

# Regional Monitoring of Coral Condition in the Florida Keys

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***Abstract**—Tropical reef corals have experienced unprecedented levels of bleaching and disease during the last three decades. Declining health has been attributed to several stressors, including exposures to elevated water temperature, increased solar radiation, and degraded water quality. Consequences of coral bleaching and disease vary; some recover, while others lose tissue, die, and succumb to algal overgrowth. In 2000, a regional monitoring project documented disease prevalence and bleaching across 41 km<sup>2</sup> of coral reefs in the Florida Keys. Thirty sites were randomly selected from a spatially-balanced grid. A radial belt transect (113 m<sup>2</sup>) was surveyed at each site and 100-300 colonies were encountered in each transect. The coral species and health status was recorded for each colony. No site had greater than 13 percent disease prevalence and ~80 percent of the reef area had <5 percent disease prevalence. The survey will be repeated in 2005, but with additional measurements to estimate colony size, percent living tissue, and living surface area. These added endpoints are expected to provide information on the consequences of bleaching, disease, and other stressors on coral communities. Data will be compiled to characterize community composition, abundance, age class structure, and survival of different species across the Florida Keys reef tract. During a pilot study in 2003, living coral tissue on large colonies of elkhorn coral *Acropora palmata* was considerably less than on small colonies, possibly indicating a major mortality event (for example, hurricane or bleaching) that occurred prior to recruitment of the smaller colonies.*

## Introduction

Tropical reef-building corals have declined to unprecedented levels during the last three decades (Antonius 1973, Gardner and others 2003, Glynn 1984, Hughes and Tanner 2000). Multiple stressors have been identified that could have led directly, or interactively, to bleaching, disease, and decline in condition. Among these is elevated water temperature, increased exposure to solar radiation, and degraded water quality, each related in some manner to global climate or land use changes. Consequences of bleaching and disease vary, depending on the severity of the stressors and the coral species affected. Some corals recover from a bleaching episode, while others may not. Both bleaching and disease can lead to loss of living coral, algal overgrowth, and eventual disintegration of the calcified skeleton.

Linkages between coral bleaching and global climate change are compelling. Massive episodes of coral bleaching have accompanied the last several El Niño phases of the Southern Oscillation (ENSO). These events have

occurred world-wide, irrespective of other impacts from local anthropogenic stressors (Hoegh-Guldberg 1999, Wilkinson and others 1999). Greater frequency, intensity, and spatial extent of bleaching have been documented since the 1982-1983 ENSO. An exceptionally strong 1997-1998 ENSO exhibited record sea-surface temperatures and coincided with the most geographically widespread and severe bleaching in history (Glynn 1984, Wilkinson 1998). Up to 95 percent of the living coral reefs from the central Indian Ocean and its margins were bleached, and bleaching occurred along the margins of the Caribbean Sea, the Indian Ocean and the Pacific Ocean. Although ENSO phases are determined by conditions measured in the Pacific Ocean, climate and weather patterns are altered worldwide (Wellington and others 2001). In the Caribbean, ENSO phases generate higher sea water temperatures and calm, stratified water conditions (doldrums) that allow increased penetration of solar radiation. These conditions are optimal for coral bleaching.

Many corals rely on photosynthetic energy derived from algal symbionts found within the polyps, or colonial

units of the coral. Since photosynthesis requires solar radiation, these corals are confined to shallow coastal waters penetrated by sunlight. Coral reefs are located in tropical and sub-tropical oceans that are exposed to the most intense solar radiation on Earth (Madronich and others 1998). This distribution, however, places corals at risk from exposure to ultraviolet light (UV), particularly the damaging UV-B wavelengths (Anderson and others 2001, Shick and others 1996). Increased penetration of UV-B to the earth's surface has been attributed to a decline in UV-absorbing ozone in the stratosphere. Although stratospheric ozone depletion in the tropics is not as great as at the poles, there is concern that any increase in the high levels already experienced could affect coral health. The most variable aspect of coral exposure to UV-B is its penetration through the water above reefs. Many local variables such as water quality and weather can influence attenuation of UV-B with depth. For example, dissolved organic matter absorbs UV-B and reduces its penetration, whereas hot, windless conditions create thermal stratification of the water column and allow greater UV-B penetration (Zepp and Schlotzhauer 1981).

