An Assessment of the Health and Resilience of Bonaire's Coral Reefs

Field Report

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Summary

From July 19-26, 2010, a dedicated team of researchers completed transect surveys on 25 reefs located on the leeward side of Bonaire and the adjacent Klein Bonaire to characterize the current status, threats, and resilience of Bonaire's reefs. The assessments focused on corals, fish, algae and motile invertebrates using belt transects, point intercept methods and photographic documentation, incorporating attributes of the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol and the IUCN bleaching resilience protocol. The main purpose of this work was to 1) assess changes in reef structure and health since the last region-wide AGRRA assessments (1998-2000) and other surveys (2001, 2005) by Bruckner; 2) identify sites in excellent health, exhibiting a high biodiversity and cover of reef building corals and an intact fish communities; and 3) characterize the health and resilience of these reefs. The intent of this project was to provide critical information that can assist the Bonaire government and Bonaire Marine Park in the conservation and management of their precious resources.

Between 5-15 m depth, cover of living coral was high on all reefs (approximately 50%), with exception of a few sites impacted by white plague outbreaks and shallow areas scoured by strong waves during previous storms. Cover by fleshy macroalgae was generally low, as compared to reefs in other Caribbean localities, although some deeper sites did have high cover of *Lobophora* and *Dictyota* spp. (brown macroalgae), and cyanobacterial mats were prominent in several locations (especially on Klein Bonaire); these algae occasionally carpeted the margins of coral colonies and were competing with living corals. *Montastraea annularis* (complex) were the dominant corals, in terms of living cover, occupying approximately 20-25% of the benthos, and making up over 50% of the total live coral cover. *Agaricia, Madracis* and *Porites* spp. were the other dominant corals, in terms of living cover. *M. annularis* complex was also most abundant taxa (numbers of colonies) at all sites overall, and also the dominant taxa between 5-10 m depth, while *Agaricia* was slightly more abundant at 15 m depth. While the proportion (number of colonies) of brooding species (especially *Agaricia, Porites*) was very high, their contribution to living coral cover was less than *M. annularis* (complex) because most colonies were small in size.

Based on size structure, abundance, levels of recruitment, and coral condition, coral communities could be divided into two primary groups, the *M. annularis* complex (*M. annularis, M. faveolata* and *M. franksi*) and all other species. Corals lumped into "other species" were small to medium-sized (mean=24 cm), and population structure exhibited a monotonic decline in size; most colonies were < 20 cm in diameter and very few colonies were over 60 cm. Although a small proportion of colonies showed active signs of disease and competition from other biotic stressors, these corals had low levels of partial mortality (8%), few completely dead colonies were observed (0.4%), and they were the predominant species colonizing dead skeletal surfaces of other corals as well as reef substrates.

The original size of *M. annularis* (complex) colonies was significantly larger (58 cm diameter) than all other species, although many had been reduced in size due to partial mortality and skeletal surfaces of colonies often contained numerous smaller tissue remnants. These corals were being affected to the greatest degree by coral diseases (white plague, yellow band disease, black band disease, dark spots disease) and other biotic stressors, including competition and overgrowth by sponges, encrusting gorgonians, hydrozoan corals and a tunicate, predation by snails and parrotfish, and damselfish algal lawns. Colonies of *M. annularis* (complex) were missing on average 30% of their tissue, although the largest corals (mean size =61 cm; about 50% of all colonies) exhibited significantly higher amounts of partial mortality (mean loss=50%) than smaller (mean=41 cm) corals (mean tissue loss=11%). The extent of partial mortality, large numbers of completely dead colonies (4.5% of 1602 examined corals), ongoing stressors that continue to plague this taxa, and absence of colonies less than 10 cm in diameter (indicative of a lack of recruitment success) is of serious concern for these reefs, as these are the dominant frame-builders and characteristically the longest lived corals in the western Atlantic. The better overall health and high levels of recruitment observed in other taxa, in combination with recent declines in *M. annularis* complex, may indicate these reefs are undergoing a shift in species assemblages, with communities being replaced by smaller, shorter lived corals.

Fish communities on Bonaire were relatively high in diversity, with a dominance by herbivores (especially parrotfishes and damselfishes). Many species of important predatory fishes were present, including the dominant western Atlantic species of snapper, grouper, jacks and grunts, although these predatory fishes may be declining as the size structure was dominated by small and medium-sized fish. In particular, grouper over 30 cm total length were very rare. Large-sized groupers are the most important members of the family, as these species change sex (large individuals are females) and the larger fish produce an exponentially higher number of offspring.

In general, Bonaire's reefs show signs of high resilience and a good ability to recover from acute disturbances. Reefs had high coral cover, low levels of disease, high levels of recruitment, and low amounts of fleshy macroalgae. There are minor problems that need to be addressed through management actions and conservation strategies. This could include 1) a program to eradicate lionfish before their numbers get out of control (these species were seen, but they appear to be rare as compared to other Caribbean Islands); 2) community-based efforts to remove an encrusting tunicate, coral-eating snails, and three-spot damselfish; 3) a nursery/restoration program to propagate *A. cervicornis* and *A. palmata* and reintroduce these corals into their former habitat; 4) steps to increase the abundance of herbivorous sea urchin (*Diadema antillarum*) populations; 5) elimination of fishing on herbivores (parrotfish caught along the shoreline using handlines) and top predators (groupers); and 6) better sewage treatment and other strategies to reduce run-off and nutrient input from hotels located along the coastline.

Acknowledgements

The intensive surveys completed In Bonaire between July 19-26, 2010 represent the dedicated efforts of a talented group of scientists and field assistants. I am grateful for the assistance and expertise provided by the team to complete rapid ecological assessments, and extensive time devoted to data entry. Special thanks go to Eric Borneman, Robin Bruckner, Kalisi Faanunu, Philip Renaud, Glynnis Roberts, Debbie Santavy and Amanda Williams, each of whom specialized in one aspect of the survey approach and applied this on 25 reefs during 8 days of intensive diving. The quantitative surveys were enhanced through additional photo-documentation by Captain Philip Renaud, and video documentation by Robin Bruckner. I am also thankful for the assistance provided by Errol Coombs. He helped with all aspects of field work as well as out of water activities, including assistance provided to Captain Renaud and Robin Bruckner in entering and exiting the water with a lot of large and heavy research equipment. Thanks also to my team for their dedicated efforts to complete data entry in a timely manner. A special gratitude goes to Amanda Williams who assisted in compiling the dive sites and creating a georeferenced map; coordinated information and photo sharing among the Living Oceans Foundation and the participants; compiled recruit, point intercept and fish data; and created several of the figures included in this report. The team is to be commended for putting up with very unusual and difficult situations, including challenging shore diving under difficult and sometimes dangerous entries, logistical issues involved in trucking around the research team, research gear, and several additional folks, and cost saving but time consuming efforts associated with meal preparation and clean-up. We also had the additional burden of a news reporter, who accompanied us in the water and needed an inordinate amount of hand-holding due to his limited dive skills and lengthy discussions due to his poor understanding of coral reefs. Al Catafulmo and the Black Durgon Inn graciously accommodated the research team during this mission, supporting all of our needs in a professional and friendly manner. I also thank the Government of Bonaire and the Bonaire Marine Park for their assistance with permits and other technical aspects associated with the work.

This research mission was especially meaningful to me, as it represents my 15th year of research in Bonaire. I arrived with a sense of doom, given the poor condition of coral reefs in most other countries I have examined over the last five years in the Caribbean, and was pleasantly surprised by the high remaining coral cover and general excellent condition of most of Bonaire's reefs. I also had the luxury of bringing my family, including my long time research partner, Robin, and our two children, Haili and Dylan, who learned to snorkel during this trip. I'll never forget looking up from my work at 50 feet below the sea to see my daughter watching me from the surface. In addition to the important research we successfully implemented, we trained two of the next generation of marine biologists. I only hope there will be coral reefs that are still in as good a shape as Bonaire's reefs were in 2010 by the time they begin their professional careers 15 years from now.

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Introduction

Until the late 1970s, benthic substrates on Caribbean reefs were occupied primarily by reef-building corals, with 50-80% benthic cover by living corals. Coral reefs exhibited a generalized zonation pattern with elkhorn coral (*Acropora palmata*) forming large, monospecific stands in the reef crest and shallow fore reef (0-5 m depth); stands of staghorn coral (*A. cervicornis*) at intermediate depths (5-25 m depth) on wave exposed reefs and in shallow, protected environments; massive corals (dominated by *Montastraea annularis* complex) throughout the fore reef (5-30 m depth) and in back reef and lagoonal areas; and plating agaricids near the base of the reef (20-40 m depth). Caribbean reefs have experienced significant losses in living coral cover over the last three decades and “classic” zonation patterns have disappeared from many locations. As a consequence of cumulative human and natural impacts, many shallow reefs throughout the western Atlantic have lost 50-90% of their living coral cover. Of particular concern, there was been a region-wide decline of 90-98% of the two dominant branching corals, *Acropora palmata* and *A. cervicornis* during the 1980s and 1990s. More recently, the most important framework corals, the *M. annularis* complex have begun to experience a similar decline.

Since the late 1990s, the most important framework corals remaining on western Atlantic reefs today, *Montastraea annularis* (species complex) are exhibiting a conspicuous trend of decline throughout the region due to disease, bleaching, predation and increased competition by other benthic organisms (Bruckner and Bruckner 2003, 2006a,b; Edmunds and Elahi 2007; Bruckner and Hill 2009). These corals are now known to be susceptible to at least five major diseases (Weil 2004, Weil and Cróquer 2009), often exhibiting signs of multiple infections simultaneously (Bruckner and Bruckner 2006a). Two of the most devastating diseases, white plague and yellow band disease, emerged in the mid 1990s; their prevalence increased dramatically throughout the region over the last decade in both nearshore and remote locations, with numerous new and devastating outbreaks occurring in deep water areas and widespread tissue loss over the last 5 years (Bruckner and Bruckner 2006a; Bruckner and Hill 2009). The rapid rates of tissue loss from white plague, along with an unusually long, but slow, sustained tissue loss from YBD are also causing impaired skeletal growth and diminished reproductive output (Bruckner and Bruckner 2006a; Weil et al. 2006). In some locations (e.g. Puerto Rico and the US Virgin Islands), 60-80% of the living cover of *M. annularis* disappeared between 2005-2006 from these events, and a similar trend was observed in 2010 in the Cayman Islands following a 2009 mass bleaching event (Bruckner 2010a). A bleaching alert was issued in July 2010, with predictions that this could be as severe, or worse, than the 2005 event. This trend is particularly worrisome, as *M. annularis* (complex) forms the framework of Caribbean reefs, individual colonies can live for hundreds of years, and these species appear to be suffering the largest losses. Continued tissue loss and fission may further reduce the reproductive potential of these colonies as the colony diverts more energy to maintenance, increasing the proportion of small, non-breeding colonies in the population. Because these corals grow extremely slowly (up to 1 cm per year) and exhibit very low levels of natural replacement (minimal recruitment has been observed by scientists over the last 20-30 years), disease and bleaching events that impact these corals can have lasting impacts on an ecological time scale (hundreds of years). These threats have elevated the potential risk of collapse of these habitats and their loss as sources for replenishment of marine life.

While coral diseases, bleaching, hurricane damage and other natural stressors have probably affected reefs since they first developed, the impacts have worsened over the last three decades, particularly when exacerbated by localized human impacts, especially agricultural and industrial runoff, sewage and overfishing, and also because of increasing acidity and warming linked to global climate change. Many of these stressors have cumulative negative impacts on coral reef ecosystem health and are tightly linked. For example, the virulence and severity of diseases appears to be elevated during and immediately following bleaching events and other periods of elevated environmental stress (Ballantine et al. 2008; Bruckner and Hill 2009; Rogers et al. 2008). Other human impacts such as overfishing of herbivores and predatory fishes can have cascading impacts on ecosystem health by removing species that are critical in controlling harmful algae, corallivores and other pest species. Furthermore, as corals die, exposed benthic substrates are monopolized by fleshy macroalgae, encrusting and bioeroding sponges, and other organisms. These “pest” species compromise remaining corals through direct competition and overgrowth, and may prevent recruitment of coral larvae and regrowth of damaged corals.

Reefs of Bonaire were examined by the PI and other researchers using a modified Atlantic and Gulf Rapid Assessment Protocol (AGGRA) approach multiple times including 1995, 1997-1998, 2000, and 2005; a recent IUCN resilience assessment was also completed in 2009. Over the last 15 years, I have witnessed a number of disease outbreaks (especially white plague and YBD) affecting *M. annularis* populations and other species in Bonaire. I also documented synergistic impacts from parrotfish predation, bleaching events, overgrowth by *Trididemnum* tunicates, sponges and gorgonians, hurricane damage, all of which are contributing to the losses of live coral and are hampering recovery. While Bonaire's reefs have retained much of their structure and proper functioning, and these reefs are generally thought to exhibit many resilience factors due to the clean oceanic waters that bath the island, near absence of run-off and pollution, and low levels of fishing pressure, large scale global perturbations such as recent coral reef bleaching events threaten the integrity of these reefs.

The survey approach used during these assessments provides relevant information on the impact of recent hurricanes and bleaching events, and relationships between coral bleaching and disease and other biotic stressors. It is also useful in documenting recent patterns of recovery via sexual recruitment and growth of juvenile corals. These assessments form one component of a global assessment of coral reefs (Global Reef Expedition, GRE) being undertaken by the Living Oceans Foundation between 2010-2015. In particular, they form an important component of the GRE's Caribbean assessments being undertaken in 2010 and 2011. The Global Expedition will utilize the same rapid assessment protocol to characterize population structure and condition of key reef species (emphasizing corals, fish and algae) across landscape scales, as well as past impacts and patterns of recovery, and current threats and resilience indicators. In addition to the regional and global comparisons that can be made during the GRE, the information can guide local and regional management and conservation initiatives.

Methods

Study Sites. Surveys were conducted on 25 reefs, with 13 reefs examined off the northern sector, 8 off the southern sector and four off Klein Bonaire (Fig. 1; Table 1).

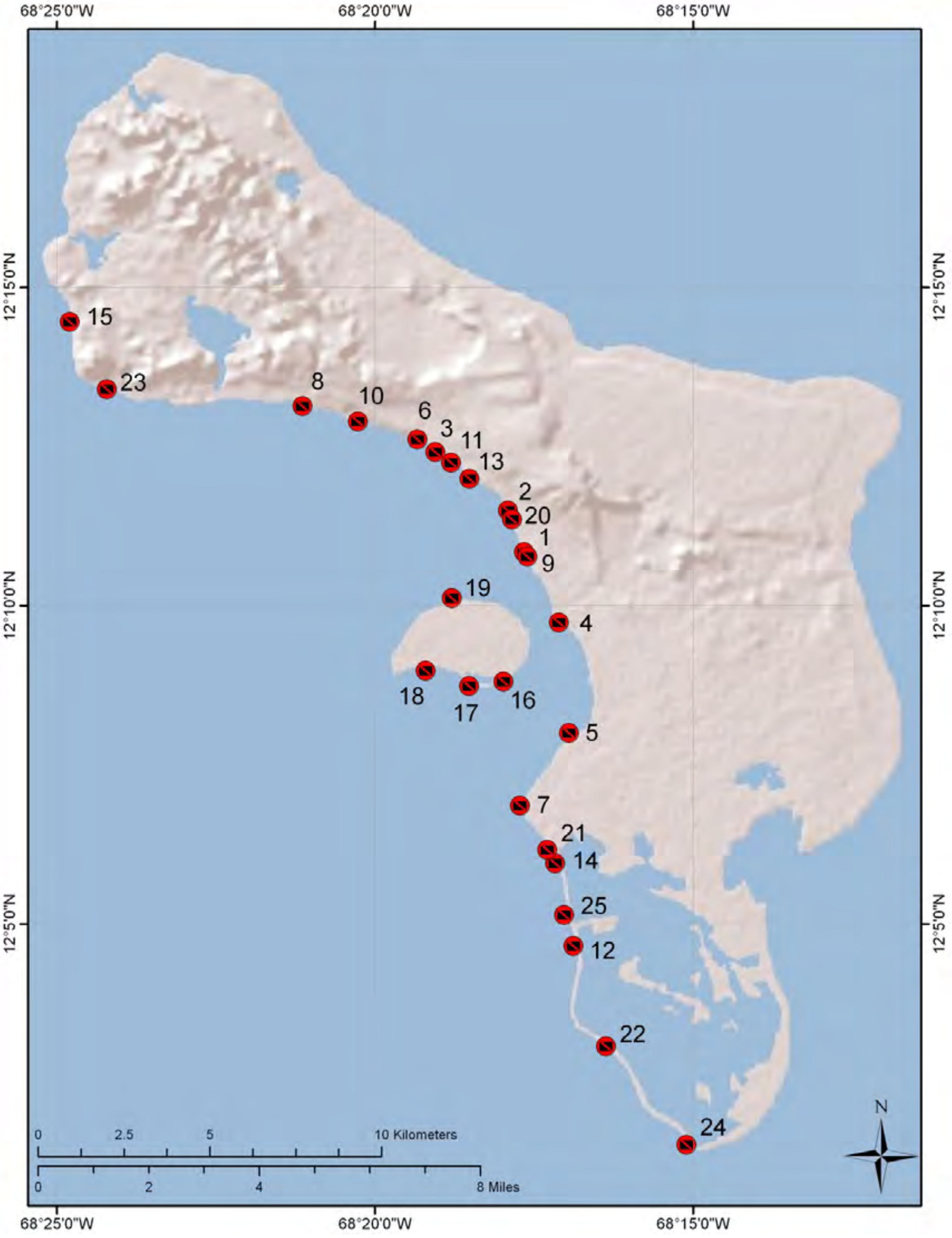

Fig. 1. Locations of reef assessments in Bonaire.

Table 1. Location and dates of surveys conducted in Bonaire

Site #	Reef Name	Date	Time	Latitude, N	Longitude, W
1	Black Durgon Reef	7/19/2010	10:15 AM	12.180745	-68.294338
2	Andrea II	7/19/2010	2:00 PM	12.1916	-68.2986
3	Weber's Joy/Witches Hut	7/19/2010	4:30 PM	12.2069	-68.31761667
4	Something Special	7/20/2010	9:30 AM	12.16225	-68.28525
5	Windsock	7/20/2010	2:50 PM	12.13331667	-68.28258333
6	1,000 Steps	7/21/2010	9:10 AM	12.21018333	-68.32231667
7	Lighthouse Point	7/21/2010	1:00 PM	12.11435	-68.29541667
8	Karpata	7/21/2010	5:00 PM	12.21896667	-68.35238333
9	Small Wall	7/22/2010	6:30 AM	12.17956667	-68.29348333
10	Tolo/Ol' Blue	7/22/2010	9:52 AM	12.21488333	-68.3379
11	Jeff Davis Memorial	7/22/2010	1:15 PM	12.20413333	-68.31341667
12	The Invisibles	7/22/2010	4:30 PM	12.07761667	-68.28138333
13	Oil Slick Leap	7/23/2010	6:40 AM	12.19995	-68.30863333
14	Alice in Wonderland	7/23/2010	9:45 AM	12.09923333	-68.28621667
15	Nukove	7/23/2010	2:30 PM	12.24093333	-68.41333333
16	Keep Sake	7/24/2010	9:10 AM	12.146800	-68.299760
17	Monte's Divi	7/24/2010	10:45 AM	12.145660	-68.308710
18	South Bay	7/24/2010	2:30 PM	12.14965	-68.32013333
19	Knife	7/24/2010	4:16 PM	12.168610	-68.313250
20	Andrea I	7/25/2010	6:00 AM	12.18921667	-68.29748333
21	Angel City	7/25/2010	9:00 AM	12.10275	-68.28826667
22	Margate Bay	7/25/2010	12:00 PM	12.05135	-68.27286667
23	Tailor Made	7/26/2010	9:30 AM	12.223380	-68.403630
24	Red Slave	7/26/2010	1:25 PM	12.02555	-68.2518
25	Jeannie's Glory	7/26/2010	4:00 PM	12.08573333	-68.28383333

Survey techniques: Coral, fish and algae community structure were examined on 25 shallow reefs on the leeward side of Bonaire and on the adjacent Klein Bonaire island (Fig. 1) targeting three depth ranges: 3-6 m, 7-12 m, and 13-18 m depth using three approaches: photographic transects, belt transects, and quadrats. Five measures were recorded for corals: 1) benthic cover; 2) coral diversity and abundance (by species); 3) coral size class distributions (by species); 4) recruitment; and 5) coral condition. For fish, data on abundance and size structure were collected along 2 m X 30 m belt transects for about 100 species of fishes, targeting species that have a major functional role on reefs or are major fisheries targets. Other indicators recorded along belt transects included large motile invertebrates (urchins, octopus, lobster, large crabs, queen conch, sea cucumbers); cover and biomass of algae (fleshy macroalgae, turf algae and crustose coralline algae); and prevalence of nuisance species. In all figures and table the four letter CARICOMP abbreviation (first letter refers to genus; next three letters refer to species) was used for coral taxa.

