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# Mapping the return of acroporid corals on fringing reefs along the west coast of Barbados

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ABSTRACT

Up until the 1980s, *Acropora* species were among the dominant coral reef building species in the western Atlantic and considered a key component in a healthy reef system. However, *Acropora* species experienced precipitous declines in population density, colony size, and overall health starting in the late1970s, largely as a result of the region-wide, genus-specific white band disease epidemic, acting together with other local stressors such as poor water quality and over-fishing. Western Atlantic *Acropora* species are now listed on CITES Appendix II, as "Critically Endangerd" by the IUCN, and as "Threatened" under the US Endangered Species Act. More recently there have been several reports suggesting that these species may be starting to recover in some locations across the Caribbean. In Barbados, anecdotal reports and photographs indicate a potential recovery of acroporids in several locations along the west and south coasts of the island. The potential recovery of acroporids on nearshore reefs in Barbados is of particular interest to the Government's Coastal Risk Assessment and Management Programme (CRMP) and is the subject of the current study. A total of 46 fringing reefs were surveyed along the west coast of Barbados from Six Mens Bay in the north to Batts Rock in the south, from June 13$^{th}$ to August 22$^{nd}$ 2015, by free-divers. The GPS co-ordinates, appearance, condition and size of every *Acropora* spp. colony found were recorded. A total of 707 colonies, consisting of both *A. palmata* and *A. prolifera*, were found and their positions were added to a detailed benthic habitat map. Colonies were found along the entire west coast and overall were most abundant in the spur and groove and reef crest zones of the fringing reefs. Abundance and density were generally low and varied considerably among reefs, although there was no obvious spatial pattern along the coast. Correlation analyses with reef area and various secondary datasets on indices of reef health indicated that both *Acropora* spp. abundance and density were significantly and positively correlated with mean % live coral cover and with *Diadema* urchin density although the latter relationship was driven by a single reef with exceptionally high densities of both. More acroporids were found on larger reefs, but reef area does not appear to be influencing colony density. General tissue lesions (likely caused by a combination of disease and predation) were apparent on almost half the colonies, and their frequency of occurrence increased with colony size. Likewise the occurrence of boring Christmas tree worms was common, being present on just over a quarter of the colonies, and also positively correlated with colony size. Presence of predatory snails (9.6% colonies) and fireworms (< 1%) fell within the lower end of the ranges reported by other studies, and was not strongly influenced by colony size. This study reports on the very early stages of a recovery of acroporids on the fringing reefs along the west coast of Barbados and provides a valuable detailed baseline dataset to guide conservation and rehabilitation efforts, and for comparative studies to monitor recovery success in the future. The results are particularly relevant to the ongoing work of the Government's CRMP with a focus on rehabilitating west coast fringing reefs.


Keywords: Acroporids, recovery, fringing reefs, Barbados

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## Table of Contents

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# 1 INTRODUCTION

## 1.1 Acroporid corals and their importance to reefs

*Acropora* species are shallow water corals, often found in close proximity to the coastline, throughout the Caribbean (Aronson et al. 2008a,b). In the Atlantic there are two true species, *Acropora palmata* (elkhorn coral) and *Acropora cervicornis* (staghorn coral) and a hybrid of these two species *Acropora prolifera* (fused staghorn coral) (Vollmer and Palumbi 2002; Van Oppen et al. 2000). The *A. palmata* species is typically found in reef zones that experience high wave action (Aronson et al. 2008b), compared to *A. cervicornis* which is usually found in the reef zones with greater depth and lower wave action (Aronson et al. 2008a). All three of these Acroporids can reproduce asexually through fragmentation, which is common with storm damage (Baums, Miller and Hellberg 2005). They also reproduce sexually, with the exception of the hybrid species, *A. prolifera*. *A. palmata* and *A. cervicornis* are broadcast spawners and reproduce sexually through the release of gametes into the water column, which occurs once annually (Baums, Miller and Hellberg 2005). *A. palmata* and *A. cervicornis* have distinguishing morphologies, however the hybrid species can be difficult to distinguish as it can express a variety of morphologies, some of which are very similar to one or the other of the two true species (Boulon et al. 2005). This is because the morphology of an *A. prolifera* colony will more closely resemble the species that contributed the egg and mitochondria during the reproductive event (Boulon et al. 2005).

Acroporid corals have played an important role in the history of Caribbean reefs as a prominent foundation species (Lighty, Macintyre and Stuckenrath 1982; Jackson 1992; Macintyre, Glynn and Toscano 2007). In this century, prior to the 1980s, *Acropora* species were among the dominant species in the western Atlantic and were considered a key component in a healthy reef system (Bruckner et al. 2002; Precht, Robart and Aronson 2004; Rogers and Muller 2012). This is because their branching shape and relatively rapid growth compared to most coral genera marks them among the more important framework building corals (Rogers and Muller 2012). This framework is important for wildlife habitat, as the three dimensional shape creates areas of protection for reef dwellers (Lirman 1999; Baums, Miller and Hellberg 2005). Furthermore, the tall robust branching structure, especially of *A. palmata*, allows it to reflect and absorb wave action, affording enhanced protection of shorelines (Bruckner et al. 2002).

## 1.2 Decline of acroporid species in the western Atlantic

Despite their status as foundation species across the western Atlantic coral reefs for several millennia (especially *A. palmata*, see Lighty, Macintyre and Stuckenrath 1982), *Acropora* species in this region have experienced precipitous declines in population density, colony size, and overall health starting in the 1970s largely as a result of a genus-specific disease epidemic (Aronson and Precht 2001; Bruckner 2002; Boulon et al. 2005). The disease, known as White Band Disease (WBD) is caused by an epizootic bacterium that only affects acroporid corals (Williams and Miller 2005). This disease has had devastating impacts on the acroporids and has been implicated as the primary cause for these species reaching such critically low numbers across the Caribbean (Precht, Robbart and Aronson 2004).

As colonies became sparse, they began to have low reproductive yields since the distance between colonies grew too far to allow for successful fertilization of gametes (Precht, Robbart and Aronson et al. 2004). This reduction in fertilization success meant that colonies began to rely more heavily on asexual fragmentation for their propagation, which has continued for several decades (Zubillaga et al. 2008). This reliance on asexual reproduction presented a greater risk to the acroporid populations across the region as it increased susceptibility to disease and other impacts due to the reduction in genetic variation (Zubillaga et al. 2008; Japaud et al. 2015). The potential recovery of the acroporids from this disease epidemic has been further hampered by local impacts linked to surrounding activities both on the land and at sea (Grober-Dunsmore, Bonito and Frazer 2006; Macintyre, Glynn and Toscano 2007). Such activities can include agricultural, industrial and domestic activities, heavy fishing of important herbivorous and predatory reef fishes as well as construction or changes to the shoreline (Macintyre, Glynn and Toscano et al. 2007). Some of the problems that arise from these activities include deterioration of water quality through waste water run-off and sedimentation; physical damage; and disruption of the trophic balance in reef communities which can negatively affect the health of most reef corals including the acroporids (see Birkeland 1997). These stressors can lead to a loss of structural integrity, low reproductive yields and higher mortality and have been implicated in the lack of recovery of Acroporids in the US Virgin Islands (Grober-Dunsmore, Bonito and Frazer 2006). Furthermore, acroporids experience predation from several invertebrates such as *Coralliophila abbreviata* (snail) and *Hermodice carunculata* (fireworm) and grazing damage from vertebrates such as *Stegastes planiforns* (three-spot damselfish) (Precht et al. 2002; Boulon et al. 2005), and are also affected by boring organisms such as *Spirobranchus giganteus* (Christmas tree worm). Presence of these organisms on colonies can lead to structural damage and mortality (Boulon et al. 2005), and heavy fishing pressure (which results in a reduction of the top down control of these organisms) as well as declines in the density of acroporids have been implicated in increased damage by these invertebrates (Baums, Miller and Szmant 2003). External impacts, such as the regional die-off of the herbivorous urchin, *Diadema antillarum* in the early 1980s, and the on-going global warming trend are also having significant negative impacts on Caribbean reef corals (Jackson et al. 2014). As with all coral species, acroporids are temperature and depth sensitive and are therefore affected by changes in sea temperatures and sea level caused by climate variability (Gardner et al. 2003; Precht and Aronson 2004), putting them at further risk in the future. Another issue linked to climate variability is an increase in the frequency and intensity of major hurricanes and other storms. This intensification of storms can increase the rate of erosion caused by breakage from wave action. As the rate of erosion increases it becomes more difficult for the coral to recover in the wake of a storm (Macintyre, Glynn and Toscano 2007).

As a result of this sharp decline in acroporid populations and the observed inability of the species to recover a number of actions aimed at increasing the awareness of, and conservation status of, these species were taken. All three species were listed on Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 1985. Subsequently, the US National Marine Fisheries Service (NMFS) identified the three species as ‘Candidate Species’ for listing under the US Endangered Species Act (ESA) in 1999 and they were transferred to the ESA ‘Species of Concern’ list in 2004. In March of the same year a US NGO, the Center for Biological Diversity (CBD) petitioned the NMFS to list the three *Acropora* species as endangered or threatened species under the ESA (Precht, Robbart and Aronson 2004). This initiated a thorough review of the species and eventual formal listing in 2006 of the two true species, *A. palmata* and *A. cervicornis* as ‘threatened’ under the ESA (NOAA Federal Register

71 FR 26852). *A. prolifera* however, did not qualify for independent listing due to the fact that it is considered a hybrid species. As pointed out by Bruckner et al. (2002), this listing meant a compulsory strengthening in the US of legal protection and conservation efforts, as well as an increase in funding to support recovery programmes and management initiatives for these species. In 2008 NMFS designated 'Critical Habitat' for both acroporids, giving them further legal protection in the US (73 FR 72210). Further, in 2012 the NMFS proposed reclassifying the two *Acropora* species to 'endangered' status, but a determination was made in 2014 that they remain listed as 'threatened' (79 FR 67358). In 2008 both *A. palmata* and *A. cervicornis* were also listed on the International Union for the Conservation of Nature (IUCN) Red List as 'Critically Endangered', noting that some areas had experienced declines in populations as great as 97% (Aronson et al. 2008a,b; Japaud et al. 2015; see also Boulon et al. 2005 for review).

### 1.3 Signs of recovery of acroporids in the western Atlantic

Despite significant concerns regarding the inability of acroporids to recover across the wider Caribbean (Boulon et al. 2005; Grober-Dunsmore, Bonito and Frazer 2006; Macintyre, Glynn and Toscano 2007) there is new evidence of a slow recovery in some areas. For instance, Macintyre and Toscano (2007) report evidence of recovering *A. palmata* at Carrie Bow Cay, Belize, and Zubillaga et al. (2008) report evidence of recovery of *A. palmata* in Los Roques, Venezuela. A recent survey in St. John, US Virgin Islands demonstrated an increase in the incidence of larger *Acropora* colonies on ten reefs over a span of six years, indicating that the growth rate in this area is faster than the rate of damage, which suggests that there is recovery taking place (Muller, Rogers and van Woesik 2014). Larson et al. (2014) also completed a study in the Gulf of Mexico that indicated recovery of *A. palmata* on 24 reefs in the Veracruz Reef System, where they found that the species was widely distributed in high abundances across the reef system and that the colonies were healthy with high reproductive potential.

### 1.4 Acroporids in Barbados

Even though fossil evidence indicates that *Acropora* corals once dominated the coral reef communities of Barbados, like other places across the Caribbean, these corals have been almost completely eradicated in the island's coastal waters (Lewis 1984; Macintyre, Glynn and Toscano 2007; see also Connell 2013 for review). However, recent evidence including: anecdotal reports from recreational and research divers; photographs taken by research divers; and annotated photographs shared on the web by D. Patriquin in 2015 (http://versicolor.ca/reef/) indicate a potential recovery of acroporids in several locations along the west and south coasts of Barbados. Although the locations of a few of these colonies have been recorded, and some colonies are being used in the ongoing lesion recovery and reproductive condition work by the Coastal Risk Assessment and Management Programme (CRMP) of the Government of Barbados Coastal Zone Management Unit (CZMU) (Baird 2015), their exact locations and size have not been methodically or comprehensively documented on any of the island's reefs.

The possible natural recovery of acroporids in Barbados is of particular relevance to the Government's CRMP project, currently funded through the Inter-American Development Bank (IDB Loan 2463/OC-BA). This project is contributing to the efforts of the CZMU to strengthen the Barbados economy by restoring marine ecosystem health and building a more resilient coast. As part of these efforts, a coral nursery programme is being considered for implementation and the species of greatest interest are the acroporids, in view of their preference for shallow (nearshore) environments, fast growth rates, complex 3-D growth form, and frequent use in other coral nursery and rehabilitation projects elsewhere in the Caribbean (Bruckner and Bruckner 2001; Baums 2008; Young, Schopmeyer and Lirman 2012; Lohr et al. 2015).

## 2 RATIONALE

Although acroporids are among the foundation species of Barbados' shallow coral reef habitats, they have suffered huge population declines in recent decades, similar to most other Caribbean countries where they virtually disappeared in the 1980s. Concomitant with this, the fringing reefs along the west coast of Barbados have suffered significant degradation (Office of Research 2014) prompting interest in engineering solutions and reef restoration efforts to stem the coastal erosion now being experienced. Acroporid corals probably offer the best hope for restoration of Barbados' fringing reefs and there is now some evidence that the acroporids may be undergoing a slow recovery in the island. However, this 'recovery' has not been formally documented nor has there been any attempt to map areas where recovery appears to be taking place, or to examine what factors may be influencing recovery patterns.

## 3 RESEARCH AIM AND OBJECTIVES

The aim of this research project was to investigate and document any signs of a return of acroporid corals to the fringing reefs along the west coast of Barbados, and to explore possible factors which may be influencing the pattern of population recovery. The specific objectives of the research were:

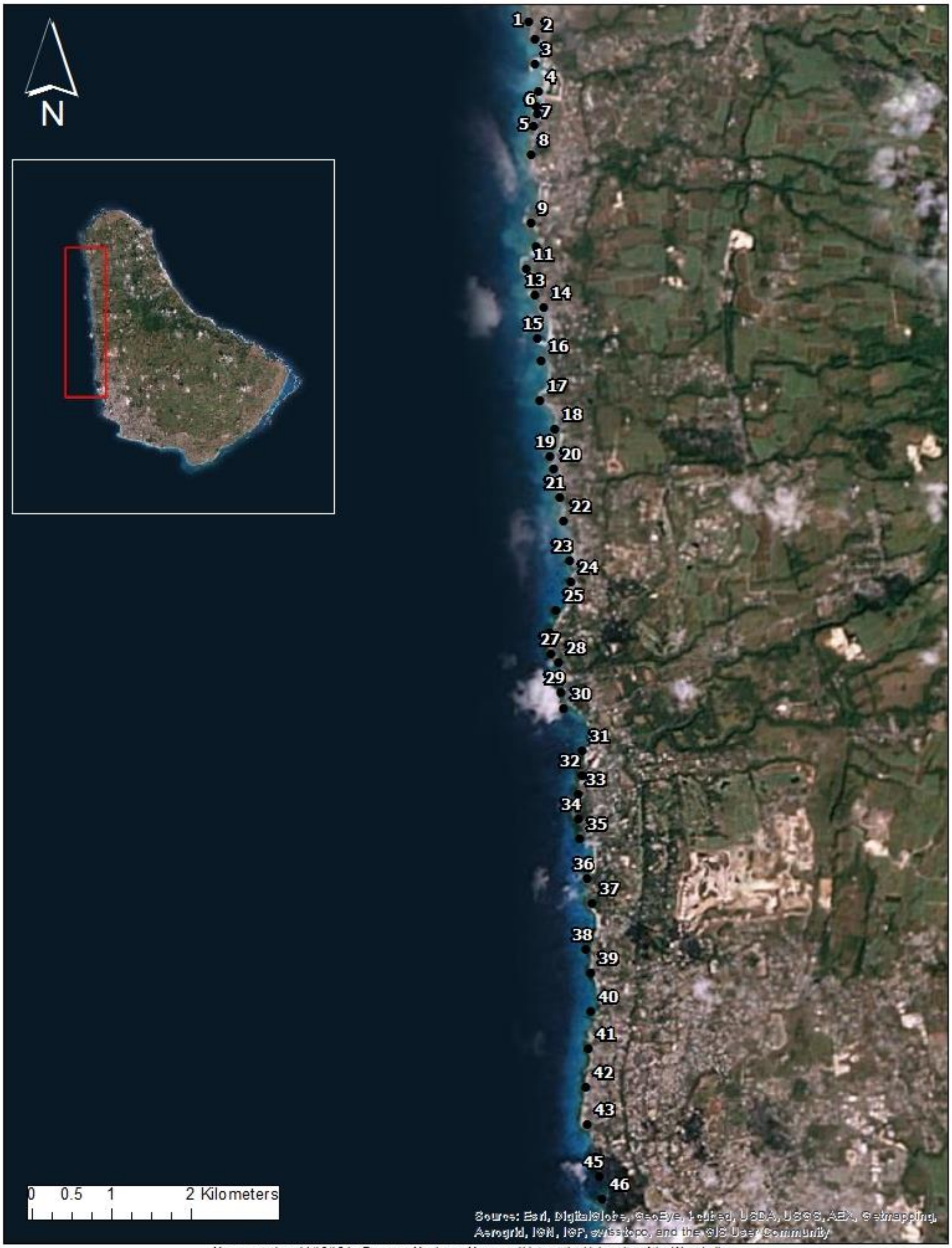
1. To document and map the locations, size and visual health status of all acroporid coral colonies on the fringing reefs and breakwaters along the west coast of Barbados.

2. To explore possible environmental correlates (e.g. area of fringing reef; area of reef zones; and indices of reef health) with presence/absence and or density of Acroporid colonies along the west coast.

## 4 METHODS

### 4.1 Study sites

The study area covered the west coast of Barbados from Six Mens Bay in the north to Batts Rock in the south. Every nearshore fringing reef and artificial breakwater along this stretch of approximately 15.5 km of coastline was sampled (Figure 1). This included 17 of the fringing reefs in the Government's long-term reef monitoring programme (RMP) (Office of Research 2014) and 36 reefs surveyed by Connell (2013). These fringing reefs extend from the shoreline up to about 330 m from shore and from approximately 41-611 m in width, as measured parallel to the shoreline (Connell 2013). Each fringing reef was identified on satellite imagery using Google Earth, and individual images were printed and laminated in order to use as a guide in the field.




Map created on 14/10/15 by Roxanne MacLean, Msc. candidate at the University of the West Indies.

**Figure 1. Approximate locations of the 46 fringing reefs along the west coast of Barbados surveyed for *Acropora* species from June 13th to August 22nd, 2015.**

## 4.2 Field data collection

### 4.2.1 Survey techniques

Visual surveys for colonies of all *Acropora* species were conducted on each of the 46 reefs via free diving with mask and snorkel. Each reef was temporarily marked off into sections approximately 30 m in width using anchored dive buoys. These sections were methodically surveyed following a standardized zigzag search pattern (Figure 2) by at least one person snorkelling and a second person above water in a kayak (Figure 3). The kayaker was responsible for setting the dive buoys, taking GPS coordinates with a handheld Garmin GPS72H unit, recording the data on a waterproof slate, and ensuring snorkelers maintain their search pattern. The kayaker and dive buoys, as well as the Folkestone Marine Reserve patrol boat (Figure 3) provided safety for the snorkelers by warning boaters and keeping traffic out of the survey area. The exact position of each colony that was located by the snorkeler was marked by the kayaker using the GPS unit. Where colonies were very close together, one GPS point was taken for a central colony and the nearest distance and direction to the neighbouring colonies were measured to the nearest 0.1 m with a survey tape.

On one reef, Mullins (reef 15), where a very high density of colonies was found between approximately 80 and 180 m from shore, the survey method used for other reefs was modified as it was virtually impossible to distinguish which colonies had been recorded and which had not. In this case, this central part of the reef was surveyed using a benthic transect method. For this method a series of straight-line benthic transects stretching north to south across the width of the reef and separated by approximately four metres were temporarily marked using survey tapes. The north start point and the south end point were marked for each transects using the GPS unit. Each transect was then followed by a snorkeler who noted the number of *Acropora* colonies found in each size class (fragment, small, medium, large and extra-large; Table 1) within two metres left and right of the tape. As such, the exact location of each colony was not recorded.