The highly complex three-dimensional structures formed by calcified coral skeletons provide a physical habitat to support high diversity and abundance of marine organisms. It is estimated that a million different marine species are dependent upon or utilize coral reef ecosystems. This diverse biota supports numerous subsistence and commercial fisheries and is a major attraction for tourists. Perhaps even more important is the role that coral structures play in coastal shoreline protection. Some have estimated that wave and current dissipation by coral reefs have protected shorelines at a value ten times greater than all other coral ecosystem services provided (Costanza and others 1997). The economic and ecological benefits of coral reefs are substantial, and much of this value can be credited directly to their physical presence.

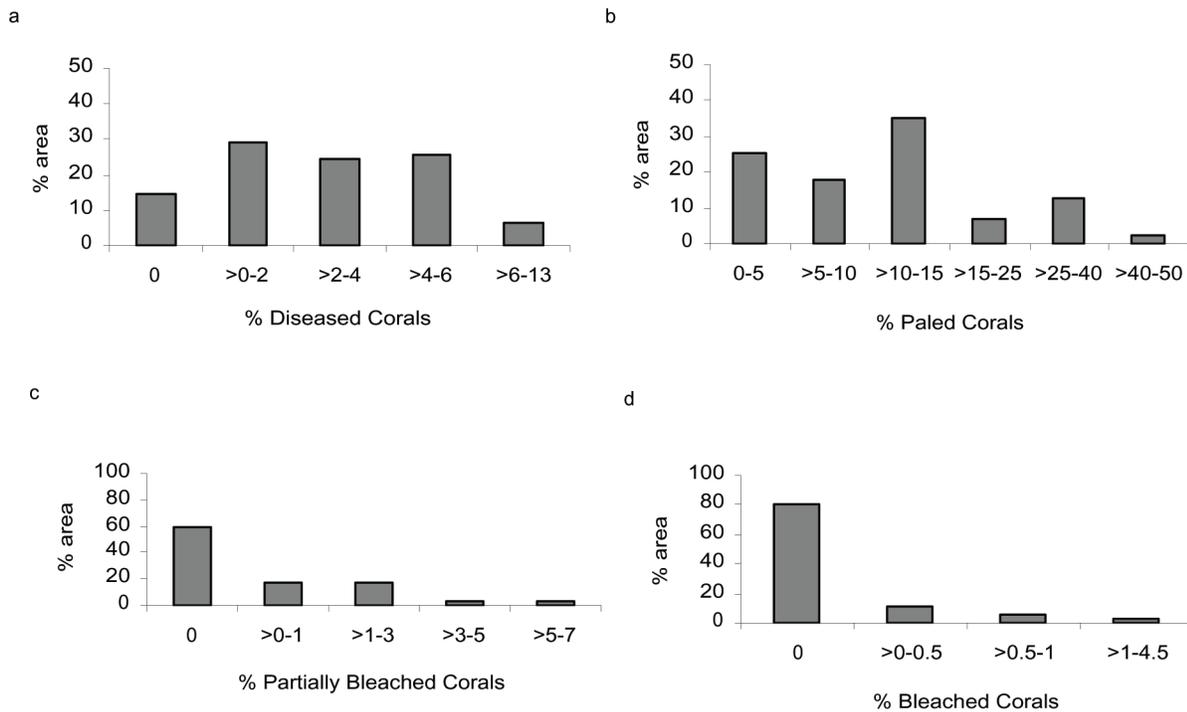
The U.S. Environmental Protection Agency's Global Change Program includes research to facilitate and conduct assessments of global change effects on aquatic ecosystems to improve society's ability to respond to future consequences. Global change stressors include climate variability and change, land use change, and ultraviolet radiation. Each of these stressors is believed to contribute to the decline of coral reefs, which appear particularly sensitive to environmental changes. Because coral reefs have survived thousands of years in a relatively unchanged physico-chemical environment, their potential as a sentinel ecosystem is high.