1. Coral community structure and population dynamics.

A belt transect 10 m long and 1 m wide is used to record the number, size and condition of colonies of all coral species for colonies larger than 4 cm diameter. A one meter bar, marked in 1 cm increments is used to measure the maximum diameter, width (perpendicular to the diameter), height, and amount of mortality. Each coral is identified to species, measured and assessed for condition. Mortality is divided into three categories: recent, transitional and old (see below, condition of corals).

Recruitment

Sampling for corals smaller than 4 cm is done using a minimum of five 0.25 m^2 quadrats per transect, with each quadrat located at fixed, predetermined intervals (e.g. 2, 4, 6, 8, 10 m), alternating between right and left side of the transect. Recruits were identified in both point intercept surveys (see below, benthic cover) and belt transects (see above, coral community structure). In addition, all corals settling on dead skeletal surfaces of colonies identified within the belt transects were recorded separately, with a single measure of diameter and an estimate of percent mortality made for those recruits exhibiting partial mortality.

2. Condition of corals

Visual estimates of tissue loss, using a 1 m bar marked in 1 cm increments, was recorded for each colony over 4 cm in diameter. If the coral exhibits recent tissue loss, the amount of remaining tissue, percent that recently died and percent that died long ago were estimated for the entire colony surface. Tissue loss was categorized as recent mortality (occurring within the last 1-5 days), transitional mortality (filamentous green algae and diatom colonization, 6-30 days) and old mortality (>30 days) (Plate 1). For each coral with partial or whole colony mortality, the cause of mortality is identified if possible. The diagnosis included an assessment of the type of disease, extent of bleaching, predation, competition, overgrowth or other cause of mortality.

Each coral was first carefully examined to identify cryptic predators such as snails (*Coralliophila abbreviata*) and fireworms (*Hermodice carunculata*). Lesions were then diagnosed into four categories: recent tissue loss, skeletal damage, color change, and unusual growth patterns; an individual colony could have multiple characteristics (e.g. color change and recent tissue loss). The location (apical, basal, medial) and pattern of tissue loss (linear, annular, focal, multifocal, and coalescing) were recorded and when possible a field name is assigned. Diseases were identified according to Bruckner 2010b and Raymundo et al. 2008, and included yellow band disease (YBD), white plague (WP), black band disease (BBD), red band disease (RBD), Caribbean ciliate infection (CCI), dark spots disease (DSD) and white band disease (WBD). The data sheet for recording coral observations is shown in Appendix I.

3. Benthic cover

Cover of benthic organisms (plants and animals) was estimated using a point intercept method. At each site, a minimum of six 10 meter long transects were deployed. The organism and substrate type was recorded every ten cm for a total of 100 points per transect. Substrates included hardground, rubble, sand/silt, and dead coral. All corals were identified to species. Gorgonians are recorded as sea fan or branching/encrusting gorgonian. Sponges were further differentiated into crustose, rope, massive, tube and barrel sponges. Algae were divided into five functional groups (fleshy macroalgae, erect coralline algae, crustose coralline algae, turf algae, cyanobacteria) with certain nuisance species recorded to genus (*Microdictyon, Lobophora, Dictyota, Stypopodium, Peyssonnelia*). Other nuisance species recorded to genus or higher taxonomic level include: tunicate (*Trididemnum),* encrusting gorgonian (*Erythropodium, Briareum),* colonial anemone (*Palythoa),* encrusting or bioeroding sponge *(Cliona langae/aprica* complex*, Cliona delitrix, Anthosigmella),* and hydrozoan coral (*Millepora)*. The data sheet for point intercept surveys is shown in Appendix II.

4. Fish assessments

On each reef two divers completed a minimum of six 30 X 2 m belt transects to assess the community structure of the dominant reef fish assemblages. All species were identified and their size is estimated to the nearest 5 cm using a T-bar marked in 5 cm increments for scale. The assessment focused on species that are ecologically relevant to the health of reefs and also important for commercial or recreational fisheries. The emphasis was on herbivores (parrotfish, surgeonfish, chubs, damselfish), invertebrate feeders and larger piscivores. Parrotfish were also separated into initial phase and terminal phase fishes. A Data sheet with all species listed is shown in Appendix III.

5. Resilience indicators

Ecological resilience relates to the entire scope of positive and negative factors affecting a community, such as the patterns of resource extraction, type and extent of pollution and presence of invasive species. There are four levels of analysis of resilience that were undertaken:

1) The primary biotic components that make up the reef community - corals, algae, large motile invertebrates and fish communities;
2) The ecological interactions that drive dynamics within and among these groups;
3) Habitat and environmental influences that directly affect reef associated organisms and interactions between them; and
4) External drivers of change, including anthropogenic and climate factors.

Resilience data were recorded on a semi-quantitative scale (Likart) of 1-5 (1=minimum, 2=low levels, 5=maximum) for approximately 50 indicators. Where an indicator can be quantified directly (e.g. visibility in meters, slope in degrees) the actual measure was recorded. Indicators included: 1) the relative abundance of every genera of corals and measures of the largest corals; 2) estimates of cover of broad categories (coral, algae and substrate); 3) physical parameters including depth, temperature, turbidity, sediment characteristics, topographic complexity, slope, and shading; 4) coral condition, prevalence of disease, and presence of coral associates and coral predators; 5) anthropogenic stressors; and 6) oceanographic and environmental parameters such as degree of exposure, facing direction of the reef, proximity to deepwater and possible upwelling, current patterns, and distance to neighboring reefs. A datasheet for resilience indicators is shown in Appendix IV.

6. Photo-documentation

Extensive photographic documentation of reef habitats and individual colonies in various states of health were taken during surveys. At each site an overview of the reef was taken from above at four compass points and then representative shots of the bottom were taken. Representative photographs of individual colonies located along belt transects with lesions, including signs of disease, predation, physical damage, and overgrowth, were also taken. One set of photo-quadrats, each 0.25 m long was taken on each reef along the same transect as that used for the point intercept survey at 2, 4, 6, 8 and 10 m.

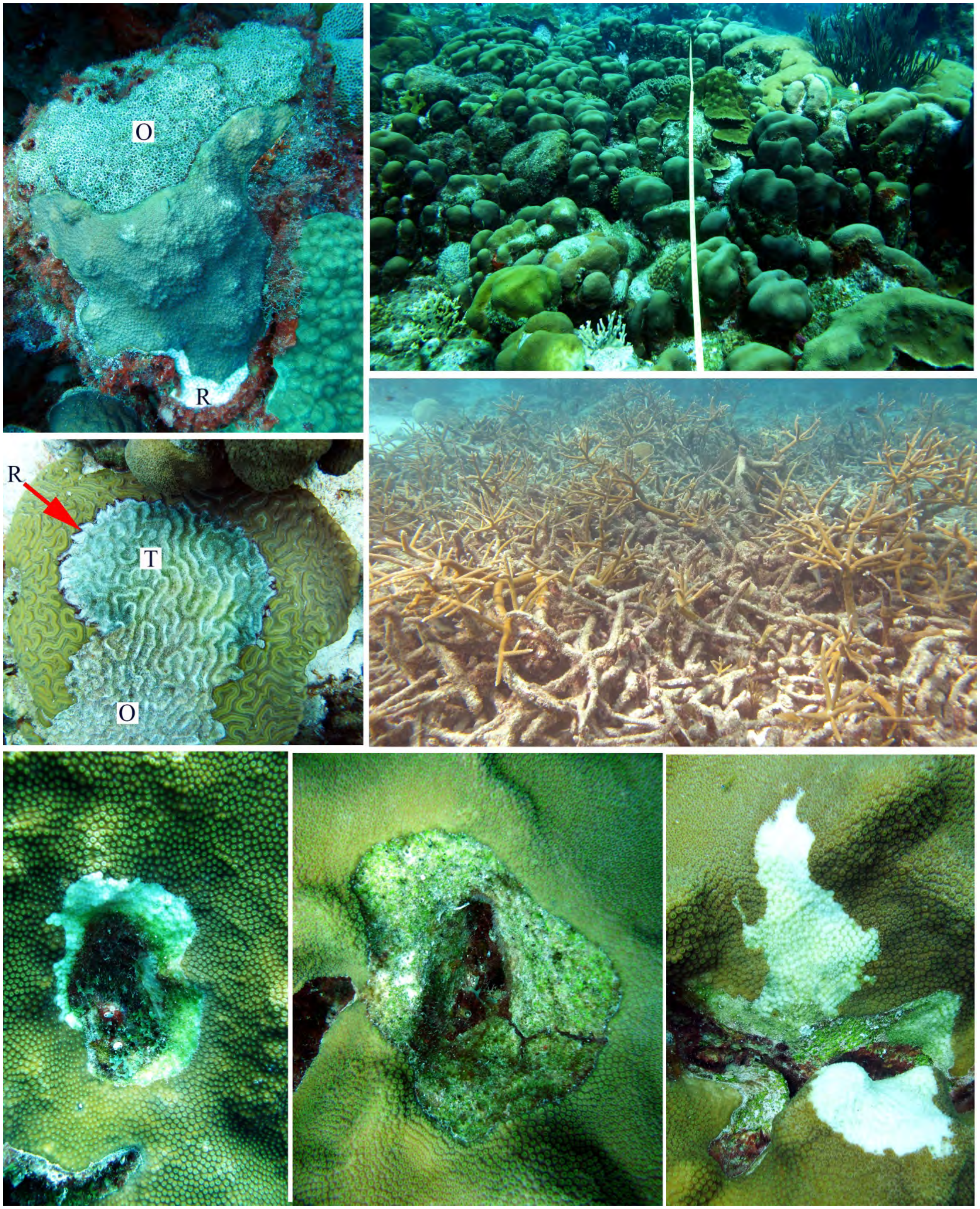

Plate 1. A. Example of *Montastraea franksi* with recent (R) and old (O) tissue loss (upper left). B. Typical belt transect in shallow water (5-8 m depth) within the *M. annularis* zone (upper right). C. Colony of *C. natans* with BBD (center left). The band is very thin, and only a narrow band of recent tissue loss (arrow) is visible. Approximately half of the exposed skeleton would be characterized as transitional mortality (T) and 40% is old mortality (O). D. A recovering *A. cervicornis* thicket on 1000 Steps. E-G.Typical patterns of tissue loss seen from white plague. The lesion initiates either at the margin of a previously denuded patch, or at the colony margin and spreads inward or upward. White areas are recent mortality, indicative of active coral disease (lower left and right photos). Often (especially at Tailor Made), a small area of tissue is lost, and then the disease disappears, as shown in the lower central photo.

Results

Coral reef community structure, including cover of benthic organisms, size structure and condition of reef building corals, abundance and size structure of approximately 100 species of reef fishes, and resilience indicators were assessed on 25 reefs off the leeward side of Bonaire in July 2010. All data were initially pooled and subdivided into three groups for comparative purposes: southern sites, northern sites and Klein Bonaire; a more detailed examination of certain parameters and sites was also undertaken. Surveys were completed at approximately 5, 10 and 15 m depth on each reef, when possible. No surveys were undertaken in locations/depths that had been scoured by recent hurricanes. As has been previously reported, many of the shallow zones (from the shore to 3-7 m) experienced large losses of corals from associated wave surge during Hurricane Omar (2008); impacted areas were still largely devoid of corals during July 2010 surveys, thus all work focused on reef areas below center of largest impact, generally encompassing the beginning of the shallow *M. annularis*-dominated assemblages.

1. Benthic cover

On most of the reefs examined in this study, coral cover was high, ranging from about 40-60%, The only exceptions were two sites on northern reefs, Webers Joy/Witches Hut and Jeff Davis Memorial, where cover ranged from about 30-35% (Fig. 2). Macroalgal abundance was relatively low (generally < 10% cover), especially when compared to other Caribbean localities. Cover of turf algae was typically 10-25%, although turf algae exceeded 30% cover on a few northern reefs. Crustose coralline algae (CCA) was noted at all sites, generally covering about 10% of the substrate. Certain sites had moderate cover of cyanobacteria (5-15%), with highest cover of cyanobacteria documented on reefs off Klein Bonaire.

A number of nuisance species, including a tunicate (*Trididemnum*), several species of bioeroding and encrusting sponges (*Cliona* spp.), colonial anemones (*Palythoa*), hydrozoan corals (*Millepora*) and the encrusting gorgonian (*Erythropodium*) were identified in point intercept surveys, although total cover was relatively low (1-3%). These species were much more common on northern reefs (*Trididemnum* was only observed on northern reefs) than either southern reefs or Klein Bonaire. In particular, four reefs (Jeff Davis, 1000 Steps, Old Blue and Karpata) has the highest cover by pest species (5-15%, respectively), although there were significant differences between depths, with highest cover at 15 m depth.

Substrates consisted primarily of long dead coral skeletons, hardground (pavement), and sand patches/channels, although some reefs had a substantial amount of rubble, especially at the shallow depths (up to 14.5% cover). Much of the coral rubble consisted of *A. cervicornis* branches that were cemented in place, although loose *Porites* and *Madracis* rubble were also recorded and numerous overturned massive (boulder) corals were identified at the shallowest depths of surveys. While the potential for bleaching was high in 2010, total cover of bleached corals during July was very low (0-1.4%).

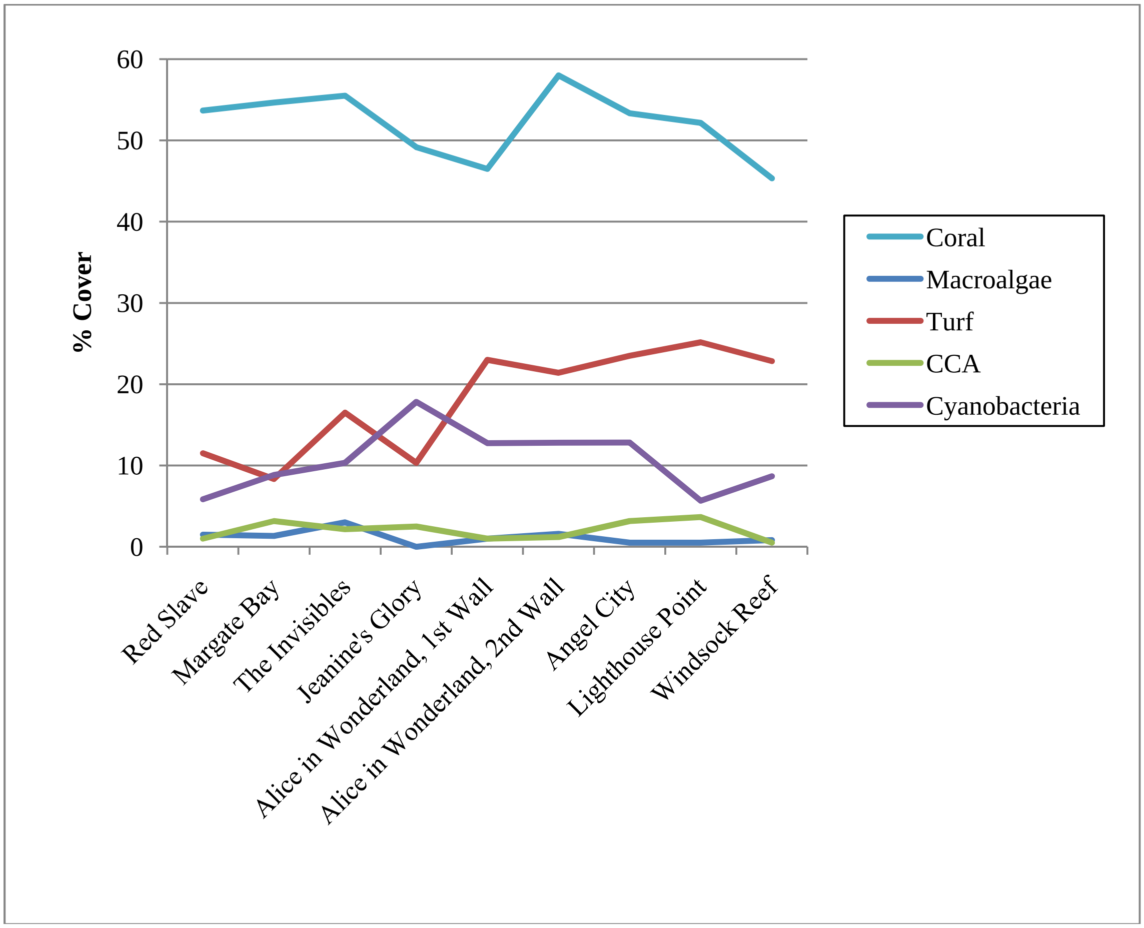

Fig. 2a. Estimates of benthic cover of living corals and major functional groups of algae on Bonaire’s southern reefs (5-15 m depth), heading from south to north.

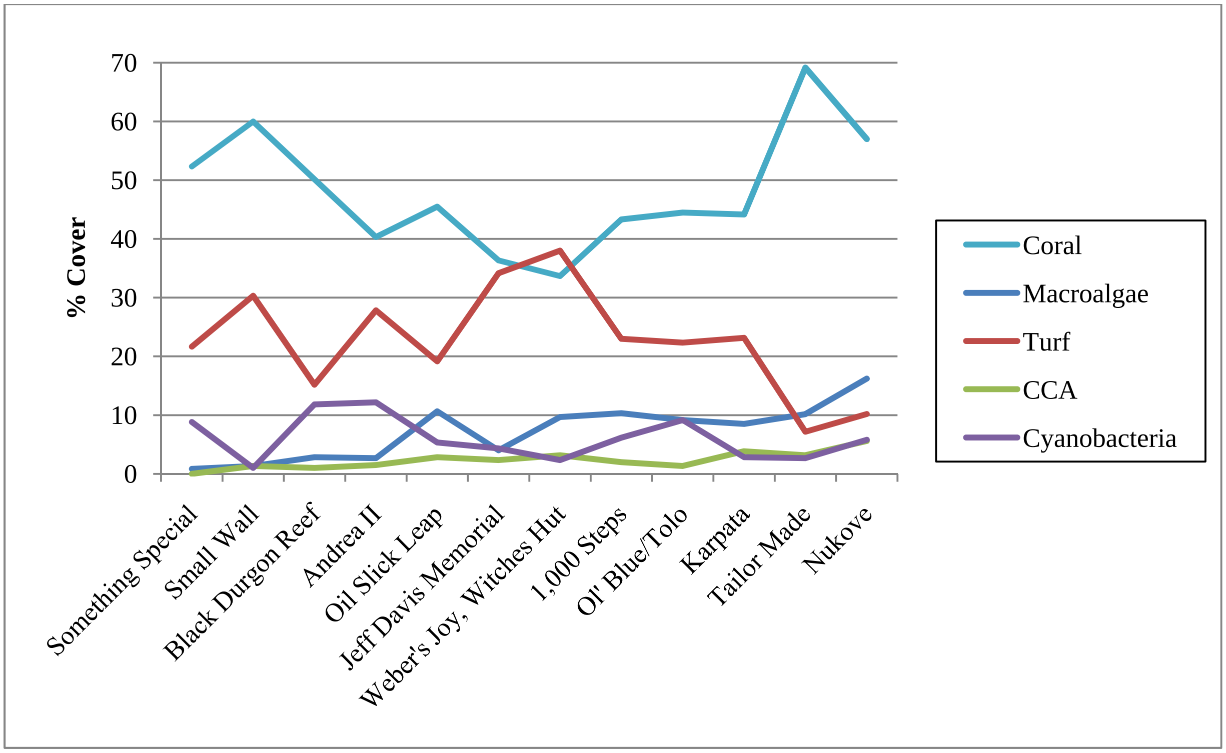

Fig. 2b. Estimates of benthic cover of living corals and major functional groups of algae on Bonaire's northern reefs (5-15 m depth), heading from south to north.

