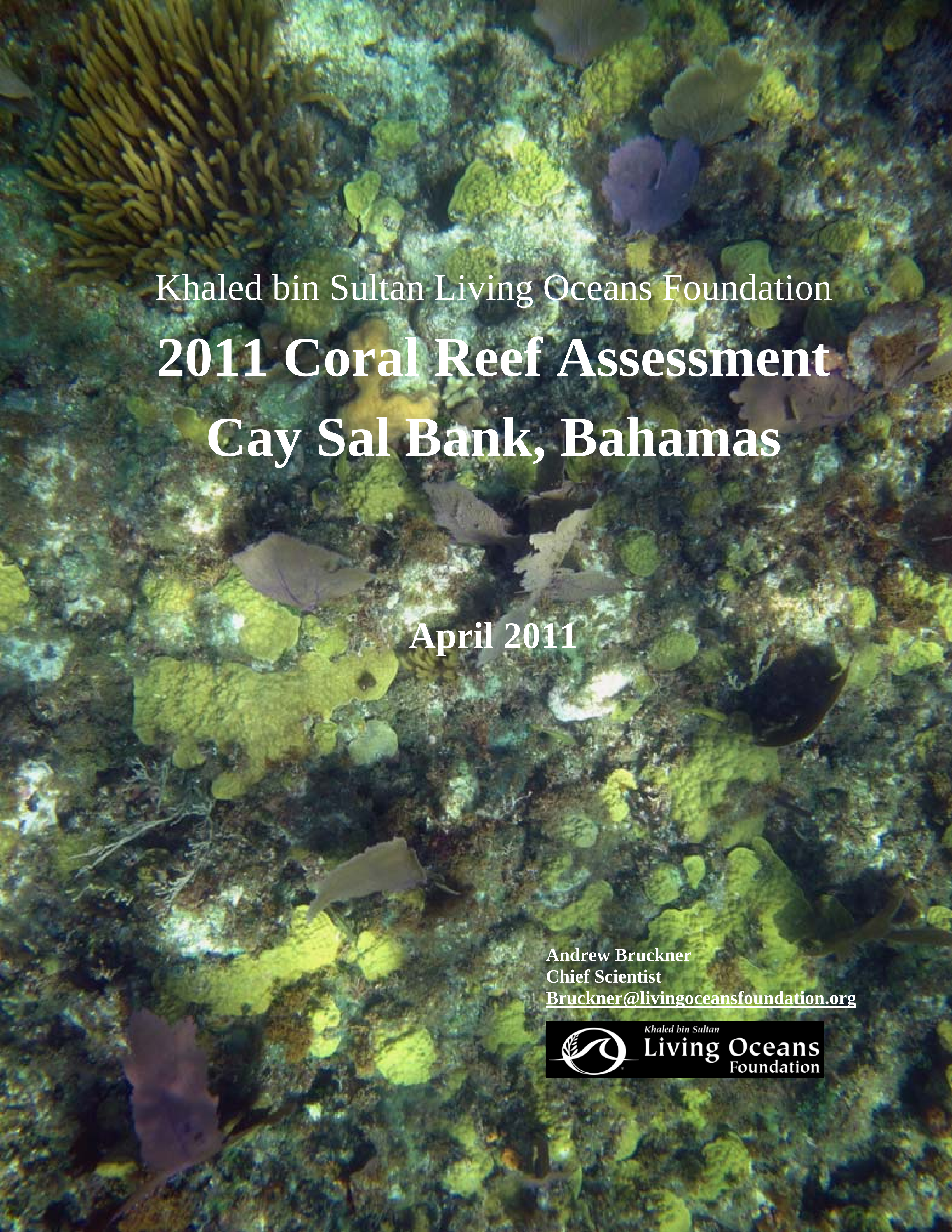

Khaled bin Sultan Living Oceans Foundation

2011 Coral Reef Assessment
Cay Sal Bank, Bahamas

April 2011

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Front cover: Photo by Andrew Bruckner

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Executive Summary

Between April 25-May 18, 2011, the Khaled bin Sultan Living Oceans Foundation (LOF) and our partners assessed the coral reefs and associated habitats of Cay Sal Bank, Bahamas. The mission encompassed 20 days at sea at 8 different anchorage locations around Cay Sal Bank. The team included LOF scientists, staff and graduate fellows, NOVA Southeastern University's National Coral Reef Institute (NCRI) scientists, Atlantic and Gulf Rapid Reef Assessment scientists and partners, and representatives from the Bahamas National Trust, Bahamas Department of Marine Resources and The Nature Conservancy, Bahamas. The ground-truthing team surveyed 684.8 miles of the Bank and collected over 1.9 million depth soundings and 565 underwater camera drops along the track to verify habitats against the satellite imagery. They also collected 79 sediment samples and ran 26 sub-bottom tracks to characterize the underlying topography of the bank. The dive team surveyed 39 unique locations around the bank, conducting a total of 508 individual SCUBA dives for a total of 22,000 minutes of submerged observations. SCUBA assessments focused on 1) characterization of the benthos including substrate type and cover and biomass of benthic organisms; 2) coral community structure, population dynamics and health; 3) fish community structure; and 4) resilience indicators including extent of herbivory, patterns of recruitment, prevalence of diseases and other stressors and patterns of coral reef recovery. Additional physical parameters including salinity, temperature and current profiles were assessed around the perimeter of the bank.

Eight benthic habitat classes were identified on Cay Sal Bank: sand flats, sparse seagrass, dense seagrass, coral bommies, patch reefs, scoured hardgrounds, shelf-edge buildups and sand shoals. Coral reef habitat types were found within the lagoon and surrounding the perimeter of the bank. Unique circular seagrass patches formed atop infilled sinkholes and around man-made structures; these contained unusually large aggregations of commercially important reef fishes.

Hardground areas capable of supporting coral reef development differed depending on location. Lagoonal sites had a mean live coral cover of 9.4% and fore reef sites had 6.5% live coral, with macroalgae covering 50-90% (mean=63%) of the bottom. Other benthic organisms included crustose coralline algae (2.6%), erect coralline algae (5%), turf algae (2.3%) and non-coral invertebrates (9.1%), with considerable variation in cover and abundance between sites. Most reef building corals were small (17.2 cm mean diameter), at a low density (3.3 corals per sq. meter) and with a low site-wide extent of partial mortality (mean = 13%). There was very little recent mortality (<1%) and only isolated cases of coral diseases affecting these species. The most abundant corals during these surveys included *S. siderea* (24%), *Agaricia agaricites* (22%) and *P. astreoides* (20%). *Acropora cervicornis* was extremely rare, being recorded as individual colonies in only two fore reef locations. *A. palmata* was also very uncommon, with isolated colonies identified around exposed land masses.

Overall, *Montastraea annularis* (complex) colonies were the largest corals found on these reefs (mean = 467 cm diameter). These species had the greatest amount of partial tissue loss (mean = 45%), and most cases live tissue was reduced to small tissue isolates with the rest of the corallum colonized by macroalgae and small brooding corals; these species made up just over 10% of all corals. These corals were formerly much more abundant and the most important framework corals on these reef, providing considerable relief and habitat for other species. While their structure is still present, larger colonies have lost most or all of their tissue throughout all shallow lagoonal and fore reef sites and mostly small colonies and tissue remnants remain. The decline of these species is

probably related to the 1998 and 2005 bleaching events and coral disease outbreaks, which has also occurred in many other locations throughout the Atlantic.

While coral diseases, aggressive invertebrates and other biotic stressors were documented, these were generally uncommon. Only isolated cases of yellow band disease and black band disease were noted. Dark spots disease was recorded on *S. siderea* and *Stephanocoenia intersepta*, which is the usual host for this disease, but in most cases there was little tissue loss associated with this condition. It was also noted on *Agaricia agaricites, Dichocoenia stokessi* and *Madracis mirabilis*, which was previously reported only from the Cayman Islands. The disease of most concern was white plague. This was present, but rare on shallow sites, while it was much more common on deeper (shelf edge) sites off the west and south, were *Montastraea faveolata* and *M. franksi* were still abundant. Many of these larger corals had prominent lesions with recent tissue loss affecting 1-10% of their surface. Another important structuring agent is the boring sponge *Cliona delitrix*. This was unusually common on *S. siderea* colonies located off the eastern end of Cay Sal, affecting up to 10% of the colonies on some reefs. It was present, but less abundant on western and southern reefs and in lagoonal sites.

Over 14,000 fish recorded in belt transects for the 68 species on the AGRRA list. The ocean surgeonfish was the most common species (12.9% of all fish), followed by the French grunt (11.2%), yellowhead wrasse (8.6%), slippery dick (8.5%, greenblotch parrotfish (7.1% and redband parrotfish (6.5%). Most fish were small (<20 cm total length). The largest fish observed were gray snapper, chubs, yellowtail snapper, barracuda, schoolmaster, and queen triggerfish, which were often 31-40 cm total length. Very few fishes were larger than 40 cm. The larger grouper species (Nassau, black, tiger, yellowmouth, yellowfin) were unusually rare (14 total of these five species seen), but all were 31 cm or larger. The mean density of fishes (all species pooled) was 68 fishes per 100 sq. m on fore reef sites and 83 fish per 100 sq. m on lagoonal sites. With exception of a few large resting schools of sailors choice, snappers and grunts observed in grassbed environments, very few large schools of fishes were noted. There was also an absence of large roving schools of surgeonfish and few larger parrotfish.

Cay Sal Bank is a remote coral reef ecosystem with low levels of human impact. It contains important nursery areas (extensive grassbeds) and both lagoonal and fore reef habitats, but mangrove communities are absent. There are many unique habitats, including proliferent coral communities surrounding the rim of blue holes, unusual coral and sponge bommies within the bank, and an extensive high coral cover (>25% cover) shallow (4-8 m depth) lagoonal sites in the southeastern end of the bank. This site, established as the first Khaled bin Sultan Legacy site formerly had extensive thickets of *A. cervicornis*, interspersed with large boulder corals (*M. faveolata, Diploria strigosa*). No remaining live *A. cervicornis* exists, however healthy boulder and brain corals were still common and much of the bottom has been colonized by plating colonies of *P. astreoides*, some of which were over 50 cm diameter. While many of the shallow fore reef sites were low-relief hardground areas with limited colonization by corals, shelf edge sites had extensive carbonate build-ups consisting of large massive and plating framework corals, intermixed with a high diversity (up to 39 species) of other corals, typical of western Atlantic reefs. Although these reefs have experienced several disturbances in the past, they appear to exhibit high resilience as 1) substrates under the macroalgae were covered in crustose coralline algae; 2) high numbers of recruits were seen including isolated *M. annularis* (complex) recruits; 3) most *M. annularis* colonies that were severely impacted by past bleaching events did not completely die; small tissue remnants are surviving and beginning to regrow; and 4) fishing pressure appears to be very low and populations of important herbivores are present.

Introduction

The Bahamas contains three major shallow (<10 m) carbonate platforms or banks, each separated by deep ocean passages, along with a number of smaller emergent land masses. The archipelago encompasses close to 15% of all shallow water coral habitats in the Tropical Western Atlantic and contains more than 700 islands overall. It extends approximately 1600 km from the Little Bahamas Bank in the northwest to Navidad Bank in the southeast, covering an area of approximately 122,000 km^2 (Trumbull 1988, Banks 1999, Sullivan Sealey and Bustamante 1999). It covers 6 degrees of latitude and 9 degrees of longitude, representing the largest shallow water bank system in the insular Caribbean/Western Atlantic. Marginal habitats such as sand, seagrass, and hard bar dominate the shallow water bank systems, while true, accreting reefs on the bank margin occupy a relatively small area overall.

Cay Sal Bank, the third largest bank in the Bahamas, is an isolated, submerged carbonate platform surrounded by deep water. It lies relatively close to the Florida Keys and Cuba, yet is remote, difficult to access and relatively unimpacted by man. Cay Sal Bank has been referred to as a drowned atoll (Agassiz 1894), although it is of a different geologic origin and is not formed around a submerged volcano. The bank is roughly triangular shape, with a base along the south rim of 105 km, a width of 66 km north-south, and a total area of over 6000 km^2 (Goldberg, 1983). Over 99% of the bank is submerged, ranging in depths from 5-16 m. There is a narrow fringe of emergent land that forms a rim around the perimeter, and surrounds a central lagoon. Land masses are comprised of small sandy vegetated islands, rocky outcrops, and lithified sand dunes. Numerous channels are found between the cays; these vary in width and depth but allow tidal exchange between the central lagoon and the oceanic waters of the outer bank margin. The outer margin is rimmed by discontinuous coral reef development.

There have been few previous studies conducted on Cay Sal Bank, The most comprehensive and recent assessment of shallow marine environments of Cay Sal was completed in 1982 (Goldberg 1982). This study combined aerial photography and in water assessments to characterize the distribution and spatial extent of various habitats and the dominant fauna. Of note, Goldberg (1983) highlighted the extensive seagrass bed communities and relatively depauperate and poorly developed reef systems. The current study, carried out by the Khaled bin Sultan Living Oceans Foundation, used Worldview2 multispectral satellite imagery and detailed groundtruthing to characterize and map shallow marine habitats. These efforts were complimented by quantitative transect surveys of coral reef habitats located within the bank and on the outer perimeter of the bank, from 7-25 m depth.

Methods

A. Study Location

Cay Sal Bank (Spanish: *Placer de los Roques*) is the third largest and the westernmost of the Bahama Banks. It is located between 23º27'N - 24º10'N and 079º25'W – 080º35'W. It is approximately 50 km from Cuba; the Nicholas Channel separates Cuba from Cay Sal Bank. The western rim of the Great Bahamas Bank, which is about 50 km away, is separated from Cay Sal by the Santaren Channel. To the north, the Straits of Florida lie between Cay Sal and the Florida Keys (USA); Key Largo is the closest land mass in the United States, located approximately 100 km from the northern tip of Cay Sal bank (Fig. 1).

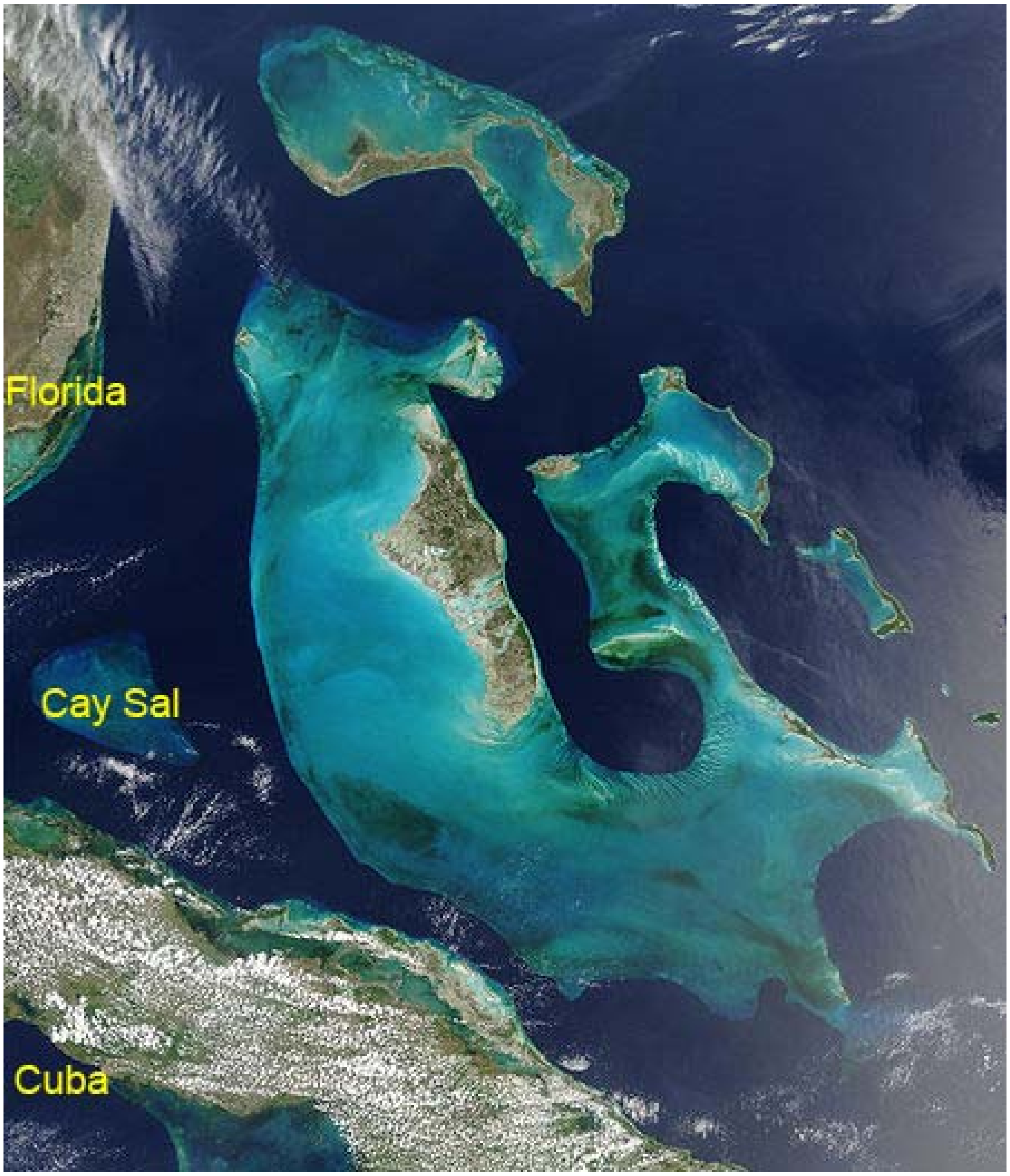


Fig. 1. Location of Cay Sal Bank.

B. Aerial Reconnaissance

All islands, rocky outcrops and shallow marine habitats were surveyed by oblique aerial photography from the Goldeneye seaplane at an altitude of 500-1000 feet. Approximately 450 aerial photographs of the major features were taken over a two hour period using a NIKON D700 DSLR with a 15-300 mm lens (Bruckner), NIKON D700 DSLR and a 60 mm lens (Renaud), and a Canon GS 11 point and shoot camera (Purkis). Key features of the bank were identified using georeferenced satellite imagery which was displayed in real time on a laptop computer as the plane navigated over the bank. A portion of the bank at the southwest end was avoided because it was in Cuban airspace.

C. Groundtruthing methods

Satellite imagery

Worldview-2 (WV2) satellite imagery provided an aerial overview of the study area, and the images were used for mission planning and navigation during data collection. DigitalGlobe delivered the WV2 scenes with geometric corrections, 11-bit digital numbers (DN), and a nearest-neighbor resample kernel. The satellite images had a spatial resolution of 2-m by 2-m (i.e., each pixel covers a 4-m^2 area), and they contained eight broad spectral bands, compared to the 4 spectral bands on Quickbird, IKONOS, and Landsat. Due to rapid light attenuation by water, the satellite was limited in the depths for which it could observe the seafloor. In the clearest waters, observations up to depths of 45 m are possible. However, satellite observations were generally limited to a depth of 25 m during the field campaign due to turbidity. The fine spatial resolution of the images allowed seafloor features, such as reef structures, seagrass meadows, and sand flats, to be identified prior to surveying of an area. This informed the dive teams' sampling site selection. The ground-truth team used the scenes in conjunction with a differential GPS device (dGPS) to navigate to landscape features of interest. The team gathered depth soundings and benthic video at these points (the methods for both are described below). The satellite imagery will be used in conjunction with image processing and feature extraction software to create the bathymetric and benthic habitat maps.

Benthic Video

An underwater video camera attached to a cable (hereto after referred to as a drop-cam) gathered video on the benthic composition at each survey site. At these points, the drop-cam was held from the survey boat enabling it to 'fly' along the sea floor as it recorded video for 15 to 60 seconds. The video was recorded to hard-disk on a laptop aboard the survey vessel in real-time, and the geographic position, time, date, boat heading, and boat speed were also recorded and burned into the video. The geopositional data were acquired by a Garmin handheld GPS device with a horizontal accuracy of approximately ±5 m. Drop-cam deployment was limited to depths above 40 m due to the limited length of the tether cable (50 m). The acquired videos will be used in the creation of the benthic habitat maps by providing the necessary information for developing the habitat classification scheme and training of classification models.

Acoustic depth soundings

Depth soundings were gathered along transects between survey sites using Hydrobox, a single-beam acoustic transducer, developed by Syqwest. The instrument emitted 3 pings per second. Depths are estimated based on the time the return-pulse's reaches the sounder's head. The depth estimates were recorded by the Hydrobox software on a field laptop aboard the survey vessel. Geopositional data were simultaneously acquired by a dGPS unit and recorded in the bathymetric file. The soundings will be used to train a water-depth derivation model, which is based on the spectral attenuation of light in the water column, that will be applied to the WV2 satellite imagery. The final topographic map will have the same spatial resolution as the satellite imagery.

Acoustic sub-bottom

Profiles of the seafloor's sub-bottom was gathered along transects using the Stratabox acoustic sounder, also developed by Syqwest. Similar to the bathymetric soundings, the sub-bottom profile emits an acoustic ping which reflects off the seafloor. However, the pulse has a lower frequency (3.5 Khz) enabling it to penetrate the seafloor. The instrument provides observations on stratal geometry beneath the seafloor along the transect lines, allowing estimates of Holocene reef-growth and sediment accumulation to be made. Geopositional data for each ping was simultaneously acquired by dGPS unit; it was recorded in the SEGY file. Profiles were run shore-perpendicular to capture the geometry of the bank flanks and span a depth range of 300 m to 5 m. Total transect length varies with the slope's angle; steeper slopes resulted in shorter transect lines.

D. SCUBA survey Techniques

Coral, fish and algae community structure were examined in 39 locations using photographic transects, point intercept surveys, belt transects, quadrats and photo-documentation of individual organisms or features (Table 1; Fig. 2). 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. Additional roving diver REEF surveys were conducted to assess total fish diversity. 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 tables the four letter CARICOMP abbreviation (first letter refers to genus; next three letters refer to species) was used for coral.

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). Recruits were divided into two categories: corals up to 2 cm diameter and larger corals, 2-3.9 cm diameter. 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.

Condition of corals

Visual estimates of tissue loss was recorded for each colony over 4 cm in diameter using a 1 m bar marked in 1 cm increments for scale,. If the coral exhibited tissue loss, estimates of the amount of remaining tissue, percent that recently died and percent that died long ago were made based on 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). For each coral with partial or whole colony mortality, the cause of mortality was 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*). All *C. abbreviata* snails were collected from corals and brought on board the Golden Shadow for measurements (maximum length and sex). Lesions were initially 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.

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 and recorded as live, bleached, recently dead or long dead.. Gorgonians are recorded as sea fan or branching/encrusting gorgonian. Sponges were differentiated into crustose, rope, massive, tube and barrel sponges, unless identification was possible. Algae were divided into five functional groups (fleshy macroalgae, erect coralline algae, crustose coralline algae, turf algae, cyanobacteria) with certain dominant taxa recorded to genus (e.g. *Microdictyon, Lobophora, Dictyota, Stypopodium, Sargassum, Peyssonnelia*).

Nuisance invertebrate species were recorded to genus or higher taxonomic level; these 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.

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.

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.

SCUBA assessment analysis

Data from the SCUBA survey sites were initially examined as an aggregate dataset (all sites except 34), and then by fore reef and lagoonal sites. Survey locations were then divided into 9 distinct sectors, based on location, depth and unique attributes of the site. This included: 1) southeast fore reef sites (site 4,5, 36-39); 2) east fore reef sites (sites 1-19 except 10, 11 and 14); 3) blue hole (site 10); 4) northern lagoonal sites (site 11, 20, 21); 5) Legacy site (site 14); 6) shallow northwest fore reef sites (site 22-24); 7) western fore sites (site 25-33); 8) sponge bommies (site 34); and 9) western lagoonal site (site 35).

Table 1. Location of 39 sites assessed on Cay Sal Bank using SCUBA.

