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THE CONDITION OF CORAL REEFS IN SOUTH FLORIDA (2000) USING CORAL DISEASE AND BLEACHING AS INDICATORS

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Abstract. The destruction of coral reef habitats has occurred at unprecedented levels during the last three decades. Coral disease and bleaching in the Caribbean and South Florida have caused extensive coral mortality with limited recovery, often coral reefs are being replaced with turf algae. Acroporids were once dominant corals and have diminished to the state where they are being considered as endangered species. Our survey assessed the condition of reef corals throughout South Florida. A probability-based design produced unbiased estimates of the spatial extent of ecological condition, measured as the absence or presence and frequency or prevalence of coral diseases and bleaching intensity over large geographic regions. This approach allowed us to calculate a quantifiable level of uncertainty. Coral condition was estimated for 4100 hectares (ha) (or 41.0 km^2) of coral reefs in South Florida, including reefs in the Florida Keys National Marine Sanctuary (FKNMS), New Grounds, Dry Tortugas National Park (DTNP), and Biscayne National Park (BNP). The absence or presence of coral disease, 'causal' coral bleaching, partial bleaching and coral paling were not good indicators of overall coral condition. It was more useful to report the prevalence of anomalies that indicated a compromised condition at both the population and community levels. For example, 79% of the area in South Florida had less than 6% of the coral colonies diseased, whereas only 2.2% (97.15 ha) of the sampled area had a maximum prevalence of 13% diseased coral colonies at any single location. The usefulness of 'causal bleaching' might be more important when considering the prevalence of each of the three different states at a single location. For example, paling was observed over the entire area, whereas bleaching and partial bleaching occurred at 19 and 41% of the area, respectively. An index for coral reef condition might integrate the prevalence and species affected by each bleaching state at individual locations. By establishing these baselines, future surveys can examine changes and trends in the spatial distribution of coral conditions in South Florida and able to score the reefs as to their health status.

Keywords: assessment, causal bleaching, coral disease, coral reefs, EMAP, Florida Keys, monitoring, paling, reef condition, South Florida

1. Introduction

Global mortality of corals has increased at unprecedented levels during the last several decades (Hughes *et al.*, 2003; Wilkinson, 1998, 2000, 2002). The rate and intensity of coral reef destruction are greater than previously documented in modern and geological records (Aronson and Pretch, 1997a, b; Hughes, 1994;

Hughes and Tanner, 2000). These conditions have prompted increased awareness and focused studies on coral disease and bleaching to understand what processes are causing the deterioration. Losses of corals and thus reef habitats by disease have been observed throughout the Caribbean (Bruckner and Bruckner, 1997; Bythell and Sheppard, 1993; Peters, 1992; Rogers, 1985; Gardner *et al.*, 2003). Most recently, a comprehensive five-year study has documented a 38% decline in live coral coverage in the Florida Keys National Marine Sanctuary (FKNMS) (Jaap *et al.*, 2001; Porter *et al.*, 2002). With increasing numbers of coral diseases reported in the FKNMS, it is clear that coral disease incidences significantly contribute to coral reef destruction (Harvell *et al.*, 1999; Patterson *et al.*, 2001; Porter *et al.*, 2002; Richardson *et al.*, 1998b; Santavy and Peters, 1997; Santavy *et al.*, 1999b).

Most disease studies have focused on a specific disease outbreak affecting one to several scleractinian coral or gorgonian sea fan species in a single location or several proximal locations (Bruckner *et al.*, 1997; Nagelkerken *et al.*, 1997a, b; Patterson *et al.*, 2001; Richardson *et al.*, 1998a; Santavy and Peters, 1997; Santavy *et al.*, 1999b). Over the last two decades, new and emerging coral diseases, as well as existing diseases affecting new host species, have been reported throughout this region (Garzón-Ferreira and Gil, 1998; Goreau *et al.*, 1998; Nagelkerken *et al.*, 1997a, b; Patterson *et al.*, 2001; Peters *et al.*, 1983; Richardson, 1993; Richardson *et al.*, 1998a; Rützler and Santavy, 1983; Rützler *et al.*, 1983; Santavy and Peters, 1997; Santavy *et al.*, 1999b, 2001). A recent study in the Keys has shown the distribution or number of stations where coral disease is present has significantly increased from 1996 to 1998 (Harvell *et al.*, 1999). The Caribbean was once dominated by elkhorn (*Acropora palmata*) and staghorn corals (*Acropora cervicornis*). Massive declines of corals, attributed to epizootics of white-band disease, white pox and hurricanes (Aronson and Precht, 1997a, b; Bythell and Shepard, 1993; Gladfelter, 1982; Gladfelter *et al.*, 1977; Patterson *et al.*, 2001), have prompted calls to classify the Acroporids as endangered species. Substantial coral mortality leads to major ecological shifts replacing corals with fleshy algae as documented in locations throughout the Caribbean (Aronson and Pretch, 1999; McClanahan *et al.*, 1999; McClanahan and Muthiga, 1998; Shulman and Robertson, 1997).

Coral bleaching is caused by loss of the obligate symbiotic algae associated with the host coral's tissue, or the loss or decline of photosynthetic pigments in the symbiotic algae. After corals bleach and lose many of their symbionts, the hosts must again acquire and/or increase the number of symbionts in their tissues. If the bleaching was a loss in the amount of photosynthetic pigment per algal cell, then the symbiotic algae must recover their photosynthetic pigments to allow both the coral host and algal symbionts to recover and live. If the symbiosis is not restored, the corals do not recover and die.

Coral bleaching occurs when corals experience stress (Meehan and Ostrander, 1997). The most notable coral bleaching has occurred as massive events affecting many coral species and reef locations associated with an increase in global sea-surface temperature and prolonged doldrum wind conditions (Wilkinson, 1998, 2000, 2002). In 1998, a universal bleaching event caused the greatest mass mortality to reef corals ever documented on a global scale. In addition to global bleaching events, individual corals can bleach under a variety of circumstances. Coral bleaching also occurs as a response from exposure to: low temperature (Steen and Muscatine, 1987; Saxby *et al.*, 2003), reduced salinity (Goreau, 1964), increased sedimentation or turbidity (Rogers, 1979; 1983), bacterial infections (Ritchie and Smith, 1998a, b; Kushmaro *et al.*, 1996, 1997), protozoan infections (Upton and Peters, 1986; Peters, personal communication), and UV light (Anderson *et al.*, 2001; Lesser, 1996; Gleason, and Wellington, 1993). Localized or individual colony bleaching was referred to as 'causal bleaching' (CHAMP 2001). Causal bleaching might result from microhabitat exposure to extreme physical conditions, pollutants, parasites, pathogens, or any stress or combination in which the symbiotic relationship is disturbed. Coral pathologists often liken coral bleaching in response to stress as a disease sign, like a fever in sick people.

