas region (Leeworthy and Wiley 2000). NPS has monitored reef fish

[12]Headboats are recreational fishing vessels that carry large groups of passengers that pay as individuals to go fishing (Bohnsack *et al.* 1994).

populations and has conducted creel surveys to determine trends in fish abundance and recreational fishing effort within park boundaries (Schmidt *et al.* 1999). The park has prohibited commercial fishing within its boundaries since 1935. FWC monitors reef fish assemblages within state waters and NMFS monitors reef fish assemblages in federal waters excluding the DRTO. The three management agencies have acted in concert to enact fishing regulations that are compatible across their jurisdictional areas.

6.2. Trends and Patterns in Fisheries Landings and Reef Fish Assemblages

Determining the long-term trends of reef fisheries and reef fish assemblages in the Tortugas region has long been the focus of the three management agencies. Although several factors are known to affect reef fish assemblage structure and biomass, commercial and recreational fishing have been the primary agents shaping reef fish assemblages in the Tortugas region since the 1920s (Bohnsack *et al.* 1994, 2003, Ault *et al.* 2005). Based on landings and fishing effort data, NMFS concluded that sharp declines in recreational landings of reef fishes (e.g., Nassau grouper [*Epinephelus gutattus*] and king mackerel) throughout from the Florida Keys between 1981−1994 correlated significantly with a substantial (500%) increase in registered recreational fishing boats (Bohnsack *et al.* 1994, Ault *et al.* 2005).

In response to observed fishery declines, state and federal management agencies enacted a suite of more than 60 regulations between 1979−1992. Regulations included minimum size limits, seasonal closures, and recreational bag limits to protect fishery species; they also permanently closed fisheries for Nassau grouper, goliath grouper (*Epinephelus itajara*), and queen conch (*Eustromus gigas*) (Bohnsack *et al.* 1994). The regulations and fishery closures were designed to reduce total fishing mortality for targeted reef fishes and stabilize fishery yields. However, the regulations were ineffective in maintaining reef fish populations and rejuvenating local fisheries largely because a species-based approach was being used to manage a multi-species fishery (Bohnsack *et al.* 1994, Ault *et al.* 1998). For example, fishery independent data on reef fishes in the Florida Keys and Tortugas region between 1979−1996 indicate that intense fishing resulted in about 50 reef fishes (snappers, groupers, grunts, jacks, porgies, and hogfish) (Figure 6.2) being harvested unsustainably according to federal overfishing standards (Ault *et al.* 1998, 2005). Several reef fishes in the Florida Keys were serially overfished because stocks of large and desirable species (e.g., goliath, red, and black groupers) were depleted and had become rare (Ault *et al.* 1998). The spawning stock biomass of black grouper was <10% of its historic size (Ault *et al.* 2005) and the average size in 2001 was 40% smaller than its average size in 1940 (Ault *et al.* 2001). Traditional fishery management measures were not successful in halting the demise of reef fish and invertebrate populations in the Florida Keys and Tortugas region.

6.3. Ecosystem-based Approaches to Rebuilding and Monitoring Reef Fish Assemblages

The Sanctuary Preservation Areas (SPAs) and the Ecological Reserves within FKNMS and the RNA within DRTO (hereafter no-take reserves) were implemented as refugia from fishing to rebuild reef fish populations in the Florida Keys and Tortugas region. Implementation of fully-protected areas was a substantial departure from previous management approaches used in the Florida Keys and were established as an ecosystem-based approach to reduce the negative effects of fisheries on reef fish assemblages. No-take reserves offered protection from extractive and destructive human activities to all ecosystem components within their boundaries. Expectations were: (1) over time, the SPAs and reserves would see significant increases in abundance and biomass of several reef fishes exploited throughout the Florida Keys, and (2) continued increases in abundance and biomass above some threshold would result in future export of fishery resources from reserves to adjacent unprotected areas via either larval dispersal or adult fish movements (Bohnsack 1998, Roberts *et al.* 2001, Ault *et al.* 2005). The expectation of larval dispersal from no-take areas in the Tortugas region to the Florida Keys was not unrealistic because the Tortuga region is upstream from the rest of the Florida Keys (Lee *et al.* 1999, Domeier 2004).

Determining the efficacy of no-take areas in rebuilding reef fish populations and protecting ecosystem components has been a goal of monitoring and research programs in the Florida Keys and the Tortugas region. Since 1999, a multidisciplinary team of scientists[13] integrated fishery-related information with data on biological, oceanographic, and habitat components of ecosystems within a Fishery Systems Science (FSS) framework to understand reef fisheries and to evaluate performance of reserves in the Florida Keys and the Dry Tortugas region (described in Ault *et al.* [2005]). The FSS framework uses age-structured stock production models to describe spatial and temporal dynamics of reef fish assemblages and to identify impacts of fishing on selected reef fish populations. Impacts of fishing on reef fishes are determined by comparing demographic metrics[14] derived for a surveyed reef fish population against federally mandated minimum standards (Ault *et al.* 2005). If the derived metrics for the surveyed reef fish population are below the minimum standard, the population is considered overfished.

At the core of the FSS framework is a monitoring program that uses synoptic visual surveys within a stratified random sampling design to assess the occurrence, abundance, and spatial distribution of reef fishes, lobsters, and stony corals on hardbottom habitats in the Florida Keys and the Tortugas region (Ault *et al.* 2005). Data from the visual surveys provide unbiased demographic estimates of organisms to identify impacts of fishing on reef fish populations as described previously (Ault *et al.* 1998, 2003, 2005); to help design the location and implementation of no-take fishery reserves (Meester *et al.* 2001, 2004, Ault *et al.* 2006a, 2007); and to evaluate the efficacy of no-take reserves (Ault *et al.* 2006a, 2007). Data collected include the average size and abundance of reef fish individuals by species as well as a suite of environmental variables that characterize the types and composition of hardbottom habitats (Franklin *et al.* 2003, Ault *et al.* 2005, Miller *et al.* 2006). The environmental variables are used as covariates in statistical models that describe spatial and temporal patterns in the abundance of reef fishes, lobsters, and stony corals (Ault *et al.* 2005). Environmental variables are used to characterize, map, and assess the condition of benthic communities in the region (Franklin *et al.* 2003, Miller *et al.* 2006). The following section reviews the major findings of the FSS framework for DRTO, which were summarized from Ault *et al.* (2006a,b[15], 2007). Details of the

[13]The institutions involved are the University of Miami, Rosenstiel School of Marine Science; National Marine Fisheries Service; University of North Carolina, National Underwater Research Center; Florida Fish and Wildlife Conservation Commission; and the National Park Service, South Florida/Caribbean Network.

[14]Examples of derived metrics are Yield-Per-Recruit and Spawning Potential Ratio. Yield-Per-Recruit is the expected lifetime yield of a cohort relative to the annual recruitment of newborns, given a known rate of fishing mortality and age or size of minimum capture. Spawning Potential Ratio is the expected lifetime spawning biomass of a population cohort relative to expected or known unexploited spawning biomass, given a rate of fishing mortality and age or size of minimum capture (Ault *et al.* 2005).

[15]In Menza *et al.*, 2006.

sampling design, survey methods, and statistical analyses for the FSS framework are given in several publications (Table 6.1).

6.4. Status and Trends of Coral Reef Fish Populations, 1999–2006

Ault *et al.* (2007) described several metrics of reef fish populations obtained from visual surveys conducted during 1999−2000, 2002, 2004, and 2006. Metrics were calculated for eight commercially important (fished or exploited) species and 14 non-fished species (Table 6.2). Derived metrics from the surveys conducted during 1999−2000 were considered the baseline condition to which metrics from subsequent years were compared to determine statistically significant biennial trends in the selected reef fish populations. Biennial trends were determined for the entire domain (DRTO) and two strata – inside and outside the RNA (Figure 6.1). Because the RNA was established in 2007, all metrics from surveys conducted before 2007 represent baseline conditions for determining future benefits of the RNA. Derived metrics were species richness (all species and the snapper-grouper complex) as well as frequency of species occurrence and mean density of selected exploited and non-exploited fishes.

Ault *et al.* (2006a) reported spatial and temporal patterns for reef fish populations in DRTO. Reef fish biodiversity was greatest in highly rugose habitats and populations of exploited and unexploited species within the RNA were similar to those found in adjacent non-RNA habitats. They observed no significant increase or decrease in mean species richness over time within DRTO for most years, except in 2006, when species increased to 39.9±0.8 species ($p<0.001$) from the 1999−2000 baseline of 34.6±0.9 species (Ault *et al.* 2006a). Mean species richness of the snapper-grouper complex increased significantly from the 1999−2000 baseline of 7.6 ±0.3 species to 8.3 ±0.3 species in 2002 ($p<0.01$) and 8.2±0.2 species in 2006 ($p<0.05$). Species richness was relatively stable between 1999−2006 inside and outside the RNA. The temporal pattern in species richness inside and outside the RNA was similar to that observed for the park.

Temporal trends in the mean frequency of occurrence of exploited species within the park were variable over time and among species. Six of eight exploited species showed either a significant increase or decrease in frequency of occurrence over time (Ault *et al.* 2006a). The occurrence of black grouper at sites increased from 25.8±3.7 sites in 1999−2000 to 35.7±4.9 sites in 2002 ($p<0.05$) and 36.7±3.2 sites in 2004 ($p<0.01$), but decreased to 24.0±3.1 sites in 2006 ($p>0.05$). The mean occurrence of mutton snapper at sites progressively increased from the baseline of 14.8±3.2 sites in 1999−2000 to 24.4±5.1 sites in 2002 ($p>0.05$) to 26.4±3.1 sites in 2004 ($p<0.01$) and to 30.2±4.5 sites in 2006 ($p<0.01$). The red grouper occurred at significantly fewer sites in 2006 (55.0±4.4 sites, $p<0.05$) compared with 1999−2000 baseline of 63.9±4.2 sites. Hogfish (*Lachnolaimus maximus*) showed a significant decline in frequency of occurrence at sites in 2002 and 2004 ($p<0.05$) compared with the 1999−2000 baseline estimate. The decrease in site occurrence was progressively smaller every two years; by 2006, the difference from the baseline estimate was not significant (Ault *et al.* 2006a). Interestingly, more exploited species on average had lower site frequencies than non-exploited species, but it is uncertain whether that pattern is real or a function of the species selected for analysis. Four of eight of the exploited species occurred at 50% or more of surveys sites, whereas seven of 14 non-exploited species reported by Ault *et al.* (2006) occurred at 50% or more of the sites.

Ten of 14 non-exploited species showed either a significant increase or decrease in proportion of sites at which they occurred over time (Ault *et al.* 2006a). Non-exploited species that showed a significant increase ($p<0.05$) in percent occurrence included ocean surgeonfish (*Acanthurus bahianus*), bluehead wrasse (*Thalassoma bifasciatum*), purple reef fish (*Chromis scotti*), spotted goatfish (*Pseudupeneus maculatus*), and cocoa damselfish (*Stegastes variabilis*). The spotfin butterflyfish (*Chaetodon ocellatus*) was the only non-exploited species that showed a significant decrease in its occurrence at sites in 2006 ($p<0.01$) compared to the 1999−2000 baseline. The redband parrotfish (*Sparisoma aurofrenatum*) initially decreased in mean percent site occurrence in 2002 ($p<0.01$), but by 2006, percent site occurrence increased and the difference relative to 1999−2000 was insignificant ($p>0.05$).

Four of eight exploited species analyzed by Ault *et al.* (2006a) either increased or decreased significantly above or below 1999−2000 baseline estimates. Domain-wide estimates of black grouper and yellowtail snapper (*Ocyurus chrysurus*) initially increased significantly in 2002 and 2004 ($p<0.05$), then decreased and by 2006, the increase above the 1999−2000 baseline was no longer significant ($p>0.01$). Mutton snapper showed an increase in density in 2004 and 2006 ($p<0.01$). Mean density of white grunt initially decreased in 2002 ($p<0.05$), but returned to baseline estimates in 2004 and 2006. Purple reef fish consistently increased in mean density above the 1999−2000 estimates.

Ten of 14 non-exploited species showed significant increases or decreases in mean densities compared to the 1999−2000 baselines ($p<0.05$). Mean densities of ocean surgeonfish, bluehead wrasse, spotted goatfish, gray angelfish (*Pomacanthus arcuatus*), purple reef fish, and cocoa damselfish in 2006 were significantly higher than 1999−2000 densities. Blue tang (*Acanthurus coeruleus*) and stoplight parrotfish (*Sparisoma viride*) initially increased in density ($p<0.05$), but their abundance reverted to baseline levels by 2006. Mean densities of spotfin butterflyfish and blue angelfish (*Holacanthus bermudensis*) decreased significantly below the baseline by 2006. Mean densities of foureye butterflyfish (*Chaetodon capistratus*), bicolor damselfish (*Stegastes partitus*), striped parrotfish (*Scarus iseri*), and redband parrotfish) also varied over time, but were not significantly different from baseline estimates ($p>0.05$).

In summary, Ault *et al.* (2006a) tracked temporal variation in reef fish metrics based on the statistical covariance between reef fish abundance and coral reef-habitat types to determine the status and trends of reef fish populations in DRTO. Using similar data and analytical techniques, Ault *et al.* (2005, 2007) characterized reef fishes and tracked their temporal trends in the TERs and the wider Tortugas region, and the FKNMS to evaluate the effectiveness of no-take reserves and other management approaches in rebuilding reef fish populations. In general, the spatial and temporal trends observed in reef fish populations within the park mirrored those observed in the TER and wider Tortugas Ecological region and the Florida Keys. The Tortugas region likely experienced an increase in the biomass of exploited species within a few years of implementation of the TER. This early increase is typical of marine reserves, although full recovery of reef fish populations is expected to take decades (Russ and Alcala 2004). Ault *et al.* (2006a, 2007) found significantly greater abundance, frequency of occurrence, and shifts toward larger sizes of black and red groupers and mutton snappers in the Tortugas North Ecological Reserve (TNER) and throughout the Tortugas region within 4−6 years of its establishment. They did not find any significant declines in the abundance of exploited species within the TER. Reef fish populations in the park may have benefited from the protection offered by the adjacent TER.

Other factors may have contributed to enhanced reef fish populations in the Tortugas region. Spatial and temporal trends observed within the park and the Tortugas region could have resulted from previously enacted management actions acting synergistically with reserve implementation. Increased minimum size limits, reduced bag limits, and other management actions that reduced fishing mortality on some reef fish populations could have augmented the protection offered by area-closures, and ultimately could have increased the abundance of exploited species in the park and throughout the Tortugas region. Reef fish populations in the park and surrounding region may have been positively or negatively affected by environmental conditions and episodic disturbances, such as hurricanes, which may have randomly affected recruitment of exploited and unexploited species in any given year. Such random environmental variation may be a logical explanation for the varied trends in reef fish abundance and biomass observed in the Tortugas region.

6.5. Biogeographic Characterization of Reef Fish Assemblages

6.5.1. Background

The monitoring studies described in Chapter 6.4 focused on reef fish populations in hardbottom habitats. These studies have not characterized or monitored trends in fish assemblages occurring in unconsolidated habitats. Fishes inhabiting coral reefs and hard substrates do not exist in isolation, but interconnect adjacent habitats through their movements. Reefs occur within a mosaic of habitats that are used by fishes through daily home range movements and ontogenetic habitat shifts. For example, some species of snappers and grunts move among adjacent habitats on diurnal migrations during which they feed in seagrass beds at night and return to the reefs during the day (Meyer *et al.* 1983). Other fishes recruit and settle in mangroves and shallow seagrass beds and migrate out to reefs in deeper water at more advanced life stages (Parrish 1989, Dorenbosch *et al.* 2006, Mumby *et al.* 2006). Unconsolidated substrates (seagrass beds and sand plains) are important to reef fishes; demographic interactions within and among these habitats are critical ecological processes that contribute to the overall health of coral reef ecosystems.

Coral reefs and hardbottom substrates in the Tortugas region are prominent and extensive benthic features, but sandy plains and seagrass beds have larger spatial extents. In 2001, NOAA’s Center for Coastal Fisheries and Habitat Research (CCFHR) began a suite of biogeographic studies to examine the effects of the TER on reef fish assemblages and benthic organisms at reef-sand interfaces (Burke *et al.* 2004). A major premise of the studies is that energy flow across reef-sand boundaries is critical to understanding reef function. Previous work by CCFHR on the west Florida shelf suggests that benthic primary production is the major energetic source supporting regional fish biomass (Currin *et al.* 2000). The studies are ongoing and focus on the spatial patterns in fish assemblage structure near the reef-sand interface to detect a reserve effect and to determine trophic energy flows among habitats (cf. Chapter 4).

6.5.2. Methods

Divers from CCFHR concurrently conducted visual surveys of fishes and collected data on benthic communities annually along two 30-m (98-ft) transects perpendicular to the interface − one into the sand and one onto the reef. Thirty permanent stations located along the reef-sand interface between 15−32 m (49–105 ft) deep were selected for sampling. The stations were randomly selected in 2001 and were revisited annually. Ten stations were established in each of three strata – reserve (in TER), park (in DRTO), and unprotected areas outside the reserve and park. Sites within each stratum were equally allocated on either side of the predominant direction of current flow across the banks (Figure 6.2). Data on the fish abundance, size, and species composition were collected and used to describe similarities and differences in reef fish assemblages among sampling strata during 2001−2005. Several metrics were calculated to (1) describe spatial and temporal trends in species abundance, sighting frequencies, and assemblage composition, and (2) identify fish-habitat relationships at reef-sand interfaces. Details on the sampling, statistical methods, and results of CCFHR monitoring studies are described in Burke *et al.* (2004).

6.5.3. Trends in Species Abundance, Size, and Assemblage Composition

The CCFHR data indicate that only a few species varied significantly among years in abundance at sand-reef interfaces between 2001−2005. Hogfish and red grouper increased in abundance across all strata, but the mean number of individuals per sample did not vary significantly among years. Interestingly, the mean abundances of two exploited[16] species – white grunt [*Haemulon plumierii*]) and yellowtail snapper – were significantly higher in 2004 and 2005 than they were in 2001 (Table 6.3). The other exploited and non-exploited species did not vary significantly among years. The CCFHR study, which focused on a much smaller spatial scale, did not find any differences in size structure of red or black grouper among the different management zones (Table 6.3).

In general, ranked abundance and sighting frequencies of reef fish species at reef-sand interfaces were similar among sampled strata; about 16 of the 25 most abundant species were observed in all three strata (Tables 6.4 and 6.5). The three strata were similar in species richness, species diversity, and in the number of exploited species (five to seven) that ranked among the 25 most abundant and most frequently sighted species (Tables 6.4 and 6.5). There was an annual increase in sighting frequency or percent occurrence for mutton snapper, gray snapper and hogfish at reef-sand interfaces between 2001−2005. Sighting frequency of red grouper did not vary significantly among years.

Analysis of size-frequency distributions suggest that the size structure of several species at reef-sand interfaces may vary spatially and temporally (Table 6.6). CCFHR reported that increasing numbers of larger black groupers were observed during later years, but that smaller red groupers (20−45 cm) were significantly more abundant in later compared with earlier years (Burke *et al.*, 2012). These differences may be due to recruitment variability, variable fishing pressure, and variable resource availability over space and time.

CCFHR reported significant spatial and temporal patterns for a few metrics that quantified assemblage composition. Species richness (the number of species per unit area) correlated positively with benthic rugosity; reef-sand interfaces with more complex benthic reefs supported higher-diversity fish assemblages than reefs with lower benthic rugosity. Species richness, species diversity (Shannon's H) and total fish abundance varied significantly among years ($p<0.05$), but not among strata or between current exposures ($p>0.05$). Multidimensional plots of

[16] 'Exploited' fish represent species subject to recreational and commercial fishing pressure, and include those species in the South-Atlantic Snapper-Grouper complex. 'Unexploited' species are species not traditionally targeted by recreational or commercial fishing, and include fishes such as damselfish, small wrasses and parrotfish (Ault *et al.* 2007, Jeffrey *et al*. 2012).

species presence and abundance resulted in better segregation of sites based on the year of data collection rather than based on sampling strata or current exposure, which further confirms that there was greater variation in species composition among years than among strata or between current exposures. Multidimensional plots did segregate park sites from those of other strata, which suggest that reef fish assemblages at DRTO may be different from assemblages outside the park (Burke *et al.*, 2012).

6.6. Snapper-grouper Spawning Aggregations

Mutton snapper (*Lutjanus analis*) spawning aggregations occur at Riley's Hump within the Tortugas South Ecological Reserve (TSER) and were described by Burton *et al.* (2005). Although Riley's Hump is not under NPS jurisdiction, protection of that location is important for reef fish assemblages, such as groupers and snappers, whose home ranges may encompass the entire Tortugas region. Burton *et al.* (2005) describe one possible effect of the TSER on fish spawning behavior. Aggregations of mutton snapper were observed annually from 1999−2004 at 15 stations to document abundances and behavior of aggregating fishes. Several visual surveys along 30-m (98-ft) transects were completed annually at 15 stations. Ten stations were sampled from 1999–2004; five sites were added in 2002 and surveyed through 2004. The abundance and behavior of mutton snapper and lunar phase were recorded for each transect. Detailed methods can be found in Burton *et al.* (2005).

Burton *et al.* (2005) reported that spawning aggregations appear to be increasing in the Riley's Hump area. They observed that more mutton snapper were aggregating and were becoming less wary of divers, a condition commonly observed in spawning individuals that might otherwise be solitary and wary of diver presence. One hypothesis is that the increased number of mutton snapper aggregating at Riley's Hump was due in part to the increased protection from fishing afforded to the mutton snapper by the TSER that was implemented in 2001. In 1999, sightings of solitary mutton snapper were reported for 27% of the surveys. In 2000, frequency of mutton snapper observations increased to 83% of surveys, but all sightings were still only of solitary individuals. Individuals observed in 1999 and 2000 demonstrated diver-avoidance behavior typical of non-spawning fish. In 2001, a tightly packed group of 10 individuals was observed at one station. In 2002, 75−100 mutton snapper swimming in a tightly packed group were observed at the same station as 2001. In 2003, a group of 75−100 mutton snapper was observed at the same station, but this time they were widely dispersed and showed more extreme diver-avoidance behavior. In 2003, another widespread aggregation of 200 mutton snapper was observed at a different station; by 2004, that aggregation had increased to 300 individuals. The large aggregations observed in 2003 and 2004 comprised actively swimming mutton snapper that appeared unwary of divers. Surveys of the aggregation occurred during the day whereas spawning activity typically occurs at dusk; spawning was not witnessed. However, the large groups observed in 2003 and 2004 are assumed to be spawning aggregations based on fish behavior, moon phase (1−2 days after the full moon), and location.

The evidence provided by Burton *et al.* (2005) suggests that spawning aggregations are beginning to rebuild at Riley's Hump. Although the numbers of mutton snapper observed do not rival the anecdotal descriptions of their abundance during previous peaks of exploitation, the documented increase in both occurrences of aggregations and numbers of aggregating mutton snapper provide encouraging evidence that the mutton snapper stock may be recovering and increasing spawning activity. These data further suggest that the implementation of the TSER may be protecting and increasing the numbers of mutton snapper in the region. An increase in the abundance and spawning activity of mutton snapper at Riley's Hump could enhance future recruitment to the Tortugas region, which means that shallow-water habitats within the DRTO are even more important as potential nursery areas for new recruits.

6.7. Characterization of Reef Fish Trophic Structure

CCFHR also has been characterizing the trophic structure of reef fish assemblages in the Tortugas region by collecting and analyzing the composition of stable carbon (C) and nitrogen (N) isotopes in the tissues of fish, phytoplankton, benthic microalgae, benthic macroalgae, seagrass, and crustaceans (crabs and shrimp). The objective of the work was to estimate the contribution of benthic primary production to fish and shellfish on the reefs. Food web analysis uses the distinct isotope characteristics of primary producers, and the fact that consumers accurately reflect the isotopic signature of their diet, to estimate the contribution of food sources in animal diets (DeNiro and Epstein 1991, Takai *et al.* 2002). Phytoplankton, which are the only source of primary production in the water column, have $\delta^{13}C$ values between -17–-21‰, and can be distinguished from all benthic primary producers, which have average $\delta^{13}C$ values ranging between -7.5‰ (seagrass) to -15.2‰ (benthic algae). N isotope values of primary producers show less variability, with mean values between 2‰ (coral) and 5.7‰ (phytoplankton; Figure 6.3).

Dual isotope plots of over 200 fish and invertebrates, including groupers, snappers, flounders, and shrimp collected from the TER revealed relationships between consumers and primary producers (Figure 6.3). Nearly every fishery organism had a $\delta^{13}C$ that was enriched compared to phytoplankton and the average value of all fish was -15.4‰. Fish relying exclusively on phytoplankton should have $\delta^{13}C$ between -16.8 and -17.8‰, depending on their trophic level and fractionation factors. A simple mixing model comparing pelagic production and a pooled value for benthic primary production suggests that well over half of the fishery production in the TER is provided by corals, benthic algae, and/or seagrass. For some organisms, the reliance on benthic production is much higher. Lane snapper, hogfish, white grunt, and blue runners have $\delta^{13}C$ greater than -15‰, indicating substantial reliance on benthic primary production. In contrast to results from the West Florida Shelf, stable isotope analyses did not indicate a strong trophic contribution of seagrass primary production to shrimp diets (Burke *et al.* 2004, Fonseca *et al.* 2006). N isotope values indicate three to four trophic levels separate herbivores (shrimp and parrotfish) from top predators (snapper and grouper) (Figure 6.3).