Long_W	Lat_N	Site	Name	Date	Depth (m)
79.570550	23.555210	1	Cay Sal 1, Anguilla Cays 1	4/28/2011	7.5
79.592820	23.580890	2	Cay Sal 2, Anguilla Cays 2	4/28/2011	11.0
79.602980	23.590690	3	Cay Sal 3, Anguilla Cays 3	4/28/2011	8.0
79.574600	23.424040	4	Cay Sal 4	4/29/2011	14.0
79.650460	23.430120	5	Cay Sal 5	4/29/2011	13.0
79.613550	23.606390	6	Cay Sal 6, Anguilla Cays 4	4/29/2011	9.5
79.681910	23.745190	7	Cay Sal 7	4/30/2011	15.0
79.655290	23.692570	8	Cay Sal 8	4/30/2011	14.5
79.610620	23.649300	9	Cay Sal 9	4/30/2011	13.5
79.804160	23.863820	10	Cay Sal 10, Blue Hole 1	5/1/2011	10.0
79.809580	23.896960	11	Cay Sal 11, Damas Cays 1, Anchor 2	5/3/2011	10.8
79.743580	23.837940	12	Cay Sal 12, Damas Cays 2	5/4/2011	14.0
79.729930	23.814050	13	Cay Sal 13, Damas Cays 3	5/4/2011	15.0
79.950850	23.722300	14	Cay Sal 14, inner reef	5/4/2011	4.2
79.803330	23.865000	10	Cay Sal 10, Blue Hole 1	5/4/2011	10.0
79.802620	24.011540	15	Cay Sal 15, Dog Rocks 1	5/5/2011	13.0
79.791110	23.958700	16	Cay Sal 16	5/5/2011	17.6
79.763730	23.887320	17	Cay Sal 17, Damas Cays 4	5/5/2011	13.8
79.804560	23.864170	10	Cay Sal 10, Blue Hole 1	5/7/2011	11.0
79.812130	24.011950	18	Cay Sal 18, Dog Rocks 2	5/8/2011	13.5
79.807270	23.990490	19	Cay Sal 19	5/8/2011	11.5
79.954610	24.038410	20	Cay Sal 20, Dog Rocks 3	5/8/2011	13.0
79.954830	24.038910	20	Cay Sal 20, Dog Rocks 3	5/9/2011	12.0
79.960500	24.046080	21	Cay Sal 21, Dog Rocks 4	5/9/2011	13.0
80.115080	24.046640	22	Cay Sal 22, Dead Man's Cays 1	5/9/2011	10.5
80.385220	23.968980	23	Cay Sal 23, Elbow Cays 1	5/10/2011	13.0
80.301270	24.007870	24	Cay Sal 24, Elbow Cays 2	5/10/2011	9.0
80.48680	23.91085	25	Cay Sal 25, Elbow Cays 3	5/11/2011	17.0
80.47313	23.93244	26	Cay Sal 26, Elbow Cays 4	5/11/2011	14.5
80.44592	23.95722	27	Cay Sal 27, Elbow Cays 5	5/11/2011	10.0
80.47625	23.92997	28	Cay Sal 28, Elbow Cays 6	5/12/2011	16.0
80.49263	23.85814	29	Cay Sal 29	5/12/2011	13.8
80.477650	23.778630	30	Cay Sal 30, Rampidas Reef 1	5/13/2011	25.0
80.47932	23.79921	31	Cay Sal 31, Rampidas Reef 2	5/13/2011	14.0
80.47852	23.81126	32	Cay Sal 32, Rampidas Reef 3	5/13/2011	13.0
80.40205	23.68629	33	Cay Sal 33, Cay Sal Island	5/14/2011	17.0
80.272320	23.785840	34	Cay Sal 34, inner bommies	5/14/2011	9.0
80.18733	23.64939	35	Cay Sal 35	5/15/2011	7.0
79.89154	23.49485	36	Cay Sal 36, southern escarpment	5/15/2011	13.0
79.851940	23.483460	37	Cay Sal 37, southern escarpment	5/15/2011	13.0
79.87989	23.49066	38	Cay Sal 38, southern wall	5/16/2011	25.0
79.8853	23.49395	39	Cay Sal 39, Anchor 8	5/16/2011	16.0

Results

A. Aerial reconnaissance

On March 24, 2011, an aerial assessment of the bank was conducted using the Goldeneye Seaplane (Fig. 2). The surveys identified habitat features of interest that were examined in detail during the research mission. The seaplane ran a track through the center of the bank and around the perimeter to identify locations of grassbeds, hardground areas, sand shoals, and reef habitats. During these assessments, an extensive spur and groove reef system was noted along nearly the entire eastern margin and half of the southwest perimeter of the bank. Shallow patch reef communities were observed near many of the emergent land masses, although much of the habitat close to land appeared to be relatively flat with minimal high-relief reef habitat. Deeper reef habitats were observed along the perimeter, northwest of Cay Sal island and extending to Elbow Cays.. Multiple circular sink holes, shoals of sea grass and lagoonal hardground patches were observed within the bank. An extensive area of sand, originally thought to be ooid sand shoals, was later determined to be moving sand waves of biological origin and not oolites.

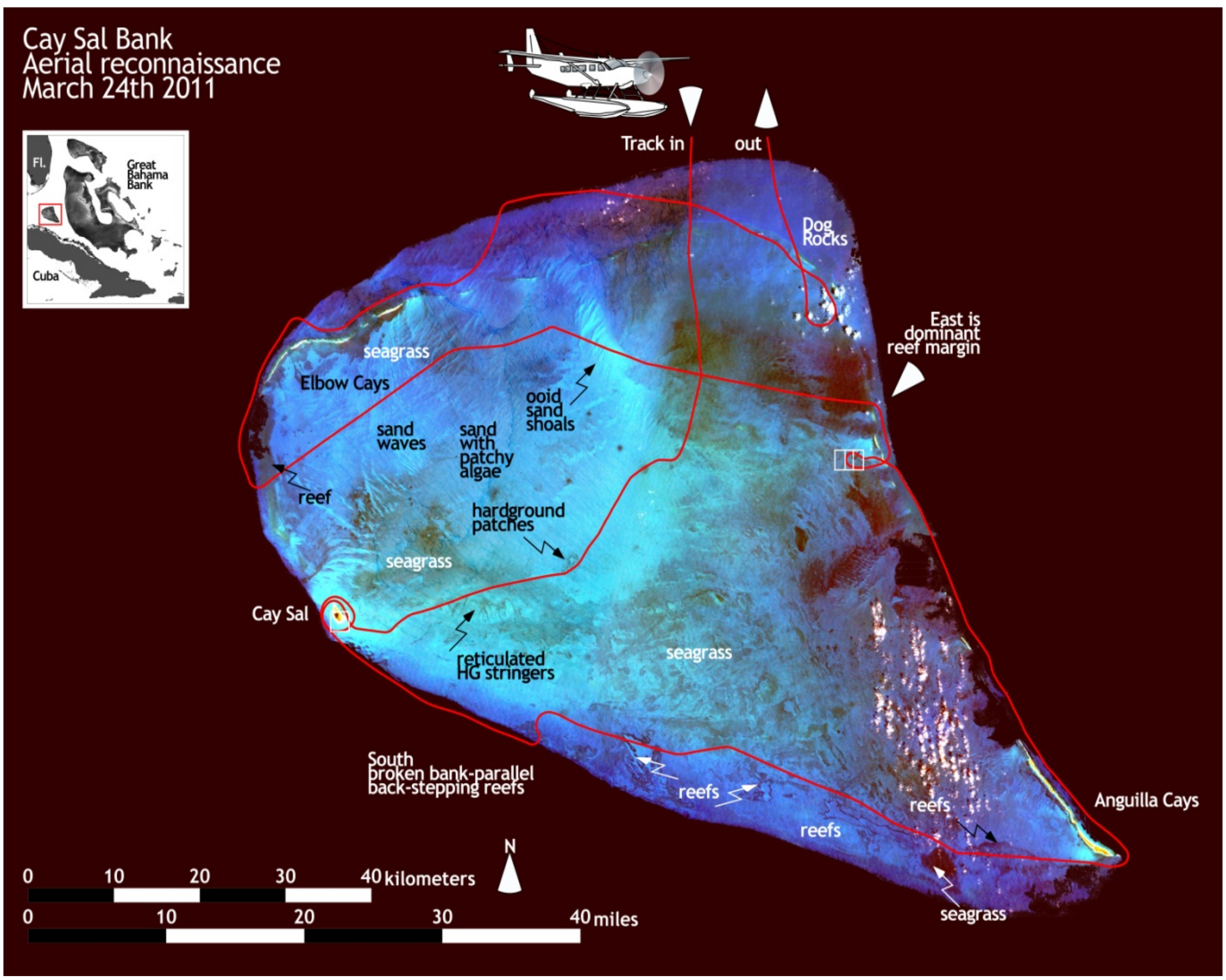


Fig. 2. Track of the Goldeneye Seaplane during aerial reconnaissance of the site, 03/24/2011.

B. Groundtruthing

Habitat types

The groundtruthing team covered a total distance of over 1100 km from depths of 0.50 m to 137.6 m to obtain detailed information on the characteristics of the shallow marine habitats. Sand flats, sparse seagrass, dense seagrass, sand with coral bommies, patch reefs, scoured hardgrounds, shelf-edge build-ups, and sand shoals were identified as benthic habitat classes. They identified numerous sink holes, blue holes that extended to over 100 m in depth, perfectly circular seagrass beds that formed on top of sediment-filled blue holes and around man-made objects such as ship wrecks, aircraft and abandoned oil exploration equipment, scoured hardground areas, and moving sand waves. Of particular interest are the profiles crossing over the sink holes. The profiles clearly show the plunging walls of the holes and the sediment in-fill that has been deposited in the hole (Fig. 4). In some cases, the sediment has reached the rim of the hole, and a layer of dense seagrass 'caps' the hole. Another important observation is the occurrence of circular seagrass beds with an iris in the middle. In three cases, man-made debris (e.g., a crashed airplane, a ship wreck) was present in the iris with a high fish biomass aggregating around the debris. These patches also appeared circular in the satellite imagery. In addition to classic western Atlantic spur-and-groove reef systems that have developed around the outer portions of the bank, unusual coral and sponge patches occurred within the bank, each differing in structure and species assemblages. One particularly intriguing area, at depths of 7-8 m, consisted of small coral bommies with many species of reef building corals and dense, colorful sponge assemblages. These sponges consist easily of over 50 different species, forming twisted ropes, fluorescent blue and yellow tubes, barrels, bright orange crusts, erect branches and vase-shaped structures intertwined with tree-like soft corals and massive and plating stony corals.

Table 2. Number of samples taken by the groundtruthing team.

Parameter	Number
Linear distance traveled:	1102.1 km(684.8 m)
Drop camera videos	565 videos (typically 30 to 60 seconds long; up to 2 minutes for unique features
Sediment samples	79
Bathymetric points along tracks:	1,908,173
sub-bottom profile tracks	26

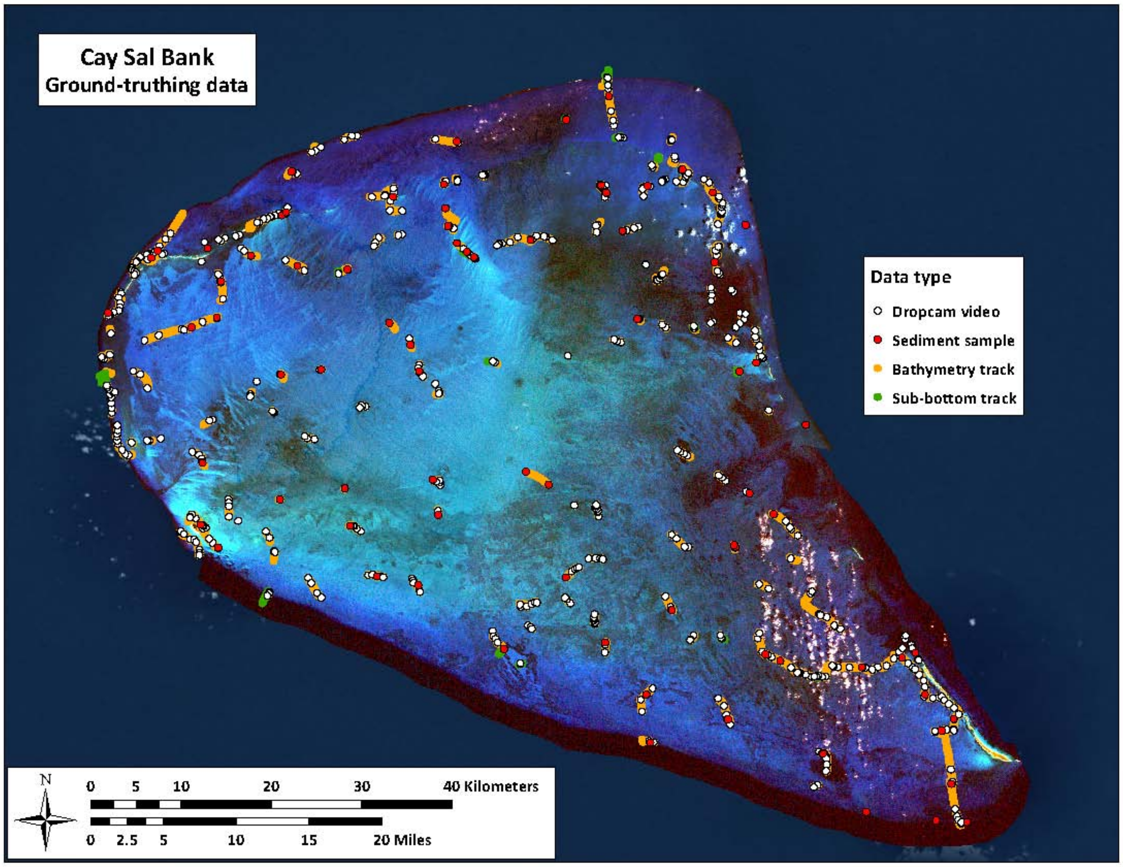


Fig. 3. Survey track of the groundtruthing team. Continuous bathymetry (yellow dots) was run along the entire track. Locations of Sediment samples (red dots), drop camera videos (open circles) and sub-bottom profiles (green dots) are superimposed onto this track.

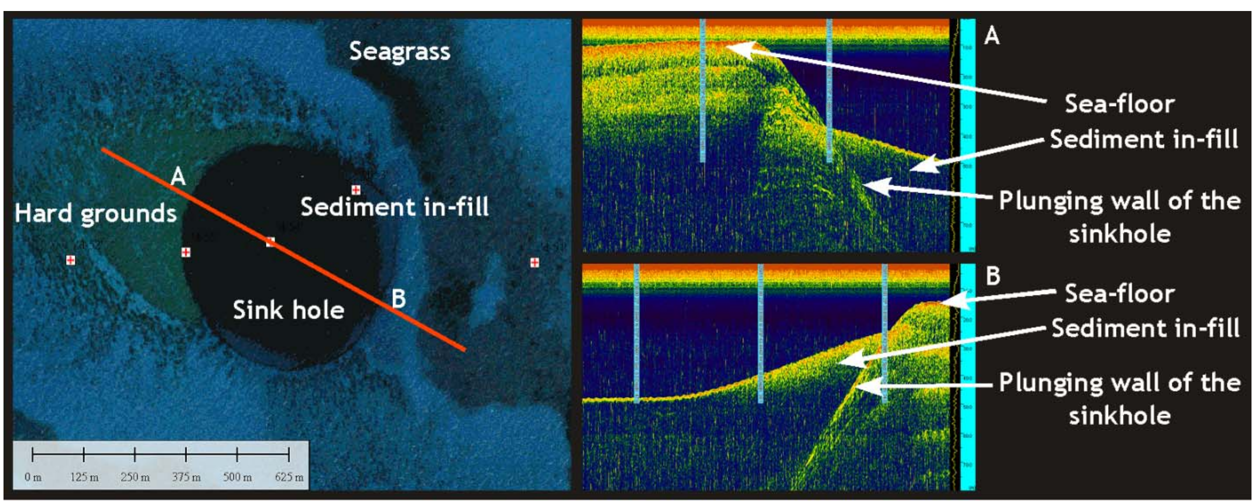


Fig. 4. Example of a sub-bottom profile over a sinkhole in Cay Sal Bank. The profile shows both the wall and sediment that has been deposited into the hole. The hole is gradually filled to the rim by the sediment.

C. SCUBA Assessments

The research team examined the coral reef community composition in 39 locations of which 31 were fore reef sites and 8 were lagoonal sites (Fig. 5). The sites ranged in depth from 7-25 m (Table 1). The team examined the benthic composition and cover, coral population structure and condition, and fish composition, size structure and biomass.

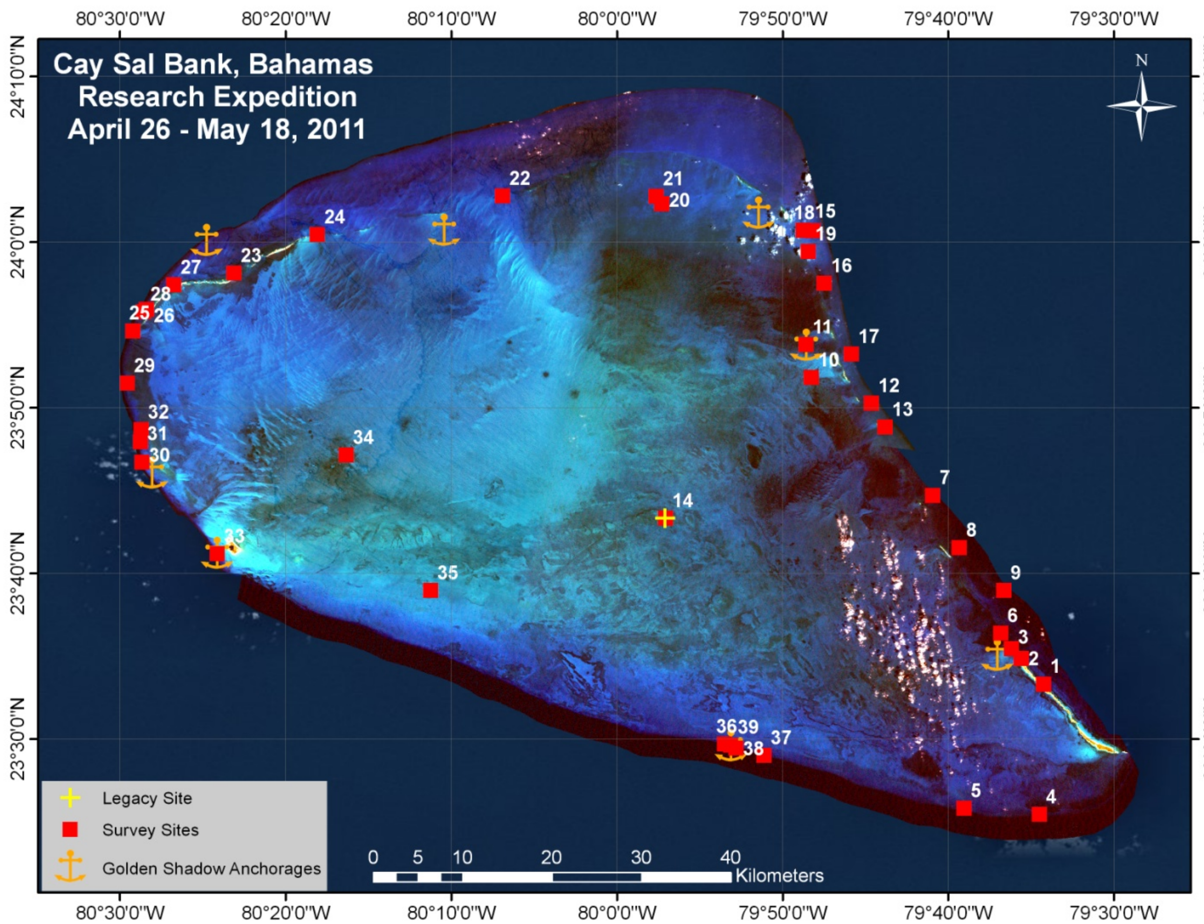


Fig. 5. Location of SCUBA assessments on Cay Sal Bank.

Benthic assemblages

Hardground areas that are capable of supporting living corals were dominated in most locations by fleshy macroalgae, which covered from 50-90% of the bottom in all but two lagoonal reef environments. Figure 6 shows the variation in cover of macroalgae among fore reef sites and figure 8 shows macroalgal cover for lagoonal sites. All sites exhibited a predominance of the green *Microdictyon* spp., brown ruffled *Lobophora* algae and *Sargassum*. *Microdictyon* was less common in lagoonal sites while *Lobophora* predominated and often formed accumulations 10-30 cm thick in sandy areas between the reef structure. Other types of algae occurred at moderately low cover, including crustose coralline algae (mean cover on all fore reef sites = 3.2 %, lagoonal reefs = 1.4), turf algae (fore reef = 2.4%, lagoonal reefs = 1.6%), erect coralline algae (fore reef= 6.6%, lagoonal reefs = 4.2%), and cyanobacteria (0.3%), with considerable variation between sites. Cover of crustose coralline algae (CCA), turf algae (TA), erect coralline algae (CMA) and cyanobacteria (CYA) are shown for each site as a series of stacked bars for the fore reef locations (Fig. 7) and lagoonal sites (Fig. 9). Site 15 had significantly higher cover of turf algae than all other sites (18.2%), while site 38 and 39 had the highest cover of CCA >8.5%). Although macroalgae was the dominant organisms covering the bottom, crustose coralline algae was also a dominant component. Benthic point intercept surveys under-represent total CCA cover because they do not take into account the CCA found beneath the macroalgae (see recruitment, below). Site 3, 8, 33 and 38 all had prominent cyanobacterial mats on soft bottom substrates and cyanobacteria covered > 1% of the hardground areas assessed with quantitative transects.

Coral cover was relatively low throughout all habitats (mean cover on all fore reef sites = 6.5% and lagoonal sites = 9.4%). More than half the fore reef sites (n=17) had less than 5% live coral cover, while 2 of the 8 lagoonal reef sites had < 5% live coral cover (Figs. 6 and 8). The highest cover overall was observed on deeper shelf edge reefs and the Legacy site within the lagoon. Other encrusting and erect sessile invertebrates occupied over 9% the bottom, with slightly higher cover on fore reef sites (9.6% vs 9.2%) and slightly higher cover of aggressive invertebrates (nuisance species like clionid sponges) on lagoonal reefs (1.3% vs.0.7%). Although aggressive invertebrates were relatively uncommon in the point intercept surveys, one species of *Cliona* (*C. delitrix*) was abnormally abundant on the northern sites, primarily occurring on *Siderastrea siderea* colonies.