## Regional Monitoring of Disease and Bleaching

The Florida Keys coral reef tract provides an opportunity to investigate the causes and effects of global change on coral reefs. It is the third largest barrier reef complex in the world and contains reefs in both remote areas and near human population centers. Major declines in coral health and coral cover have occurred during the last thirty years on these reefs. A Coral Reef Monitoring Project has been supported by US EPA Region 4 since 1996 to compare coral coverage at 160 permanent stations in the Florida Keys National Marine Sanctuary (FKNMS). From 1996-2000, a 38 percent decline in live coral coverage has been documented (Jaap and others 2000, Porter and others 2002, Wheaton and others 2001). Much of this loss has been attributed to mortality caused by hurricane damage, coral bleaching, and coral diseases (Antonius 1981, 1985, 1988, Dustan and Halas 1987, Richardson and others 1998, Santavy and Peters 1997, Santavy and others 1999, 2001, 2004).

A similar survey was conducted by US EPA, Gulf Ecology Division (GED) to document the frequency and distribution of coral disease and bleaching across the entire reef tract in August 2000. Performed in collaboration with FKNMS, 30 stations in the Upper, Middle, and Lower Keys; New Grounds; and the Dry Tortugas in South Florida were surveyed. An EMAP-type sampling protocol was used to select site locations (Summers and others 1995). The probability-based design produced unbiased estimates of the spatial extent of ecological condition with a quantifiable level of uncertainty which measured both the distribution and frequency of coral disease in the Florida Keys Tract. The design was implemented in three steps: a regional stratification was developed, a hexagonal grid was overlaid on the sample frame, and then multiple sites were randomly selected within the grid cells (Santavy and others 2004). The original study area encompassed a nearly 10,000 km<sup>2</sup> area within the boundaries of the FKNMS, Biscayne National Park (BNP), and the Dry Tortugas National Park (DTNP). Areas were eliminated from the sample frame were if they were determined by professional judgment to contain only dead or geological reef structure. After exclusion of these reef areas, the total study area was approximately 45 km<sup>2</sup> (4100 ha).

A radial belt transect (113 m<sup>2</sup>) was used to examine, count and identify fifteen coral species, eleven diseases, and three bleaching conditions (Santavy and others 2001). The distribution of the coral disease was



**Figure 1.** Distribution of the coral health indicators as a function of the frequency of occurrence throughout the area sampled in 2000. The following coral health indicators included: a) coral disease, b) coral paling (light bleaching), c) partially bleached corals affecting 10-50 percent of the total colony, and d) bleached corals affecting greater than 50 percent of the total colony.

determined by presence or absence at each site, and prevalence of disease and bleaching were determined by the percent of the susceptible coral community affected at each site (fig. 1). Diseases were present in 85  $\pm$  9 percent (95 percent confidence intervals) of the area sampled, and were widely distributed throughout South Florida. While the distribution of disease was widespread, the prevalence was generally low. Maximum prevalence at any one site was 13 percent, with 2.2 percent of the sampling area containing this maximum level. Approximately 31 percent of the area had 0.4 percent-2 percent prevalence, 28 percent had 2 percent-4 percent prevalence, and 24 percent had 4 percent-9 percent prevalence. Future surveys will be used to document trends in the distribution and frequency of coral disease in South Florida.

Disease prevalence across the Florida Keys reef tract was considerably less than previous reports. Lower prevalence could be a consequence of coral losses documented during this period (Santavy and others 2001, 2004a, 2004b). Other studies have also reported high (38 percent) coral losses (Porter and others 2002, Wheaton and others 2001). Of particular concern has been the dramatic decline of the once dominant reef-building elkhorn (*Acropora palmata*) and staghorn (*A. cervicornis*) corals (Patterson and others 2002).