An important role for benthic algae in fishery production in shallow marine waters is supported by modeling and stable isotope analysis of food webs (Okey *et al.* 2004, Takai *et al.* 2002). Benthic production is an important part of the fisheries food web in the Dry Tortugas, as are corals. Overlapping end member $\delta^{13}C$ values of corals and algae make it difficult to distinguish between the groups with stable isotope analysis.

6.8. Drifter Studies

Drifters were released from Riley's Hump in 2000–2001 with the objective of predicting the fate of larvae spawned over the area. Drifter movement was variable; drifters dispersed from Riley's Hump to the West Florida Shelf, the Florida Keys, and the East Florida Shelf (see Burke *et al.* 2004 for details). The results suggest that Riley's Hump (within TSER) is likely an important source of larvae for a wide area (Burke *et al.* 2004, Domeier 2004). Planktonic fish larvae also were collected with Bongo nets towed along transects radiating away from Riley's Hump. The samples have not been sorted and identified, but when complete, the results will provide estimates of spawning activity and spawning intensity at Riley's Hump and a better understanding of dispersal of from Riley's Hump to other areas of the Dry Tortugas.

6.9. Summary

CCFHR's involvement in the Dry Tortugas region, particularly in the biological effects of the TER and DRTO, includes reef fish distributions, movements, and abundances; reef fish trophic structure; spawning aggregations and larval export; spillover of individuals into the greater Dry Tortugas region and waters of the southeastern U.S.; and characterization of benthic faunal assemblages in protected and unprotected areas (Table 6.7). Although each of the component studies provides useful information, an integrated view of their findings suggests that reef fish assemblages in the Tortugas region may be rebounding and that management actions, including implementation of reserves, may be having net positive effects on fishery resources. One of the most obvious reasons to establish a marine protected area (MPA) like TER is to provide a 'haven' for those species and habitats that are vulnerable to over-exploitation and resource depletion. Theory predicts that within MPA boundaries, biota should demonstrate positive responses to protection, including higher abundance and biomass, larger size of target species and individuals, and more intact/undisturbed habitats as a result of limiting or preventing fishing (Russ *et al.* 2005). Areas surrounding the MPA may experience reduced abundances, biomass, and/or diversity, smaller individuals, and/or reduced quality habitat as a result of displacing fishing effort from the reserve and concentrating it in areas open to fishing (Halpern *et al.* 2004, Stump 2005). The CCFHR studies suggest that TER has a diverse and abundant reef fish community and that conditions of reef and benthic fish communities have improved compared to unprotected or less-protected areas around TER. For example, CCFHR data indicate that many reef-fish species, particularly exploited species, have larger abundances, total biomass, and/or sizes in the reserve compared to other management strata. Trawling data indicate that benthic communities are benefiting from the protection of the reserve; the benthic community within TER appears to be more abundant and diverse than in areas subject to shrimp trawling.

Within just five years of implementing TER, it appears that the condition of individuals, species, and assemblages within the reserve have improved compared to those in surrounding, less-protected areas. These results should be considered with caution for three reasons. First, it is difficult to separate management effects from habitat-related effects because the three management levels differed in reef fish management regimes, average depth, and spatial distribution of benthic habitats (Fonseca *et al.* 2006). Second, the research studies span the five years immediately following the establishment of the TER. It may take decades to detect some effects of marine reserves due to many factors, including long-lived, slow-growth life histories of target species, and the time needed for changes in exploited species to cascade down the food web (Beverton and Holt 1957, McClanahan and Mangi 2000). Short-term effects of marine protected areas have been observed in other areas (Roberts *et al.* 2001). Third, increased hurricane activity in 2004–2005 may have affected fish assemblages and confounded management effects. Continued monitoring should provide a long-term dataset to evaluate the effects of TER on fish patterns within the reserves, as well as within the greater Tortugas region.

Another reason for establishing marine protected areas is to increase productivity over a wider area. The benefits of the TER to the wider Tortugas Region could include (1) larval export produced from spawning events within the reserve, (2) spillover as juveniles move from the TER to habitats outside the TER, and (3) spillover as adults move from the TER to similar habitats outside the TER. Positive effects of the MPA to surrounding areas probably lags behind more immediate effects of within-TER benefits; it may take longer for individuals within the reserve to establish spawning populations and/or to reach abundances high enough for individuals to spill over into surrounding areas (McClanahan 2000, McClanahan and Mangi 2000, Russ and Alcala 2004).

The data CCFHR provide preliminary evidence that TER will likely benefit the status of resources within the greater Tortugas region. Burton *et al.* (2005) documented the re-establishment of large spawning aggregations of mutton snapper in the Riley's Hump region of TSER. CCFHR's drifter-releases indicate that spawning aggregations in the Riley's Hump area could result in larval export to the West Florida Shelf, the East Florida Shelf, and the Florida Keys. Integrating the findings of these two studies suggests that as target species like mutton snapper increase in abundance and reproductive efforts within TER, larval export to areas surrounding the reserve will likely increase.

CCFHR's Simrad and stable isotope studies were designed to elucidate trophic structure and habitat requirements/utilization patterns of coral reef fishes. The studies document that although coral reef fishes are associated with coral reefs, they also use resources in adjacent habitats, such as seagrass beds. The movement of individuals across habitat types, whether for daily feeding events or ontogenetic habitat shifts (Dahlgren and Eggleston 2000), might result in the movement of individuals across reserve boundaries into surrounding areas.

Table 6.1. Publications describing trends in reef fish assemblages in the Tortugas region and the development of a Fisheries Systems Science model for managing reef fisheries.

Ault, J. S., S. G. Smith, J. A. Bohnsack, J. Luo, D. E. Harper, and D. B. McClellan. 2006. Building sustainable fisheries in Florida 's coral reef ecosystem: positive signs in the Dry Tortugas . Bulletin of Marine Science 78(3): 633-654.
Bartholomew, A., J.A. Bohnsack, S.G. Smith, J.S. Ault, D.E. Harper, and D.B. McClellan. 2006. Influence of marine reserve size and boundary length on the initial response of exploited reef fishes in the Florida Keys National Marine Sanctuary, USA. Landscape Ecology 23(Suppl. 1):55-65.
Ault, J. S., S. G. Smith, and J. A. Bohnsack. 2005. Evaluation of average length as an estimator of exploitation status for the Florida coral reef fish community. ICES Journal of Marine Science 62:417-423.
Ault, J. S., J. A. Bohnsack, S. G. Smith, and J. Luo. 2005. Towards sustainable multispecies fisheries in the Florida USA coral reef ecosystem. Bulletin of Marine Science 76(2):595-622.
Humston, R., J. S. Ault, M. F. Larkin, and J. Luo. 2005. Movements and site fidelity of bonefish (*Albula vulpes*) in the northern Florida Keys determined by acoustic telemetry. Marine Ecology Progress Series 291:237-248.
Humston, R., D. B. Olson, and J. S. Ault. 2004. Behavioral assumptions in models of fish movement and their influence on population dynamics. Transactions of the American Fisheries Society 133:1304-1328.
Meester, G. A., A. Mehrotra, J. S. Ault, and E. K. Baker. 2004. Designing marine reserves for fishery management. Management Science 50(8):1031-1043.
Bohnsack, J. A., J. S. Ault, and B. Causey. 2004. Why have no-take marine protected areas? American Fisheries Society Symposium 42:185-193.
Wang, J.D., J. Luoand, and J. S. Ault. 2003. Flows, salinity, and some implications for larval transport in south Biscayne Bay, Florida. Bulletin of Marine Science 72(3):695-723.
Ault, J. S., J. Luo, and J. D. Wang. 2003. A spatial ecosystem model to assess spotted seatrout population risks from exploitation and environmental changes. Pages 267-296 *in* S. A. Bortone, editor. Biology of Spotted Seatrout. CRC Press, Boca Raton, Florida.
Franklin, E. C., J. S. Ault, S. G. Smith, J. Luo, G. A. Meester, G. A. Diaz, M. Chiappone, D. W. Swanson, S. L. Miller, and J. A. Bohnsack. 2003. Benthic habitat mapping in the Tortugas region, Florida. Marine Geodesy 26(1-2):19-34.
Meester, G. A., J. S. Ault, S. G. Smith, and A. Mehrotra. 2001. An integrated simulation modeling and operations research approach to spatial management decision making. Sarsia 86:543-558.
Lindeman, K. C., P. A. Kramer, and J. S. Ault. 2001. Comparative approaches to reef monitoring and assessment: an overview. Bulletin of Marine Science 69(2):335-338.
Miller, S. L., M. Chiappone, D. W. Swanson, J. S. Ault, S. G. Smith, G. A. Meester, J. Luo, E. C. Franklin, J. A. Bohnsack, D. E. Harper, and D. B. McCllelan. 2001. An extensive deep reef terrace on the Tortugas Bank, Florida Keys National Marine Sanctuary. Coral Reefs 20(3):299-300.
Chiappone, M., S. L. Miller, D. W. Swanson, J. S. Ault, and S. G. Smith. 2001. Comparatively high densities of long-spine sea urchins in the Dry Tortugas, Florida. Coral Reefs 20(2):137-138.

Table 6.2. Change (%) in mean population density of selected exploited and non-target fish species from baseline years 1999–2000 relative to the survey years 2002, 2004, and 2006 in Dry Tortugas National Park. Statistically significant changes from baseline years are shown as: ns = not significant; *= p<0.05; ** = p<0.01; *** = p<0.001 (source: Ault et al. 2007).

	2002		2004		2006	
Taxa	**Change (%)**		**Change (%)**		**Change (%)**	
Exploited						
red grouper (*Epinephelus morio*)	13.3	ns	-9.3	ns	-16.4	ns
black grouper (*Mycteroperca bonaci*)	212.8	**	131	***	45.9	ns
mutton snapper (*Lutjanus analis*)	191	ns	146.3	***	94.5	**
gray snapper (*Lutjanus griseus*)	-0.8	ns	286.3	ns	-55.1	ns
yellowtail snapper (*Ocyurus chrysurus*)	100.4	*	128.4	***	-21.6	ns
hogfish (*Lachnolaimus maximus*)	-6.1	ns	-24.6	ns	-15.4	ns
white grunt (*Haemulon plumierii*)	-38.8	*	3.8	ns	-0.4	ns
bluestriped grunt (*Haemulon sciurus*)	141.7	ns	260	ns	0.3	ns
Unexploited						
ocean surgeon (*Acanthurus bahianus*)	-30.5	ns	-8.7	ns	46.1	*
blue tang (*Acanthurus coeruleus*)	83.2	***	97.3	***	24.6	ns
foureye butterflyfish (*Chaetodon capistratus*)	53.8	ns	28.2	ns	-25.5	ns
spotfin butterflyfish (*Chaetodon ocellatus*)	38.1	ns	0.3	ns	-39.2	***
bluehead wrasse (*Thalassoma bifasciatum*)	84.4	***	52.9	***	33.6	***
spotted goatfish (*Pseudupeneus maculatus*)	16.7	ns	172.3	***	128.8	***
blue angelfish (*Holacanthus bermudensis*)	87.7	**	27.1	ns	-32.6	*
gray angelfish (*Pomacanthus arcuatus*)	25.9	ns	115.2	ns	28.7	*
purple reeffish (*Chromis scotti*)	453.9	*	243.3	***	86.1	*
bicolor damselfish (*Stegastes partitus*)	80.6	**	16.6	ns	-29.5	ns
cocoa damselfish (*Stegastes variabilis*)	20.3	ns	6.1	ns	45.9	***
striped parrotfish (*Scarus iseri*)	12.8	ns	9.8	ns	8.7	ns
redband parrotfish (*Sparisoma aurofrenatum*)	-11.3	ns	56.3	ns	-29.7	ns
stoplight parrotfish (*Sparisoma viride*)	38.4	ns	85.7	***	-23.3	ns

Table 6.3. Results of Bonferonni-corrected Kruskal-Wallis tests for significant effects of year (2001−2005); management strata (sites within Dry Tortugas National Park [DRTO], sites within Tortugas Ecological Reserve [TER], and sites outside DRTO and TER); and current exposure (south-facing or north-facing) on the mean abundances of selected reef fishes at reef-sand interfaces. Significant effects are denoted as follows: "*" = $p \leq 0.004$ and n.s. = not significant; n=150 for each species (source: Ault et al. 2007).

Species	Year	Management Strata	Current Exposure
bar jack (*Carangoides ruber*)	n.s.	n.s.	n.s.
black grouper	n.s.	n.s.	n.s.
bluehead wrasse	n.s.	*	n.s.
bluestriped grunt	n.s.	n.s.	n.s.
cocoa damsel	n.s.	n.s.	n.s.
hogfish	n.s.	n.s.	n.s.
red grouper	n.s.	n.s.	n.s.
spotted goatfish	n.s.	n.s.	n.s.
stoplight parrotfish	n.s.	n.s.	n.s.
striped parrotfish	n.s.	n.s.	n.s.
white grunt	*	n.s.	n.s.
yellowtail snapper	*	n.s.	n.s.

Table 6.4. The 25 most abundant species, in descending order of abundance, at all stations (first column) and all stations within each management stratum (last three columns). Ranks are based on total abundances of each species at all stations for five years of sampling. Species in italics are exploited or targeted species by fishers; those not italicized are non-exploited species (source: Burke et al. 2012).

All stations	**'Out' stations**	**'Park' stations**	**'Reserve' stations**
masked goby	masked goby	masked goby	masked goby
purple reeffish	bluehead wrasse	*grunt species*	purple reeffish
grunt species	*grunt species*	purple reeffish	*grunt species*
bluehead wrasse	purple reeffish	*tomtate*	bluehead wrasse
tomtate	*tomtate*	*yellowtail snapper*	*yellowtail snapper*
yellowtail snapper	blue chromis	striped parrotfish	*tomtate*
blue chromis	slippery dick	bluehead wrasse	yellowtail reeffish
striped parrotfish	bicolor damselfish	blue goby	striped parrotfish
slippery dick	striped parrotfish	yellowtail reeffish	slippery dick
yellowtail reeffish	yellowhead wrasse	*white grunt*	bicolor damselfish
blue goby	*yellowtail snapper*	cocoa damselfish	silversides
bicolor damselfish	blue goby	slippery dick	cocoa damselfish
cocoa damselfish	yellowhead jawfish	yellowhead jawfish	yellowhead wrasse
yellowhead wrasse	Creole wrasse	striped grunt	*French grunt*
yellowhead jawfish	cocoa damselfish	*gray snapper*	blue goby
white grunt	brown chromis	bicolor damselfish	bar jack
striped grunt	goby species	sand perch	blue tang
brown chromis	*bluestriped grunt*	yellowhead wrasse	*white grunt*
French grunt	princess parrotfish	butter hamlet	blue chromis
silversides	blue parrotfish	*French grunt*	threespot damselfish
Creole wrasse	striped grunt	bridled goby	redband parrotfish
blue tang	*white grunt*	spotted goatfish	goldspot goby
bar jack	beaugregory	blue tang	striped grunt
spotted goatfish	silversides	chalk bass	brown chromis
threespot damselfish	*French grunt*	redband parrotfish	yellowhead jawfish

Table 6.5. The 25 most frequently observed species, in descending order of sighting frequency, at all stations (first column) and all stations within each management stratum (last three columns). Ranks are based on sighting frequencies of each species at all stations for five years of sampling (source: Burke et al. 2012).

All stations	'Out' stations	'Park' stations	'Reserve' stations
bluehead wrasse	bluehead wrasse	bluehead wrasse	bluehead wrasse
purple reeffish	bicolor damselfish	purple reeffish	purple reeffish
striped parrotfish	striped parrotfish	striped parrotfish	striped parrotfish
cocoa damselfish	slippery dick	cocoa damselfish	cocoa damselfish
masked goby	purple reeffish	masked goby	masked goby
yellowtail snapper	yellowhead wrasse	*yellowtail snapper*	*yellowtail snapper*
butter hamlet	butter hamlet	butter hamlet	butter hamlet
slippery dick	cocoa damselfish	slippery dick	slippery dick
red grouper	masked goby	*red grouper*	*red grouper*
blue goby	*yellowtail snapper*	blue goby	blue goby
blue angelfish	blue tang	blue angelfish	blue angelfish
hogfish	spotted goatfish	*hogfish*	*hogfish*
white grunt	*white grunt*	*white grunt*	*white grunt*
redband parrotfish	foureye butterflyfish	redband parrotfish	redband parrotfish
yellowtail reeffish	blue angelfish	yellowtail reeffish	yellowtail reeffish
blue tang	*red grouper*	blue tang	blue tang
black grouper	redband parrotfish	*black grouper*	*black grouper*
yellowhead wrasse	reef butterflyfish	yellowhead wrasse	yellowhead wrasse
bicolor damselfish	tobaccofish	bicolor damselfish	bicolor damselfish
tobaccofish	blue goby	tobaccofish	tobaccofish
gray angelfish	*hogfish*	gray angelfish	gray angelfish
scamp	stoplight parrotfish	*scamp*	*scamp*
yellowhead jawfish	*saucereye porgy*	yellowhead jawfish	yellowhead jawfish
tomtate	yellowhead jawfish	*tomtate*	*tomtate*
barred hamlet	threespot damselfish	barred hamlet	barred hamlet

Table 6.6. Results of Kolmogorov-Smirnov tests for effects of year, management strata, and current exposure on size-frequency distributions. An asterisk (*) indicates a significant effect at the 0.004 level (Bonferroni correction computed as 0.05/12 = 0.004); n.s. = not significant. Levels that were significantly different (for factors with more than two levels) are indicated after the asterisk (source: Burke et al. 2012).

Species	Year	Management strata	Current exposure
bar jack	* all possible pairs except 1 & 5	* all possible pairs	*
black grouper	* 5 from all other years	n.s.	n.s
bluehead wrasse	* all possible pairs except 1 & 3	* out & reserve, out & park	*
bluestriped grunt	* all possible pairs except 1 3, 1 & 4, 4 & 5	* out & reserve, out and park	*
cocoa damsel	* all possible pairs except 3 & 1, 4 & 1, and 2 & 3	* park and reserve, out and park	n.s
hogfish	* 1 & 5 and 3 & 5	* out and reserve	n.s.
red grouper	* 5 from all other years	n.s.	n.s.
spotted goatfish	* 1 & 4, 1 & 5, 2 & 4, 2 & 5, 3 & 4, 4 & 5	* out and reserve, park and reserve	*
stoplight parrotfish	n.s.	n.s.	n.s.
striped parrotfish	* all possible pairs except 1 & 4 and 4 & 5	n.s.	n.s.
white grunt	* all possible pairs except 1 & 2, 3 & 4	* park and reserve, out and park	*
yellowtail snapper	* all possible pairs	* all possible pairs	*

Table 6.7. Summary of ongoing or completed Center for Coastal Fisheries and Habitat Research projects on the Tortugas fish community.

Name	Investigator	Description	Status	References
Stable isotope characterization of food webs	Carolyn Currin	Using stable isotopes to infer dietary patterns and demonstrate the transfer of benthic primary production to reef fish and shellfish	Analyses ongoing	Burke *et al.* 2004
Drifter release studies	John Hare	Released drifters from Riley's Hump to track potential paths of larvae spawned over Riley's Hump; drifters showed high variability, but spread to various parts of the Florida Keys, west Florida Shelf and East Florida Shelf	Completed	Burke *et al.* 2004
Trawling data	John Burke	Beam trawling in paired protected and unprotected sites along the border of TER North to compare benthic invertebrate and fish patterns.	Analyses ongoing	Fonseca *et al.* 2006
Riley's Hump mutton snapper	Mike Burton	Visual transect surveys to monitor mutton snapper spawning aggregations shows a dramatic increase in spawning aggregation from 10 individuals in 2001 to over 300 individuals in 2004	Completed, published	Burton *et al.* 2005.
SIMRAD	Mark Fonseca	TBD	TBD	TBD

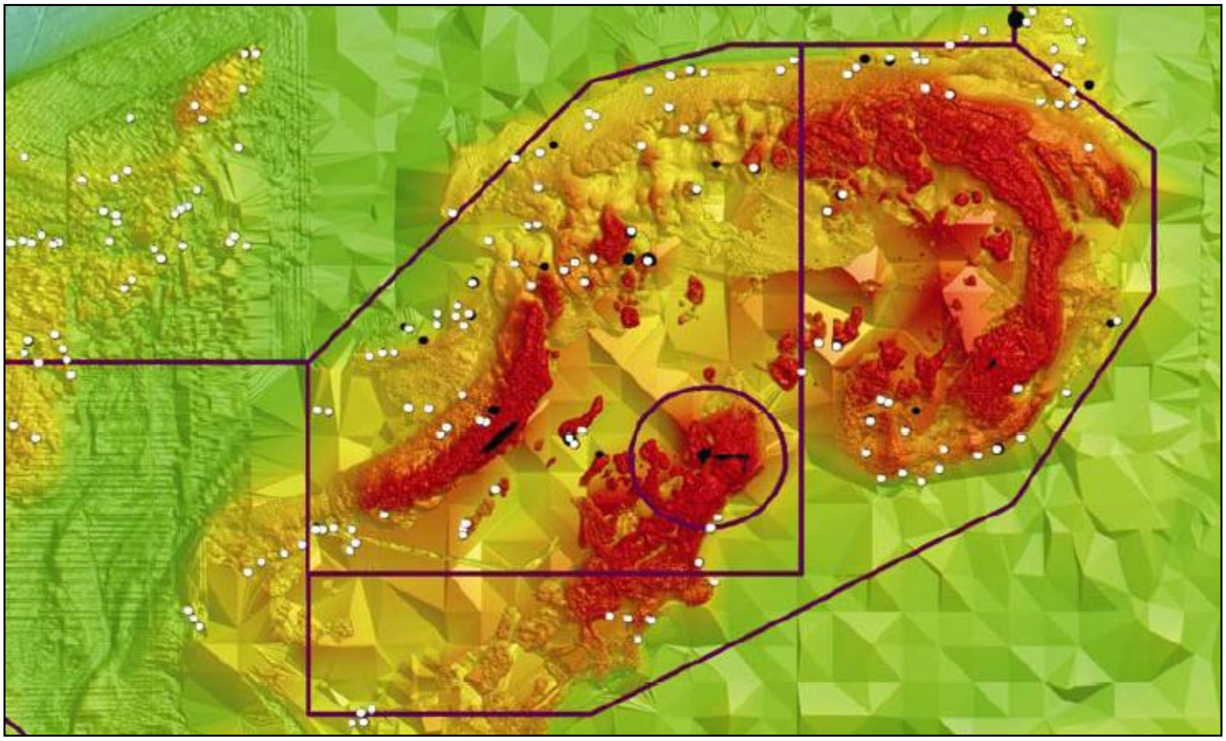


Figure 6.1. Locations of reef fish visual census surveys conducted within habitat grids (177 m^2 [1,905 ft^2]) in the Tortugas region. Black circles show positive relative density (number of animals per 177 m^2) [1,905 ft^2]) of pre-exploited phase black grouper (*Mycteroperca bonaci*). White circles indicate that no black grouper were seen during four replicate dives within a given habitat (adapted from Ault *et al.* 2007).

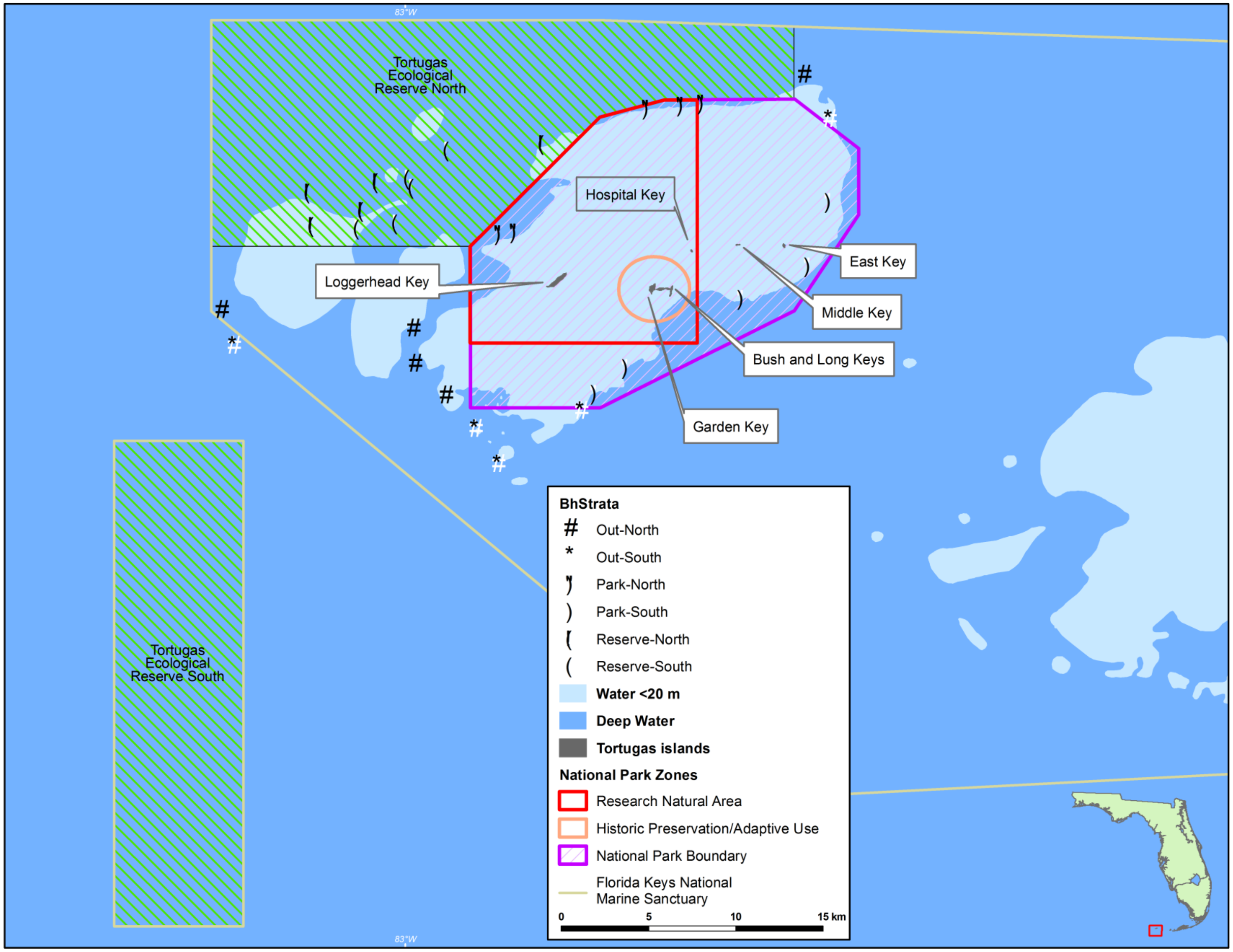


Figure 6.2. Location of permanent reef-sand interface sites in the Dry Tortugas region, the Tortugas Ecological Reserve, and the Dry Tortugas National Park surveyed by NOAA's Center for Coastal Fisheries and Habitat Research.