The objective of our study was to assess the current condition of coral reefs throughout South Florida. We report the presence or absence of coral diseases and bleaching and the prevalence or frequency of coral disease and three intensities of bleaching as indicators of condition. We employed a probability-based survey design similar to the approach used by EPA's Environmental Monitoring and Assessment Program (EMAP) (Summers *et al.*, 1995). This sampling strategy allowed us to estimate the area affected by the presence of coral diseases and bleaching, and the frequency ranges for these indicators. The principal results reported the proportional amount of area in which coral diseases and bleached corals were present and the frequency distribution of their occurrence. Information was used to generate areal estimates indicating the extent and intensity of coral disease and bleaching. By assessing condition, future surveys can be compared to a baseline for determining changes and trends in the spatial distribution of coral condition in South Florida.

2. Materials and Methods

2.1. Survey Design

The survey area encompassed coral reefs within the Florida Keys National Marine Sanctuary (FKNMS), New Grounds, Dry Tortugas National Park (DTNP), and Biscayne National Park (BNP). The sampling design was achieved in three steps: (1) boundaries of coral resource developed from benthic maps and local experts, (2) geographic regions were stratified into reef sectors, and (3) random selection of multiple sites from reefs sectors (Summers, *et al.*, 1995) (Figure 1). Areas of the Florida Keys that contained hard coral bottom were demarcated based on benthic habitat maps of the Florida Keys (FMRI, 1998). Habitat boundaries were refined and confirmed by local experts to include areas that were known to have living

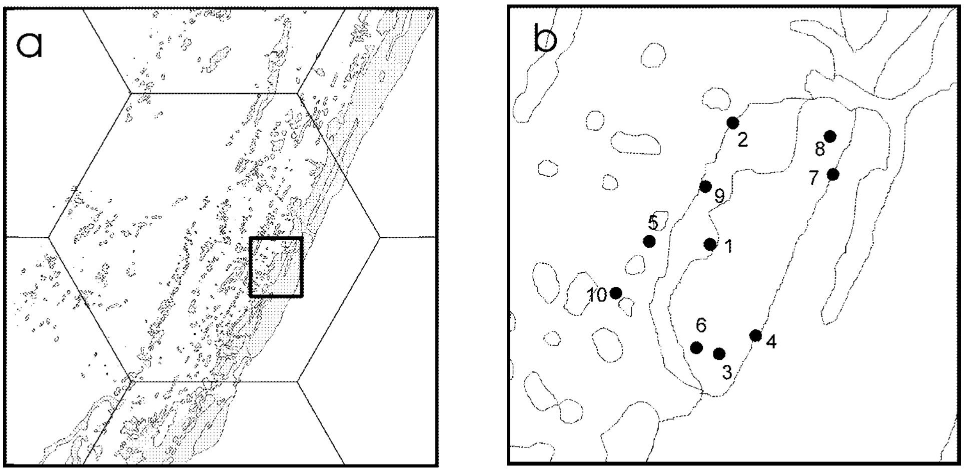

Figure 1. The sampling design was implemented by overlaying hexagonal cells on a gridded map of South Florida coral reefs (*a*). A reef sector was randomly chosen, as seen in the boxed insert in *a*. Ten locations were randomly chosen from this reef sector (*b*). The first location (1) was assessed for suitability of sampling. Nine other locations were used as alternate sites and considered in sequential order if the previous was not suitable (*b*).

corals and to eliminate areas that contained only dead or geological reef structure (Wheaton *et al*., 1995; 1996). This process was done for all known reefs mapped in the FKNMS; we referred to these individual areas as reef sectors. Delineation of these habitat locations or reef sectors allowed us to develop a sample frame (i.e., a list of potential sites) to represent the target populations, namely, living reef corals in the Florida Keys.

From this sample frame, a sample survey design was developed to estimate the areal extent and intensity of coral diseases and bleaching in the sampled coral community. The survey area of South Florida was stratified into two geographical regions, the Eastern Keys (Upper, Middle, and Lower Keys) and the Western Keys (Key West, New Grounds, and Dry Tortugas). A grid was placed over the entire survey area within each stratum resulting in 14 sampling cells in the East and 16 sampling cells in the West. A sampling location was randomly located within each cell of the grid that intersected with reef resource for a total of 30 sites (one per cell) representing the entire coral resource in South Florida. This type of spatially-balanced survey design is appropriate for estimating the spatial extent of ecological condition (i.e., presence and prevalence of disease) with a quantifiable level of uncertainty (Summers, 2001). Each of the 30 sites selected was assigned to an individual reef area or sector that was closest to the chosen sampling location within each cell. Each selected reef sector was assigned a specific weight based on the areal extent of the resident coral reef community (km^2) represented by the sector. The total area of the sampled resource, that is living reef corals, was the sum of all the individual reef sector areas contained in the grid.

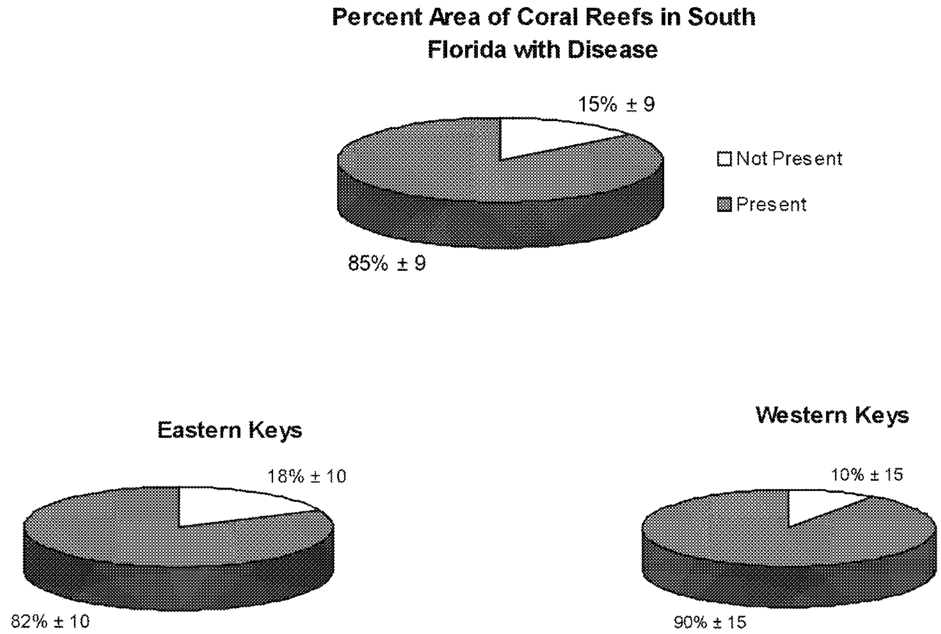

Figure 2. Estimates of coral disease presence in the South Florida area and within the Eastern and Western Keys regions.

Because the accuracy of the base habitat map used to define the sample frame was questionable, we selected 10 potential sites for the selected reef sector in each cell to ensure that coral would be encountered during sampling (Figure 1b). These were chosen in the selected reef sector since it was physically impossible to travel tens of miles between each point on different reef sectors in the order of selection to visually confirm that live coral was present for sampling. The survey conditions were limited by our ship time, divers time underwater, and daylight as to the amount of distance traveled to establish sampling sites. These random sampling locations (10 points within each reef sector) were geo-referenced with latitude and longitude coordinates. The additional nine 'oversamples' or alternate sites ensured that each reef sector was appropriately represented in the survey. Each group of sites was referenced to that specific reef sector, and each site within each sector group was assigned a sequential number.