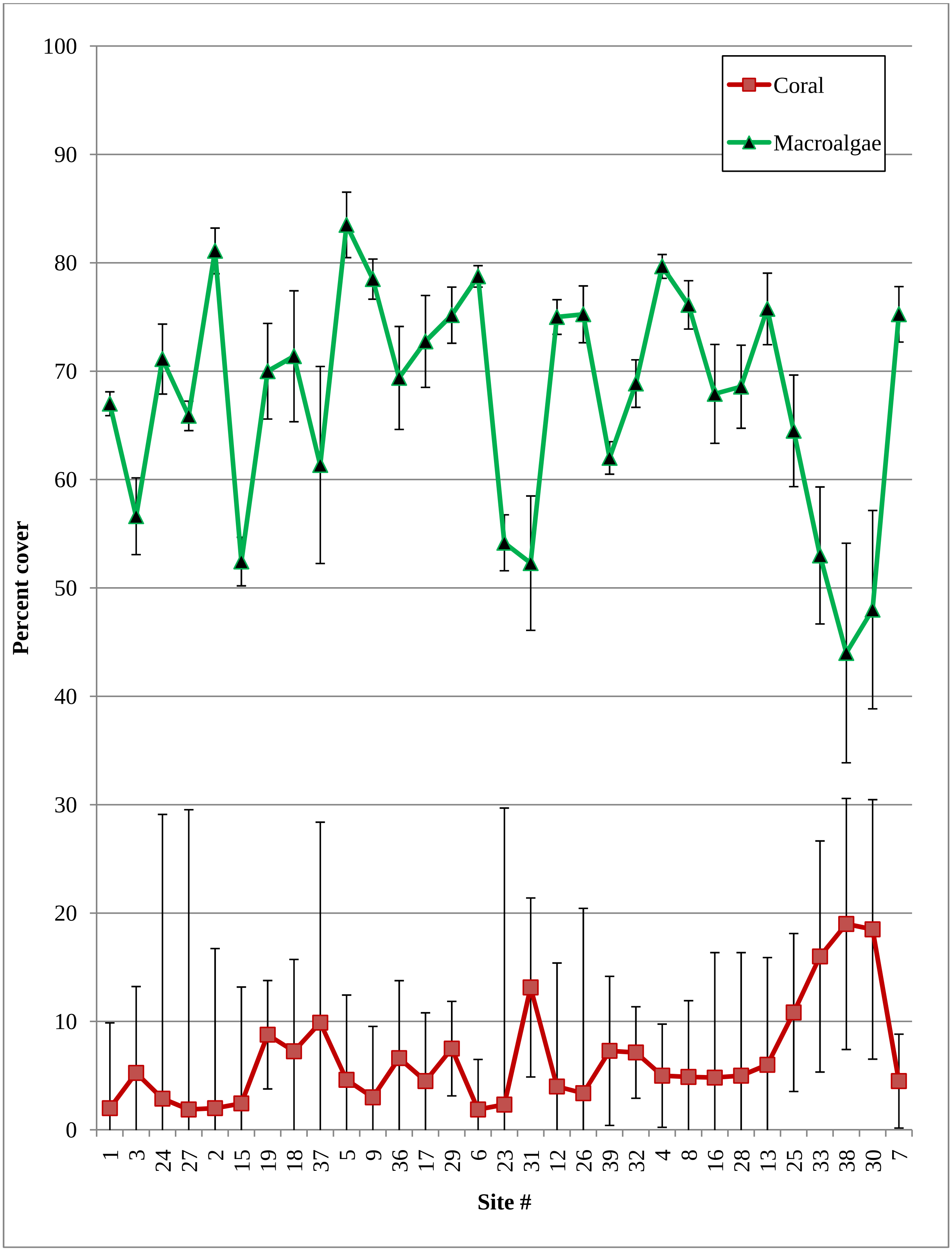


Fig. 6. Benthic cover of fleshy macroalgae (green) and live coral (red) at fore reef sites in Cay Sal, Bahamas. Sites are listed from the shallowest to deepest.

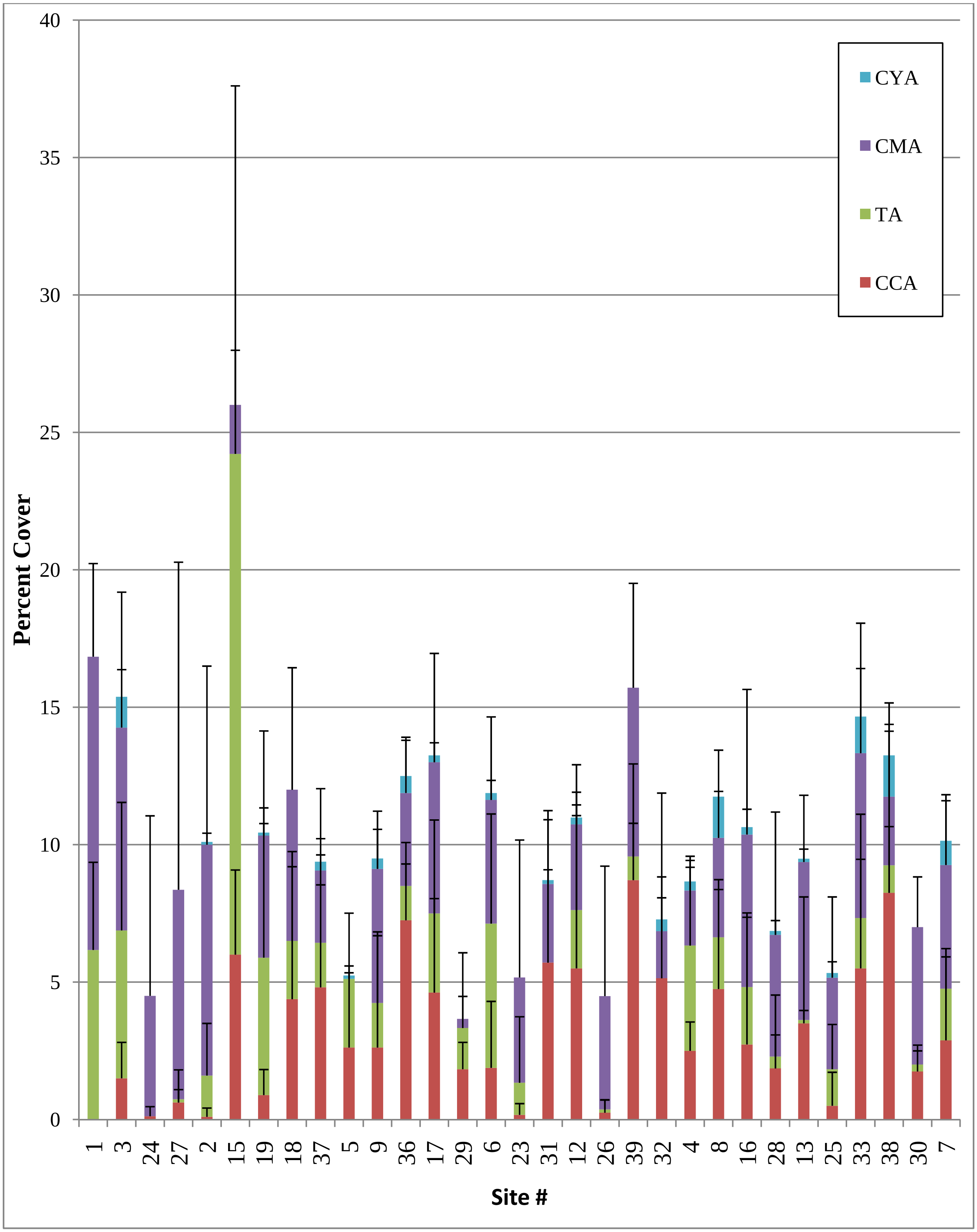


Fig. 7. Cover of crustose coralline algae (CCA), turf algae (TA), erect coralline algae (CMA) and cyanobacteria (CYA) on fore reef locations at Cay Sal, Bahamas. Sites are shown from shallowest (site 1) to deepest (site 7).

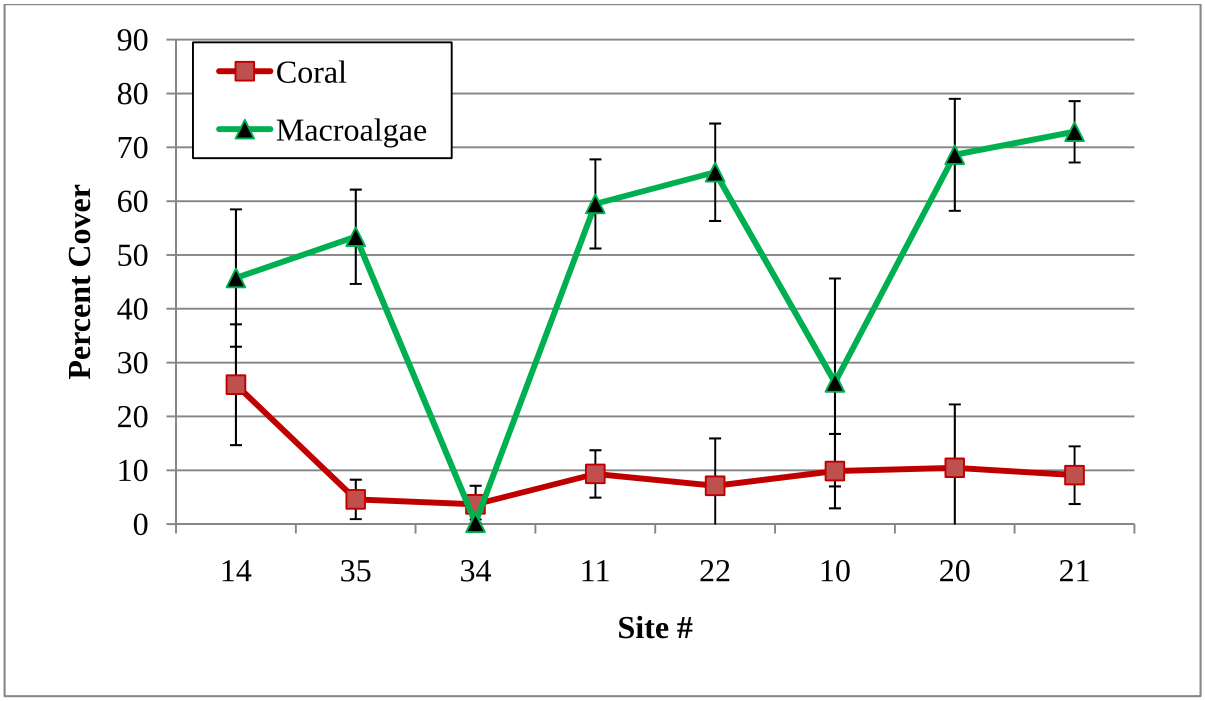


Fig. 8. Benthic cover of coral (red) and fleshy macroalgae (green) within lagoonal sites on Cay Sal, Bahamas. Sites are listed from shallow to deep.

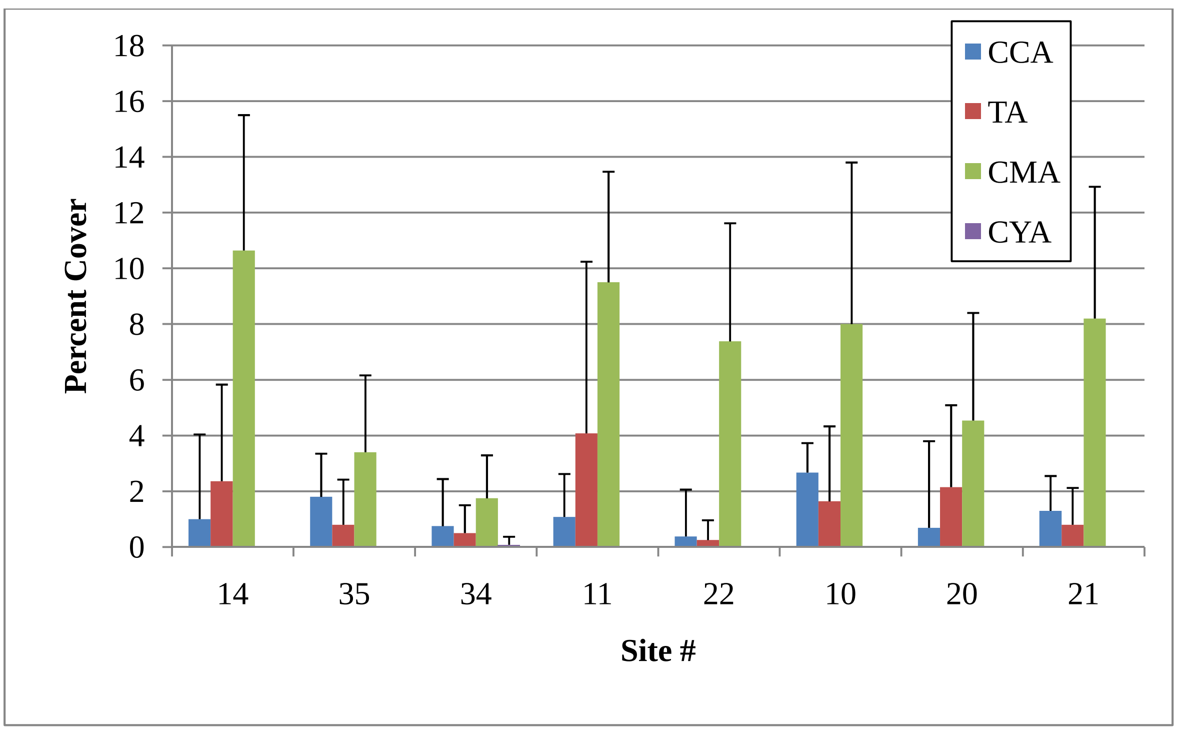


Fig. 9. Cover of crustose coralline algae (CCA), turf algae (TA), erect coralline algae (CMA) and cyanobacteria (CYA) on lagoonal reef locations at Cay Sal, Bahamas. Sites are shown from shallowest (site 14) to deepest (site 21).

Coral assessments

During April and May 2011 a total of 152.5 belt transects, each 10 m X 1 m in length were completed at 38 sites with additional assessments done on an inner lagoonal sites (#34, coral bommies) and within a 10 m X 10 m legacy site (site 14).

A. **Coral composition.** The belt transects contained a total of 4586 corals that were 4 cm or larger in diameter. The transects contained 30 scleractinian coral species and two hydrozoan corals with 5 additional species recorded outside of the transect areas. The dominant corals, in terms of abundance were *S. siderea* (24% of all corals 4 cm or larger), *Agaricia agaricites* (22%) and *Porites astreoides* (20%). Just over 10% of all corals were in the *Montastraea annularis* complex, most of which were *M. faveolata* (7.5% of all corals). Other dominant corals included *M. cavernosa* (6%), *P. porites* (5.2%) and *Stephanocoenia intersepta (*2.8%). All other species made up less than 1.5% of the population each (Fig. 10).
B. **Coral density.** The number of corals ranged from a minimum of 0.5 to 12 corals per square meter with a site-wide mean of 3.3 corals/m^2. A total of 10 out of 38 sites had less than 2 corals/ m^2 while 20 sites had 2-5 corals/m^2. Higher densities 6-12 corals/m^2) were recorded at 8 sites (Fig. 11).
C. **Coral size structure.** Most corals observed on these reefs were small (mean size of all corals 17.2 cm diameter, sd=18.4 and 9.9 cm in height, sd=14.3). The smallest corals were found at site 35 (9.2 cm diameter, 5.2 cm height) while the largest were at site 38 (36.7 cm diameter, 25.8 cm height). Overall corals at 17 sites had a mean diameter of < 15 cm while the mean diameter of corals at 11 sites was over 20 cm (Fig.12). There was a weak but significant correlation between colony size and density of corals (r^2= 0.11, p=0.044).
D. **Partial mortality.** In general, the amount of partial mortality observed on corals was very low. Living corals observed within transects were missing a mean of 4-21% of their tissue with a mean site-wide mortality (all sites and corals are pooled) of 13%. Mean partial mortality at 9 sites was <10% while corals from 15 sites were missing >15% of their tissue (Fig. 13). There was a weak, but significant positive correlation between colony size and amount of partial mortality (r^2= 0.14, p=0.02). In contrast, there was no correlation between colony density and amount of partial mortality (r^2= 0.02, p=0.34).

   In general, the amount of recent mortality when all species were pooled was low (<1%) and most of the partial mortality recorded was classified as old mortality (occurring more than one month prior to surveys), although recent (occurring within the last 5 days) and transitional (occurring within the last 6-29 days) mortality exceeded 1% on 10 sites with a maximum of 2.1% at site 6.

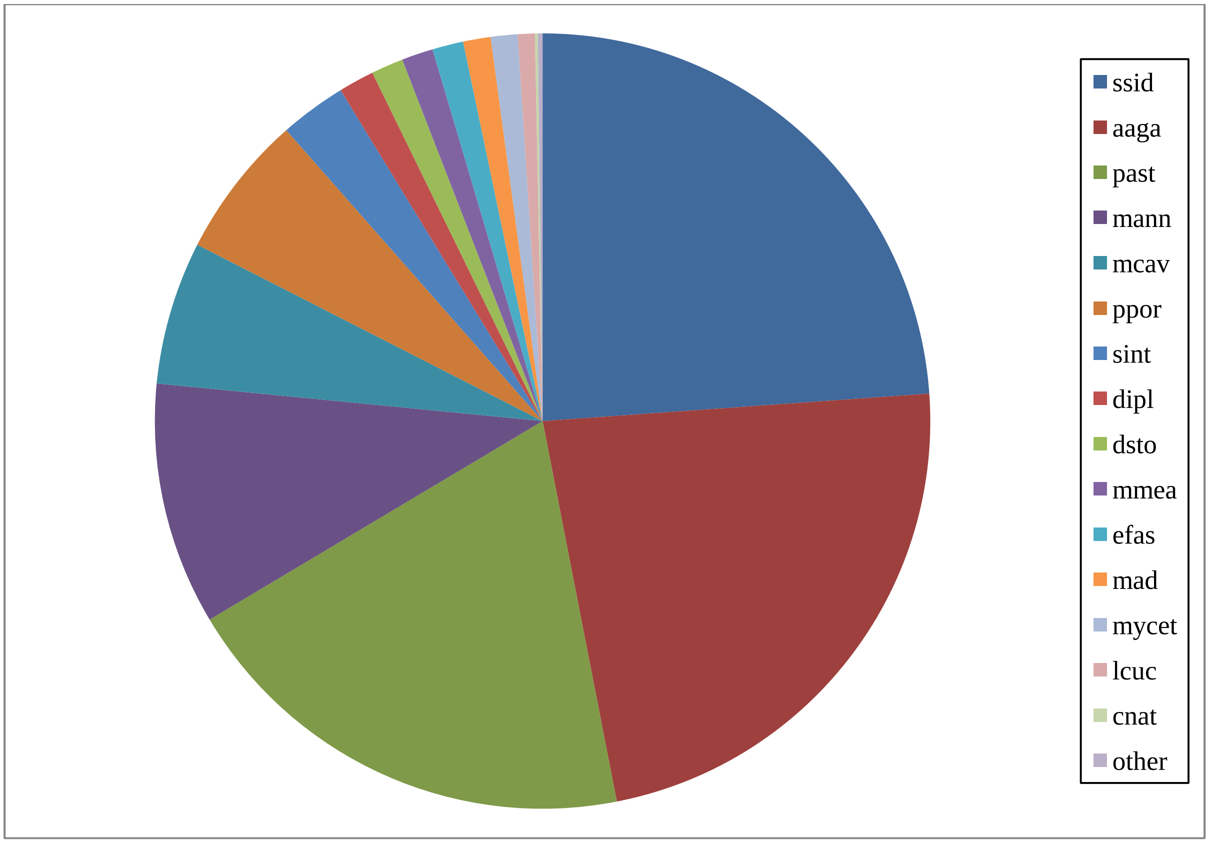


Fig. 10. Abundance of reef building corals within belt transects conducted on reefs off Cay Sal, Bahamas. Corals from site 34 are not included.

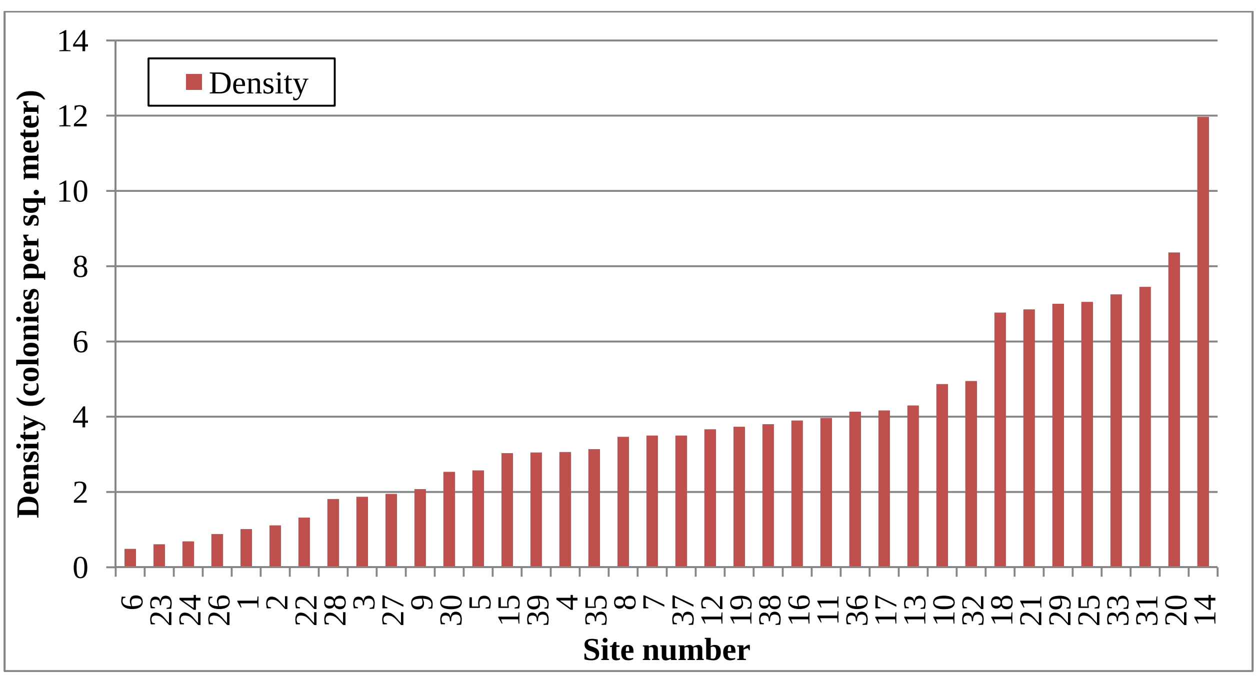


Fig. 11. Density of corals (No. colonies/m^2) observed within belt transects on Cay Sal reefs, Bahamas. Sites are listed from lowest to highest density; site 34 is not included.

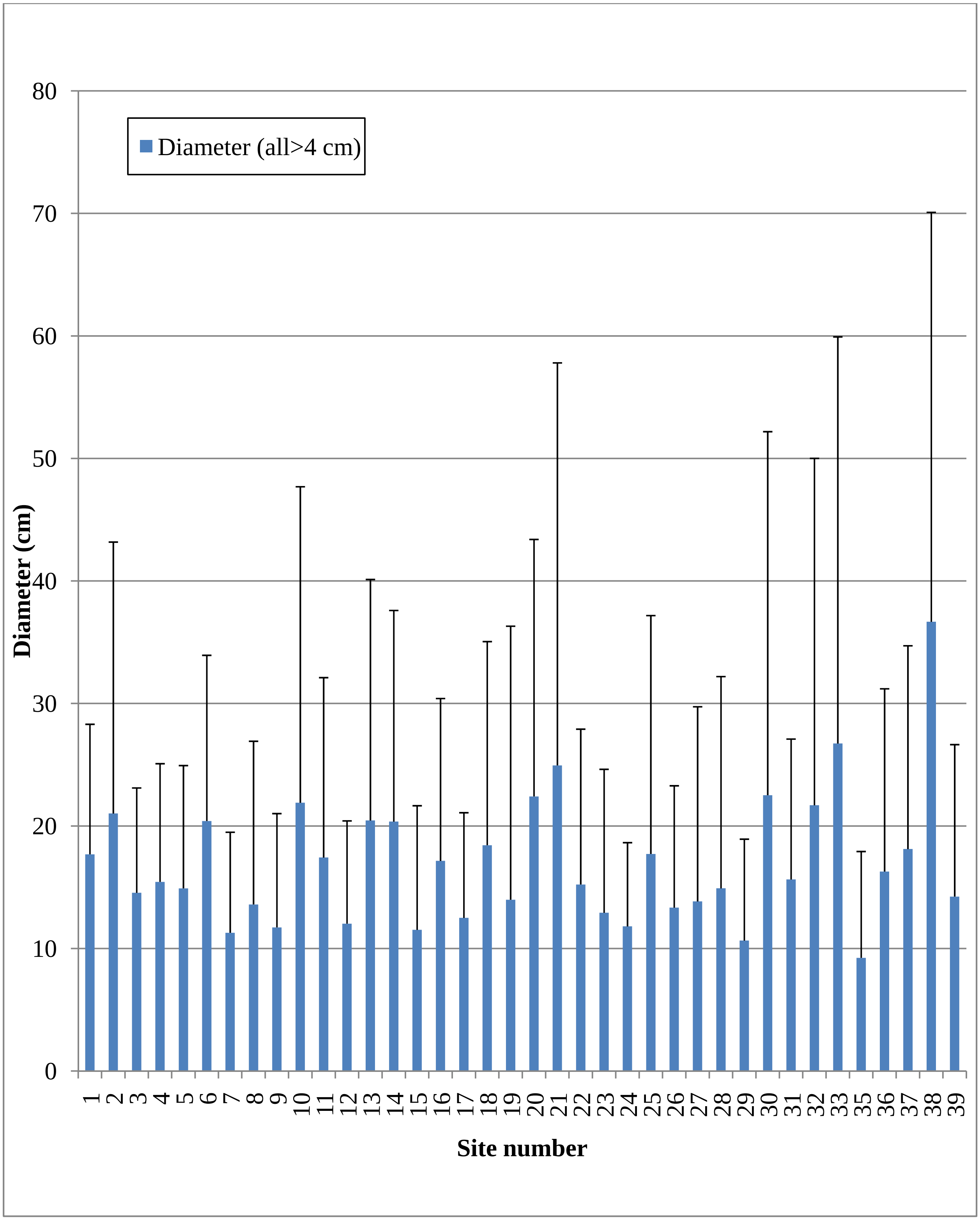


Fig. 12. Mean diameter (cm) and standard error of all corals (pooled species) recorded in belt transects on Cay Sal reefs, Bahamas. Reefs are listed in order of the surveys, from site 1-39; site 34 is not included.