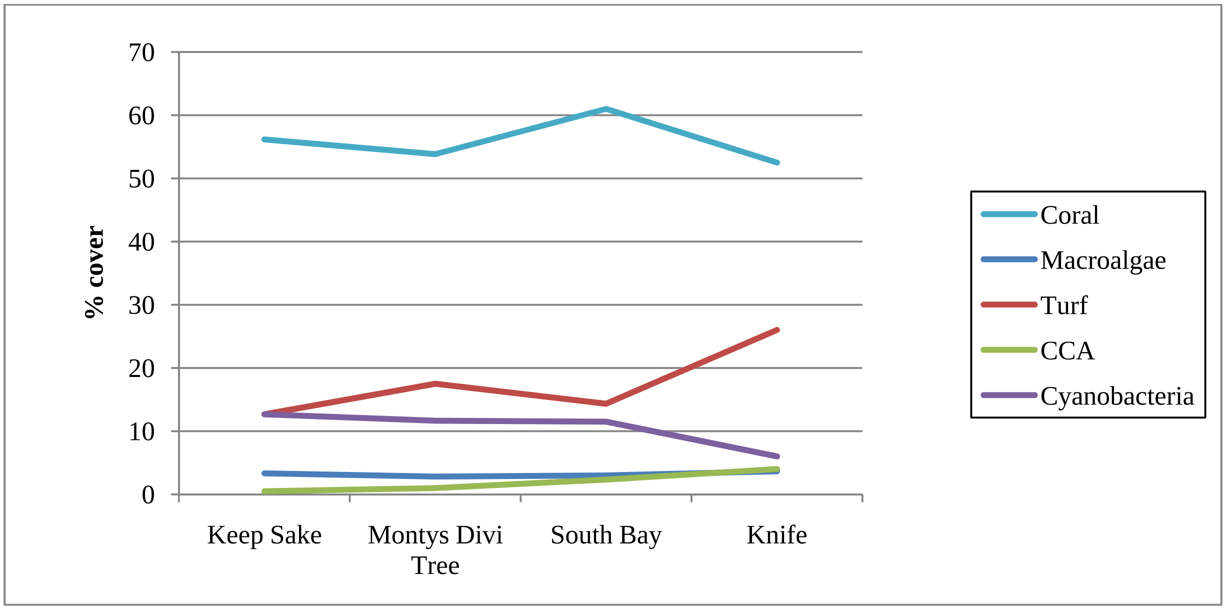

Fig. 2c. Estimates of benthic cover of living corals and major functional groups of algae on reefs off Klein Bonaire (5-15 m depth), heading from south to north.

2. Coral species composition

Composition of corals (proportion of different taxa, by depth), as determined from the point intercept and belt transects, showed slight variations among depths and methods. In general, *M. annularis* complex was the dominant taxa (by cover; 20-25% of all corals; 27% by abundance) at all sites, followed by *Agaricia, Porites* and *Madracis*. Several species (especially the dominant brooding corals) were numerically dominant on some reefs, exceeding the abundances of each of the species of *M. annularis* (complex), but because of their small size, their contribution to living coral cover was substantially less than the total cover by *M. annularis* (complex) (Fig. 3).

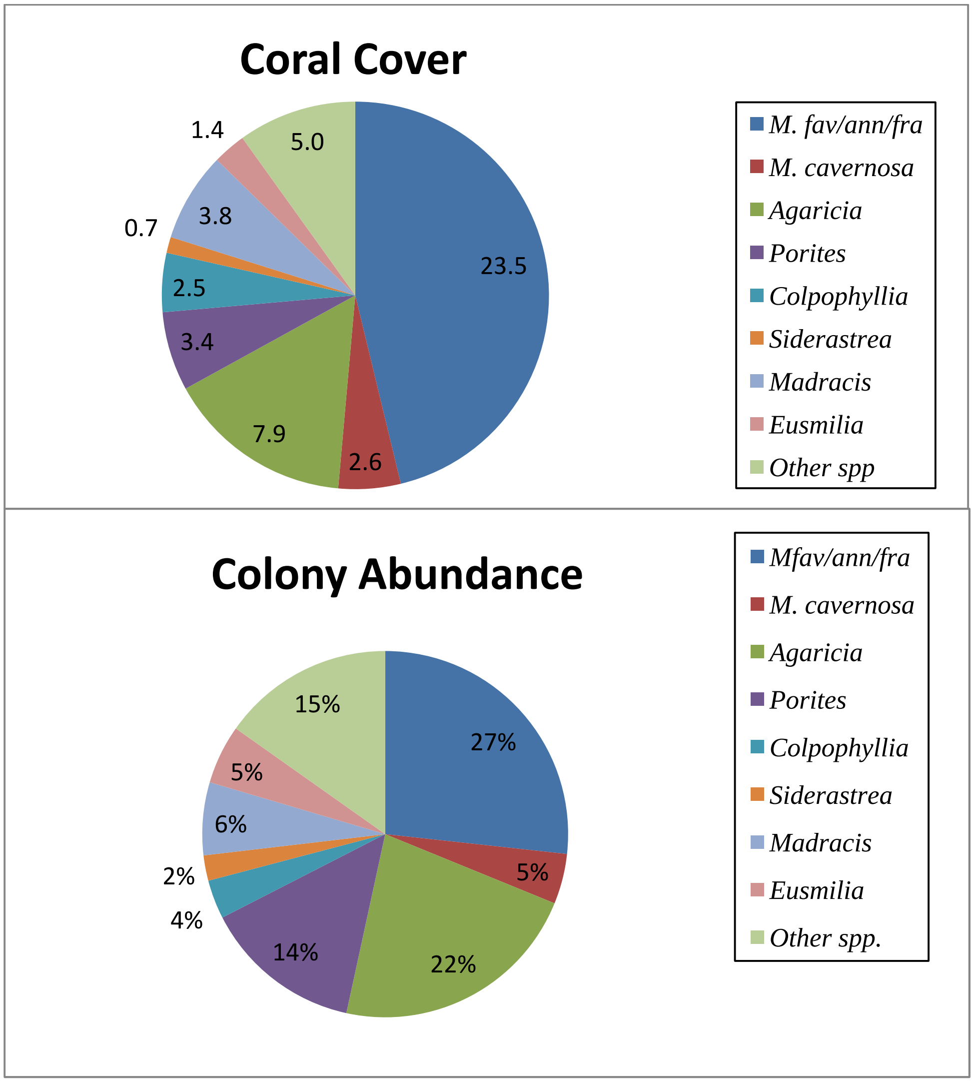

Fig. 3. Coral cover (top) and colony abundance (bottom) for the dominant coral taxa on reefs off Bonaire (pooled for all sites and depths).

Cover of major functional groups of reef building corals showed slight variations between sites and depths (Fig. 4-6). For instance, cover of *M. annularis* complex was lowest on northern reefs (pooled for all depths; 22% vs 24%) while cover of *Agaricia* spp. was lowest on southern reefs (6.6% vs 9%). Klein Bonaire also had a higher cover by *Madracis mirabilis* (>6%), possibly because this coral formed large thickets on several reefs. There were also some differences in cover between depths: *Agaricia* had the highest cover on all reefs at 15 m, as did *Eusmilia fastigiata*. In contrast, *Porites* had the highest cover at 10 m and 15 m depth than at 5 m. *Madracis* spp. was most variable, having the highest cover at 5 m depth on northern and southern reefs, and 10 m depth on Klein Bonaire (Fig 4b, 5b, 6b). *Stephanocoenia intersepta* rarely showed up in the point intercept surveys, while this coral was relatively abundant in belt transects. *Acropora palmata* and *A. cervicornis* were virtually absent from all point interecpt surveys, and only identified infrequently in belt transects. Following near eradication of these species in the 1980s, these corals were showing signs of recovery in the mid 1990s, but were extensively damaged by Hurricane Lenny in 1999. Signs of recovery were again evident by 2005, but subsequent storms knocked back both species. Isolated colonies of *A. palmata* have persisted at Karpata, and a few other locations. *A. cervicornis* is virtually extinct from most northern reefs (except for Jeff Davis and 1000 Steps) and Klein Bonaire, but small thickets still remain in sandy areas off southern reefs, especially on Invisibles. These thickets were not quantitatively assessed because they were generally found landward of the major reef structure (e.g. in front of the *M. annularis* community) in relatively shallow water.

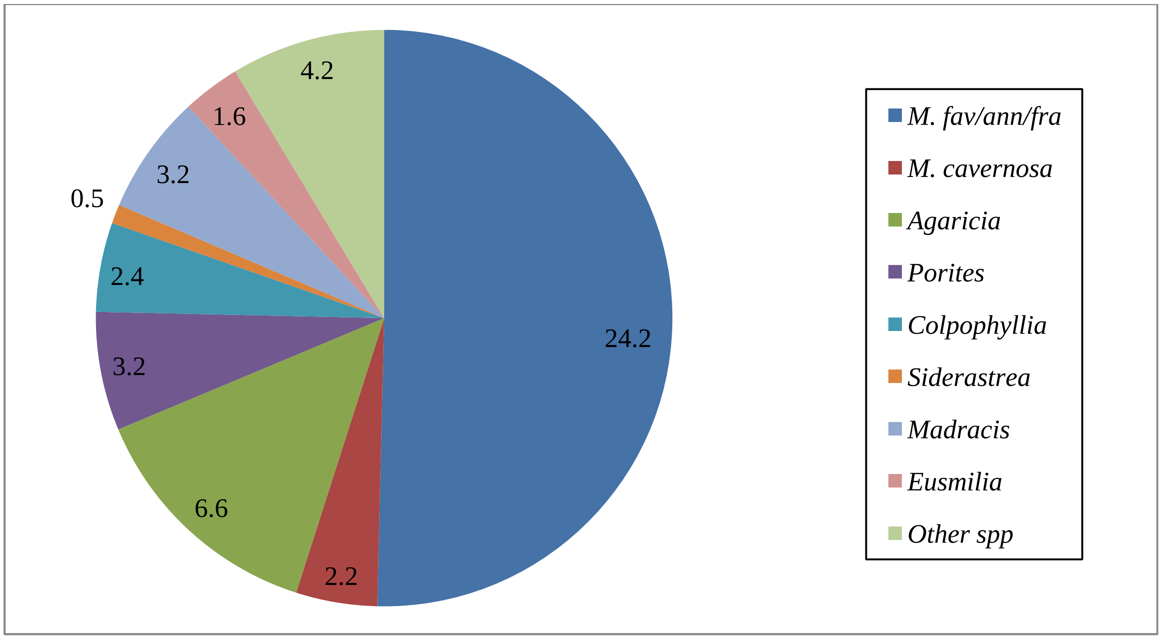

Fig. 4a. Percent cover of dominant coral taxa on north end of Bonaire (pooled for all sites and depths)

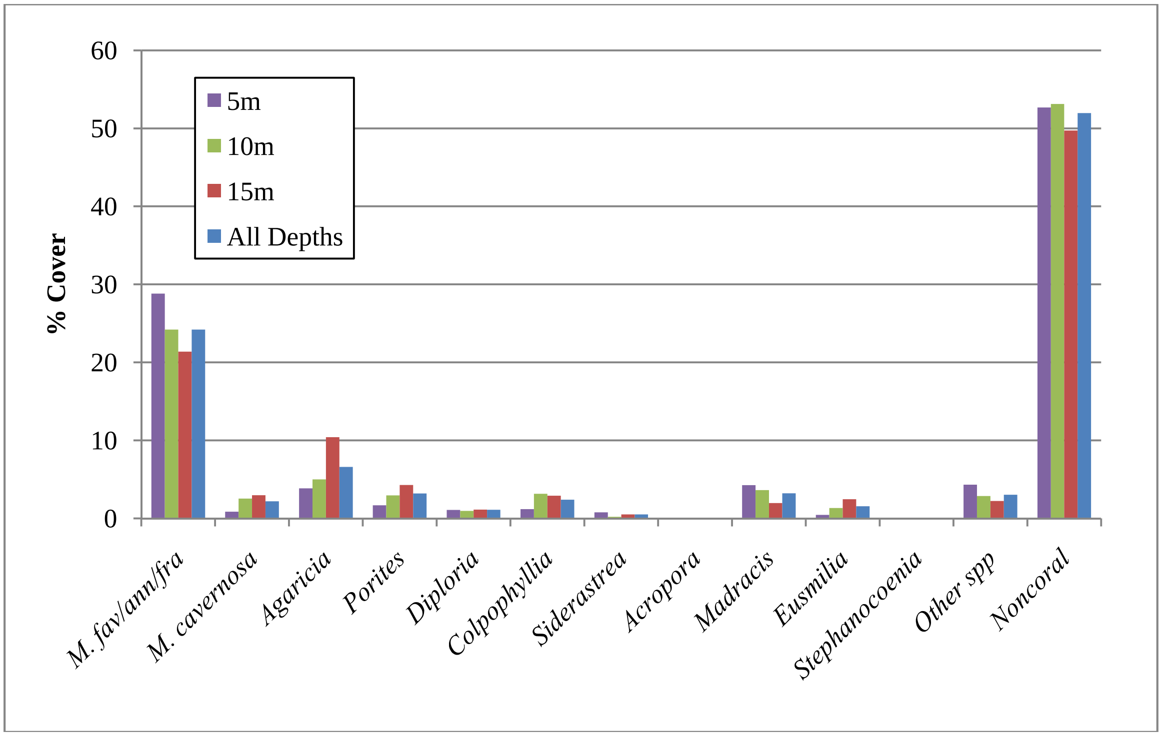

Fig. 4b. Percent cover of reef building corals and non-coral categories for the north end of Bonaire (pooled for all sites) at 5, 10 and 15 m depth.

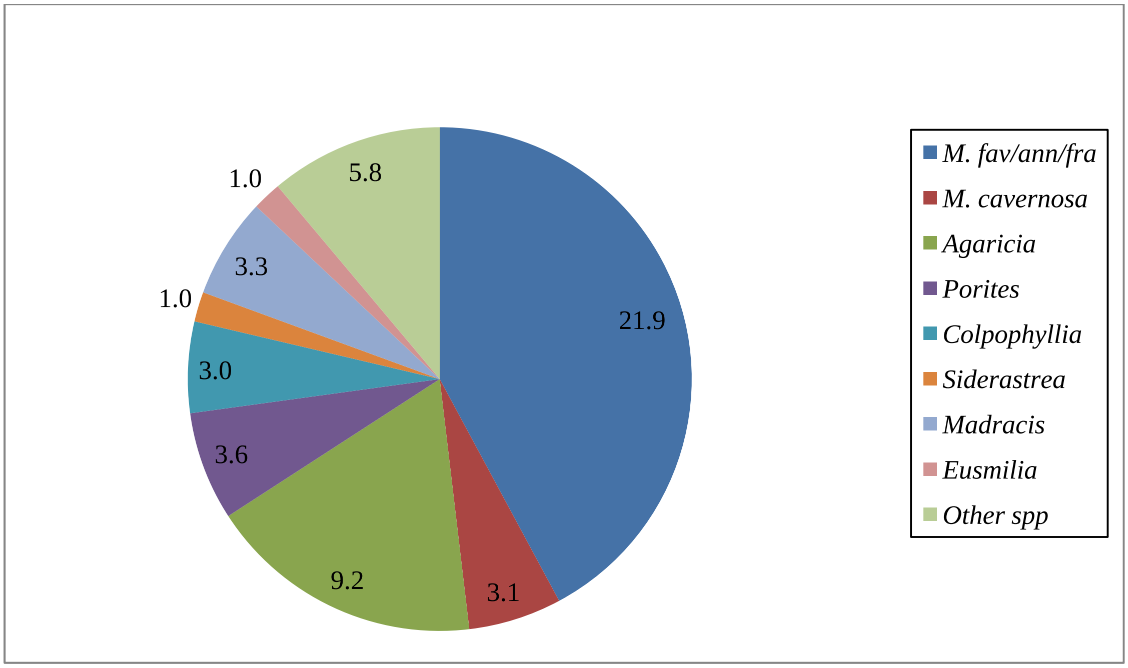

Fig. 5a. Percent cover of dominant coral taxa on south end of Bonaire (pooled for all sites and depths).

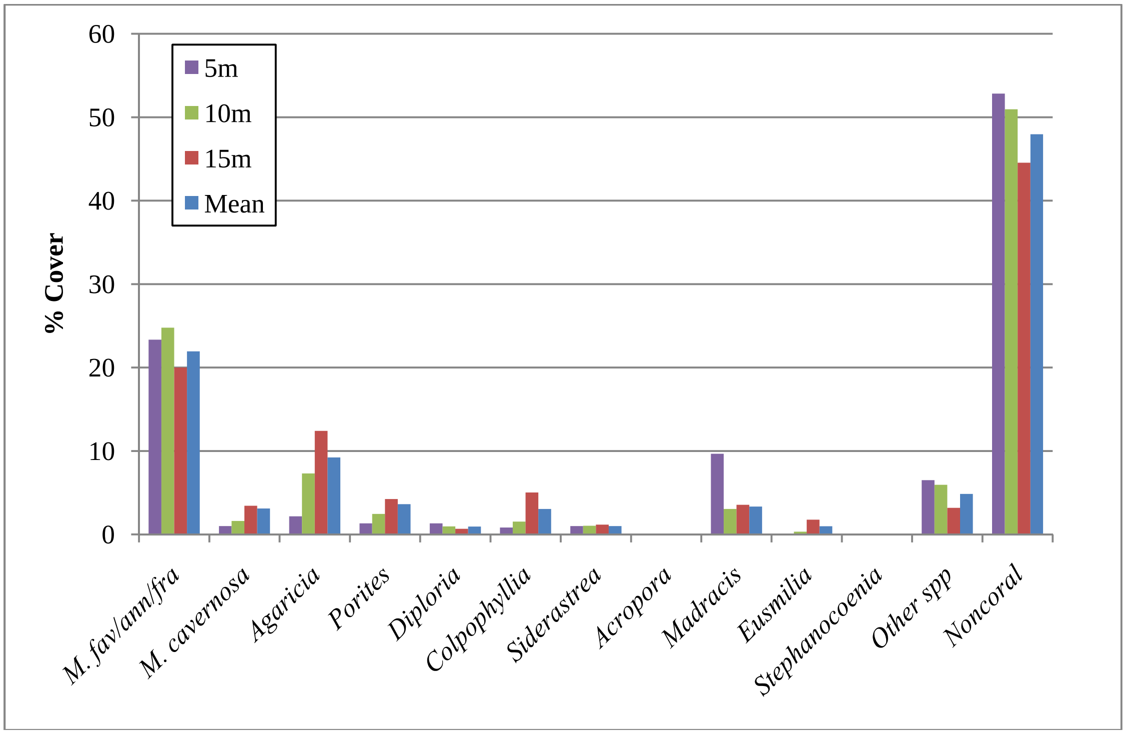

Fig. 5b. Percent cover of reef building corals and non-coral categories for the south end of Bonaire (pooled for all sites) at 5, 10 and 15 m depth.