During the survey implementation, divers tested the validity of the sampling frame before continuing the survey. The divers first visited the '1' designated site within a reef sector and assessed the site's suitability for sampling. A site was deemed suitable if there was > 5% coral coverage. If suitable, the site was surveyed. If, however, the site had < 5% coral coverage, the divers moved to the first alternate or oversample site selected for the reef sector. Site '2' was evaluated for its

TABLE I

Station locations including assignment to region, keys sector, and latitude/longitude in degrees, decimal minutes

Region	Keys sector	Reef name	Latitude	Longitude
Eastern Keys	Lower Keys	Cliff Green Patch Reef	24° 30.216′	81° 46.059′
Eastern Keys	Lower Keys	Eastern Sambo Reef Deep	24° 29.303′	81° 39.951′
Eastern Keys	Lower Keys	Eastern Sambo Reef Shallow	24° 29.501′	81° 39.814′
Eastern Keys	Lower Keys	Looe Key Reef Deep	24° 32.523′	81° 24.918′
Eastern Keys	Lower Keys	Looe Key Reef Shallow	24° 32.716′	81° 24.477′
Eastern Keys	Lower Keys	Western Head Patch Reef	24° 29.863′	81° 48.334′
Eastern Keys	Middle Keys	Alligator Reef Shallow	24° 50.772′	80° 37.381′
Eastern Keys	Middle Keys	Sombrero Reef Shallow	24° 37.531′	81° 06.424′
Eastern Keys	Middle Keys	Tennessee Reef Shallow	24° 44.698′	80° 46.873′
Eastern Keys	Middle Keys	West Turtle Shoal Patch Reef	24° 41.956′	80° 58.021′
Eastern Keys	Upper Keys	Carysfort Deep Reef	25° 13.248′	80° 12.592′
Eastern Keys	Upper Keys	El Radabob Hard Bottom	25° 07.195′	80° 22.703′
Eastern Keys	Upper Keys	Grecian Rocks Reef Shallow	25° 06.450′	80° 18.410′
Eastern Keys	Upper Keys	Turtle Patch Reef	25° 17.683′	80° 13.145′
Western Keys	Dry Tortugas	Bird Key Reef 3	24° 37.190′	82° 52.000′
Western Keys	Dry Tortugas	Bird Key Reef 6	24° 37.852′	82° 52.705′
Western Keys	Dry Tortugas	Loggerhead Key Reef 2	24° 37.798′	82° 56.171′
Western Keys	Key West	Eastern Dry Rocks Reef 1	24° 27.575′	81° 50.755′
Western Keys	Key West	Eastern Dry Rocks Reef 4	24° 27.728′	81° 50.338′
Western Keys	Key West	Rock Key Reef 1	24° 27.211′	81° 51.602′
Western Keys	Key West	Rock Key Reef 2	24° 27.291′	81° 51.562′
Western Keys	Key West	Sand Key Reef 1	24° 27.140′	81° 52.587′
Western Keys	Key West	Sand Key Reef 2	24° 27.119′	81° 52.650′
Western Keys	Key West	Sand Key Reef 3	24° 27.087′	81° 52.799′
Western Keys	Key West	Western Sambo Reef 2	24° 28.858′	81° 43.077′
Western Keys	Key West	Western Sambo Reef 3	24° 28.772′	81° 42.871′
Western Keys	Key West	Western Sambo Reef 5	24° 28.842′	81° 43.069′
Western Keys	New Grounds	New Grounds Reef 1	24° 40.510′	82° 21.670′
Western Keys	New Grounds	New Grounds Reef 2	24° 40.009′	82° 26.650′
Western Keys	New Grounds	New Grounds Reef 4	24° 40.386′	82° 22.483′

suitability to sample (Figure 1b). This process continued in order of the randomly selected sites until up to five suitable sites were found in a reef sector. The selection of sites in each reef sector was carefully tracked because this information was necessary to determine the inclusion probability associated with each site. During statistical analysis, the probability that each site was included in the design was used to calculate the weight assigned to that site when we estimated the proportion of area with certain ecological conditions. The number of sites (out of 10) that were visited until a suitable site was selected, was also used to revise our estimates of the total area of coral habitat in each region (Table I). Reef sectors, where none of the randomly selected sites met the minimum coral coverage requirement, were abandoned and were determined to be not part of the survey target population.

In some cases, a reef sector was not visited or, it was sampled more than once in different locations. These instances were usually the result of difficult field logistics which could not be resolved in the limited ship time available for the survey. The difficult field logistics included no detailed benthic maps or knowledge of the location of living reef corals, inaccessible locations which could not be approached by ship or small boat, distant locations from the base ship, and unsafe diving conditions. Whether more than one sample was completed, alternate sites were used, or no sampling was conducted in a sector, this 'caveat' information was deemed as equally important as the actual sampling data and documented *in-situ*. These deviations to the survey design were generally qualified three ways: 1) unable to sample for some physical reason (i.e., inaccessibility); 2) misidentified as part of the target population; and 3) unknown. Data qualified in such a way resulted in actions ranging from correcting sampling frame information for future surveys to factoring adjustments for data analyses.

2.2. Survey Methodology

The coral disease survey was conducted during 6–19 August 2000 in South Florida. All surveys were conducted using the radial arc transect method developed for coral disease studies (Santavy *et al*., 2001). In general, SCUBA was used on deeper reefs and snorkel was used on shallow reefs for the assessment. A stainless steel rod was positioned in a stainless steel pipe installed at the study sites with a 12 m line fastened to the rod. A line tender held the line taut and slowly moved the line in an arc around the fixed central point. Three divers swam in concentric circles directly over the line, one recorded the number of colonies of each coral species, another recorded the number of colonies of each species that displayed signs of specific diseases, while a third recorded the number of colonies of each species that displayed signs of a bleaching state. The divers counted colonies larger than 10 cm that fell directly below each 2 m segment of the line. If at least half of the colony or more was within the transect segment, it was included in the transect. In previous studies, it was determined that only the 8 to 10 m segment was required to obtain a reliable estimate of coral disease (Mueller *et al*., 1998; Santavy *et al*., 1999a, 2001).

Ten disease conditions affecting 16 species of scleractinian corals and gorgonian sea fans were enumerated (Table II). Three species of coral, *Montastraea annularis, Montastraea faveolata*, and *Montastraea franksi* contained within the

TABLE II

Coral species that are affected by the diseases monitored are indicated by (●) in the table

Species	Disease									
	Aspergillosis	Black-band disease	Dark spots disease	Hyperplasia	Red-band disease	White pox/ Patchy necrosis	White plague	White-band disease type 1	White-band disease type 2	Yellow-blotch disease
Acropora cervicornis						●		●	●	
Acropora palmata								●		
Colpophyllia natans		●	●		●		●			
Dendrogyra cylindrus							●			
Dichocoenia stokesii				●			●			
Diploria labyrinthiformis		●					●			
Diploria strigosa		●		●			●			
Gorgonia spp.	●	●	●			●				
Montastraea annularis[a]		●	●				●			●
Montastraea faveolata[a]		●	●				●			●
Montastraea franksi[a]		●	●				●			
Montastraea cavernosa		●					●			
Mycetophyllia danaana							●			
Mycetophyllia ferox							●			
Mycetophyllia lamarckiana							●			
Siderastrea siderea		●	●				●			
Solenastrea bournoni							●			
Stephanocoenia michelini			●				●			

[a] These species are contained within the *Montastraea annularis* complex (Weil and Knowlton, 1994).