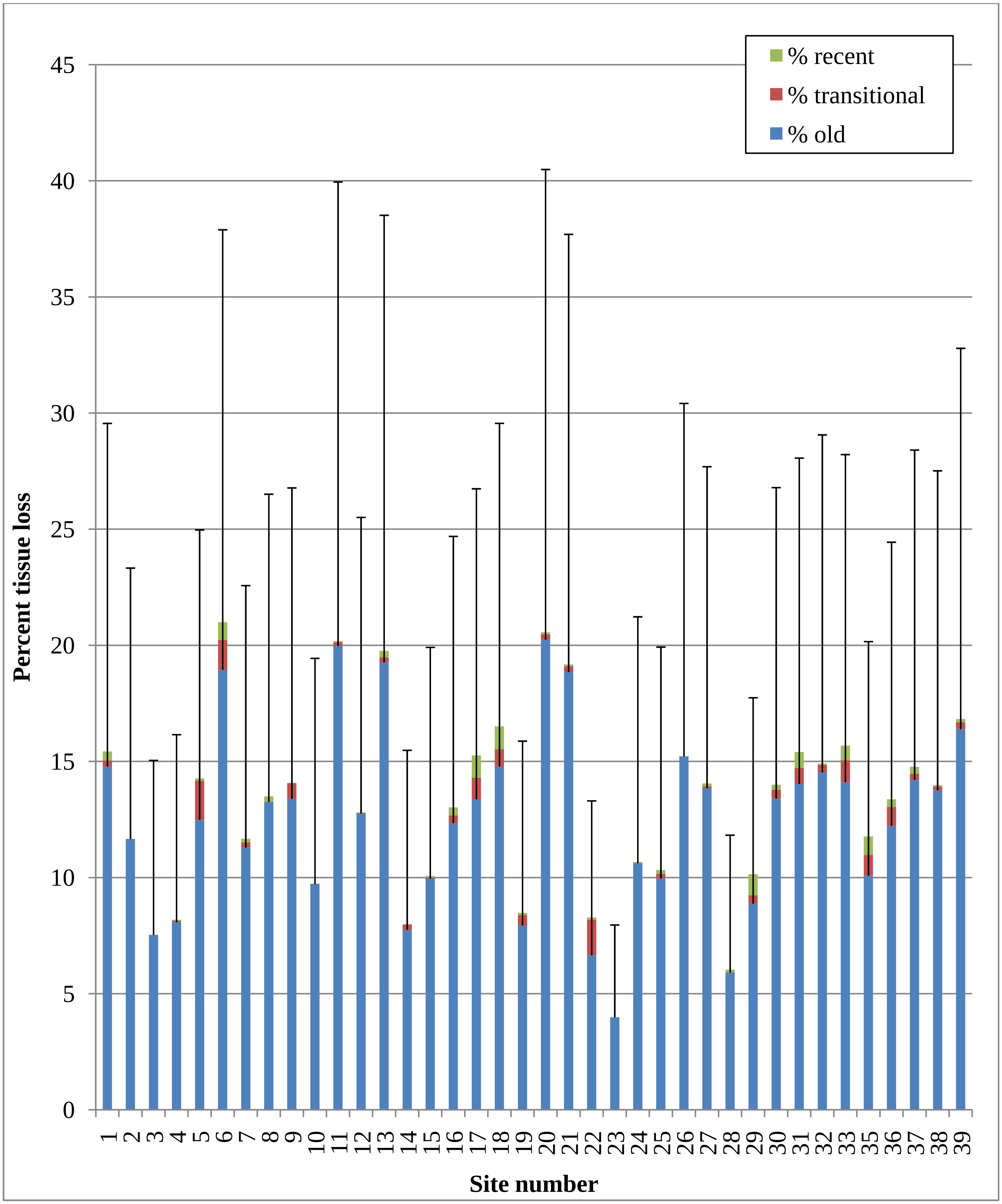


Fig. 13. Mean (+se) amount of partial mortality observed on live corals (all species pooled for each site) shown for all fore reef and lagoonal sites except site #34. Mortality is recorded as old tissue loss (blue), transitional tissue loss (red) and recent tissue loss (green).

Coral species comparisons

Coral species were pooled into 10 major functional groups based on their abundance and life history traits and examined for differences in size structure and amount of partial mortality. *Montastraea annularis* complex included the largest corals on these reefs (max= 260 cm diameter; mean = 47 cm) followed by brain corals in the genus *Diploria* and *Colpophyllia* (mean= 26 cm), *M. cavernosa* (mean = 22 cm), *S. siderea* (15.7 cm) and *P. porites* (15.1 cm). While isolated corals, including colonies of *Siderastrea siderea*, *Agaricia lamarki*, *Porites astreoides*, *P. porites*, *Meandrina meandrites*, and several other species were significantly larger than 25 cm diameter, the mean size of corals in all other functional groups was less than 15 cm diameter (Fig. 14). The height of these functional groups showed a similar size distribution (Fig. 15) with exception of colonies of *Dendrogyra cylindricus*, which were typically much taller than all surrounding corals.

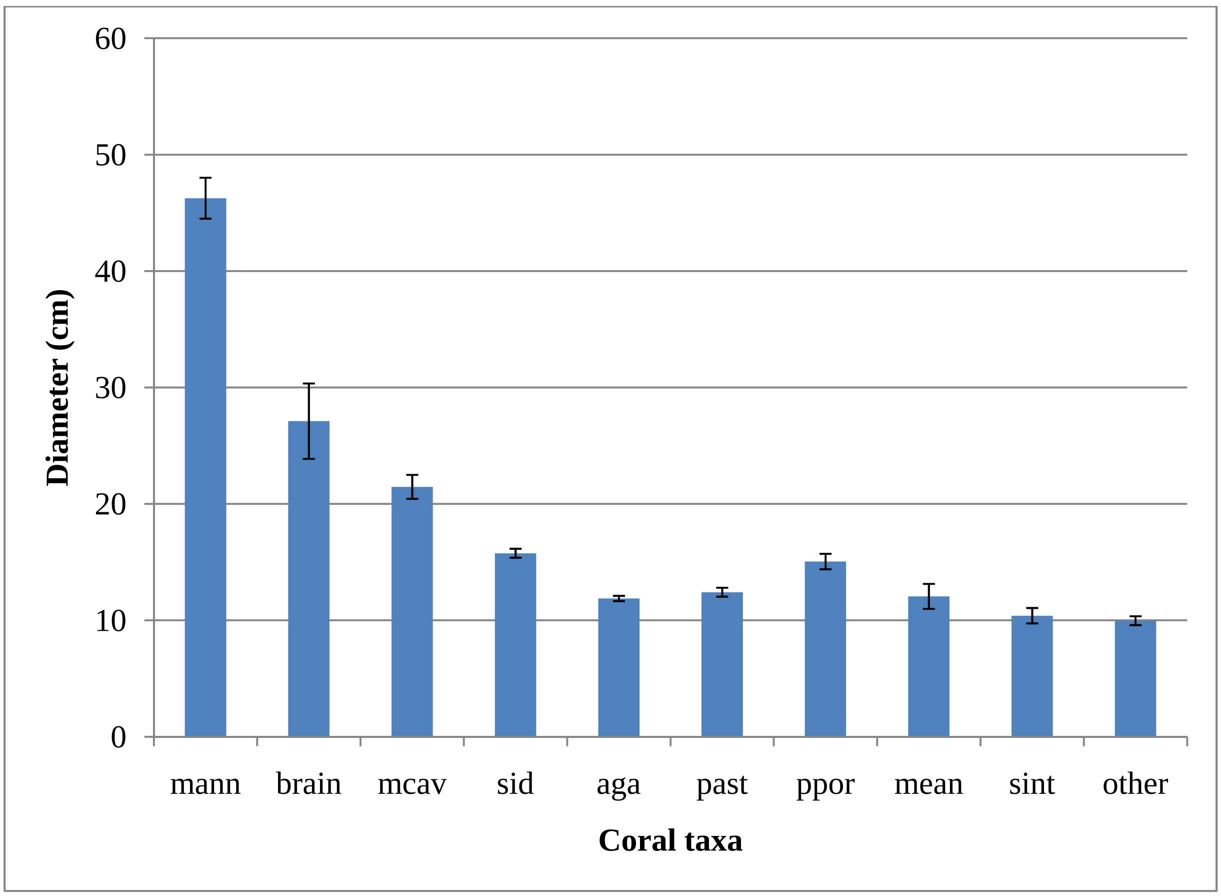


Fig. 14. Mean diameter (cm) of major functional groups of corals on Cay Sal, Bahamas. *Montastraea annularis* complex= mann; *Diploria* spp. and *Colpophyllia natans* = brain, *Siderastrea* spp. = sid, *Agaricia* spp. = aga, *Porites astreoides*=past, *P. porites* = ppor, *Meandrina meandrites*= mean, *Stephanocoenia intersepta*= sint, and 8 other species are lumped under “other”. Corals from site 34 are not included.

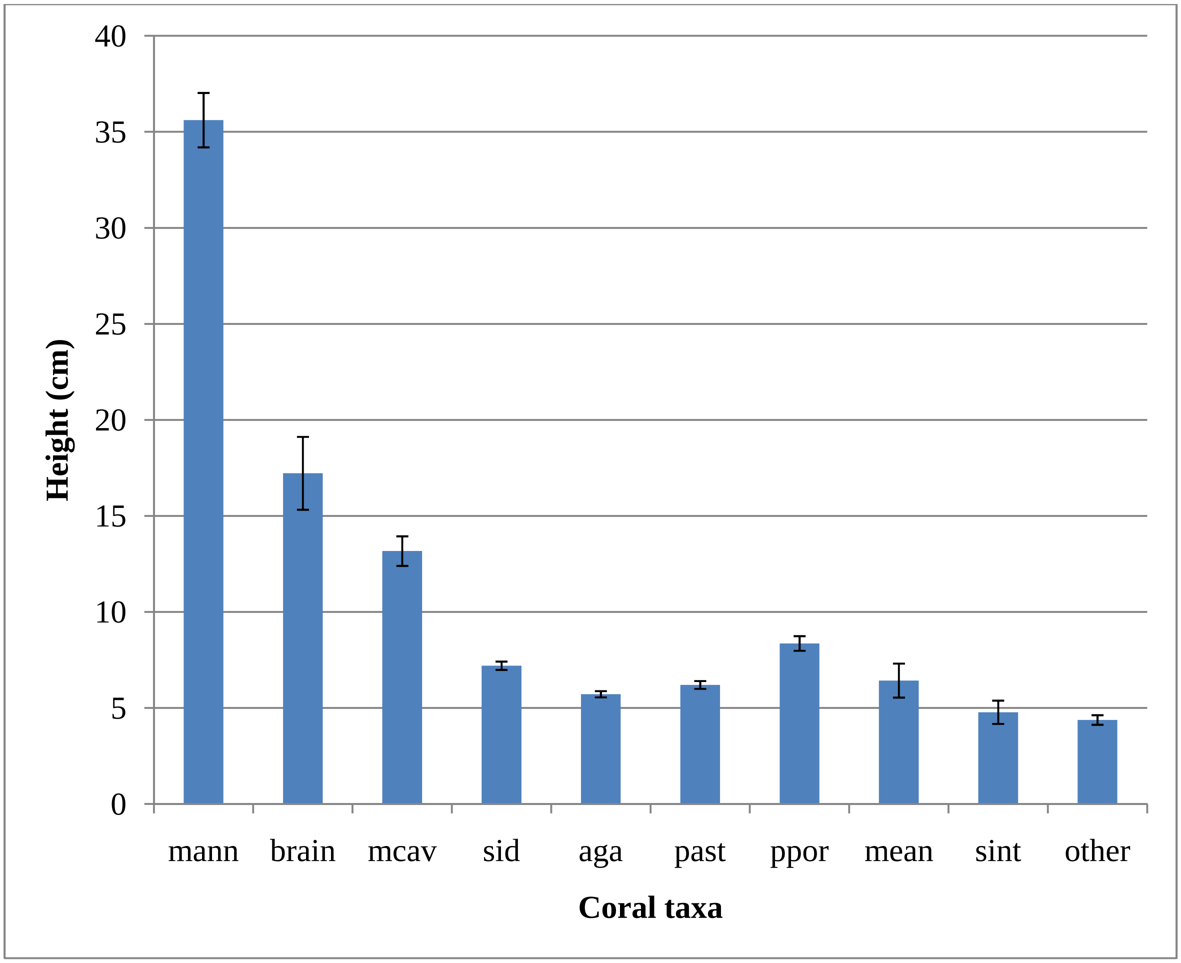


Fig. 15. Mean height (cm) of major functional groups of corals on Cay Sal, Bahamas. *Montastraea annularis* complex= mann; *Diploria* spp. and *Colpophyllia natans* = brain, *Siderastrea* spp. = sid, *Agaricia* spp. = aga, *Porites astreoides*=past, *P. porites* = ppor, *Meandrina meandrites*= mean, *Stephanocoenia intersepta*= sint, and 8 other species are lumped under "other". Corals from site 34 are not included.

The amount of partial mortality varied considerably among functional groups with colonies of *Montastraea annularis* complex sustaining the highest amount of tissue loss (mean = 45%) followed by brain corals (mean = 15%), *M. cavernosa* (14% and *P. porites* (12%). Most tissue loss (>97%) was categorized as old mortality, with the greatest amount of recent and transitional mortality observed in *P. porites* (1.9%), *M. cavernosa* (1.3%) and *M. annularis* complex (1.1%). Partial mortality was highly correlated with size when colonies were pooled into functional groups (r^2=0.93, p<0.001).

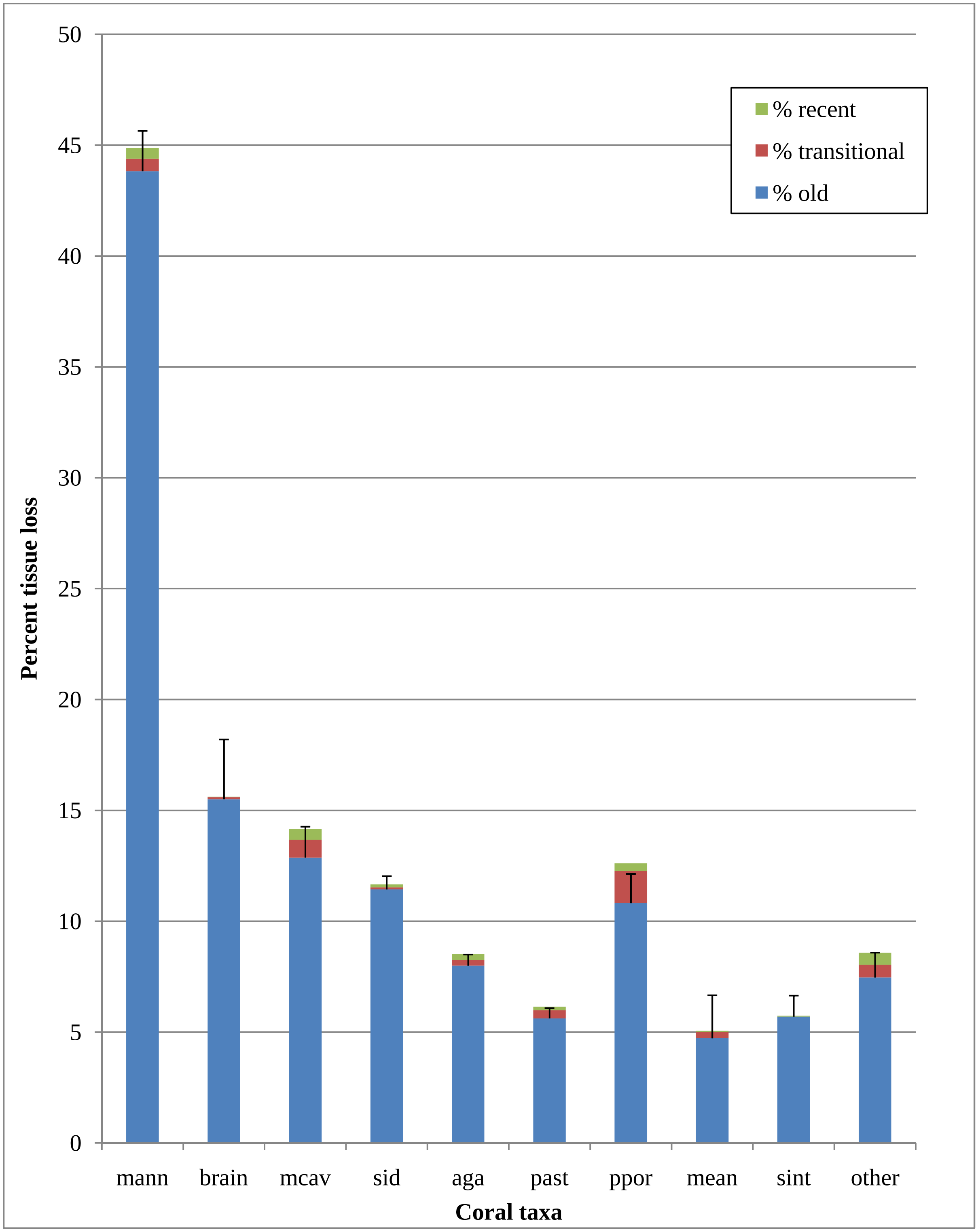


Fig. 16. Mean (+se) amount of partial mortality observed on live corals (pooled for each functional group) from all sites except site #34. Mortality is recorded as old tissue loss (blue), transitional tissue loss (red) and recent tissue loss (green).

Fish Community Structure

Fish community structure was assessed using a total of 363 quantitative belt transects, each 30 X 2 m length, with 287 conducted on fore reef sites and 76 completed in lagoonal sites. This included an assessment of 68 species of fish in 20 functional groups. A total of 14,009 fish of the 68 species were identified within all transects and assessed for density, size structure (total length; Table 3) and biomass. The ocean surgeonfish was the most common species observed on Cay Sal overall (12.9% of all fish), followed by the French grunt (11.2%), yellowhead wrasse (8.6%), slippery dick (8.5%) greenblotch parrotfish (7.1%) and redband parrotfish (6.5%). The top 33 species are shown in Fig. 17.

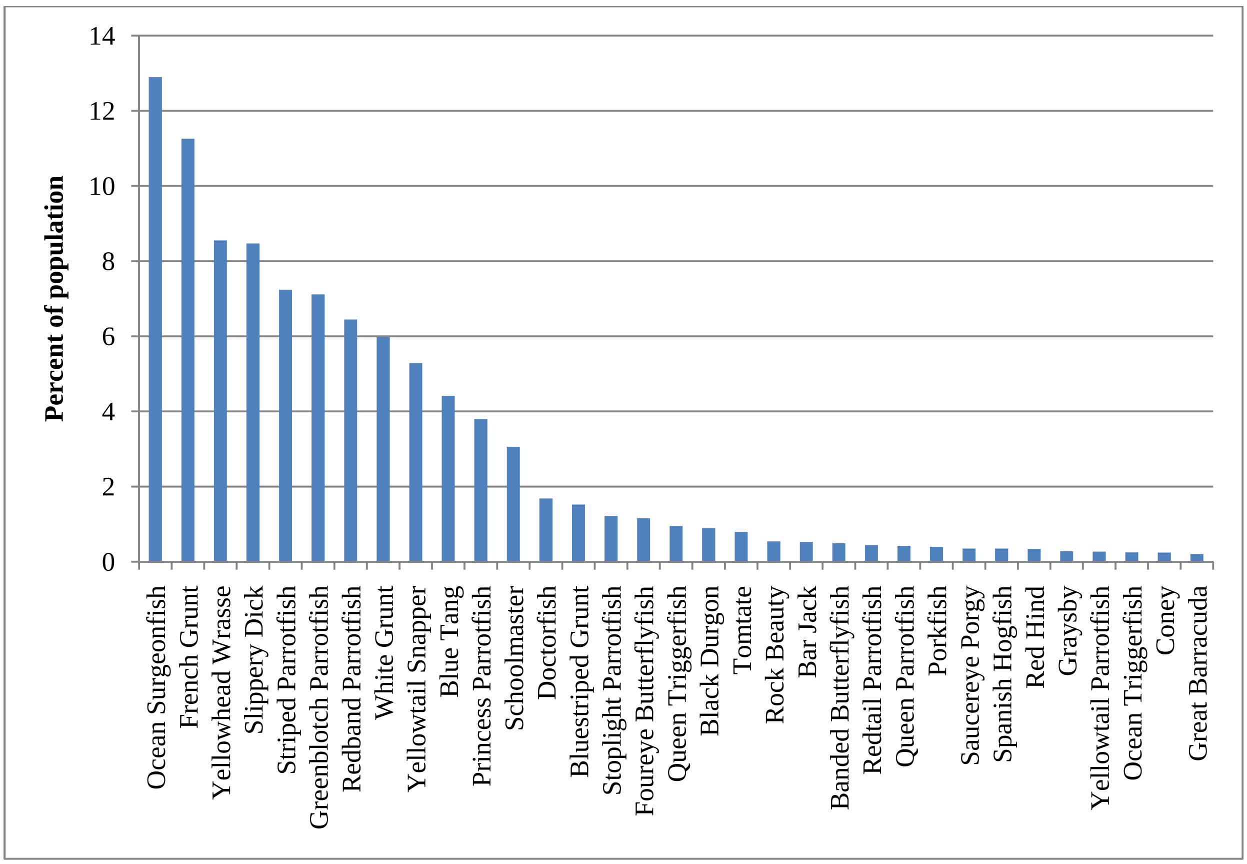


Fig. 17. Total abundance of the dominant species recorded along belt transects illustrated as the percent of the total population for all reefs (pooled).

The sizes of the 68 species pooled into 5 cm size classes are shown for each of the 68 species in table 3. The gray snapper, chub, yellowtail snapper, barracuda, schoolmaster, queen triggerfish and black durgon were the largest fishes observed on these reefs. Several large groupers were also identified (Nassau, black, tiger and yellowfin grouper); these fishes were extremely rare, typically occurring one or two reefs as individual fishes, and making up less than 0.04% of all fishes recorded overall on all sites (Table 3).

Table 3. Abundance of reef fishes in each size class. All reefs are pooled.