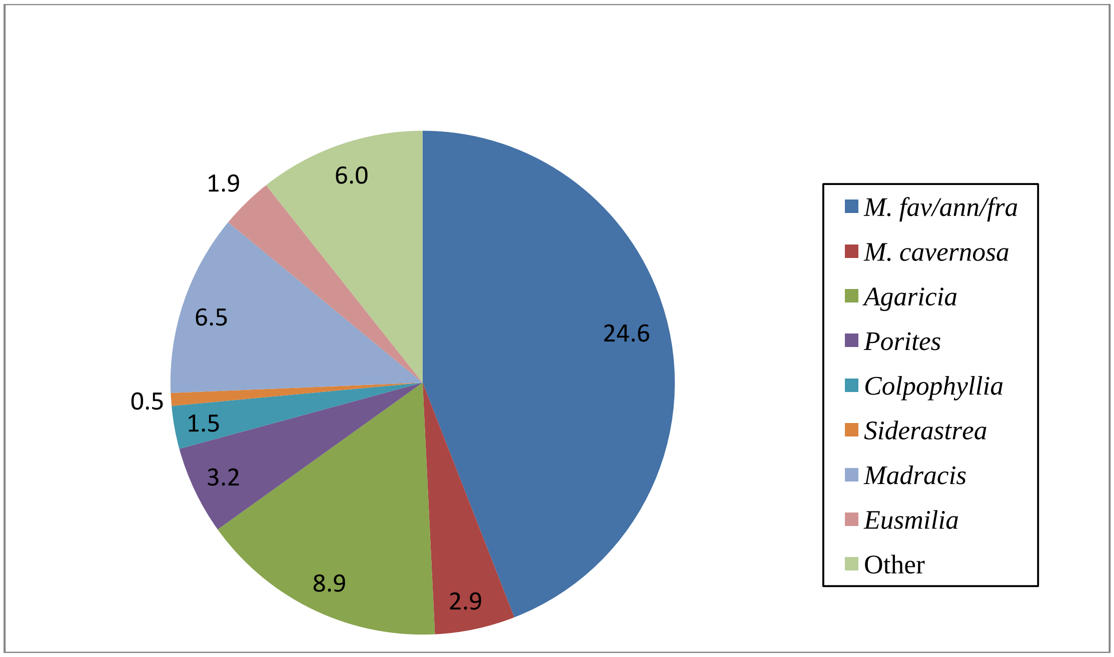

Fig. 6a. Percent cover of dominant coral taxa on Klein Bonaire (pooled for all sites and depths)

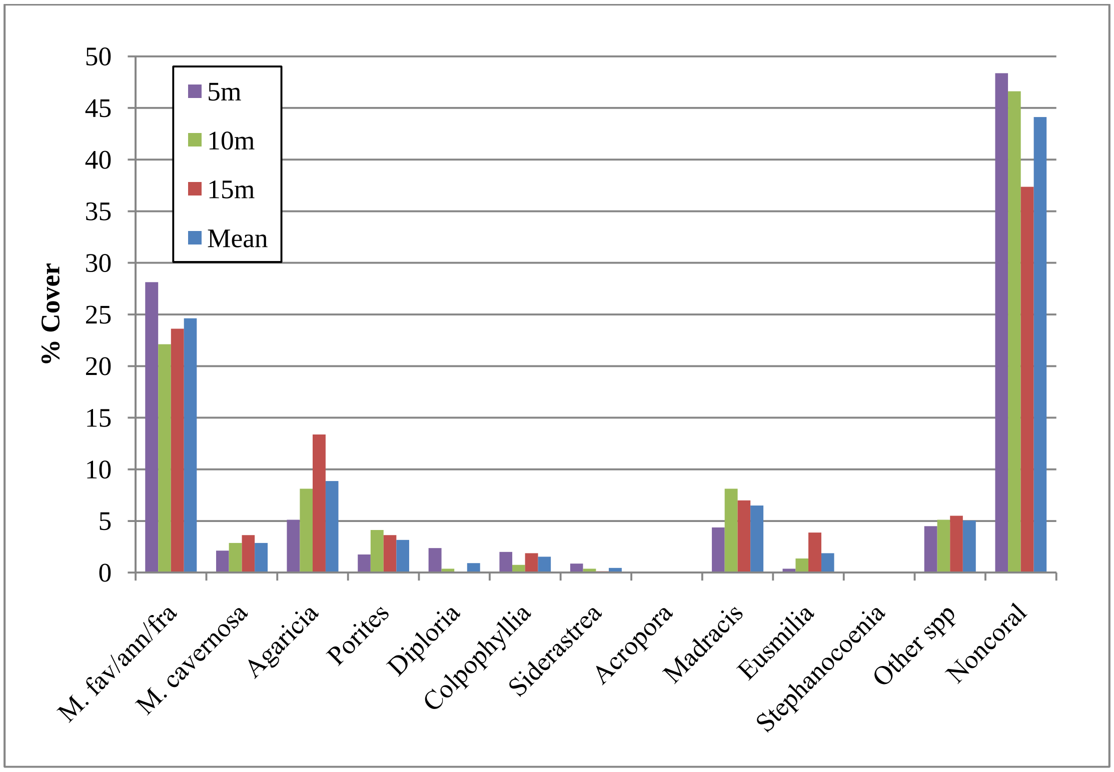

Fig. 6b. Percent cover of reef building corals and non-coral categories for Klein Bonaire (pooled for all sites) at 5, 10 and 15 m depth.

3. Coral composition and size structure

A total of 5957 corals 4 cm or larger in diameter were identified within 10 m belt transects on 25 reefs in Bonaire by Bruckner. *M. annularis* was the dominant functional group of corals, in terms of numbers of colonies. Approximately 27% of all corals consisted of the *M. annularis* complex. Reefs in the north and off Klein Bonaire had a higher proportion of *M. annularis* (complex) colonies (30 and 29% respectively), when compared to reefs in the south (21%). In addition, *M. annularis* was significantly more abundant than *M. faveolata* and *M. franksi* on northern reefs and Klein Bonaire, while abundance of *M. faveolata* and *M. franksi* was very similar in all locations. The second most abundant functional group was the genus *Agaricia* (18-26% of all corals). This genus was the dominant taxa on southern reefs and the second most abundant taxa in other locations. The genus *Porites* was the third most abundant taxa (Fig. 7).

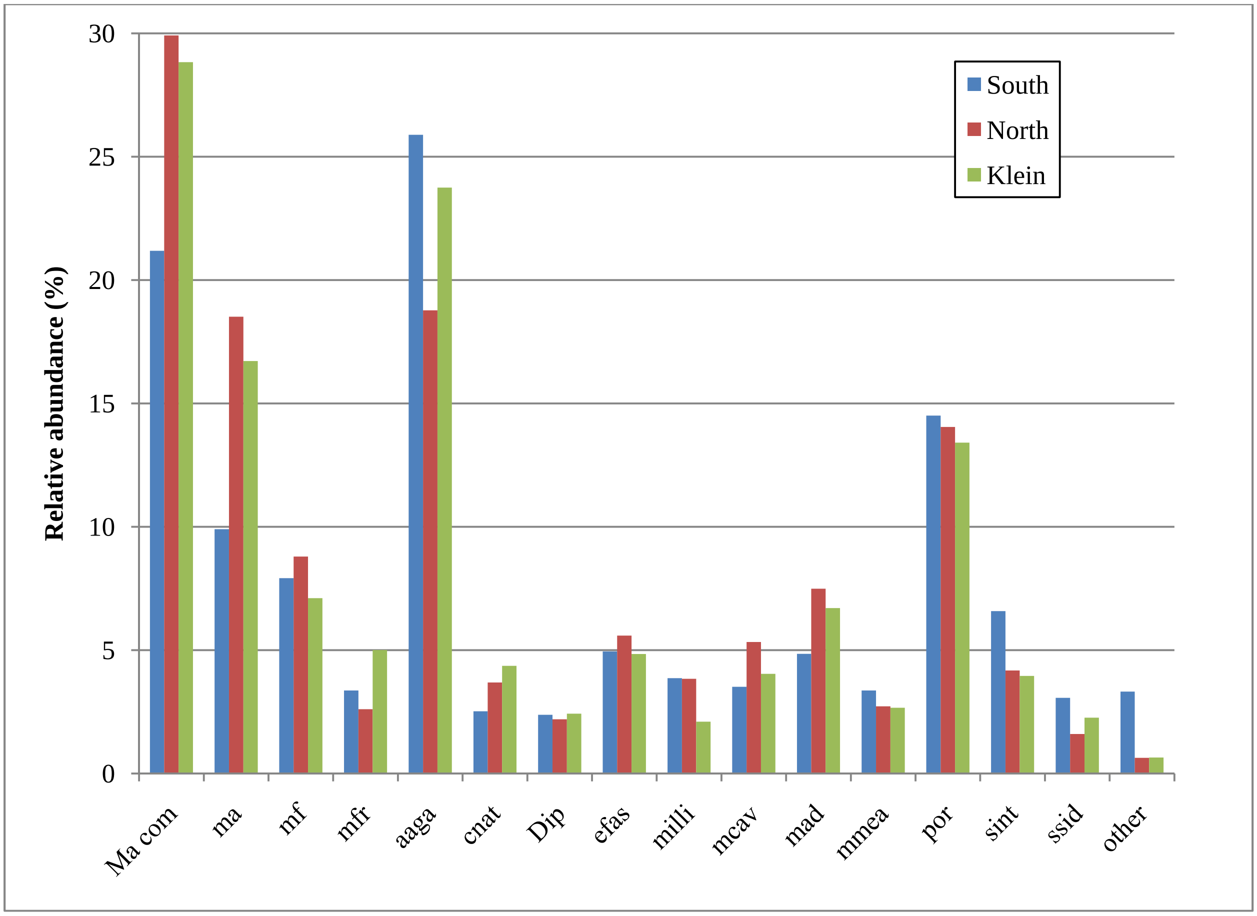

Fig. 7. Abundance of each of the major functional groups of corals (% of total number of colonies of all species) for southern reefs (blue bars), northern reefs (red bars) and Klein Bonaire (green bars). Ma com refers to the three species of *M. annularis* (complex).

Corals ranged in size from 4 cm (smallest coral assessed in belt transects; 0-3 cm corals assessed separately using quadrats and on exposed skeletal surfaces) to over 450 cm diameter, with a maximum height of 460 cm (Fig 8, 9). The size structure of *M. annularis* (complex) shows a bell shaped distribution with few small colonies (<20 cm) and few very large colonies (>200 cm) and a large number of medium-sized corals (30-80 cm diameter); the population structure also exhibited a second peak for colonies that were 150-199 cm diameter. Colonies of other species (all species pooled except *M. annularis* complex) were dominated by very small colonies (<20 cm) and populations in all locations (all sites pooled, as well as northern, southern and Klein Bonaire reefs) exhibited a monotonic decline in size with very few colonies over 60 cm in diameter.

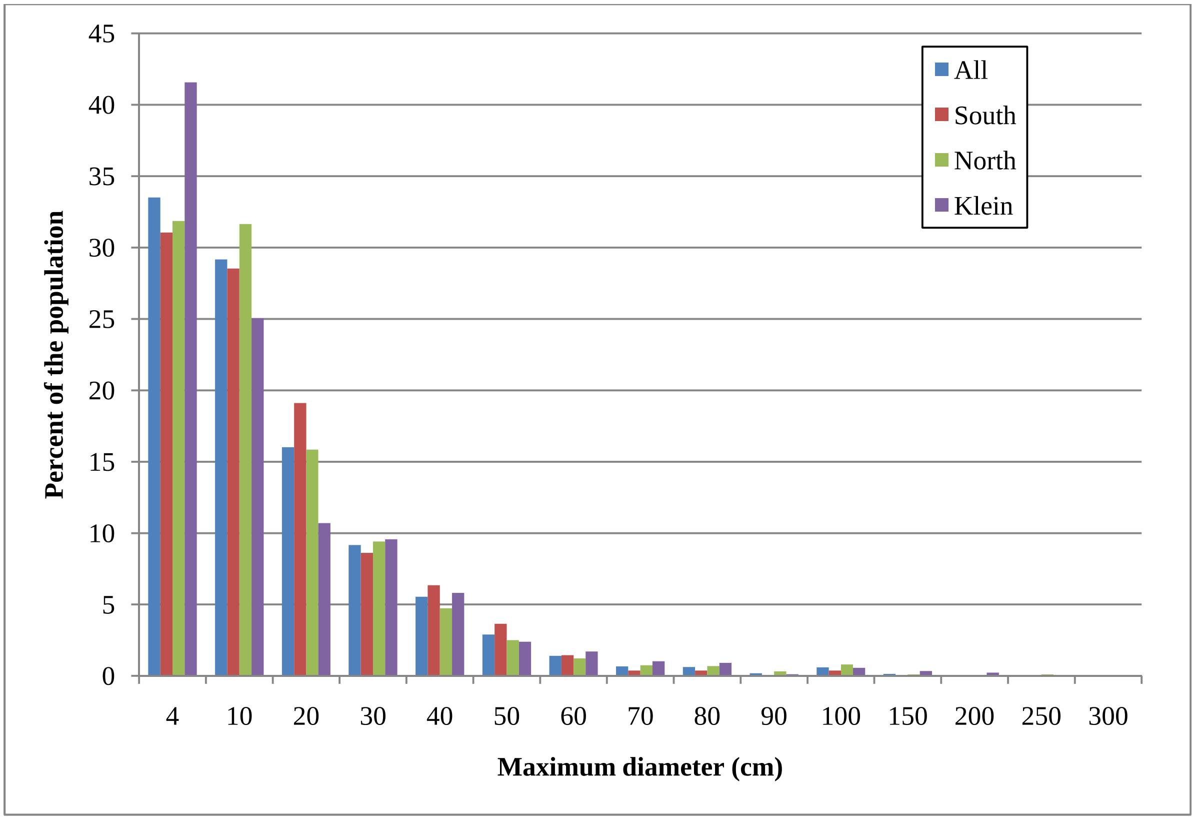

Fig. 8. Size structure of all species of corals (pooled) except the *M. annularis* complex shown for all sites (blue bars, pooled species), southern reefs (red bars), northern reefs (green bars) and Klein Bonaire (purple bars).

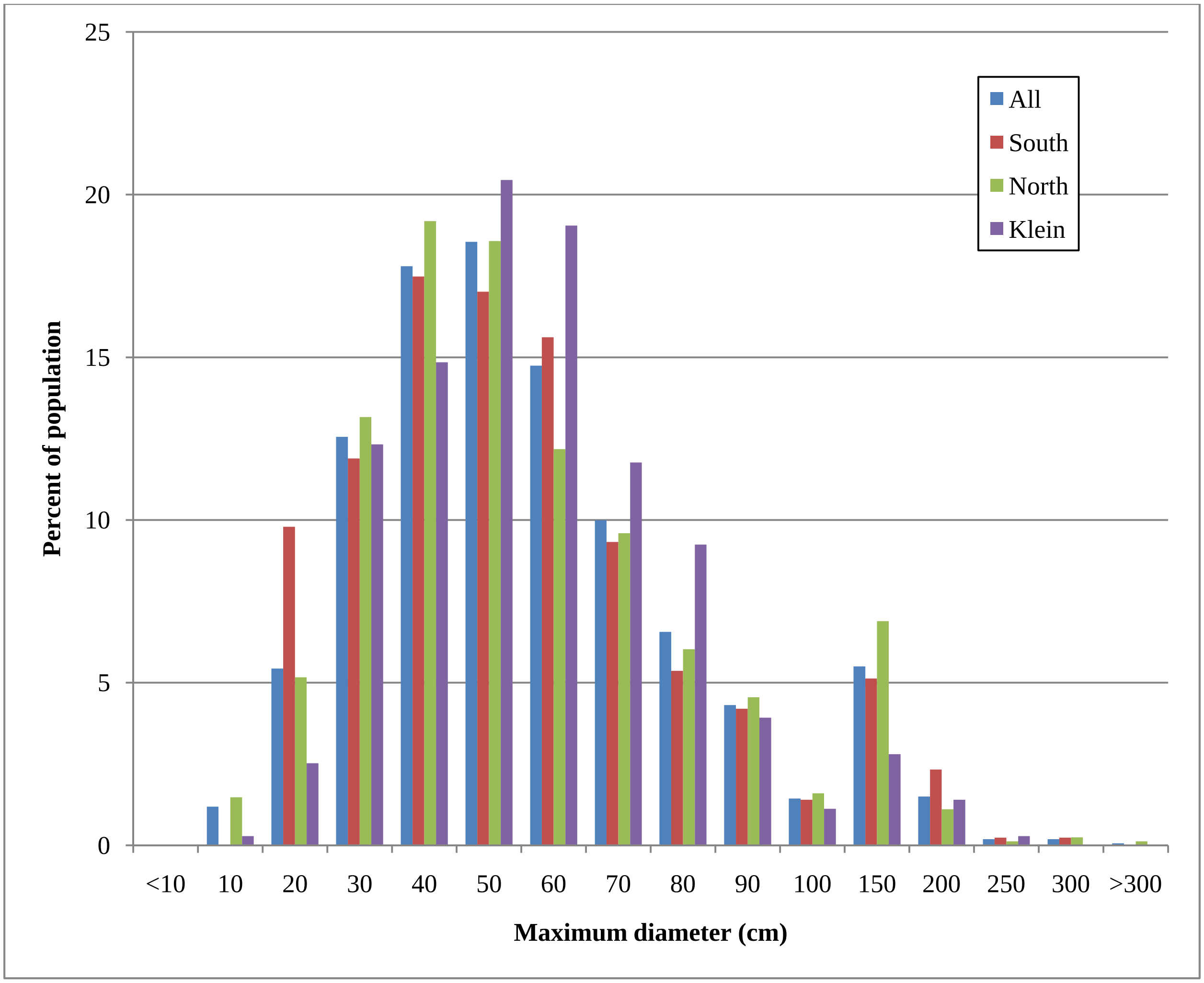

Fig. 9. Size structure of *M. annularis* complex shown for all sites (blue bars, pooled species), southern reefs (red bars), northern reefs (green bars) and Klein Bonaire (purple bars).

Colonies of *M. annularis* (complex) were significantly larger than all other species (mean diameter = 58 cm, versus 24 cm for other species pooled; original diameter of the colony), although large (> 1 m diameter) colonies of *Siderastrea siderea*, *Stephanocoenia intersepta*, *Colpophyllia natans* and extensive (2-5 m wide) thickets of *Porites porites* and *Madracis mirabilis* were seen. There was a notable absence of smaller colonies (<10 cm) of *M. annularis* (complex). It is important to note that these figures illustrate the diameter of the entire corallum (the original skeletal surface area) and not the size of tissue remnants on larger skeletal surfaces. Many colonies that were formerly 1-3 m in diameter or larger had been reduced in live tissue area, and individual corals often consisted of multiple tissue remnants that were reduced to a few cm in diameter (see coral condition).

4. Coral Condition

The amount of partial mortality observed on corals located within belt transects varied from 0-99%, with significant differences between species, colony sizes and locations. For *M. annularis* (complex) the 1602 colonies examined include 73 that had completely died (4.5%) with surviving colonies missing a mean of 28% of their tissue. Tissue loss for these species included 25% old mortality and 3% transitional and recent mortality. When examined by size, colonies of *M. annularis* (complex) missing less than 30% of their tissue were significantly smaller in size (mean diameter = 48 cm; mean tissue loss=11%; n=889) than colonies with 30-99% partial tissue loss (mean=61 cm diameter; mean tissue loss= 50%; n=639). However, a correlation analysis using the entire range of sizes (no pooling into size classes) showed that tissue loss was not significantly correlated with colony size (Fig.10a). This may be due to the fact that colonies exhibited a high range of tissue loss in all size classes: each size class contained colonies with no mortality, moderate levels of mortality and extensive mortality. Individual colonies of *M. annularis* (complex) were also frequently divided into a number of smaller patches of live tissue; on average, each coral was subdivided into 6.6 separate tissue remnants.