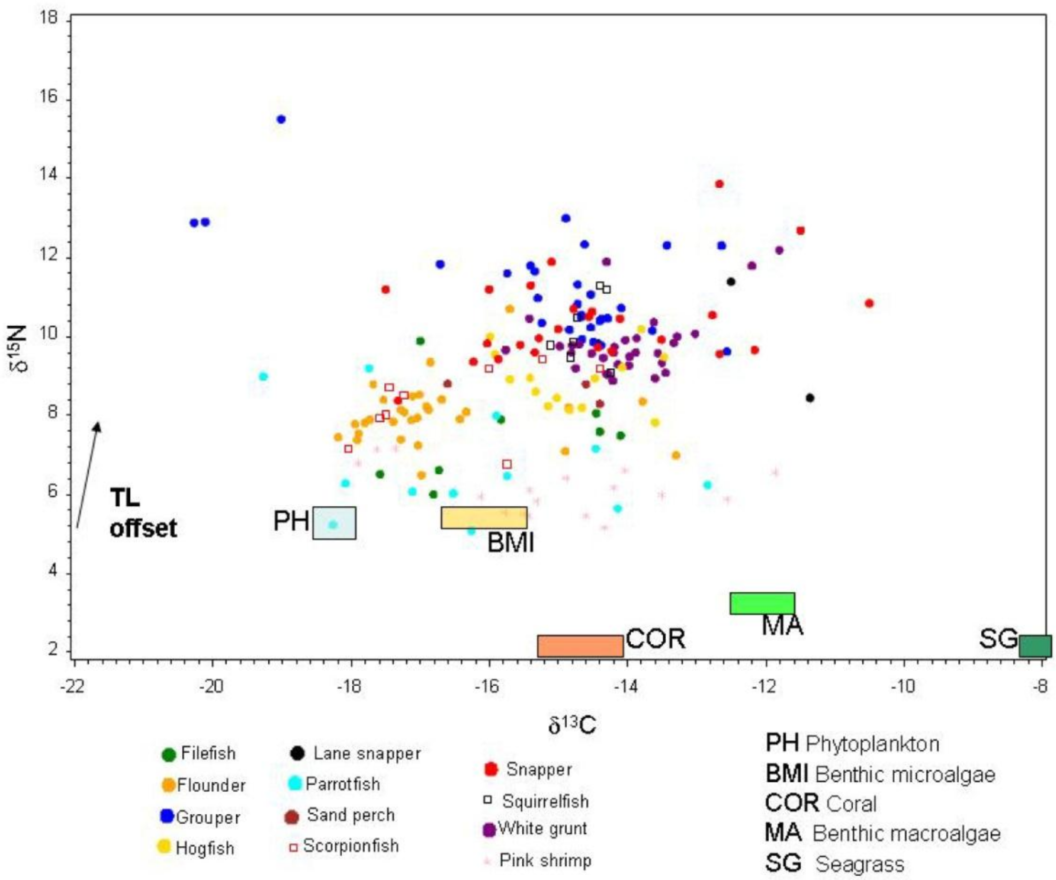


Figure 6.3. The δ13C and δ15N values of consumer organisms and primary producers collected in the Tortugas Ecological Reserve, 2000–2004. Rectangles represent the mean and standard error of values for primary producers, including phytoplankton (PH), benthic microalgae (BMI), corals (COR), benthic macroalgae (MA), and seagrasses (SG) (source: Jeffrey *et al*. 2012).

Chapter 7: Condition of Sea Turtles and Seabirds

Christopher F. G. Jeffrey and Sarah D. Hile

Birds and sea turtles are important components of marine ecosystems and their presence and abundance can be indicators of the ecological status of nearshore areas. For example, birds require specific habitats for nesting and changes in the spatial extent or configuration of required habitats can influence the size of bird nesting colonies (Doyle *et al.* 2002). Some bird species bioaccumulate and are sensitive to contaminants; noticeable reductions in local densities could indicate the negative influence of stressors, such as elevated levels of pesticides or habitat loss. Sea turtles nest on specific beaches and a significant reduction in the number of nesting sea turtles on natal beaches may indicate increasing levels of local or global stressors that negatively affect turtle abundance (Figure 7.1). Given that the home range of most wildlife species generally encompasses a variety of habitats, maintaining ecological processes that meet the optimal requirements for supporting thriving wildlife populations can result in the protection of the entire ecosystem.

This chapter focuses on the status and ecological condition of sea turtles and seabirds within the Dry Tortugas National Park (DRTO). Historical and current temporal trends and spatial patterns in the presence and abundance of sea turtles and seabirds in the park are described to determine if the park functions as an ecosystem that provides support to resident and migratory fauna. The existing literature was reviewed to characterize sea turtle and seabird populations known to occur in the park and to describe trends in their abundances.

7.1. Sea Turtles

Populations of sea turtles observed in the Tortugas region are most likely part of larger regional populations that traverse the Atlantic Ocean. Sea turtles are wide-ranging, pelagic marine reptiles that migrate throughout the world's oceans as adults, but return to natal sandy beaches to nest and lay eggs (Figure 7.1). Eggs generally hatch within two to three months after which the hatchlings emerge from underground nests and scurry to water and forage in the world's oceans as pelagic juveniles for approximately 5−20 years. Juvenile sea turtles then leave the open ocean to take up residence in specific feeding grounds in shallow, coastal regions, such as the Dry Tortugas (Musick and Limpus 1997, Luschi *et al.* 2003). Sexually mature male and female sea turtles migrate to specific areas for breeding, after which males return to the foraging grounds, and gravid females return to natal beaches for egg-laying. The seven islands of DRTO provide 4.2 km^2 (1.6 mi^2) of land and 7 km (4.4 mi) of coastline as potential nesting habitat for female sea turtles (Van Houtan and Pimm 2006).

Prior to the arrival of Europeans in the Americas in the 1500s, sea turtles were very abundant in the Dry Tortugas region. Ponce de León named the area "Las Tortugas" because of the local abundance of sea turtles. Numerous accounts have documented the historical abundance of sea turtles, but subsequent overexploitation between 1513−1935, the year when DRTO was established, substantially reduced turtle abundance in the Tortugas region (Williams and Dawson 1985, Steadman and Stokes 2002, Safina 2006). High exploitation rates during the 1800s were driven primarily by a high demand for turtle meat for provisioning ships and soldiers at Fort Jefferson on Garden Key. For example, between 1858−1859 more than 17,995 kg (39,670 lb) of sea turtle meat were consumed by soldiers at Fort Jefferson (NPS 2005). Comparisons of pre-

Columbian accounts of turtle abundances with modern-day estimates suggest that turtles in the Tortugas region and other parts of the western Atlantic are 99% depleted from previous population levels (National Research Council 1990, McClenachan *et al.* 2006, Safina 2006). Implementation of DRTO in 1935 did not fully reduce the level of sea turtle exploitation in the Tortugas region because poaching of nest eggs may have continued well into the 1960s, and large numbers of turtles continued to be killed as by-catch from the shrimp fishing industry until 2003 when turtle exclusion devices (TEDs) became mandatory (Van Houtan and Pimm 2006). Overexploitation has been blamed for decimating sea turtle populations in the Tortugas region and throughout the Caribbean.

Five species of sea turtles occur in the Tortugas region: loggerhead (*Caretta caretta*), green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), leatherback (*Dermochelys coriacea*) and Kemp's ridley (*Lepidochelys kempii*). Loggerhead and green sea turtles are the most common known to nest there based on annual monitoring surveys conducted between 1979−2003 by the Florida Fish and Wildlife Conservation Commission (FWC) (Meylan *et al*. 1995, Van Houtan and Pimm 2006; Figure 7.2). There were three sightings of leatherback turtle nests on East Key in 2004. Hawksbill juveniles reportedly forage on reefs in DRTO, but have never been observed to nest there. Kemp's ridley turtles are seldom observed in the Tortugas region (Van Houtan and Pimm 2006). Most turtle nesting occurs on East Key followed by Loggerhead Key: loggerhead and green turtles reflect this spatial pattern in nesting.

Nesting surveys from the Caribbean suggest that sea turtle populations in the Western Atlantic have been increasing since the 1980s. FWC data on the annual abundance of sea turtle nests at DRTO concur with this trend, but loggerhead and green sea turtles had different annual patterns in the number of nests observed between 1994−2004 (Figure 7.3). Van Houtan and Pimm (2006) analyzed FWC turtle nesting data from DRTO and found an increasing trend in the density of loggerhead turtle nests (counts per kilometer of beach searched) between 1995−2000, and a decreasing trend in turtle nest density between 2000−2004. Reasons for the apparent temporal increase in loggerhead turtle nesting at DRTO were unclear, but the temporal decrease between 2000−2004 may have resulted from a 50% decrease in hatchling success caused by beach erosion from tropical storms, invasive plants (*Casuarina* spp.), and nest predation by ghost crabs and other predators. Densities of green sea turtle nests showed a two-year periodicity, but no trend between 1995−2004 (Van Houtan and Pimm 2006) (Figure 7.3).

The temporal trends in the overall density of loggerhead and green turtle nests at DRTO were not uniformly reflected among the islands of the park (Figure 7.4). For example, counts of loggerhead turtles at Loggerhead Key did not steadily increase between 1994−2000, but rather alternated between highs and lows during successive years, whereas total counts on the other islands remained relatively unchanged during the same period. Total counts of loggerhead nests at East Key remained relatively unchanged between 1996−2000 before declining between 2001−2004. Nest counts for loggerhead sea turtles at Loggerhead Key did not decrease between 2000−2004, although the overall nest count throughout the DRTO did (Figure 7.3). The differences in the trend of total nest counts among islands indicate that factors affecting hatchling success may be island-specific (e.g., beach erosion on one island versus nest predation on another island). Differences in the temporal trends in nest counts among the islands demonstrate spatial variability among islands and underscore the importance of collecting data that are spatially and temporally representative of the ecosystem being studied to understand the observed demographic patterns and trends.

All sea turtles that nest in the Tortugas region are protected under Florida statutes and the United States Endangered Species Act (ESA), and have had their conservation status elevated by inclusion on the International Union for Conservation of Nature (IUCN) Red List of Species (http://www.iucnredlist.org/). Although they are protected, sea turtles in the Tortugas are negatively affected by habitat loss and degradation, incidental capture in fishing gear, marine pollution, entanglement in debris, and boat-related accidents. Many of the threats to sea turtles occur outside of the Tortugas region during their migrations of thousands of kilometers. The migratory behavior of sea turtles makes it difficult to obtain information on the ecological status of their populations and to link local conservation efforts to future population abundances. Nevertheless, DRTO provides the most isolated and least disturbed nesting habitat for sea turtles in the U.S. (NPS 2005) and its remoteness may be beneficial to the turtles that nests there. Monitoring data suggest that there is a positive correlation between protection of sea turtle nesting beaches and the observed increase in the population of sea turtles in the Western Atlantic Ocean since the 1980s (McClenachan *et al.* 2006, Safina 2006). Protection of sea turtle nesting beaches in the park may contribute to the resurgence of Western Atlantic sea turtles. Interestingly, loggerhead sea turtles at DRTO are genetically distinct from other loggerhead populations in the southeastern U.S. and are considered a separate subpopulation (Van Houtan and Pimm 2006).

7.1.1 Summary

A major goal of this review was to determine if the DRTO continues to provide the ecosystem components to support resident and migrant wildlife populations. The information synthesized in this section indicates that sea turtles continue to use the ecosystems of the park. Although turtle abundance in the Tortugas region is substantially lower now compared to pre-European times, loggerhead turtles nested in the park in increasing numbers from 1994−2000 and in decreasing numbers from 2001−2004. The fact that the trend in overall loggerhead turtle nesting activity in the park mirrored that of the wider Caribbean is encouraging because it suggests that the Tortugas islands were not worse off than other areas in the Caribbean for nesting turtles. Green sea turtles are less abundant and showed no apparent trend in nesting frequency. Hawksbill, leatherback, and Kemp's ridley sea turtles are uncommon and there is not much information available on the nesting activity of these species within DTRO.

Given that sea turtles are important natural resources and are protected by state and federal legislation, it is puzzling that the park has discontinued monitoring of nesting turtles (FWC 2008, Eaton *et al.* 2008). Sea turtle nest monitoring at DRTO was done by FWC until 2004as part of Florida's statewide Nesting Beach Survey. FWC also runs an Index Nesting Beach Survey, but that survey does not include the Tortugas region. FWC reports that loggerhead turtle nesting activity within the state of Florida declined during 2000−2008, but the nesting of green and leatherback turtles increased during the same period. It is unknown if nesting activity of loggerhead, green, and leatherback sea turtles at DRTO reflect that of the state. Turtle monitoring should be reinstated at DRTO to determine current trends in nesting activity and population abundance.

Given that the loggerhead turtle population at Tortugas is a genetically distinct sub-population, characterizing and understanding temporal demographic trends is important for their management. Van Houtan and Pimm (2006) provide good recommendations for developing sampling designs for monitoring sea turtles. Resource managers in the SFCN ranked sea turtles 20th among 44 vital signs chosen as indicators of the ecological condition of parks within the network (Patterson *et al*. 2008c). Thus far, a conceptual ecological model and a draft monitoring plan have been developed for monitoring sea turtles at selected parks. The draft protocol outlines plans to assess success of turtle nesting and to estimate successful reproduction of turtles to the hatchling stage. However, there are no plans to address these objectives at DRTO specifically, although DRTO management recently has funded a USGS project to study movements and local habitat use by nesting turtles (Patterson *et al*. 2008c).

The exhaustive review of information did not find long-term monitoring data necessary to quantify the ecological condition or infer long-term demographic trends of sea turtle populations at DRTO. Van Houtan and Pimm (2006) concluded that the existing turtle monitoring data for DRTO are “temporally and spatially limited” and do not provide a basis for drawing broad ecological conclusions about the status of sea turtle populations in the park. The factors affecting turtle abundance and nesting activities at DRTO cannot be determined from existing data. Are the animals colonizing more beaches within the park, or are they nesting on fewer beaches each year? Are there specific beaches that some turtle species use for nesting? The greatest threats to sea turtle populations include loss of nesting beaches, degradation in quality of nesting beaches and foraging habitats, nest predation, collisions with boats, entrapment in fishing gear or trash, and disease. Have there been reductions in the levels of these threats or stressors to sea turtles at DRTO, and have the reductions resulted in an increase in turtle nesting activity at DRTO? These are some of the resource questions that should be addressed by park managers if they are to meet the mandated goal of preserving and protecting ecological resources for the future.

7.2. Birds

In 1992, the FWC compiled an atlas on the occurrence of breeding birds of Florida (http://www.myfwc.com/bba/chapt2.htm). The atlas provides information on the possible, probable, or confirmed occurrence of bird species within 7.5-minute topographic quadrangles (quads) as well as historical information on the general status, habitat, and condition of breeding species in Florida. Species occurrence within quads was based on bird sightings by volunteers between 1986−1991. The Audubon Society of Florida maintains information about important areas for bird watching within the state (http://iba.audubon.org/iba/viewState.do?state=US-FL). Important bird areas (IBAs) are sites documented to support significant populations of one or more species of native birds (Pranty 2002). These sites typically include breeding or wintering habitats for threatened or endangered bird species or those with restricted ranges. Information from these two sources was compiled to describe the bird fauna of DRTO. Although dated, these sources are the most comprehensive and publicly accessible information on bird fauna for DRTO.

7.2.1 Bird Species Richness and Diversity

DRTO is a well-known destination for bird watching and, in 2002, it ranked 10th out of the 13 IBAs of Florida (Pranty 2002). The total land area of the park is only 4.2 km^2 (1.6 mi^2) and the region has relatively low species richness compared with other areas in Florida (Figure 7.5). Yet the sandy islands attract several Neotropical birds during spring and fall migrations between

North and South America (Dunne 2001). DRTO was identified as a nesting site as early as 1513, making it “one of the oldest bird nesting rookeries in North America” (Sprunt 1948). Many species of songbirds (warblers, vireos, etc.) from North America, as well as other less common West Indian species (the Ruddy Quail-Dove [*Geotrygon montana*], Variegated Flycatcher [*Empidonomus varius*], Loggerhead Kingbird [*Tyrannus caudifasciatus*], Bahama Swallow [*Tachycineta ctaneoviridis*], Bahama Mockingbird [*Mimus gundlachii*], Thick-billed Vireo [*Vireo crassirostris*] and Yellow-faced Grassquit [*Tiaris olivacea*]) can be observed at the park (Pranty 2002). Approximately 299 species of birds have been observed at the DRTO (NPS 2004). Twelve of the 299 species are common for three or more seasons. Three species, the Brown Pelican (*Pelecanus occidentalis*), Double-crested Cormorant (*Phalacrocorax auritus*) and Mourning Dove (*Zenaida macroura*), are common all year (NPS 2004; Table 7.1). Spring has the highest number of bird species with a common abundance (n=91), followed by fall (n=28), winter (n=11), and summer (n=8). Only nine bird species are known to breed in the park, with seven of those species nesting regularly (NPS 2004; Table 7.2).

7.2.2 Seabirds

The coastline of the DRTO islands provide critical nesting habitats for at least seven seabird species: the Brown Pelican (*Pelecanus occidentalis*), Least Tern (*Sternula antillarum*), Sooty Tern (*Sterna fuscata*), Brown Noddy (*Anous stolidus*), Masked Booby (*Sula dactylatra*), Magnificent Frigatebird (*Fregata magnificens*), and Roseate Tern (*Sterna dougallii*; Pranty 2002, FWC 2003, Watson 2005). Brown Pelicans are very abundant and occur throughout Florida (Figure 7.6). In 1970, the species was federally listed as endangered because of catastrophic, DDT-related population declines in the southeast U.S. and along the West Coast. It is now delisted because populations rebounded throughout its U.S. range (FWC 2003). Least Terns are also common throughout Florida, but are only occasionally observed in the Tortugas region (Figure 7.7). The species is endangered in several states, but is of special concern in Florida (Watson 2005; http://ecos.fws.gov/speciesProfile/SpeciesReport.do?spcode=B07N). The other five species nest only in the Tortugas region and are described in more detail below.

Sooty Tern sightings at DRTO have been recorded since 1903 and over 500,000 individuals have been banded there since the early 1950s (Pranty 2002). Sooty Terns arrive at DRTO to breed in February or March and disperse from breeding colonies by September (FWC 2003). The birds show high breeding site fidelity, with young birds returning to the same location where they fledged (FWC 2003). They lay a single egg and fledglings migrate across the Atlantic to Africa for about six years before returning to natal breeding sites. Adults forage on fish and squid day and night in the Gulf of Mexico or the Caribbean Sea. The nesting population at Bush Key is the only known breeding population in Florida (Figure 7.8). In 1964, the number of breeding pairs was estimated at 190,000, but the population decreased to 25,000–40,000 in 1992 (FWC 2003). There is no information about the number of birds currently breeding at Bush Key. In 1992, Sooty Terns were listed as a species of special concern by the Florida Committee on Rare and Endangered Plants and Animals because of its restricted range, but it is not listed by the state as being imperiled (FWC 2003). Robertson and Robertson (1996) observed oil on the feathers of Sooty Terns nesting at Bush Key, which suggested that oil slicks from spills in Louisiana and the Campeche Bank, Mexico could be carried to the Tortugas region.

Brown Noddies also nest at DRTO islands and often breed in colonies with Sooty Terns. Instead of nesting on the ground however, they build nests 1–4 m (3−13 ft) above ground in bushes (e.g., prickly-pear cactus or red mangroves [*Rizophora mangle*]; Sprunt 1948, FWC 2003). The species exhibits breeding-site fidelity; breeding pairs apparently return to the same nest year after year. Like Sooty Terns, they feed on fish and squid plucked from the sea surface. The only known rookery for Brown Noddies in the continental U.S. is on Bush Key (FWC 2003; Figure 7.9). In 1919, the population at DRTO was estimated at 25,000 nests or breeding pairs, but that number dwindled to about 400 pairs by 1938, probably as a result of predation by feral rats (FWC 2003). A reduction in the number of rats caused by hurricanes correlated with an increase in the number of Brown Noddies at DRTO and the breeding population rebounded to about 2,000 pairs by 1964 and 2,000−3,000 pairs by 1992 (FWC 2003). Because of its restricted breeding range in Florida, the Brown Noddy was listed as a ‘species of special concern’ by the Florida Committee of Rare and Endangered Plants and Animals, but this listing does not apply today.

Masked Boobies breed in small groups of about 10−50 birds, and their nesting sites at DRTO are the only ones known to occur in the continental U.S. (Clapp and Robertson 1986, FWC 2003; Figure 7.10). Based on historical NPS records, they generally occur at DRTO throughout the year, but are most numerous between April and October. Masked Boobies were first recorded to breed and nest at DRTO in 1984 when a nesting pair was observed on Middle Key (Clapp and Robertson 1986). Other Masked Booby nests and eggs were subsequently observed on Hospital and East Keys, but nesting success has been hampered by storm-related flooding and erosion of these ephemeral low-relief (<1 m [3 ft] above sea level) islands. About 1–6 breeding pairs of Masked Boobies have been observed to nest on East, Middle, and Hospital Keys of DRTO every winter since the 1980s, but no more than five young birds in total have been observed to fledge from there (Clapp and Robertson 1986, FWC 2003).

Magnificent Frigatebirds are oceanic birds that spend much of their lives on the wing, nest in red mangrove trees, and are common in summer, but rare during winter months. Like other seabirds, they forage by face dipping for surface dwelling fish and invertebrates, such as flying fish and squids (Diamond 1975). They also are opportunistic feeders on fisheries bycatch and steal food from other seabirds by pursuing them in the air and forcing them to disgorge their food – a behavior known as klepto-parasitism (Calixto-Albarran and Osomo 2000). The islands of the Tortugas are the only known nesting site of Magnificent Frigatebirds in the continental U.S. (Figure 7.11). The species was first confirmed to nest in Florida in 1969 when a colony of 100 nesting pairs was observed at the Marquesas. The size of the Marquesas colony fluctuated between 50−250 nesting pairs during the 1970s, but decreased to about 36 nesting pairs during the 1980s (FWC 2003). In 1988, a colony of 40 nesting pairs of Magnificent Frigatebirds was observed for the first time at Long Key, Dry Tortugas. It is believed that the Marquesas colony migrated to Long Key because of increased disturbances by recreational fishers and boaters (FWC 2003).

Roseate Terns are coastal seabirds that plunge-dive for small fish and breed along the eastern coastline from Maine to Florida, in many Caribbean islands, and in Central America (FWC 2003). They are seasonal residents during summer in the Florida Keys and Tortugas region (Figure 7.12). They typically build nests on the ground, but are also nest on rooftops. Historical observations of nesting populations indicate that Roseate Terns have alternated between the Dry Tortugas islands and the Lower Keys for breeding from the 1960s through the 1990s (Robertson 1964, 1978, FWC 2003, Hood 2006). In 1987, a colony was discovered at Pelican Shoals, a small island located 8 km (5 mi) south of Key West. During 2005, Hurricanes Dennis, Katrina, Rita, and Wilma destroyed Pelican Shoal and critical Roseate Tern habitat, but the hurricanes improved tern habitat at the Dry Tortugas by depositing rubble and burying vegetation along beaches (Hood 2006). Staff from FWC and NPS successfully lured the birds to the Dry Tortugas with decoys that emitted Roseate Tern recordings. As of July 2006, an established colony at DRTO had 42 adults and 16 chicks among the decoys (Hood 2006). The Roseate Tern is a threatened species in Florida because of its limited range and small population (FWC 2003).