ScientificName	CommonName	NF	Lav	0-5	6-10	11-20	21-30	31-40	>40
Holacanthus bermudensis	Blue Angelfish	1	50.0	0	0	0	0	0	1
Holacanthus ciliaris	Queen Angelfish	17	25.2	1	3	1	4	8	0
Holacanthus tricolor	Rock Beauty	76	10.9	5	42	27	1	1	0
Pomacanthus arcuatus	Gray Angelfish	24	30.0	0	0	3	10	9	2
Pomacanthus paru	French Angelfish	15	35.7	0	0	1	2	9	3
Sphyraena barracuda	Great Barracuda	29	50.0	0	0	0	0	0	29
Lactophrys bicaudalis	Spotted Trunkfish	1	35.5	0	0	0	0	1	0
Chaetodon capistratus	Foureye Butterflyfish	162	7.5	31	120	11	0	0	0
Chaetodon ocellatus	Spotfin Butterflyfish	17	12.9	0	6	11	0	0	0
Chaetodon sedentarius	Reef Butterflyfish	12	3.9	9	3	0	0	0	0
Chaetodon striatus	Banded Butterflyfish	69	12.1	3	26	40	0	0	0
Prognathodes aculeatus	Longsnout Butterflyfish	22	5.8	9	13	0	0	0	0
Kyphosus spp.	Chub	14	47.9	0	0	0	0	2	12
Microspathodon chrysurus	Yellowtail Damselfish	5	14.0	0	1	4	0	0	0
Aluterus scriptus	Scrawled Filefish	2	50.0	0	0	0	0	0	2
Cantherhines pullus	Orangespotted Filefish	13	14.5	0	3	9	1	0	0
Monacanthus tuckeri	Slender Filefish	1	2.5	1	0	0	0	0	0
Anisotremus virginicus	Porkfish	56	15.9	0	0	54	2	0	0
Haemulon album	White Margate	7	25.5	0	0	2	3	2	0
Haemulon aurolineatum	Tomtate	112	13.6	0	30	81	1	0	0
Haemulon carbonarium	Caesar Grunt	14	24.8	0	0	1	13	0	0
Haemulon flavolineatum	French Grunt	1577	12.2	261	318	947	51	0	0
Haemulon plumierii	White Grunt	838	23.4	0	10	173	641	14	0
Haemulon sciurus	Bluestriped Grunt	213	25.3	0	0	14	190	9	0
Caranx ruber	Bar Jack	74	24.8	6	1	8	45	11	3
Gymnothorax moringa	Spotted Moray	1	50.0	0	0	0	0	0	1
Cryptotomus roseus	Bluelip Parrotfish	2	8.0	0	2	0	0	0	0
Scarus coeruleus	Blue Parrotfish	16	3.9	15	0	0	1	0	0
Scarus iseri	Striped Parrotfish	1014	9.5	141	606	243	23	1	0
Scarus taeniopterus	Princess Parrotfish	532	14.2	52	226	130	81	41	2
Scarus vetula	Queen Parrotfish	59	18.7	0	15	25	11	6	2
Sparisoma atomarium	Greenblotch Parrotfish	997	3.3	851	146	0	0	0	0
Sparisoma aurofrenatum	Redband Parrotfish	903	15.6	129	214	267	247	46	0
Sparisoma chrysopterum	Redtail Parrotfish	62	30.8	0	0	2	25	35	0
Sparisoma radians	Bucktooth Parrotfish	19	6.0	7	12	0	0	0	0
Sparisoma rubripinne	Yellowtail Parrotfish	38	21.2	7	7	3	6	15	0
Sparisoma viride	Stoplight Parrotfish	171	20.3	37	35	17	22	50	10
Diodon holocanthus	Ballonfish	1	25.5	0	0	0	1	0	0
Diodon hystrix	Porcupinefish	1	35.5	0	0	0	0	1	0
Calamus bajonado	Jolthead Porgy	8	35.5	0	0	0	0	8	0
Calamus calamus	Saucereye Porgy	49	23.3	0	0	16	28	5	0
Calamus penna	Sheepshead Porgy	5	27.5	0	0	0	4	1	0
Sphoeroides spengleri	Bandtail Pufferfish	1	8.0	0	1	0	0	0	0
Pterois spp.	Lionfish	8	30.5	0	0	0	4	4	0
Cephalopholis cruentata	Graysby	39	18.9	0	5	19	13	2	0
Cephalopholis fulva	Coney	34	22.5	0	3	6	24	1	0
Epinephelus guttatus	Red Hind	48	36.5	0	0	1	9	27	11
Epinephelus striatus	Nassau Grouper	2	50.0	0	0	0	0	0	2
Mycteroperca bonaci	Black Grouper	1	50.0	0	0	0	0	0	1
Mycteroperca interstitialis	Yellowmouth Grouper	1	35.5	0	0	0	0	1	0
Mycteroperca tigris	Tiger Grouper	5	47.1	0	0	0	0	1	4
Mycteroperca venenosa	Yellowfin Grouper	5	44.2	0	0	0	0	2	3
Lutjanus analis	Mutton Snapper	1	35.5	0	0	0	0	1	0
Lutjanus apodus	Schoolmaster	429	35.0	0	1	2	86	290	50
Lutjanus griseus	Gray Snapper	14	28.4	0	0	0	10	4	0
Lutjanus mahogoni	Mahogany Snapper	18	23.3	0	0	5	12	1	0
Ocyurus chrysurus	Yellowtail Snapper	741	32.8	0	0	27	261	374	79
Acanthurus bahianus	Ocean Surgeonfish	1807	11.1	484	267	1020	36	0	0
Acanthurus chirurgus	Doctorfish	236	18.7	0	16	132	88	0	0
Acanthurus coeruleus	Blue Tang	618	13.1	34	179	377	28	0	0
Balistes vetula	Queen Triggerfish	133	34.5	1	1	2	28	84	17
Canthidermis sufflamen	Ocean Triggerfish	35	42.5	0	0	0	0	18	17
Melichthys niger	Black Durgon	125	28.8	0	1	3	76	44	1
Xanthichthys ringens	Sargassum Triggerfish	19	22.5	0	1	8	6	4	0
Bodianus rufus	Spanish Hogfish	49	9.7	20	14	9	4	2	0
Halichoeres bivitattus	Slippery Dick	1187	7.8	383	563	238	3	0	0
Halichoeres garnoti	Yellowhead Wrasse	1198	6.0	645	399	152	2	0	0
Halichoeres radiatus	Puddingwife	3	10.5	0	2	1	0	0	0
Lachnolaimus maximus	Hogfish	3	20.2	1	1	0	0	0	1

The size distribution of the dominant species, grouped into five functional groups (grunt, parrotfish, seabass, snapper and surgeonfish) , are shown for fore reef sites (Fig. 18) and lagoonal sites (Fig. 19). The first set illustrates the breakdown of each functional group into the five size classes, represented as the percent of the total population of that functional group. The second set of figures illustrates the overall percentage (pooled for all species in the five functional groups) of each size class for each of the five groups. The vast majority of the parrotfishes were 20 cm or less in total length, while grunts were typically 11-30 cm TL, snapper were 20-40 cm TL, and surgeonfish were mostly 11-20 cm. There was a notable absence of juvenile snapper and seabass, indicating that these species had recruited to Cay Sal from outside of the bank.

The density of fishes by site is shown for all species and for commercially important species in figure 20. The mean density of fishes per 100 m^2 for all species pooled was 59 individuals of the 68 species on fore reef sites and 83 fish/100 m^2 for lagoonal sites. Of this number, a mean density of 12 commercially valuable fishes per 100 m^2 were recorded on fore reef sites and 18/100 m^2 on lagoonal sites. Only two fore reef sites (24 and 4) and two lagoonal sites (20 and 22) had a density of fish that exceeded 100/100 m^2. The highest density of commercially valuable fishes (54/100m^2) was recorded on site 10.

Parrotfish occurred at a mean density of 9.4/100m^2 on fore reef sites and 14.1/100m^2 on lagoonal reefs. The highest densities of parrotfish were recorded on site 12 (27.4) and 16 (21.4) on the fore reef, and 11 (34.3) and 14 (29.9) on lagoonal reefs. Surgeonfishes were slightly less dense, occurring at a mean density of 7.6/100m^2 on the fore reef and 6.8/100m^2 on the lagoonal reefs. These species typically occurred as individuals or in small schools (10 fish/group) rather than large schools of 1000s of fish as typically observed elsewhere in the Caribbean (Fig 20).

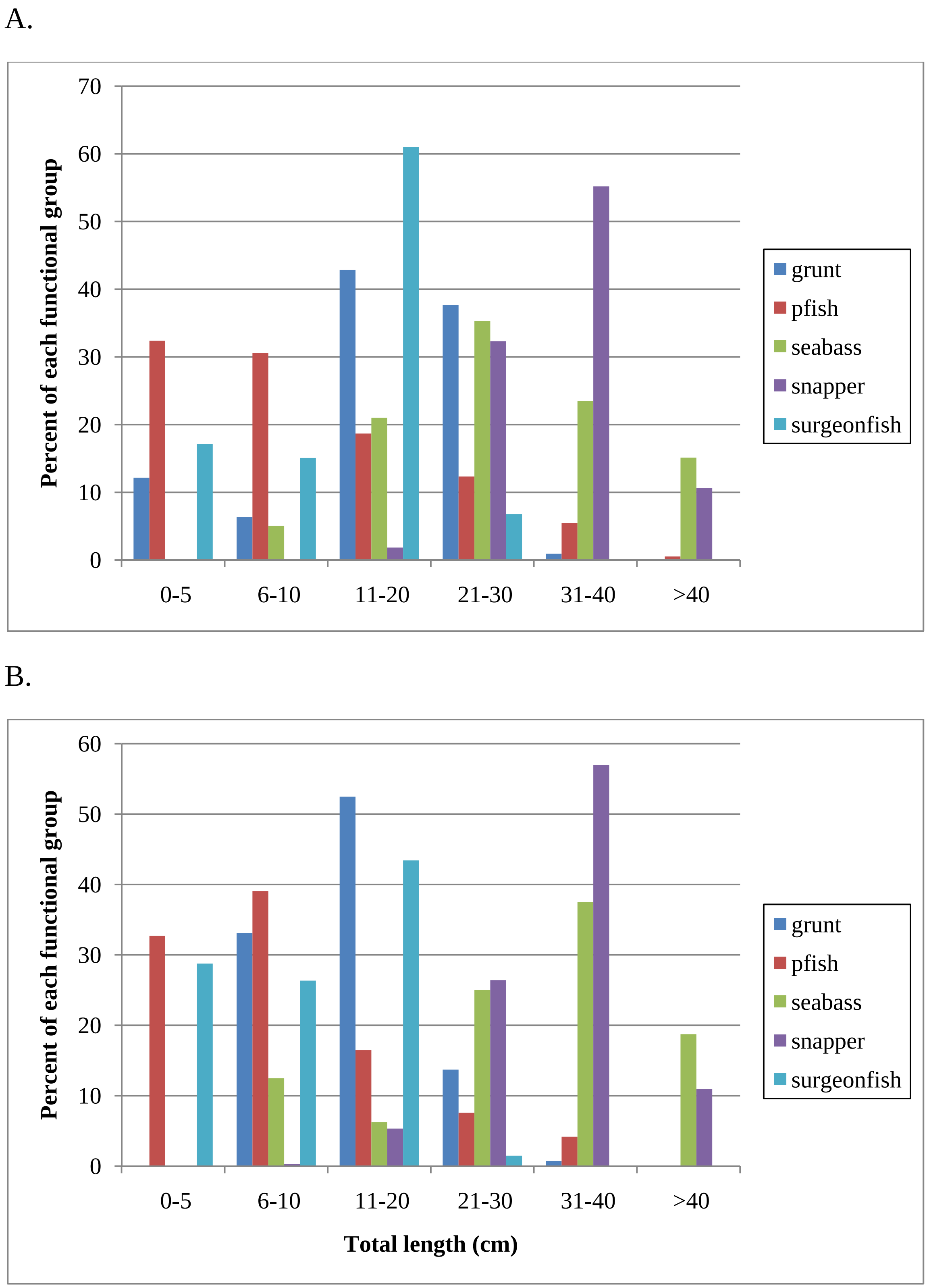
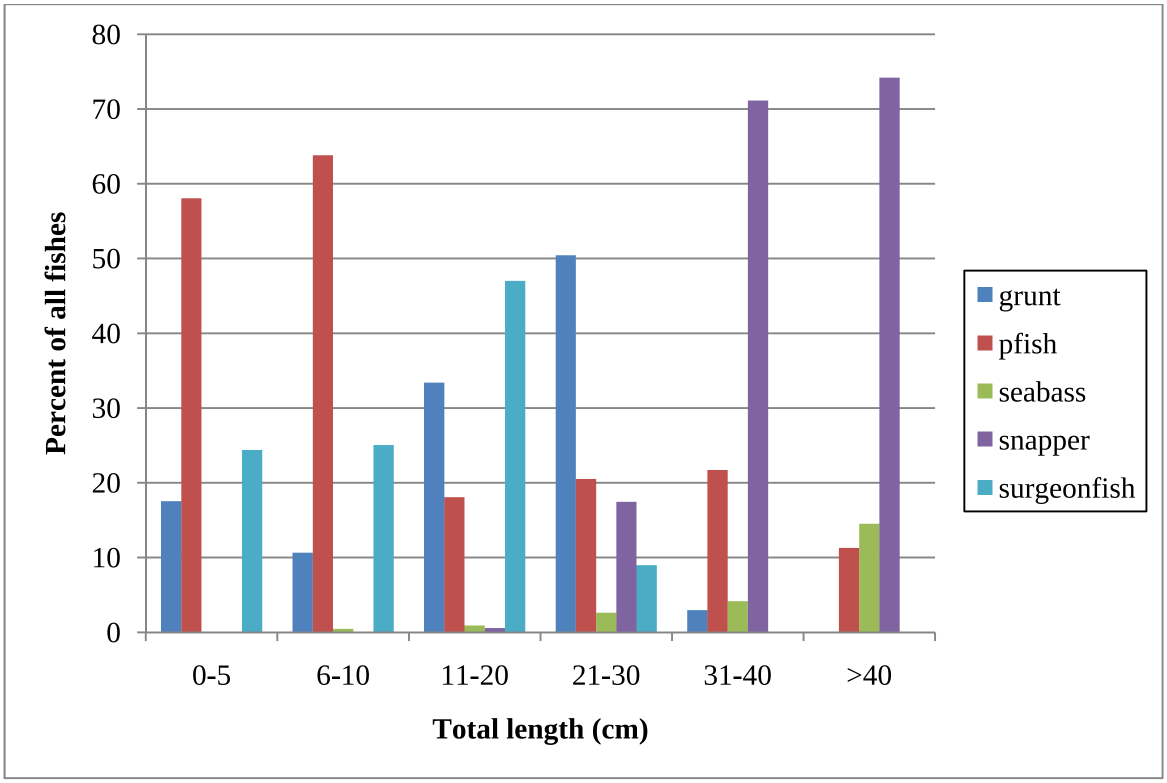


Fig. 18. Size structure of the five dominant functional groups of fishes identified on Cay Sal Reef. Damselfish, due to their low abundance, were not included. A. Fore reef sites. B. Lagoonal sites.

A.



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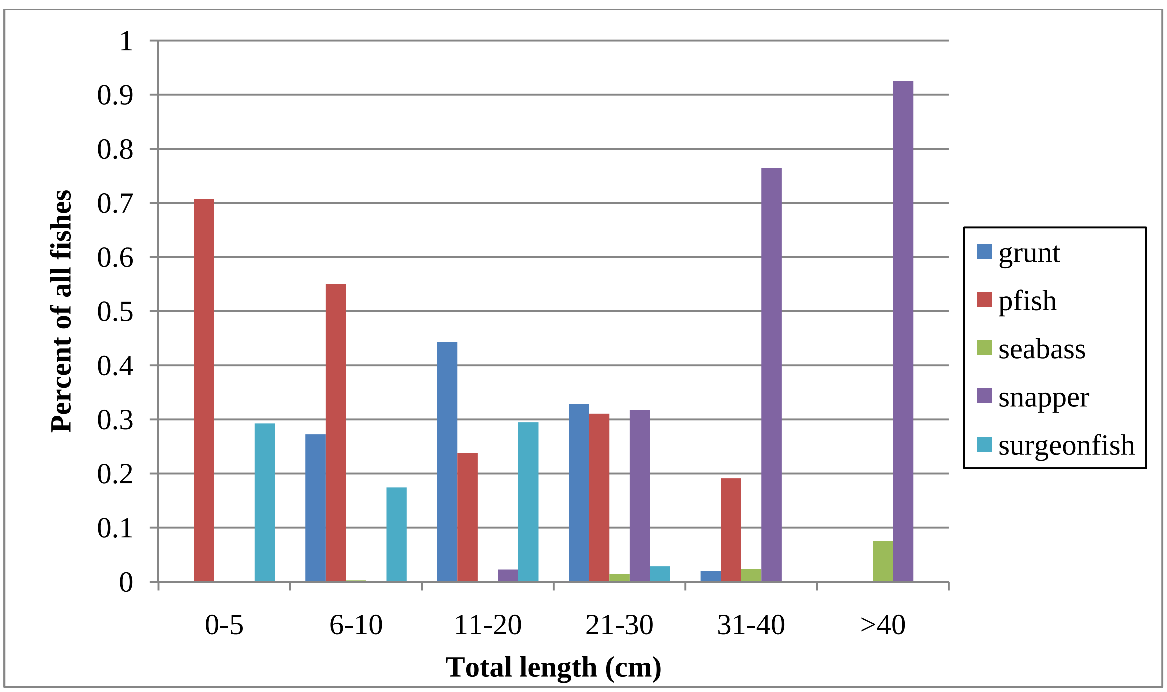
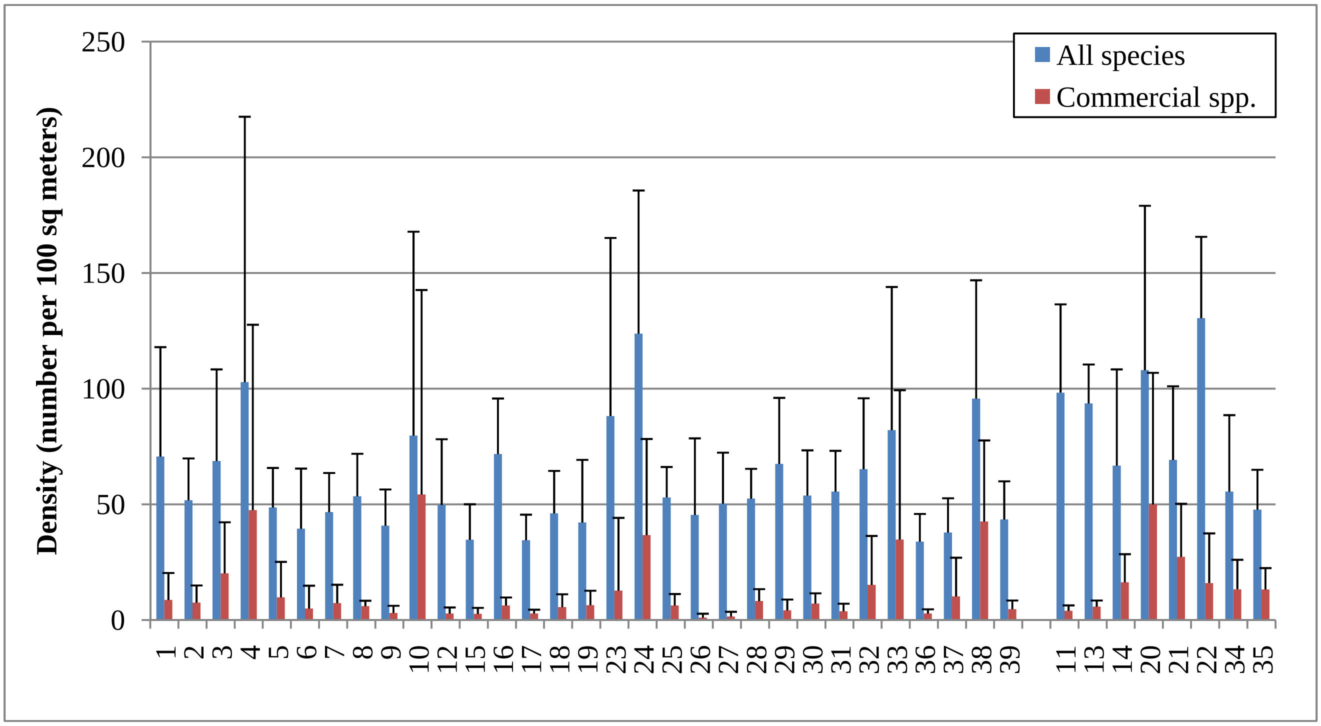


Fig. 19. Percent of the total population of the five dominant functional groups in each size class. All reefs are pooled into A. Fore reef sites. B. Lagoonal sites.

A.



B.

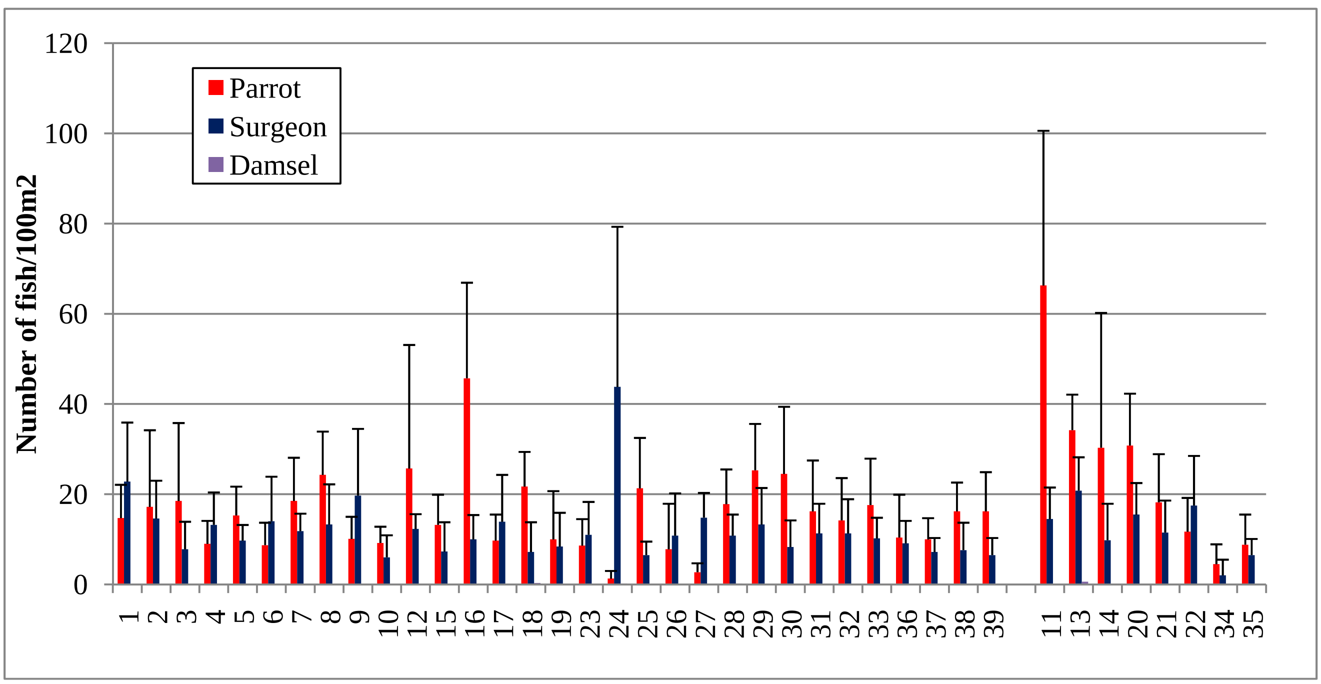


Fig. 20. Density of fishes recorded as the number of fishes per 100 square meter recorded on belt transects at Cay Sal. Sites are divided into fore reef locations(1-39) followed by lagoonal sites (11, 13, 14, 20, 21, 34, 35). A. Density of all species pooled and commercially important species. B. Density of parrotfish, surgeonfish and damselfish. All parrotfishes 5 cm and larger in total length are pooled as “parrot” and surgeonfish, doctorfish and blue tangs are pooled as “Surgeon”. Damselfish were rare throughout all sites (<1 individual /100m^2).