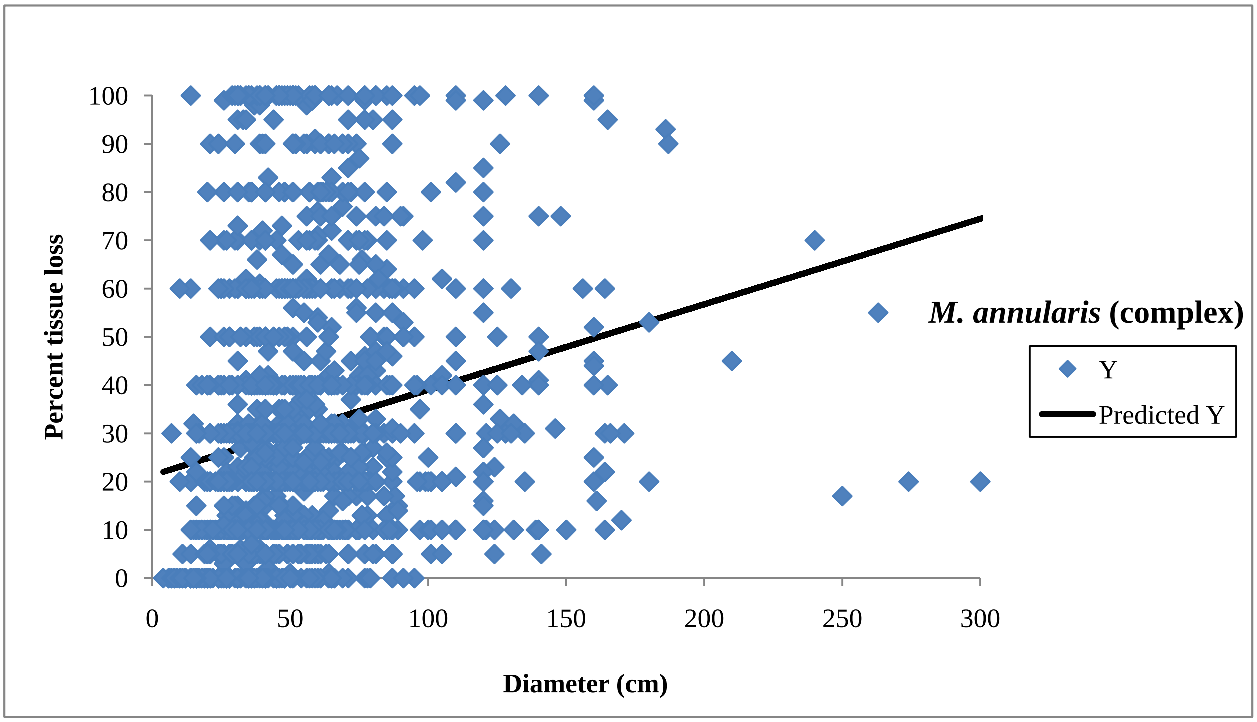

Fig. 10a. Relationship between partial tissue mortality and colony size (maximum diameter) for *M. annularis* complex (pooled for all sites). There was no apparent correlation between size and percent partial tissue loss (r^2 =0.04).

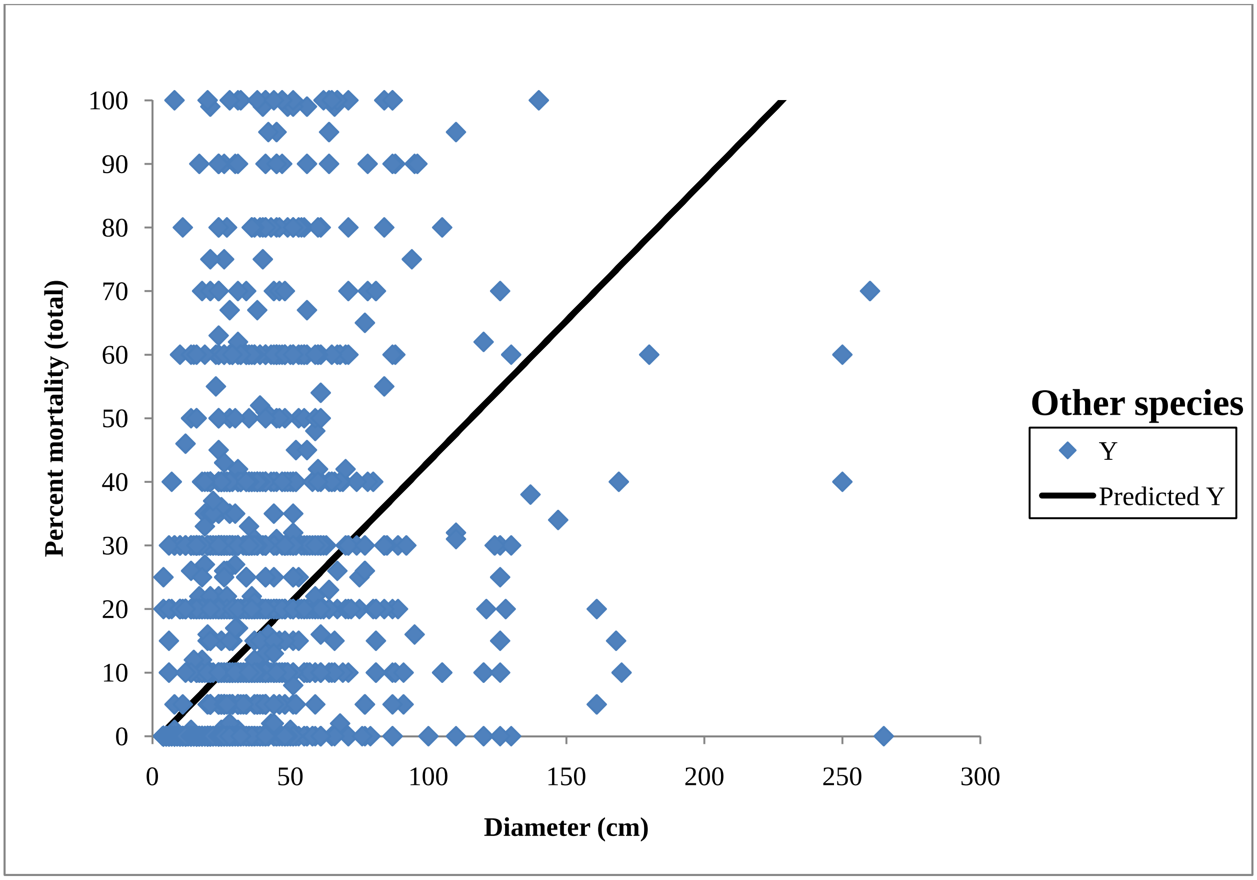

Fig.10b. Relationship between partial tissue mortality and colony size (maximum diameter) for all species of corals (pooled for all sites) except *M. annularis* complex. The correlation between size and percent partial tissue loss was minimal, but significant (r^2 =0.26).

Tissue loss for other corals (all species except *M. annularis* complex) was significantly lower (mean partial tissue loss=8%) than that observed in *M. annularis* (complex) and fewer dead colonies were identified (n=20, 0.4%). Interestingly, partial mortality for colonies that had colonized reef substrates was higher than partial mortality for colonies that had colonized exposed skeletal surfaces of living corals (9.4% vs 7.6%). These corals were also less frequently subdivided into smaller tissue remnants (mean=1.41 remnants/colony), possibly because they were younger and smaller in size overall (Fig. 13).

4a. Factors causing tissue loss

Recent tissue loss observed on corals could be partitioned into coral diseases, signs of predation, damselfish algal lawns, hurricane damage, and competitive interactions by algae, sponges, tunicates, cnidarians and other organisms. Disease was by far the largest source of mortality, with white plague of most concern and other diseases having minor impacts. The highest disease

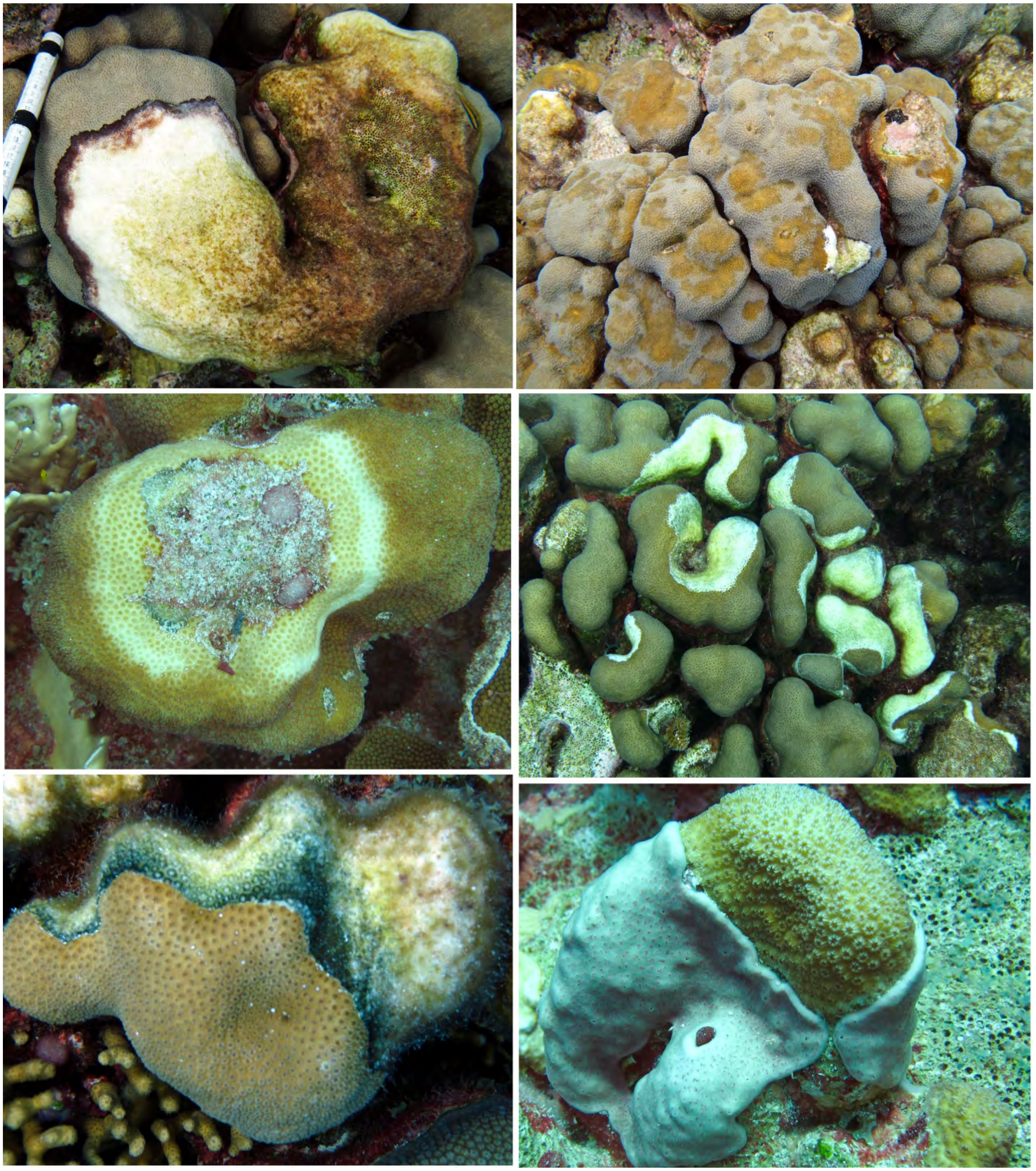

Plate 2. Conditions affecting *M. annularis* and *M. faveolata*. A. Black band disease on *M. annularis*. Distance between black band on scale bar is 10 cm (top left). B. Dark spots disease on *M. annularis*. A small BBD infection is also visible on this coral (upper right). C. Characteristic yellow band disease lesion on a single lobe of *M. annularis* (center left). The center of the lobe died previously from YBD. The dark tissue adjacent to exposed skeleton is next to die, and the advancing front of the band is generally pale yellow in color. D. Characteristic spread of white plague across a colony of *M. annularis* (center right). Multiple lobes show active signs of the disease. Caribbean ciliate infection affecting a lobe of *M. annularis* (lower left). E. Overgrowth of *M. annularis* by *Trididemnum* tunicate (lower right).

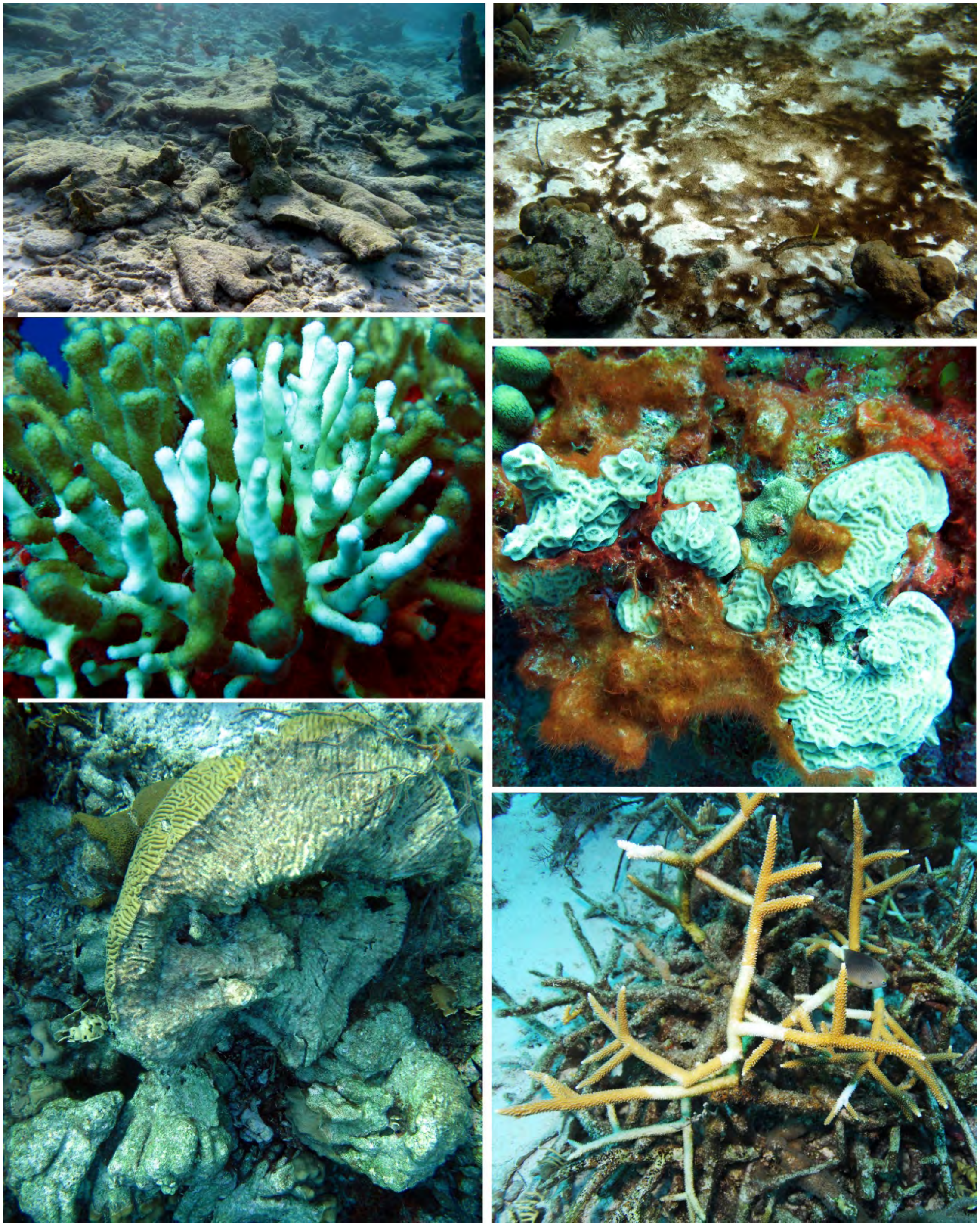

Plate 3. Examples of conditions degrading the resilience of Bonaire's reefs. A. Shallow areas formerly occupied by *A. palmata* (upper left) and *A. cervicornis* were largely devoid of coral, except for dead coral rubble due to recent storm damage. B. Cyanobacterial mats were present on numerous reefs, often covering extensive areas of sand (upper right). C. Disease was relatively uncommon, with exception of white plague, which was observed on 18 species of corals including *Madracis mirabilis* (center left). D. Cyanobacteria often formed mats over coral skeletons, slowly killing the colony (center right). E. Hurricane damage was apparent in shallow areas; often coral skeletons were smashed and overturned as seen in the center left. F. *A. cervicornis* was relatively rare. Remaining colonies were often affected by three spot damselfish (right center) damselfish, which bite at branches leading to algal colonization and tissue loss; fireworm predation, snail predation and coral diseases (WBD in this photo) are also hampering their recovery.

prevalence overall was observed on *M. annularis* (complex) colonies on southern reefs, with white plague affecting nearly 12% of all colonies (Table 2). The other most significant source of mortality to *M. annularis* (complex) included damselfish algal lawns and fish bites (spot biting and focused biting by parrotfishes). Overgrowth by the tunicate, *Trididemnum*, was only observed on northern reefs. All of these factors were observed on other corals as well (with exception of YBD), although the prevalence was lower (Table 2, 3).

	N	WP	YBD	BBD	DSD	GA	CCI
ALL Ma	1602	7.6	1.9	0.12	0.1	0.1	0.9
Ma South	430	11.6	1.6	0.2	0.2	0.0	1.2
Ma North	814	6.3	2.3	0.1	0.1	0.0	0.7
Ma Klein	358	5.9	1.1	0.0	0.8	0.3	1.1
Other All	4352	0.8	0.0	0.0	1.4	0.0	0.0
Other South	1592	0.9	0.0	0.0	2.3	0.0	0.0
Other North	1881	0.7	0.1	0.0	1.0	0.0	0.0
Other Klein	879	0.6	0.0	0.2	0.8	0.0	0.0

Table.2 Prevalence of coral diseases (% of colonies showing active signs of tissue loss from disease) for *M. annularis* (complex) and all other species for all sites, southern reefs, northern reefs and Klein Bonaire. Conditions included white plague (WP), yellow band disease (YBD), black band disease (BBD), dark spots disease (DSD), growth anomalies (GA) and Caribbean ciliate infections (CCI).

	N	Snails	Fish Bite	Foc Bite	Tunicate	Sponge	Damselfish
ALL Ma	1602	0.8	3.0	2.4	2.6	0.2	10.3
Ma South	430	0.5	3.0	2.1	0.0	0.5	7.0
Ma North	814	1.2	2.1	1.7	5.0	0.1	10.7
Ma Klein	358	0.3	5.0	4.5	0.0	0.3	13.4
Other All	4352	0.2	0.2	0.1	0.4	0.3	1.6
Other South	1592	0.1	0.1	0.1	0.0	0.5	1.3
Other North	1881	0.4	0.2	0.1	0.9	0.1	1.8
Other Klein	879	0.0	0.3	0.2	0.0	0.1	2.0

Table 3. Prevalence of other biotic factors affecting corals including predation by *C. abbreviata* (Snails), spot biting by parrotfishes (Fish Bite), focused biting by stoplight parrotfishes (Foc Bite) and overgrowth by *Trididemnum* (Tunicate), *Cliona langae/aprica*, *Cliona delitrix*, and *Anthosigmella* (Sponge) and *Stegastes planifrons* three spot damselfish (Damselfish) algal lawns.