**Table 1. Range of maximum diameters used to classify *Acropora* colonies into specific size classes.**

| Range of Max. Diameter (cm) | Size Class |
|---|---|
| **<10** | Fragment |
| **10-30** | Small |
| **30-50** | Medium |
| **50-100** | Large |
| **>100** | eXtra Large |

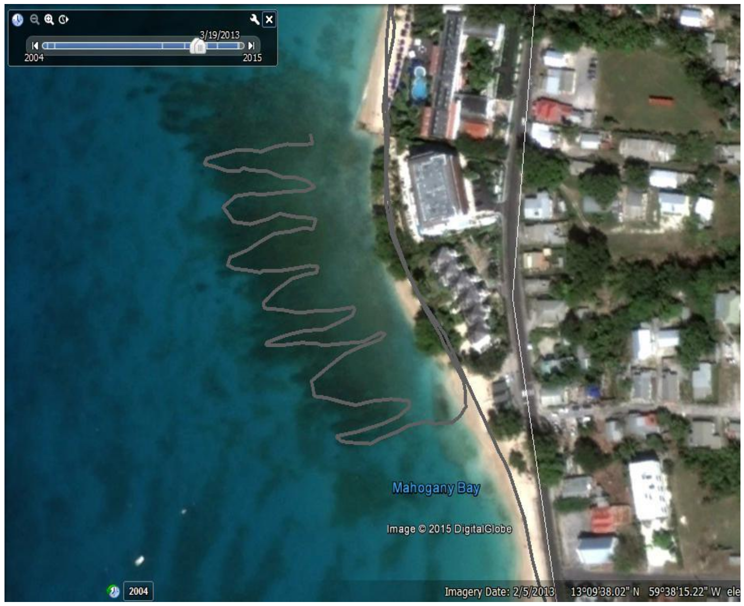



**Figure 2**. **An example of the route (traced using the GPS unit) taken by the kayak setting out marker buoys on a fringing reef, to ensure that snorkelers maintained a methodical search pattern during *Acropora* surveys**.


**Figure 3. The kayak with dive flag and the Folkestone Marine Reserve patrol boat assisting with the *Acropora* surveys of the west coast fringing reefs.**

### 4.2.2 Biological data

Where ever possible, each *Acropora* colony encountered during the surveys was measured for maximum height to the nearest 0.5 cm using a metal ruler and was photographed from above with an underwater camera (Olympus Tough TG3 or Nikon Coolpix S32) with a 20 cm long by 2 cm wide graduated pipe placed on or beside the coral as a scale (Figure 4). Some of the colonies could not be measured or photographed. These included: colonies in very shallow water where the camera could not be held high enough above the subject to get a complete planar surface photograph; colonies in rough water that could not be measured or photographed for fear of

**Figure 4. Photographs of the free diving method used to measure and photograph *Acropora* colonies found along the west coast of Barbados. *Left* - shows measurement of maximum colony height. *Right* - shows placement of scale bar for planar photograph.**

damaging the colony; colonies that were extremely dense (e.g. Mullins reef 15) that were not photographed or measured due to time constraints in the field. Photographs were used as a record of appearance and were later analysed to determine size and health condition of each colony.

## 4.3 Secondary data

Existing data for the fringing reefs in this study were used to investigate possible environmental correlates with the acroporid presence/abundance data. These data included: a semi-qualitative index of general reef health for each of the fringing reefs (Connell 2013); a digitized habitat map covering all of the fringing reefs and showing the separation of reef flat, reef crest, and spur and groove habitat zones (IDB-CZMU CRMP Project unpubl.); and quantitative reef monitoring programme data on the mean percent macro-algae cover, mean percent live coral cover, *Diadema* density and number of coral species collected in the summer of 2012 for 17 of the fringing reefs as part of the Government's long-term Reef Monitoring Programme (RMP) (Office of Research 2014).

## 4.4 Data handling and analysis

### 4.4.1 Mapping

The GPS coordinates of all *Acropora* colonies recorded in this survey were downloaded using MapSource software and exported to a Microsoft Excel database (Appendix 1). These coordinates were added as X,Y data into ArcGIS software and plotted on a georeferenced satellite image basemap of the west coast of Barbados (DigitalGlobe) using ArcMap 10.2. All colony locations were also overlaid on a 2015 digitized benthic habitat map (IDB-CZMU CRMP Project unpubl.) showing the areas of reef coral spur and groove, reef crest, and reef flat zones. Using this benthic habitat map, the areas of each fringing reef and of each reef zone were calculated (by calculating the geometry in ArcMap 10.2) and the number of colonies in each of these reef zones along the west coast was then extrapolated. Since the GPS coordinates for Mullins (reef 15) only included the north start and south end points of each transect, the locations of each colony were estimated by distributing the number of colonies found in each transect equally across the entire stretch of the belt transect.

### 4.4.2 *Acropora* characteristics

#### 4.4.2.1 Size

Colony size attributes (maximum measured height in cm, calculated planar surface area in $m^2$, calculated maximum diameter in cm, and assigned size class [F, S, M, L, X see Table 1]) were also recorded in the Excel database for each colony measured and photographed (Appendix 1).

Planar photographs taken of each individual colony were used as a record of their appearance and analysed using Image J software to calculate each colony's planar surface area and determine the maximum diameter (as measured across the widest part of the colony; Figure 5). Each colony was also categorised based on their maximum diameter as either a Fragment, Small, Medium, Large or eXtra-large colony (Table 1). In the case of Mullins (reef 15) for colonies that were not measured or photographed, but were recorded in the field by number and size class only, the planar surface area for each colony was estimated based on the mean planar surface area for each size class calculated for all other colonies measured across all reefs combined.

#### 4.4.2.2 Health indices

Each colony was assessed from the individual colony photographs for presence of any invertebrate predators including *Coralliophila abbreviata* (snails) and *Hermodice carunculata* (fire worms), borers such as *Spirobranchus giganteus* (Christmas tree worms), tissue lesions or bleaching (possibly from disease) or other disturbances such as whether or not the colony was overturned (Figure 6). Any colonies that were not photographed (including a high proportion of those on Mullins reef 15) were not scored for health indices.

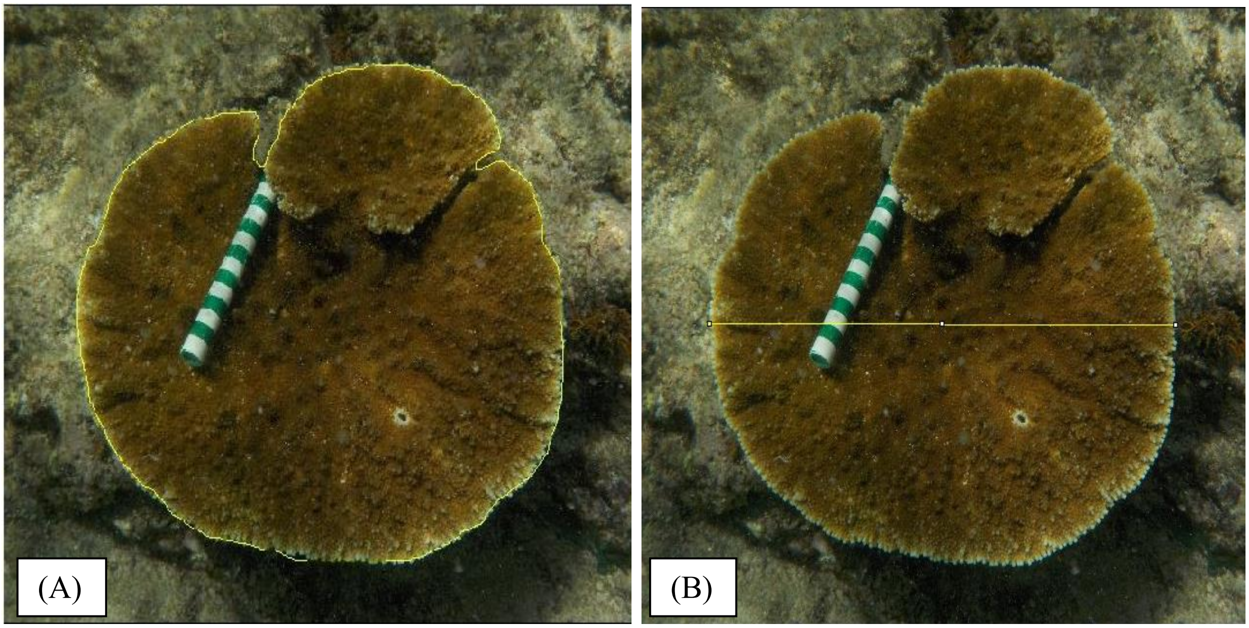



**Figure 5. Analysis of *A. palmata* colony photographs taken with the scale bar along the west coast of Barbados from June 13th to August 22nd 2015, using Image J software showing: (A) an example of the planar surface area calculated from the perimeter (drawn in yellow); and (B) the maximum diameter (drawn as yellow line).**

#### 4.4.2.3 Abundance and density indices

Abundance and density was measured using two different indices. Firstly abundance was measured as the number of colonies found and density was measured as the number per hectare of reef. This was calculated for each fringing reef and for each habitat zone separately. A second measure of abundance was taken as the planar surface area of *Acropora* colonies, and the second measure of density was measured as area of total colony surface area per benthic area of reef and presented as a percent benthic cover by *Acropora* for each reef.

The reef areas and areas of each habitat zone were calculated to the nearest $m^2$ from the benthic habitat map using ArcGIS software and later converted to hectares in Excel.

### 4.4.3 Environmental correlates

The numerical reef health index for each of 36 reefs assigned by Connell (2013) was plotted against the abundance and density of *Acropora* colonies recorded in this study for each of these reefs using Excel, and the relationship was examined using Pearson's correlation. Likewise, the quantitative data on coral species diversity, mean percent coral cover, *Diadema* density and mean percent macroalgae cover for the 17 reefs included in the Government's long-term RMP was also plotted against abundance and density of *Acropora* spp. on each fringing reef and examined using Pearson's correlation analyses.

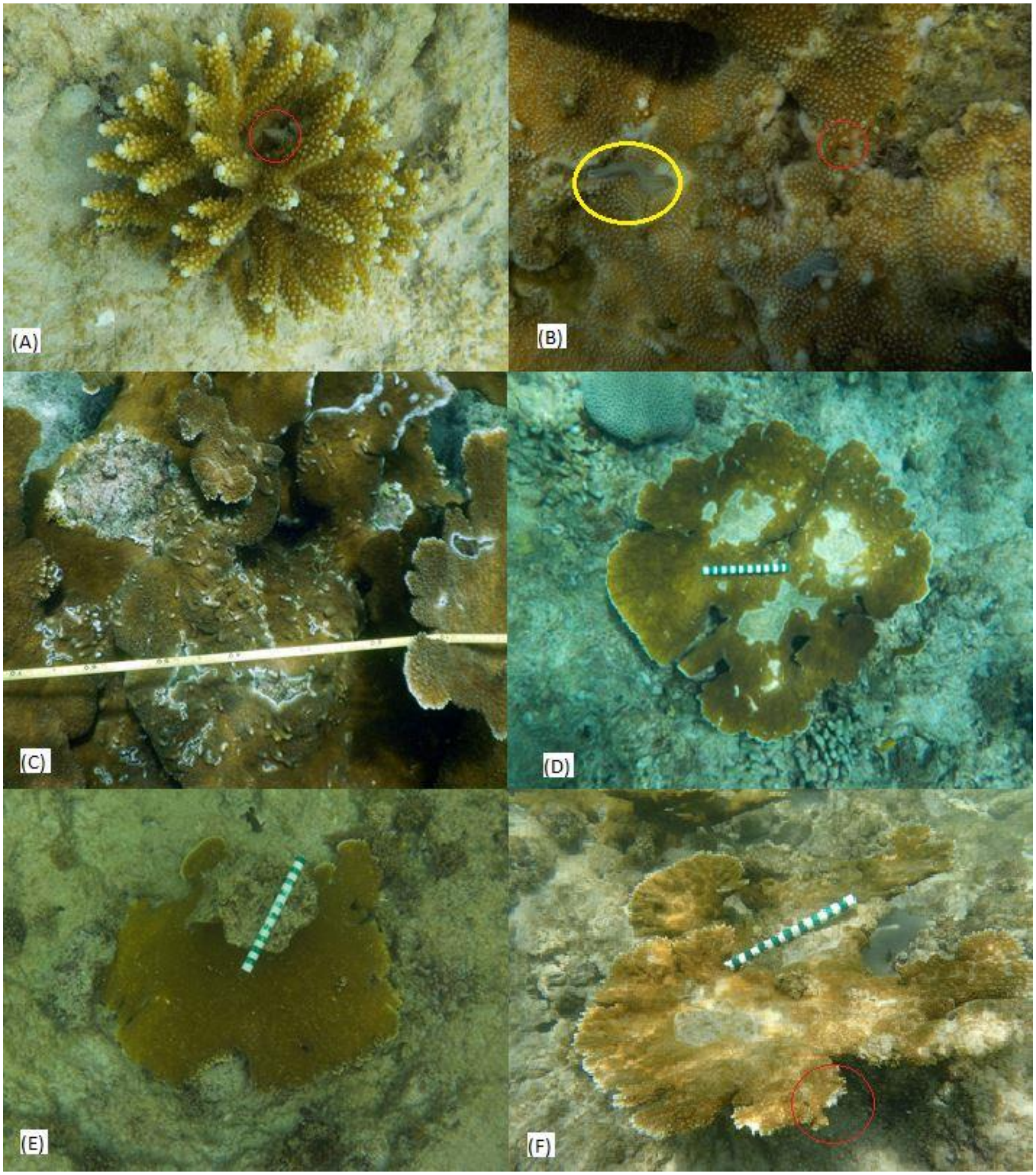



**Figure 6. Examples of predators, borers, lesions and other disturbances to *Acropora* colonies used as measures of heath. Photographs show presence of: (A) predatory snail; (B) predatory fire worm (outlined in yellow) and boring Christmas tree worms (outlined in red); (C) colony covered in boring Christmas tree worms; (D) general lesions; (E) overturned colony; and (F) breakage (grazing). Photo (C) taken by Renata Goodridge, all others taken by authors.**

# 5 RESULTS

## 5.1 Reef characteristics

A total of 46 fringing reefs and artificial breakwaters along the west coast of Barbados from Six Mens Bay in the North to Batts Rock in the south were surveyed between June 13th and August 22nd, 2015. The reefs surveyed in this study included 36 reefs surveyed by Connell (2013) in his broad-scale assessment of their ecological condition, as well as 17 of the reefs with permanent monitoring sites belonging to the Government's long-term reef monitoring programme (RMP) (Office of Research 2014). The general location, identification number, and size (area) of each reef are given in Table 2, together with the numbers and names assigned to these reefs by Connell (2013) and by the RMP (Office of Research 2014). The GPS coordinates and area of each reef by habitat zone are given in Appendix 2. A summary of the quantitative reef health indicators available from the RMP for a subset of the fringing reefs in 2012 is given in Appendix 3.

## 5.2 *Acropora* characteristics

### 5.2.1 Overall abundance

A total of 707 acroporid colonies were found across all reefs surveyed, representing a total *Acropora* planar surface area of 148.6 m$^2$ (Table 3). The vast majority were *A. palmata* and easy to distinguish from the other two species, with their characteristic palmate growth forms (Figure 7). A total of 21 colonies were positively identified as the hybrid, *A. prolifera*. Most of these (14 colonies) were found in a small area of Vauxhall (reef 34) and were easy to distinguish from the two true species (*A. palmata* and *A. cervicornis*) since they had the 'bushy' morphology typical of hybrid crosses where the egg comes from *A. cervicornis* (see Vollmer and Palumbi 2002) (Figure 7). However, there were other cases in which it was difficult to distinguish with certainty between *A. palmata* and *A. prolifera* with a palmate morphology (a hybrid originating from an *A. palmata* egg) (Figure 7). Therefore, for the purpose of this study, both species were grouped together for the analyses, and simply referred to as *Acropora* or *A. palmata*. There were no *Acropora cervicornis* found on any of the fringing reefs in this study.

The abundance of colonies by number and by planar area was highly variable among reefs with individual fringing reefs hosting from 0 (19 reefs) up to 482 *Acropora* colonies covering 98.8 m$^2$ (Table 3, Figures 8 and 9). The mean number of *Acopora* colonies per reef is 15.3, whilst the mode is 0-5 colonies and the majority (87%) of reefs have less than 15 colonies (Figure 10). The mean planar area of *Acropora* colonies per reef is 3.3 m$^2$, whilst the mode is 0-1 m$^2$ (Figure 11).

### 5.2.2 Spatial distribution

#### 5.2.2.1 Among reefs

*A. palmata* colonies were found on 27 reefs (59% of all reefs surveyed) along the entire west coast from Port St. Charles (reef 3) in the north to Batts Rock (reef 46) in the south (Table 3, Figures 8 and 12). However the overall spatial distribution was highly variable. Although there is no clear pattern from north to south, there are several noticeable clusters of reefs with two or more *Acropora* colonies present, as well as several gaps where none were found. For instance,

**Table 2. The ID number, general location, and area of 46 fringing reefs sampled for *Acropora* along the west coast of Barbados from June 13th to August 22nd, 2015. Also shown are the respective reef numbers and names used by Connell (2013) and by the Government's long-term Reef Monitoring Programme (Office of research 2014).**

| Reef Location | Reef No. | Area ($m^2$) | Reef Name (Connell) | Reef No. (Connell) | Reef name (RMP) | Site No. (RMP) |
|---|---|---|---|---|---|---|
| **Six Mens Bay** | 1 | 15156 | South Fish Pot | 3 | - | - |
| **Six Mens Bay** | 2^ | 14936 | North Port St. Charles | 4 | - | - |
| **Port St. Charles** | 3* | 300 | - | - | - | - |
| **Almond Bay** | 4^ | 18092 | South Port St. Charles | 5 | - | - |
| **Almond Bay** | 5 | 6368 | Heywoods | 6 | - | - |
| **Almond Bay** | 6 | 8300 | Heywoods | 6 | Heywoods | 2 |
| **Almond Bay** | 7 | 12332 | South Heywoods | 7 | - | - |
| **Speightstown** | 8 | 35392 | N. Speightstown | 8 | N.Speightstown | 3 |
| **Cobblers Cove** | 9 | 66208 | Plantations | 9 | Plantations | 4 |
| **Godings Bay** | 10^ | 5600 | - | - | - | - |
| **Godings Bay** | 11 | 47708 | Sandridge | 10 | Sandridge | 5 |
| **Godings Bay** | 12 | 10601 | Kings Beach | 11 | - | - |
| **Godings Bay** | 13 | 16446 | Kings Beach | 11 | - | - |
| **Godings Bay** | 14 | 13788 | North Mullins | 12 | - | - |
| **Mullins** | 15 | 35195 | Mullins | 13 | Mullins | 6 |
| **Gibbs Bay** | 16 | 30137 | South Mullins | 14 | - | - |
| **Gibbs Bay** | 17 | 32108 | Greensleeves | 15 | Greensleeves | 7 |
| **Reeds Bay** | 18 | 13412 | - | - | - | - |
| **Tropicana** | 19 | 27428 | Tropicana | 16 | Tropicana | 8 |
| **Weston** | 20^ | 8740 | South Reeds Bay | 17 | - | - |
| **Weston** | 21 | 11780 | Weston | 18 | - | - |
| **Weston** | 22 | 17524 | Driftwood | 19 | Driftwood | 9 |
| **Alleynes Bay** | 23 | 13172 | North Jet Ski | 20 | - | - |
| **Alleynes Bay** | 24 | 6868 | Jet Ski | 21 | Jet Ski | 10 |
| **Alleynes Bay** | 25 | 17940 | Glitter Bay | 22 | - | - |
| **Bachelors Hall** | 26 | 19440 | Bachelor Hall | 23 | Bachelor Hall | 11 |
| **Bachelors Hall** | 27 | 27212 | Heron Bay | 24 | Heron Bay | 12 |
| **Bachelors Hall** | 29 | 4584 | - | - | - | - |
| **North Bellairs** | 29 | 16664 | Bellairs | 25 | - | - |
| **South Bellairs** | 30 | 40172 | Bellairs | 25 | Bellairs | 13 |
| **Holetown** | 31 | 8540 | - | - | - | - |
| **Holetown** | 32 | 13768 | Holetown | 26 | - | - |
| **Holetown** | 33^ | 23216 | South Holetown | 27 | - | - |
| **Vauxhall** | 34^ | 25940 | Vauxhall | 28 | - | - |
| **Vauxhall** | 35^ | 22644 | Vauxhall | 28 | - | - |
| **Sandy Lane** | 36 | 24212 | Sandy Lane | 29 | Sandy Lane | 14 |
| **Paynes Bay** | 37 | 20124 | South Sandy Lane | 30 | - | - |
| **Tamarind** | 38 | 12176 | Bamboo Beach | 31 | Bamboo Beach | 15 |
| **Mahogany Bay** | 39 | 13872 | Payne's Bay | 32 | - | - |
| **The Cliff** | 40 | 16648 | - | - | - | - |
| **Crystal Cove** | 41 | 16336 | Beach Village | 34 | Beach Village | 16 |
| **Fitts Village** | 42 | 23804 | Jordan's | 35 | - | - |
| **Waves** | 43 | 21116 | Fitt's Village | 36 | Fitt's Village | 17 |
| **Waves** | 44 | 10388 | South Fitt's Village | 37 | - | - |
| **Batts Rock** | 45 | 8448 | South Fitt's Village | 37 | - | - |
| **Batts Rock** | 46 | 24596 | Batt's Rock | 38 | Batt's Rock | 18 |
| **Total** | 46 | | | 36 | | 17 |