7.2.3 Summary

A major goal of this review was to determine if the DRTO continues to provide the ecosystem components needed to support resident and migrant wildlife populations. The information synthesized in this section indicates that birds continue to forage and breed in the park, which shows that park ecosystems are supporting wildlife. The National Audubon Society lists the park as one of the important birding areas in Florida, and the Tortugas region provides the only breeding sites within the continental U.S. for three species of seabirds. Resource managers have been successful in getting Roseate Terns to nest in the park as they did historically. These findings confirm that seabirds are an important natural resource for the park. However, shoreline erosion and the availability of coastal vegetation affect colonization of the Tortugas islands by seabirds. Historically, the Tortugas region supported up to 11 low-relief islands, but only eight currently exist. Some islands disappear after being flooded and eroded during periods of hurricane activity (Sprunt 1948, Musick and Limpus 1997, Safina 2006), but reappear because of sand deposition during periods of hurricane inactivity (Shinn *et al.* 1977, Davis 1982, Doyle *et al.* 2002). The ephemeral nature of Tortugas islands, along with sparse vegetation, exotic plants, and increased human visitation, are significant stressors to breeding seabirds at DRTO (Pranty 2002).

The exhaustive review of information did not find the type of long-term monitoring data required to quantify the ecological condition of the seabird populations at DRTO. Although historical records for the Tortugas region are quantitative, much of the existing data were not collected by statistically-sound sampling designs and cannot be extrapolated to determine the ecological condition of seabird populations or infer population trends at the park. Some monitoring and research work on Sooty Terns is being conducted by wildlife biologists of Everglades National Park, but those surveys are not park-wide. Ongoing seabird projects within DRTO include monitoring of Brown Noddy and Sooty Tern colonies with point-count methods, monitoring of Neotropical migrants by private parties, and direct counting of Brown Pelican, Masked Booby, and Magnificent Frigatebird colonies (Watson 2005). It is unknown if these data are used by park staff for management and conservation of seabird populations. Broad-scale (i.e., park-wide), long-term monitoring of colonial birds abundance is essential if the park's mandated goal of conserving wildlife for the future is to be met. Monitoring programs should not only identify bird abundance, but should also determine spatial and temporal variability to identify the factors that affect the their spatial distribution and abundance.

Watson (2005) identified specific needs to increase information about and management of avian fauna at the park. Watson's recommendations include:

- More inventory to better understand the current role and importance of the park for fall migrants;

- Increased monitoring through Christmas Bird Counts and scientifically-based monitoring of migrants;

- Increased banding of Sooty Terns;

- Increased research on nesting chronology and demography of Magnificent Frigatebird colonies;

- Increased research on nesting chronology and reproductive success of the Masked Booby; and

- Verification and entry of observational avian data into existing databases, such as NPSpecies, eBird, and Everglades National Park databases.

A well-defined seabird sampling plan using habitat information to guide selection of sites should be developed to characterize the spatial distribution of colonial nesting birds. The monitoring plan should use a probabilistic sampling frame from which probabilities of sampling selection can be derived. Bart (2005) provides a good review of sampling designs for bird surveys. The SFCN considers sea (colonial nesting) birds an important vital sign of the ecological status of parks within the network (SFCN 2007b). A conceptual ecological model and draft monitoring plan have been developed for monitoring seabirds at DRTO and three other parks in the network. The draft protocol outlines plans to supplement current bird sampling at DRTO. The objectives include: (1) monitoring colonies and nesting status of birds at historic long-term sites and (2) monitoring populations and distributions of wading birds at a regional scale.

Table 7.1. Bird species that have a common abundance for three or more seasons within a year at Dry Tortugas National Park (source: NPS 2004).

Common name	**Species name**	**# seasons**
Brown Pelican	*Pelecanus occidentalis*(Linnaeus 1766)	4
Double-crested Cormorant	*Phalacrocorax auritus* (Lesson 1831)	4
Mourning Dove	*Zenaida macroura* (Linnaeus 1758)	4
Magnificent Frigatebird	*Fregata magnificens* (Mathews 1914)	3
Cattle Egret	*Bubulcus ibis* (Linnaeus 1758)	3
Black-bellied Plover	*Pluvialis squatarola* (Linnaeus 1758)	3
Ruddy Turnstone	*Arenaria interpres* (Linnaeus 1758)	3
Sanderling	*Calidris alba* (Pallas 1764)	3
Laughing Gull	*Larus atricilla* (Linnaeus 1758)	3
Royal Tern	*Sterna maxima* (Boddaert 1783)	3
Sooty Tern	*Sterna fuscata* (Linnaeus 1766)	3
Brown Noddy	*Anous stolidus* (Linnaeus 1758)	3

Table 7.2. List of bird species known to breed in Dry Tortugas National Park. Asterisks (*) indicate rare species (source: NPS 2004).

Common name	**Species name**
Masked Booby	*Sula dactylatra* (Lesson 1831)
Brown Pelican	*Pelecanus occidentalis* (Linnaeus 1766)
Magnificent Frigatebird	*Fregata magnificens* (Mathews 1914)
Laughing Gull	*Larus atricilla* (Linnaeus 1758)
Roseate Tern	*Sterna dougallii* (Montagu 1813)
Least Tern*	*Sterna antillarum* (Lesson 1847)
Sooty Tern	*Sterna fuscata* (Linnaeus 1766)
Brown Noddy	*Anous stolidus* (Linnaeus 1758)
House Sparrow*	*Sula dactylatra* (Lesson 1831)

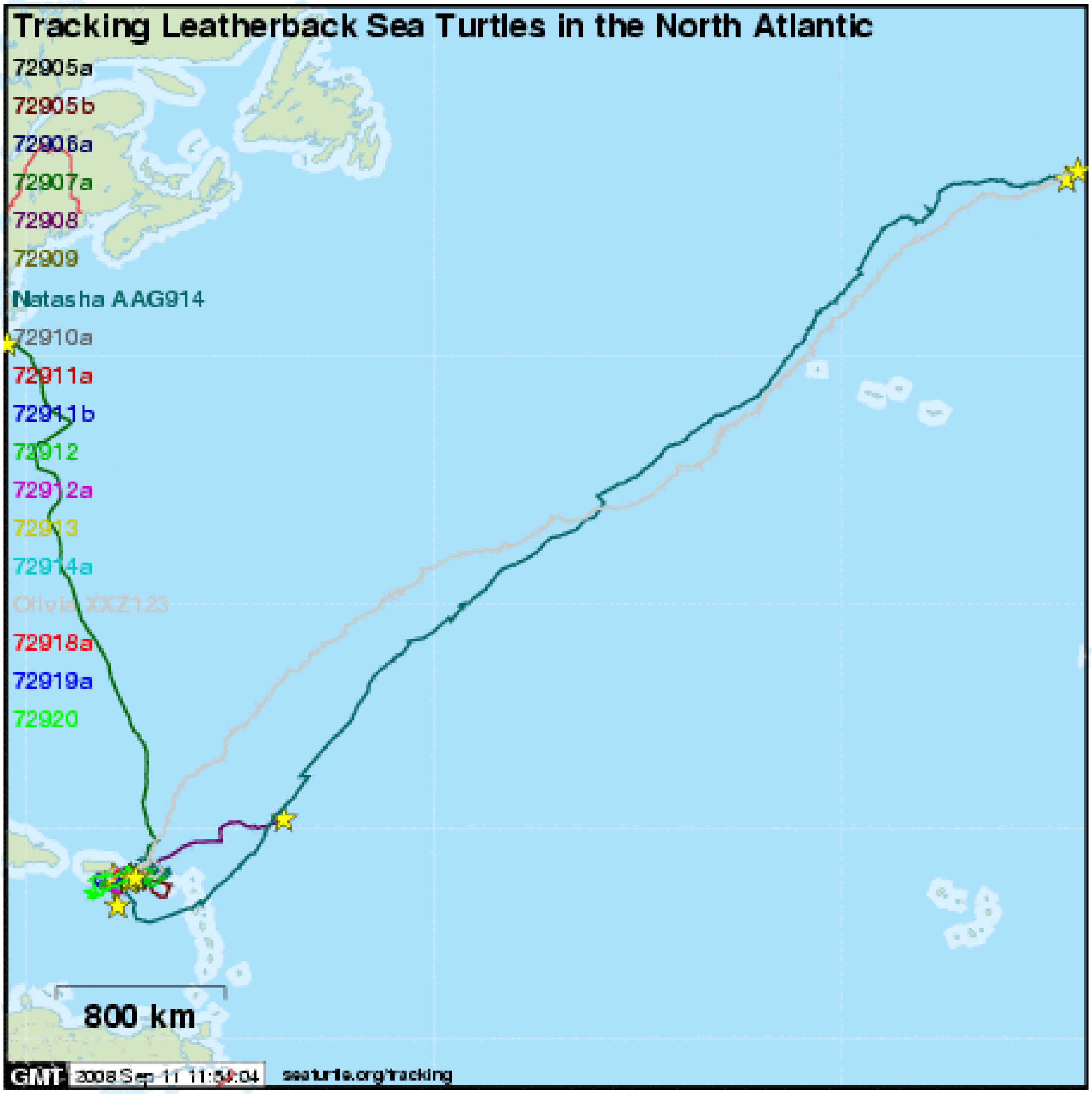


Figure 7.1. Satellite tracks of leatherback sea turtles tagged at Sandy Point beach in St. Croix, US Virgin Islands (source: http://www.seaturtle.org).

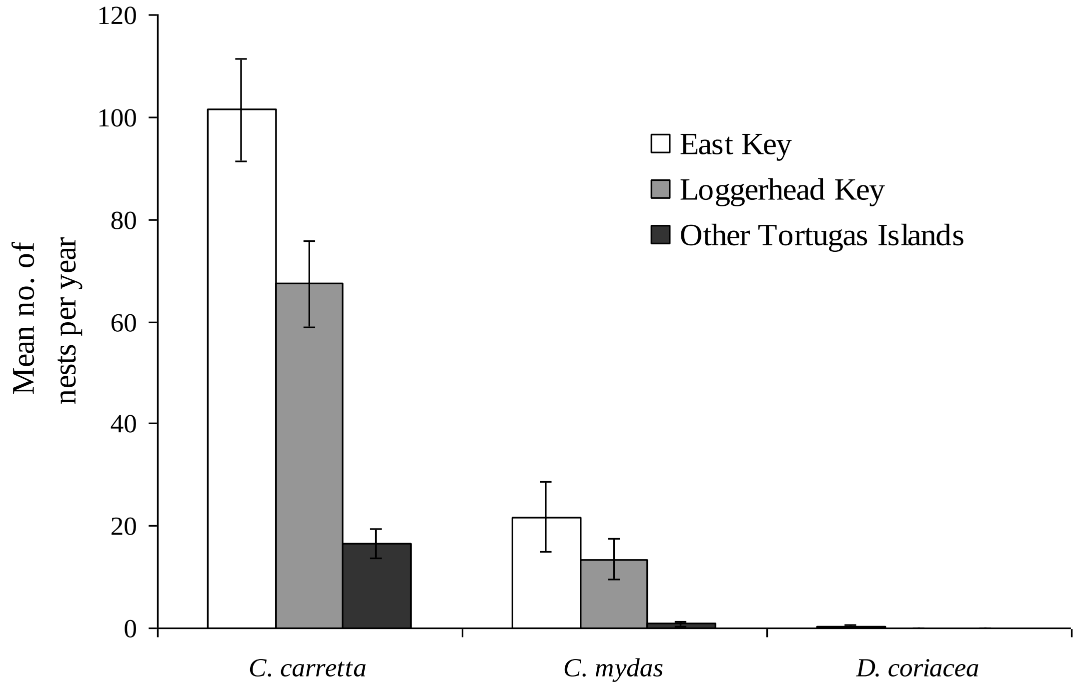


Figure 7.2. Mean annual counts of turtle nests by species on island beaches in the Dry Tortugas National Park, 1994–2004. Mean ranks of nest counts are significantly different among islands for loggerhead and green turtles (n=10 years) (source: Florida Fish and Wildlife Research Institute; http://research.myfwc.com/images/articles/2377/sea_turtle_nesting_on_florida_bchs_93-07.pdf).

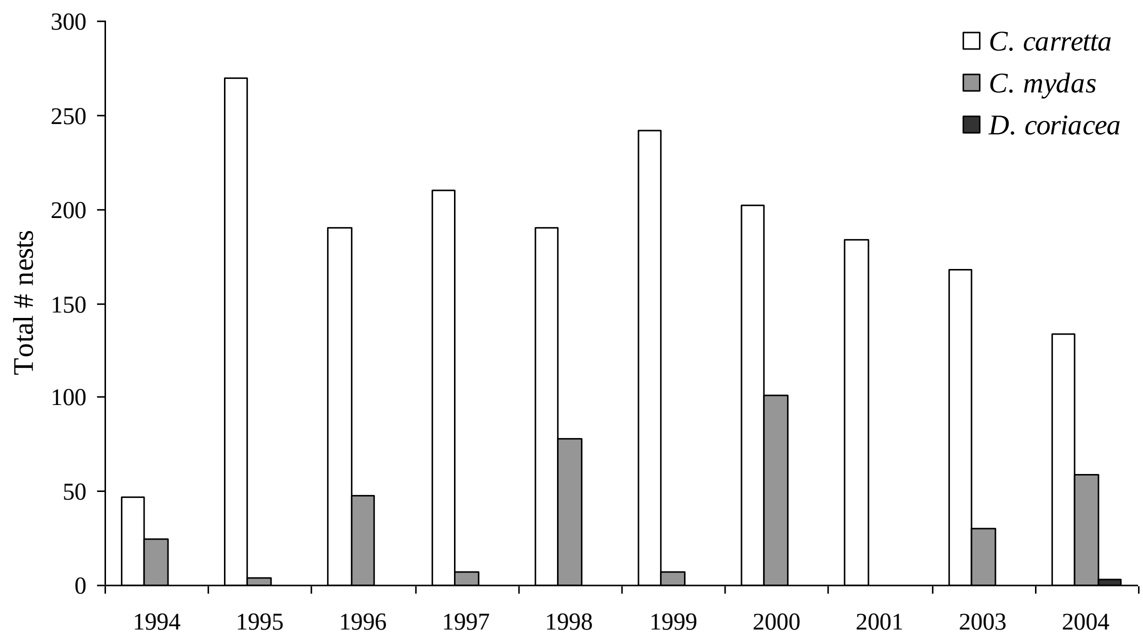


Figure 7.3. Annual counts of turtle nests by species on beaches in Dry Tortugas National Park, 1994−2004. Loggerhead = *Caretta caretta*; green = *Chelonia mydas*; leatherback = *Dermochelys coriacea*. (source: Florida Fish and Wildlife Research Institute; http://research.myfwc.com/images/articles/2377/sea_turtle_nesting_on_florida_bchs_93-07.pdf).

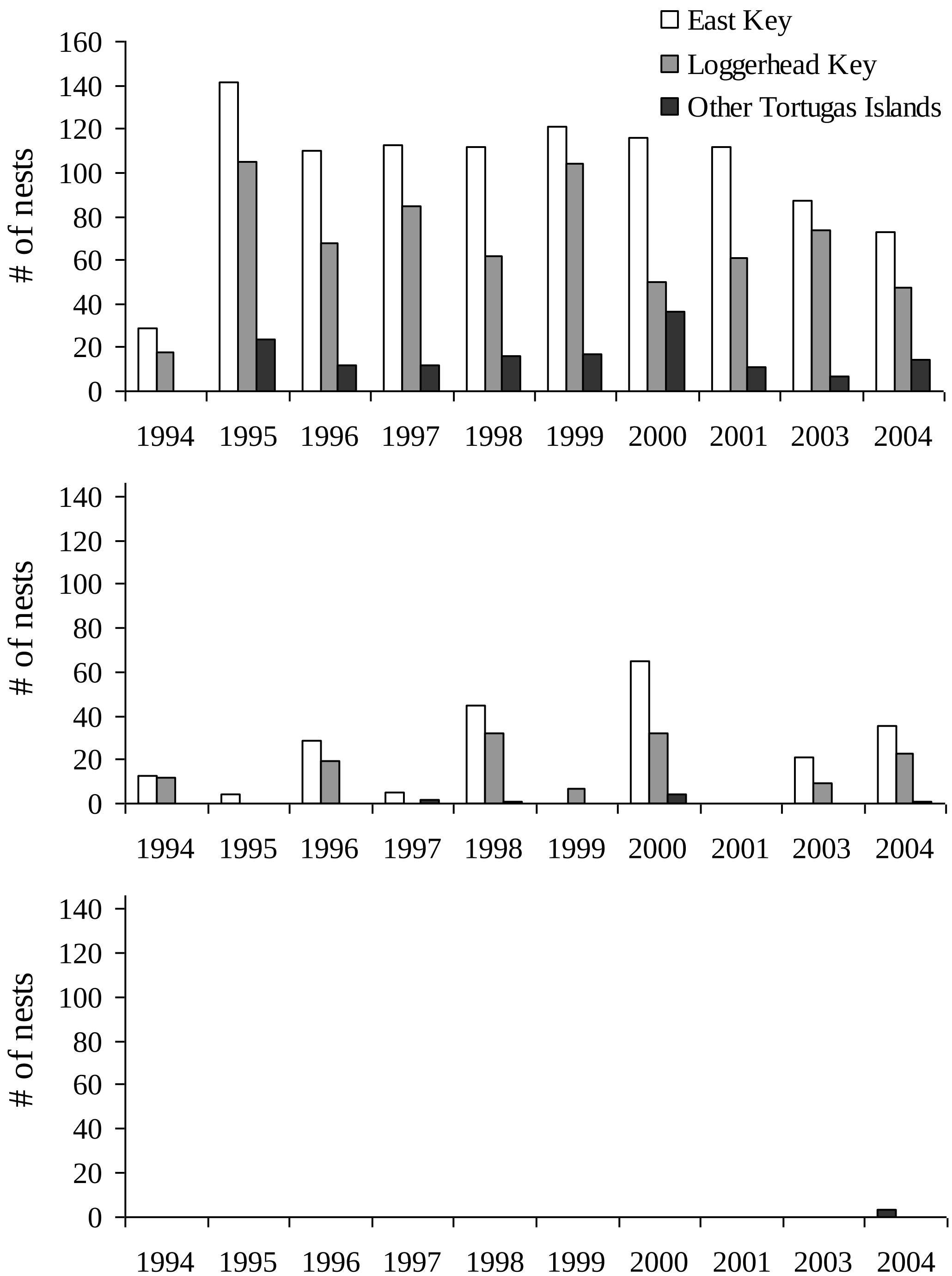


Figure 7.4. Annual counts of turtle nests on beaches in Dry Tortugas National Park, 1994–2004 (source: Florida Fish and Wildlife Research Institute; http://research.myfwc.com/images/articles/2377/sea_turtle_nesting_on_florida_bchs_93-07.pdf).

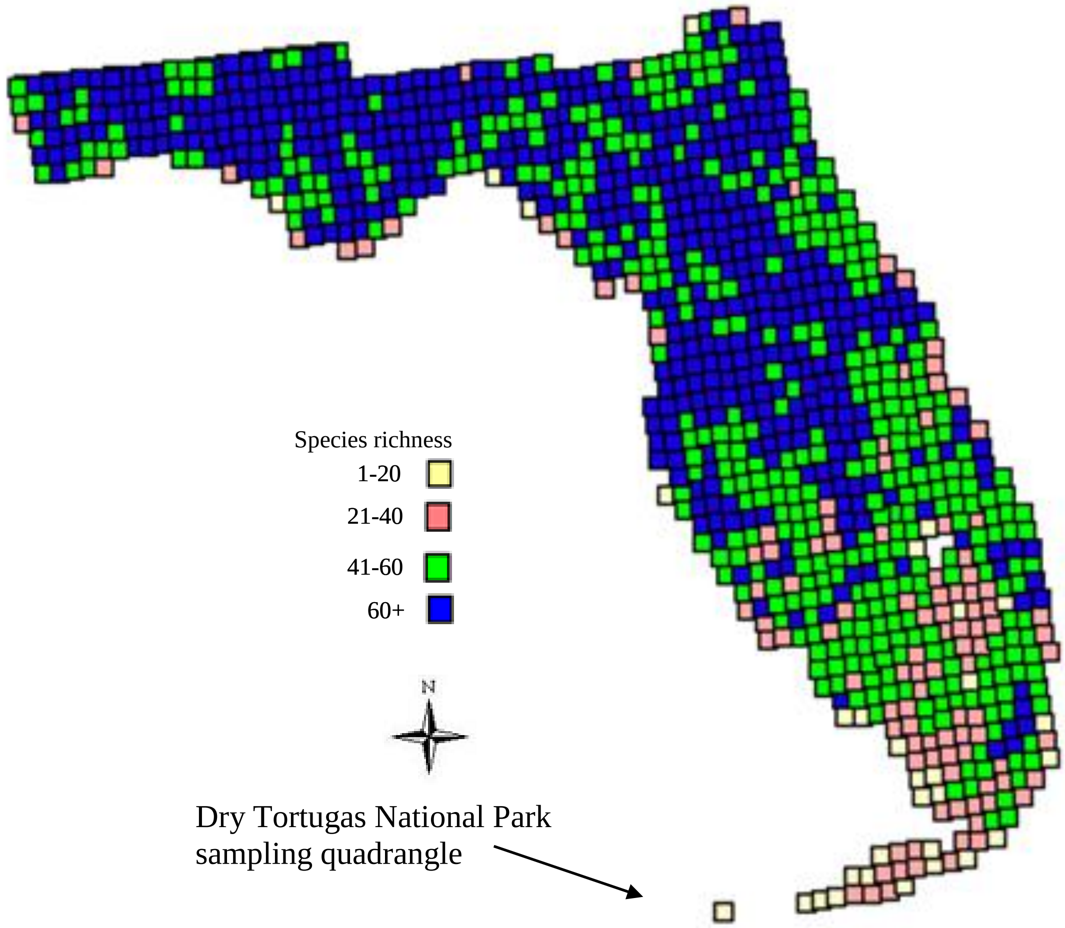


Figure 7.5. Spatial distribution of bird species richness in Florida, 1986–1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

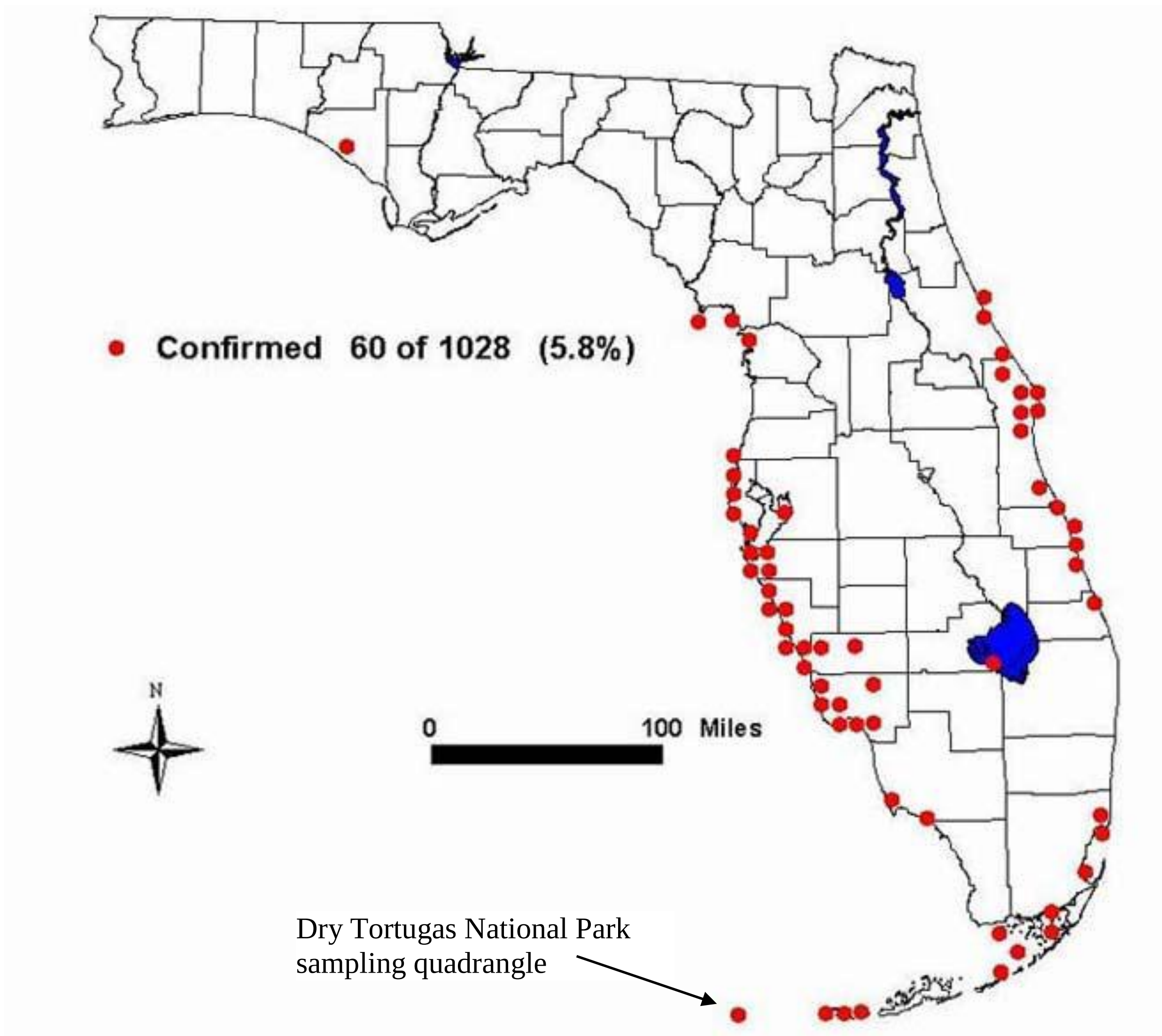


Figure 7.6. Spatial distribution of Brown Pelican (*Pelecanus occidentalis*) sightings in Florida, 1986−1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