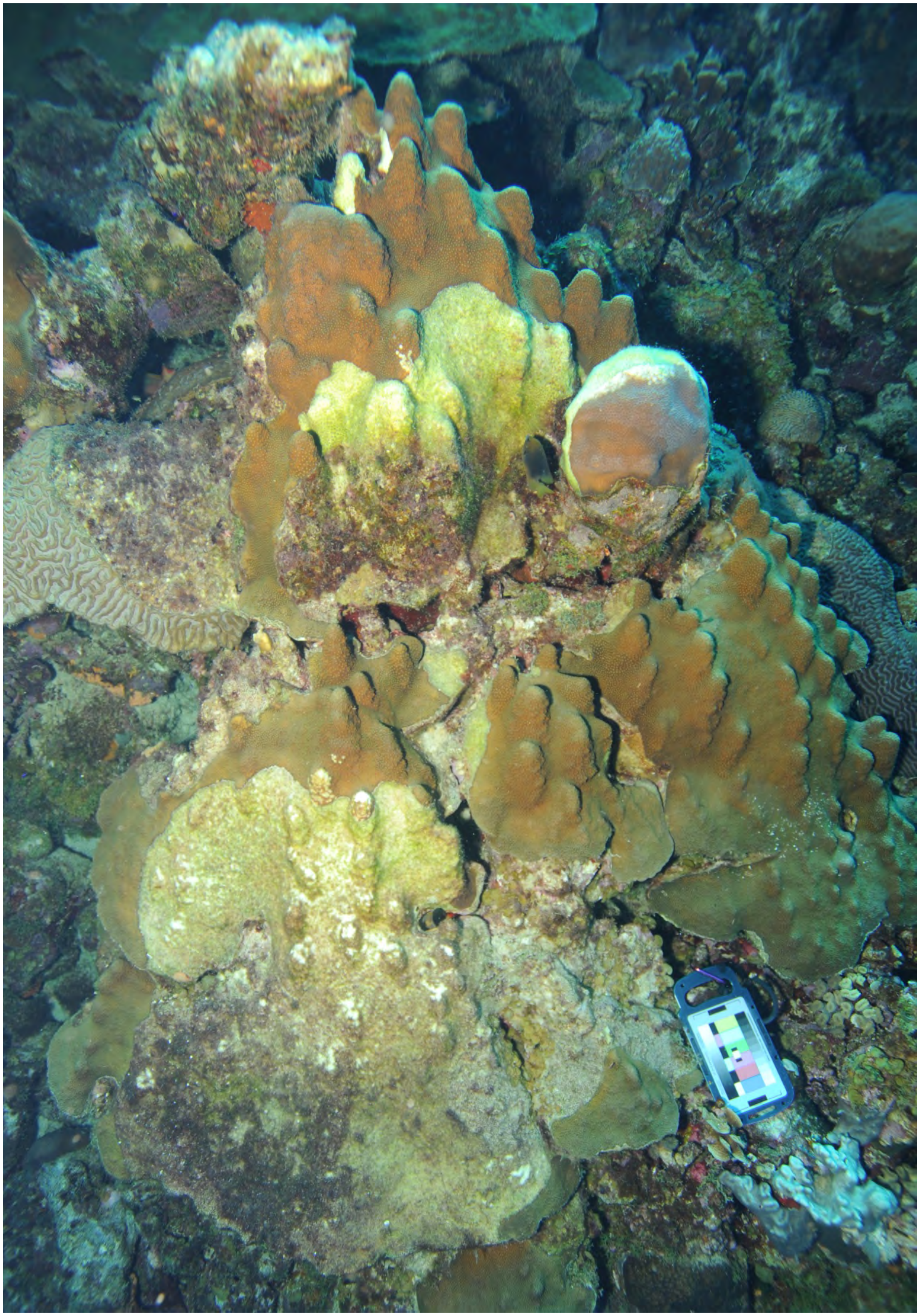

Plate 4. Large colony of *M. faveolata* with white plague. Colony has lost over half of its tissue. Recent tissue loss is apparent in the upper portion of the colony. Most of the remainder of the exposed skeleton shows transitional tissue loss occurring over the last 30 days or so. The *C. natans* colony also was affected by white plague but the disease is now in remission. Recent tissue loss from white plague is also evident in the lobe of *M. annularis*.

5.

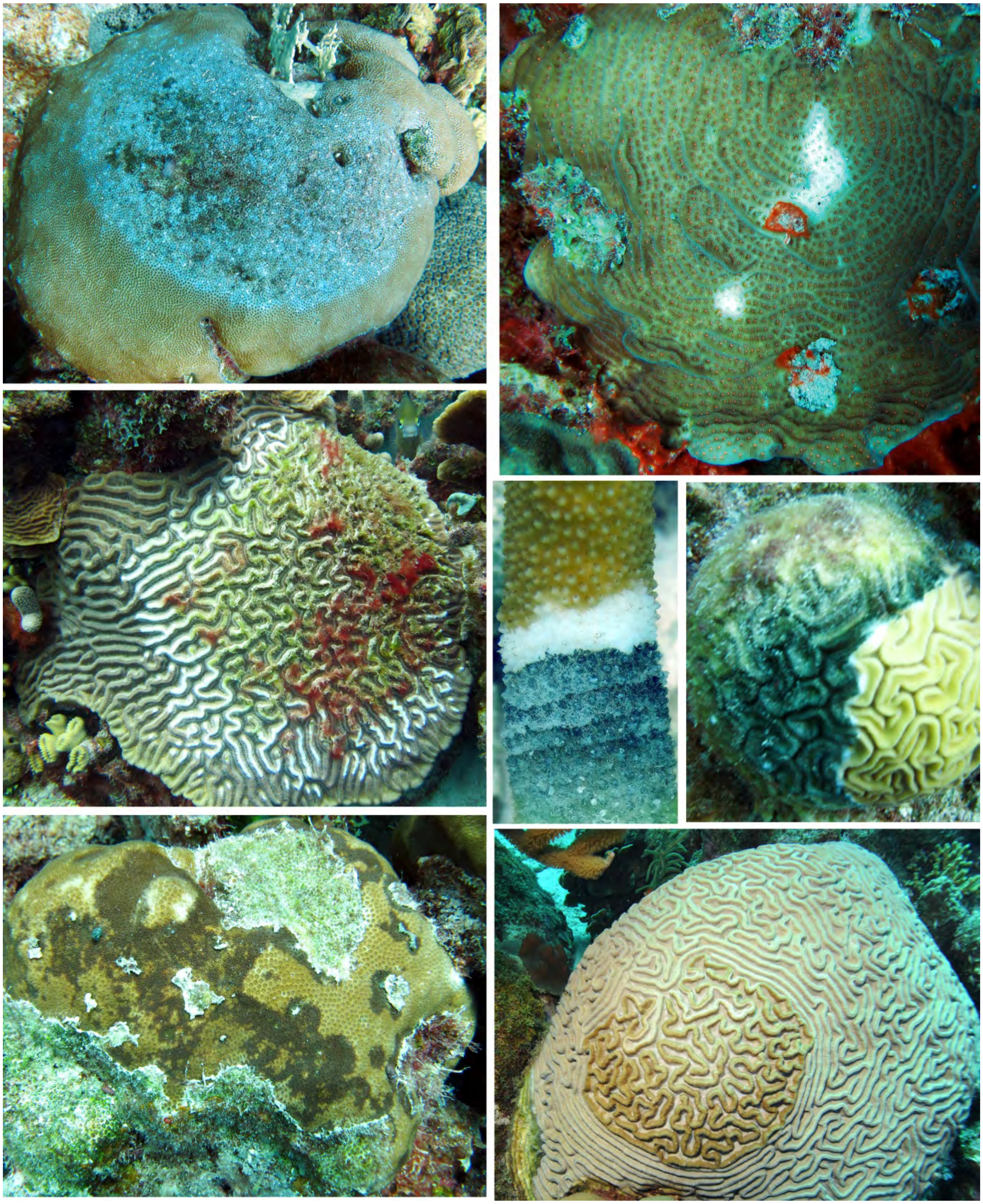

Plate 5. Conditions affecting other species of corals. A. Damselfish algal lawn on *Siderastrea siderea* (top left) and *C. natans* (middle left). The condition on *C. natans* has been incorrectly referred to as “ridge mortality disease”. B. Lesions created by coral eating snails (*C. abbreviata*) on a plating colony of *Agaricia agaricites*. The snail is located at the margin of the central lesion, but is well camoflauged by cyanobacteria. D. E. Manifestation of Caribbean ciliate infections on *A. cervicornis* and *D. labyrinthiformis* (center and center right). F. Dark spots disease on *Stephanocoenia intersepta* (lower left). G. A growth anomaly on *Diploria strigosa* (lower right).

5. Recruitment

A. Corals settling on dead coral skeletons

Many of the exposed skeletal surfaces of corals (249 out of 5957 corals examined) that had experienced partial colony mortality were colonized by new stony corals. Overall, 830 recruits of 16 species were identified on these corals, with up to 12 recruits observed on a single colony. These recruits were up to 30 cm in diameter, with most (49%) from 4-7 cm in diameter and <10% that were 3 cm or smaller (Fig. 13). *Agaricia agaricites* (43%) and *P. astreoides* (27%) were the most common recruits, although broadcast spawners were also observed (Fig. 11). There was a notable absence of *M. annularis* (complex) recruits.

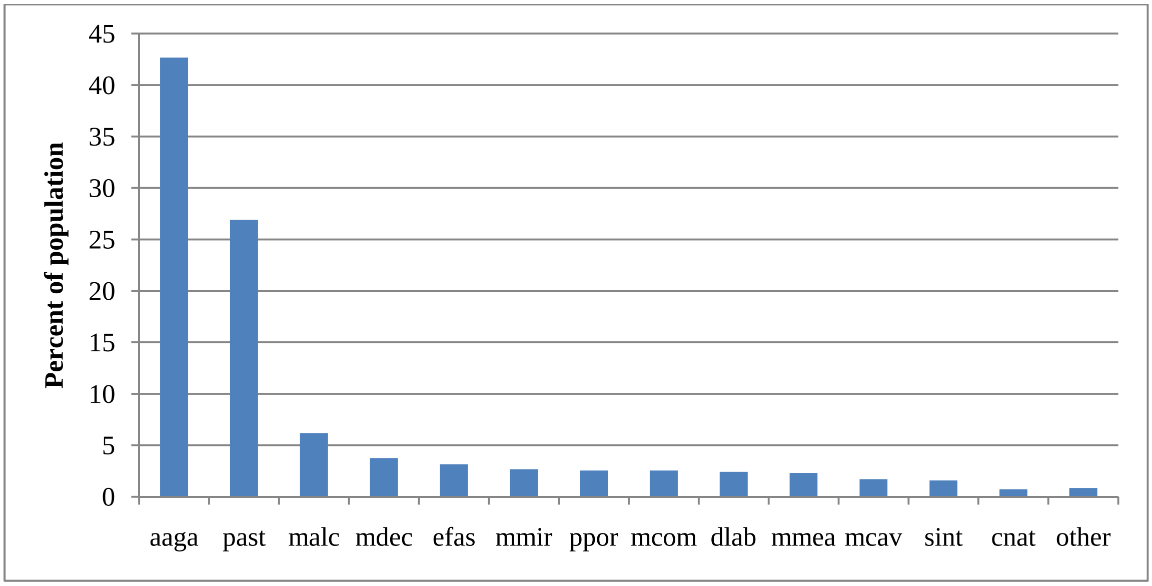

Fig. 11. Relative abundance of species of corals that recruited onto dead coral skeletal surfaces.

Recruits had colonized 12 species of corals, although most were observed on *M. annularis* (36%) and *M. faveolata* (35%) (Fig. 12). A much higher proportion of *M. annularis* (complex) skeletons on Klein (19%) were colonized by newly settling corals than that observed on northern (13%) and southern (5.3%) reefs. Exposed skeletal surfaces of other species were less frequently colonized by new corals, with exception of *M. cavernosa* and *S. siderea* on southern reefs. Corals that supported new recruits were missing nearly 60% of their tissue, on average. Colonies supporting recruits on southern reefs had a much higher amount of partial mortality overall, with

M. annularis (complex) colonies missing more tissue overall. *M. annularis* (complex) colonies that supported recruits were similar in size in all three locations, and they were significantly larger than all other species that were colonized by new corals (Table 4).

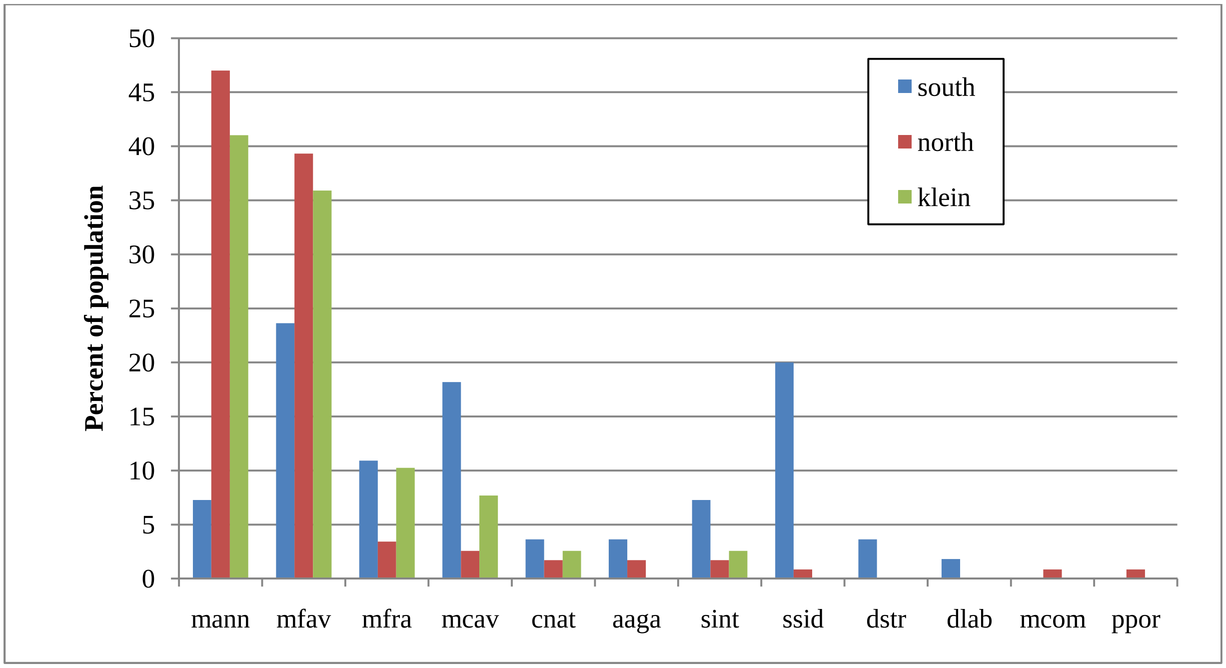

Fig. 12. Coral taxa observed with recruits on exposed skeletal surfaces.

	# Corals	% of total	# Tissue Remnants	Max Diam (cm)	Width (cm)	Max Height (cm)	% Old mortality	% Recent & transitional mortality	% Total mortality
All	249	4.7	4.8	66	60	58	58	0.8	59
Ma south	23	5.3	3.3	70	61	53	71	1.7	73
Ma north	105	12.9	5.9	74	67	66	60	0.9	61
Ma Klein	67	19.3	5.5	65	59	60	51	0.7	52
Other south	32	2.2	2.4	49	44	38	63	0.0	63
Other north	12	0.8	2.2	49	45	40	49	1.1	50
other Klein	21	1.6	2.1	51	48	46	52	0.0	52

Table 4. Number, size structure and condition of corals that had exposed skeletal surfaces colonized by other scleractinian and hydrozoan corals. Sites and corals are pooled into seven categories: all sites and species pooled; all *M. annularis* complex from southern, northern and Klein Bonaire reefs, and all other species (all corals except for *M. annularis* complex) on southern, northern and Klein Bonaire reefs.

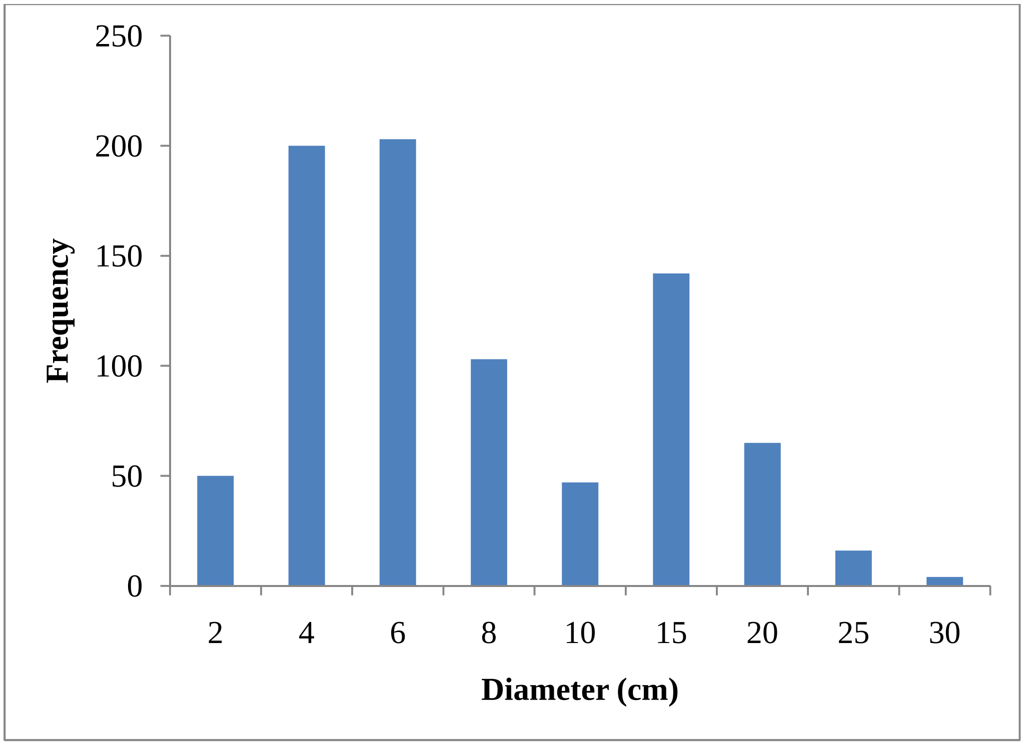

Fig. 13. Size structure of corals that had colonized exposed skeletal surfaces.

While *M. annularis* (complex) was not observed recruiting onto any exposed skeletal surfaces, juvenile corals (4 cm or larger) that had settled on dead coral surfaces represented 17.5% of the corals of these species that were identified within transects. This phenomena illustrates the high levels of recent recruitment and rapid growth of newly settling corals contributing to an increase in the proportion of these taxa, as compared to the *M. annularis* (complex) which has not shown any new recruitment to replace colonies that died. The highest proportion of the new settlers recorded on exposed skeletal surfaces were from reefs off Klein Bonaire.