**^** indicates reefs that **incorporate artificial breakwaters**, * indicates reef is entirely an **artificial breakwater**

**Table 3. Summary data for *Acropora palmata* shown separately for each of the 46 reefs surveyed along the west coast of Barbados from June 13th to August 22nd, 2015. Data included for each reef are total number of colonies found; the maximum height and surface area of each colony averaged across all colonies; the total surface area of all colonies; the number of colonies per hectare of reef; and the contribution of *Acropora* to the benthic area of reef shown as percent cover of entire reef area.**

| Reef ID # | Location | # of Colonies | Mean max height (cm) | Mean area ($m^2$) | Total *Acropora* area ($m^2$) | Density (colonies/ha) | % cover |
|---|---|---|---|---|---|---|---|
| **1** | Six Mens Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **2** | Six Mens Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **3** | Port St. Charles | 3 | 52 | 1.22 | 3.66 | 100 | 1.22 |
| **4** | Almond Bay | 12 | 24.7 | 0.34 | 3.72 | 6.63 | <0.0001 |
| **5** | Almond Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **6** | Almond Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **7** | Almond Bay | 5 | 23 | 0.32 | 1.59 | 4.05 | 0.00013 |
| **8** | Speightstown | 1 | 26 | 0.64 | 0.64 | 0.28 | <0.0001 |
| **9** | Cobblers Cove | 13 | 21.3 | 0.34 | 4.41 | 1.94 | <0.0001 |
| **10** | Godings Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **11** | Godings Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **12** | Godings Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **13** | Godings Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **14** | Godings Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **15** | Mullins | 482 | - | 0.21 | 98.75 | 136.95 | 0.0028 |
| **16** | Gibbs Bay | 2 | - | 0.51 | 1.01 | 0.66 | <0.0001 |
| **17** | Gibbs Bay | 12 | 21.1 | 0.41 | 4.97 | 3.69 | 0.00015 |
| **18** | Reeds Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **19** | Tropicana | 45 | 19.5 | 0.15 | 6.39 | 16.04 | 0.00023 |
| **20** | Weston | 0 | 0 | 0 | 0 | 0 | 0 |
| **21** | Weston | 0 | 0 | 0 | 0 | 0 | 0 |
| **22** | Weston | 3 | 5.3 | 0.14 | 0.41 | 1.71 | <0.0001 |
| **23** | Alleynes | 2 | - | 0.06 | 0.12 | 2.28 | <0.0001 |
| **24** | Alleynes | 0 | 0 | 0 | 0 | 0 | 0 |
| **25** | Alleynes | 1 | - | 1.33 | 1.33 | 0.56 | <0.0001 |
| **26** | Bachelors Hall | 2 | 67.5 | 1.03 | 2.07 | 1.03 | 0.00012 |
| **27** | Bachelors Hall | 3 | 9.3 | 0.07 | 0.20 | 1.10 | <0.0001 |
| **28** | Bachelors Hall | 0 | 0 | 0 | 0 | 0 | 0 |
| **29** | North Bellairs | 2 | 13.3 | 0.05 | 0.11 | 1.20 | <0.0001 |
| **30** | South Bellairs | 13 | 13.3 | 0.2 | 2.63 | 2.24 | <0.0001 |
| **31** | Holetown | 1 | - | 0.88 | 0.88 | 1.17 | 0.00010 |
| **32** | Holetown | 1 | - | 0.43 | 0.43 | 0.73 | <0.0001 |
| **33** | Holetown | 0 | 0 | 0 | 0 | 0 | 0 |
| **34** | Vauxhall | 21 | 11.8 | 0.13 | 2.49 | 8.10 | <0.0001 |
| **35** | Vauxhall | 18 | 12 | 0.11 | 2.25 | 8.39 | <0.0001 |
| **36** | Sandy Lane | 28 | 20.7 | 0.26 | 7.21 | 9.88 | 0.00025 |
| **37** | Paynes Bay | 6 | 20.7 | 0.11 | 0.44 | 2.67 | <0.0001 |
| **38** | Tamarind | 7 | 10.1 | 0.13 | 0.51 | 5.43 | <0.0001 |
| **39** | Mahogany Bay | 0 | 0 | 0 | 0 | 0 | 0 |
| **40** | The Cliff | 1 | 0.5 | 0.01 | 0.01 | 0.60 | <0.0001 |
| **41** | Crystal Cove | 0 | 0 | 0 | 0 | 0 | 0 |
| **42** | Fitts Village | 3 | - | 0.29 | 0.86 | 1.27 | <0.0001 |
| **43** | Waves | 2 | - | - | - | 0.90 | 0 |
| **44** | Waves | 0 | 0 | 0 | 0 | 0 | 0 |
| **45** | Batts Rock | 0 | 0 | 0 | 0 | 0 | 0 |
| **46** | Batts Rock | 18 | 14.8 | 0.09 | 1.50 | 7.32 | <0.0001 |
| **Overall mean** | | 15.3 | 9.1 | 0.20 | 3.3 | 7.10 | 0.003 |
| **Overall total** | | 707 | | | 148.6 | | |

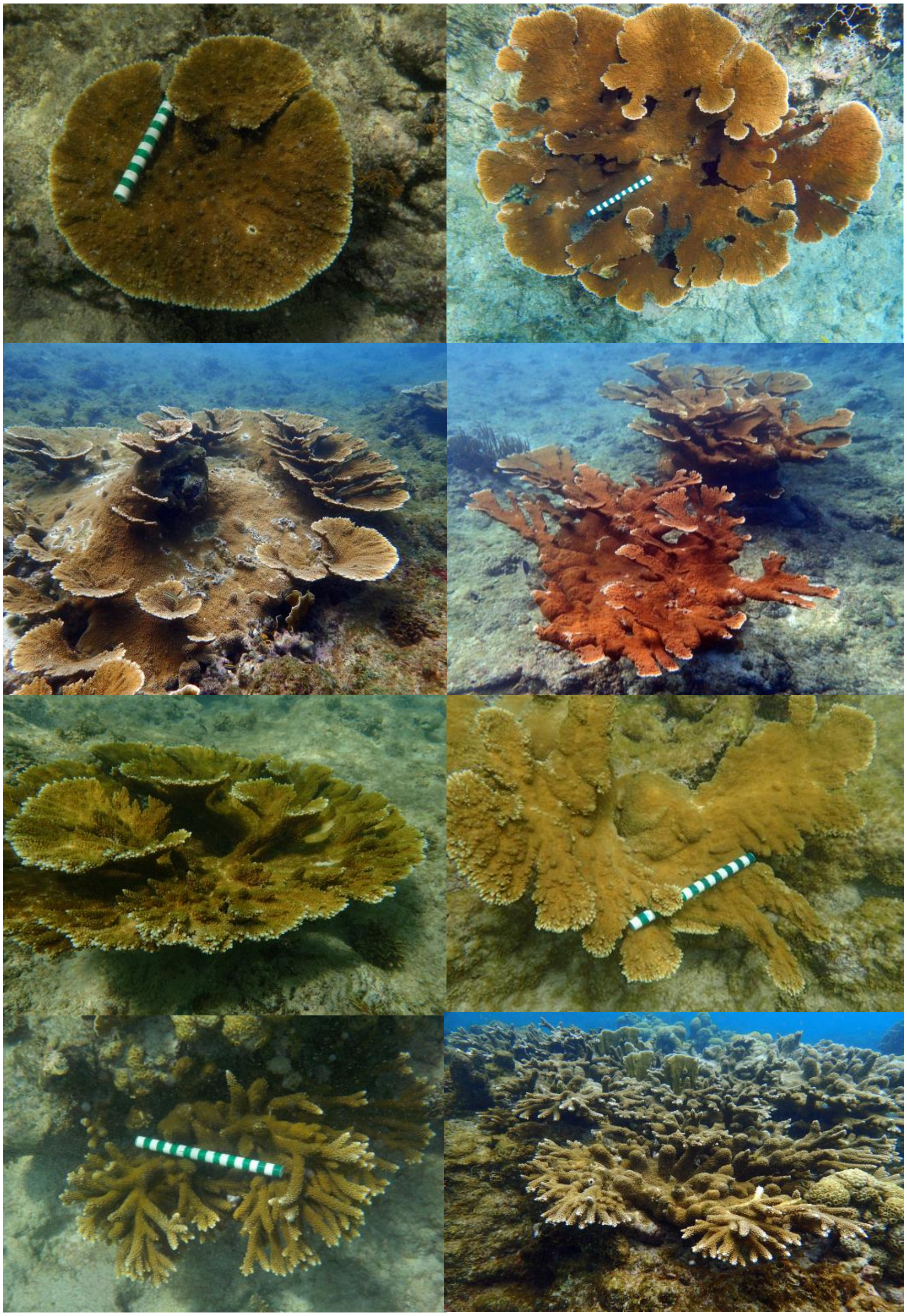


**Figure 7. Examples of the various morphologies of *Acropora* colonies found on the fringing reefs along the west coast of Barbados. *Top panel* shows typical symmetrical palmate morphology of a small and a large colony of *A. palmata*. *Second row left* shows morphology of *A. palmata* regrowing from an upturned colony, and *right* shows colonies growing in deeper water, oriented perpendicular to the normal swell direction. *Third row* shows possible *A. prolifera* colonies of palmate form typical of hybrids with an egg from *A. palmata*. *Bottom panel* shows *A. prolifera* colonies of the bushy type typical of hybrids with an egg from *A. cervicornis*.**

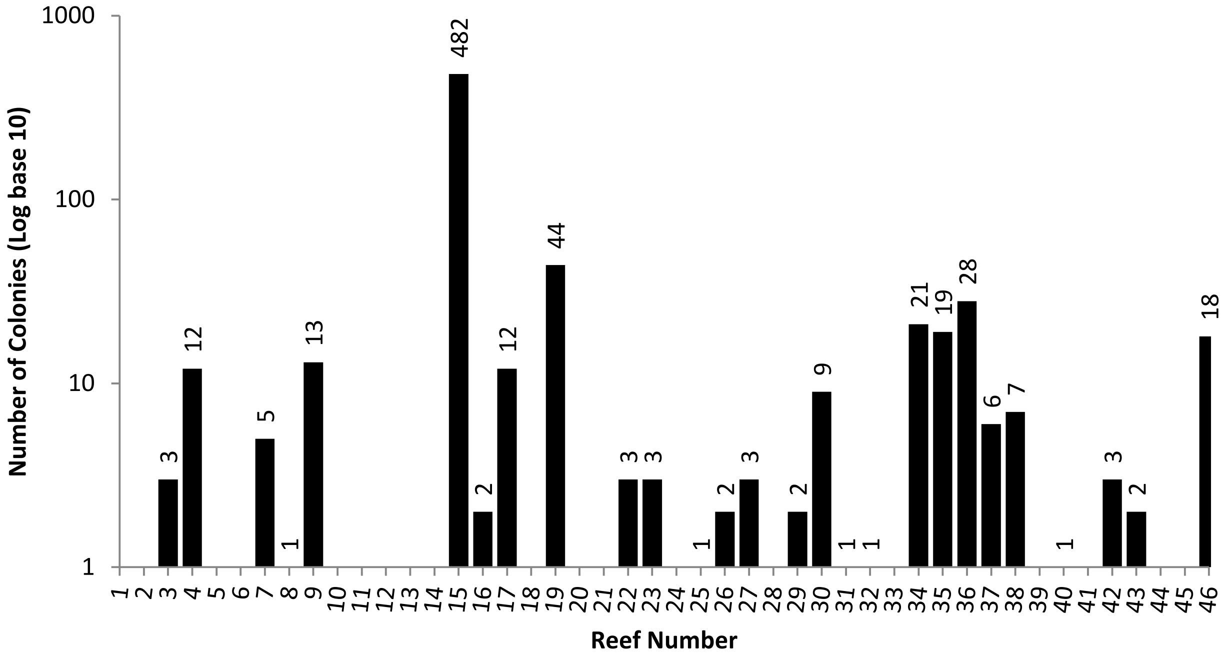



**Figure 8. The distribution (on a logarithmic scale base 10) of abundance of Acropora colonies on each of the 46 fringing reefs surveyed along the west coast of Barbados from June 13th to August 22nd, 2015. Reefs are numbered from north to south along the west coast.**

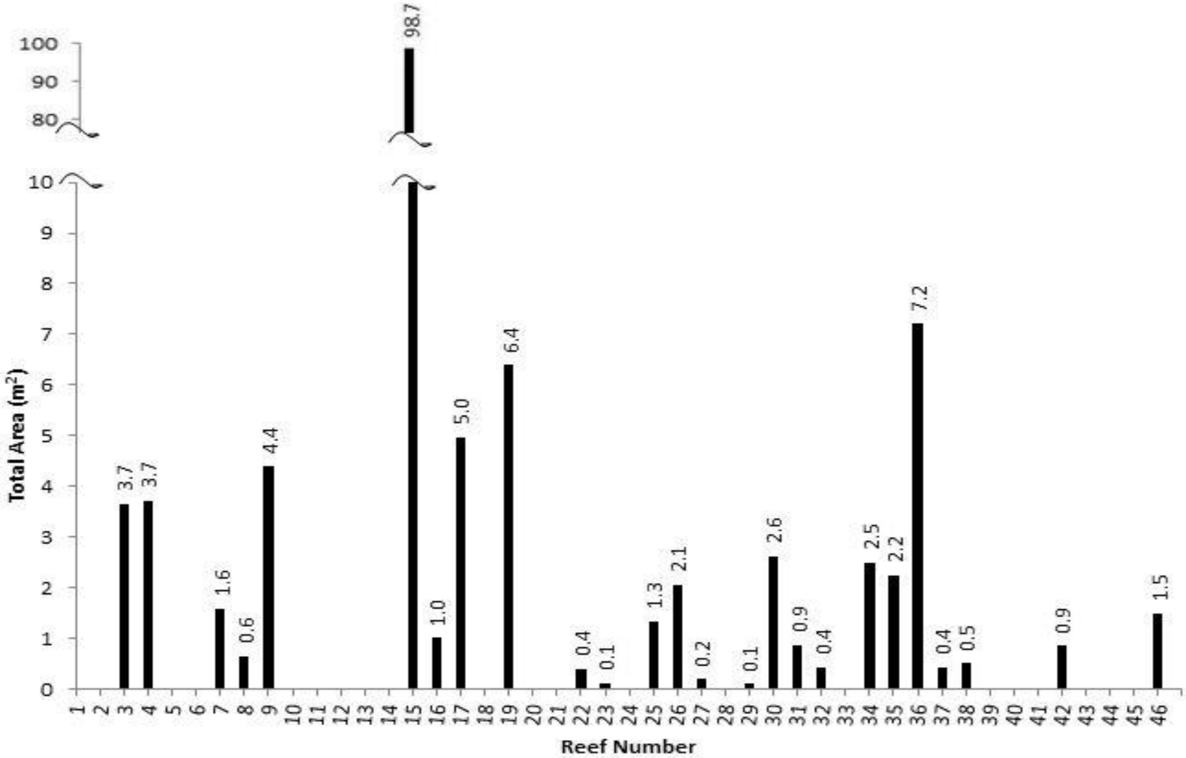



**Figure 9. Distribution of the total planar surface area of *Acropora* for fringing reefs along the west coast of Barbados in 2015. Numbers above the bar show the values. The value for reef 15 (Mullins) *Acropora* area was estimated using the mean planar surface areas of each size class.**

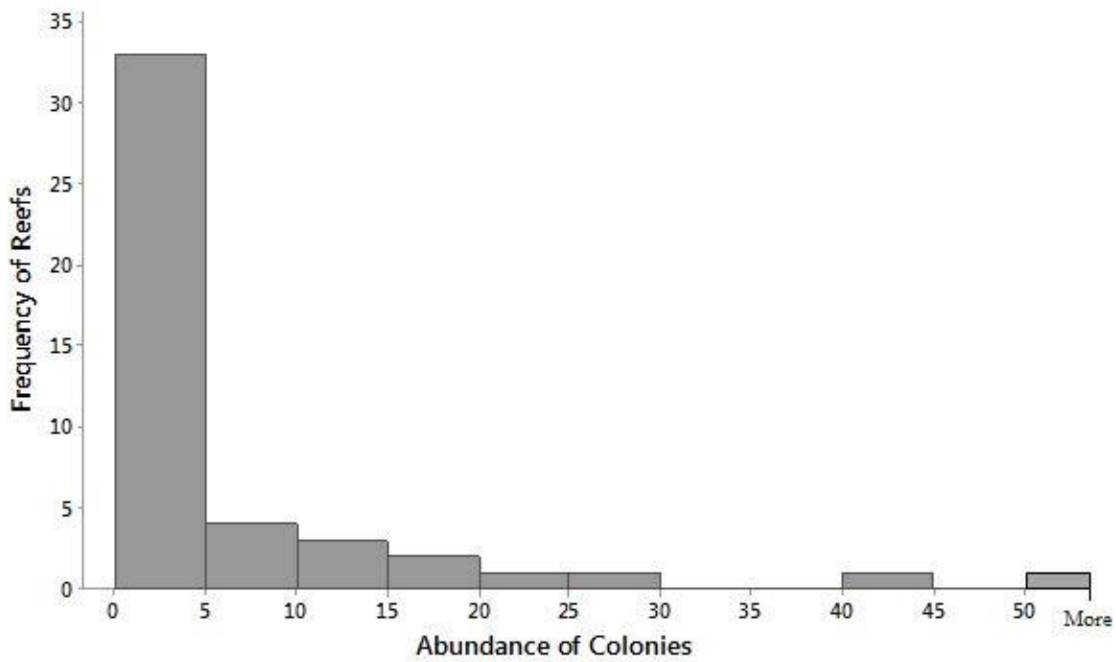



**Figure 10. Frequency distribution showing the abundance (as numbers) of *Acropora* colonies observed per reef over the 46 reefs surveyed along the west coast of Barbados from June 13th to August 22nd, 2015.**

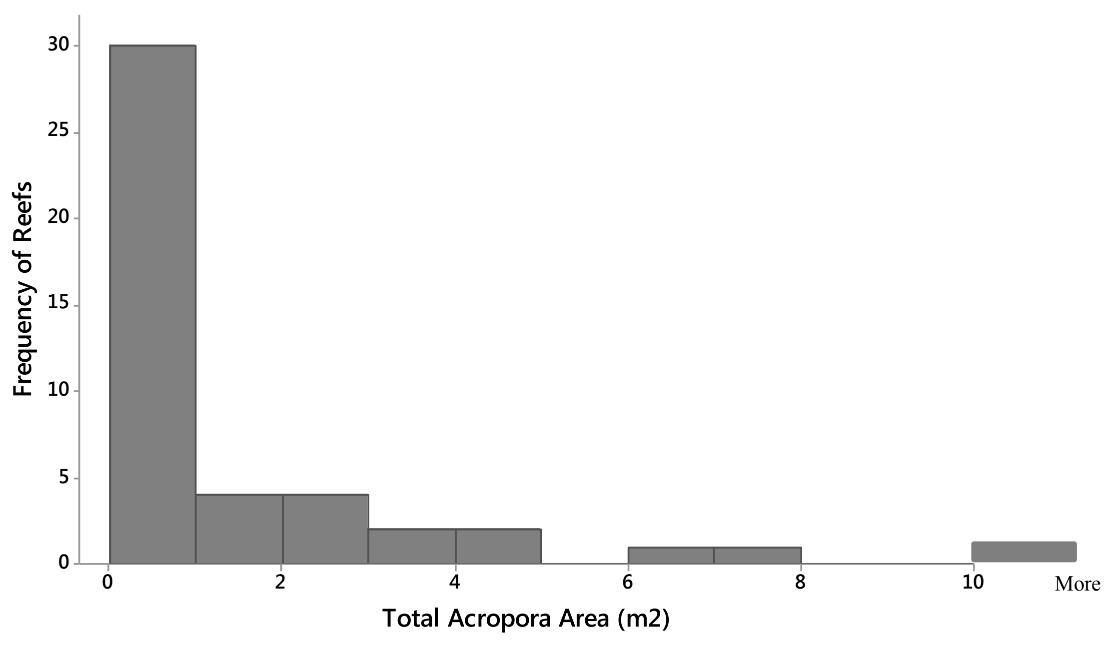



**Figure 11. Frequency distribution showing the abundance (as area) of *Acropora* colonies observed per reef over the 46 reefs surveyed along the west coast of Barbados from June 13th to August 22nd, 2015.**

four of the five reefs spanning from Mullins to Tropicana (reefs 15-19), all reefs spanning from Bachelors Hall to South Bellairs (reefs 26-30), and all reefs spanning from Vauxhall to Tamarind (reefs 34-38) where found to have two or more *Acropora* colonies (Table 3, Figures 8 and 13). Noticeable gaps of three or more neighbouring reefs that were found to have only one or no colonies include reefs in Godings Bay (reefs 10-14), reefs in front of Holetown (reefs 31-33) and reefs from Mahogany Bay to Crystal Cove (Reefs 39-41) (Table 3, Figures 8 and 14).