With continued declines in South Florida corals, the EPA research effort has expanded to include characterization of coral condition. New measurements have been added to evaluate the cumulative consequences of bleaching and disease, as well as other stressors on coral individuals and populations. Reef-to-reef comparisons of disease prevalence are sometimes confounded by different taxonomic composition (for example, some sites do not have susceptible host species). The new condition measures are unrelated to taxonomic composition and will allow direct comparisons across reefs and geographic areas.

## Indicators of Coral Condition

Surveys for prevalence and distribution of disease across the region provided one measure of coral condition and a baseline for detecting trend. An expanded approach was needed to evaluate the consequences of disease and other stressors to coral populations. This required development of condition indicators that would reflect population-level parameters: survival, growth, and reproduction. At the same time, application to a regional assessment required that numerous sites be surveyed, so the amount of time that could be spent at each site was

limited. Three coral condition indicators were proposed that required adding only two observations to the existing disease survey protocol. These were estimates of total coral surface area (TSA; based on size class) and percent living coral tissue (%LC).

The new measurements provided meaningful endpoints. Estimates of TSA indicated coral reef structural size and complexity (rugosity) and the habitat value that accompanies greater surface area. It also afforded a record of the cumulative, or historical, capacity of the habitat to grow, and sustain corals. Estimation of %LC provided a comparison of living tissue vs. dead coral skeleton, and can be used to examine potential associations of tissue loss with disease and other stressors. Living surface area (LSA) represented the existing capacity of the environment to sustain corals. Also, LSA estimated the actual amount of living coral (m<sup>2</sup>) available for growth and reproduction.

Although TSA, %LC, and LSA can provide useful insight to status and trend of coral populations, it is imperative for future management action that declining condition is ultimately linked to causes. For coral reefs, a major obstacle to establishing causal associations has been the variability in reef species composition. For example, disease occurrence is not easily compared across reefs that vary in host density. Estimation of TSA, LSA, and %LC overcome this obstacle because the measures are independent of species composition. They can be used to compare reefs across geographical regions, reef types, water quality, human influences, and occurrence of bleaching and disease. Differences in condition among reefs or study areas can then be used to draw associations with potential stressors (causative factors) that may be degrading corals. Several of these potential stressors were measured but not discussed here.

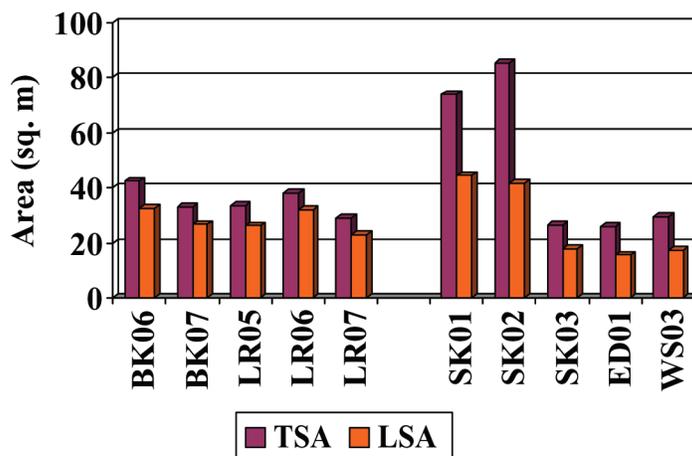
A pilot project was performed in autumn 2003 to generate an operational survey plan and to illustrate potential interpretations from the candidate indicators. Five stations in the Key West area near anthropogenic activity and five stations in the more remote Dry Tortugas were surveyed. Total Surface Area was estimated through classification of corals in size classes (volumetric) and assignment of a surface area equal to five times the size of one side of a cube containing the size class volume. Estimates of %LC were in 20 percent ranges (0-20 percent, 21-40 percent, etc.).

Data from these ten stations showed greater coral abundance and total surface area (TSA) at Key West stations (table 1), but considerably lower %LC than at Dry Tortugas. In fact, despite a dramatically higher TSA at Key West (240.9 vs 175.9 m<sup>2</sup>), the actual living coral (LSA) at each study area (fig. 2) was quite similar (136.9 vs 140.0 m<sup>2</sup>). The two study areas also differed in species

**Table 1.** Number of coral colonies, total estimated surface area (TSA), calculated surface area of living coral (LSA) and the estimated percent of living coral (%LC) for all colonies encountered within the transects at each of five stations in the Dry Tortugas and Key West study areas. Totals were determined from combined data of all stations in each study area.