Herbivorous reef fish communities and grazing pressure in Cay Sal (Bahamas)

A. Density and biomass of herbivorous reef fish

In addition to the specific AGRRA fish transects additional surveys were conducted to more thoroughly characterize herbivorous fish. Herbivorous reef fish, including 3 species of surgeonfish and 10 common species of parrotfish were counted at 22 sites (Fig. 21) using 8 belt transects of 30 x 4 m per site. The total length (TL) of each individual was visually estimated and for parrotfish, life phase was also noted.

Table 4. Species counted using 30 x 4 m belt transects in the present study

Family	Species
Acanthuridae	*Acanthurus tractus*
	Acanthurus chirurgus
	Acanthurus coeruleus
Scaridae	*Scarus taeniopterus*
	Scarus iserti
	Scarus vetula
	Scarus guacamaia
	Scarus coeruleus
	Sparisoma aurofrenatum
	Sparisoma viride
	Sparisoma rubripinne
	Sparisoma radians
	Sparisoma atomarium

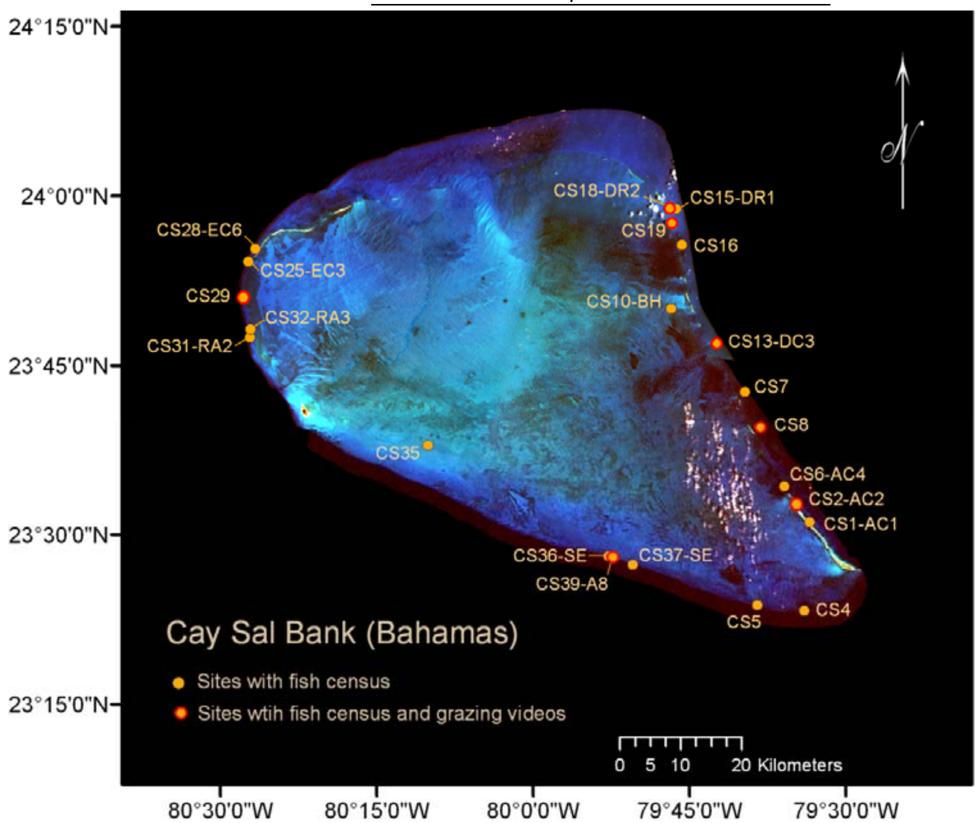


Fig. 21. Locations of herbivorous fish surveys.

B. Afternoon grazing intensity

The grazing rate of several species of herbivorous reef fish in both Caribbean and Pacific reefs is moderate in the mornings and increases during late morning to early afternoon (Choat and Clements 1993, Bruggemann et al. 1994, Bellwood 1995, Polunin et al. 1995). Therefore, to capture the peak in feeding activity on different reefs around Cay Sal, grazing intensity of herbivorous reef fish communities was assessed between 11:30 and 15:30 in 8 of the sites where UVC were conducted. To capture the feeding behavior of the herbivorous fish community undisturbed by the presence of divers, 10 high-definition video cameras (GO-PRO Hero 1080) were deployed in each reef site and held stationary on the bottom using 2-pound lead weights. A diver switched the cameras on between 11:30 and 12:00 h showing a white board with the date, time, reef site name and the height of the mound or promontory where the camera was placed. Each camera was set at least 5 m apart from every other and programmed to film continuously over an area of at least 1 m^{-2} of predominantly grazable reef substrata (e.g. hard bottom covered algal turfs, encrusting coralline algae or macroalgae). Once all cameras were switched on, all divers exited the water. Cameras were switched off and retrieved back to the surface for footage downloading and battery recharging between 15:30 and 16:00 h.

During a one-dive experiment two divers recorded a footage to calculate the area appearing in focus within the field of view of a GoPro camera when it was set at resolution R4 (1280×960 pixels; 4:3 aspect ratio) forming a 45° angle with the horizontal, and at different heights above the substrata. This experiment involved mounting a single camera on an underwater tripod to film a relatively flat section of the substrate. The camera filmed a 5-m measuring tape extended on the substratum perpendicular to the lens while two divers held two PVC pipes with 10-cm marks perpendicularly to the measuring tape, and at both sides of it. Both divers moved the PVC pipes simultaneously along the full length of the measuring tape. A video of this scene was made at 6 different heights (0.0, 10, 20, 30, 40 and 50 cm) to simulate the common heights of calcareous promontories found in the reef when placing the cameras during the grazing surveys. Projecting this video on a TV screen allowed the surveyor to draw 6 different grids of 10 cm^{-2} cells to be used with footage obtained placing the camera at different heights on the reef.

C. Benthic features: algal height and density of coral recruits and juveniles

Algal heights were measured along 4 of the belt transects used to count herbivorous reef fish. At the end of a typical fish census the surveyor rolled back the 30-m measuring tape. The tape was used as a guide for the surveyor to stop every 5 meters and take at least 10 measurements of the algae present under the tape. Algae were measured to the nearest millimeter using a plastic ruler and macroalgae in particular were identified to a genus level.

D. Density and biomass of herbivorous reef fish (spatial patterns)

11 Species of roving herbivorous reef fish (3 acanthurids and 8 scarids) were commonly encountered in Cay Sal Bank reefs. Mean density of herbivorous reef fish in Cay Sal Bank ranged from 3.2 to 13.5 individuals 120 m^{-2}, with the highest values occurring on two sites in the east side of the bank

(CS16 and CS7), but also on one of the sites surveyed on Rampidas reef in the northwest side of the Bank and at CS36-SE in the southwest. Mean biomass of herbivorous reef fish in Cay Sal Bank ranged from 41 to 1767.6 g 120 m^{-2}, with the highest value occurring at two sites located in the south end of the bank (CS36-SE and CS5) .Only one site (CS36-SE) had both the highest density and biomass of herbivorous reef fish. In 54% of the sites the community of roving herbivorous fish was dominated by parrotfishes, whereas in 18% it was dominated by surgeonfishes and in 27% of the sites it comprised a fairly homogeneous mixture of the two families. *Acanthurus tractus* was the most abundant species in 73% of the surveyed sites all around Cay Sal. *Scarus iseri, Scarus taeniopterus* and *Sparisoma aurofrenatum* were the commonest species in a minority of the sites (Fig. 23).

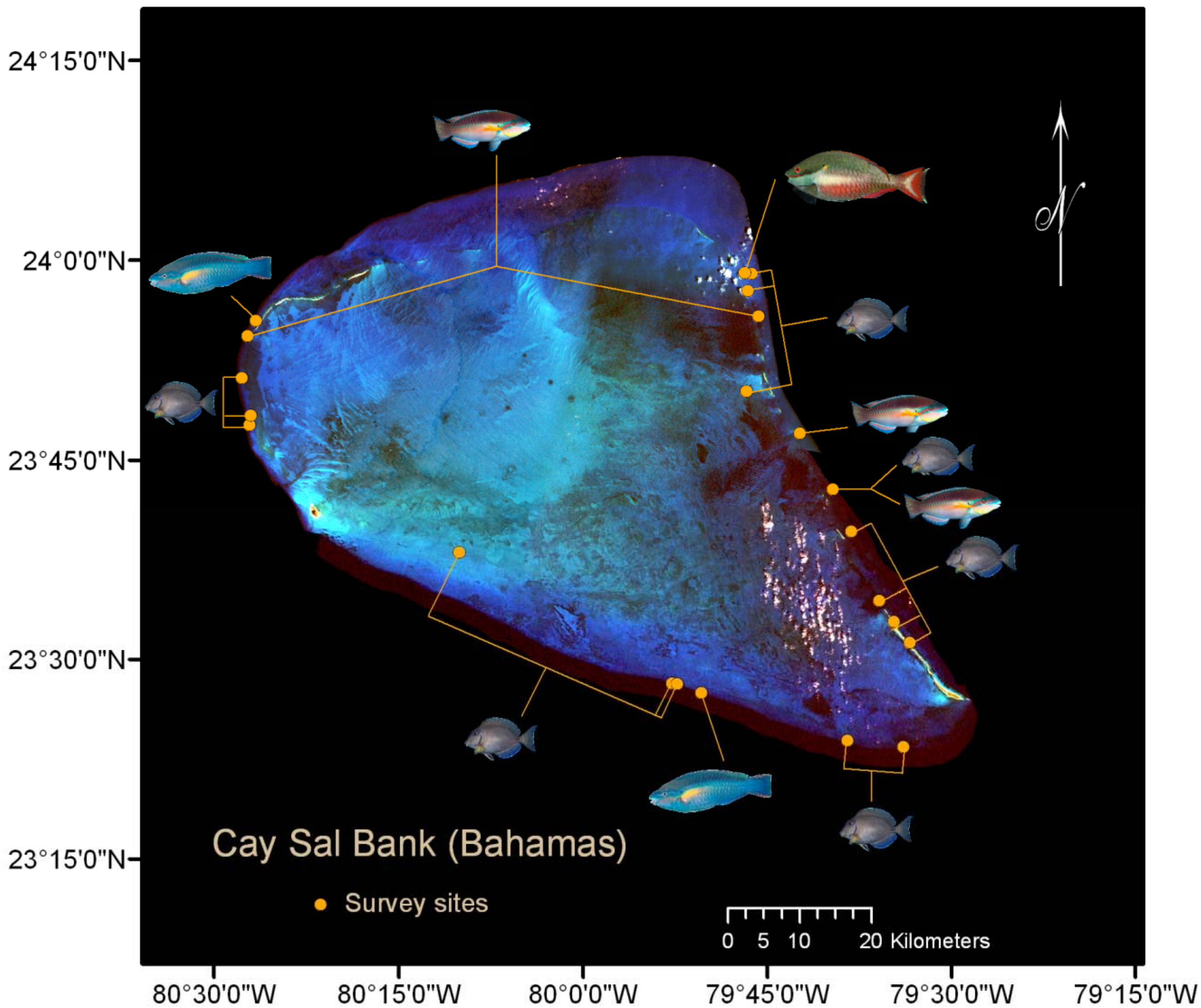


Fig. 22. Map of Cay Sal indicating the percent of surgeonfish (dark green) and parrotfishes (light green) found at each study site.

E. Similarity among sites in species composition and density of herbivorous reef fish

Ordination of the survey sites according to their similarity in terms of density of herbivorous reef fish produced 7 distinct clusters (Fig 23). At 80% of similarity, the reefs surveyed on Elbow Cays clustered together, and the Rampidas reefs clustered with their closest site on the northwest region of the bank (i.e. CS29). Sites on the southeast corner of the bank (e.g. CS5, CS4 and CS37) conformed a similar cluster, whereas sites located at a considerable distance (i.e. CS8, CS19 and CS39) comprised an equally similar cluster. Two of the sites surveyed on the Anguilla Cays, together with CS35 at the opposite side of the atoll comprised a group with some of the lowest densities of herbivorous fish in Cay Sal whereas the southernmost site at Anguilla Cays clustered with two more sites on the east side of the Bank that had relatively higher densities of herbivores.

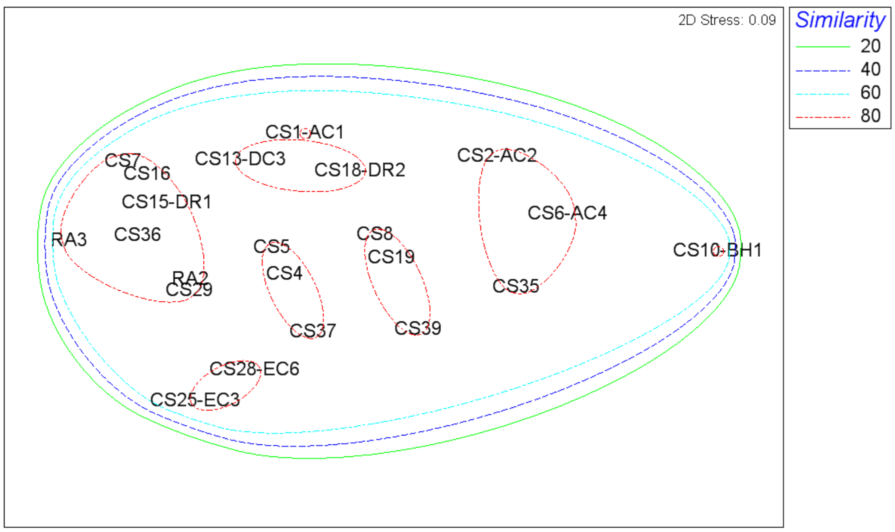


Fig. 23. Multidimensional scaling plot indicating the clusters of sites formed at a different levels of similarity in terms of density.

F. Relationships between fish and benthic data

Parrotfish grazing intensity has been found to be positively related with density of coral recruits (Mumby et al. 2007) and the mechanism behind this relationship is most likely that scarids generate suitable space for coral larvae to settle. In the near future, it will be possible to test if the grazing intensity (calculated from high definition footage) explains the spatial variability of recruits and juveniles density in Cay Sal Bank. In the mean time the relationship between parrotfish density and the density of both coral recruits and juveniles was examined (Fig 24). The density of recruits and juveniles appeared to increase with the abundance of parrotfishes in some of the shallow and deep survey sites of Cay Sal Bank. However not all sites behaved according to this general trend, and no significant relationship was found. This may be because of physical characteristics of these sites which may also play an important role in driving the density of recruits, or because the effectiveness of parrotfish density as a proxy for their grazing intensity is limited (Mumby et al. 2007).

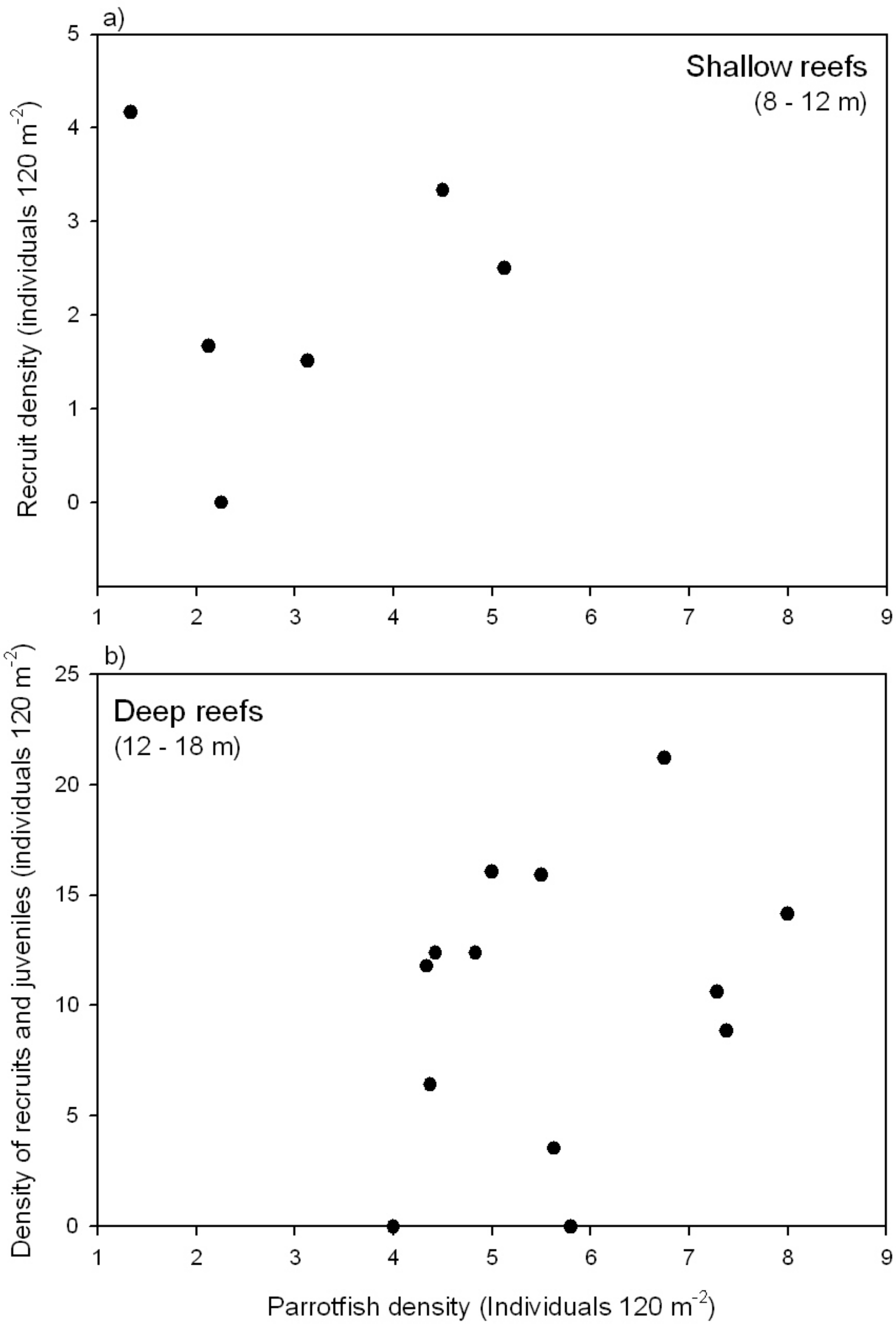


Fig. 24. Scatter-plot indicating obscured relationships between parrotfish density (individuals $120m^{-2}$) and density of recruits and juvenile corals (individuals < 5cm in diameter) in A) shallow reefs (8 - 12 m) and B) deep reefs (12.5 - 18 m) in Cay Sal Bank.

Due to the controls that herbivorous reef fish are known to exert in the reef algal community, a relationship may exist between herbivores and the algal height in Cay Sal reefs. It seemed reasonable to expect that in places where herbivores were most abundant, algal height would be lower, indicating that the reef substratum is being grazed more effectively thus preventing it from becoming dominated by tall thick turfs or macroalgae that would impair coral settlement. Contrary to our expectations, no significant relationships were observed between algal height and overall density of herbivorous reef fish or parrotfishes either in shallow or deep reefs. In shallow reefs, the algal height was significantly related to the density of surgeonfish (by a polynomial shaped curve, R^2= 0.89 Fig 25). This positive relationship, may indicate that reefs supporting higher algal biomass may be able to support higher abundance of surgeonfish.

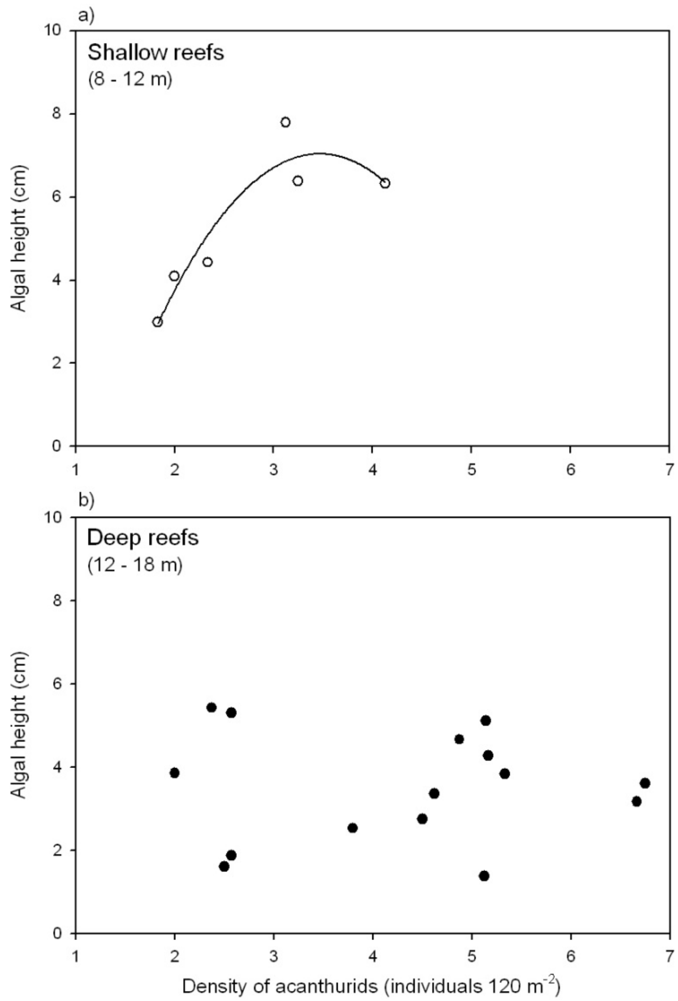


Fig. 25. A. Positive relationship (described by a polynomial curve), between the mean density of acanthurids (individuals 120 m^{-2}) and the mean algal height (cm) in shallow reefs in Cay Sal. No significant relationship of this kind occurred in deep reefs (B).

Regional analysis

Survey sites were subdivided into 9 distinct locations, based on location, depth and unique attributes of the site. This included: 1) southeast fore reef sites (site 4,5, 36-39); 2) east fore reef sites (sites 1-19 except 10, 11,14); 3) blue hole (site 10); 4) northern lagoonal sites (site 11, 20, 21); 5) Legacy site (site 14); 6) shallow northwest fore reef sites (site 22-24); 7) western fore sites (site 25-33); 8) sponge bommies (site 34); and 9) western lagoonal site (site 35).

A. Benthic communities

Benthic assemblages varied significantly among the nine sectors for most of the categories. High live coral cover was observed in the Legacy site (26%), blue hole (9.9%), northern lagoonal sites (9.4%) and western fore reef (8.5%), while the lowest cover was at the sponge bommies (3.7%), shallow northwest (4.3%) and western lagoonal site (4.6%). Over 60% of the bottom was covered by macroalgae at five sectors with slightly lower cover at northern lagoonal sites (54%), Legacy site (45%), and blue hole (26%). The sponge bommies had virtually no (<1%) macroalgae (Fig. 26). Southeast fore reef sites had the highest cover of CCA (5.5%) while the shallow northwest sites had the lowest (0.2%). The Legacy site had the highest amount of erect coralline algae (10.6%), which primarily included *Halimeda* (Fig. 27 a) The Legacy site had the highest cover of aggressive invertebrates (5%) followed by the blue hole (2.5%) (Fig. 27 b).