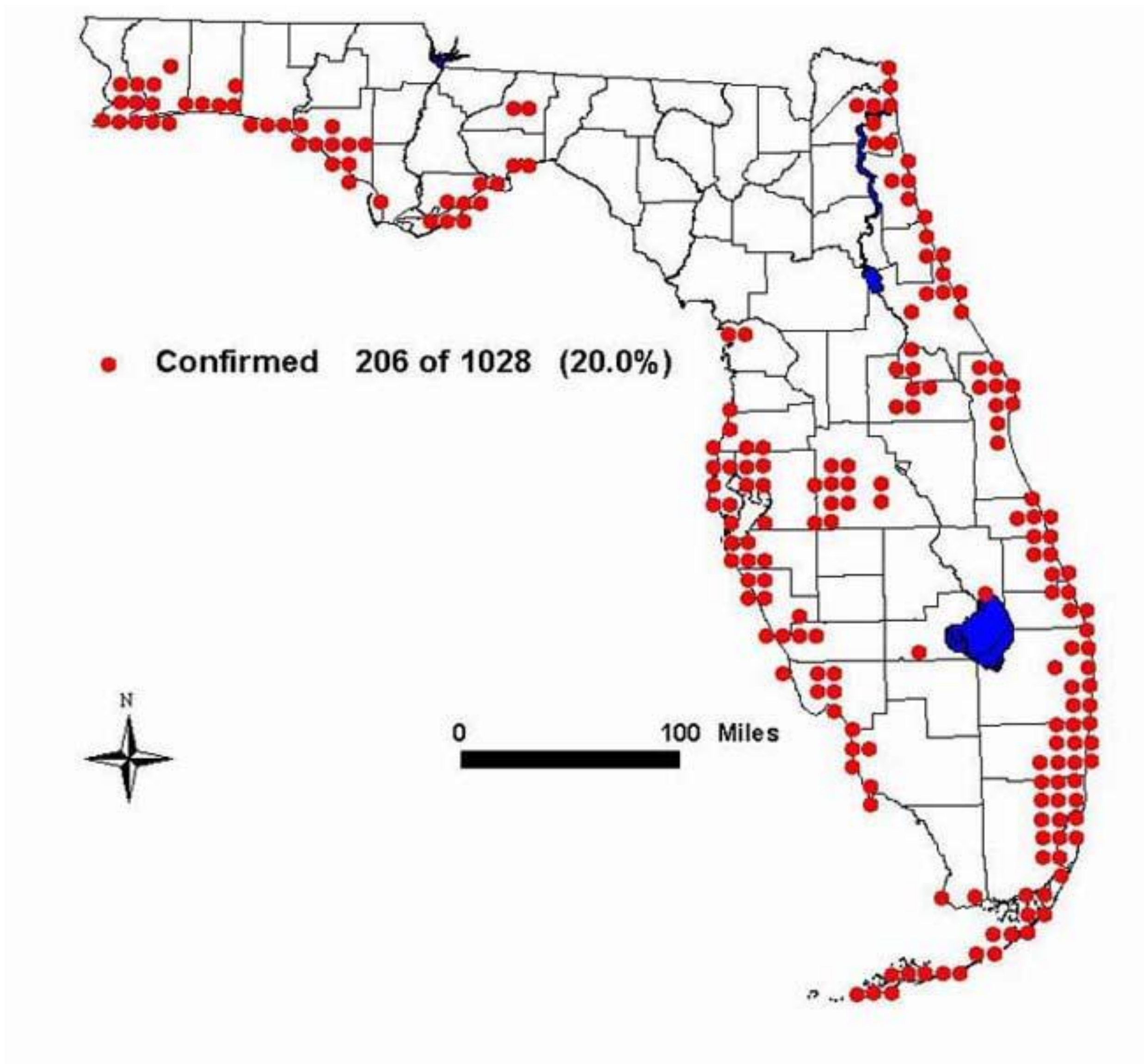


Figure 7.7. Spatial distribution of Least Tern (*Sterna antillarum*) sightings in Florida, 1986−1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

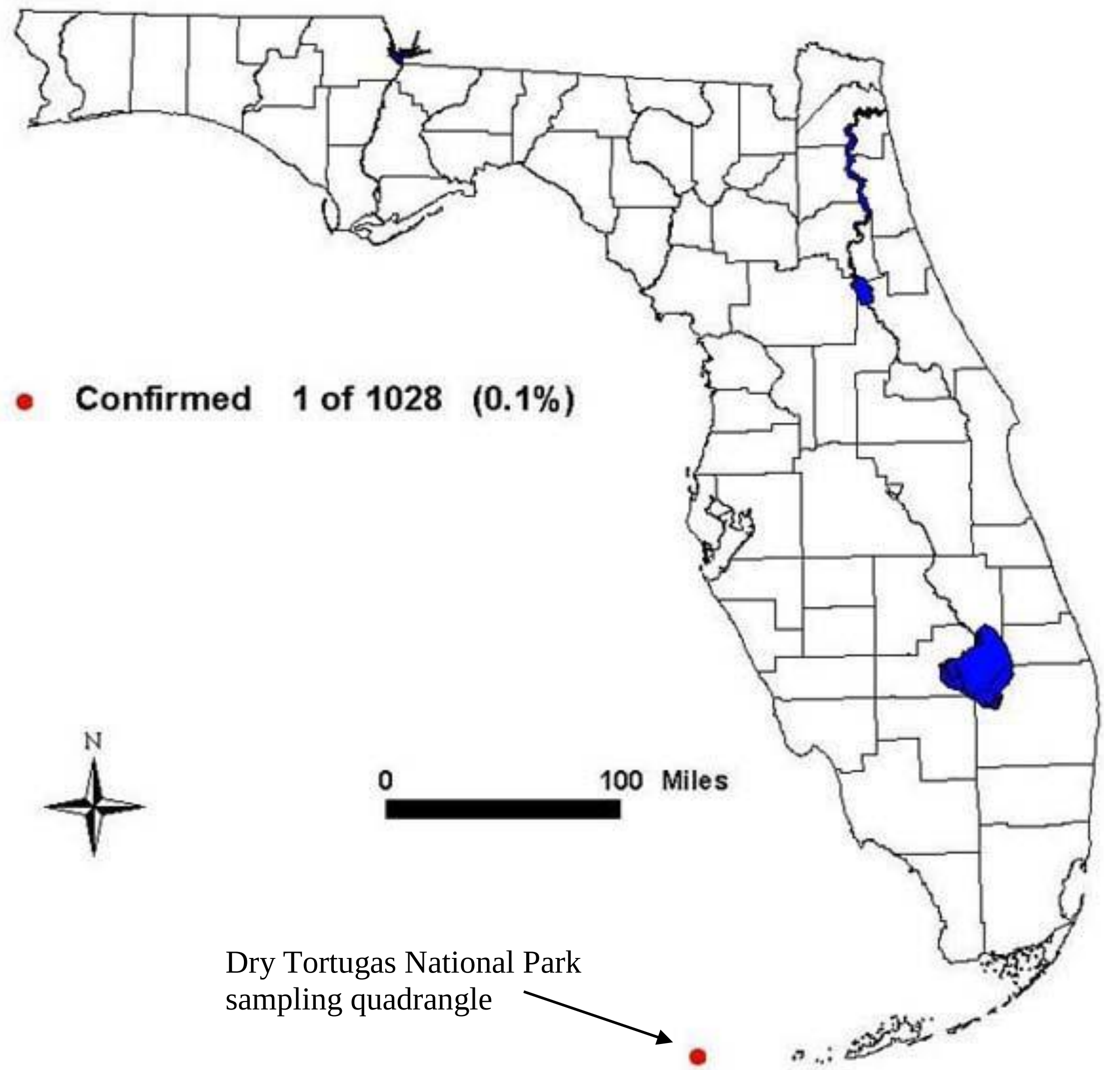


Figure 7.8. Spatial distribution of Sooty Tern (*Sterna fuscata*) sightings in Florida, 1986−1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

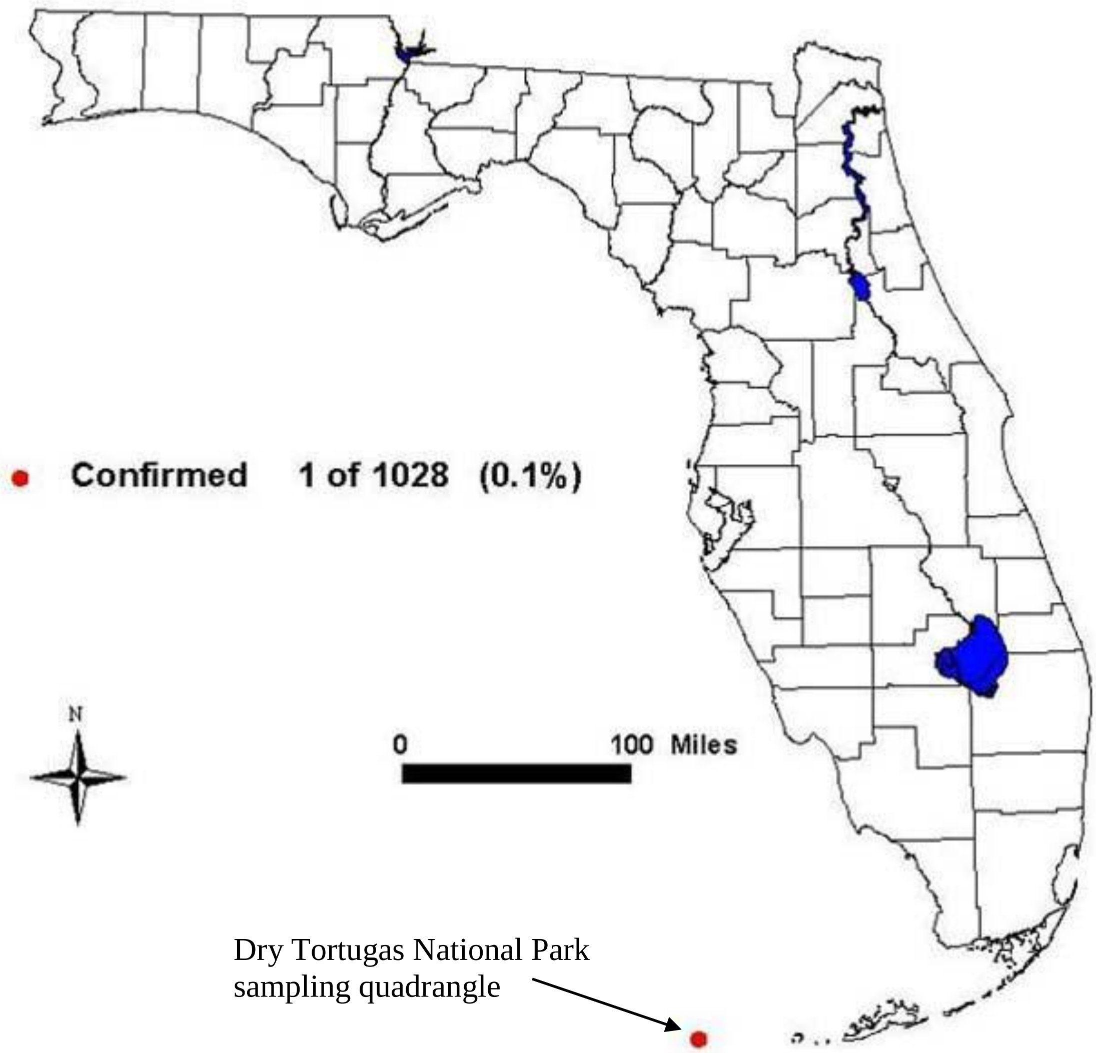


Figure 7.9. Spatial distribution of Brown Noddy (*Anous stolidus*) sightings in Florida, 1986−1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

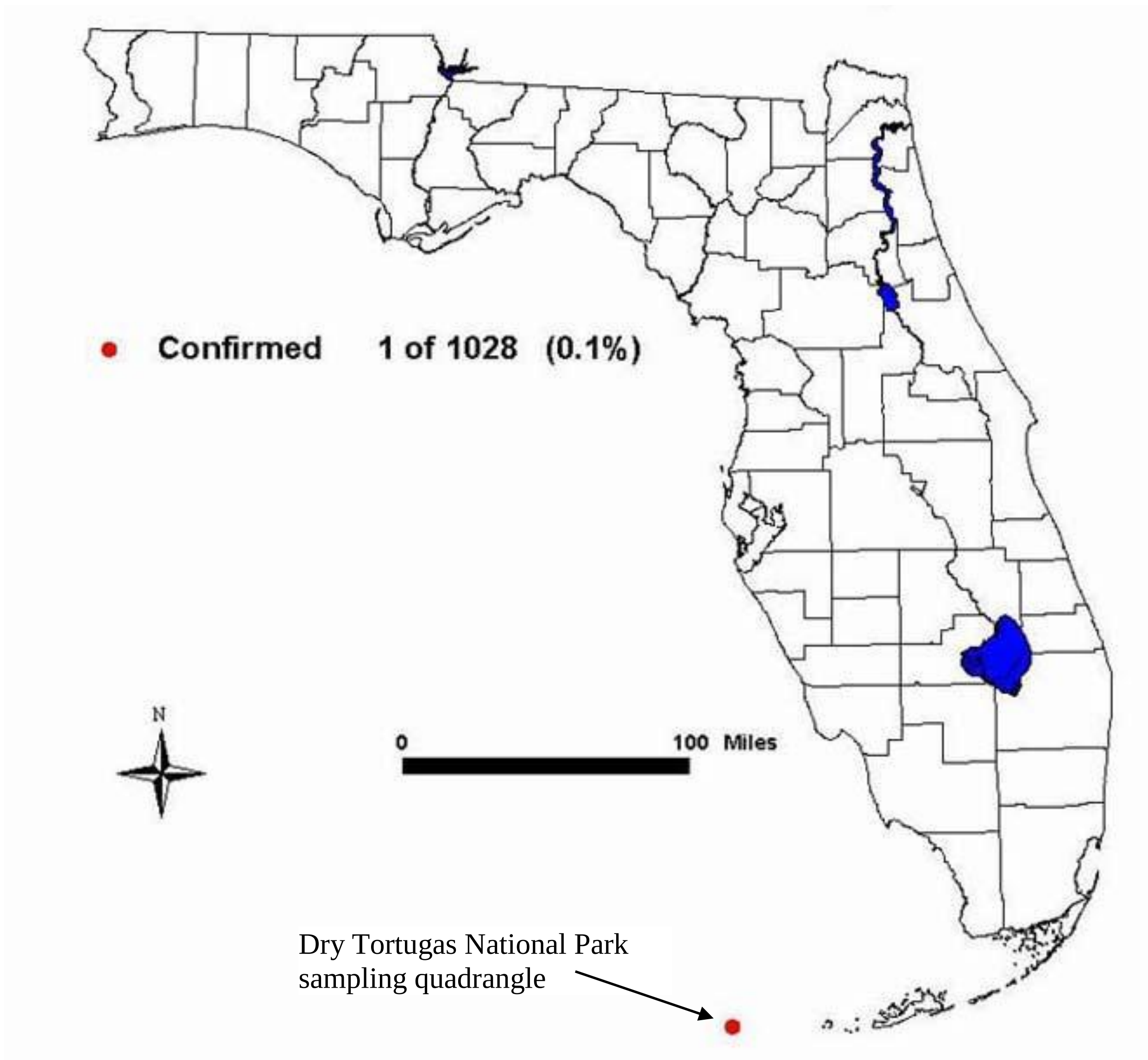


Figure 7.10. Spatial distribution of Masked Booby (*Sula dactylatra*) sightings in Florida, 1986−1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

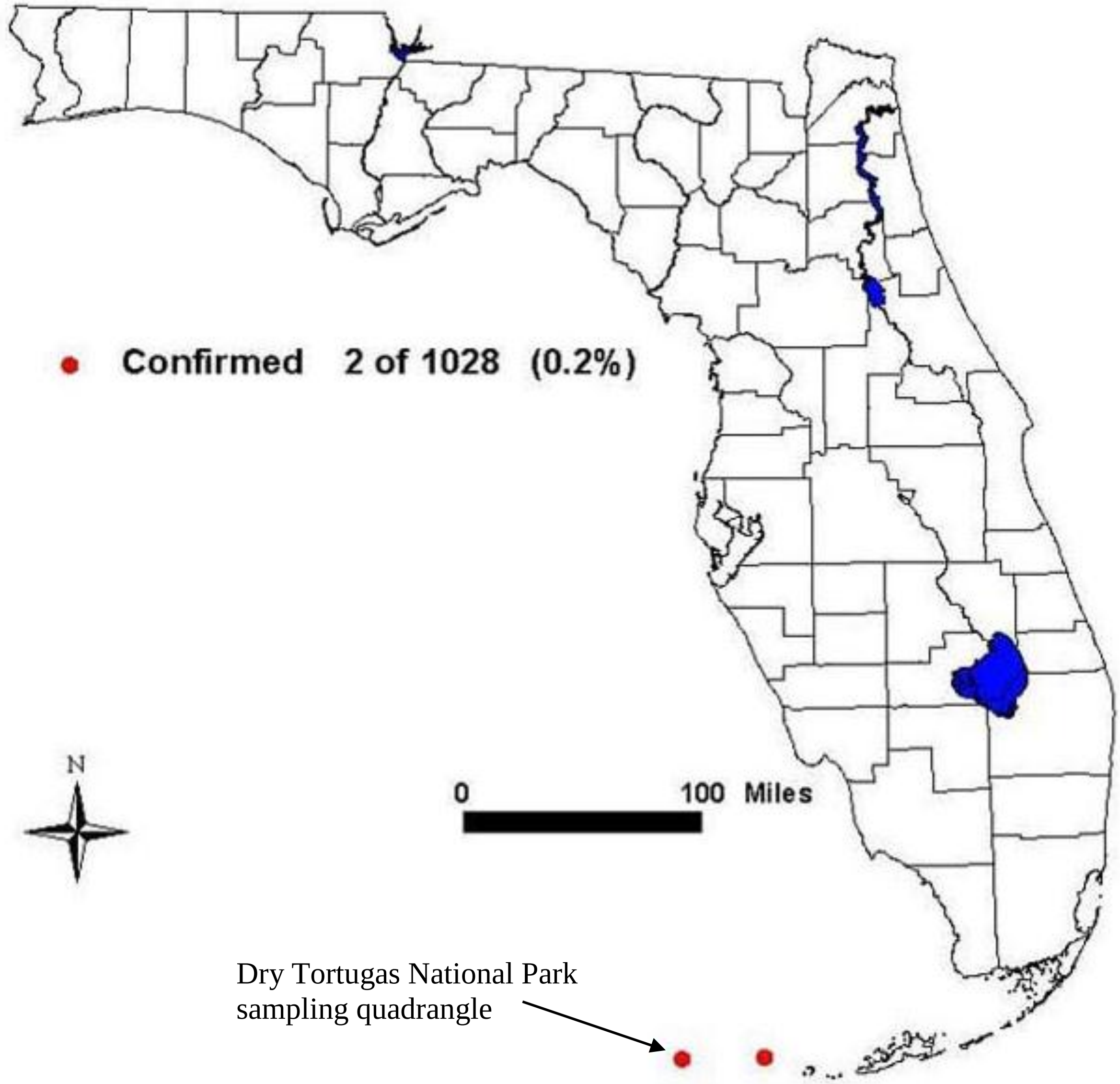


Figure 7.11. Spatial distribution of Magnificent Frigatebird (*Fregata magnificens*) sightings in Florida, 1986–1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

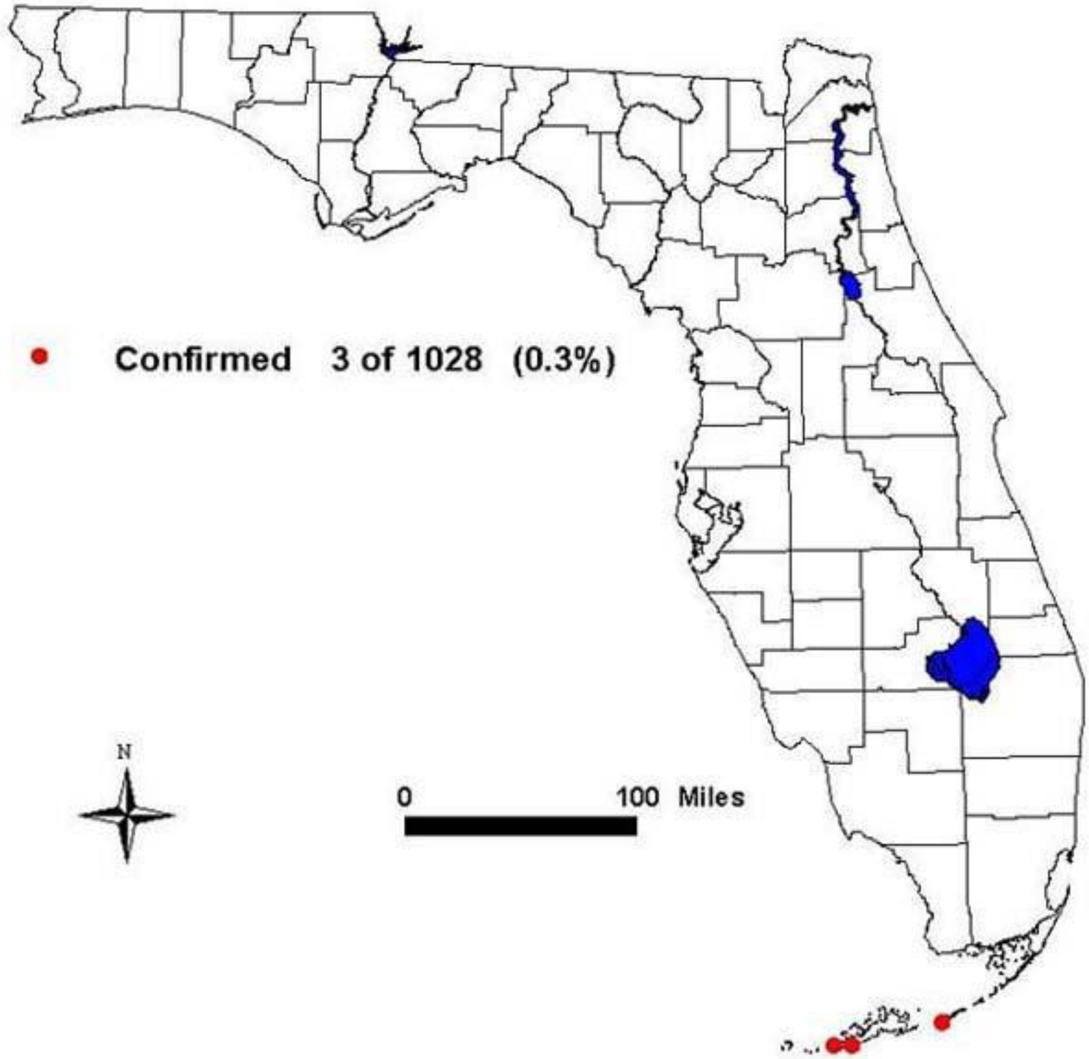


Figure 7.12. Spatial distribution of Roseate Tern (*Sterna dougallii*) sightings in Florida, 1986−1991 (source: Kale *et al.* 1992, Florida Fish and Wildlife Conservation Commission 2003).

Chapter 8. Condition of Marine Natural Resources

Christopher F. G. Jeffrey

Environmental and anthropogenic stressors affected the condition, abundance, and availability of natural resources in the Tortugas region. Many of the stressors act at multiple scales and have a range of effects on various components of coral reef ecosystems. This chapter evaluates the condition of marine resource components in the Tortugas region based on: (1) data available from monitoring and research projects, (2) existing and potential stressors to natural resources in the Tortugas region, and (3) the quality of information on natural resources and stressors. Resource-stressor matrices (Tables 8.2–8.10) were developed to associate stressors with resource components and to categorize their impact on natural resources. For each cell in the resource-stressor matrix, the extent of a stressor's impact was categorized as identified in Table 8.1.

The extent of information on stressors and their effects on each ecosystem components and associated natural resources were also included in resource-stressor matrices (Tables 8.3–8.10). The extent of information on stressors and natural resources in the Tortugas region were categorized and ranked shown in Table 8.2.

A summary of the stressors, resource categories, and extent of knowledge are provided in Table 8.11, which formed the basis for determining the overall ecological condition of resources in the Tortugas region. The percent of resource components affected by stressors and the percent of stressors affecting each resource component were summarized as pie charts from the stressor-resource matrices. For each resource, the proportion of stressors within each stressor-impact category and each information category were also summarized as pie charts. Finally, each natural resource component was assigned a qualitative rank of "Good," "Caution," or "Significant concern" for ecological condition based on aggregated information-richness and stressor-extent scores.