	Number of Colonies	TSA (m <sup>2</sup> )	LSA (m <sup>2</sup> )	%LC
<b>Dry Tortugas</b>				
BK06	178	42.4	32.4	76.4
BK07	94	33.1	26.7	80.8
LR05	149	33.4	26.2	78.6
LR06	165	38.1	32.0	84.1
LR07	104	29.0	22.7	78.2
<b>Total</b>	<b>690</b>	<b>175.9</b>	<b>140.0</b>	<b>79.6</b>
<b>Key West</b>				
SK01	240	73.8	44.4	60.1
SK02	350	85.1	41.8	49.2
SK03	162	26.5	17.7	66.8
ED01	155	25.8	15.5	59.8
WS03	90	29.6	17.4	58.6
<b>Total</b>	<b>997</b>	<b>240.9</b>	<b>136.9</b>	<b>56.8</b>

## Total and Living Surface Area



**Figure 2.** Total coral surface area (TSA) at each station in Dry Tortugas (left side) and Key West (right side) compared to living coral surface area, which was calculated from TSA and %LC (2003 survey).

diversity, size distributions and the contribution of different species to total coral surface area (tables 2 and 3).

The TSA metric provided an alternate perspective for taxonomic distribution. Traditionally, the number of colonies of each species provides information on species richness. In contrast, TSA provides the relative contributions of different species to community habitat. *Agaracia agaracites* was numerically the dominant species in Key West, but because it is a physically small species, the surface area contribution was limited in comparison

**Table 2.** Count, size distribution (5 classes) and estimated surface area contribution of 15 species recorded from transects at five stations at the Dry Tortugas study area in 2003. Percentage contribution to colony number and total surface area of all colonies recorded in Dry Tortugas is also shown.\*Species not recorded for Key West study area (table 3).

Dry Tortugas Study Area									
Genus species	Colonies		Size Distribution (L)					Surface Area	
	(#)	(% of total)	1	10	50	100	200	(m <sup>2</sup> )	(% of total)
<i>A. cervicornis</i>	25	3.6	10	10	5	-	-	6.2	3.5
<i>A. agaricia</i>	1	0.1	1	-	-	-	-	0.1	0.1
<i>C. natans</i>	1	0.1	-	1	-	-	-	0.2	0.1
<i>D. clivosa</i>	234	33.9	119	60	44	9	2	62.8	35.7
<i>D. labyrinthiformis</i>	2	0.3	-	1	1	-	-	0.9	0.5
<i>D. strigosa</i>	59	8.6	28	11	14	3	3	21.8	12.4
<i>D. stokesii</i>	6	0.9	4	2	-	-	-	0.7	0.4
<i>M. alcicornis</i>	116	16.8	46	51	16	2	1	28.9	16.4
<i>M. annularis</i>	2	0.3	1	-	-	1	-	1.1	0.6
<i>M. cavernosa</i>	14	2.0	2	4	6	1	1	7.9	4.5
<i>M. faveolata</i>	24	3.5	3	1	4	2	14	29.2	16.6
<i>P. astreoides</i>	150	21.7	130	20	-	-	-	11.1	6.3
<i>P. porites</i>	46	6.7	44	2	-	-	-	2.7	1.5
<i>S. siderea</i>	9	1.3	5	2	2	-	-	2.1	1.2
<i>Solenastrea sp.*</i>	1	0.1	-	1	-	-	-	0.2	0.1
	<b>690</b>	<b>100</b>	<b>393</b>	<b>166</b>	<b>92</b>	<b>18</b>	<b>21</b>	<b>175.9</b>	<b>100</b>

**Table 3.** Count, size distribution (5 classes) and estimated surface area contribution of 22 species recorded from five stations at the Key West study area in 2003. Percentage of contribution to colony number and total surface area of all colonies recorded in Key West is also shown.\*Species not recorded for Dry Tortugas study area (table 2).