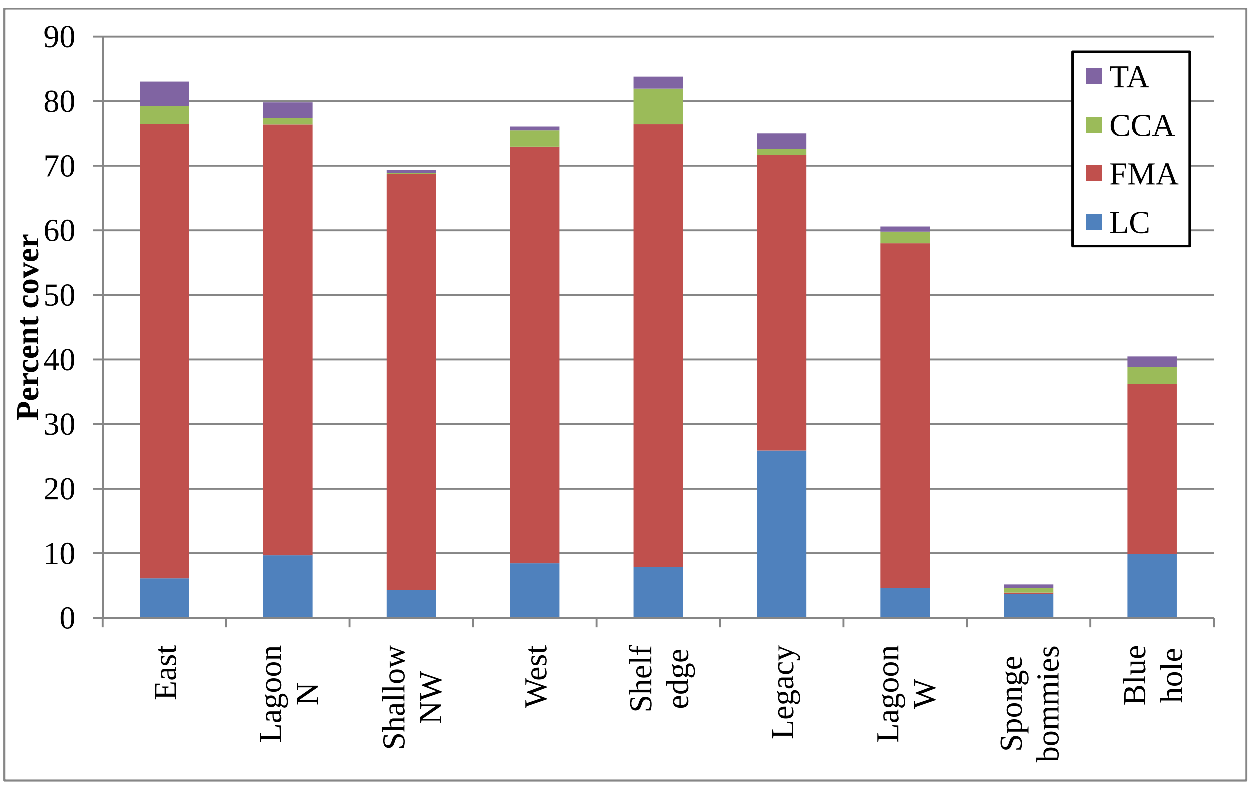
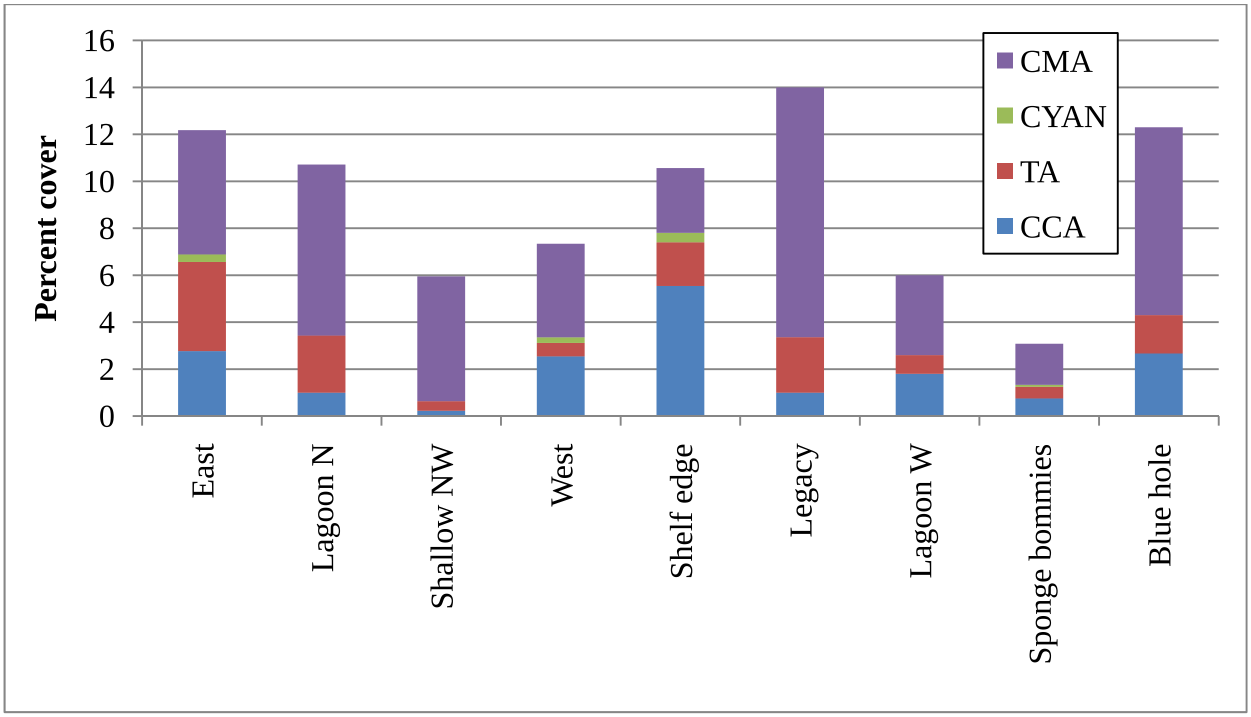


Fig. 26. Cover of coral, fleshy algae and crustose coralline algae at the 9 locations.

A.



B.

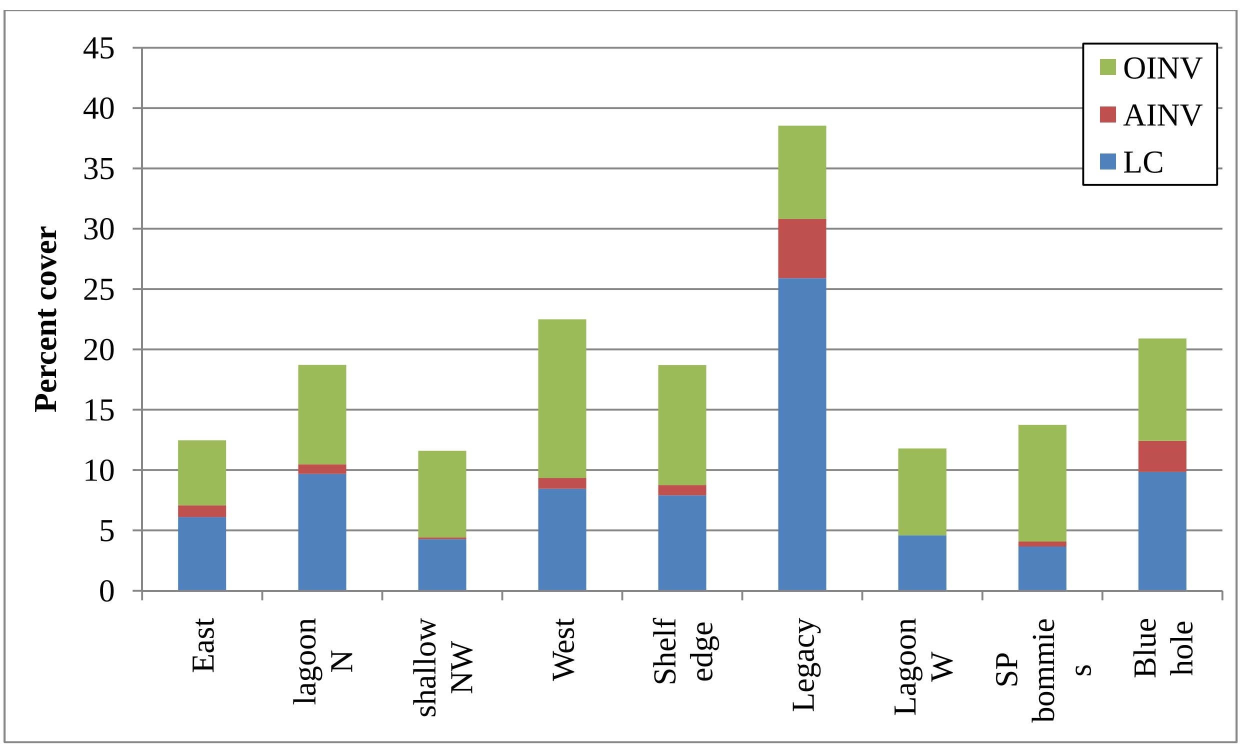


Fig. 27. Benthic cover at the nine locations. A. Cover of erect macroalgae (CMA), cyanobacteria (cyan), turf algae (TA) and crustose coralline algae (CCA). B. Cover of live coral (LC), aggressive invertebrates (AINV) and other invertebrates (OINV).

B. Coral communities

Coral communities varied in species composition, size and extent of mortality between each of the nine aggregate locations. While the dominant corals overall were *A. agaricites*, *P. astreoides*, *S. siderea*, *M. annularis* and *M. cavernosa*, these species were rare at some sites. The Legacy site had the lowest diversity with nearly 90% of the population consisting of *P. astreoides* (Table 5); this species made up 20% of the population on western sites and only 7-12% of the corals in all other sites. *P. astreoides* was also significantly larger on three of the lagoonal sites (mean= 14-20 cm diameter) than on fore reef sites, and was smallest at the lagoonal site in the southwest. Colonies of *P. astreoides* over 50 cm diameter were seen at the Legacy site. *Agaricia* spp. was most common on western and southeastern sites (>30% of the population) and colonies were slightly larger (mean = 13 cm diameter). The smallest *Agaricia* colonies were found at the shallow northwest sites, although it was much less common (6% of the population) as compared to other sites. *M. annularis* (complex) were the largest corals overall, although they made up less than 6% of the population at all sites except the Blue Hole. This taxa was absent from the shallow northwest sites and colonies were smallest on the east reefs (mean = 35 cm diameter). Colonies of *Siderastrea siderea* also differed in size, with significantly larger corals in the four lagoonal areas. The mean diameter, width and height for the four dominant species is shown in figure 28 a-d.

Table 5. Abundance of the dominant corals within each region shown as the percent of the total population examined.

	SNW	Edge	West	East	N Lagoon	Blue Hole	Legacy	S Lagoon
aga	5.6	36.5	31.9	21.3	18.2	17.1	2.0	7.5
past	10.5	7.8	20.1	11.3	8.1	6.8	88.1	48.6
ppor	27.8	23.7	19.0	31.3	24.6	29.5	3.2	19.9
ssid	26.5	13.8	8.6	10.5	22.9	4.8	2.4	11.0
mann	2.5	6.0	4.2	1.8	4.5	23.3	4.3	1.4
mcav	11.7	1.4	1.1	5.8	2.5	2.7	0.0	0.0
dip	1.2	4.1	4.8	2.4	2.5	4.1	0.0	2.1
mad	13.6	2.7	0.9	6.2	3.1	0.0	0.0	0.0
sint	0.6	2.4	7.4	4.3	5.6	2.1	0.0	0.0
other	0.0	1.7	1.9	5.1	8.1	9.6	0.0	9.6

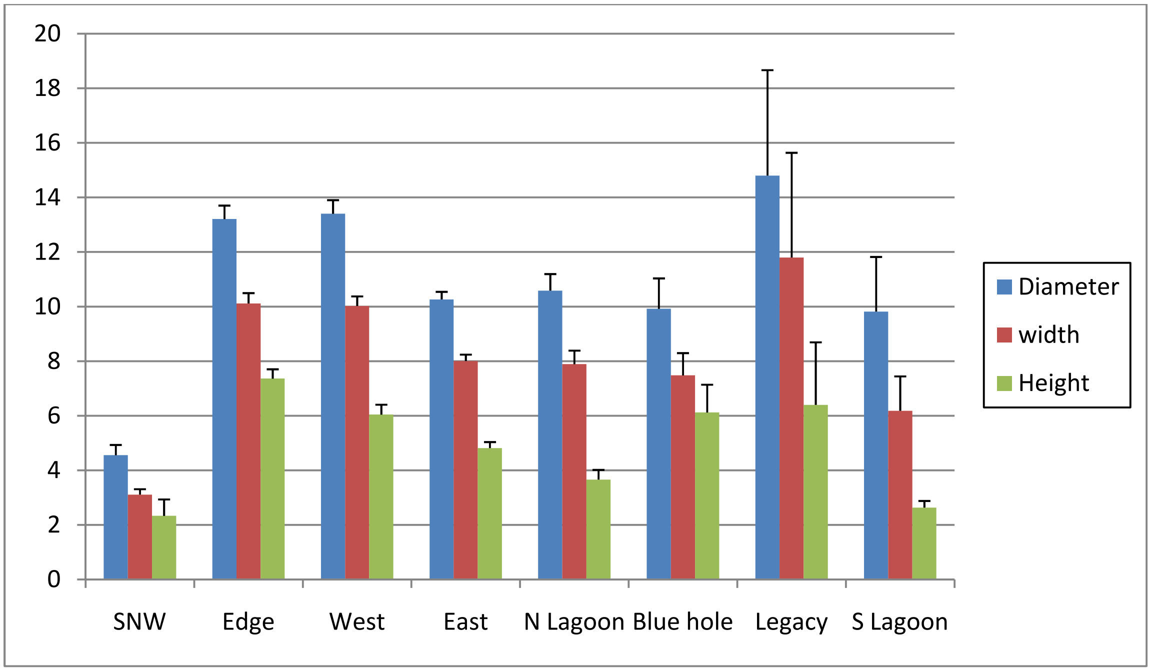


Fig. 28a. Size of *Agaricia agaricites* colonies in eight locations on Cay Sal Bank.

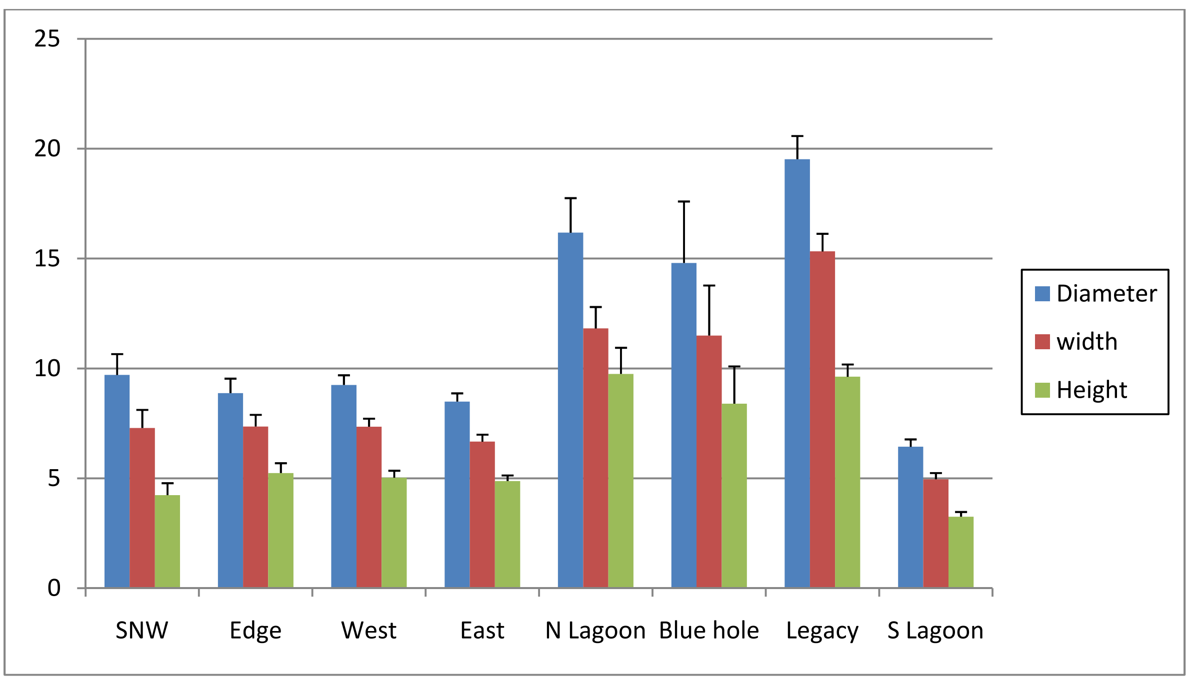


Fig. 28b. Size of *Porites astreoides* colonies in eight locations on Cay Sal Bank.

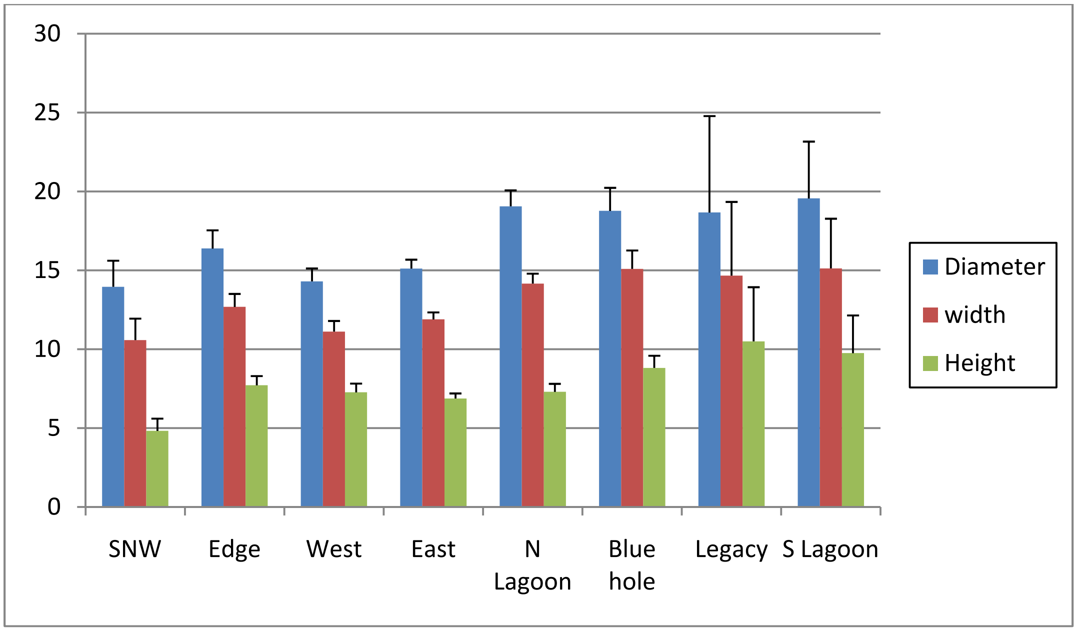


Fig. 28c. Size of *S. siderea* colonies in eight locations on Cay Sal Bank.

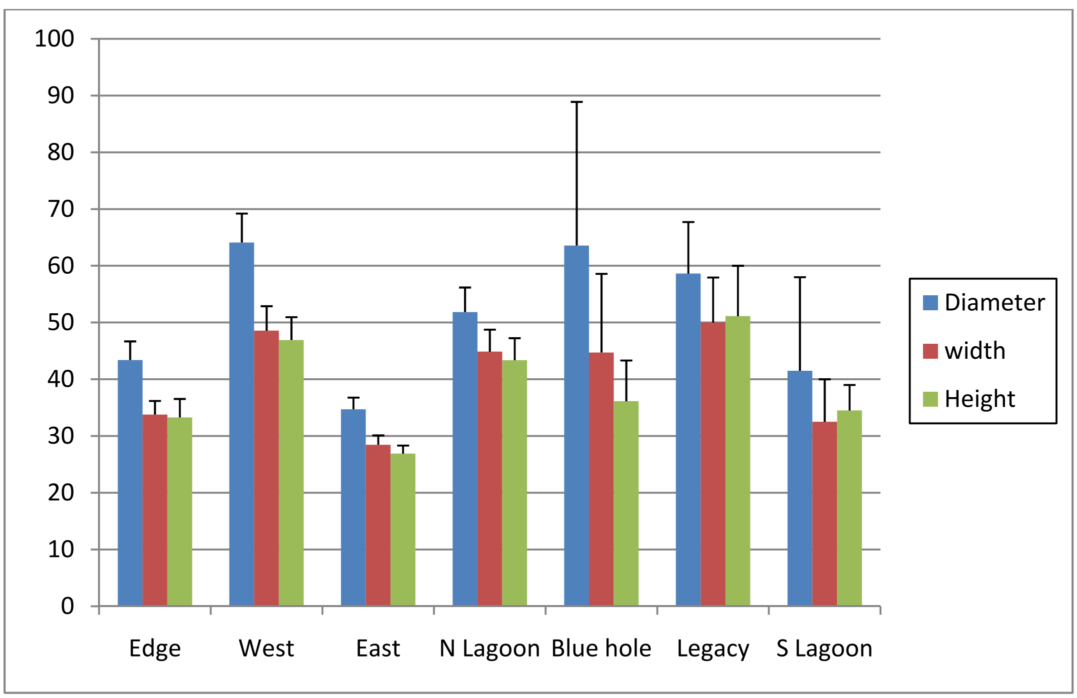


Fig. 28d. Size of *M. annularis* (complex) colonies in seven locations on Cay Sal Bank.