#### 5.2.2.2 By habitat zone

The actual locations of *A. palmata* colonies within each fringing reef, plotted on geo-referenced DigitalGlobe images with reef habitat overlays, are shown in Figures 15-27 and GPS coordinates are available for all 707 colonies in the archived database (available from author on request).

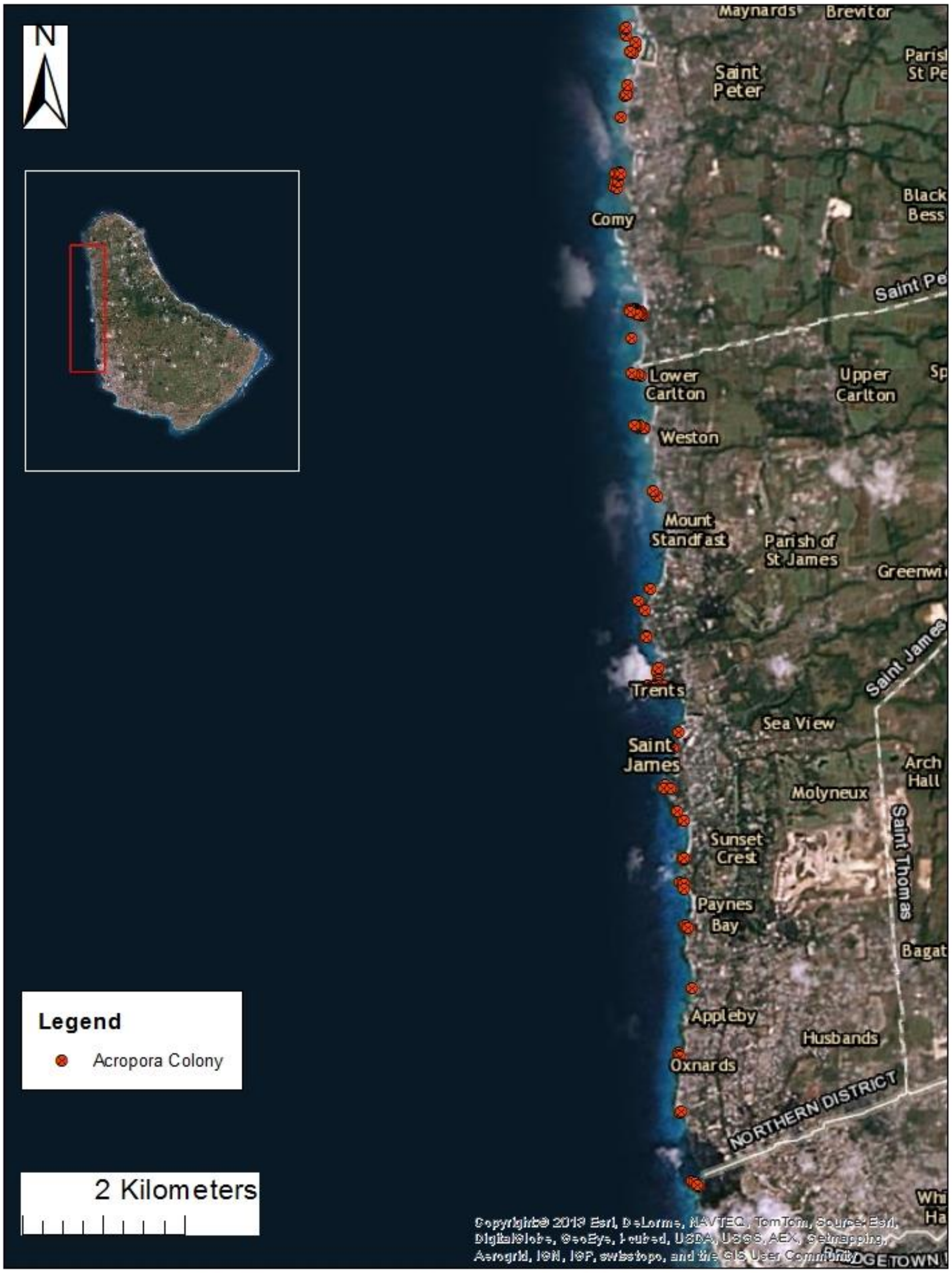
*Acropora* colonies were found in all three of the reef habitat zones (i.e. reef flat, reef crest, and spur and groove) and their distribution across these habitats is summarized in Figure 28. However, several colonies were not located on any of the three reef habitat zones possibly due to inaccuracy of the GPS coordinates. Therefore, the reef zone location was only recorded for 691 of the colonies found. Based on the entire dataset, it would appear that acroporids are most commonly found in the most offshore zone in spur and groove habitat, with 415 colonies (60%) located in this zone (Figure 28a). However this number is largely affected by the 406 colonies found in the coral spur and groove zone on a single reef, Mullins (reef 15). Excluding all colonies (n = 482) on Mullins (reef 15) from this analysis indicates the majority (40 %) of colonies on the remaining reefs are found in the reef crest zone (91 colonies), 32% are found in the spur and groove zone (71 colonies) and the reef flat zone contained the lowest number with 47 colonies (21%) located in this zone (Figure 28b).

### 5.2.3 Density

#### 5.2.3.1 Among reefs

Despite the broad occurrence of acroporids on many of the fringing reefs, the overall density (number of colonies per hectare of reef area) is low; ranging from zero (19 reefs) to 137 colonies per hectare (1 reef), with an overall average of 7 colonies per hectare (Table 3). Most reefs had less than 3 colonies per hectare with the exception of Port St. Charles breakwater (reef 3) and Mullins fringing reef (reef 15) that both had exceptionally high densities (greater than 100 colonies per hectare). Tropicana (reef 19) was notable with a density of 16 colonies per hectare, as well as the three-reef cluster from Vauxhall to Sandy Lane (reefs 34-36) which all had densities greater than 8 colonies per hectare (Figure 29).

As with the overall density measured as number of colonies per hectare of reef, the percent cover of *Acropora* is generally low, ranging between 0% and 1.2% of total benthic reef area, with an average of just 0.003% cover (Table 3, Figure 30). The reef with the highest percent cover is the relatively small Port St. Charles breakwater. Mullins (reef 15) also had a notable percent cover of *Acropora* at 0.0028% of total benthic reef area, whilst all other reefs had a density that was an order of magnitude lower (Table 3, Figure 30).

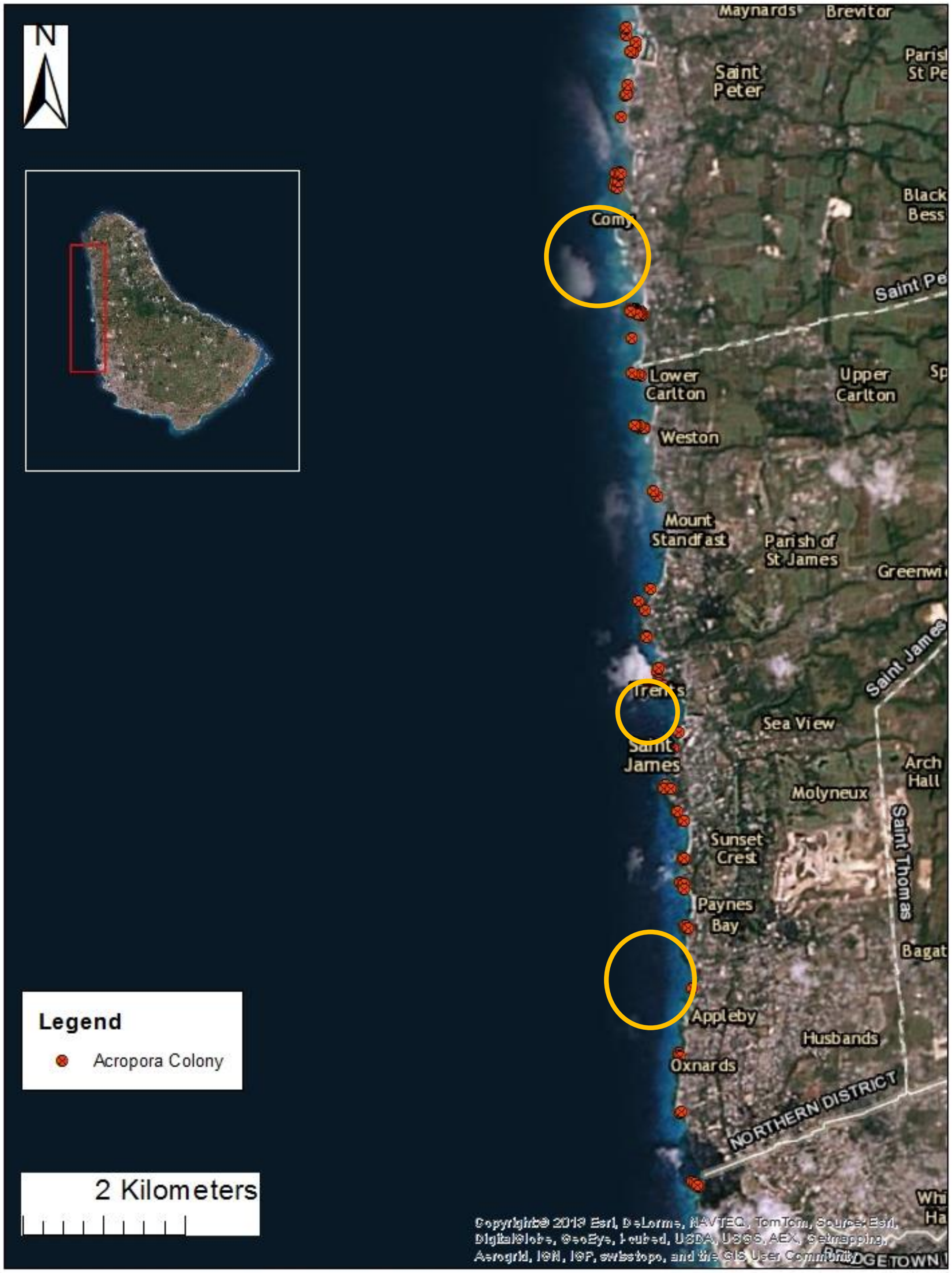



Map created on 16/10/15 by Roxanne MacLean, Msc. candidate at the University of the West Indies.

**Figure 12. The overall spatial distribution of *Acropora* colonies found along the west coast of Barbados from June to August, 2015.**


Map created on 16/10/15 by Roxanne MacLean, Msc. candidate at the University of the West Indies.

**Figure 13. The spatial distribution of *Acropora* colonies indicating clusters (circled in red) of neighbouring fringing reefs along the west coast of Barbados with three or more colonies found during the June to August survey in 2015.**




Map created on 16/10/15 by Roxanne MacLean, Msc. candidate at the University of the West Indies.

**Figure 14. The spatial distribution of *Acropora* colonies showing fringing reef clusters (circled in yellow) along the west coast of Barbados with either zero or only one colony found during the June to August survey in 2015.**


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**Figure 15. Map of the locations of *Acropora* colonies found between June 13th and August 22nd overlaid with the benthic habitat classifications of reef numbers 1 to 4 on the west coast of Barbados in 2015.**


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**Figure 16. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 5 to 8 on the west coast of Barbados in 2015.**

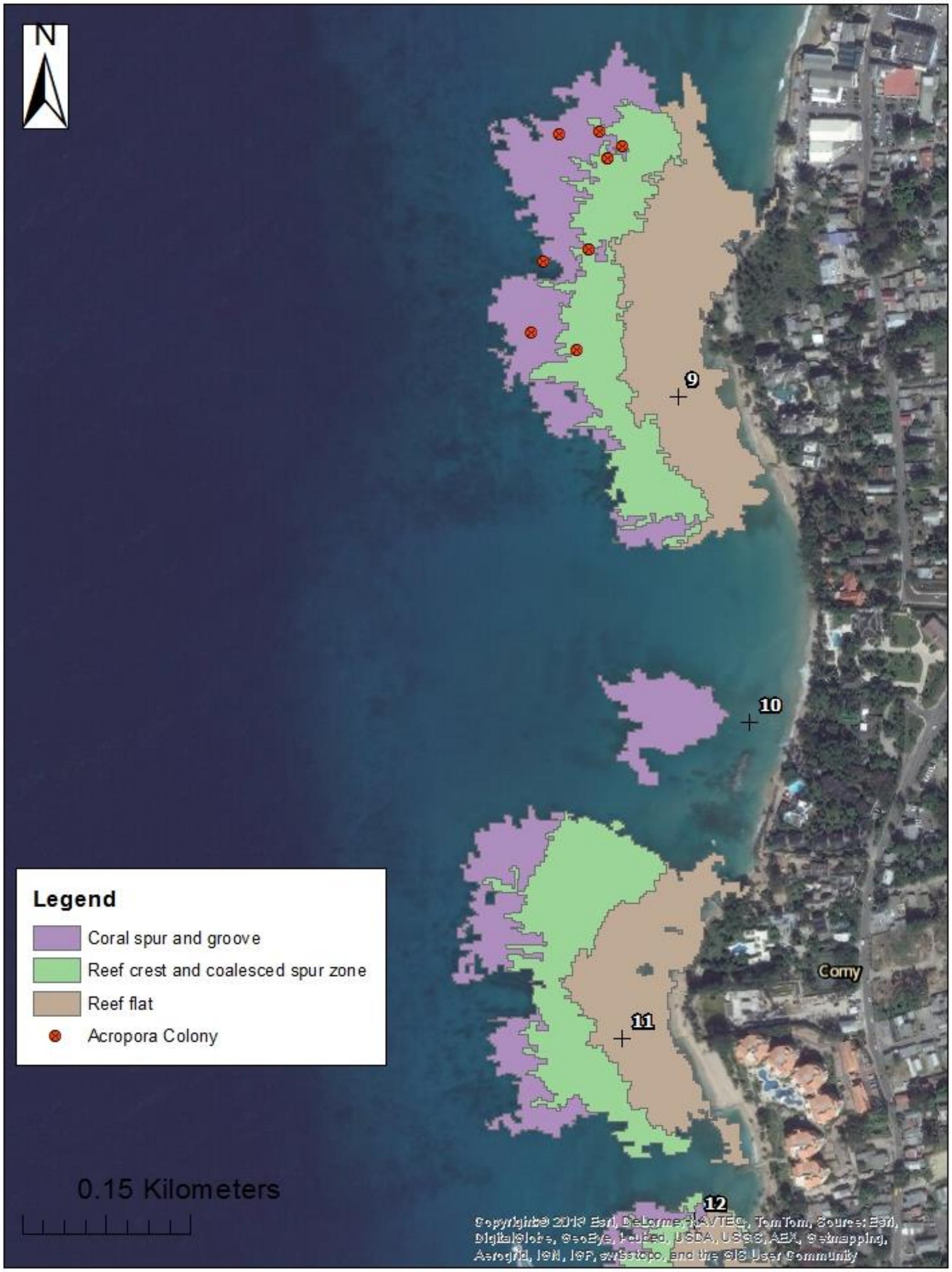


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**Figure 17. Map of the locations of *Acropora* colonies found between June 13$^{th}$ and August 22$^{nd}$, overlaid with the benthic habitat classifications of reef numbers 9 to 11 on the west coast of Barbados in 2015.**

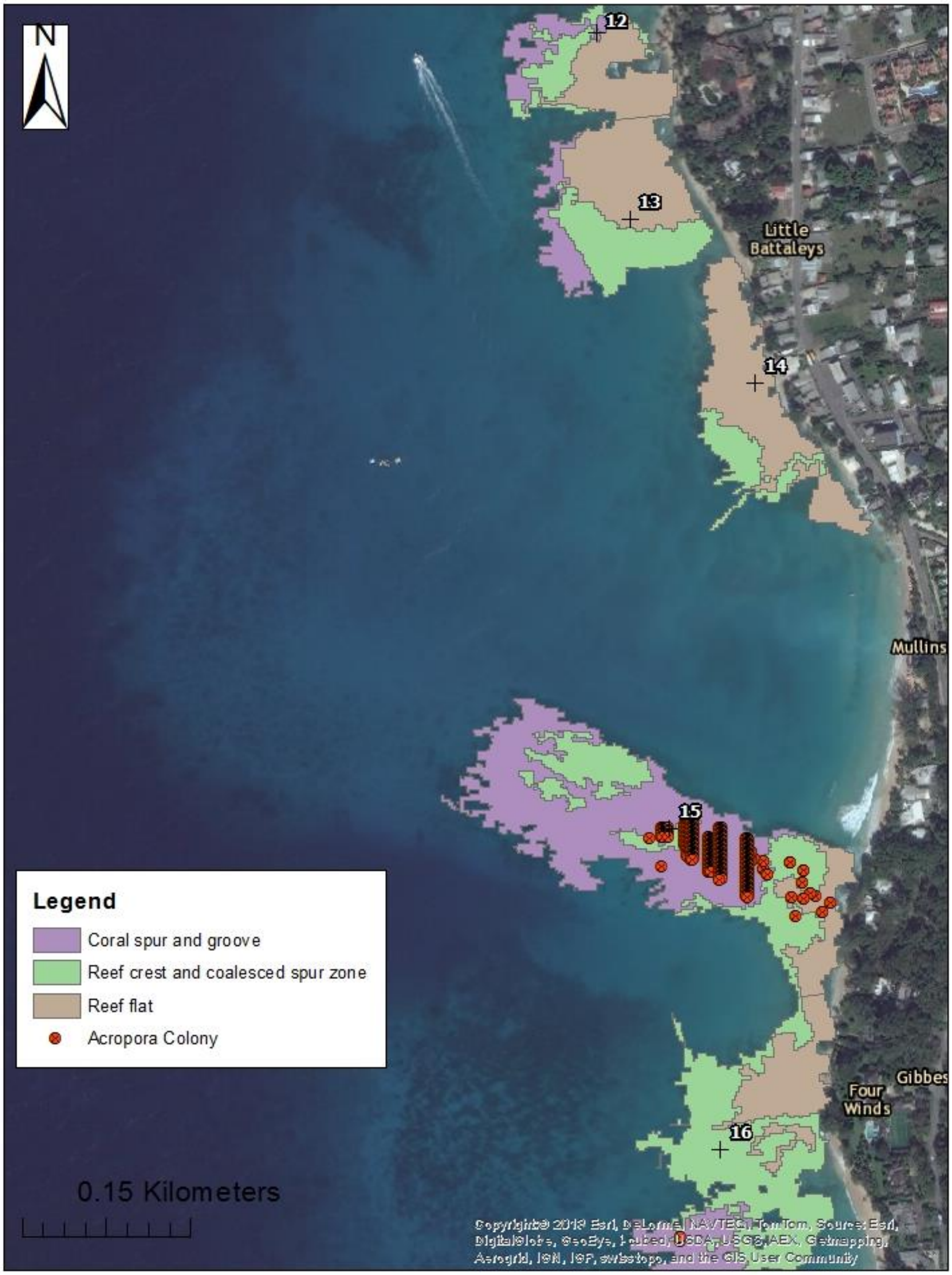


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**Figure 18. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 12 to 16 on the west coast of Barbados in 2015.**


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**Figure 19. Map of the locations of *Acropora* colonies found between June 13$^{th}$ and August 22$^{nd}$, overlaid with the benthic habitat classifications of reef numbers 16 to 18 on the west coast of Barbados in 2015.**