An aggregate Information score (*I*) was calculated for each resource component as follows:

$$I = \frac{\overline{X}_{rank}}{Rank_{\max}}$$, where, $$\overline{X}_{rank} = \frac{N_{Good} + N_{Fair}}{N_{Good} + N_{Fair} + N_{Poor} + N_{Inferential}}$$, and $Rank_{\max}$ is the maximum

information category (*Good*) assigned to a cell in the resource stressor matrix (Table 8.11). The *I* score ranged from 0–1, with 0 indicating that no information was available and 1 indicating that "*Good*" information was available for all resource-stressor cells. For I <0.5, resource components were categorized as"*Insufficient Data*," meaning that available data were inadequate to determine the ecological condition of the resource. For $I \geq 0.5$, an aggregate stressor score (*S)* was used to assign ranks of ecological condition to each resource and was calculated as follows:

$$1 - \frac{\overline{X}_{rank}}{Rank_{\max}}$$, where, $$\overline{X}_{rank} = \frac{N_{EP} + N_{PP} + N_{HP} + N_{OK} + N_{--}}{N_{EP} + N_{PP} + N_{HP} N_{OKl} + N_{--} + N_{unk}}$$, and $Rank_{\max}$ is the

maximum stressor category assigned to a resource-stressor cell. The *S* Score ranged from 0 to 1, with 0 indicating poor ecological condition (i.e., stressor has a negative impact on the resource) and 1 indicating good ecological condition (i.e., stressor has no known effect on the resource. Ecological ranks were assigned as follows:

$S > 0.75$ – Good,

$0.5 < S < 0.75$ – Caution, and

$S < 0.50$ – Significant Concern.

Although *I* and *S* scores were derived from qualitative and subjective rankings of stressors and the available information on their effects, they provide a consistent and objective method to minimize bias when assigning ranks of ecological condition. Descriptors of the ecological condition rankings used in this report are as follows:

Good	Published studies report no negative long-term trends in selected resource metrics. Published studies indicate that the resources in the Tortugas region are relatively more pristine compared with adjacent locations such as the Florida Keys. Published studies indicate that the resource is affected by 25% or fewer of the stressors summarized in Table 8.11.
Caution	Published studies report historical or long-term negative trends in selected metrics, but recent data (since 1990) indicate that the resource may be improving. Published studies also indicate that the resource component in the Tortugas region is not relatively more pristine compared with those in adjacent locations. Published studies indicate that the resource is affected by 26–74% of the stressors summarized in Table 8.11.
Significant concern	Published studies report drastic negative trends in selected resource metrics, and suggest that future declines in resource metrics are possible. Publish studies indicate that selected resource metrics are negatively affected by more than 75% or more of the stressors summarized in Table 8.11.
Insufficient data	Available data are inadequate to determine temporal and spatial trends or are insufficient to determine the effects of stressors on selected resource metrics.

8.1. Oceanographic and Climatic Stressors

8.1.1. Extent of the Problem

Table 8.3 provides a list of specific oceanographic stressors affecting natural resources in DRTO and the surrounding region. Climate and oceanography are major forces structuring marine natural ecosystems in the Tortugas region. Three primary stressors are associated with climate change: increasing sea surface temperatures (SST), sea level rise and ocean acidification (Chapters 3 and 8). Increasing SST is a major stressor to coral reef ecosystems, but whether it is problematic in the Tortugas region is uncertain. A temporal plot of AVHRR SST data from 1985−2005 for the Tortugas region does reflect an increasing trend in SST observed for the Gulf of Mexico (Van Houtan and Pimm 2006). Yet the frequency of SST anomalies[17] observed in the Tortugas region remained fairly constant between 1985–2005, unlike that observed in the

[17] SST Anomaly is defined as the number of weeks during which SST increased 1°C (1.8°F) above normal.

Caribbean Sea (Figure 8.1). Above average SSTs have been correlated with widespread and severe coral bleaching in the Caribbean and the Florida Keys in recent years, but only minor bleaching episodes have been observed in the Tortugas region (Donahue *et al.* 2008). Increasing SST was classified as "Existing," "Historical," or "Potential" for 33% of the resource components assessed in this report (Figure 8.2).

Sea level rise may not pose a major threat to submerged benthic resources (e.g., seagrasses and corals) except where they are located at the lower limits of the photo-adaptive zone (reviewed in Chapter 8). However, sea level rise could inundate and erode the low-lying Tortugas islands thereby reducing the availability of nesting beaches for sea turtles and colonizing birds (Chapters 7 and 8). Sea level rise represented only a "Potential Problem" for 56% or the resource components assessed in this report (Figure 8.2). Ocean acidification represented a "Potential Problem" for 33% of resource components in the Tortugas region because the negative effects of ocean acidification in marine ecosystems, although hypothesized, remain largely unknown (Figure 8.2).

Table 8.3 lists two stressors categorized as extreme events: cold/warm fronts and tropical storms. The phenomenon of periodic cold or warm fronts represented an "Existing Problem" for 22% of the resource components assessed for the Tortugas region (Figure 8.2). In the past, cold and warm fronts have decimated frame building (e.g., acroporids) coral populations in the Tortugas region, which have yet to recover to pre-1970 levels of abundance and cover (reviewed in Chapter 4). This absence of a recovery of corals to historic levels may be related to the relatively rapid changes in global ocean climate in recent times (Davis 1982, Jaap *et al.* 2008) (Chapter 4). Given that cold and warm fronts are stochastic events, they are likely to occur and affect coral populations in the future. Tropical storms also represented an "Existing Problem" and affected all (100%) of the resource categories assessed (Figure 8.2). Examples of specific effects of tropical storms on resource components in the Tortugas region are provided in Chapters 4–8.

8.1.2. Extent of the Information

The extent of data on the oceanography and climate of the Tortugas region was rated "Good" for four of the five resource-stressor cells in Table 8.3. However, data on the effects of ocean acidification on submerged ecosystems in the Tortugas were scant. Dire negative consequences (e.g., increased dissolution of reef structure and bioerosion) have been hypothesized for coral reefs under scenarios of increased ocean acidification. Information on ocean acidification was rated as "Inferential" (Table 8.3). Chapter 3 reviews studies describing oceanographic and circulatory patterns in the Tortugas region. One caveat is that very few studies have successfully correlated changes in oceanographic conditions through time with the large-scale declines in natural resources in the Tortugas region.

8.2. Stressors Affecting Water Quality

8.2.1. Extent of the Problem

Water quality in the Tortugas region was affected by only 12% of stressors assessed in this report (Figure 8.3). Stressors that affected water quality were tropical storms ("Existing Problem" 6%) and sedimentation ("Potential Problem" 6%). Nutrient enrichment and contaminants were not considered stressors to water quality and were rated an "Unlikely Problem" for that resource. Nutrient and contaminants are unlikely to reduce water quality in the Tortugas because the region is remote and upstream from potential land-based sources of pollution (Chapter 3).

8.2.2. Extent of the Information

The extent of data on stressors affecting water quality in the Tortugas was rated “Good” for three of four stressors: tropical storms, sedimentation, and nutrient enrichment (Table 8.4). The four stressors represented 25% of the stressor categories assessed in this report (Figure 8.4). The assigned ratings were based on the spatially explicit data for several water quality variables collected by Boyer and Briceño (2006, 2007). No information sources were found on the presence or absence of contaminants or their effects on water quality in the Tortugas region. The conclusion that nutrients and contaminants are an unlikely problem with respect to water quality in the Tortugas region is “Inferential” (Table 8.4).

8.3. Stressors Affecting Coral Reefs and Hardbottom

8.3.1. Extent of the Problem

Coral reef and hardbottom resources in the Tortugas region were affected by many of the stressors assessed in this report. Ten of 17 (59%) stressors were considered “Existing,” “Historical,” or “Potential” for the abiotic component;13 stressors (76%) were ranked similarly for the biotic component of reefs (Table 8.5, Figure 8.3). Three stressors (oil and gas exploration, nutrient enrichment and marine debris) were classified “Unlikely Problems” for the abiotic component of coral reefs (Table 8.5). Commercial fishing and habitat destruction were categorized as “Historical Problems” because commercial shrimp boats operated outside of the park boundaries prior to implementation of reserves in the Tortugas region. Two stressors (oil and gas exploration and nutrient enrichment) were considered “Unlikely Problems” for the biotic components of reefs (Table 8.5). There have been no studies verifying sedimentation of reefs in the Tortugas region, but it was classified as a “Potential Problem” because physical re-suspension of marine sediments from wave action is possible and detrimental to coral reefs (Richmond *et al.* 2007). Chemical contaminants and their effects on coral reefs and hardbottom resources were classified as an “Unknown Problem” because they have not been investigated in the Tortugas region.

8.3.2. Extent of the Information

The extent of information on the known stressors affecting coral reefs and hardbottom resources ranged from “Good” to “Inferential,” but there were no stressors for which information ranked as “Poor” (Table 8.5). Chapter 4 reviews information on coral reefs and hardbottom areas in the Tortugas region.

8.4. Stressors Affecting Seagrasses and Algae

8.4.1. Extent of the Problem

Several stressors (41%) may have affected seagrass and algal communities in the Tortugas region (Table 8.6, Figure 8.3). Tropical storms and sedimentation were classified as “Existing Problems” that affected the areal coverage and shoot density of seagrasses. Tropical storms, which are relatively frequent in the Tortugas region, have affected the abiotic and biotic components of seagrass and algal communities by redistributing sediments and ultimately changing seagrass spatial patterns of abundance and distribution. Commercial shrimp trawling outside of the park up until the implementation of the reserves in 2001 may have affected spatial patterns in seagrass distribution in the past and was classified as a “Historical Problem.” If seagrass and algal communities in the Tortugas were damaged, and whether they have recovered from impacts of commercial trawling remains unknown. Recreational boating, which is allowed within DRTO, along with boat groundings may be “Potential Problems” for shallow-water seagrass and algal beds and were classified as such. A recent study by NPS described scarring of shallow-water seagrass beds in Florida Bay by recreational boats as a significant problem (SFRNC 2008); the same may be true in the Tortugas region. Two stressors (oil and gas exploration) and nutrient enrichments were classified as "Unlikely Problems" for seagrass and algal communities (Table 8.6).

8.4.2. Extent of the Information

The extent of information for seagrass and algal communities was rated "Good" for tropical storms and nutrient enrichment (Table 8.6). Information for seagrasses was rated "Inferential" for eight other stressors because there is much information about stressor effects on seagrasses for the Tortugas region.

8.5. Stressors Affecting Reef Fishes

8.5.1. Extent of the Problem

Nine of the 17 stressors assessed in this report were applicable to reef fishes and most involved resource extraction (Table 8.7). Drastic declines in reef fish landings during the 1980s and 1990s lead to efforts e to reduce extraction and to rehabilitate reef fish populations in the Tortugas region. In 1935, commercial extraction was prohibited within park boundaries (Chapter 6). In 2001, commercial extraction was also prohibited within the TERs. Several regulations were enacted to limit the species targeted, gear types used, and daily catches landed from the region (http://www.nps.gov; http://floridakeys.noaa.gov/regs/welcome.html). More recently (2007), the implementation of the RNA within the DRTO further restricted recreational extraction. Despite these efforts to reduce resource extraction, populations of targeted species, such as black and red grouper, have not rebounded to pre-1979 abundance levels (Figure 8.2).

It may be that commercial and recreational fishing remain major stressors on reef fish populations in the Tortugas region. Historical fishing may have driven exploited reef fish populations to extremely low levels from which recovery will take decades. Areas currently prohibited from fishing within DRTO are small relative to the home range size of most commercially targeted species and the protection provided to target species is limited to only part of their home range. In the Tortugas region, commercial fishing still occurs in around and adjacent to prohibited areas, recreational fishing also still occurs within the park but outside prohibited areas, and evidence from socioeconomic studies suggests that fishers displaced by the Ecological Reserves have shifted their fishing efforts to the east of the park (Leeworthy *et al*., 2012). In this assessment, commercial fishing was considered a "Historical Problem" because of its legacy effects on targeted fish populations, whereas recreational fishing was considered an "Existing Problem." Marine debris in the form of lost or abandoned fishing gear has been problematic throughout the Florida Keys and was also considered in this assessment as an "Existing Problem" for the Tortugas region (Andrews *et al.* 2005, Donahue *et al.* 2008).

Other stressors applicable to reef fish resources were ocean acidification, tropical storms, and non-native species introductions ("Potential Problems") and trade in live species ("Unlikely Problem"). Reduced pH associated with ocean acidification potentially could alter the chemical cues used by larval fishes for settlement, which ultimately would affect spatial and demographic patterns of adult fish populations (Munday *et al.* 2009). Tropical storms may alter spatial patterns in fish distribution and fish habitats or cause extreme variability in fish recruitment patterns (Ault *et al.* 2004, 2006a). Lionfish, an introduced Pacific species, has invaded the Bahamas and the Florida Keys and was first observed at DRTO in 2009 (USGS 2011).

8.5.2. Extent of the Information

The information on stressors affecting reef fish resources received variable ratings (Table 8.7). The extent of information was rated "Good" for tropical storms, commercial and recreational fishing, and non-native species introductions. Information was rated "Inferential" for ocean acidification, habitat destruction, boat groundings and damage, and marine debris. The information on trade in live species was rated "Fair."

8.6. Stressors Affecting Sea Turtles

8.6.1. Extent of the Problem

Of the 17 stressors assessed, six (35%) were classified as "Existing," "Historical," or "Potential" problems for sea turtle populations in the Tortugas region (Table 8.8). The only stressor classified as an "Existing Problem" was tropical storms; storms and the associated wave action erode turtle nesting beaches and negatively affect nesting and hatchling success (Chapter 7). Similar to reef fishes, commercial fishing was categorized as a "Historical Problem" for sea turtles because populations have failed to recover from the excessive exploitation that occurred prior to the establishment of the park in 1935 (Chapter 7). Large numbers of turtles still were being killed as by-catch from shrimp trawling in Tortugas' fishable waters until 2003, when Turtle Exclusion Devices became mandatory. Conversely, Van Houtan and Pimm (2006) found only a slight "negative relationship between the number of boat days (a measure of shrimp fishery effort) and the number of green and loggerhead turtle nests observed in the Tortugas region between 1995−2004. They concluded that the shrimp fishery may have had minimal effects on turtle nesting activity during that period. Recreational fishing remains a "Potential Problem" for sea turtles because of possible collisions with boats and injuries from recreational fishing gear[18]. Sea level rise, recreational boating and visitation, marine debris, and invasive species (e.g., Australian pine, *Casaurina equisetifolia*) were considered "Potential Problems" for sea turtles because these stressors often damage nesting habitats and adversely affect reproductive success (Table 8.8).

Two stressors were rated "Unlikely Problems" for sea turtles in the Tortugas region. Increasing SST was rated an "Unlikely Problem" because (1) it is debatable whether SST is increasing in the Tortugas region and (2) the only reported effect of increasing SST on sea turtles was earlier nesting during years with warmer SSTs which has no obvious negative demographic effects (Van Houtan and Pimm 2006). Oil and gas exploration does not occur in the Tortugas region and was also rated an "Unlikely Problem" for sea turtles.

It is unknown if boat groundings and anchor damage and chemical contaminants were stressors for sea turtles. Boat groundings and anchors damage hardbottom and seagrass habitats that turtles use for foraging, but it is unknown if such damage adversely affects sea turtle abundance, nesting activity, or population trends. Chemical contaminants may be an unlikely stressor in the Tortugas region; however, sea turtles are wide-ranging pelagic species, and it is unknown to what extent they are exposed to pollutants and contaminants outside of the Tortugas region. For example,

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[18] Park regulations recommend against fishing activities near turtles and promote the use of circle hooks to avoid catching or injuring turtles (http://www.nps.gov).

some chemical contaminants (e.g., organochlorines, perfluorinated compounds and brominated flame retardants) have been identified in loggerhead and Kemp's ridley sea turtles off the South Carolina coast (Young *et al.* 2005, Keller *et al.* 2005).

8.6.2. Extent of the Information

The information on stressors affecting sea turtles received variable ratings (Table 8.8). The extent of information was rated "Good" for several stressors: Increasing SST, tropical storms, commercial and recreational fishing, and non-native species introductions. Information was rated "Inferential" for sea level rise, habitat destruction, boat groundings and anchor damage, nutrient enrichment, marine debris, and chemical contaminants. The information on oil and gas exploration was rated "Fair." Information on recreational use (i.e., boating and visitation) was rated "Poor," and trade in live species was rated "Unknown."

8.7. Stressors Affecting Seabirds

8.7.1. Extent of the Problem

Twelve of the 17 stressors assessed were considered applicable to seabirds (Table 8.9). Tropical storms were the only stressor classified as an "Existing Problem." Strong waves generated by storms erode beaches used by seabirds for nesting and negatively affect reproductive success (Sprunt 1948, Musick and Limpus 1997). Seabirds adversely affected by beach erosion include the Masked Booby, Sooty Tern, and the Magnificent Frigatebird. Other seabird populations at DRTO have benefited from tropical storms. In 2005, consecutive hurricanes (Dennis, Katrina, Rita, and Wilma) improved nesting habitat for Roseate Terns through the deposition of rubble and by burying vegetation along Tortugas beaches, which led to the reestablishment of a Roseate Tern nesting colony (Hood 2006). The abundance of Brown Noddys nesting on Bush Key increased after hurricanes decimated feral rat populations that preyed on the birds (FWC 2003).

Commercial and recreational fishing, sea level rise, oil and gas exploration, and marine debris were labeled "Potential Problems" for seabirds. Recreational fisheries and commercial fisheries outside of managed areas compete with seabirds for food resources. Competition could reduce feeding success and is a potential stressor for seabirds. Fishing attracts seabirds and the gear could injure them when they go after the catch. Seabirds migrate to areas where oil and gas exploration is common (e.g., Gulf of Mexico). For example, Robertson and Robertson (1996) observed oil on the feathers of Sooty Terns nesting at Bush Key. Marine debris was rated a "Potential Problem" because accumulation of debris on beaches after tropical storms reduces nesting habitat for seabirds (Hood 2006).

Nutrient enrichment was rated an "Unlikely Problem" and chemical contaminants were rated a "Historical Problem" for seabirds in the Tortugas region (Table 8.9). Nutrients are unlikely to affect nesting seabirds in the Tortugas because the region is remote and upstream from land-based pollution sources. Chemical contaminants may not be a problem in the Tortugas region; however, seabirds are wide-ranging, migratory species, and they may be exposed to pollutants and contaminants outside during their migrations. Organochlorines, perfluorinated compounds, and brominated flame retardants have been identified in marine predators, such as bottlenose dolphins in the Gulf of Mexico (Houde *et al.* 2005) and sea turtles in the southeastern U.S.(Young *et al.* 2005, Keller *et al.* 2005). Jodice *et al.* (2007) report that polybrominated diphenyl ethers (PBDEs) were common in pelican eggs collected from an island off the South Carolina coast. In the past, chemical contaminants have negatively affected seabird populations in the Tortugas region. During the 1970s, biomagnification of dichlorodiphenyltrichloroethane (DDT) through the food web caused catastrophic declines in Brown Pelican abundance throughout the Southeast, but populations have rebounded since the pesticide was banned (FWC 2003). Chemical contaminants were rated as a "Historical Problem" because of the historical effects of DDT on bird populations.

Non-native species introduction was classified as an "Unlikely Problem" for seabirds (Table 8.9). In the past, feral rats preyed upon ground nests and fledgling birds and a recent land bridge between Fort Jefferson and Bush Key provided a pathway for rats to migrate from Fort Jefferson and prey on species that nest on Bush Key[19] (Figure 8.3). However, the park staff has controlled rat predation successfully through an aggressive eradication program; rats do not seem to be affecting the birds nesting on Bush Key (Watson 2005). The abundance of introduced Australian pine, which had previously colonized beaches and reduced the availability of nesting habitat for birds, has been reduced to allow the resurgence of native vegetation that is more suitable for seabird nesting. It is unknown if increasing SSTs and ocean acidification should be considered as stressors for sea birds.

8.7.2. Extent of the Information

There was a paucity of information about stressors affecting seabirds in the Tortugas region (Table 8.9). The highest information rating given to stressor categories was "Fair" (tropical storms and invasive species). The extent of information was rated "Poor" for commercial and recreational fishing and oil and gas exploration. Information was rated "Inferential" for sea level rise, marine debris, and chemical contaminants because published studies from other locations suggest that these stressors could adversely affect seabirds. Information about the effects of sea level rise and ocean acidification on seabirds was rated "Unknown" (Table 8.8).

8.8. Assessment of Resource Condition

Table 8.8 summarizes the categories assigned to stressors and impacts and the information available for each resource component assessed in this report. This table was used to develop Information (*I*) and Stressor-extent (*S*) scores for rating the ecological condition of each resource assessed. To receive a condition rank, resource components must have received an *I* score ≥ 0.5. Water quality received *I* and *S* scores of 1.00[20] and 0.09 respectively; it was the only resource component to receive a rating of "Good" for ecological condition (Table 8.11). Water quality was affected by only 12% of the stressors and 24% of the stressors received a rating of "Fair" or higher for information pertaining to that resource. No temporal trends in water quality were reported in the literature reviewed. Based on data from Boyer and Briceño (2006, 2007), concentrations of dissolved oxygen and nutrients (i.e., nitrogen, phosphorus, and organic carbon) were fairly stable between 1995−2005. Water quality in the Tortugas region was also much better than in adjacent areas. Boyer (2005, 2007) observed much lower concentrations of dissolved nutrients in the Tortugas region than in the Florida Keys. Likewise, the average concentration of CHLA was much lower in the Tortugas region than on the West Continental Florida Shelf (Boyer and Briceño 2006, 2007).

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[19]The land bridge between the islands was created from sediment redistribution as a result of hurricane activity (Watson 2005)

[20] The information score of 1.00 was based on four stressors applicable to water quality in the Tortugas region, three of which received a "Good "or "Fair" ranking for information (Table 8.2).

The coral reef and hardbottom resource component received a rating of "Caution" for its abiotic component and 'Significant concern" for its biotic component (Table 8.11). This rating was based on the *I* score of 0.59 for both abiotic and biotic components and *S* scores of 0.47 and 0.56 for abiotic and biotic components respectively. Most of the available literature on coral reef and hardbottom areas reported temporal and spatial trends for living components rather than for non-living components. The metric most commonly measured to characterize the status of coral reefs was percent coral cover. Although the main causes of decline have been debated, most published studies support the conclusion that living coral cover has declined drastically in the Tortugas region during the past century. Published estimates indicate that average coral cover in the Tortugas region was less than 20% in 2005 (Chapter 4, Figure 4.7) compared with an average cover greater than 50% as recent as 1975 (Davis 1982, Jaap *et al.* 2008). Comparisons of anecdotal data also suggest that acroporid corals were much more spatially extensive and abundant in the Tortugas region in the past compared to the present (Davis 1982, Jaap and Sargent 1993, Jaap *et al.* 2008) (Chapter 4).

The seagrasses and algal community resource component received *I* scores of 0.20 and 0.22 for its abiotic and biotic components respectively (Table 8.11), which indicate that available information was inadequate to determine the ecological condition of seagrasses and algae. Only 12% of the stressors received a rank of "Good" or "Fair" for available information, even though 41% of stressors were applicable. The monitoring of seagrasses at permanent sites by DRTO staff is too limited to determine temporal and spatial trends for the park (Chapter 5). A useful data set for DRTO to obtain is Fourqurean and Escorcia (2006).

An ecological condition rank of "Caution" was assigned to reef fishes in the Tortugas region. The reef fish resource component received *I* and *S* scores of 0.56 and 0.51 respectively (Table 8.11). About 47% of stressors assessed were applicable to reef fishes, but information was rated "Good" or "Fair" for only 29% of the stressors. The abundance, size and species composition of reef fish assemblages are below historical levels (Bohnsack *et al.* 1994). Several exploited and unexploited fish populations have increased in abundance and fish size within marine reserves compared with fished areas in the Tortugas region since their implementation in 2001, and an increase in the frequency of exploited black and red groupers in the Tortugas region has been observed (Ault *et al.* 2007). Observations suggest that that a mutton-snapper aggregation may be reforming in the region (Burton *et al.* 2005).

Sea turtles received *I* of 0.58 and *S* scores of 0.38 and "Significant Concern" for ecological condition. Of the 17 stressors assessed in this report, 35% were applicable to sea turtles and 41% had information rated "Good" or "Fair." A 10-year time series (1994−2004) exists for turtle sightings and nesting activity in the park; however, the data are spatially limited and the time-series may be too short to infer long-term demographic trends for sea turtles. Published studies reviewed in this report indicate that abundances of sea turtles in the Tortugas region are substantially lower now than during pre-European times (Chapter 4). Data from 1994−2004 indicate that nesting activities of loggerhead and green sea turtles in the Tortugas region have been variable over time and between the two species. Hawksbill, leatherback, and Kemp's ridley sea turtles were uncommon and few data on their nesting activities were available (Van Houtan and Pimm 2006). Spatial patterns exist in the distribution of turtle nesting activities among the Tortugas islands. Average annual turtle nest density was highest at East Key, followed by

Loggerhead Key (Chapter 7, Figure 7.2). Annual trends in nest abundance also were spatially variable among the Tortugas islands (Chapter 7, Figure 7.4).

The sea bird resource component received *I* and *S* scores of 0.20 and 0.34 respectively (Table 8.11). The low *I* score indicated that the available information was inadequate to determine the ecological condition of seabirds. Only 12% of the stressors received a rank of “Good” or “Fair” for available information, even though 41% of stressors were applicable to seabirds. The rank of “Inadequate Data” was assigned to seabirds for ecological condition. A long but dated time series (1986−1991) is available for sea birds in the Tortugas region, but bird count data were not collected with appropriate statistical and sampling rigor to determine temporal and spatial trends and current ecological condition of sea birds in the park (Chapter 7).