B. Recruits observed in quadrats

A total of 1688 0.25 m^2 quadrats were examined on 25 reefs in Bonaire. Over 40% of the quadrats contained at least one coral (0-3 cm in diameter, classified here as a recruit). A higher proportion of quadrats on southern reefs contained recruits (45%), while 40% and 37% of quadrats contained recruits on northern reefs and Klein Bonaire, respectively. Individual quadrats contained a maximum of 5 recruits (northern and southern reefs) and 8 recruits (Klein Bonaire) each. Eighteen different species of scleractinian corals and two hydrozoan corals were observed in quadrats. There was a notable absence of sexual recruits of *M. annularis, M. faveolata* and *M. franksi*, although numerous tissue remnants <4 cm in diameter were noted. The dominant corals observed as recruits included *A. agaricites*, *P. astreoides*, and *Madracis* spp. (Fig. 14). Species identified as adults within transects, but not observed in smaller size classes included *Mussa angulosa*, *Mycetophyllia lamarckiana* and *M. aliciae, Dendrogyra cylindricus, Isophyllia sinuosa and I. rigida, S. intersepta, Scolymia* spp., *Acropora palmata*, and *A. cervicornis.* Other includes *Dichocoenia stokessi*, *Manacina aeriolata*, *Mycetophyllia ferox,*

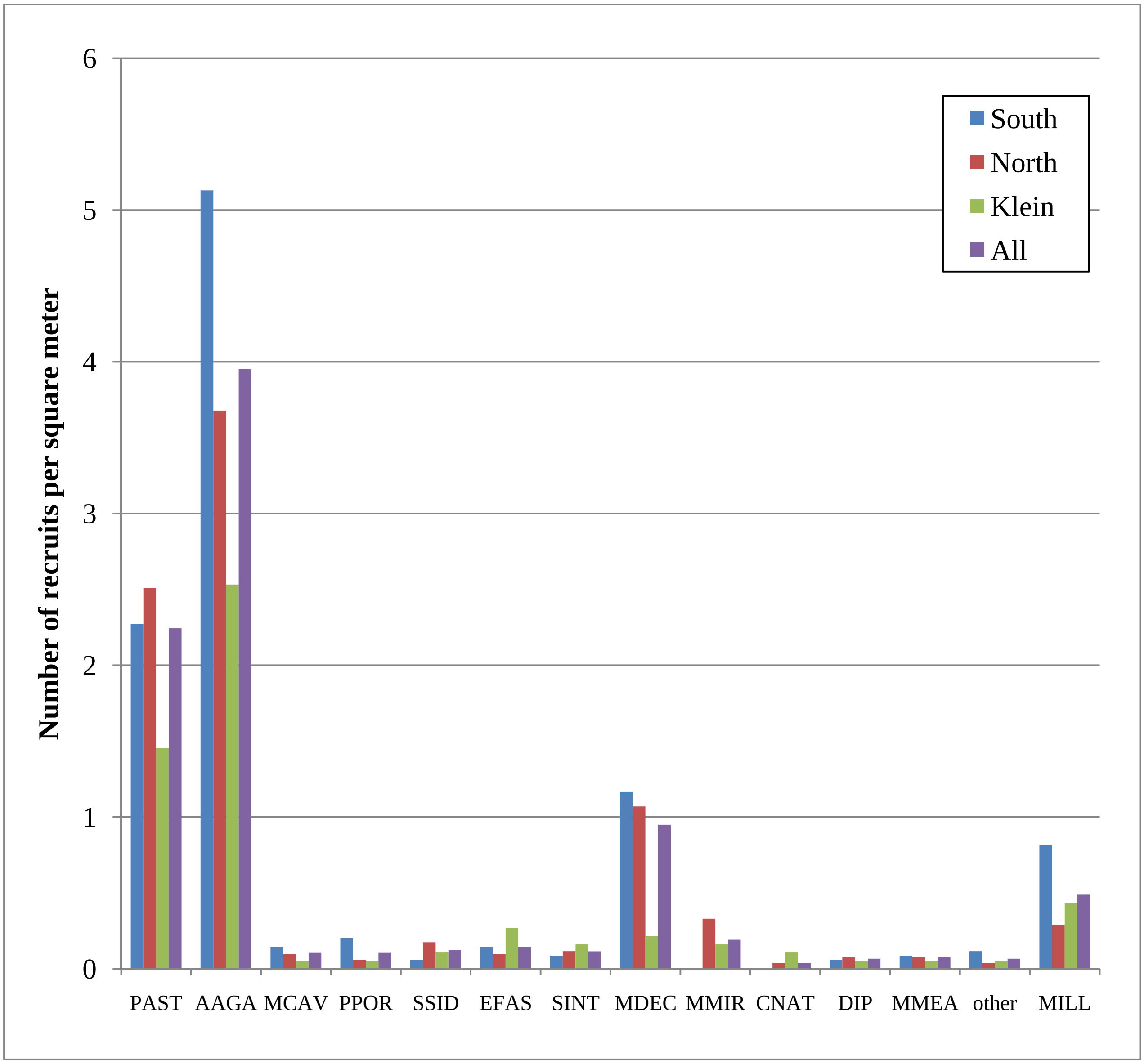

Fig. 14. Species of corals < 4cm in diameter identified in quadrats pooled in southern reefs (blue), northern reefs (red), Klein Bonaire (green), and all reefs and depths pooled (purple).

6. Fishes

Of approximately 100 species of reef fishes included in this assessment, parrotfish made up 24-28% of all fishes documented within belt transects. The next most abundant group, damselfishes (three spot, yellowtail, dusky and longfin damselfish) was highly variable in abundance between sites, with the highest numbers observed on Klein Bonaire (37% of all fishes recorded). There were relatively large populations of grunts and snappers, although both were less abundant on reefs surrounding Klein Bonaire (5-8% of all fishes recorded). Large predators, especially groupers were observed on most reefs, although their numbers were fairly low (Fig. 15).

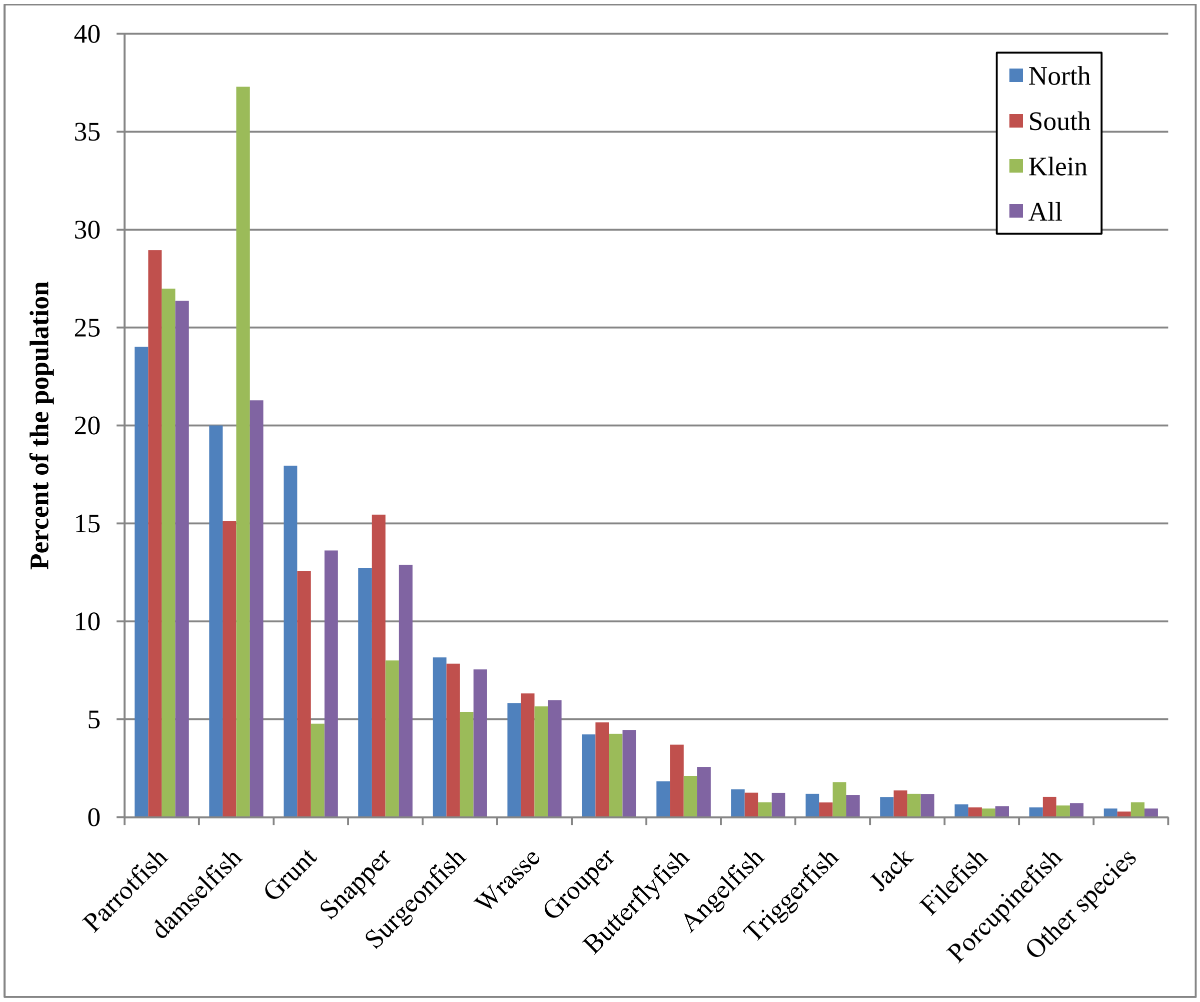

Fig. 15. Relative abundance of target species of fish (96 species, 5 cm or larger in total length) identified on reefs off Bonaire. Fishes were pooled for all sites (purple), northern reefs (blue), southern reefs (red) and Klein Bonaire (green).

Most fish recorded in belt transects were small to medium in size, with few fishes over 40 cm in total length. Parrotfish exhibited a bell shaped curve, with a dominance by fishes in the 11-20 cm size classes (Fig 16a). Most groupers were 6-20 cm TL with very few small (<6 cm TL) and large (>30 cm) sized grouper (Fig. 16b).

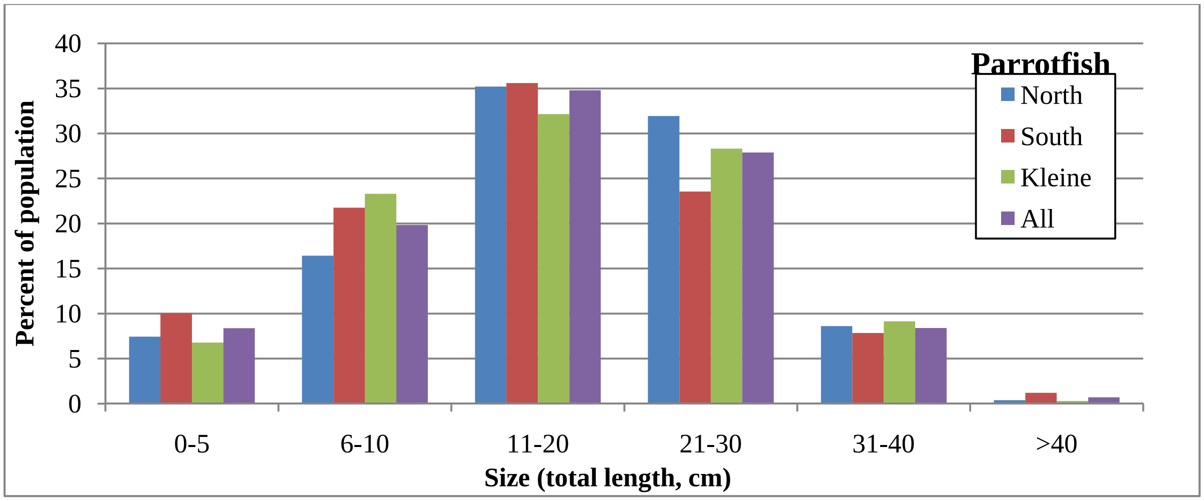

Fig. 16 a. Size structure (total length in cm) of parrotfishes observed on northern (blue), southern (red), and Klein Bonaire (green) reefs and all reefs and depths pooled (purple).

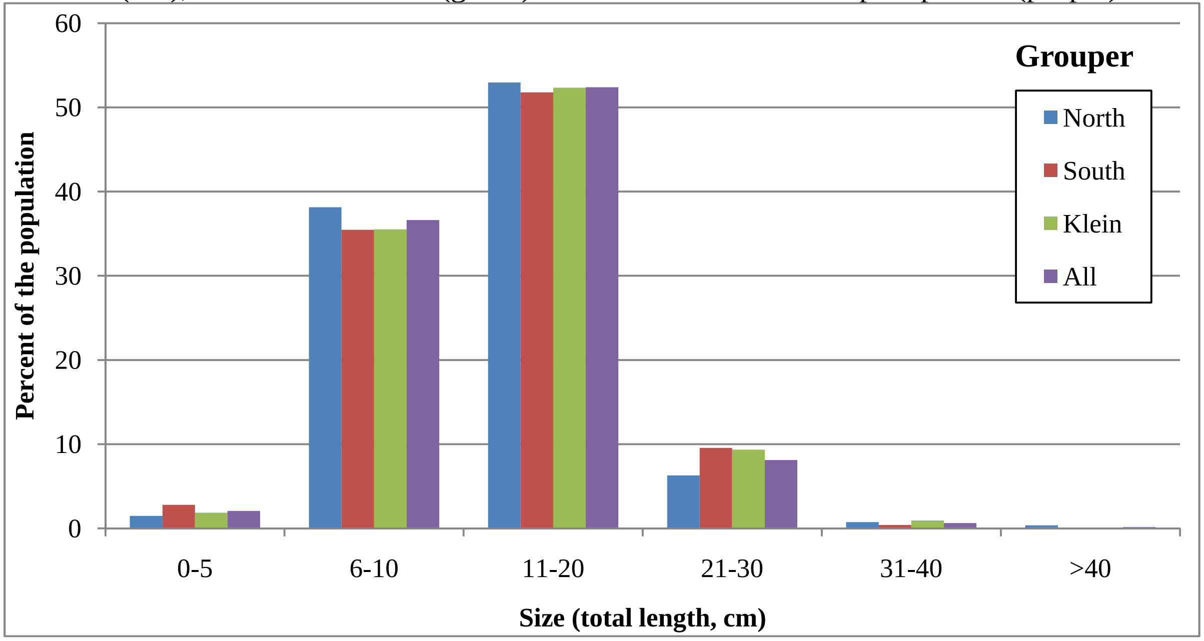

Fig. 16b. Size structure (total length in cm) of groupers observed on northern (blue), southern (red), and Klein Bonaire (green) reefs and all reefs and depths pooled (purple).

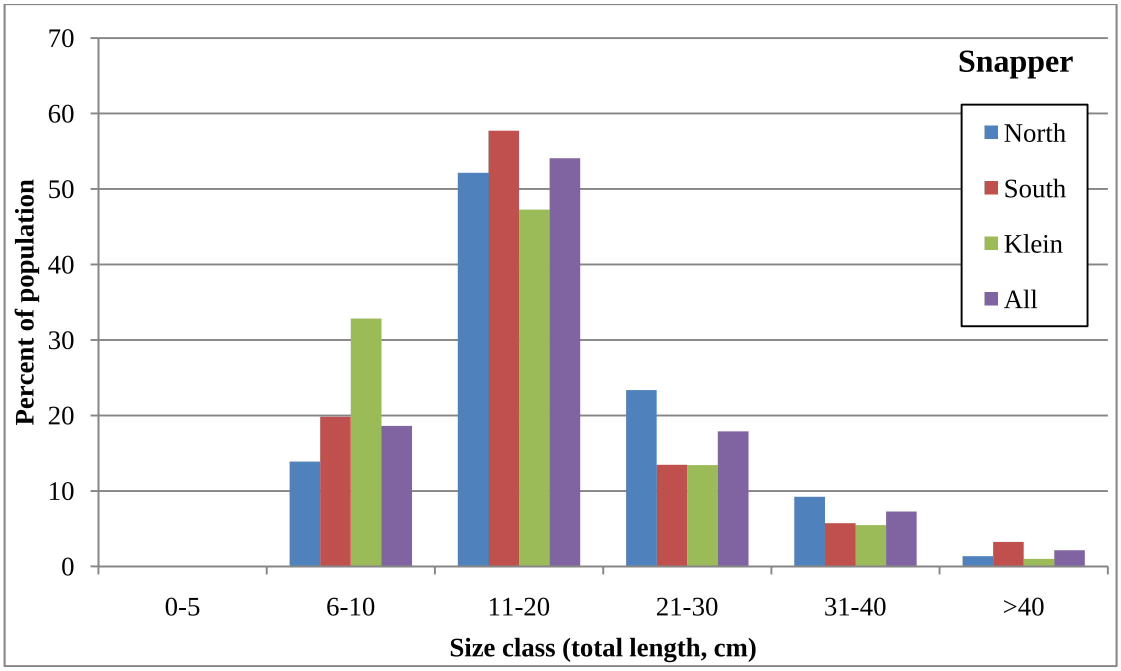

Fig. 16c. Size structure (total length in cm) of snappers observed on northern (blue), southern (red), and Klein Bonaire (green) reefs and all reefs and depths pooled (purple).

Snappers were mostly intermediate in size (11-20 cm); there was a notable absence of juveniles (<6 cm) and small numbers of large (>30 cm) fishes, although a greater proportion of snappers were in the largest size classes, as compared to groupers. The absence of juvenile snappers is expected, as we did not survey nursery habitats utilized by these species.

7. Resilience Indicators

Resilience assessments conducted by Dr. Debbie Santavy are not included in this report as these data were not yet available. A general summary of some of the factors enhancing and/or degrading resilience is presented below.

Bonaire's reefs are among the most healthy reefs in the western Atlantic today, with most sites showing higher cover of living coral and a larger remaining population of *M. annularis* (complex) when compared to other locations. These reefs exhibit many factors that illustrate high resilience including:

- Limited runoff/sedimentation associated with low rainfall, an absence of mountains, limited agriculture, and little ongoing development. The only concern associated with land-based activities is the apparent absence of sewage treatment and the large number of hotels located on the leeward side of the island, in close proximity to the fringing reefs. Mats of cyanobacteria and patches of green fleshy algae were identified in several locations directly off the hotels which is suggestive of nutrient input.

- A steep fore reef slope and presence of deepwater adjacent to reef communities may enhance the cooling of reefal waters during periods of thermal anomalies. While reefs of Bonaire have exhibited mass bleaching on several occasions (1995 and 1998), flushing and upwelling may have minimized bleaching-related impacts. Bonaire escaped the mass bleaching events of 2005 and 2009, both of which caused extensive mortality in the eastern Caribbean and other locations. At the time of these surveys bleaching was minimal, although 2010 was predicted to be a severe bleaching year and Bonaire's reefs did start to show signs of bleaching after these assessments were completed.
- Presence of high coral cover and large numbers of herbivores limits the amount of macroalgae that can colonize reef substrates. Unlike other Caribbean localities, these reefs had very little macroalgae, with exception of some deeper areas where *Dictyota* and *Lobophora* were recorded, an apparent increase of *Peyssonnelia*, and the occurrence of cyanobacterial mats in some areas.
- High levels of recruitment on both exposed skeletal surfaces and reefal substrates. While most of these are short-lived brooders, high numbers of important reef builders (*Colpophyllia, Diploria, Eusmilia, Siderastrea, Stephanocoenia* and *M. cavernosa*) were also observed. The only concern is the absence of *M. annularis* (complex) and *Acropora* spp. recruits.
- Low levels of turbidity (due to limited runoff and absence of plankton blooms) creates amenable conditions for reef-building corals due to their light requirements for photosynthesis.
- Relatively steep sloping fringing reefs. While the reefs are very close to shore, land-based pressures are minimal and the presence of a reef slope that leads quickly to deep water may allow greater flushing and removal of debris, sediment and organisms detached during storms, minimizing burial by sediments and maintaining cool reef environments. The steep slope may also enhance exchange of plankton between the reef and offshore and deepwater locations.