Key West Study Area									
Genus species	Colonies		Size Distribution					Surface Area	
	(#)	(% of total)	1	2	3	4	5	(m <sup>2</sup> )	(% of total)
<i>A. cervicornis</i>	3	0.3	-	1	1	1	-	6.2	3.5
<i>A. palmata*</i>	57	5.7	16	6	7	10	18	8.5	20.1
<i>A. agaricia</i>	252	25.3	233	19	-	-	-	16.1	6.7
<i>C. natans</i>	9	0.9	5	1	-	2	1	4.3	1.8
<i>D. stokesii</i>	10	1.0	5	5	-	-	-	1.4	0.6
<i>D. clivosa</i>	7	0.7	4	1	1	-	1	2.8	1.2
<i>D. labyrinthiformis</i>	8	0.8	6	1	-	1	-	1.6	0.7
<i>D. strigosa</i>	8	0.8	4	1	1	1	1	3.9	1.6
<i>M. meandrina*</i>	3	0.3	-	1	-	1	1	3.0	1.3
<i>M. alcicornis</i>	199	19.9	156	30	13	-	-	3.6	9.8
<i>M. complanata*</i>	28	2.8	20	4	2	1	1	6.1	2.5
<i>M. annularis</i>	3	0.3	-	2	-	1	-	1.5	0.6
<i>M. cavernosa</i>	72	7.2	22	21	15	8	6	5.0	4.5
<i>M. faveolata</i>	32	3.2	3	12	1	9	7	5.3	10.5
<i>M. franksii*</i>	7	0.7	-	5	2	-	-	2.5	1.0
<i>Mycetophelia sp.*</i>	1	0.1	1	-	-	-	-	0.1	0.1
<i>M. danaana*</i>	2	0.2	1	1	-	-	-	0.3	0.1
<i>M. ferox*</i>	2	0.2	1	1	-	-	-	0.3	0.1
<i>P. astreoides</i>	175	17.5	109	55	11	-	-	25.7	10.7
<i>P. porites</i>	30	3.0	18	10	1	1	-	5.0	2.1
<i>S. siderea</i>	77	7.7	24	32	10	6	5	30.4	12.6
<i>S. michelini*</i>	12	1.2	7	5	-	-	-	1.5	0.6
	<b>997</b>	<b>100</b>	<b>635</b>	<b>214</b>	<b>65</b>	<b>42</b>	<b>41</b>	<b>240.9</b>	<b>100</b>

**Table 4.** Average percent living coral (%LC) for each species encountered at five stations in Dry Tortugas and Key West in 2003. The number of colonies included in each average is denoted in parentheses; N/a denotes no colonies at that study area.

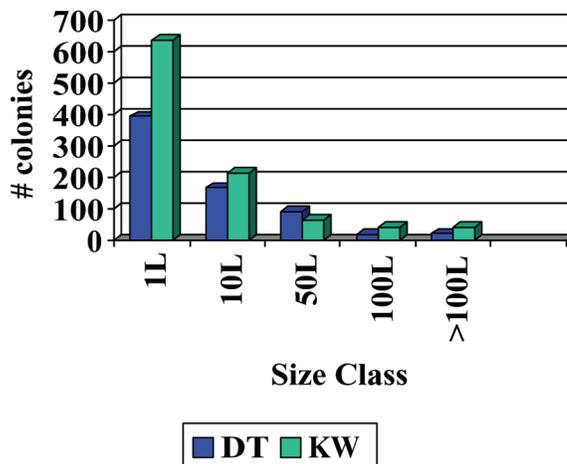
Genus species	Dry Tortugas	Key West
<i>A. cervicornis</i>	95.0 (25)	76.0 (3)
<i>A. palmata</i>	N/a	37.4 (57)
<i>A. agaricia</i>	99.0 (1)	98.2 (252)
<i>C. natans</i>	70.0 (1)	76.2 (9)
<i>D. stokesii</i>	94.5 (6)	66.7 (10)
<i>D. clivosa</i>	88.4 (234)	94.9 (7)
<i>D. labyrinthiformis</i>	99.0 (2)	88.1 (8)
<i>D. strigosa</i>	86.3 (59)	68.4 (8)
<i>M. meandrina</i>	N/a	76.3 (3)
<i>M. alcicornis</i>	94.2 (116)	90.2 (199)
<i>M. complanata</i>	N/a	91.0 (28)
<i>M. annularis</i>	65.0 (2)	83.3 (3)
<i>M. cavernosa</i>	83.9 (14)	69.5 (72)
<i>M. faveolata</i>	64.4 (24)	67.8 (32)
<i>M. franksii</i>	N/a	70.0 (7)
<i>Mycetophelia</i> sp.	N/a	99.0 (1)
<i>M. danaana</i>	N/a	99.0 (2)
<i>M. ferox</i>	N/a	99.0 (2)
<i>P. astreoides</i>	94.6 (150)	89.5 (175)
<i>P. porites</i>	88.6 (46)	85.0 (30)
<i>S. siderea</i>	79.4 (9)	60.1 (77)
<i>Solenastrea</i> sp.	90 (1)	N/a
<i>S. michelini</i>	N/a	78.8 (12)