8.9. Summary and Information Needs

The Dry Tortugas region is a unique marine ecosystem with luxurious coral reefs, seagrass meadows, and extensive areas of unconsolidated sediments. Coral reef ecosystems in the Tortugas region are relatively pristine compared to other areas in the Caribbean. Data on circulatory patterns and oceanographic processes provide evidence that the region is an upstream source of critical nutrients, food, larvae, and other planktonic organisms to adjacent areas, such as the Florida Keys (Lee *et al.* 1994, Lindeman *et al.* 2000). Conditions are due primarily to the remoteness of the Dry Tortugas from densely populated areas in the Florida Keys and the Florida mainland and the multibillion dollar commercial and sport fisheries of south Florida supported by the Tortugas region. However, the Tortugas region may not be as pristine as claimed and its distance from human population centers may not provide an adequate buffer from anthropogenic stressors.

Of the nine resource components assessed, water quality received an ecological condition ranking of “Good”; two components – nonliving portion of coral reef and hardbottom and reef fishes – received a rating of “Caution”; and two components – the biotic components of coral reef and hardbottom substrates and sea turtles − received a rating of “Significant Concern.” Seagrass and algal communities and seabirds were not rated because the available information was inadequate. The findings suggest that marine resources in the Tortugas region are affected by several stressors, some of which act synergistically.

Tropical storms was the dominant stressor in the Tortugas region affecting all resource components assessed (Figure 8.2). Commercial and recreational fishing were also dominant stressors affecting 78% of the resource components assessed (Figure 8.2). The most stressed resource was the biotic component of coral reef and hardbottom resources, which was affected by 76% of the stressors (Figure 8.3). Water quality is the resource category in the most pristine condition; it was negatively affected by only 12% of stressors (Figure 8.3).

The systematic assessment of marine natural resources in the Tortugas region revealed several gaps in information. The Dry Tortugas is one of the best studied marine ecosystems in the U.S., with information dating as far back as the mid-1800s (Schmidt and Pikula 1997, Davis 1982, Shinn and Jaap 2005). Yet much remains unknown about the ecology of the region. For example, of the nine marine resource components reviewed in this report, the living component of coral reefs and hardbottom resources had the best rated information; 25% of stressor categories were rated “Good” for information richness (Figure 8.5). In contrast, there was a general lack of information for seagrass and algal communities and sea birds (Figure 8.5).

The goals of this assessment were to identify: (1) the state of knowledge for natural resources that exist within DRTO, (2) the state of knowledge for natural and anthropogenic stressors and threats that affect these resources, and (3) current and future strategies to help DRTO managers meet their management objectives. Based on the literature reviewed, the following recommendations are offered to park managers:

1) Despite the preponderance of research and monitoring studies that have been conducted at DRTO in the past century, only a limited amount of natural resources data are available to park staff for planning and decision making. It likely results from ownership and publication rights of researchers to the data they collect.

- ❖ **Recommendation:** NPS should incentivize researchers to share data with resource managers and park managers should develop a repository for data collected during monitoring and research studies conducted within park boundaries. Monitoring and research studies should be tracked through permits issued for conducting research in the park. The staff of the SFCN uses this model to gather and archive reef fish and coral data collected by its partners from parks in southeast Florida and the Caribbean. This process should be extended to include data sets on other natural resources, such as seagrasses, birds, and turtles.

2) Several federal and state agencies and academic organizations conduct monitoring and research programs in the park (Chapter 2). Many of these programs collect data for their own management or research agendas. Although it may seem cost-effective in the short-term to depend on these programs to obtain natural resource information within the park, data collected by these programs may not match the needs of DRTO resource managers (e.g., collected at the appropriate spatial and temporal scales relevant to management of the park). For example, data from sampling designs that provide precise metrics at the scale of the Florida Keys reef tract may not provide the precision necessary to detect differences among sampling strata at the scale of the park (Chapter 6). Data collected at randomly selected sites are not always suitable or precise enough for detecting temporal trends. Data collected from permanent sites are not best suited for characterizing spatial patterns of resources.

- ❖ **Recommendation:** NPS staff should evaluate existing monitoring and research programs carefully to determine what data types are best suited to their management needs. They should work with other agencies to increase sharing of relevant data among researchers and the DRTO. Monitoring programs should be designed and implemented to collect data that meet the specific goals and objectives of park managers. The strategy recommended here would ensure that the best ecological information available is used to make management decisions and fill existing gaps in the types of data needed for sustainable management of natural resources. A good example of the recommended strategy is the science plan developed by a multi-agency team to assess conservation efficacy of the DRTO (SFNRC and FWC 2007). The science plan focuses mainly on the effects of the RNA on reef fish assemblages. A similar process should be used to develop monitoring and research plans for other natural resources, such as corals, seagrasses, seabirds, and sea turtles.

3) Coral reefs in the Tortugas region are very different from what they were 100 years ago. Historical reports and maps suggest that live coral was widely distributed and abundant on hardbottom substrates in the Tortugas region. This historical view contrasts sharply with reports from current monitoring projects indicating that live coral is now significantly less abundant and less widely distributed. Long-term declines in the spatial extents and abundance of living coral may have resulted from the cumulative and synergistic effects of environmental and anthropogenic human stressors. Trends in the trajectory of coral reefs in the DRTO, Tortugas region, and the Florida Keys during the past decade, suggest that future declines in coral cover are likely.

- ❖ **Recommendation**: DRTO management staff should develop discrete and achievable goals for protecting coral reefs in the park from anthropogenic stressors that could increase the susceptibility of reefs to natural stressors that are beyond the control of managers. Such goals are dependent on the establishment of baseline levels of coral cover and colony abundance so that future change in these metrics could be compared. Establishment of baselines and future targets will require well-designed monitoring programs that adequately characterize the spatial and temporal variability known to exist in coral reef ecosystems. Every effort should be made to obtain and use monitoring data from existing programs to develop a spatially robust and comprehensive resource management program for corals.

4) Seagrass beds remain the most spatially expansive substrates within the park. Turtle and eelgrass dominate substrates <10 m (<33 ft) deep and paddle grass is more abundant at depths >10 m (>33 ft). Seagrasses are important to coral reefs in the Tortugas region because their primary productivity forms the basis of food webs that support reef fish assemblages and provide connectivity among hardbottom habitats through trophic energy flows. Algal communities are spatially extensive, but typically are ephemeral and occur on hard (e.g., rubble) and soft (sand) substrates. Currently, two annual monitoring programs sample benthic communities in seagrass and algal beds within DRTO, but data on the status and condition of seagrass and algal beds in the park are not readily available to park managers and are not precise or adequate to determine the current ecological condition of seagrasses.

- ❖ **Recommendation**: DRTO management staff should expand sampling programs that currently monitor the ecological condition of seagrass beds. Existing monitoring projects are steps in the right direction, but the number of sites currently being monitored is inadequate to quantify and characterize the spatial extent and the ecological condition of seagrass beds in the park. A probabilistic sampling design that includes all types of seagrass beds in all management use zones should be developed to characterize seagrasses occurring within the park. Data that characterize the magnitude and spatial extent of stressors (i.e., prop-scarring from motor boats) should be collected along with biological data (i.e., percent cover, shoot density, and blade length of seagrasses). The two sets of information could be used to develop guidelines for motorboat use in the cultural and historic zones to minimize the human impacts on shallow seagrass beds.

5) Reef fish assemblages are the most comprehensively sampled and well-characterized natural resource in the Tortugas region. Fish assemblages are essential and prominent components of the marine ecosystems occurring in the Dry Tortugas, but have suffered significant declines in the abundance and size of desirable species because of historical overfishing. Although full recovery is expected to take decades, the establishment of no-take reserves coupled with a suite of management actions that reduced fishing mortality already may be having a net positive effect on previously exploited reef fish populations. Several studies have characterized population abundance and size of exploited species and are tracking their temporal trends to evaluate the effectiveness of no-take reserves, including the newly established RNA within DRTO. While reef fish assemblages of coral reefs and hardbottom areas have been well characterized, reef fish assemblages in unconsolidated sediments are poorly characterized. Reef fishes in Tortugas region use a mosaic of habitat types, including unconsolidated sediments through daily home range movements and ontogenetic habitat shifts.

❖ **Recommendation**: Existing programs that characterize reef fish assemblages on reef and hardbottom substrates within various park management zones should continue. Efforts should be made by park staff to characterize reef fish assemblages occurring in unconsolidated habitats. Existing data on reef fishes should be analyzed to determine baseline levels for reef fish metrics against which future data could be compared. The recently developed science plan for evaluating the conservation efficacy of the RNA recommends several additional performance goals and measures for reef assemblages that should be implemented (SFNRC and FWC 2007).

6) Seabirds and sea turtles are important components of marine ecosystems. Sea turtle abundance in the Tortugas region is substantially lower now compared to pre-European times, but sea turtles continue to nest on beaches within the park. Sea birds continue to forage and breed in the park and the National Audubon Society continues to list DRTO as an important birding area in Florida. The Tortugas region is the only breeding site within the continental U.S. for three species of seabirds. Resource managers have encouraged Roseate Terns to nest successfully in the park as they did historically. Important stressors affecting turtle nesting and seabird colonies at DRTO include shoreline erosion, coastal vegetation, exotic plants, and increased human visitation. There are no monitoring programs for sea turtles in the park and monitoring of seabirds occurs at only a few sites.

❖ **Recommendation**: A well-defined sampling plan that uses habitat information to guide site selection should be developed to characterize the spatial distribution of sea turtles and colonial nesting birds within the park.

7) Coral reef ecosystems in the Tortugas region are plagued by multiple stressors that act at various scales and have a range of effects. Environmental stressors have acted synergistically to reduce coral cover and abundance in the Tortugas region during the last century. Anthropogenic stressors have contributed to loss of live coral cover, declining species diversity, overall decline of coral reef ecosystem health, and a reduction of natural resources such as reef fishes. Few studies have assessed the effects of stressors on natural resources despite studies that have monitored and documented temporal and spatial variability changes in coral reef resources in the Tortugas region. Thus, it is very

difficult to differentiate between natural and anthropogenic causes of resource degradation in coral reef ecosystems. Currently, the most likely source of anthropogenic stress to natural resources in the Tortugas region is recreational activities of humans. Most other extractive activities are prohibited in the TER and the DRTO. Recreational activities, such as boating, fishing, and scuba diving associated with increased visitation to the Tortugas, will place increased anthropogenic stress on the region's coral reef ecosystems. The cumulative impacts of reef-related recreational activities could have a profound negative long-term effect on the natural resources of the Tortugas region.

- **Recommendation**: Park management staff should assemble a team of experts to develop monitoring and sampling programs to characterize impacts of stressors on various natural resources within the DRTO. Park staff should work with known experts to develop strategies to mitigate the potential negative effects of increased visitation and visitor use on natural resources of the park.

Table 8.1. Categories and rankings used to describe the impacts of stressors on natural resources in Dry Tortugas National Park (DRTO).

Stressor extent	Rank	Description
Existing problem (EP)	1	Convincing historical (before 1990) or current (1990 to present) evidence that the stressor affects resources at DRTO negatively.
Historical problem (HP)	2	Convincing evidence exist that stressor affected resources at DRTO prior to 1990, but is no longer a problem.
Potential problem (PP)	3	Stressor is known to affect natural resources negatively, but there is no convincing evidence that it negatively affects resource at DRTO; threat could become a stressor in the near future.
Unlikely problem (OK)	4	Stressor has been investigated and no convincing evidence exist that stressor affects resources negatively; stressor has been alleviated by a management action.
Not applicable (--)	5	Stressor is not known to affect the resource or ecosystem component.
Unknown (UNK)	0	There is insufficient data to determine if the stressor has negative effects on natural resources at DRTO; effects of stressor has not been investigated at DRTO.

Table 8.2. Categories and rankings of information used to describe the impacts of stressors on natural resources in Dry Tortugas National Park.

Information extent	Rank	Description
Good	4	Published studies have documented the effects of the stressor on a natural resource or ecosystem component in the Tortugas region.
Fair	3	No published studies exist, but unpublished monitoring data exist to show the effects of the stressor on a natural resource or ecosystem component in the Tortugas region.
Poor	2	Only anecdotal information exists to indicate that the stressor may be affecting a natural resource or ecosystem component in the Tortugas region;
Inferential	1	No data exist to indicate that stressor is impacting natural resources or ecosystem component in the Tortugas region, but stressor is known to affect the natural resources elsewhere.
Unknown	0	No information was available.

Table 8.3. Oceanographic stressors of natural resources in the Tortugas region. Colors describe the extent to which the stressors may be affecting natural resources (cf. Chapter 3).

Threat	Oceanography and Climate Variables	Extent of Problem	Metrics	Data Summaries/References	Extent of Information
Climate Change	Increased sea surface temperature (SST)	PP	SST, ocean color	Lee *et al*. 1999, Kourafalou *et al*. 2005, Johns 2003	Good
	Sea level rise	--	Altimetry; tide level	Lee *et al*. 1999, Kourafalou *et al*. 2005, Johns 2003	Good
	Ocean acidification (reduced pH)	UNK	pH	Kuffner *et al*. 2008, Albright *et al*. 2008, Munday *et al*. 2009	Inferential
Extreme Events	Cold / warm fronts	EP	SST, ocean color	Agassiz 1883, Davis 1982, Jaap and Sargent 1994, Jaap *et al*. 2008	Good
	Tropical storms	EP	Current flow and direction; wave height; salinity	Lee *et al*. 1999, Kourafalou *et al*. 2005, Hiildalgo *et al*. 2003	Good

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.4. Stressors affecting water quality resources in the Tortugas region. Colors describe the extent to which stressors are affecting water quality (cf. Chapter 3).

Threat	Stressor	Water Quality	Metrics	Data Summaries/References	Extent of Information
Extreme Events	Tropical storms	EP	Frequency of storm occurrence; turbidity; salinity; density	Lee *et al*. 1999, Kourafalou *et al*. 2005	Good
Pollution	Sedimentation	PP	Turbidity, light attenuation, PAR	Boyer and Briceño 2006, 2007, Lee *et al*. 1999, Kourafalou *et al*. 2005	Good
	Nutrient enrichment	OK	N, P, Chl, DO, TOC, silicate	Boyer and Briceño 2006, 2007	Good
	Chemical contaminants	OK	Remote location (distance from land); presence/absence of contaminants	None available	Inferential

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.5. Stressors affecting coral reef and hardbottom resources in the Tortugas region. Colors describe the extents to which stressors are affecting reef and hardbottom resources (cf. Chapter 4).

Threat	Stressor	Coral Reef and Hardbottom Communities		Metrics	Data Summaries/References	Extent of Information
		Abiotic	Biotic			
Climate Change	Increased sea surface temperature	EP	EP	SST; coral disease incidence and prevalence; percent bleached coral cover, no. of colonies bleached	Santavy *et al.*, 2001, Jaap *et al.* 2008, NOAA Coral Watch Program	Good
	Sea level rise	PP	PP	Tide level gauges; sea level height (altimetry)	Lee *et al.* 1999, Kourafalou *et al.* 2005, Johns 2003	Inferential
	Ocean acidification	PP	PP	pH; reef calcification rates	Kleypas 2007, Precht and Miller 2007, Hoegh-Guldberg *et al.* 2007, NOAA Coral Watch Program	Inferential
Extreme Events	Cold /warm fronts	--	EP	SST; ocean color; coral disease incidence and prevalence; percent bleached coral cover; no. of colonies bleached; degree heating weeks	Agassiz 1882, Davis 1982, Jaap and Sargent 1994, Jaap *et al.* 2008	Good
	Tropical storms	EP	EP	Storm occurrence; incidence of physical damage to benthic organisms; abundance of frame building corals	Andrews *et al.* 2005, Miller *et al.*, 2006, Jaap *et al.* 2008, Donahue *et al.* 2008	Good
	Disease epidemics	EP	EP	Storm occurrence; disease incidence and prevalence	Patterson *et al.* 2002, CREMP Monitoring, Miller *et al.* 2006, Andrews *et al.* 2005	Good
Resource Extraction	Commercial fishing	HP	HP	Community structure metrics (benthic diversity; coral abundance or cover; algal cover)	Miller *et al.* 2006	Inferential
	Recreational fishing	EP	EP	(species diversity; coral abundance or cover; algal cover)	Miller *et al.* 2006	Inferential
	Trade in live species	--	--	Collection and sale of reef organisms; number of permits issued for collection of reef organisms	Andrews *et al.* 2005, Donahue *et al.* 2008	Inferential
	Habitat destruction from fishing gear	HP	EP	Area of habitat affected; gear type abundance	Andrews *et al.* 2005, Donahue *et al.* 2008	Fair

Table 8.5 continued.

Threat	Stressor	Coral Reef and Hardbottom Communities		Metrics	Data Summaries/References	Extent of Information
		Abiotic	Biotic			
Resource Extraction	Boat groundings and anchor damage	EP	EP	Number of grounded vessels; area sea bottom (benthic substrate) damaged	Andrews *et al.* 2005, Donahue *et al.* 2008, Elliot 2003, NOAA office of Response and Restoration (OR&R) Incident News (http://www.incidentnews.gov/results)	Good
	Oil and gas exploration (spills)	OK	OK	Number of vessel groundings; habitat area affected; volume of oil, fuel, and other pollutants spilled	Andrews *et al.* 2005, Donahue *et al.* 2008, Elliot 2003, NOAA OR&R Incident News (http://www.incidentnews.gov/results)	Fair
Pollution	Sedimentation	PP	PP	Volume of sediment, sediment chemistry, rate of sedimentation; re-suspension loads	Andrews *et al.* 2005, Donahue *et al.* 2008, Richmond *et al.* 2008	Inferential
	Nutrient enrichment	OK	OK	N, P, Chl, DO, TOC, silicate etc.	Boyer and Briceño 2006, 2007	Good
	Marine debris (e.g., derelict fishing gear)	OK	PP	Number of pieces	Chiappone *et al.* 2002, 2005	Fair
	Chemical contaminants	UNK	UNK	Presence/absence of contaminants	none available	Inferential
Invasive Species	Nonnative species introductions	--	PP	Presence/absence, and abundance of invasive species	Andrews *et al.* 2005, Donahue *et al.* 200, http://www.reef.org	Good

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.6. Stressors affecting seagrass and algae communities in the Tortugas region. Colors describe the extents to which stressors are affecting seagrass and algal resources (cf. Chapter 5).

Threat	Stressor	Seagrass and Algal Communities		Metrics	Data Summaries/References	Extent of Information
		Abiotic	Biotic			
Extreme Events	Tropical storms	EP	EP	Storm frequency; seagrass percent cover; areal extent; shoot density	Fourqurean *et al.* 2002 (http://serc.fiu.edu/seagrass/)	Good
Resource Extraction	Commercial fishing	HP	HP	Fishing effort; seagrass percent cover; areal extent; shoot density	None available	Inferential
	Recreational fishing	PP	PP	Same as commercial	None available	Inferential
	Habitat destruction from fishing gear	HP	PP	Gear type; seagrass percent cover; areal extent; shoot density	None available	Inferential
	Boat groundings and anchor damage	PP	PP	Seagrass percent cover; areal extent; shoot density	Elliot 2003	Inferential
	oils and gas exploration, oil spills	OK	OK	Seagrass percent cover; areal extent; shoot density	None available	Inferential
Pollution	Sedimentation	EP	EP	Sedimentation rates and volume; seagrass percent cover; areal extent; shoot density	None available	Inferential
	Nutrient enrichment	OK	OK	Nutrient (N & P) levels; seagrass percent cover; areal extent; shoot density	Boyer and Briceño 2006, 2007 (http://serc.fiu.edu/wqmnetwork/FKNMS-CD/)	Good
	Marine debris (e.g., derelict fishing gear)	PP	PP	Gear type; seagrass percent cover; areal extent; shoot density	None available	Inferential
Invasive Species	Nonnative species introductions	--	UNK	Presence / absence or abundance of invasive species	None available	Inferential

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table. 8.7. Stressors affecting reef fishes in the Tortugas region. Colors describe the extents to which stressors are affecting reef fish resources (cf. Chapter 6).

Threat	Stressor	Reef Fishes	Metrics	Data Summaries/References	Extent of Information
Climate Change	Ocean acidification	PP	Larval settlement rates	Munday *et al.* 2009	Inferential
Extreme Events	Tropical storms	PP	Storm frequency, fish abundance, density, size, community structure and trophic structure	Ault *et al.* 2004, 2006	Good
Resource Extraction	Commercial fishing	HP	Fishing effort and catch per unit effort; reef fish size; species presence/absence	Bohnsack *et al.* 1999, Ault *et al.* 1999, 2001, 2006, Bohnsack *et al.* 2003, Leeworthy and Wiley 2000, Leeworthy *et al*. 2012	Good
	Recreational fishing	EP	Reef fish abundance, size, trophic structure, fisheries effort and catch per unit effort	Bohnsack *et al.* 1999, Ault *et al.* 1999, 2001, 2006, Bohnsack *et al.* 2003, Leeworthy and Wiley 2000, Leeworthy *et al*. 2012	Good
	Trade in live species	OK	Number of permits; number of organisms landed	Andrews *et al.* 2005, Donahue *et al.* 2008, FWC	Fair
	Habitat destruction from fishing gear	HP	Fish abundance, density, size, community structure and trophic structure	None available	Inferential
	Boat groundings and anchor damage	PP	Fish abundance, density, size, community structure and trophic structure	None available	Inferential
Pollution	Marine debris (e.g., derelict "ghost" fishing gear)	EP	Fish abundance, density, size, community and trophic structure	Andrews *et al.* 2005, Donahue *et al.* 2008	Inferential
Invasive Species	Nonnative species introductions	PP	Presence /absence, and abundance of invasive species	Andrews *et al.* 2005, Donahue *et al.* 2008 (http://www.reef.org)	Good

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.8. Stressors affecting sea turtles in the Tortugas region. Colors describe the extents to which stressors are affecting seat turtle resources (cf. Chapter 7).

Threat	Stressor	Sea turtles	Metrics	Data summaries/references	Extent of information
Climate Change	Increased sea surface temperature	OK	Onset of nesting activity	Van Houtan and Pimm 2006	Good
	Sea level rise	PP	Extent of nesting beaches	Van Houtan and Pimm 2006, Meylan *et al.* 1995	Inferential
Extreme Events	Tropical storms	EP	Extent and number of nesting beaches; turtle nest density; turtle nesting activity	Van Houtan and Pimm 2006, Meylan *et al.* 1995, SFNRC and FWC 2007 (http://www.myfwc.com/seaturtle/)	Good
Resource Extraction	Commercial fishing	HP	Number of turtles caught as bycatch	Van Houtan and Pimm 2006	Good
	Recreational fishing	PP	Number of turtles caught as bycatch	Van Houtan and Pimm 2006	Good
	Trade in live species	--	Number of permits issued	SFNRC and FWC 2007 (http://www.myfwc.com/seaturtle/)	Unknown
	Habitat destruction from fishing gear	--	Areal extent of nesting beaches; number of vessel grounding	Van Houtan and Pimm 2006, Meylan *et al.* 1995	Inferential
	Boat groundings & anchor damage	UNK	Number and incidence of turtles affected; area of nesting and foraging habitat affected	Van Houtan and Pimm 2006, Meylan *et al.* 1995	Inferential
	Offshore oil and gas exploration, oil spills	OK	Number and incidence of turtles affected	Andrews *et al.* 2005, Donahue *et al.* 2008, Elliot 2003, NOAA OR&R Incident News (http://www.incidentnews.gov/results)	Fair
Non-extractive Resource Use	Recreational use (boating and visitation)	PP	Number of visitors; number of boating permits issued; data from visitor use and creel surveys	Van Houtan and Pimm 2006, SFNRC and FWC 2007	Poor

Table 8.8 continued.

Threat	Stressor	Sea Turtles	Metrics	Data Summaries/References	Extent of Information
Pollution	Nutrient enrichment	--	Disease incidence in turtles	Lafferty *et al.* 2004	Inferential
	Marine debris (e.g., derelict fishing gear)	PP	Number and incidence of turtles affected	None available	Inferential
	Chemical contaminants	UNK	Level of contaminants in tissues	Innis *et al.* 2008, Oros *et al.* 2009, Keller *et al.* 2005	Inferential
Invasive Species	Nonnative species introductions; turtle nest predators	PP	number of nests affected by predation; number of nests affected by *Casuarina* spp. density	Houtan and Pimm 2006	Good

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.9. Stressors affecting seabirds in the Tortugas region. Colors describe the extents to which stressors are affecting seabird resources (cf. Chapter 7).

Threat	Stressor	Seabirds	Metrics	Data summaries or references	Extent of information
Climate Change	Increased sea surface temperature	UNK	None available	None available	Unknown
	Sea level rise	PP	Area of nesting habitat affected; # of nesting birds	None available	Inferential
	Ocean acidification	UNK	None available	None available	Unknown
Extreme Events	Tropical storms	EP	Number of nests affected; bird and nest density	Clapp and Robertson 1986, FWC 2003, Hood 2006	Fair
Resource Extraction	Commercial fishing	PP	Number of nests affected	FWC 2003	Poor
	Recreational fishing	PP	Number of nests affected	FWC 2003	Poor
	Offshore oils and gas exploration, oil spills	PP	Number of birds affected; bird density	Robertson and Robertson 1996	Poor
Pollution	Sedimentation	--	None available	None available	Unknown
	Nutrient enrichment	OK	None available	Boyer and Briceño 2006, 2007 (http://serc.fiu.edu/wqmnetwork/FKNMS-CD/)	Unknown
	Marine debris (e.g., on nesting beaches)	PP	Number of nests affected	Incidence and abundance of marine debris	Inferential
	Chemical contaminants	HP	Number of birds affected; bird density; tissue concentration	Pranty 2002, FWC 2003, Watson 2005, Jodice *et al.* 2007	Inferential
Invasive Species	Nonnative species introductions	OK	feral rat density; nest density; number of birds affected; area of nesting habitat	FWC 2003	Fair

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.10. Summary of stressors, the extent to which they affect natural resources, and the extent of information available for each stressor in the Tortugas region (cf. Chapters 3–8). CRHC = coral reef and hardbottom communities; SGAC= seagrass and algae communities.