- Limited fishing pressure. The strict restrictions on fishing on reef species has helped maintain critical species of fishes that control the health of Bonaire's reefs. Grouper populations have declined from levels present in the 1980s and 1990s, but these species may rebound now that fewer restaurants serve grouper (a notable shift to offshore pelagics has been observed over the last 5 years). Fishing using handlines along the shoreline by children and for subsistence should be eliminated as one of the key targets appears to be parrotfish, and these species are important herbivores.
- Relatively low prevalence of diseases. Certain conditions of concern in the late 1990s and early 2000s, such as yellow band disease have greatly diminished in prevalence and severity. Black band disease, red band disease, Caribbean ciliate infections, dark spots disease and white band disease were noted on these reefs, but these conditions generally affected only isolated colonies. Of highest concern, white plague seems to still be prevalent on these reefs. This disease has led to high levels of losses of massive frame-builders (especially some of the largest and oldest colonies of *M. annularis* and *M. faveolata*) in some locations, especially on the outer reefs (2nd reef system) off the southern reefs (e.g. Alice in Wonderland, Angel City, Jeannie's Glory). One of the northern reefs (Tailor Made) contains high numbers of unusually large *M. annularis* and *M. faveolata* colonies in excellent condition, although many of these showed recent signs of disease. At this time, these diseases appear to cause only small amounts of partial mortality at the margins of the colony, before going into remission (see plate 1).
- Certain pest species appear to be fairly abundant, although these show high variation between sites. Of greatest concern are the apparently increasing numbers of *Stegastes planifrons* (three spot damselfish) that are colonizing and establishing algal lawns on massive framework corals. *Trididemnum* (encrusting tunicate) is a continuing problem on northern reefs; *Cliona* (bioeroding sponges), *Erythropodium* (encrusting gorgonian), *Palythoa* (colonial anemone), and the hydrozoan coral *Millepora* are relatively common and are causing localized mortality to corals through overgrowth. Coral eating snails (*C. abbreviata*) were observed in several locations, but the numbers were fairly low. While these are unlikely to be a problem for massive and plating corals, remaining *A. palmata* and *A. cervicornis* colonies should be carefully monitored and all snails should be removed, given the vulnerable state of these corals.

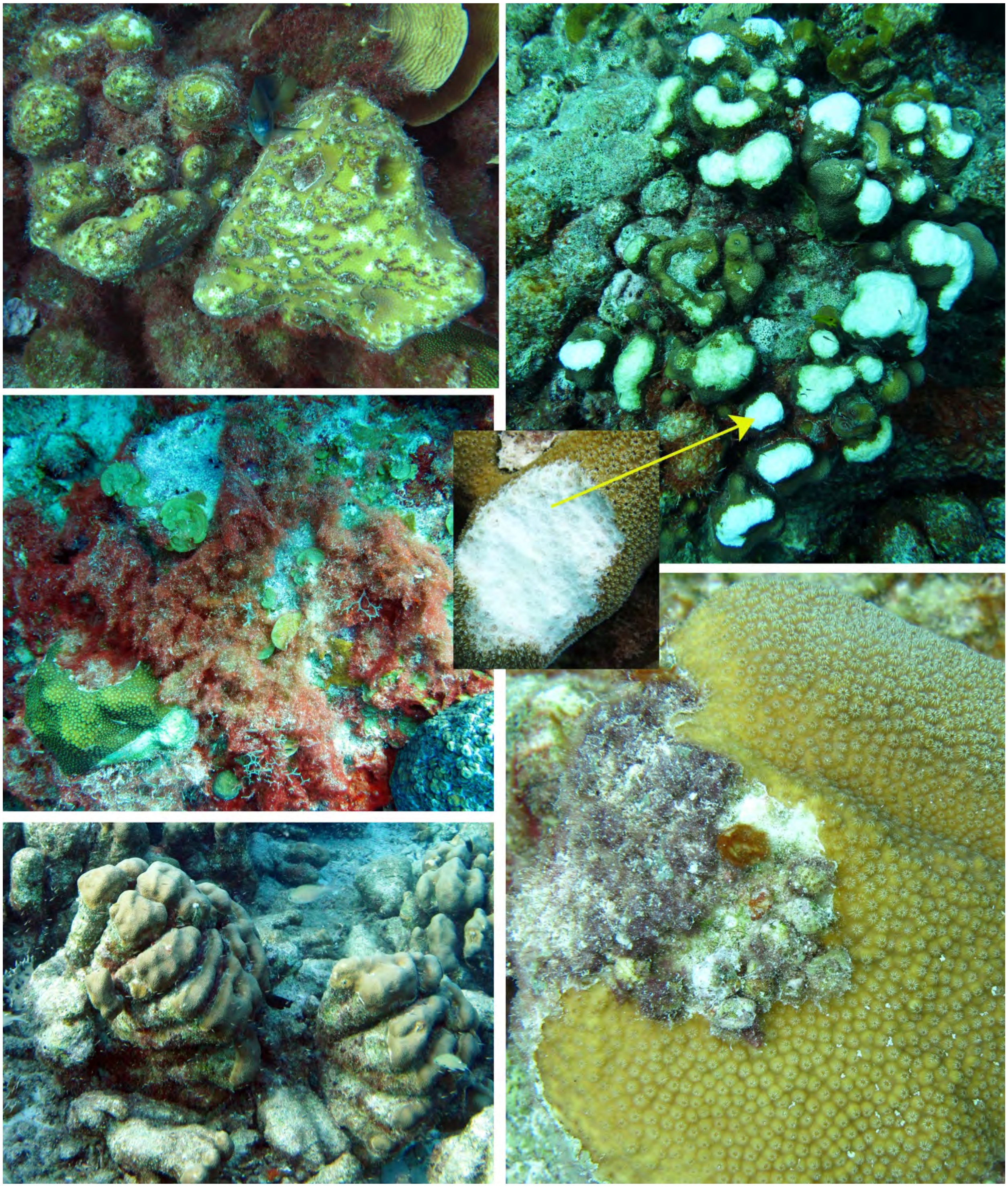

Plate 6. Examples of conditions degrading resilience. A. Three spot damselfish algal lawn on *M. annularis* (Top left). Note filamentous algae and focal tissue loss. B. Focused biting on *M. annularis* by *Sparisoma viride* (top right). Both tissue and upper layers of skeleton are removed. See inset of a closeup of focused biting. C. *M. faveolata* that has nearly died (center left). Colony has active white plague. In addition, areas killed long ago are colonized by macroalgae (*Lobophora*) and cyanobacteria. D. *M. annularis* colony toppled by wave action during a previous storm (lower left). E. Predation on *M. annularis* by *C. abbreviata* snails (lower right).

- Minimal physical impacts. Diver damage has the potential to negatively impact reef building corals, given the large number of divers that visit these reefs and the predominance of shore diving. However, these impacts have been lessened by the presence of a well-maintained mooring at each site for dive boats, and a requirement for a thorough dive briefing for each new visitor. Bonaire is also largely out of the hurricane belt. Although there have been several recent hurricanes that have caused damage (especially Lenny in 1999 and Omar in 2008), leading to a near eradication of corals close to the shore in shallow water, the reefs showed rapid recovery following Lenny and many sites examined in 2010 seem to be showing positive signs of recruitment onto stabilized rubble and dead coral surfaces.
- Of most concern is the near extinction of A. *palmata* and *A. cervicornis*. These corals used to form large stands immediately off the shore and in the nearshore, shallow sandy fields adjacent (landward) to the *M. annularis* zone. Only isolated living colonies of *A. palmata* were identified, and many areas that formerly had colonies of this species were characterized by fields of rubble with no remaining live coral fragments and no recovery through recruitment. During Hurricane Omar, *A. cervicornis* was virtually eliminated from many locations that were on their way to recovery following Lenny, although small thickets were identified on a few northern reefs (1000 Steps, Witches Hut and Jeff Davis) and southern reefs (Invisibles and Jeannie's Glory). Because of the absence of sexual recruits (and the poor recruitment ability of this coral), Bonaire could benefit from an ecological restoration effort targeted at these corals.

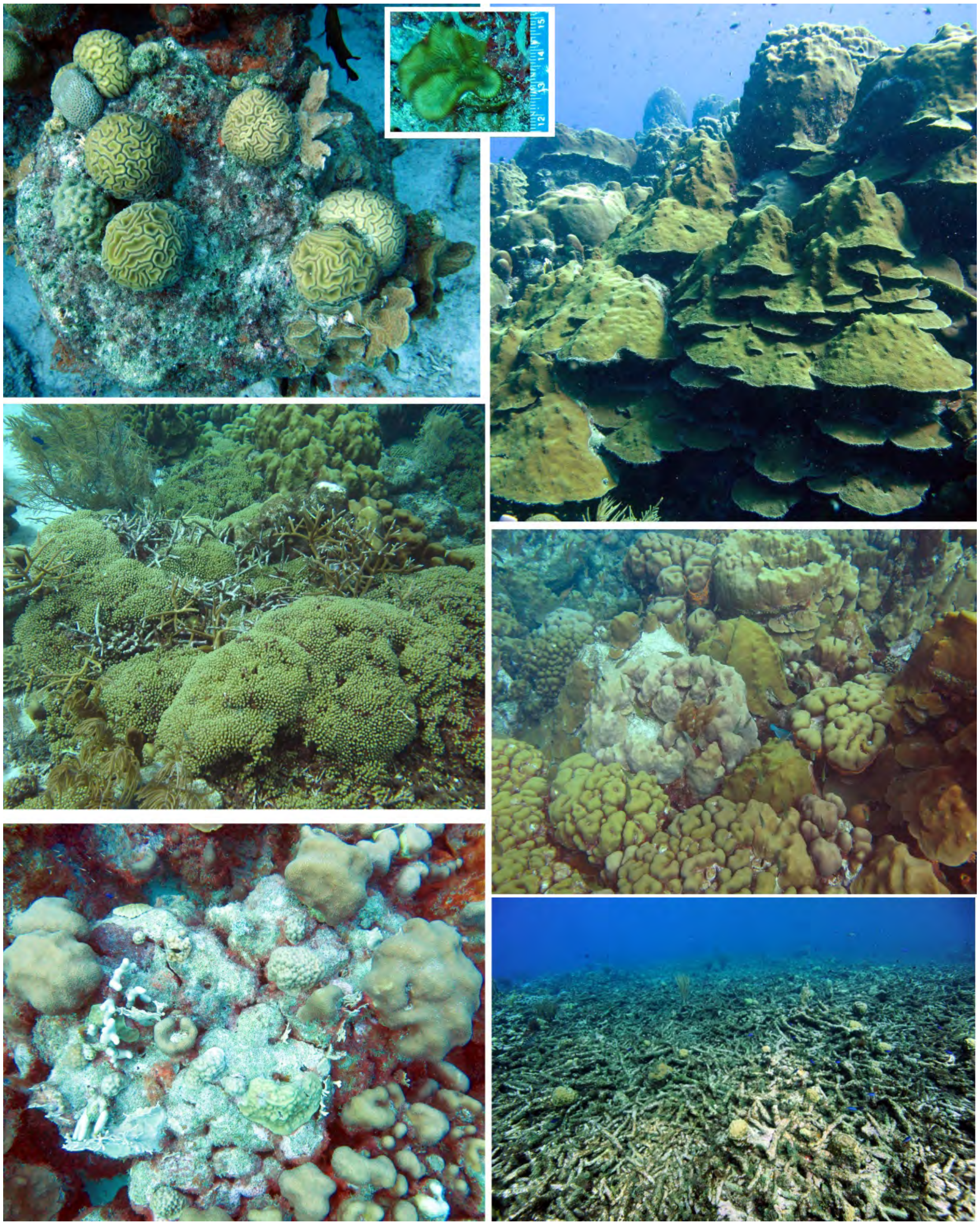

Plate 7. Examples of highly resilient reef communities in Bonaire. A. Dead corals are rapidly colonized by coral recruits, which show high survival and rapid growth rates (upper left). B. Small *C. natans* recruit (top center). C. Large (1-5 m tall) colonies of *M. faveolata* can still be found in abundance on Bonaire's reefs (top right). These corals are rapidly disappearing from other Caribbean localities. D. Classic thickets of *Madracis mirabilis* and *A. cervicornis*, intermixed with lobate *M. annularis* colonies in shallow water (3-5 m depth) like those described by Goreau (1959) still exist in Bonaire (left center). E. Reefs with exceptionally high cover, consisting primary of important, long-lived framebuilders in the *M. annularis* (complex) are found on many northern reefs (right center). F. Although colonies of *M. annularis* are being affected by disease, bleaching, predation and other factors, exposed skeletal surfaces are rapidly colonized by other corals, instead of the typical shift from coral to macroalgae as seen in other parts of the Caribbean (lower left). G. Many of the former *A. cervicornis* thickets have collapsed from storm damage, disease, and other factors. However on northern reefs, coral fragments have been fused by crustose coralline algae and new corals are recruiting onto the branch fragments (lower right).

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Scientific Team and responsibilities (other individuals may accompany me)

Name	Duty
Dr. Andrew Bruckner	Lead scientist; benthic assessments including coral belt transects, point intercept, resilience assessment
Glynnis Roberts	fish community structure along belt transects
Kalisi Faanunu	fish community structure along belt transects
Eric Borneman	benthic surveys;
Dr. Debbie Santavy	Coral disease surveys, resilience assessments
Robin Bruckner	Video
Amanda Williams	Point intercept transects; recruitment quadrats
Capt Philip Renaud	Photo-documentation; recruitment quadrats
Errol Coombs	Field Assistant

Appendix I

Surveyor:	Site Name:		Reef Type:	Reef Zone:
Date:	Day #: Site #:	Latitude:	Subzone/Habitat	
Start Time:	Bottom Temp.: °C/ °F	Longitude:		
Start Depth: ft/ m		Site Comments:		
End Depth: ft/ m		Transect Comments:		
All ≥ 4 cm Corals				

Species Code	# Isolates	Maximum (cm)			% Bleach (P, BL)	% Partial Mortality			Disease	Predation overgrowth	Comments
		Length	Width	Height		New	Trans	Old			

Appendix 2

Surveyor:			**Site:**			**Date:**		**Time:**		**Temperature:** °C/ °F		
Compass Bearing:			Start Depth: ft/ m			End Depth: ft/ m					Quadrats	
Transect #:	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	#	≤ 2 cm Coral Recruits
0 cm											1	
10 cm												
20 cm											2	
30 cm												
40 cm											3	
50 cm												
60 cm											4	
70 cm												
80 cm											5	
90 cm												
Compass Bearing:			Start Depth: ft/ m			End Depth: ft/ m					Quadrats	
Transect #:	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	#	≤ 2 cm Coral Recruits
0 cm											1	
10 cm												
20 cm											2	
30 cm												
40 cm											3	
50 cm												
60 cm											4	
70 cm												
80 cm											5	
90 cm												
Compass Bearing:			Start Depth: ft/ m			End Depth: ft/ m					Quadrats	
Transect #:	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	#	≤ 2 cm Coral Recruits
0 cm											1	
10 cm												
20 cm											2	
30 cm												
40 cm											3	
50 cm												
60 cm											4	
70 cm												
80 cm											5	
90 cm												

Substrate codes

DC = dead coral
RDC = recently dead coral
BL = fully bleached
HG = hardground
R = rubble
S = sand
C = live coral
I = invert

Coral codes

use first letter of genus
and three letters of species

Condition

ID disease, predation, bleaching, other compromising feature

Algae codes

m = macroalgae
t = turf
cca=crustose coralline
e = erect coralline
cy = cyanobacteria
TS = turf + sed.

Special algae

Dic = dictyota
Lob = lobophora
Mic = microdictyon
Hal = halimeda
Peys = Peyssonellia

Invert

Gorg = seafan
Octo = soft coral
Anem = anemone
Paly = palythoa
Tun = tunicate
SP = sponge
RSP = rope sponge
TSP = tube sponge
BSP = barrel sponge
ESP = encrusting sponge

AINV = aggressive invert

Nuisance species

Eryth = Erythroodium
Paly = Palythoa
Clidel = Cliona delitrix
Clio = Cliona (brown)
Tridi = Trididemnum
Chon=Chondrilla sponge

Appendix 3

Location:		**Date/Time:**				
Depth:	Transect No.					
Dir:	cm total length					
Min:	0-5	6-10	11-20	21-30	31-40	>40
Angelfish						
French						
Gray						
Rock Beauty						
Queen						
Butterflyfish						
Foureye						
Banded						
Spotfin						
Reef						
LongSnout						
Grunt						
Porkfish						
White						
Bluestriped						
French						
Tomtate						
Smallmouth						
Caesar						
Spanish						
Sailors Choice						
Margate						
Parrotfish						
Stoplight (IP)						
Stoplight (TP)						
Redfin (IP)						
Redfin (TP)						
Redband (IP)						
Redband (TP)						
Princess (IP)						
Princess (TP)						
Striped (IP)						
Striped (TP)						
Queen (IP)						
Queen (TP)						
Redtail (IP)						
Redtail (TP)						
Midnight						
Rainbow						
Greenblotch						
Blue						
Porgy						
Jolthead						
Sheepshead						
Saucereye						
Moray eel						
Lionfish						

Name/Buddy:			**Dive No:**			
	0-5	6-10	11-20	21-30	31-40	>40
Seabass						
Tiger						
Red Hind						
Graysby						
Nassau						
Black						
Rock Hind						
Coney						
Yellowfin						
Yellowmouth						
Snapper						
Schoolmaster						
Gray						
Mahogany						
Yellowtail						
Lane						
Cubera						
Mutton						
Dog						
Surgeonfish						
Ocean Surgeon						
Doctorfish						
Blue Tang						
Queen Trigger						
Black Durgon						
Whitespot file						
Scrawled filefish						
Orangespot File						
Chub						
Yellowtail Damsel						
3spot Damsel						
Spanish Hogfish						
Barracuda						
Bar Jack						
Blue Runner						
Hogfish						
Slippery dick						
Yellowhead wrasse						
Puddingwife						
Porcupine						
Baloonfish						
Burrfish						
Cowfish						
Trunkfish						
Bar jack						
Permit						
Other						

Appendix 4

Caribbean 2010 Resilience Assessments. *6) Site resilience observations*

Date: *Site:* *Collector:*

	Variable	**#**	***Comments***
1-Cover	H/S Coral cover		
	Fleshy Algae		
	Turf/sediment		
	Turf algae		
	CCA		
	Cyanobacteria		
	Hardground		
	Rubble		
	Sediment		
	Sponge		
2. Physical attributes	Topographic complexity - micro		
	Topographic complexity -		
	Sediment texture		
	Sediment layer		
	Temperature		
	water movement		
	deep water (30-50m)		
	depth of reef base		
	wave energy/ exposure		
	depth (m)		
	aspect		
	slope (degrees)		
	phys. shading		
	canopy corals		
	Visibility (m)		
	Exposed low tide		
	Ponding/pooling		
5-Anthropogenic	Nutrient input		
	Development		
	Pollution (chem)		
	Pollution (solid)		
	Turbidity/Sedimen		
	Physical damage		
	Fishing pressure		
	Destructive fishing		
	Other		

Site	*Description, sketch, etc.*		
	Lionfish		
	Diadema		
	Lobster		
3-Bleaching/Mortality	Bleaching		
	Mortality-new		
	Mortality-old		
	Recovery-old		
	Coral disease		
4-Coral associates	Obligate feeders		
	Branching residents		
	Competitor		
	Bioeroders (external)		
	Bioeroders (internal)		
	Corallivores (negative)		
	Recruits/m2		
3- Coral Gene	*Largest corals*		
	Other		

Dom/Abun/Comm/Uncomm/Rare

Acer		Dcliv		Ppor		Efas		Malc	
Apal		Dstr		Past		Mang		Mcom	
Aaga		Dlab		Pfur		Mmir		Ffra	
Alam		Mann		Pdiv		Mdec		Isin	
Aten		Mfav		Sint		Mfor		Irig	
Aga		Mfr		Sbou		Mpha		Lcuc	
Cnat		Mcav		Shya		Mfer		Mare	
Dcyl		Mmea		Ssid		Mlam			
Dstoc		Scol		Srad		Mali			