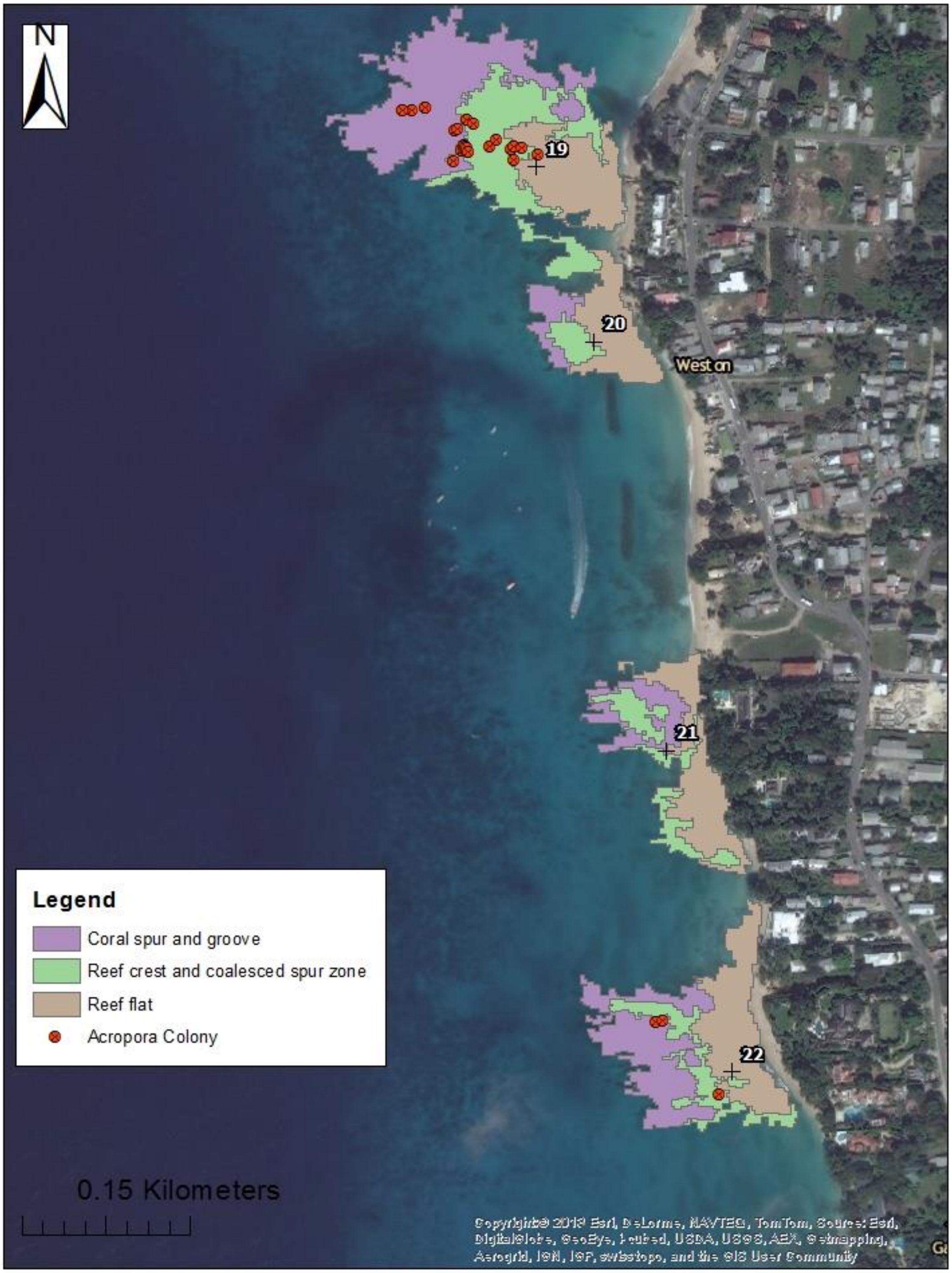


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**Figure 20. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 19 to 22 on the west coast of Barbados in 2015.**


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**Figure 21. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 23 to 26 on the west coast of Barbados in 2015.**

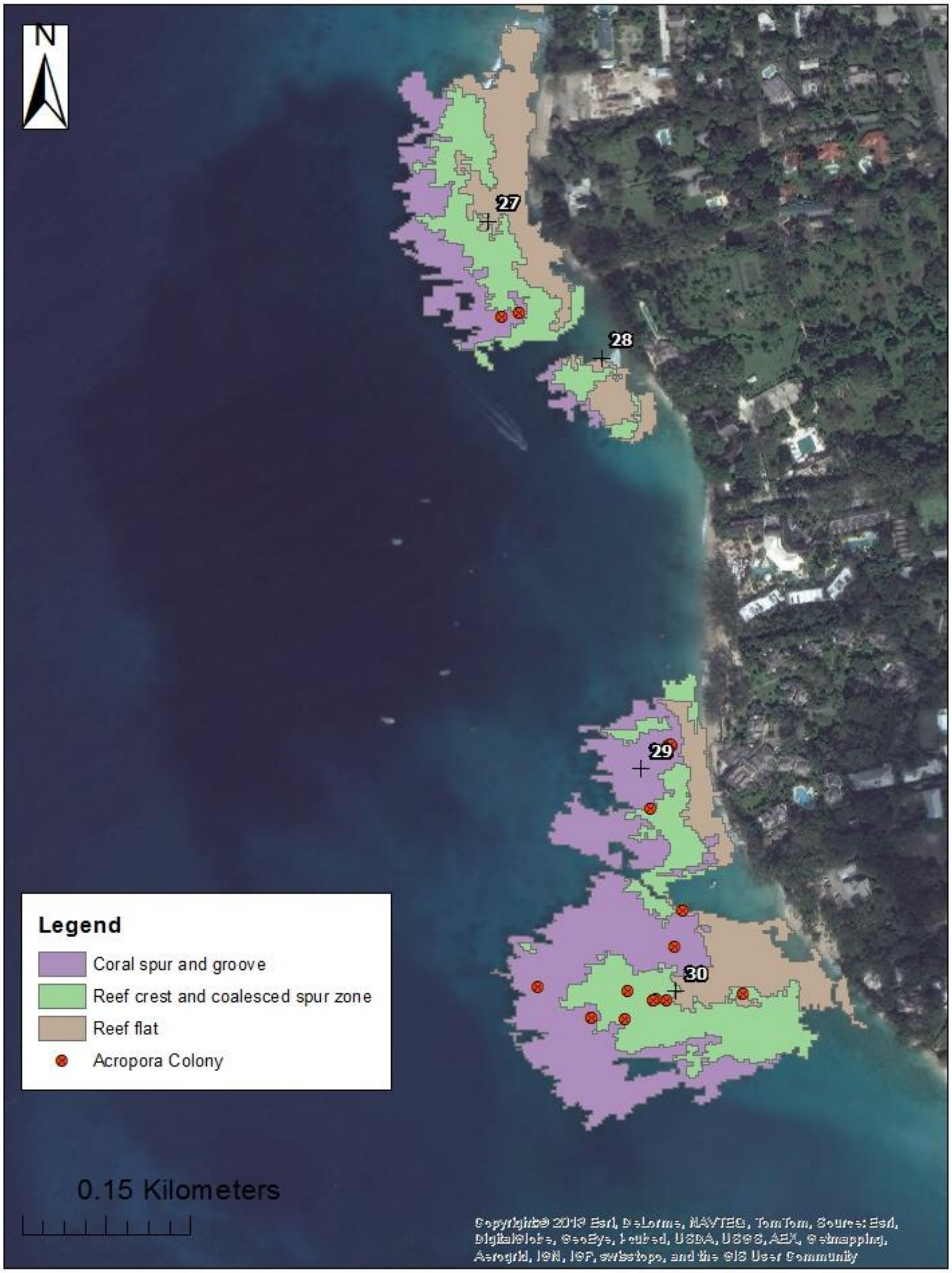


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**Figure 22. Map of the locations of *Acropora* colonies found between June 13$^{th}$ and August 22$^{nd}$, overlaid with the benthic habitat classifications of reef numbers 27 to 30 on the west coast of Barbados in 2015.**

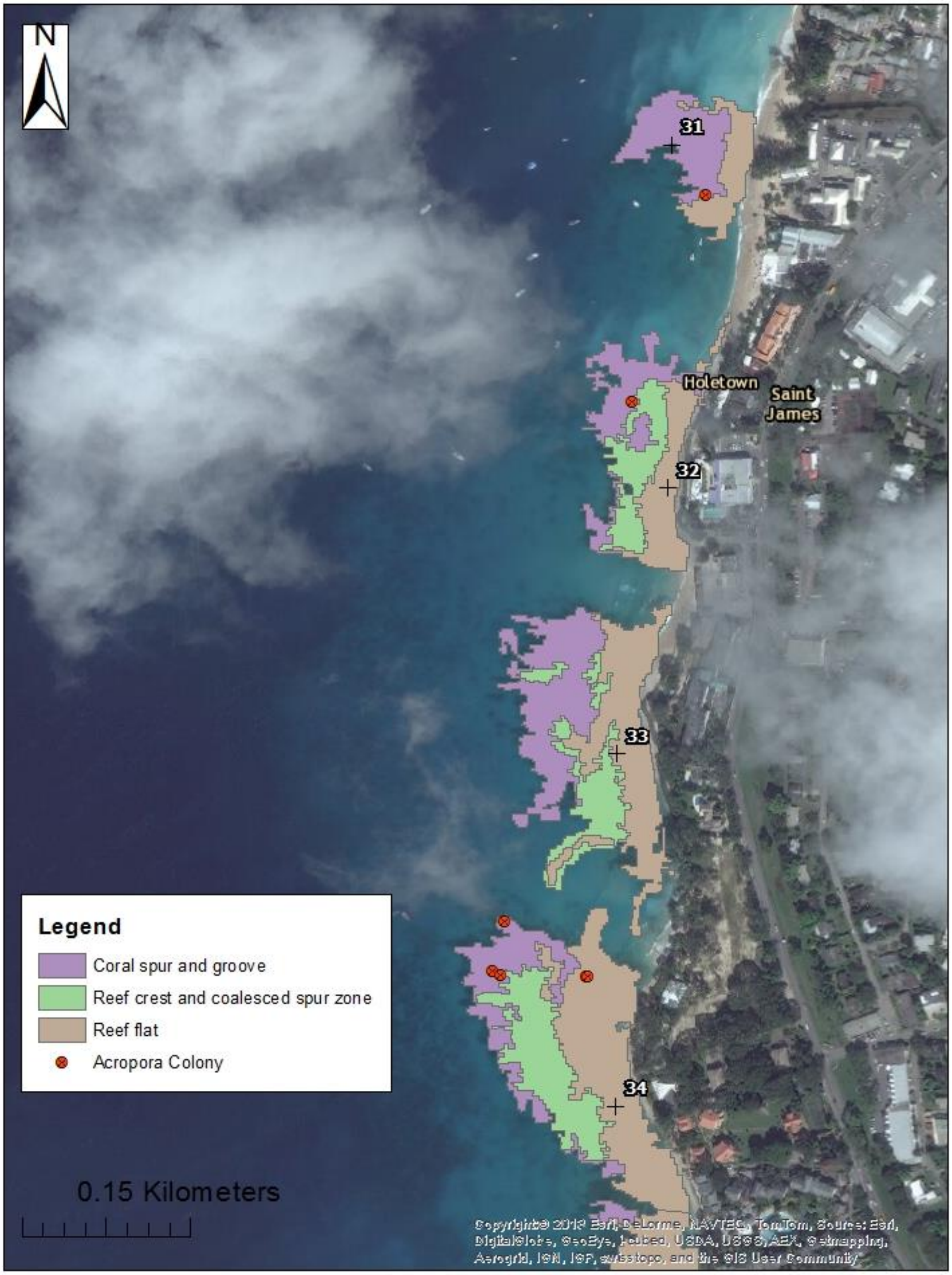


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**Figure 23. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 31 to 34 on the west coast of Barbados in 2015.**

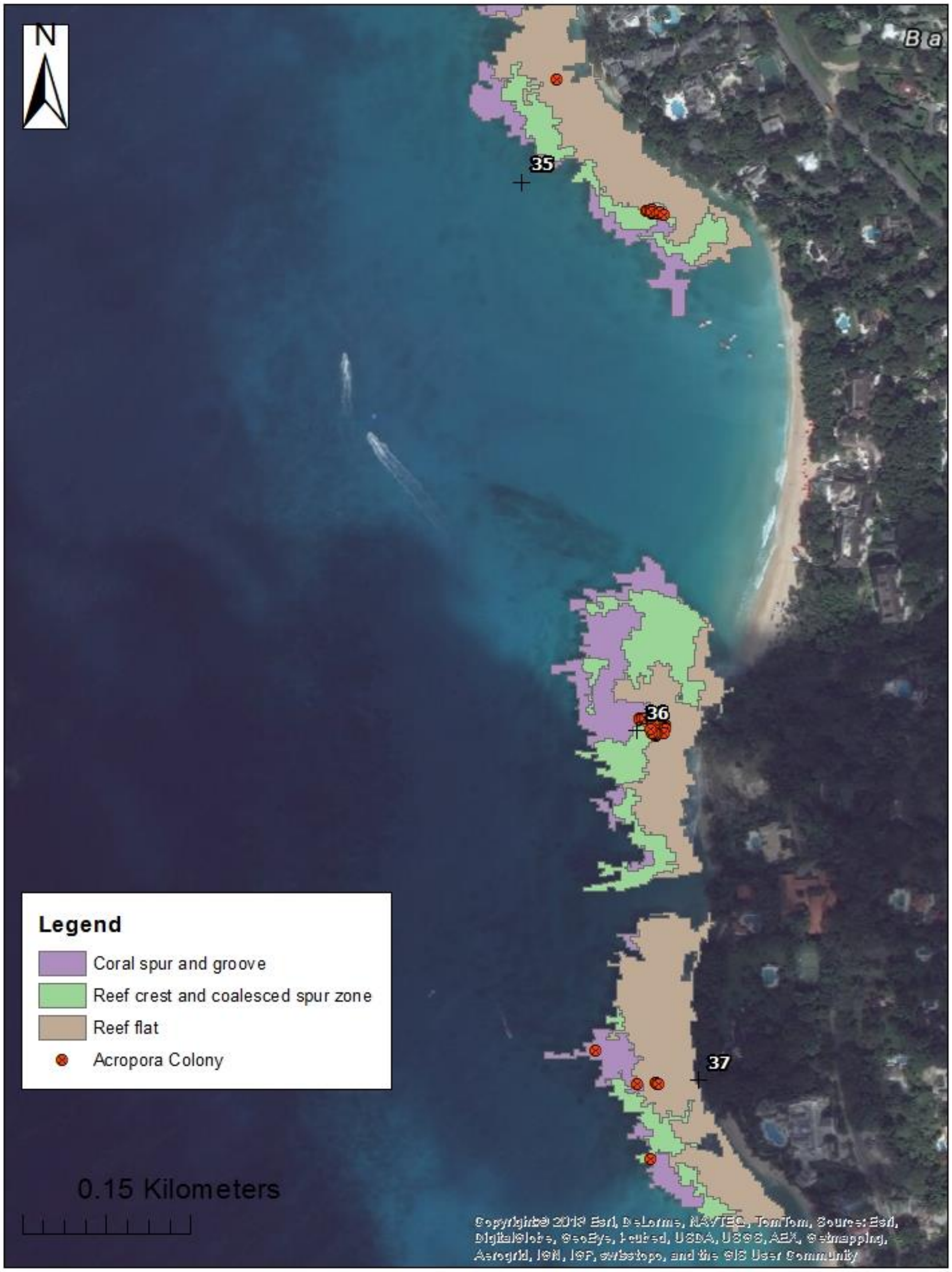


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**Figure 24. Map of the locations of *Acropora* colonies found between June 13$^{th}$ and August 22$^{nd}$, overlaid with the benthic habitat classifications of reef numbers 35 to 37 on the west coast of Barbados in 2015.**

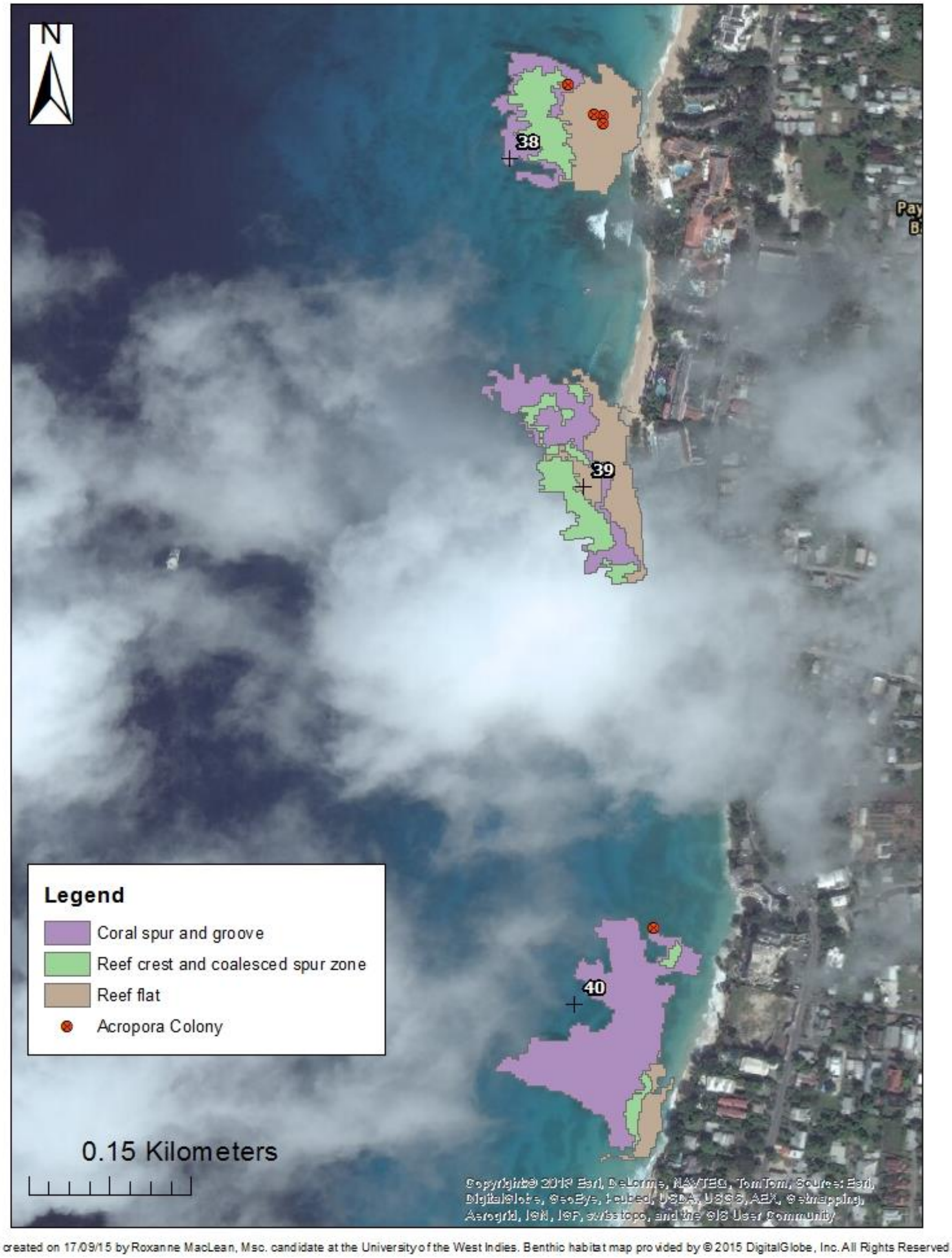


**Figure 25. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 38 to 40 on the west coast of Barbados in 2015.**


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**Figure 26. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 41 and 42 on the west coast of Barbados in 2015.**

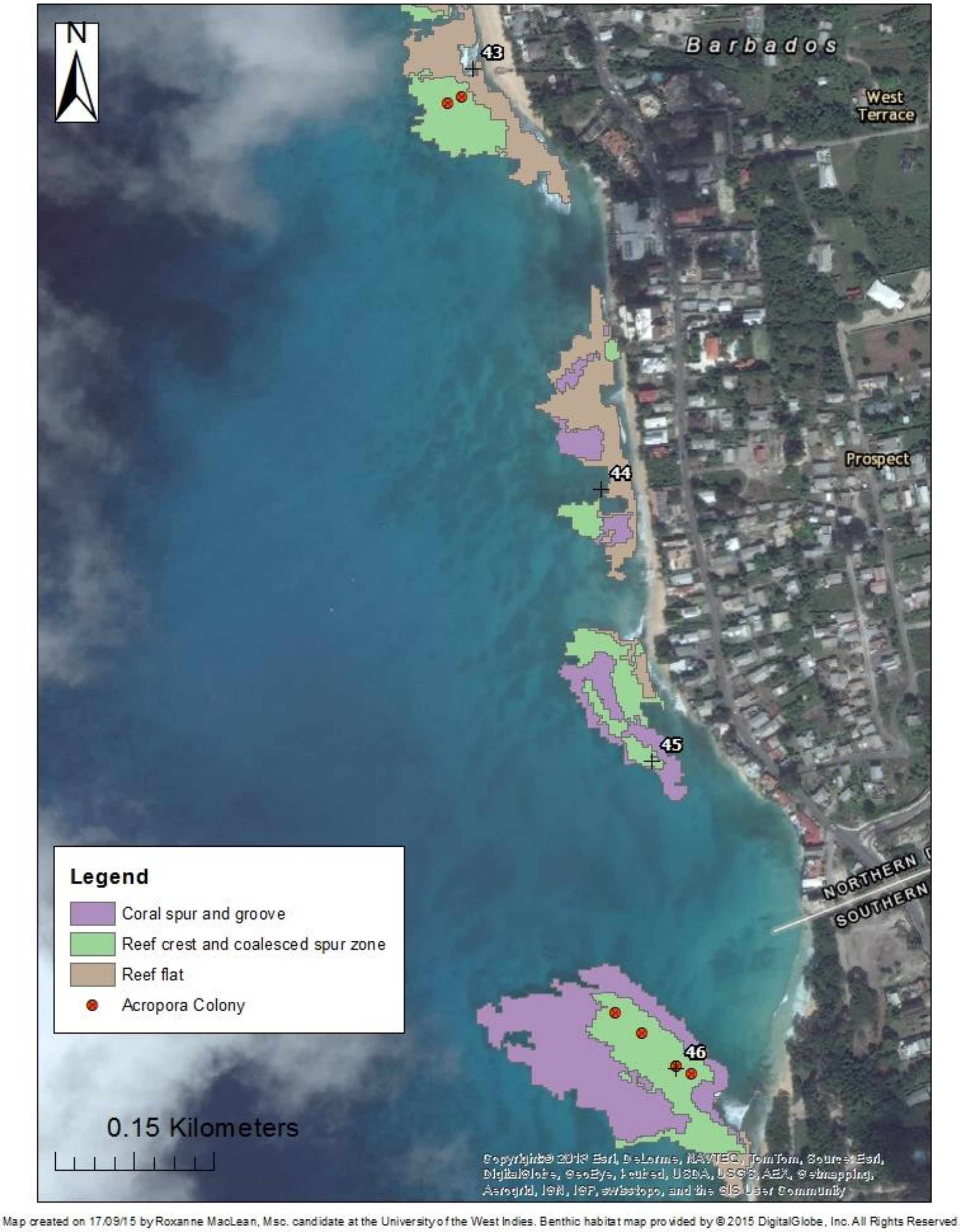


**Figure 27. Map of the locations of *Acropora* colonies found between June 13th and August 22nd, overlaid with the benthic habitat classifications of reef numbers 43 to 46 on the west coast of Barbados in 2015.**