		Natural Resource Categories								
				CRHC		SGAC				
Threat	Stressor	Oceanography and Climate	Water Quality	Abiotic	Biotic	Abiotic	Biotic	Reef Fishes	Turtles	Seabirds
Climate Change	Increased sea surface temperature	G	U	G	G	U	U	U	G	U
	Sea level rise	G	U	Inf	Inf	U	U	U	Inf	Inf
	Ocean acidification	Inf	U	Inf	Inf	U	U	Inf	U	U
Extreme Events	Cold/warm fronts	G	U	G	G	U	U	U	F	U
	Tropical storms	G	G	G	G	G	G	G	G	F
	Disease epidemics	U	U	G	G	U	U	U	U	Inf
Resource Extraction	Commercial fishing	U	U	Inf	Inf	Inf	Inf	G	G	P
	Recreational fishing	U	U	Inf	Inf	Inf	Inf	G	G	P
	Trade in live species	U	U	Inf	Inf	U	U	F	U	P
	Habitat destruction from fishing gear	U	U	F	F	Inf	Inf	Inf	Inf	U
	Boat groundings and anchor damage	U	U	G	G	Inf	Inf	Inf	Inf	U
	Oil and gas exploration and spills	U	U	F	F	Inf	Inf	U	F	P
Pollution	Sedimentation	U	G	Inf	Inf	Inf	Inf	U	U	U
	Eutrophication (nutrient enrichment)	U	G	G	G	G	G	U	Inf	U
	Marine debris (e.g., derelict fishing gear)	U	U	F	F	Inf	Inf	Inf	Inf	Inf
	Chemical contaminants	U	G	Inf	Inf	U	U	U	U	Inf
Invasive Species	Nonnative species introductions	U	U	G	G	Inf	U	G	G	F

Extent of problem	OK = Unlikely problem	HP = Historical problem	EP = Existing problem	PP = Potential problem	Unk = Unknown	-- = Not applicable
Knowledge base	G = Good	F = Fair	P = Poor	Inf = Inferential	Unknown	

Table 8.11. Summary of ecological condition of resource categories based on stressor-resource matrix in Table 8.8.

	Natural Resource Categories							
		Coral reef and hardbottom		Seagrass and algae				
	Water quality	Abiotic	Biotic	Abiotic	Biotic	Reef fishes	Sea turtles	Seabirds
Proportion of stressors affecting resources	12%	59%	76%	41%	41%	47%	35%	41%
Proportion of stressors with good or fair information on effects	24%	59%	59%	12%	12%	29%	41%	12%
Park-desired condition	Intact and Pristine Marine Ecosystem (NPS 2005); for water quality	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for coral reefs	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for coral reefs	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for seagrasses	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for seagrass and algal beds	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for reef fishes	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for sea turtles	Intact and Pristine Marine Ecosystem (NPS 2005); undefined for seabirds
Recommended metrics to determine Park-desired condition	Dissolved oxygen, total nitrogen, turbidity	Spatial extent of reef and hardbottom communities	Coral cover; colony density; disease prevalence and incidence;	Spatial extents of seagrass and algae habitats	Seagrass shoot density; Species composition; productivity indices	Species composition, abundance and size; presence commercially-important species (e.g., black and red grouper)	Aerial extent of nesting beaches; turtle sighting frequency; turtle nesting activity	Nesting activity; aerial extent of nesting habitat; seasonal and annual bird counts; abundance by life-stage.
Overall condition	Good	Caution	Significant concern	Inadequate data	Inadequate data	Caution	Significant concern	Inadequate data
Information score	1.00	0.59	0.59	0.20	0.22	0.56	0.58	0.20
Stressor extent score	0.09	0.47	0.56	0.55	0.60	0.51	0.38	0.34

Table 8.11 continued.

		Coral reef and hardbottom		Seagrass and algae				
	Water quality	**Abiotic**	**Biotic**	**Abiotic**	**Biotic**	**Reef fishes**	**Sea turtles**	**Seabirds**
Temporal trends in resources	None reported. Concentrations of dissolved oxygen and nutrients (nitrogen, phosphorus, and organic carbon) were fairly stable between 1995−2005 (Boyer and Briceño 2006, 2007).	Insufficient data to determine temporal trends	Living coral cover has declined drastically. Average coral cover in 2005 is <20% compared with an average cover >50% before 1975 (Agassiz 1883, Davis 1982, Jaap *et al.*, 2008). Prior to the 1970s, Acroporid corals were spatially extensive and very abundant, but now they have virtually disappeared (Davis 1982, Jaap and Sargent 1993, Jaap *et al.*, 2008).	Insufficient data to determine temporal trends	Data specific to the status and condition of seagrass and algal beds are not readily available to DRTO; Repeated sampling at permanent sites monitored by Park staff are spatially limited and inadequate to determine temporal and spatial trends for the park (Chapter 5, this report). A useful data set to obtain is Fourqurean and Escorcia 2006).	Abundance, size, species composition of reef fish assemblages are below historical levels (Bohnsack *et al.* 1994). Several exploited and unexploited fish populations have increased in abundance and size within marine reserves since implementation in 2001 (Ault *et al.* 2007); Evidence suggests that a mutton-snapper aggregation may be reforming (Burton *et al.* 2005). There was an increase in the frequency of exploited black and red groupers (Ault *et al.* 2007)	Abundances of sea turtles are substantially lower than in pre-European times. From 1994−2004, nesting activities of loggerhead and green sea turtles have been variable in time and between species. Hawksbill, leatherback, and Kemp's ridley are uncommon (little data on nesting; Van Houtan and Pimm 2006). Existing data and recent trends are spatially and temporally limited and should not be used to infer long-term demographic trends.	Unknown. Existing quantitative data on sea birds in the Tortugas region are dated (1986-1991), and were not collected with appropriate statistical and sampling rigor to determine temporal and spatial trends and the current ecological condition of sea birds at the park (Chapter 7).

Table 8.11 continued.

		Coral reef and hardbottom		Seagrass and algae				
	Water quality	**Abiotic**	**Biotic**	**Abiotic**	**Biotic**	**Reef fishes**	**Sea turtles**	**Seabirds**
Spatial patterns in resource	Concentrations of dissolved nutrients much lower than in the neighboring Florida Keys. Chlorophyll a is much lower in the Tortugas region than on the West Florida Shelf (Boyer and Briceño 2006, 2007).	Coral reef metrics have been used to characterize and map coral reefs and hardbottom based on spatial patchiness (Franklin *et al.* 2003)	Data on spatial density of coral colonies used to optimize sampling designs; but spatial trends have not been analyzed (Miller *et al.* 2006).	Insufficient data to determine spatial trends	Data specific to the status and condition of seagrass and algal beds are not readily available to DRTO; Repeated sampling at permanent sites monitored by Park staff are spatially limited and inadequate to determine temporal and spatial trends for the park (Chapter 5, this report). A useful data set to obtain is Fourqurean and Escorcia 2006).	The abundance of exploited species in fished areas declined or did not change over time compared to areas within marine reserves since 2001	Average annual nest density was highest at East Key, followed by Loggerhead. Annual trends in nest abundance were spatially variable among the Tortugas islands.	Unknown. Existing quantitative data on sea birds in the Tortugas region are dated (1986-1991), and were not collected with appropriate statistical and sampling rigor to determine temporal and spatial trends and the current ecological condition of sea birds at the park (Chapter 7).

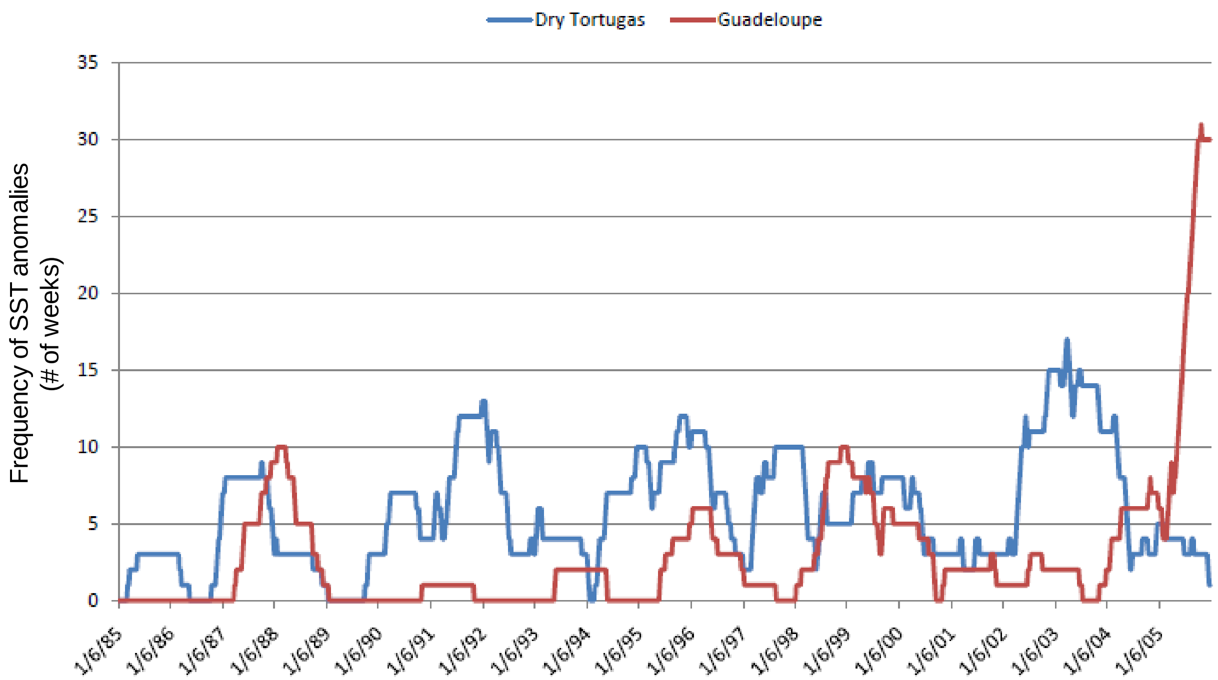

Figure 8.1. Sea surface temperature anomalies for the Dry Tortugas and Guadeloupe Island (eastern Caribbean) from the Coral Reef Temperature Anomaly Database (CoRTAD). CoRTAD is a compilation of sea surface temperature (SST) and thermal stress metrics derived from remotely sensed SST collected weekly at 4 km (2.5 mi) resolution,1985–2005 (source of graphic: V. Ransibrahmanakul; source of data: K. Casey (http://www.nodc.noaa.gov/SatelliteData/Cortad/).

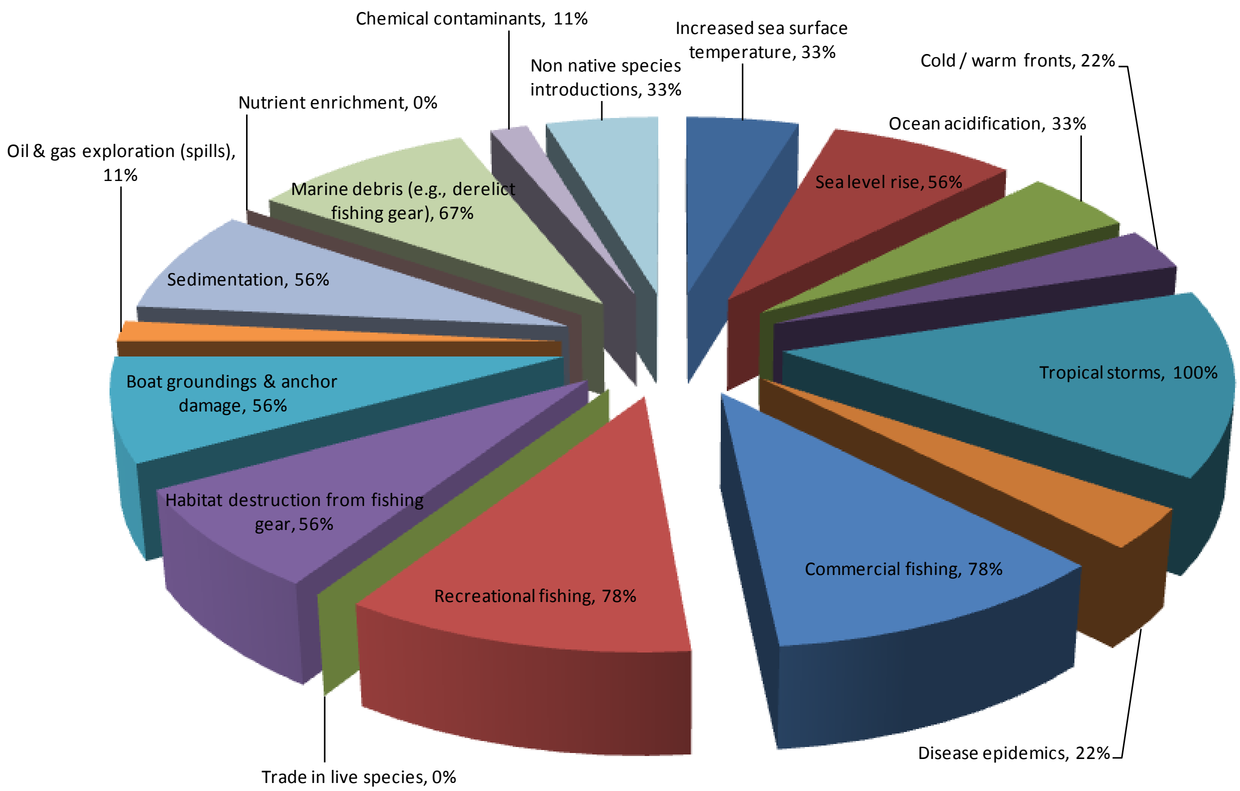

Figure 8.2. Percent of resources affected by stressors in the Tortugas region. The extent of stressor effects on natural resources are summarized in Table 8.9.

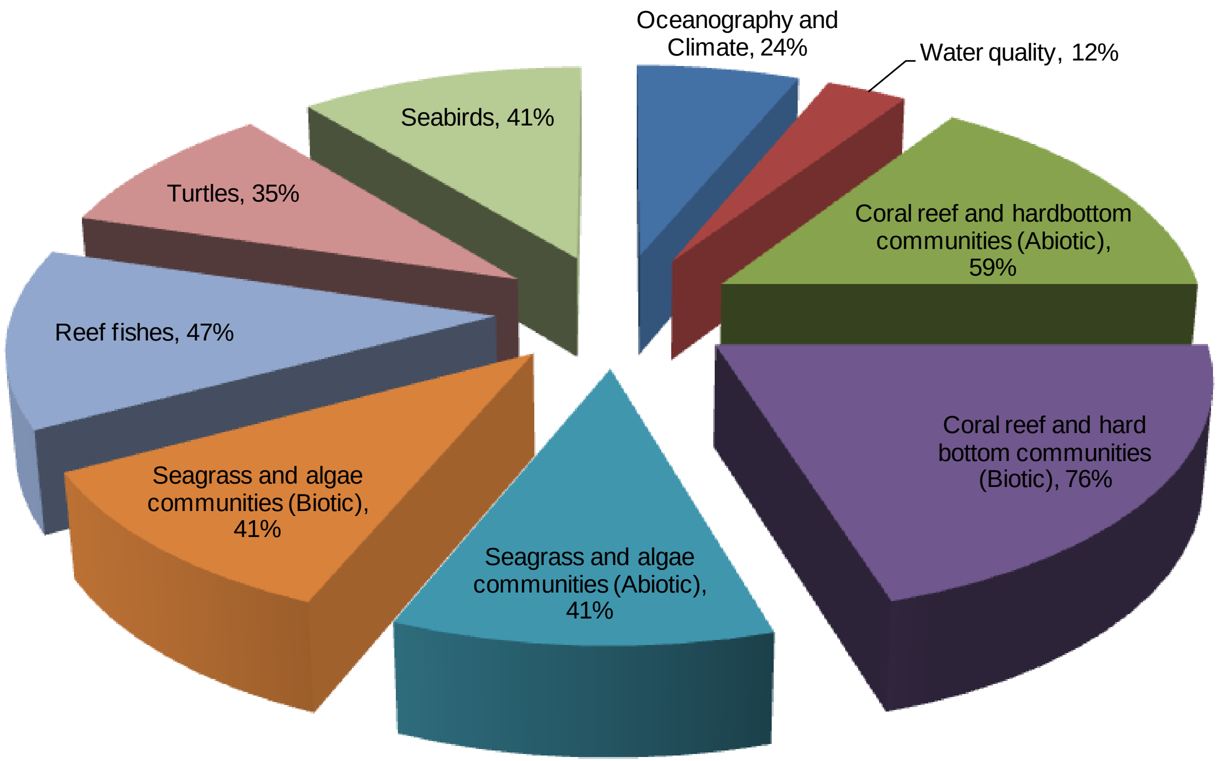

Figure 8.3. Percent of stressors affecting natural resources in the Tortugas region. The extent of stressor effects on natural resources are summarized in Table 8.9.

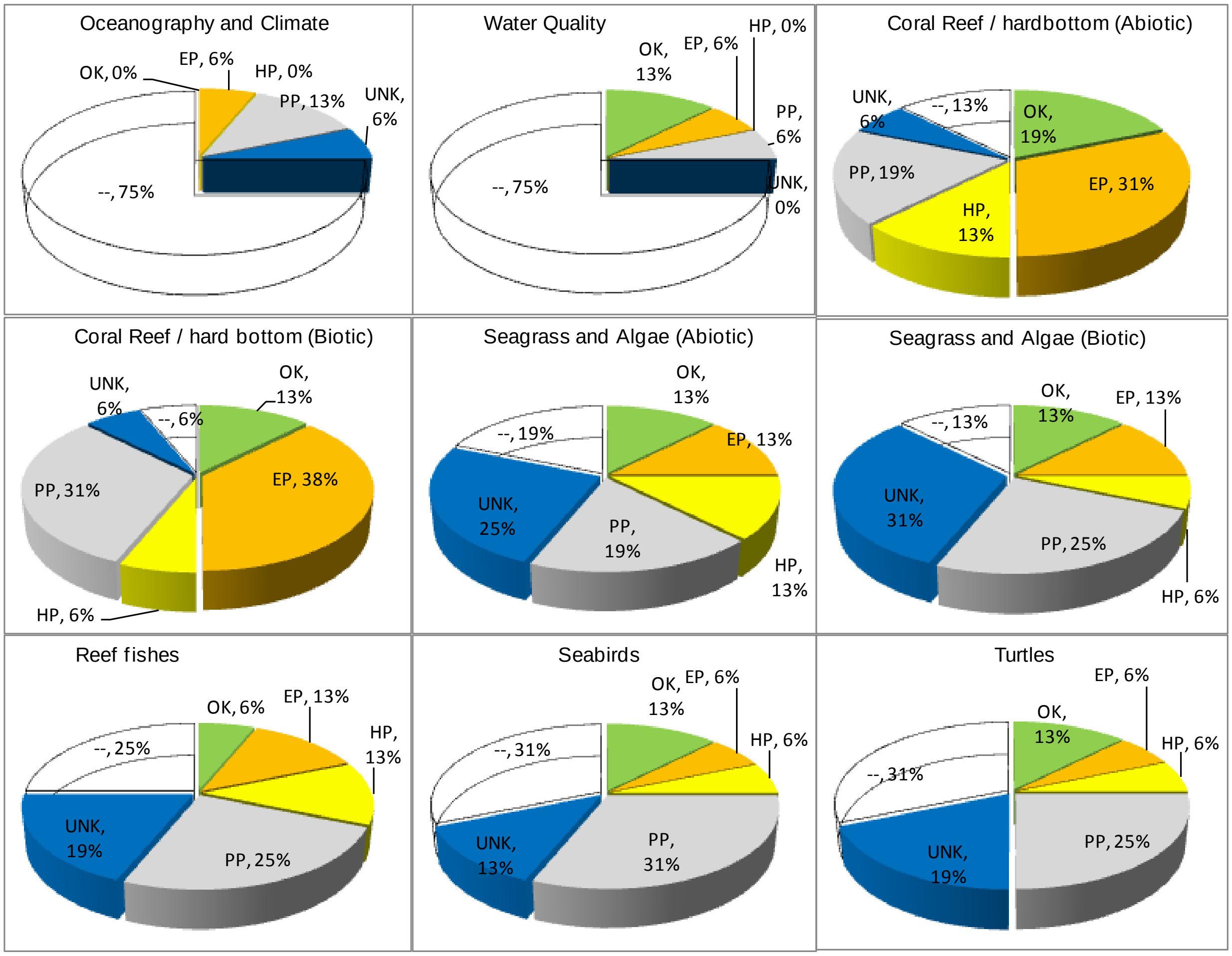

Figure 8.4. Summary of the extent of problems for stressors affecting natural resources in the Tortugas region. Data are derived from the stressor-resource matrix (Table 8.9) and represent the percent of each stressor category for each natural resource (EP = existing problem, HP = historical problem, PP = potential problem, OK = not currently a problem, UNK = unknown, – = not applicable).

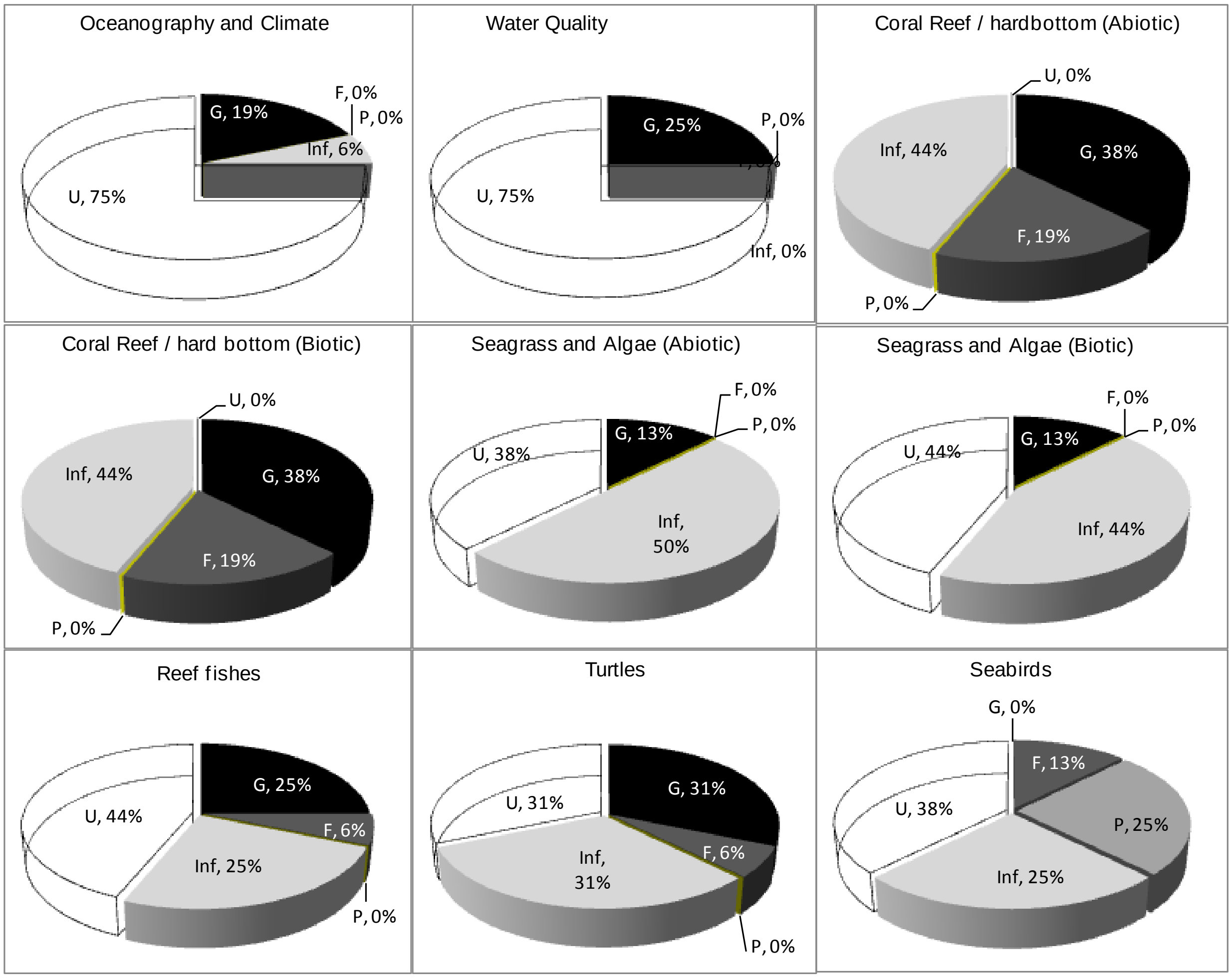

Figure 8.5. Summary of the information on stressors affecting natural resources in the Tortugas region. Data are derived from the stressor-resource matrix (Table 8.9) and represent the percent of each information category for each natural resource (G = good, F = fair, P = poor, I = inferential, U = unknown).

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National Park Service
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Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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