to *Porites astreoides* and *Siderastrea siderea*. In Dry Tortugas, *Diploria clivosa* was greatest in abundance and surface area.

Because data were collected on individual colonies, relationships could be examined at the regional, reef and even species level. For example, differences in %LC among species (Table 4) could indicate whether a particular species has lost more tissue than other species in the same area, or whether the same species has lost more tissue in one study area than another. Two species, *Colpophyllia natans* and *Montastrea faveolata*, had low %LC at both study areas, whereas *Diploria clivosa*, *Porites astreoides* and *P. porites* exhibited high %LC at both study areas. Several species had lower %LC in Key West than in Dry Tortugas, including *Acropora cervicornis*, *Dichocoenia stokesii*, *Diploria strigosa*, *Montastrea cavernosa*, and *Siderastrea siderea* (table 4).

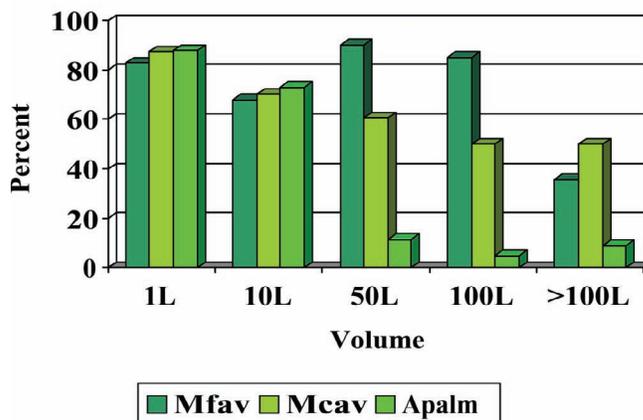
Size estimates also provided useful insights. At both study areas, there were high numbers of small individuals and declining abundance with increasing size (fig. 3). However, TSA and LSA for each size class varied between the study areas. For Dry Tortugas, the greatest surface area was contributed by coral in the mid-size range and in Key West, by corals in the large-size

## Size Class Distribution



**Figure 3.** Distribution of coral colonies from Dry Tortugas and Key West across five different size class estimates (2003 survey).

## Avg % LC for Three KW Corals



**Figure 4.** Average percent living coral (%LC) for *Montastrea faveolata*, *M. cavernosa*, and *Acropora palmata* from Key West stations observed in different size classes (2003 survey).

range. Most species, like *D. clivosa* at Dry Tortugas, showed a decline in percent living coral for the larger size classes. This could be due to chronic losses over added years of existence. The %LC for *Acropora palmata* was substantially different from two other large coral species in Key West, *Montastrea faveolata* and *M. cavernosa*, when examined by size class (fig. 4). Colonies greater than the 10L size class exhibited less than 10 percent living coral whereas the Montastreids retained substantially higher living tissue in even the highest (>100L) size class.