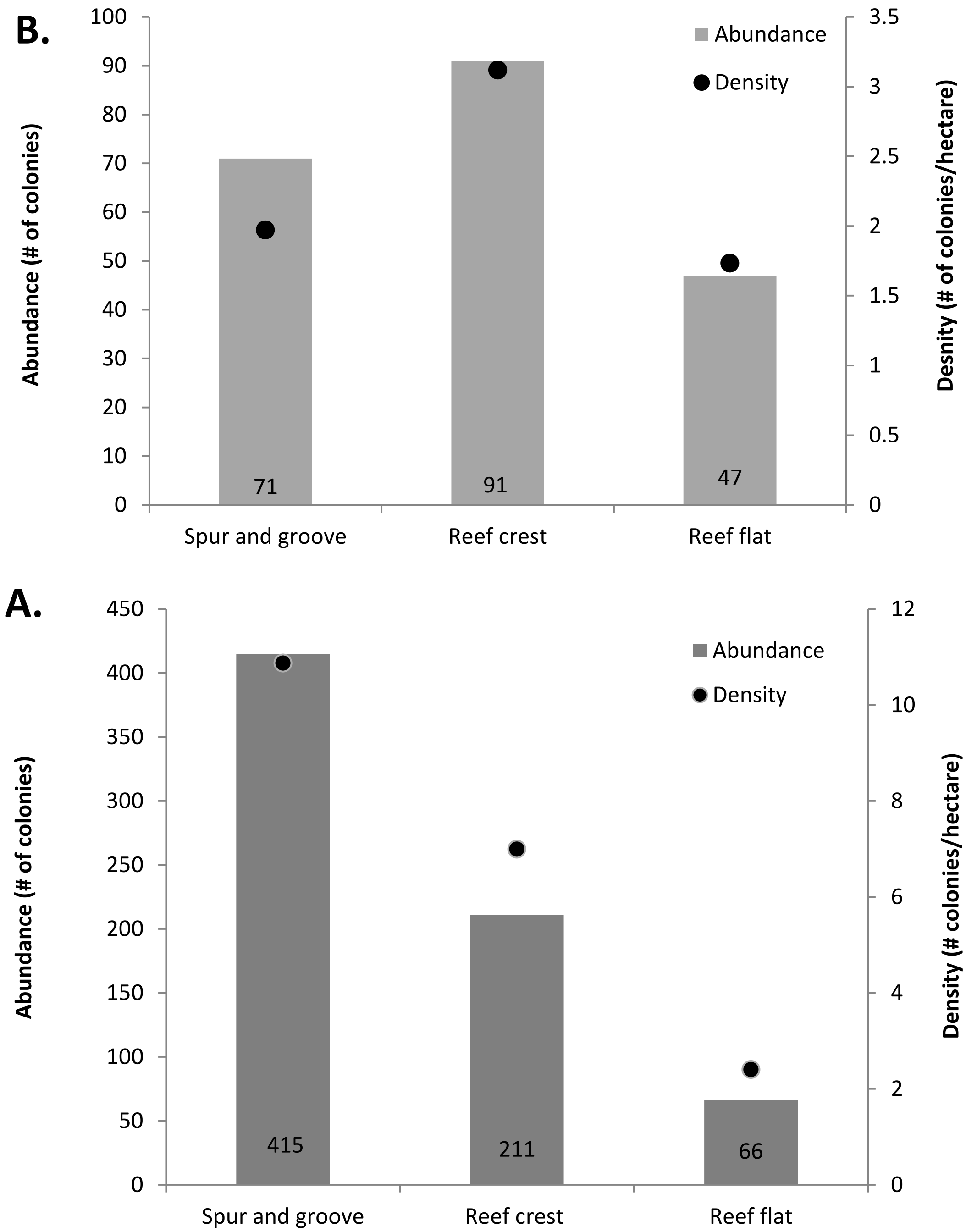


**Figure 28. The abundance and density per reef zone for *Acropora* colonies found along the west coast fringing reefs of Barbados between June 13th and August 22nd, 2015. A – shows data for all reefs surveyed (n = 692 colonies), B – shows data excluding Mullins (reef 15) (n = 209 colonies).**

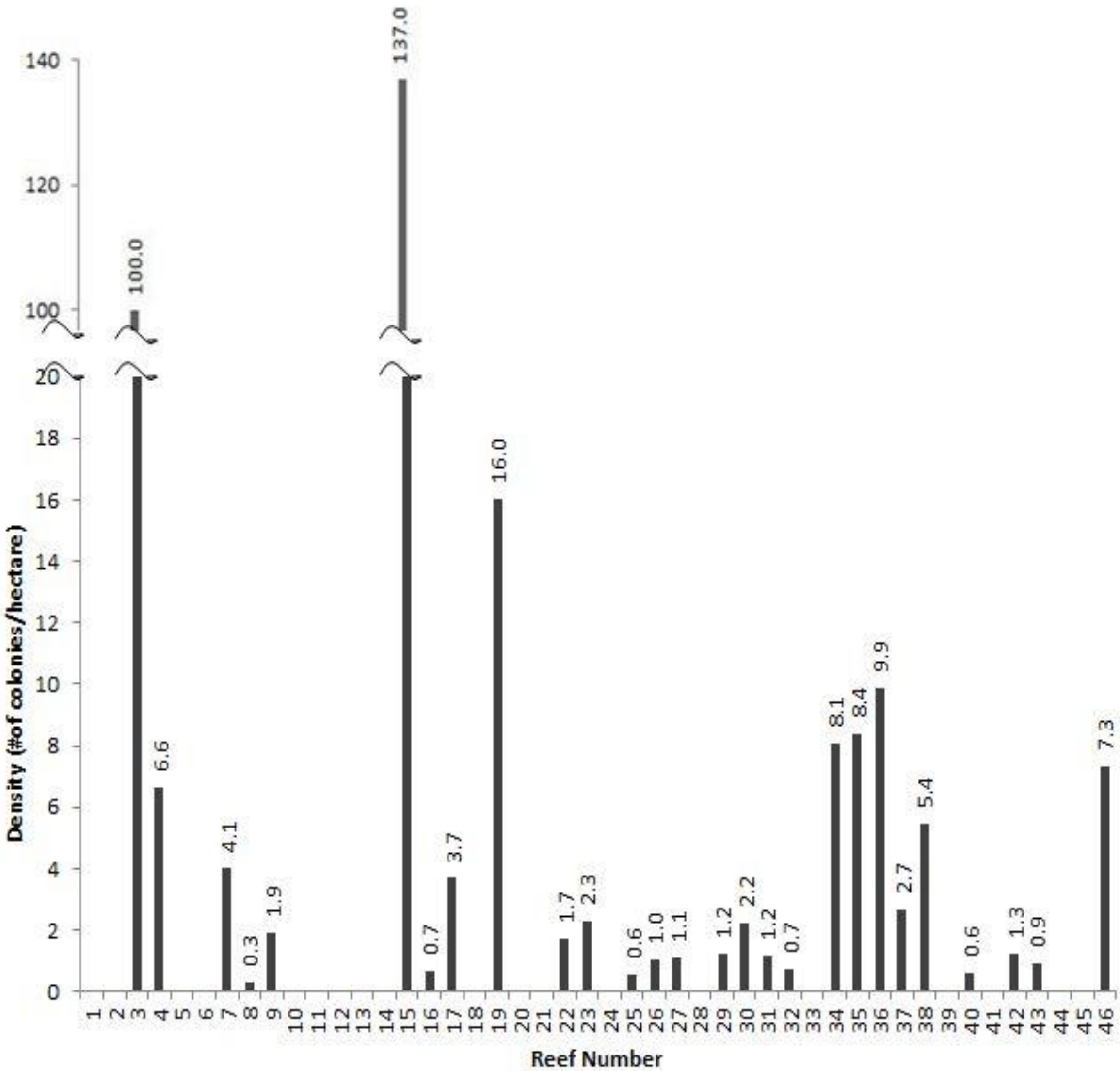


**Figure 29. Distribution of the density of *Acropora* colonies (measured as number of colonies per hectare of reef) for each of the 46 reefs surveyed along the west coast of Barbados from June to August, 2015.**

5.2.3.2 By habitat zone

The density per reef zone was also examined; however like the abundance, the distribution was largely skewed by Mullins (reef 15). The density of *Acropora* colonies was highest in the coral spur and groove zone when including Mullins, with a density of 10.9 colonies per hectare compared with 7.0 colonies per hectare in the reef crest zone and 2.4 colonies per hectare in the reef flat (Figure 28a). When the Mullins data were excluded from the analysis, the zone with the highest density of colonies was the reef crest (3.1 colonies $ha^{-1}$), followed by the spur and groove zone (2.0 colonies $ha^{-1}$) and the reef flat zone (1.7 colonies $ha^{-1}$) (Figure 28b).

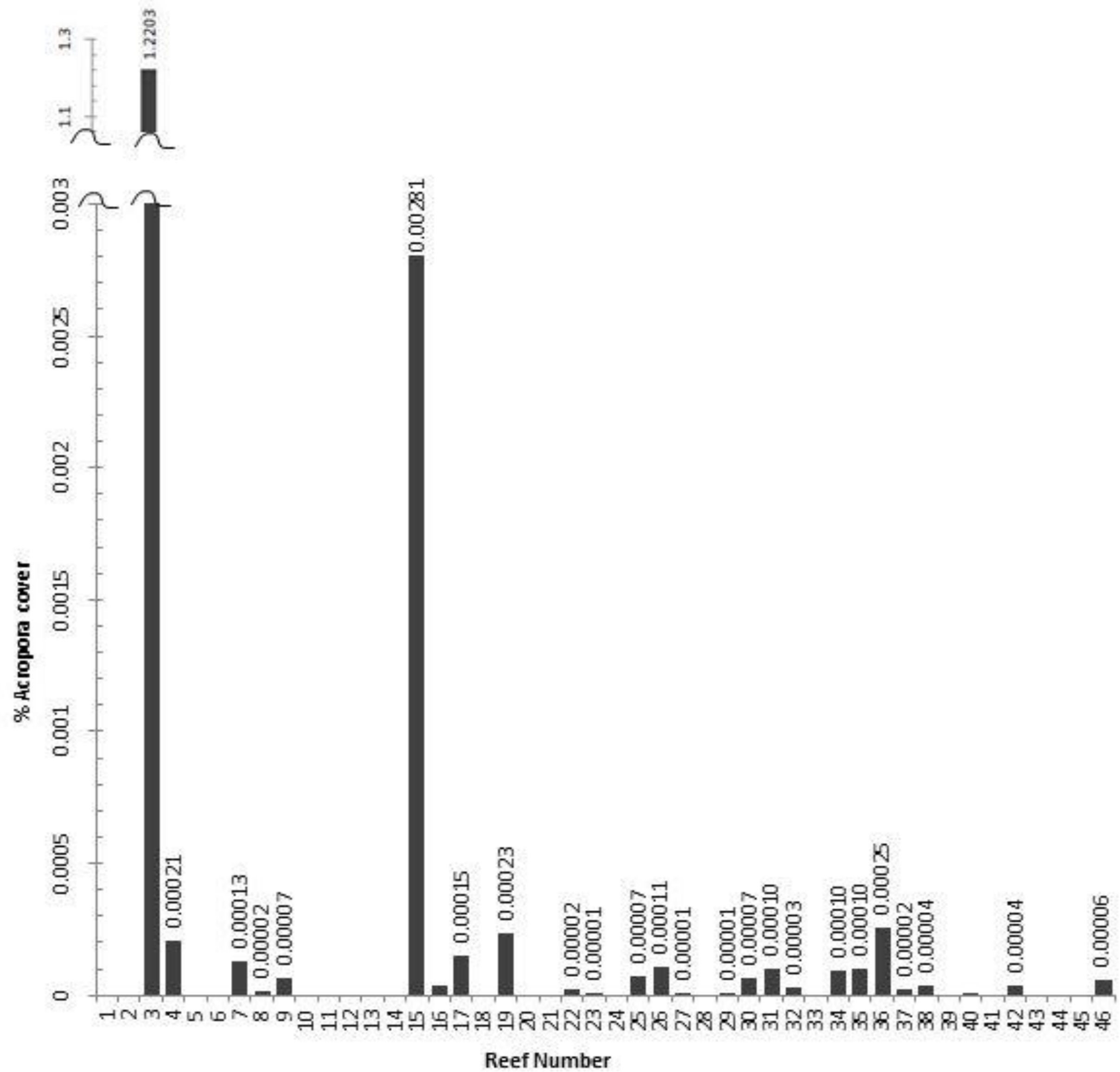


**Figure 30. Distribution of the percent cover by *Acropora* for each of the 46 reefs surveyed along the west coast of Barbados from June 13th to August 22nd, 2015. Note the percent *Acropora* cover for Mullins (reef 15) was estimated using size classes rather than from photographs of individual colonies. The y axis was broken from 0.003-1.1% in order to show the data for reef 3.**

### 5.2.4 Size and condition

#### 5.2.4.1 <u>Size</u>

The *Acropora* colonies that were measured (n= 267) ranged in maximum height from 0.5 to 120 cm and in planar surface area from 0.002 – 2.46 $m^2$. The reefs with the largest and likely oldest colonies (greatest mean maximum height and mean planar surface area) were reef 26 (Bachelors Hall) and reef 3 (Port St. Charles) (Figures 31 and 32). However, the largest individual colony with the greatest planar surface area and greatest maximum height was located on reef 9 (Cobblers Cove). Note however that the greatest number of large colonies and most likely also the largest overall colonies were found in the spur and groove area of Mullins (reef 15) (Figure

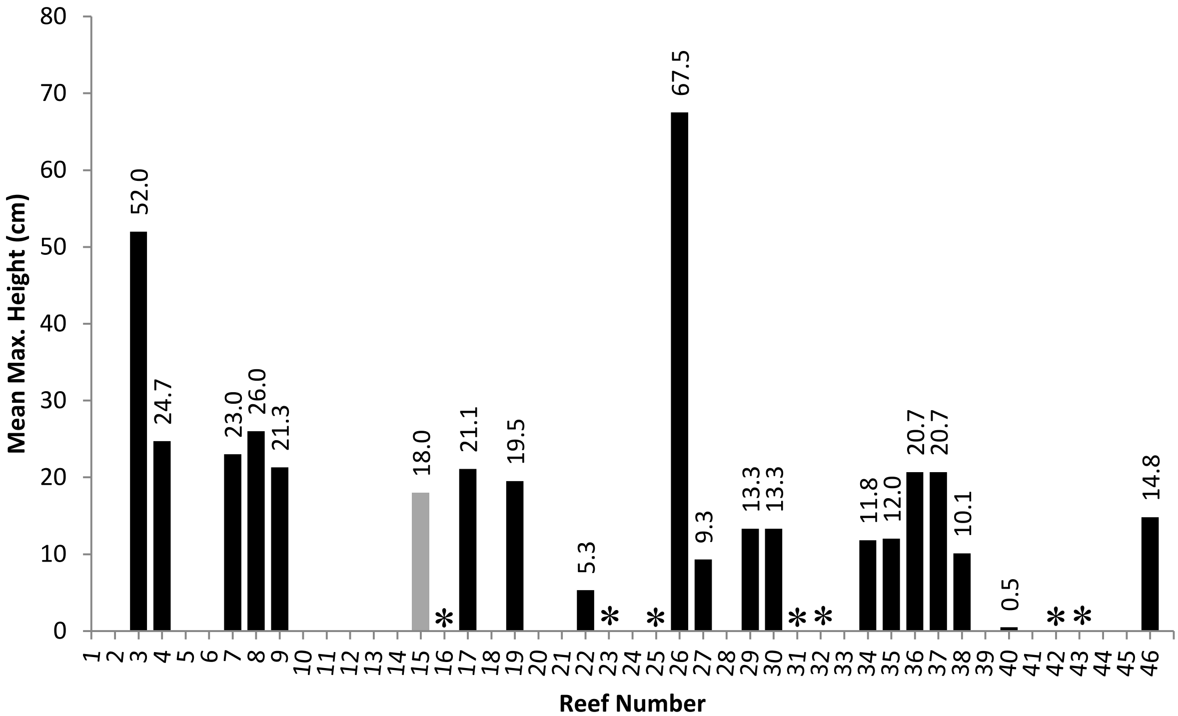


**Figure 31. Distribution of the mean maximum heights of the *Acropora* colonies located on each of the 46 reefs surveyed along the west coast of Barbados (June - August, 2015). The mean maximum height was estimated for reef 15 using the average height of colonies in each size class and is indicated by the grey bar. * indicates reefs that had colonies present, but for which no maximum height was recorded.**

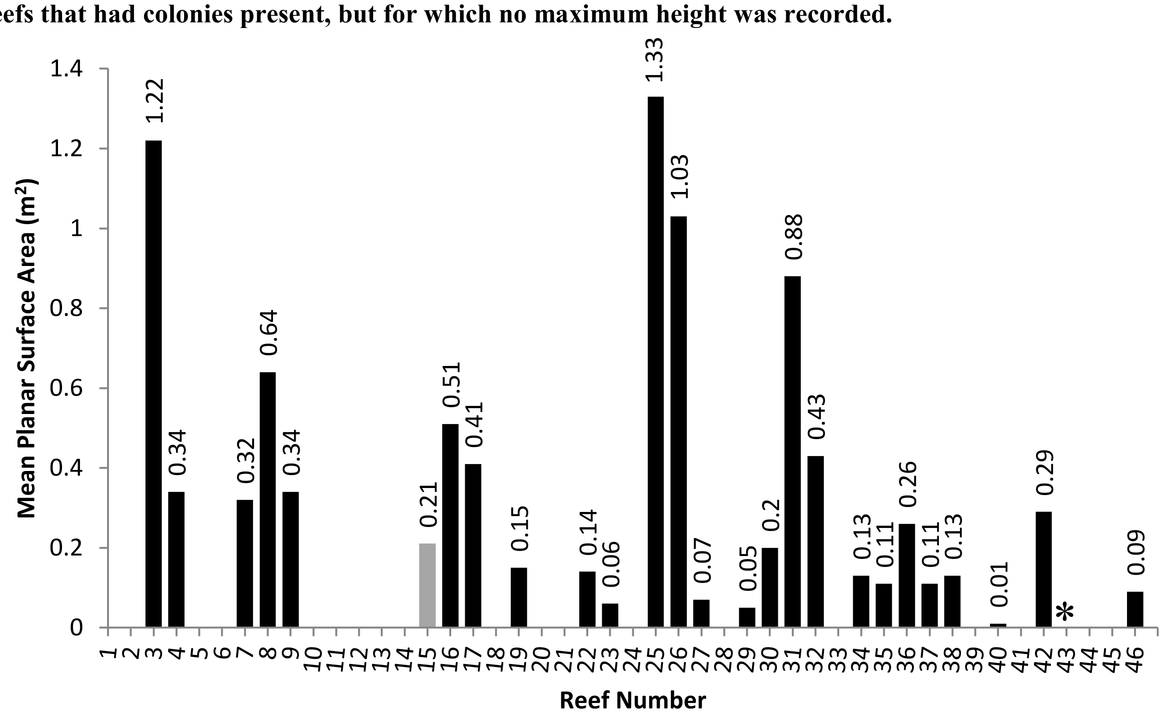


**Figure 32. Distribution of the mean planar surface area of the *Acropora* colonies located on each of the 46 reefs surveyed along the west cost of Barbados (June – August, 2015). The mean planar surface area for Mullins reef was estimated using the average surface area in each size class and is indicated by the grey bar. * indicates reef 43, the only reef that did not have planar surface area recorded for any colonies.**

33), but were not measured. The colonies that were measured on this reef, were from the reef flat area, and were much smaller (Figures 31 and 32). Almost equal numbers of colonies were categorized as either small (25%), medium (22%) or large (23%) (Figure 34). There were fewer but almost equal proportions of colony fragments (13%) and extra-large colonies (17%) found during the surveys (Figure 34). Extra-large colonies were often found on the outer deeper edges of the reef in the coral spur and groove zone, whilst the smaller colonies and fragments occurred further inshore often in the reef flat zone.