Montastraea annularis complex were combined as a single taxon for data analysis (Weil and Knowlton, 1994). Two gorgonian species, *Gorgonia flabellum* and *Gorgonia ventalina*, were combined as *Gorgonia* spp. Only diseased colonies containing active lesions were enumerated, if the cause of recent death was not apparent it was not scored for a specific disease. Methods used to distinguish coral diseases have been detailed in recent publications (McCarty and Peters, 1998; Santavy and Peters, 1997; Santavy *et al.*, 2001). Patchy necrosis disease (Bruckner and Bruckner, 1997) and white pox (Patterson *et al.*, 2001) could not be resolved based on descriptions in the literature and might be the same disease; therefore, we used the term patchy necrosis disease/white pox to describe the lesions found on *Acropora palmata* colonies. We did not distinguish between white plague type 1 (Dustan, 1977) and 2 (Richardson *et al.*, 1998a, b), but identified these conditions only as white plague. We used a combination of signs defined in the literature (Kim *et al.*, 1997; Nagelkerken *et al.*, 1997a, b; Smith *et al.*, 1996) to identify aspergillosis on seafans (Santavy *et al.*, 2001).

Coral bleaching was recorded as another indicator of condition. The bleaching indices recorded were not associated with the widespread episodic bleaching that is caused by worldwide increases in sea-surface temperatures. We presumed that the individual colony bleaching we observed was caused by other environmental factors which impairs the colony's health. The term 'causal bleaching' was used to distinguish it from massive bleaching. Bleaching observations were categorized into three stages: paling, partial bleaching, and bleaching. Paling was scored if the colony's tissue appeared as mottled or very light in pigmentation but not as white tissue. Partial bleaching was scored if 10–50% of the colony's tissue was white. Bleaching was scored if greater than 50% of the colony's tissue was white.

2.3. Data analysis

All analyses were completed using SAS/STAT (SAS Institute, Version 8, Cary, NC, 1999) using cumulative distribution functions (CDF) to assess the areal extent of coral disease and bleaching incidents in the Eastern and Western Keys. The randomized site selection and area weights apportioned to each site were critical in calculating CDFs and associated variances (Cochran, 1977). While the CDFs were standard weighted frequency distributions, the variance estimates (95% confidence intervals) were computed using a modified formula from Cochran to approximate the mean squared error of the CDF estimate (Cochran, 1977 eq. 11.30; Summers, *et al.*, 1993).

In some cases, adjustments were made in the calculations in order to prevent skewed results. If portions of the intended survey area were not sampled, the total area for the entire resource was adjusted so that the results reflected estimates for reef sectors that were actually sampled. In order to compute the estimates with a known uncertainty, the inclusion probability for each site was determined. The inclusion probability is based on the size of the reef sector, the total area to be sampled, and the number of sites visited before a suitable site was found. In effect, the inclusion probability acts as a weighting factor for the estimate of coral disease or bleaching state incidence at each site. Replicates in this study were additional sampling locations within the same reef sectors and, therefore, not true replicates. These 'replicates' were treated as additional independent sampling sites with an inclusion probability that was reduced proportionately to the number of 'replicates' within a reef sector. In reef sectors where an alternate site was chosen in lieu of the original sampling location, the area weight representing the location was adjusted to reflect the change in the target population. These additional factors were calculated into the equations, ensuring that a single reef sector did not bias the overall results.

3. Results

Prior to implementing the survey design we estimated the total reef area in South Florida to be 4416 hectares (ha) (44.0 km^2) with the Eastern Keys area encompassing 2599 ha (26.0 km^2) and the Western Keys area encompassing 1817 ha (18.2 km^2). Areas west of the Lower Keys and between the New Grounds and Dry Tortugas were not included in the analysis due to the absence of reliable benthic maps. The actual area represented by the study was 4100 ha (41.0 km^2) or 93% of the original estimated area. The Eastern and Western Keys were represented respectively by 2495 ha (25.0 km^2) and 1605ha (16.1 km^2) or 96 and 88% of the original estimated reef areas.

3.1. Presence and Prevalence of Coral Disease

A large portion of the sampled area had coral disease present (Figure 2). The presence of disease at a site was positive if a single diseased colony was found during the assessment. At least one coral colony with active disease present, in any single location, was observed in 85% ± 9 (CDF ± 95% confidence intervals) of the area sampled (Figure 2). The Eastern Keys had a lower presence of coral disease (82% ± 10 of the area sampled) as compared to the Western Keys (90% ± 15) (Figure 2). Coral disease was widely dispersed throughout the South Florida region and did not seem to be confined to particular sites or regions.

The proportion or number of colonies affected by disease(s) was referred to as disease prevalence. The maximum percentage of coral colonies at a single site affected with disease or the disease prevalence was 13%, within 2.2% (97 ha) ± 4 of the sampling area. The prevalence of coral disease in South Florida is shown as the CDF in Figure 3. Approximately 662 ha (15% ± 9 of the total area sampled) contained no coral disease, whereas 1369 ha (31% ± 14) had 0.4–2.2% of the colonies affected by coral disease (Figure 4a).

Coral disease prevalence did not vary significantly between the Eastern and Western Keys regions (Figure 4b). No coral disease was present in 468 ha (18%

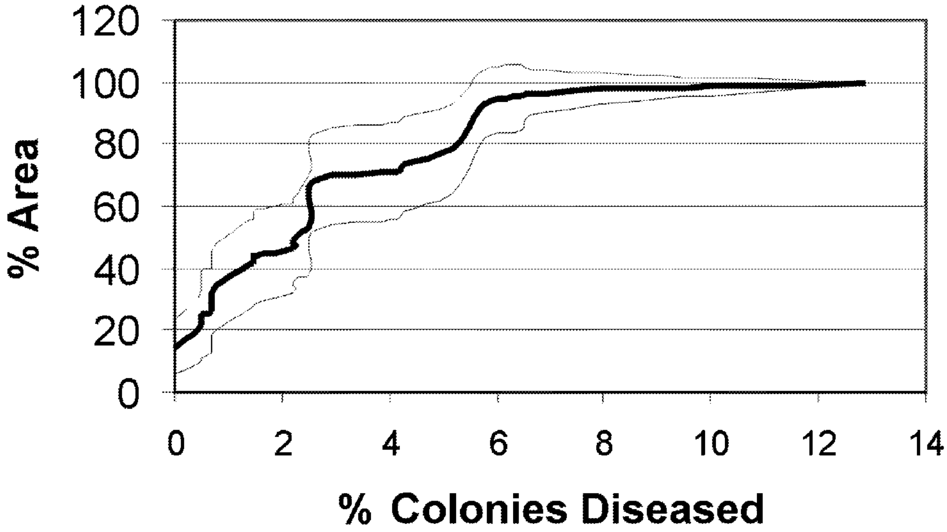

Figure 3. Cumulative distribution function depicting overall areal estimates associated with coral disease prevalence or extent in South Florida (–) and 95% confidence interval (—).