# Estimating Surface Area from Size Classes

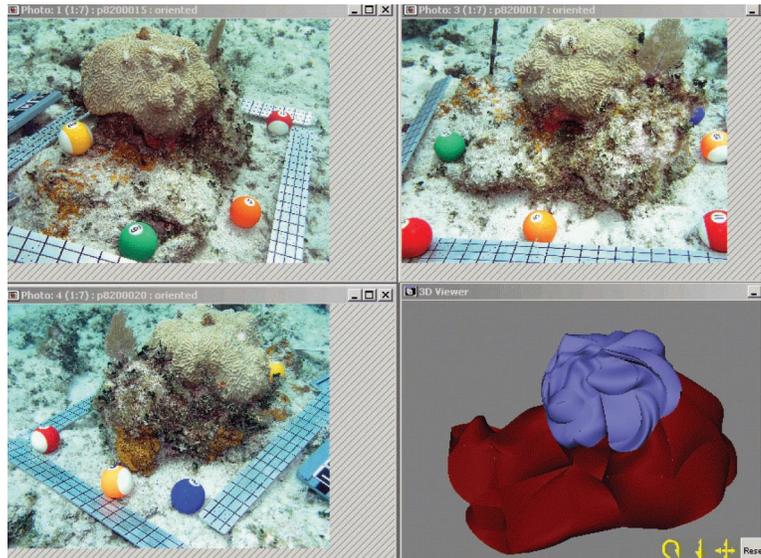
Estimates of TSA are an integral component of this approach to coral condition. Yet, surface areas estimated from volumetric size classes do not account for the structural complexities unique to each species (for example, branching). Nonetheless, a generic, first-order estimate was made with the assumption that a cube-shaped coral will fill the entire volume of its size class. This is reasonable because most corals in a size class will actually be smaller than the entire volume, a concession balanced by the lack of any consideration for physical complexities that would increase surface area.

Refinements to the first-order surface area estimates are being made through analysis of digital images of coral colonies, similar to the technique described by Bythell and others (2001). A series of nine or more photographs were taken from various angles around individual colonies of various species and size classes. Scale bars and billiard balls were placed around the base of a colony (fig. 5) as static orientation reference points for generating the computer model. The different images were reconciled using a computer software program (PhotoModeler7 Pro 5) designed to produce accurate 3-dimensional models from overlapping still photographs. Points were visually selected along the natural contours of the specimen and linked to produce curved lines that delineated colony topography and generated a 3-dimensional model. The surface area of the model is automatically calculated by the computer as the sum of the component contours. Surface area determinations are more accurate with greater numbers of points, curves, and surfaces used to define the coral structure. Optimization of the technique is being examined through comparison of model output with highly accurate surface areas determined by laser scanning.

As expected, preliminary analysis of the 3-dimensional models indicates that surface areas for hemispherical coral colonies (for example, brain corals) were generally overestimated by the assigned values whereas branched colonies (for example, *Acropora* spp.) were underestimated. Once more accurate estimates for each species and size class are available, new surface areas can be substituted for the currently assigned values.

## Acknowledgments

Disease and coral condition surveys were performed in collaboration with the National Oceanic



**Figure 5.** Coral colonies were photographed with gridded scales and pool balls as reference points to develop a 3-D computer model that depicts contours of the coral surface. Surface area of both living (blue) and dead (red) coral is determined using commercially-available computer software.

and Atmospheric Administration (NOAA) National Ocean Service and the Florida Keys National Marine Sanctuary FKNMS. The support of the scientific staff and crews of EPA's RV ANDERSON and NOAA's RV FOSTER is greatly appreciated. The National Park Service provided dive boat support in the Dry Tortugas. This work was performed under Scientific Research and Collecting Permit #DRTO-2003-SCI-0010, Study # DRTO-00007 issued by the National Park Service (Dry Tortugas) to D. Santavy, L. MacLaughlin, W. Fisher, E. Mueller and W. Davis, and Florida Keys National Marine Sanctuary Permit FKNMS-2003-050 issued to W. Fisher by FKNMS (NOAAs National Marine Sanctuary Program).

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