**Figure 33. Examples of high densities of *Acropora* with many large colonies located in the spur and groove zone of Mullins (Reef 15).**

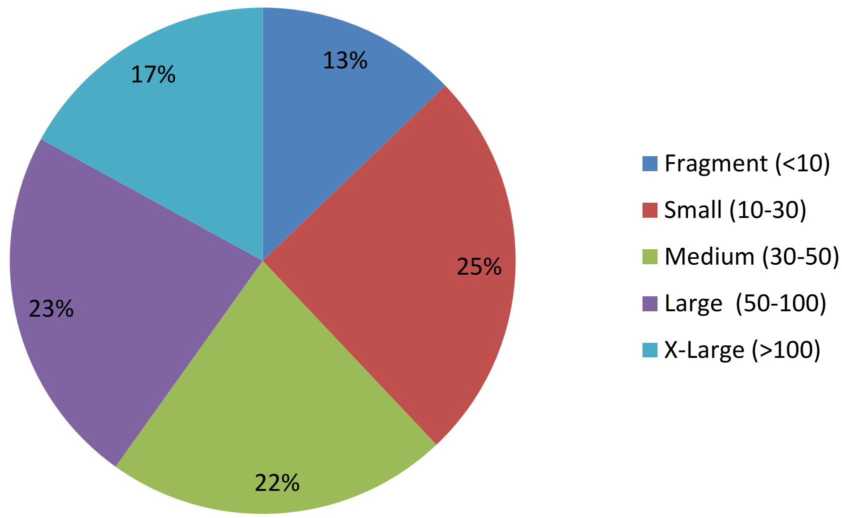


**Figure 34. Percentages of *Acropora* colonies found on fringing reefs on the west coast of Barbados in 2015 in each size-class. Size classes (shown with their range in cm) are based on the maximum colony diameter measured from the photographs of each individual colony.**

#### 5.2.4.2 Predation and disturbances

The occurrence of *Acropora* predators, lesions, borers and other disturbances are summarized in Table 4 and Figure 35. The corallivorous snail (*Coralliophila abbreviata*) was found on 9.5% of the colonies examined. Corallivorous fireworms (*Hermodice carunculata*) were found on a small portion (0.8%) of colonies; whereas the boring Christmas tree worms (*Spirobranchus giganteus*) were found to be present (sometimes in high abundance) on 26.6% of colonies examined. Almost half (47.9%) of the colonies were found to have general lesions likely caused by one or more predators, diseases, bleaching, or grazing, and 7.0% of colonies were found overturned by some disturbance (e.g. wave action, boat traffic, surfers, etc.). It should be noted however that predators and disturbances were not recorded for the 406 colonies found on the centre part of Mullins (reef 15) since no planar photographs of the individual colonies were taken.

**Table 4 Summary of the occurrence (% of colonies) of predators, borers, lesions and overturned colonies shown for each size category of *Acropora* as observed on fringing reefs along the west coast of Barbados in June to August 2015.**

| Colony size | n | Snails | Fireworms | Christmas tree worms | Lesions | Overturned |
|---|---|---|---|---|---|---|
| Small+fragments | 67 | 1.56 | 0.00 | 14.93 | 32.84 | 8.96 |
| Medium | 48 | 8.33 | 2.08 | 18.75 | 37.50 | 2.08 |
| Large | 83 | 15.66 | 0.00 | 31.71 | 55.42 | 8.54 |
| X-large | 44 | 11.36 | 2.27 | 43.18 | 68.18 | 6.82 |
| Total | 242 | 9.47 | 0.82 | 26.64 | 47.93 | 7.02 |

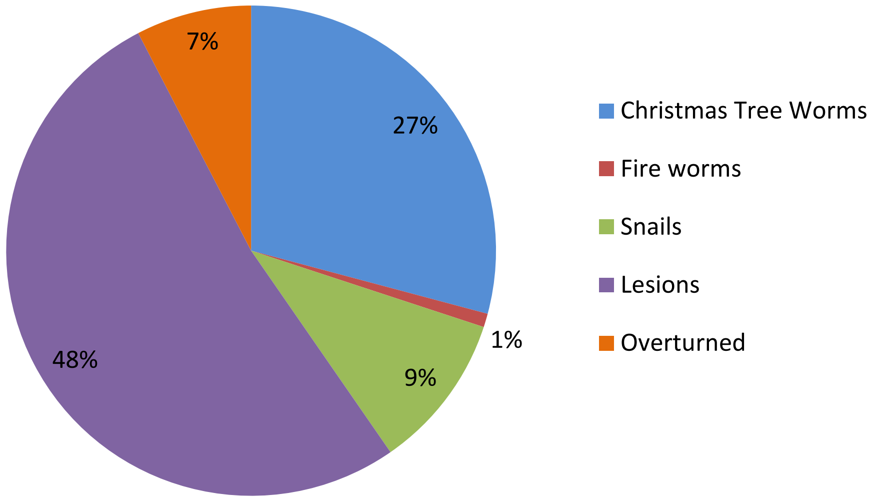


**Figure 35. Percentage of *Acropora* colonies (n = 242) on the 46 fringing reefs surveyed along the west coast of Barbados between June and August 2015, that were affected by predators, borers, lesions or were overturned.**

Size of colony appeared to influence some of these indices of condition. For example, the % occurrence of Christmas tree worms increased steadily with colony size (Table 4) and colonies with the boring worms were significantly larger in planar surface area (mean area = 0.37 $m^2$) than colonies without them (mean area = 0.18 $m^2$; One-Way ANOVA, F = 15.07, df = 1, p = 0.001). Likewise, % occurrence of lesions increased steadily with colony size (Table 4) and size of colonies with lesions (mean area = 0.31 $m^2$) was significantly larger than colonies without lesions (mean area = 0.16 $m^2$; One-Way ANOVA, F = 11.88, df = 1, p = 0.001). Presence of predatory snails also increased steadily with size up to large sized colonies (Table 4). However, overall there was no significant difference in the mean colony size between those with and without snails, fireworms or those that had been overturned or not (One-Way ANOVAs, p-value >0.05 in all cases).

## 5.3 Environmental correlates

### 5.3.1 Ecological

Correlations between *Acropora* abundance per reef and various ecological parameters describing each reef are shown for all reefs in Figure 36 (*left panel*) and with Mullins (reef 15) omitted in Figure 36 (*right panel*), and the results of the Pearson's correlations are summarised in Table 5. Likewise, correlations between *Acropora* density on each reef and the same ecological parameters are shown for all reefs in Figure 37 (*left panel*) and with Mullins (reef 15) omitted in Figure 37 (*right panel*) and correlation analyses are also summarised in Table 5. The patterns observed for correlations between the ecological parameters and *Acropora* abundance (Figure 36) were extremely similar to those observed for correlations with *Acropora* density (Figure 37) and are therefore described simultaneously.

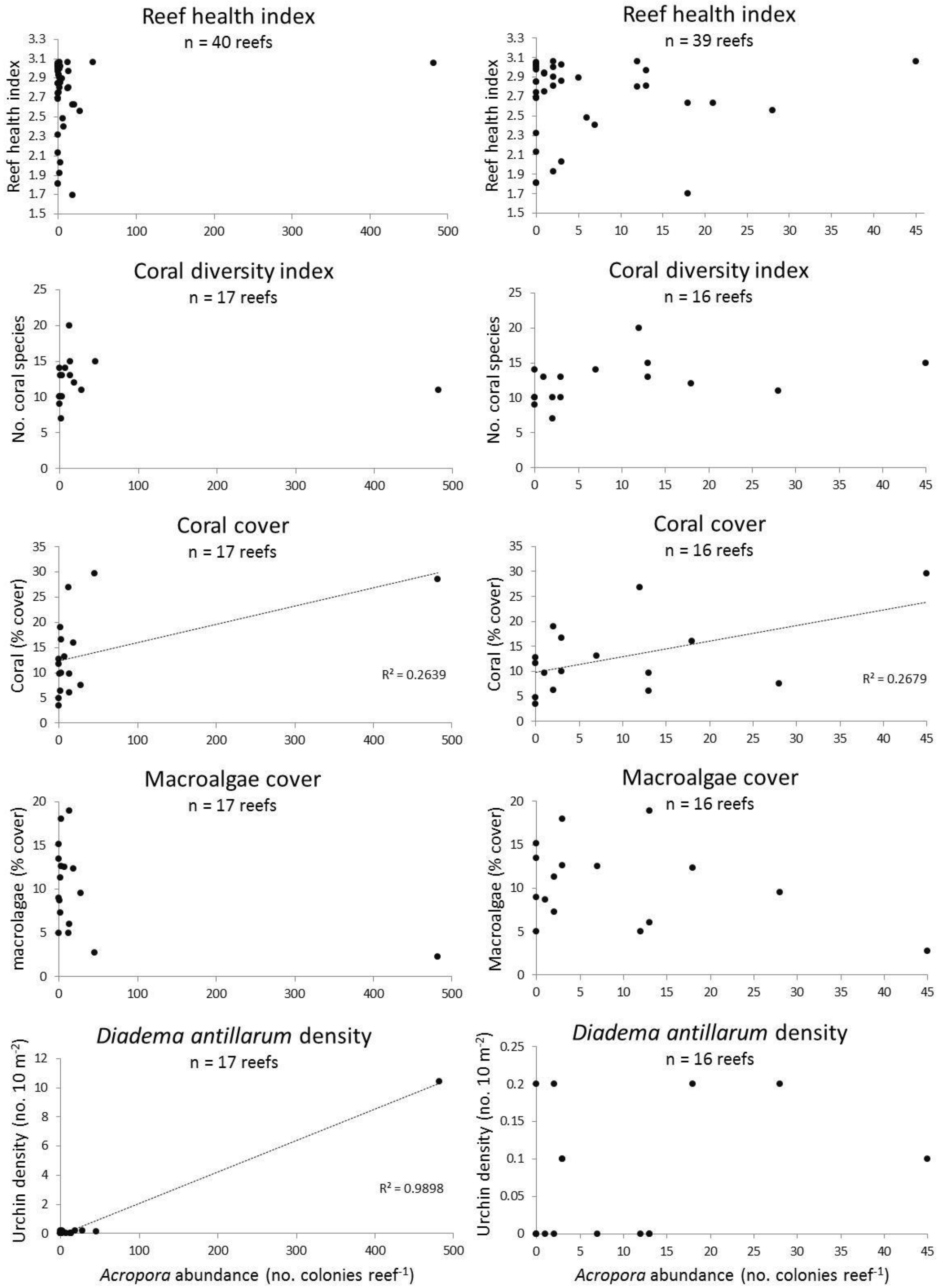


**Figure 36. Correlations between *Acropora* abundance and various environmental parameters for each reef. *Left panel* shows all reefs, *right panel* shows data without Mullins (reef 15). The semi-quantitative broad Reef Health Index was derived by Connell (2013); all other parameters are from Government's permanent reef monitoring programme (Office of Research 2014). Only significant correlations are shown. Data are given in Appendix 3 and results summarised in Table 5.**

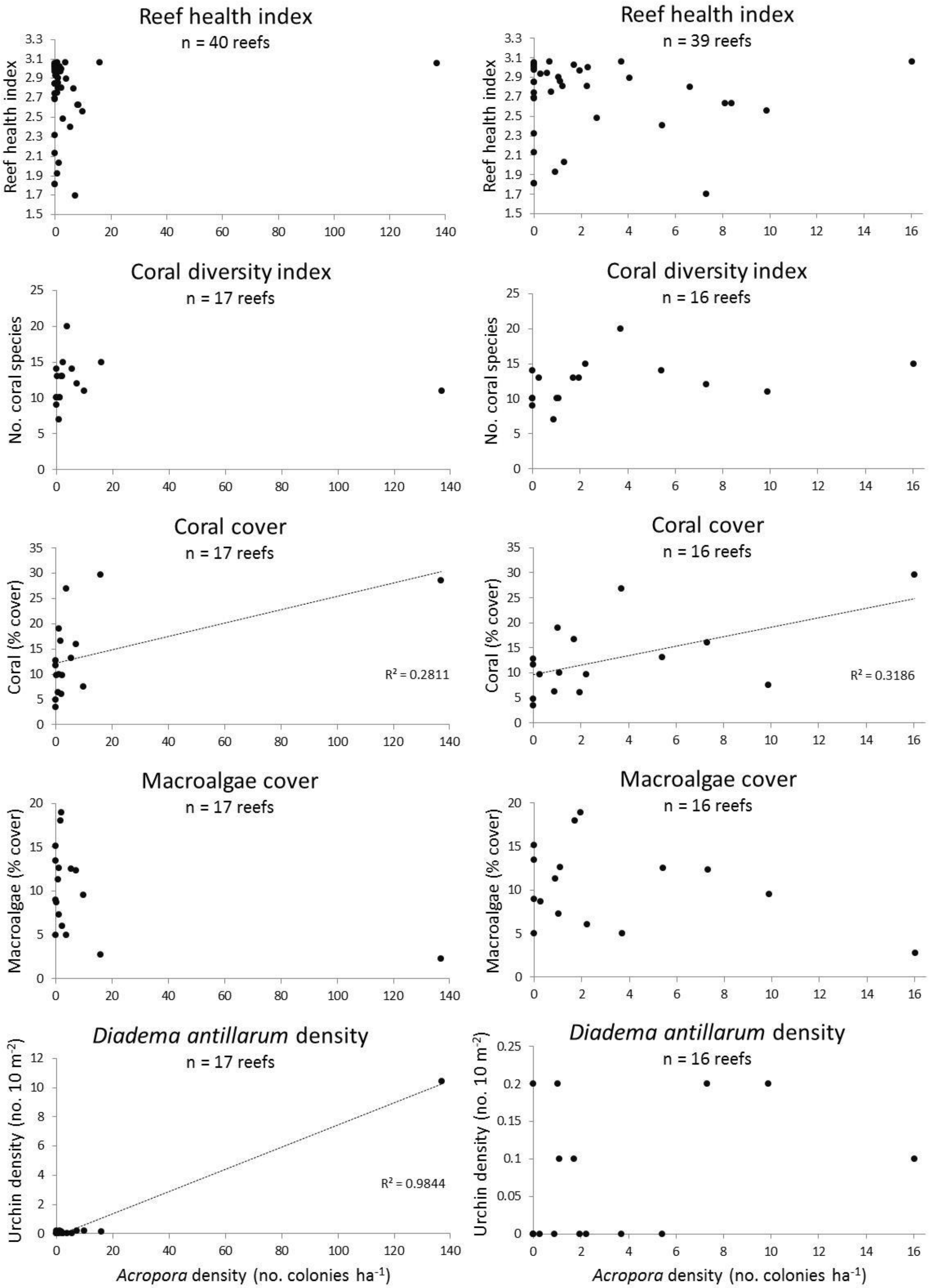


**Figure 37. Correlations between *Acropora* density and various environmental parameters for each reef. *Left panel* shows all reefs, *right panel* shows data without Mullins (reef 15). The semi-quantitative broad Reef Health Index was derived by Connell (2013); all other parameters from Government's permanent reef monitoring programme (Office of Research 2014). Only significant correlations are shown. Data are given in Appendix 3 and results summarised in Table 5.**

**Table 5. Summary of test results for Pearson correlation analysis of *Acropora* abundance and density values (determined during fringing reef surveys along the west coast of Barbados between June 13th and August 22nd 2015) versus environmental parameters for each reef. The semi-quantitative broad Reef Health Index was derived by Connell (2013); all other parameters are from Government's permanent reef monitoring programme and were measured in 2012 (Office of Research 2014).**

| *Acropora* parameter | Dataset | Test statistic | Reef health index | Coral diversity index (no. species) | Mean coral % cover | Mean macroalgae % cover | *Diadema* density (urchins ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Abundance (colonies reef$^{-1}$) | All reefs | r | 0.141 | -0.61 | 0.514 | -0.434 | 0.995 |
| | | p | 0.387 | 0.815 | .035 | 0.082 | <0.0001 |
| | | n | 40 | 17 | 17 | 17 | 17 |
| | Mullins (reef 15) omitted | r | 0.000 | 0.374 | 0.518 | -0.363 | 0.281 |
| | | p | 0.998 | 0.154 | 0.040 | 0.167 | 0.292 |
| | | n | 39 | 16 | 16 | 16 | 16 |
| Density (colonies ha$^{-1}$) | All reefs | r | 0.134 | -0.057 | 0.530 | -0.440 | 0.992 |
| | | p | 0.411 | 0.828 | 0.029 | 0.077 | <0.0001 |
| | | n | 40 | 17 | 17 | 17 | 17 |
| | Mullins (reef 15) omitted | r | -0.037 | 0.326 | 0.564 | -0.352 | 0.339 |
| | | p | 0.821 | 0.217 | 0.023 | 0.182 | 0.199 |
| | | n | 39 | 16 | 16 | 16 | 16 |

NB. Significant correlations highlighted in grey

There were significant positive correlations between *Acropora* and the mean % coral cover for all reefs with and without Mullins (reef 15). There was also a highly significant positive correlation between *Acropora* and *Diadema* urchin density when all reefs were considered. This relationship was clearly driven by the exceptionally high values for both parameters on Mullins (reef 15). There was also a weak negative correlation between *Acropora* and mean % macroalgae cover for all reefs, although it was not significant at the 5% level for abundance or density (Table 5). There was no correlation between *Acropora* and Connell's semi-quantitative reef health index, and no correlation with the coral diversity index (Figures 36 and 37, Table 5).

### 5.3.2 Physical

Correlations between *Acropora* abundance per reef and area of reef or reef zone for each reef are shown for all reefs in Figure 38 (*left panel*) and with Mullins (reef 15) omitted in Figure 38 (*right panel*), and the results of the Pearson's correlations are summarised in Table 6. Likewise, correlations between *Acropora* density on each reef and the same physical parameters are shown for all reefs in Figure 39 (*left panel*) and with Mullins (reef 15) omitted in Figure 39 (*right panel*) and correlation analyses are also summarised in Table 6.

There were significant positive correlations between *Acropora* abundance and size of the spur and groove reef zone for all reefs, and for all reef areas (entire reef area and all zones) except the nearshore reef flat zone when Mullins (reef 15) was removed from the dataset (Figure 38, Table 6), suggesting that the larger the area, the more *Acropora* colonies there are likely to be.