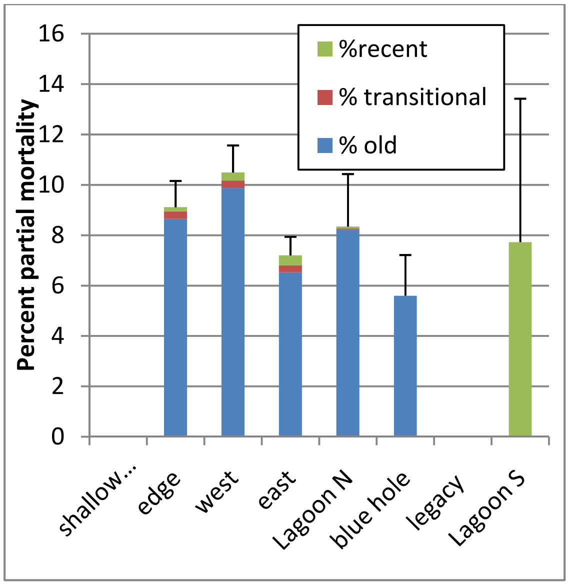


Fig. 29a. *Agaricia agaricites*

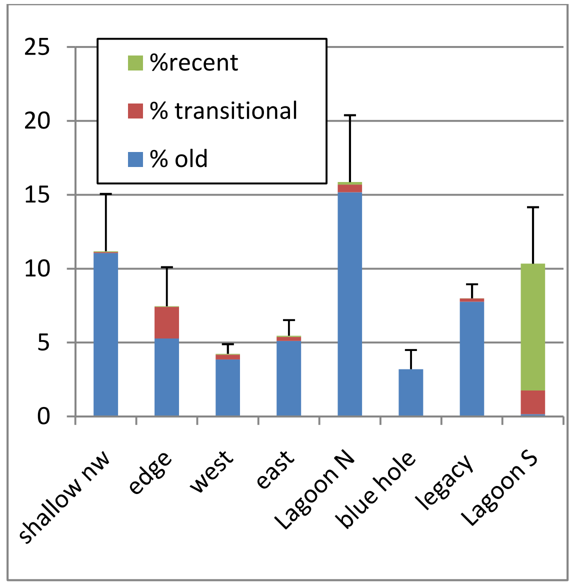


Fig.29b. *Porites astreoides*

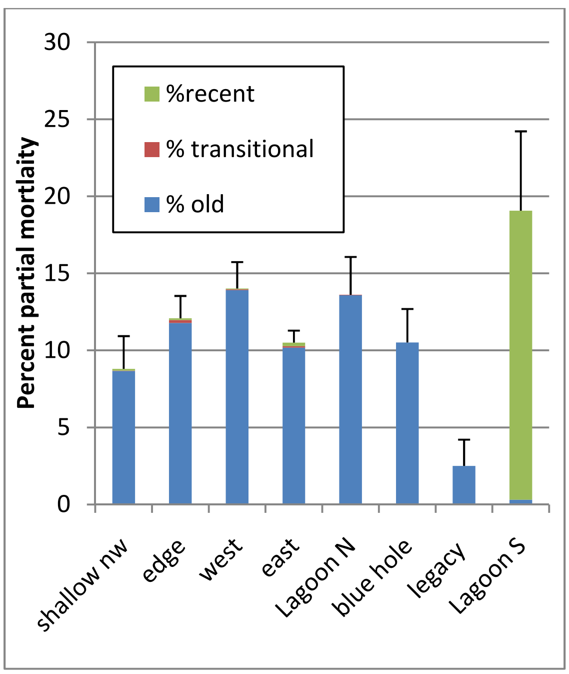


Fig. 29c. *Siderastrea siderea*

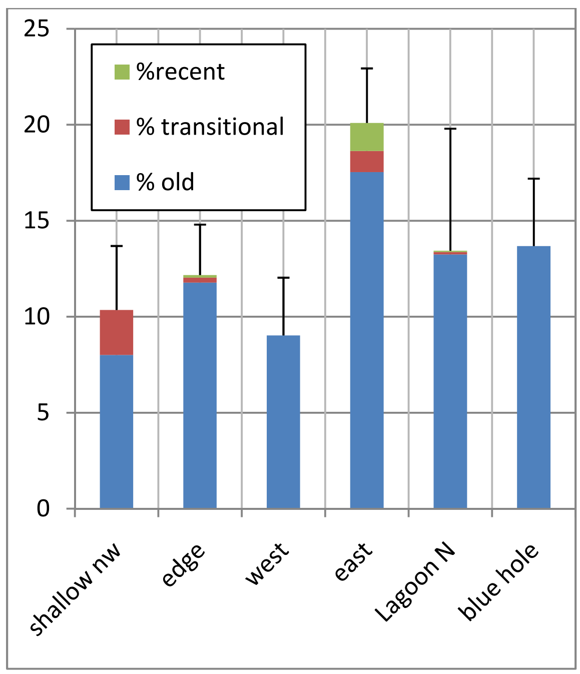


Fig. 29d. *Montastraea cavernosa*

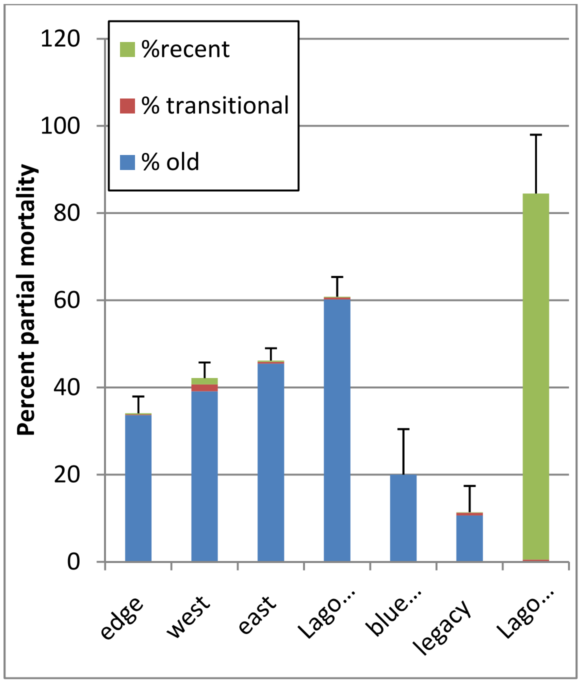


Fig. 29e. *Montastraea annularis (complex)*

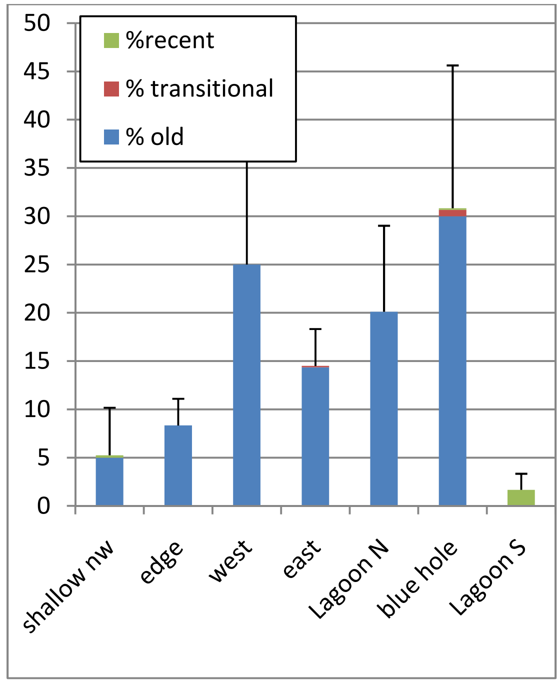


Fig. 29f. Extent of mortality in *Diploria*

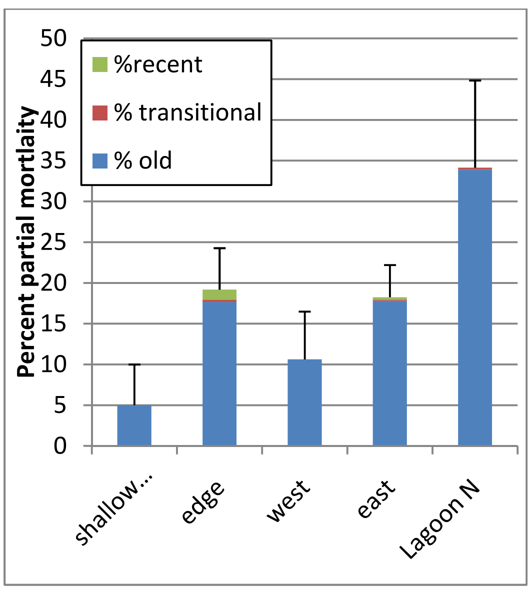


Fig. 29g. *Porites porites*

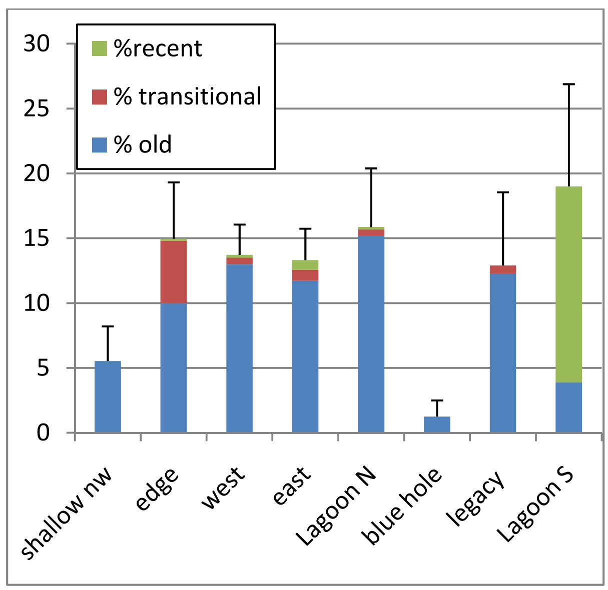


Fig.29h. *Madracis* spp.

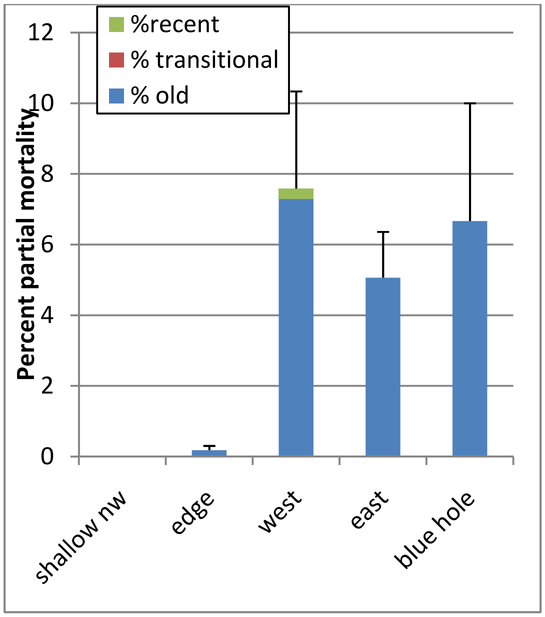


Fig. 29i. *Stephanocoenia intersepta*

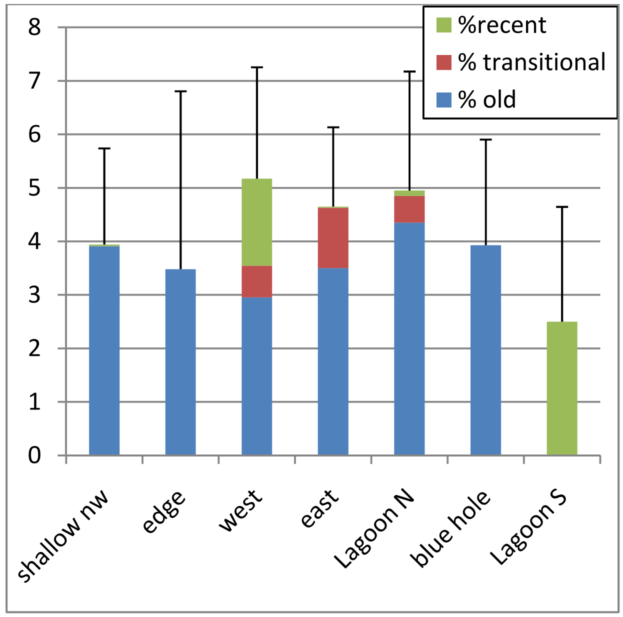


Fig. 29j. All other species (pooled)

Fig. 29. Amount of partial mortality in selected species and/or functional groups pooled for each of the 7 locations. If a species is absent from a particular location, that location is omitted. For locations that contained a particular species, but all colonies were completely live (e.g. no partial mortality), the location is listed. Data are shown as stacked bars subdivided into old mortality (blue), transitional mortality (red) and recent mortality (green). Error bars represent the standard error for total mortality.

Overall, the extent of partial mortality was relatively low in all species except *Montastraea annularis* complex. The vast majority of colonies primarily exhibited old mortality, with low levels of transitional and recent mortality. In general colonies were missing 5-20% of their tissue, with higher levels seen in certain species (e.g. *M. annularis*) and in certain locations. M. annularis (complex) had the highest level of partial mortality overall, except at two sites within the lagoon, the Legacy site and the Blue Hole. *Porites porites*, which occurred in five of the seven locations, had nearly twice as much partial mortality in the lagoon, when compared to fore reef sites. The only exception to this was a shallow lagoonal site at the southwestern end of Cay Sal (Lagoon S). This site had a very low diversity and abundance of corals, most colonies were small and most showed prominent patches of recent mortality affecting 5-20% of their surface. One species, *M. annularis* had a mean of over 80% recent mortality, however only two small colonies of this species were observed within the site.

Site 34 was a unique habitat located within the lagoon at 5-7 m depth on the southwestern end of Cay Sal. It was characterized as a hardground with a thin veneer of sand. Interspersed throughout the site were small coral/sponge bommies. These occurred at a density of 1 every 1-2 square meters. and ranged in size from 20 cm (diameter) to about 2 m. Each bommie was colonized by sponges and coral. The sponge assemblage included a high diversity of growth forms including tube, ball, encrusting and rope sponges. Corals were dominated by small colonies of *Siderastrea*, *Porites astreoides* and *M. cavernosa*, with a number of other species (Fig 30 and 31). There was a notable absence of macroalgae at this site and most corals were in excellent condition.

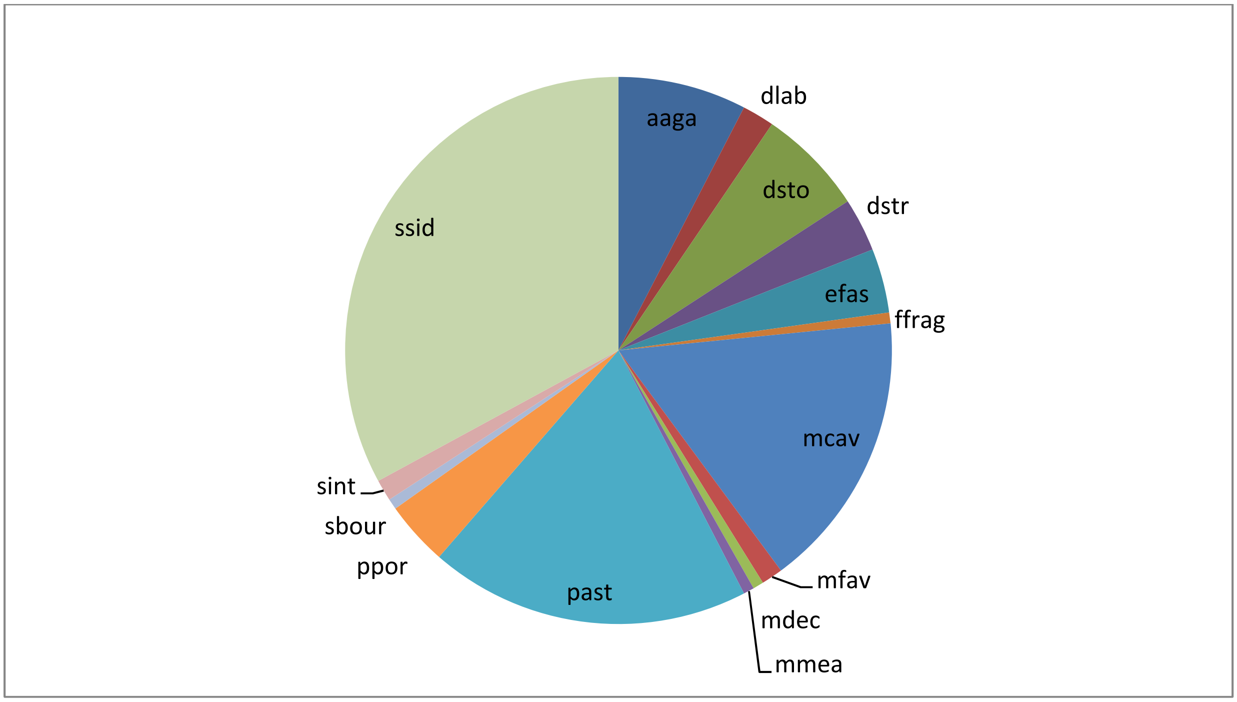


Fig. 30. Abundance of reef building corals within belt transects conducted on reefs off Cay Sal, Bahamas within site 34.

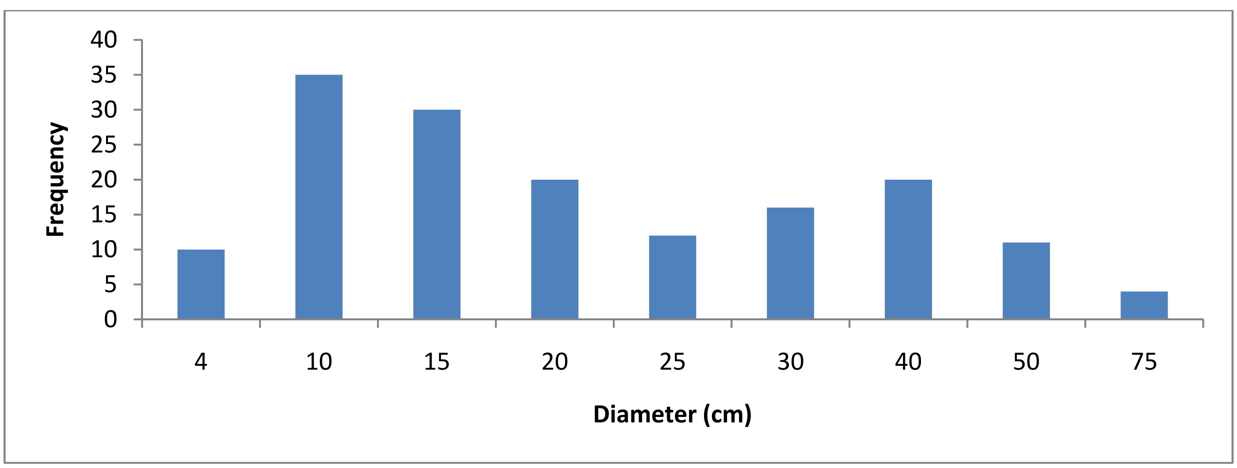


Fig. 31. Proportion of corals (all species pooled) in each size class within site 34.

Acknowledgements

I am indebted to our science team for their hard work. Special thanks for the logistical support and facilities provided by the Golden Shadow Officers and Crew, all of whom worked long hours leading up to the research project and each and every day of this mission to ensure the comfort and safety of our team, and contribute to the Khaled bin Sultan Living Oceans Foundation's mission of ocean conservation. The gracious financial support and state-of-the art research ship provided by HRH Prince Khaled bin Sultan made this Expedition possible and for his generosity and dedication to coral reef conservation, we are forever grateful. The project could not have been completed without the assistance of the Department of Marine Resources, Bahamas, Bahamas National Trust, The Nature Conservancy and the College of the Bahamas. In particular, thanks to Tamica Rahming for logistical support; Eric Carey for assistance in convening several key meetings with Bahamian experts and organizations and for identifying key research sites and needs; and Roland Albury (for the Director of Marine Resources) from the Department of Marine Resources, Ministry of Agriculture and Marine Resources for his assistance with the permit application process and the many changes we proposed throughout the project. I am also grateful for the involvement and commitment of the local scientists from each of these essential Bahamian organizations, including Indira Brown, Lindy Knowles, Leno Davis, Alexio Brown, Tavares Thompson, Alannah Vellacott, Alex Henderson, Agnessa Lundy, and Krista Sherman. The research was conducted under permit MAF/FIS/17 .

Scientific Team and responsibilities

Name	Duty
Dr. Andrew Bruckner	Lead scientist; benthic assessments including coral belt transects, recruitment quadrats, coral disease surveys, resilience assessment
Capt Philip Renaud	Photo-documentation; recruitment quadrats
Amanda Williams	Point intercept transects; recruitment quadrats
Dr. Judith Lang	Coral assessments, algal assessments
Dr. Bernhard Riegl	Coral assessments, recruitment, phototransects
Dr. Sam Purkis	Groundtruthing
Jeremy Kerr	Groundtruthing
Dr. Sonia Bejarano	Herbivorous fish surveys, herbivory research, fish behavior
Ken Marks	Fish community structure along belt transects
Dave Grenda	Fish community structure along belt transects
Alexandra Dempsey	Point intercept transects; recruitment quadrats
Indira Brown	Roving fish surveys
Lindy Knowles	Fish transects
Leno Davis	Roving fish surveys
Alexio Brown	Roving fish surveys
Tavares Thompson	Roving fish surveys
Alannah Vellacott	Benthic and fish assessments
Alex Henderson	Roving fish surveys
Bill Mills/Charles Kinder	Video documentation

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

Appendix III

Surveyor:	Date:	Site Name:			AGRRA Code:	
Day #: Site #:	Latitude:		Longitude:		Bottom Temp.:	°C / °F
Transect #:	Start Time:		Start Depth: ft / m			
Site Comments:			Transect Comments:			
Group	**0-5 cm**	**6-10 cm**	**11-20 cm**	**21-30 cm**	**31-40 cm**	**> 40 cm**
Family Angelfish						
Butterflyfish						
Grunt						
Parrotfish						
Grouper/Hind						
Snapper						
Surgeonfish						
Triggerfish						
Chub						
Moray						
Species Hogfish						
Puddingwife						
Slippery Dick						
Spanish Hogfish						
Yellowhead Wrasse						
Orangespotted Filefish						
Scrawled Filefish						
Whitespotted Filefish						
Jolthead Porgy						
Pluma						
Saucereye Porgy						
Sheepshead Porgy						
Balloonfish						
Porcupinefish						
Bar Jack						
Permit						
Bandtail Pufferfish						
Great Barracuda						
Spotted Trunkfish						
Yellowtail Damselfish						
Lionfish						

Surveyor:	Date:	Site Name:			AGRRA Code:	
Day #: Site #:	Latitude:		Longitude:		Bottom Temp.:	°C / °F
Transect #:	Start Time:		Start Depth: ft / m			
Site Comments:			Transect Comments:			
Group	**0-5 cm**	**6-10 cm**	**11-20 cm**	**21-30 cm**	**31-40 cm**	**> 40 cm**
Family Angelfish						
Butterflyfish						
Grunt						
Parrotfish						
Grouper/Hind						
Snapper						
Surgeonfish						
Triggerfish						
Chub						
Moray						
Species Hogfish						
Puddingwife						
Slippery Dick						
Spanish Hogfish						
Yellowhead Wrasse						
Orangespotted Filefish						
Scrawled Filefish						
Whitespotted Filefish						
Jolthead Porgy						
Pluma						
Saucereye Porgy						
Sheepshead Porgy						
Balloonfish						
Porcupinefish						
Bar Jack						
Permit						
Bandtail Pufferfish						
Great Barracuda						
Spotted Trunkfish						
Yellowtail Damselfish						
Lionfish						

References

Agassiz, A. 1894. Reconnaissance of the Bahamas and the elevated reefs of Cuba in the stream yacht "Wild Duck" January to April, 1893. Bull. Mus. Comp. Zool. Harvard. 26:81-84.

Banks, K.W. 1999. Analysis of Modern Carbonate Sediments: Lubber's Bank, Abaco, Bahamas. M.S. Thesis. Florida Atlantic University, Boca Raton, Florida, USA. 104p

Goldberg, W.M. 1983. Cay Sal Bank, Bahamas: A biologically impoverished, physically controlled environment. Atoll Research Bulletin. 273:1-23.

Bellwood, D.R. 1995. Direct estimate of bioerosion by 2 parrotfish species, *Chlorurus gibbus* and *C. sordidus*, on the Great Barrier Reef, Australia. . Marine Biology 121:419-429.

Bohnsack, J.A. and D.E. Harper. 1998. Length-weight relationships of selected marine reef fishes from the southeastern United States and the Caribbean. National Oceanic and Atmospheric Administration Technical Memorandum NMFS-SEFC-215

Brock, V.E. 1954. A preliminary report on a method of estimating reef fish populations. Journal of Wildlife Management 18:297-308.

Bruggemann, J.H., M.W.M. Kuyper, and A.M. Breeman. 1994. Comparative analysis of foraging and habitat use by the sympatric Caribbean parrotfish *Scarus vetula* and *Sparisoma viride* (Scaridae). Marine Ecology Progress Series 112:51-66.

Choat, J.H. and K.D. Clements. 1993. Daily feeding rates in herbivorous labroid fishes. Marine Biology 117:205-211.

Mumby, P.J., A.R. Harborne, J. Williams, C.V. Kappel, D.R. Brumbaugh, F. Micheli, K.E. Holmes, C.P. Dahlgren, C.B. Paris, and P.G. Blackwell. 2007. Trophic cascade facilitates coral recruitment in a marine reserve. Proceedings of the National Academy of Sciences of the United States of America 104:8362-8367.

Polunin, N.V.C., M. Harmelin-Vivien, and R. Galzin. 1995. Contrasts in algal food processing among 5 herbivorous coral reef fishes. Journal of Fish Biology 47:455-465.

Raymundo L.J., C.S. Couch, A.W. Bruckner, C.D. Harvell, T.M. Work, E. Weil, C.M. Woodley, E. Jordan-Dahlgren, B.L. Willis, G.S. Aeby, and Y. Sato. 2008. Coral Disease Handbook: Guidelines for assessment, monitoring and management. CRTR, Australia 131 pp

Sullivan Sealey, K.M. and G. Bustamante. 1999. Setting geographic priorities for marine conservation in Latin America and the Caribbean. The Nature Conservancy, Arlington, Virginia, USA. 125pp.

Trumbull, W.J. 1988. Depositional History of a Windward, Open Marginal Lagoon: Northern Great Bahama Bank. M.S. Thesis, University of North Carolina at Chapel Hill, 122p.