± 11 of area sampled) in the Eastern Keys compared to 176 ha (10% ± 15) in the Western Keys. The maximum prevalence of coral disease at a single location in the Eastern and Western Keys was 9 and 13%, respectively. Disease prevalence greater than 6% occurred in a very small portion of all areas sampled [44 ha (2% ± 9) in Eastern Keys and 98 ha (5% ± 11) in Western Keys].

3.2. Presence and prevalence of bleaching and paling

In South Florida, 836 ha (19% ± 4 of the area sampled) had at least one colony that was bleached (> 50%), while 1828 ha (41% ± 4 of the area) had at least one colony that was partially bleached (10–50%). All locations had at least one paled colony observed. The maximum prevalence or proportion of colonies bleached or partially bleached corals in South Florida was very low. The maximum bleaching prevalence was 4%. It occurred in only 2% ± 4 of the area or 98 ha. The maximum partial bleaching prevalence was 6%. It occurred in 2% ± 4 of the area or 264 ha. Paled colonies were throughout our survey area, although the maximum paling prevalence of 47% occurred in only 264 ha (2% ± 8 of the area).

The prevalence of bleaching was quite low in South Florida during the survey (Figure 5a). A greater area experienced bleaching in the Western Keys [39 ± 4 (701 ha)] than in the Eastern Keys [5% ± 4 (135 ha)] (Figure 5b). The Western Keys had bleaching prevalence ranging from 0.4–4%, while the Eastern Keys maximum prevalence was only 0.2% at any location. The presence of partial bleaching was 41% ± 8 (1564 ha) of the area sampled, whereas partial bleaching prevalence ranged from 0.3 to 7% (Figure 6a). Partial bleaching was negligible in the Eastern

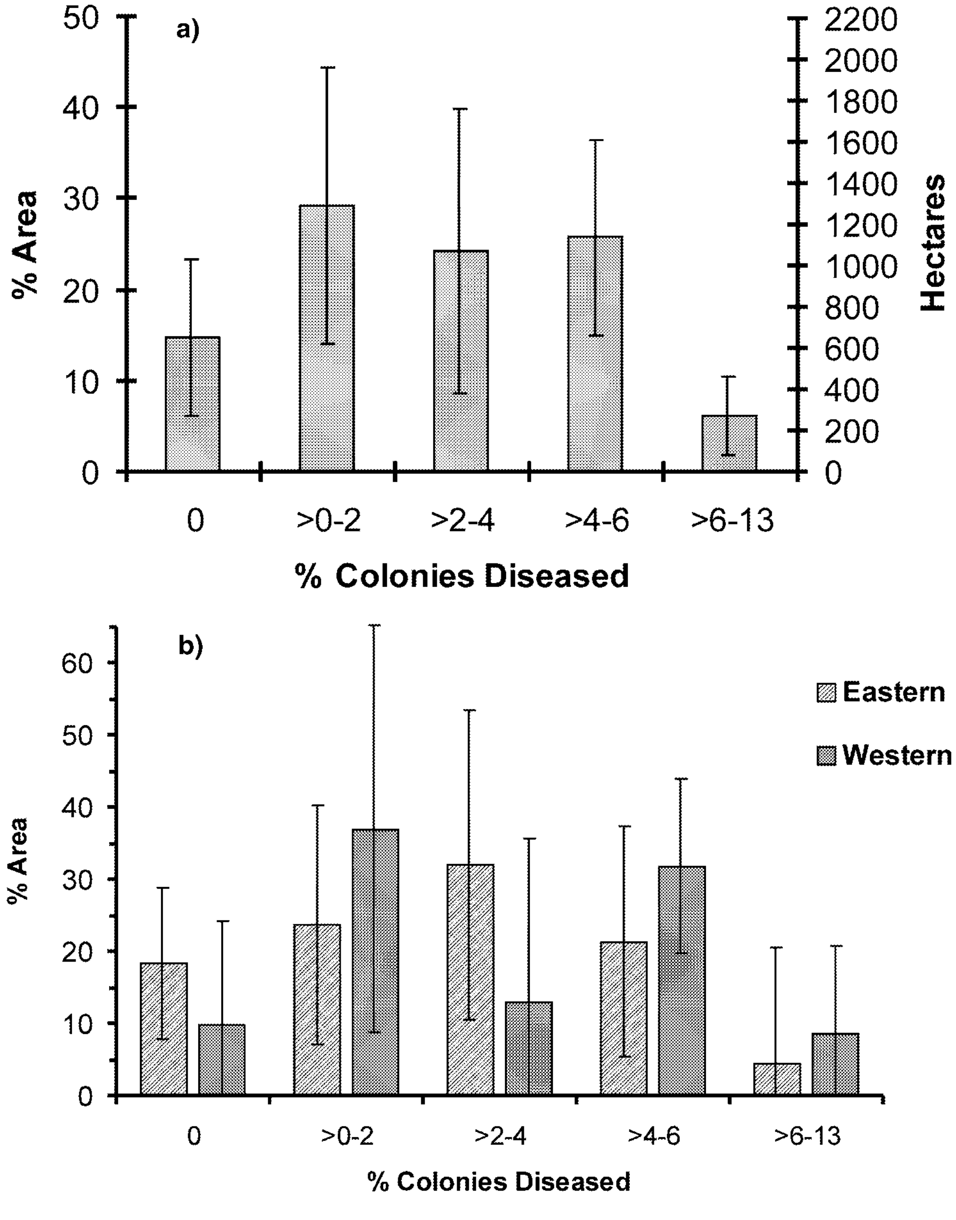

Figure 4. Estimates of area with 0–13% disease prevalence or percent of colonies affected by disease in: a) entire South Florida area; b) Eastern Keys and West Keys. Error bars represent 95% confidence levels.

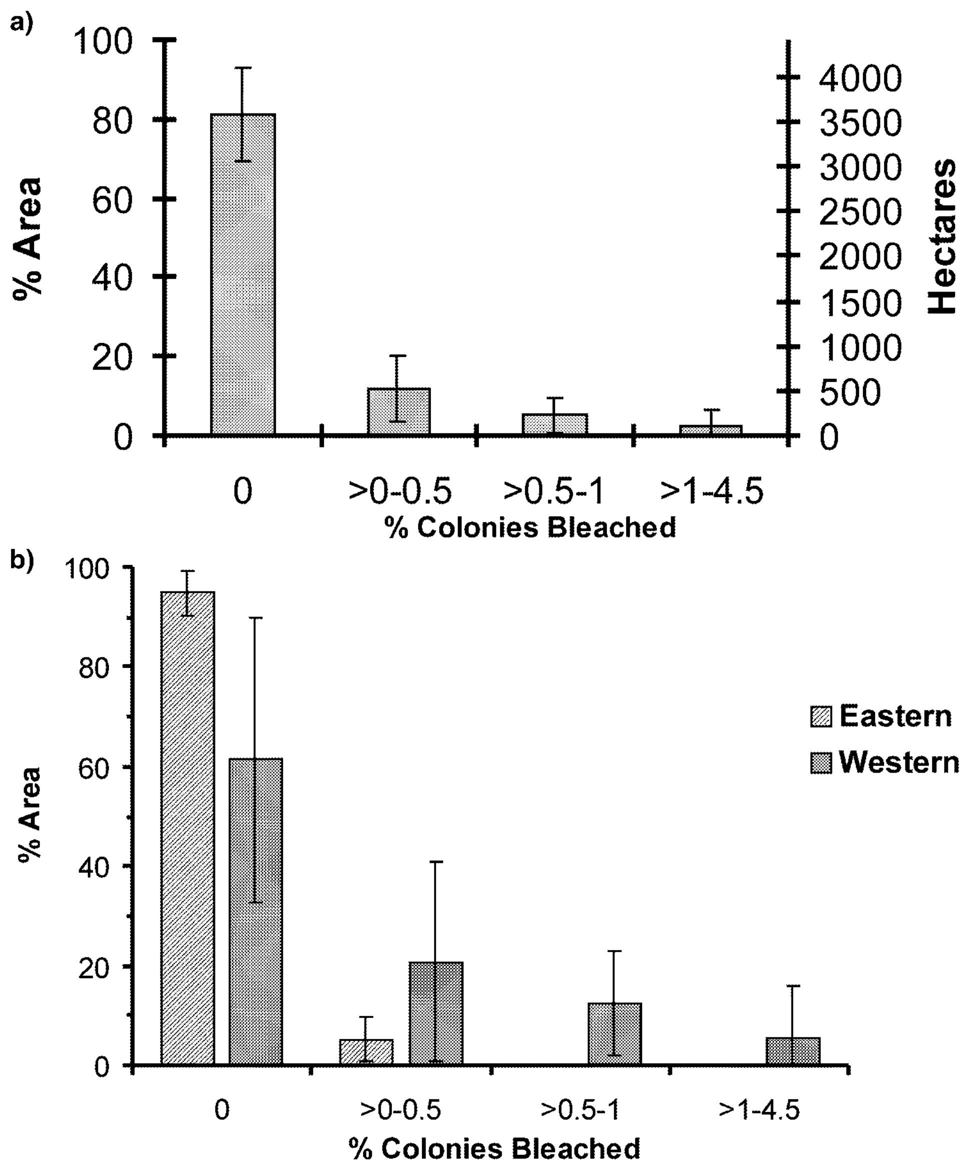

Figure 5. Estimates of area with 0–4.5% bleaching prevalence or percent of colonies bleached for: a) entire South Florida area, b) Eastern Keys and West Keys. Bleaching scored when > 50% of colony bleached. Error bars represent 95% confidence levels.

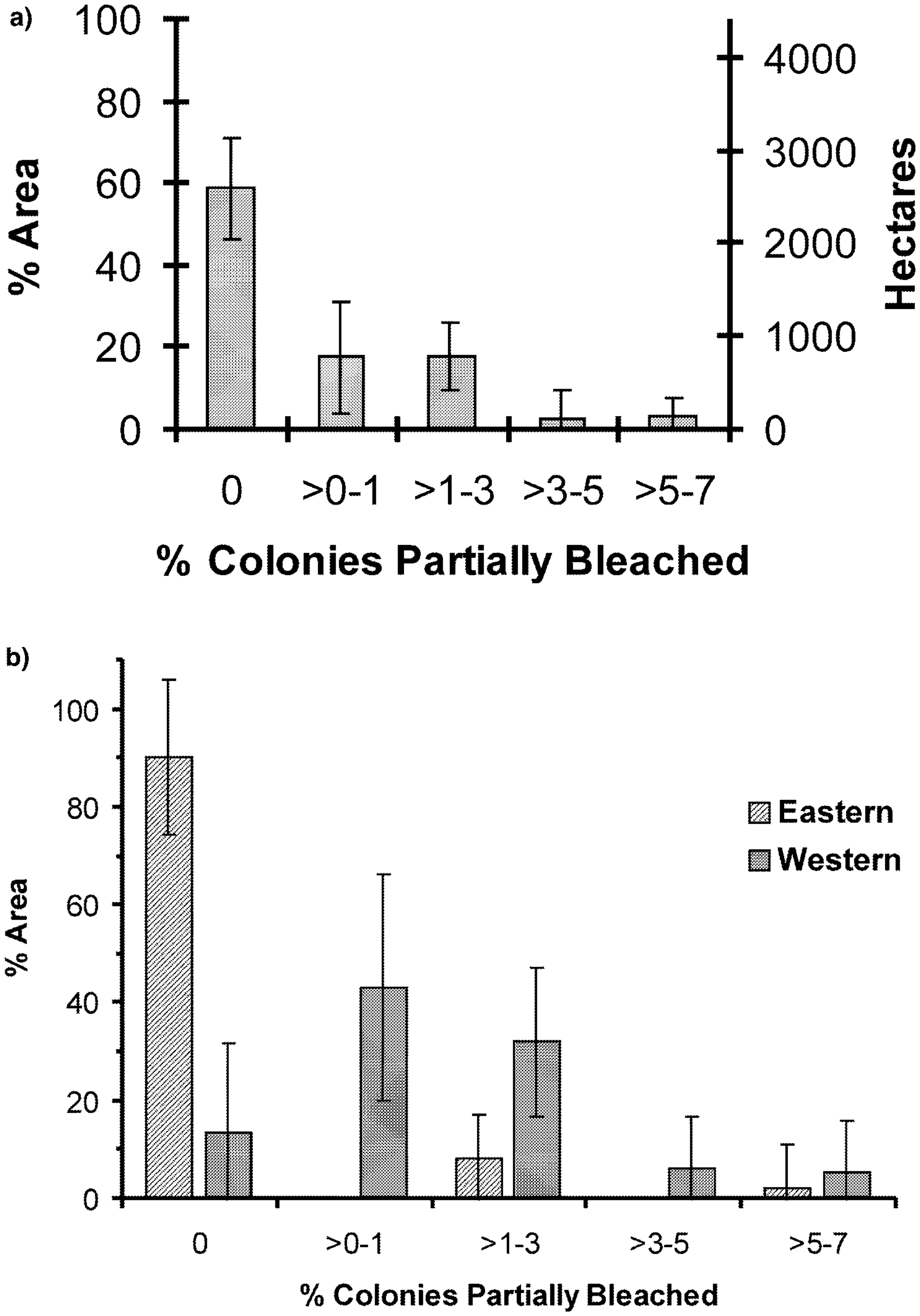

Figure 6. Estimate of area with 0–7% partially bleached prevalence or percent of colonies partially bleached for: a) entire South Florida area; b) Eastern Keys and West Keys. Partial bleaching scored when $10 \geq$ and ≤ 50 of entire colony was bleached. Error bars represent 95% confidence levels.

Keys, but much more widely distributed and prevalent in the Western Keys (Figure 6b). The Western Keys had more than 75% ± 15 (1359 ha) of the area with 0.3 to 3% prevalence of partial bleaching. Less than 12% of the Western Keys had more than 3% partially bleached colonies at one location.

Paled colonies were widely distributed in South Florida. They occurred in virtually every site sampled, although paling prevalence among the sites was highly variable. Most locations had a paling prevalence of 10–15% (Figure 7a), although 263 ha (6% ± 4 of the area) had greater than 25% of the colonies paled. Overall, the Eastern Keys had a lower paling prevalence, with 2447 ha (95% ± 4) containing less than 15% paled colonies at a single location (Figure 7b). The Western Keys had variable frequencies of paled colonies which were highly distributed throughout this region. Only 98 ha (5% ± 11) of the Western Keys region had the maximum paling prevalence of 40–50%.

4. Discussion

Previous studies of coral diseases have sought to describe specific disease outbreaks in limited areas, with a primary focus on black-band disease (Bruckner *et al*., 1997; Edmunds, 1991; Feingold, 1988; Gladfelter, 1982; Gladfelter *et al*., 1977; Kuta and Richardson, 1996; Nagelkerken *et al*., 1997a, b; Patterson *et al*., 2001; Richardson *et al*., 1998b). We sought to understand the condition of reef corals by assessing the absence/presence and frequency/prevalence of coral diseases and bleaching over large geographic regions. Using a probability-based survey design, we selected stations prior to visiting the site. This allowed us to obtain unbiased estimates of the presence and prevalence of coral disease and bleaching. This strategy should allow us to begin to distinguish natural disease levels from elevated disease levels induced by anthropogenic and climatic factors.

4.1. Presence and prevalence of coral disease

We estimated the condition of reef corals using biological indicators of health for 41 km^2 (4100 ha) of coral reefs in BNP, FKNMS, New Grounds, and DTNP. The FKNMS has jurisdiction more than 9600 km^2 of coastal waters off the Keys excluding the areas of BNP and DTNP (NOAA, 1996). The FKNMS has a total of 50 km^2 (4921 ha) of coral reefs zoned into Sanctuary Preservation Areas, Ecological Reserves, and Special Use or Research Only (NOAA, 1996). The amount of area that encompasses coral reefs is not estimated in the DTNP, but BNP has approximately 291 km^2 (29,140 ha) of coral reef habitat although this entire area probably does not contain live corals, but primarily geological structures of reef relief (http://www.nps.gov/bisc/index.htm). Areal estimates for our survey in the Eastern and Western Keys were 25 km^2 (2495 ha) and 16 km^2 (1605 ha), respectively using these data.

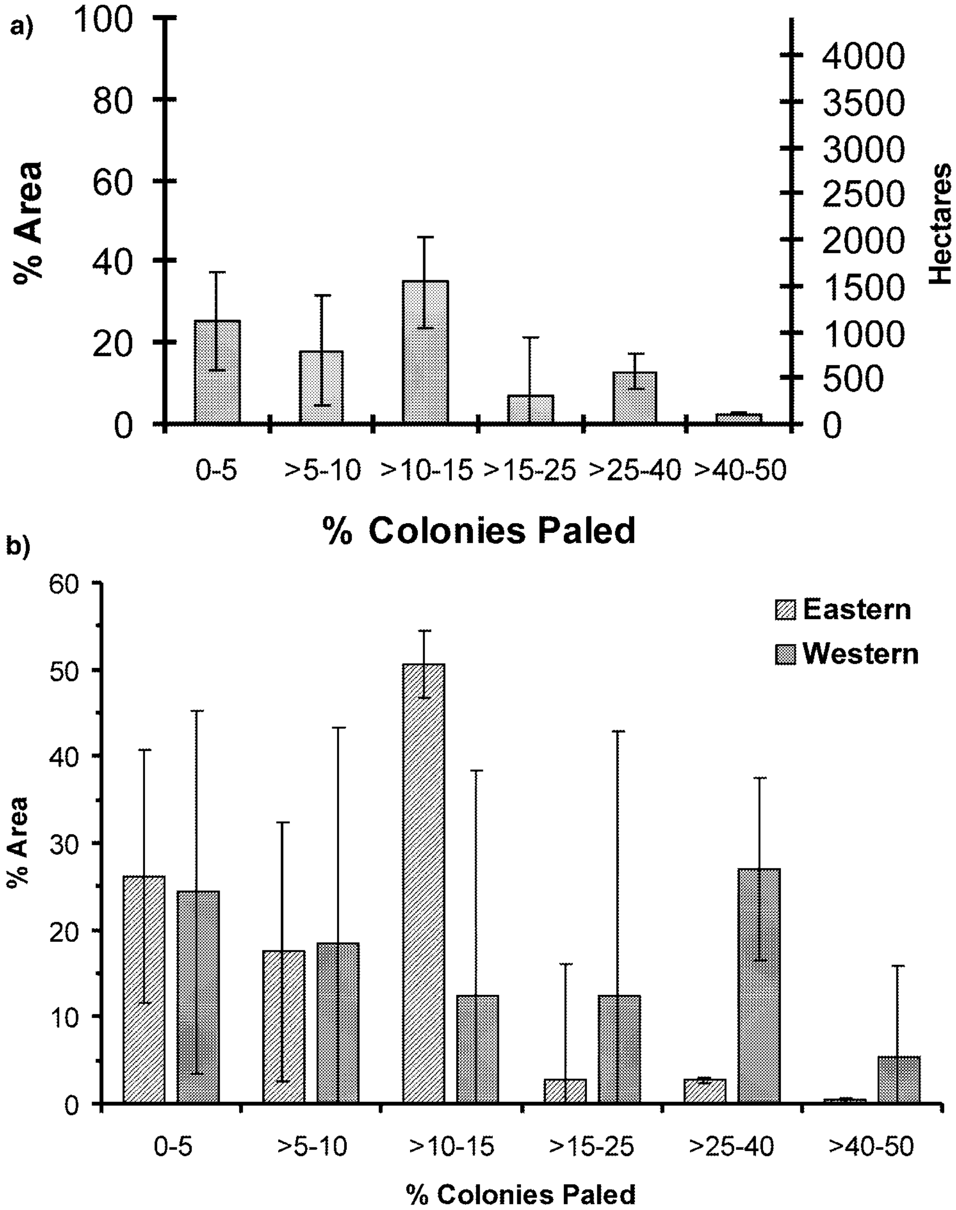

Figure 7. Estimate of area with 0–50% paled prevalence or percent of colonies paled for: a) entire South Florida area; b) Eastern Keys and West Keys. Paling scored when colony had lightened tissue pigmentation but not resulting in translucent white tissue. Error bars represent 95% confidence levels.

We determined that presence of coral disease alone was not a good indicator of overall coral condition, because 85% of the area had coral disease on at least one colony. Disease presence on an individual in a population is a natural occurrence and does not always signal decline in the health of a population or community (Sinderman, 1990; Sparks 1985). A much more useful biological indicator of coral communities was the prevalence, of coral disease throughout the region. The prevalence allowed the overall condition of corals to be quantified. If a small percent of an area has a high prevalence of disease, this might indicated an elevated disease level above the population or community's natural state. The factors responsible for the higher disease prevalence could signal stress potentially caused by altered environmental quality. In this 2000 coral survey, our results suggest that disease prevalence at levels of 6% or lower could be a natural background level in South Florida (Figures 3 and 4a). Approximately 79% ± 11 of the area in South Florida had less than 6% of the coral colonies with disease. We suggest those coral disease levels significantly higher than 6% might indicate health problems within the coral communities in South Florida. Only 2.2% ± 4 (97.15 ha) of the sampled area had a maximum prevalence of 13% diseased coral colonies which might signal critical conditions.

In general, there were no significant differences between the Eastern and Western regions for the presence (Figure 2) or prevalence of disease (Figure 4b). In the Eastern Keys, 5% ± 16 (117 ha) of the area and in the Western Keys, 9% ± 12 (155 ha) of the area had greater than 6% of the colonies affected with disease. Another study indicated that the Key West reefs have the maximum disease prevalence (Santavy *et al*., 2001). It might be revealing to use additional studies designed to evaluate the distribution of specific diseases over a broad geographic region to compare natural disease prevalence vs. elevated prevalence due to environmental and/or climatic disturbances. It is very likely that different diseases would show disparate patterns that are influenced by diverse environmental parameters derived from both natural and anthropogenic processes.

4.2. Presence and Prevalence of Coral Bleaching and Paling

The results from this study emphasize the importance of qualifying and quantifying the incidence of anomalies in populations or communities. The presence of coral disease, coral bleaching, and/or coral paling are not useful indicators for understanding overall coral health or condition for populations and communities over large areas. Whereas, reporting the prevalence of anomalies could indicate compromised health at both the population and/or community levels. Paling colonies were present at all locations, although the prevalence varied. The presence of bleached and partially bleached colonies were 19% ± 4 (836 ha) and 41% ± 4 (1828 ha), respectively, although the prevalences were very low for both states (Figures 6 and 7). The prevalence of bleached colonies was very low, with 11% ± 8 of the areas having less than 0.5% of the total colonies in this state (Figure

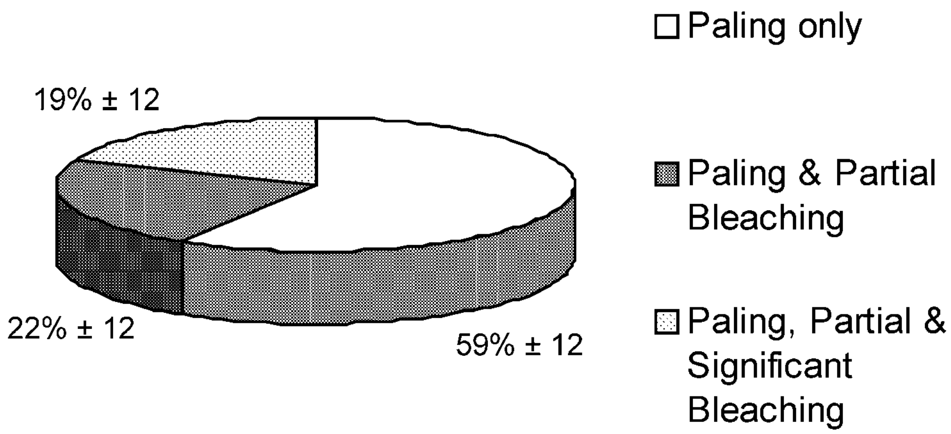

Figure 8. Estimated proportion of South Florida area with one of following bleaching state: coral paling, partially bleached (10–50% colony affected) or bleached (> 50% colony affected). Paling colonies have significantly lightened tissue pigmentation but not resulting in translucent white tissue.

5a). Only 7% ± 4 of the areas had between 0.5% and a maximum of 4.5% of the colonies bleached. Interestingly, the Western Keys had a greater prevalence of bleached and partially bleached colonies than the Eastern Keys during our survey (Figures 5b and 6b). The prevalence of partial bleaching also was relatively low, approximately, and 35% ± 8 of the area had 3% or less of the total coral colonies partially bleached (Figure 6a). Only 6% ± 4 of the areas had greater than 3%, with a maximum of 7%, partially bleached prevalence. Our results suggest that when significantly more than 3% of the colonies partially bleached at a particular location in South Florida, it might signal changes in environmental conditions deleterious to coral health.

Since there was not a massive bleaching event for corals during the summer of 2000 in South Florida, the localized bleaching, partial bleaching, and paling that was observed was attributed to decreased health or fitness of the coral colony, regardless of the cause. It is known that coral bleaching or loss of color can be caused by many other factors besides elevated sea-surface temperature (Glynn 1993, 1996; Lesser, 1996, Mumby *et al.*, 2001; Ware *et al.*, 1996). Hoegh-Guldberg (CHAMP, 2001) suggested that there were distinct agents that caused coral bleaching and were different from the agents that caused 'massive coral bleaching'. He implied a combination of factors other than elevated sea-surface temperature can induce 'causal bleaching' (CHAMP, 2001) as compared to massive bleaching. He further explained that thermal events trigger massive coral bleaching, which can be aggravated by secondary factors like high PAR light, UV radiation, hypoxia due to reduced water movement, perhaps starvation, and other factors. These different responses could be based on a variety of physiological and genetic factors of the corals.

The presence of more than one bleaching state at a single location might be more important in understanding coral condition than examination of the frequency of individual bleaching states over the entire area (Figure 8). It is known that different species have different tolerances to factors which induce massive bleaching. An index for bleaching that integrates more than one bleaching state might be useful in assessing the overall condition of coral. The proportion of area in South Florida that contained corals with all three bleaching states present was 19% ± 12 (839 ha) (Figure 8). The proportion of South Florida corals that were observed at a single location with at least one colony paled and another colony partially bleached was 22% ± 12 (971 ha). There were no locations where only paled colonies and bleached colonies cooccurred. The remainder of the locations contained at least one paled colony.

One site that contains all bleaching states might indicate different stages or severity of a chronic exposure in progress or alternatively, recovery from a stressed to a more healthy condition. To exemplify the first scenario, paling might signify a minor disturbance of the symbiosis for which most individuals can compensate and remain in stable health condition. When a colony has a reduced capacity to compensate for a decline in symbiotic algae concentration, the coral's health might be manifested as increased paling leading to partial bleaching and eventually bleaching. The dynamics affecting its health could be related to the severity and length of single or multiple stressor(s) exposure(s), for example, localized increases in temperature, light, salinity and/or pathogens. Alternatively, the coral may be pale or partially bleached after reacquisition of its algal symbionts in a recovery stage from past bleaching to an improved health condition. In our study 22% 12 ± of the area in South Florida had both paled and partially bleached corals at a single location (Figure 8). Consequently, the response state might indicate the onset of stress, decreased severity of the stressor, or the recovery from a past stress response.

Variations in bleaching patterns associated with massive bleaching episodes have been addressed extensively in the literature, but most of these discussions have assumed the onset to be associated with increased sea-surface temperatures. Buddemeier and Fautin (1993) have suggested those bleaching patterns on and between colonies are due to consistent habitat differences in bleaching resistance at a given locale. Corals in habitats that are exposed to more variable conditions or stresses tend to be bleached less than those in less variable environments (Buddemeier and Fautin, 1993; Glynn, 1996). Differences in bleaching resistance may be ascribed to acclimatization, adaptation, or diverse 'ecospecies' that occupy different habitat niches.

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