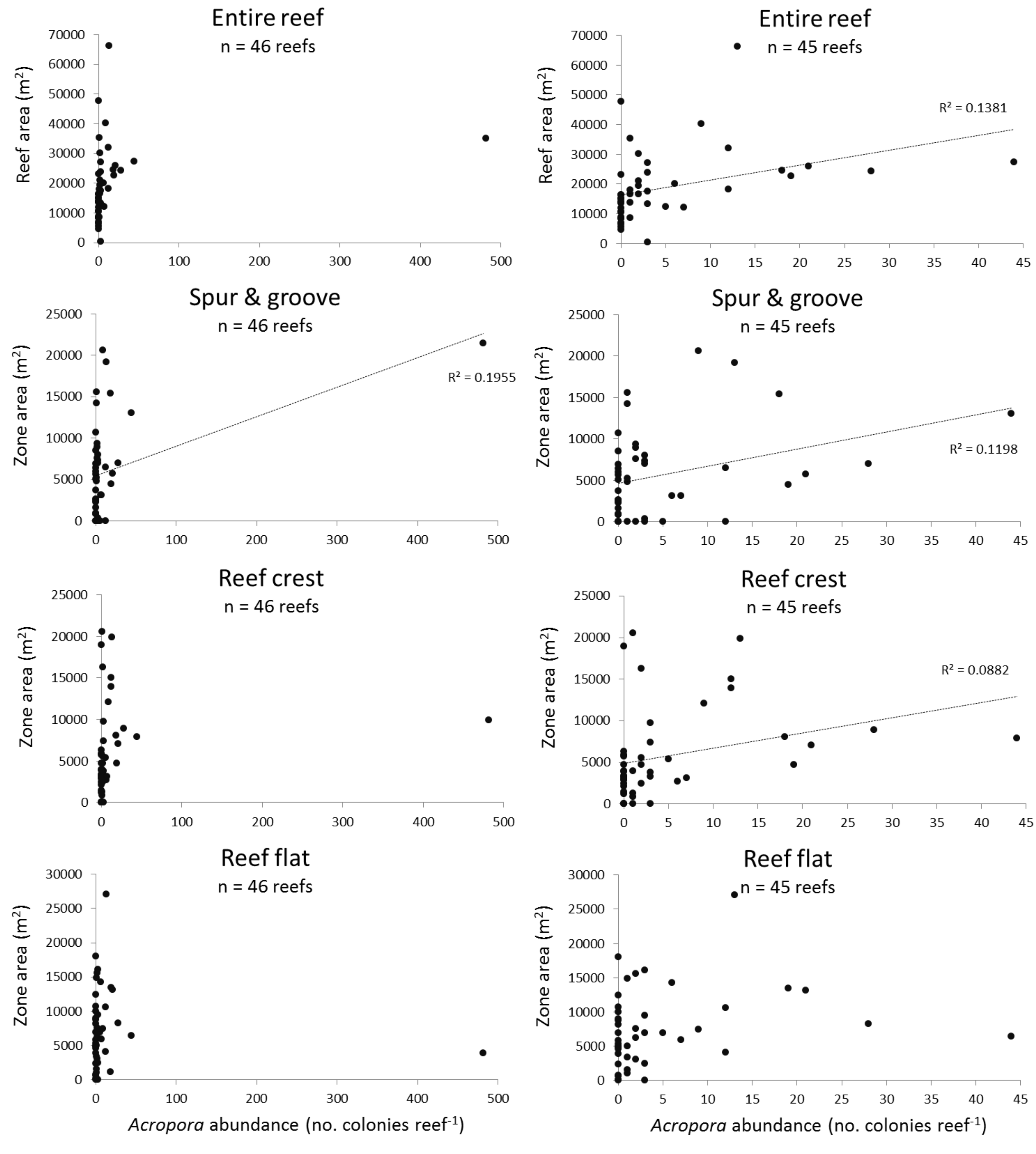


**Figure 38**. **Correlations between *Acropora* abundance and area of reef or reef zone for each reef. *Left panel* shows all reefs, *right panel* shows data without Mullins (reef 15). Only significant correlations are shown. Reef area data are given in Appendix 2 and results summarised in Table 5.**

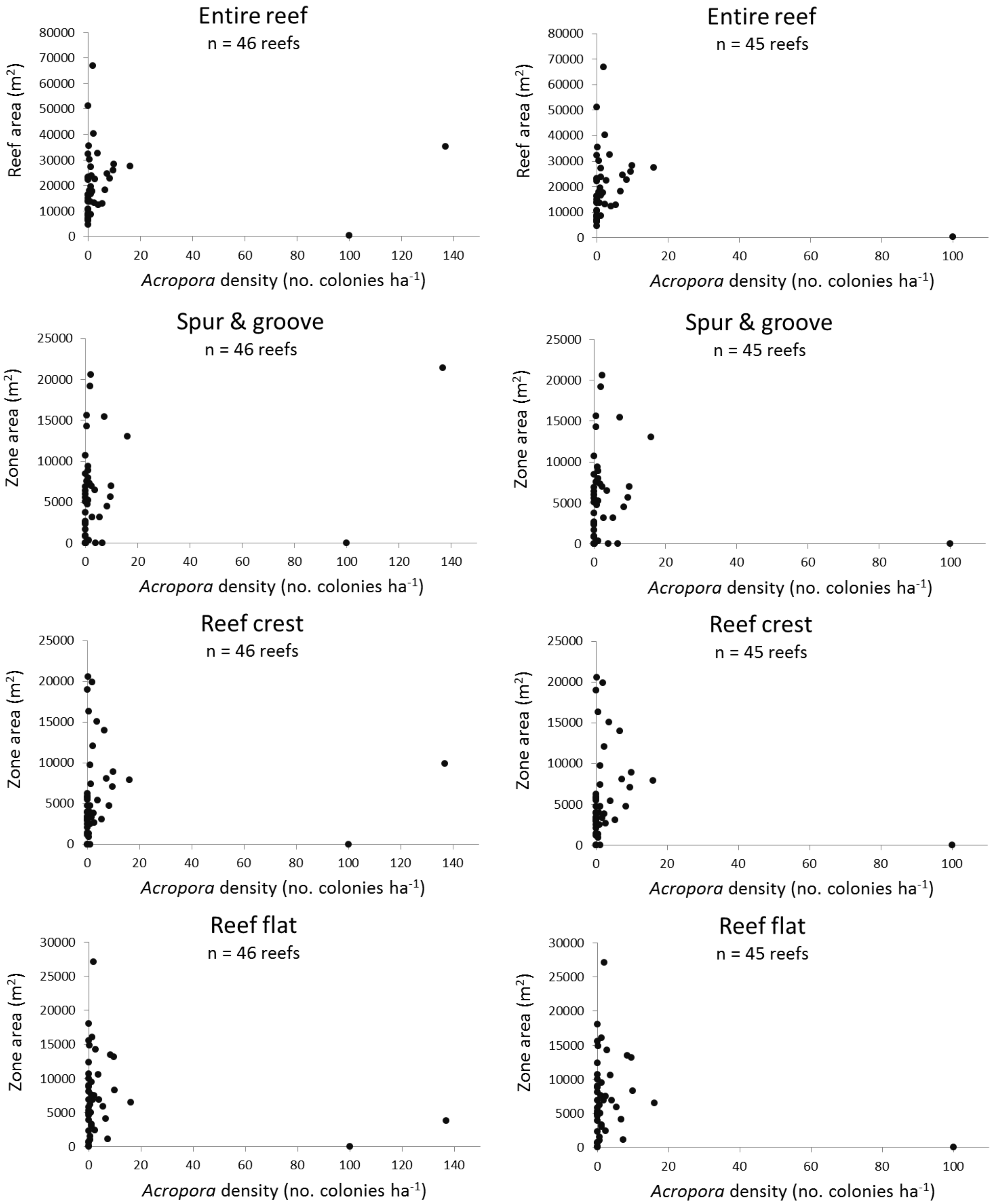


**Figure 39. Correlations between *Acropora* density and area of reef or reef zone for each reef. *Left panel* shows all reefs, *right panel* shows data without Mullins (reef 15). None of the correlations are statistically significant. Reef area data are given in Appendix B and results summarised in Table 5.**

**Table 6. Summary of test results for Pearson correlation analysis of *Acropora* abundance and density values (determined during fringing reef surveys along the west coast of Barbados between June 13th and August 22nd 2015) versus physical parameters (areas) for each reef.**

| *Acropora* parameter | Dataset | Test statistic | Entire reef area | Area of spur & groove zone | Area of reef crest zone | Area of reef flat zone |
|---|---|---|---|---|---|---|
| Abundance (colonies reef$^{-1}$) | All reefs | r | 0.224 | 0.442 | 0.148 | -0.068 |
| | | p | 0.134 | 0.002 | 0.327 | 0.654 |
| | | n | 46 | 46 | 46 | 46 |
| | Mullins (reef 15) omitted | r | 0.351 | 0.346 | 0.297 | 0.182 |
| | | p | 0.018 | 0.020 | 0.048 | 0.233 |
| | | n | 45 | 45 | 45 | 45 |
| Density (colonies ha$^{-1}$) | All reefs | r | 0.039 | 0.266 | 0.022 | -0.178 |
| | | p | 0.796 | 0.074 | 0.844 | 0.238 |
| | | n | 46 | 46 | 46 | 46 |
| | Mullins (reef 15) omitted | r | -0.179 | -0.105 | -0.112 | -0.175 |
| | | p | 0.238 | 0.492 | 0.464 | 0.251 |
| | | n | 45 | 45 | 45 | 45 |

NB. Significant correlations highlighted in grey

However, there were no significant relationships between *Acropora* density and areas of reef or reef zones (Figure 39, Table 6), suggesting no recruitment preference for larger or smaller sized reefs by the acroporids.

## 6 DISCUSSION

A surprisingly large number (n = 707) of *Acropora* colonies were found along the west coast of Barbados. This abundance is far more than anticipated based on the relatively low numbers reported by the marine park rangers and other recreational divers and snorkelers, as well as the fact that *Acropora* recovery has not been described in any of the Government's RMP surveys conducted every five years since 1982. Furthermore the reports by Lewis (1984) and Lewis and Oxenford (1996) only mention *Acropora* rubble and do not describe any live colonies.

However, although the overall abundance of colonies is surprisingly high for Barbados, the density of colonies at the individual reef level is considerably lower than for other recent studies reporting recovery. For example, Larson et al. (2014) reported colony densities ranging from 0.02 – 0.28 colonies/m$^2$ with an overall mean of 0.08 colonies/m$^2$ across 24 reefs surveyed in the Veracruz reef system in the Gulf of Mexico. These are substantially higher than our own densities (range: 0 – 0.0137 colonies/m$^2$; mean: 0.0007 colonies/m$^2$) along the west coast of Barbados. Likewise, Muller, Rogers and van Woesik (2014) reported much higher densities than our own (range: 0.003 – 0.162 colonies/m$^2$; mean: 0.036 colonies/m$^2$) at the reef level, for 10 recovering reefs in St. John USVI in 2010. This is also the case for Cayo de Agua in Los Roques where Zubillaga, Bastidas and Cróquer (2005) reported a mean density of 0.32 colonies/$m^2$. Interestingly, Zubillaga et al (2008) went as far as to define *A. palmata* populations in recovery in Los Roques as those with small to medium colony sizes and densities > 0.1 colony/$m^2$, with a low prevalence of diseases, and low density of predators (0.25 snails per colony). As such, our populations would still appear to lie outside this definition, based on densities alone which are orders of magnitude lower, even for the reefs with the highest occurrence of *Acropora*. However, it is worth noting that our densities were calculated for whole reef area, rather than for strict zones of *A. palmata* natural habitat within a reef, as surveyed by Zubillaga et al. (2008) for the 10 reef sites examined in their study.

With regard to disease and predation, we did not attempt to record diseases separately, in view of the difficulty in distinguishing among white pox (WPx), white band disease (WBD), a condition simply known as 'patchy necrosis' and lesions caused by other agents such as predators and grazers (see Boulon et al. 2005). We therefore lumped all of these conditions together simply as presence of lesions. This likely explains why our result (47.9 % colonies had lesions) appears very high when compared with other disease reports for the acroporids (range 4 – 38%, see Boulon et al. 2005). Our prevalence rate of the predatory snail (present on 9.5% colonies) falls at the lower end of the range reported for acroporid populations across the Caribbean (10-20%; Baums, Miller and Szmant . 2003), although it is higher than the 5.6% reported by Zubillaga et al. (2008) in recovering *Acropora* populations in Los Roques, and the 2% reported by Larson et al. (2014) in recovering populations in Veracruz. Predation by fireworms (< 1%) appears similarly low in our study and Larson et al. (2014), and little appears to have been reported on the prevalence or impacts of the Christmas tree worm, although Ben-Tzvi, Einbinder and Brokovich (2006) suggest that the relationship may benefit the coral. Overall our prevalence of predators was likely high enough to be partially affecting recovery, as the presence of predators can cause colonies to become more vulnerable to epizootic disease and other environmental impacts (Boulon et al. 2005; Grober-Dunsmore, Bonito and Frazer 2006; Japaud et al. 2015). Interestingly, our data corroborate the findings of Muller, Rogers and van Woesik et al. (2014) who reported that larger colony sizes are more susceptible to disease (in our case lesions) and predation (snails), likely because larger colonies have a greater surface area that makes them more favourable to attack.

While the overall distribution of *Acropora* colonies did not seem to follow a consistent pattern along the entire coast, there were noticeable clusters of neighbouring reefs that experienced higher abundances than others, and clusters with no or very low abundance. Tomascik and Sander (1987) and Tomascik (1991) reported an eutrophication gradient along the west coast with nutrient concentrations decreasing from south to north. They also reported that eutrophication had a negative influence on successful coral recruitment, such that we might have expected to find a consistent north-south pattern to the recovery of acroporids. This expectation was strengthened by a much more recent study of water quality along the west coast of Barbados conducted as part of the Government's IDB-CZMU CRMP project. In this study, the Nitrogen 15 stable isotope ($\delta^{15}N$) ratio, a strong indicator of sewage versus agricultural derived nitrogen was determined from gorgonian and macroalgae tissue samples taken from multiple sites along the west coast in 2014 and 2015 (Baird 2015). The results from both gorgonians and macroalgae were consistent in demonstrating a gradient of sewage derived nitrogen from south to north, with sewage being the primary nitrogen source for reefs from Bridgetown to Holetown and agriculture being the primary source from Holetown northwards to Maycocks (Baird 2015).

Although this recent study says nothing about the concentration of nitrogen in the water column, sewage pollution has been implicated in an increase in *Acropora* diseases such as WPx and a shift towards more macroalgae dominant reefs in Puerto Rico by Hernández-Delgado et al. (2008). This would support the expectation in Barbados of greater recovery of *Acropora* along the west coast towards the northern end. Whilst it is true that the three reefs with the highest density of *Acropora* (Port St Charles, Mullins and Tropicana) are in the more northerly section of the west coast, there are many other reefs in this section that have none, or very low densities, and therefore water quality does not appear to be the only driver for the observed distribution in this case.

An examination of various other ecological and physical parameters contributed little more to unveiling the factors that may be driving the pattern of recovery. Larger reefs and larger spur and groove and reef crest zones tended to have higher abundance of *Acropora*, but reef size was not correlated with the density of colonies. There was no correlation between *Acropora* and the semi-qualitative reef health index derived by Connell (2013), but there were significant, albeit weak, correlations between *Acropora* abundance and/or density and live coral cover as derived by the independent RMP (Office of Research 2014), and a very weak, insignificant but negative relationship with macroalgae cover, suggesting that Acropora is doing better on reefs favoured by other corals and perhaps where macroalgae is less abundant. This is also supported by the significant positive relationship between *Acropora* and the herbivorous urchin, *Diadema antillarum* although it was clearly driven by the high values of each at the Mullins site. The lack of a relationship when Mullins reef was removed could be attributed to the overall very low numbers of *Diadema* urchins, which are themselves still recovering from a Caribbean-wide disease epidemic in the early 1980s (Lessios 1988).

Reef clusters with greater abundance of *Acropora* included reefs located in areas of high recreational traffic such as North and South Bellairs and Vauxhall reefs, which lie within the marine park and experience high levels of visitation, especially by novel snorkelers. Furthermore, Mullins and Tropicana reefs periodically experience high wave action, making them popular surfing spots at certain times of the year. Both high waves and anthropogenic recreational activity (inexperienced snorkelers and accidental surfing ‘wipe-outs’) can lead to coral breakage. As such, an increased level of asexual reproduction through fragmentation may be responsible for a greater abundance and density of colonies on these reefs. Lirman (2000, 2003) reported on potential positive impacts of a limited frequency of storms on *Acropora palmata* populations in terms of increased numbers of colonies and expansion of the populations through fragmentation, although he noted that these populations will have reduced sexual reproduction capacity as a result of damaged adult colonies and fragments below the minimum size for reproduction. In addition to the possible increase in fragmentation rates, those reefs within the no-take Folkestone Marine Park boundaries have higher abundance of large sized herbivorous fish (e.g. parrotfishes) (Valles and Oxenford 2015), which are important for controlling the growth of algae, and thus may improve coral recruitment success on these reefs (see Boulon et al. 2005).

Although a large number of colonies were found in the coral spur and groove zone of Mullins (reef 15), the majority of colonies on other reefs were found in the reef crest zone. This is likely because of the species’ preference for settling in shallow areas of flat rock with high wave action (Aronson et al. 2008b), both of which are present in this reef zone. Colonies found in the spur and groove zone were often larger in height and area. These colonies may be benefitting from less sedimentation as the water clarity in this zone was often observed during the surveys to be superior to the water clarity in-shore, thus increasing the amount of sunlight available for growth (see Boulon et al. 2005). Colonies found in the in-shore zones were often fragments of larger colonies that had evidently broken off and been carried inshore by wave action.

The large numbers of recent *Acropora* fragments and irregular-shaped, small-sized colonies on the fringing reefs, and the very low densities across many reefs would seem to indicate that the current primary mode of reproduction for this recovering population in Barbados is likely to be through asexual fragmentation. This will ultimately limit the gene pool and increase the vulnerability of the population to other stressors, thereby compromising the potential for successful sustained recovery (Zubillaga et al. 2008, Japaud et al. 2015). A preliminary histopathology analysis of reproductive condition of large *Acropora palmata* colonies sampled in Barbados during the expected spawning period of this species in the summer of 2014 by the IDB-CZMU CRMP project provided additional evidence of poor capacity for sexual reproduction (Baird 2015). Only 2 of 60 colonies had viable ova and sperm expected to lead to successful spawning, whilst the others appeared to have been compromised by organic and chemical pollution (Baird 2015). Note however that some sexual reproduction is likely to be occurring on at least some of the west coast reefs as evidenced by the presence of definite and putative hybrid colonies. These *Acropora prolifera* colonies indicate sexual reproduction between *A. palmata* and *A. cervicornis* and although no *A. cervicornis* colonies were found on the fringing reefs surveyed in this study, several colonies are known to exist in the deeper patch reef area immediately seaward of some of the fringing reefs (e.g. Vauxhall reef, see annotated photographs of D. Patriquin at: http://versicolor.ca/reef/).

## 7 CONCLUSIONS AND RECOMMENDATIONS

Even though there were no previous *Acropora* surveys completed in Barbados, the data obtained from this study can still be compared to the anecdotal evidence, quantitative and qualitative information from the Government's RMP surveys, reports from Lewis (1984) and Lewis and Oxenford (1996) to show that some recovery has occurred. This study now provides a valuable detailed baseline study for future comparative studies. The location, abundance, density, size and health indicators now available for every colony can be used to guide conservation and rehabilitation efforts and monitor recovery success.

The recovery of *Acropora* populations, like other corals, is likely a complex process depending on a number of interacting drivers. As suggested by Hughes et al. (2002), these could include factors such as adult stock size and their level of fecundity; hydrodynamic features that would have a significant influence on the transport of larvae; and patterns of early mortality that would influence the abundance of recruits.

Successful recovery and persistence of acroporids in Barbados will ultimately depend on our ability to mitigate the multiple local stressors that are likely constraining sexual reproduction and successful recruitment of coral larvae, and impacting the overall health and resilience of acroporids to external stressors such as increased sea surface temperatures from global warming. The most important of these is almost certainly water quality, not only the high levels of nutrients and suspended particulate matter, but other toxic chemicals that can disrupt the reproductive capacity of corals even at very low concentrations.

In the meantime, special protection of existing hotspots with high abundance of acroporids should be considered a priority to allow further expansion of these populations, and to provide opportunities for strategic, small-scale coral restoration projects involving nursery rearing and out-planting of these potentially fast growing species. This is particularly significant, given the current interest in fringing reef restoration along the west coast of Barbados and the very low number of *Acropora* colonies reported from the current west coast study sites of the on-going IDB-CZMU CRMP.

Future study should involve acquisition of genetic data from the recovering *Acropora* populations. Genetic data are needed to determine the current level of genetic diversity within the local population and the extent to which the recovery is being driven by sexual reproduction versus fragmentation. This will provide vital information on the potential resilience of the local population to future environmental changes and disease epidemics. These data should also help inform coral nursery projects to ensure greatest success in restocking reefs.

## 8 REFERENCES


Aronson, R., A. Bruckner, J. Moore, B. Precht and E. Weil. 2008a. *Acropora cervicornis*. The IUCN Red List of Threatened Species: 1-7

———. 2008b. *Acropora palmata*. The IUCN Red List of Threatened Species: 1-6

Aronson, R. B. and W. F. Precht. 2001. White-band disease and the changing face of Caribbean coral reefs. *Hydrobiologia* 460: 25-38.

Baird, W. F. and Associates. 2015. *Coastal Risk Assessment and Management Program Ecosystem Based Adaptation Pilot Project June 2015 EBA Workshop Summary*. Ottawa: W.F. Baird and Assoc. Coastal Engineers Ltd.

Baums, I. B. 2008. A restoration genetics guide for coral reef conservaton. *Molecular Ecology* 17:2796-2811.

Baums, I. B., M. W. Milller, A. M. Szmant. 2003. Ecology of a corallivorous gastropod, *Coralliophila abbreviata*, on two scleractinian hosts I: Population structure of snails and corals. *Marine Biology* 142: 1083-1091.

Baums, I. B., M. W. Miller and M. E. Hellberg. 2005. Regionally isolated populations of an imperiled Caribbean coral, *Acropora palmata*. *Molecular Ecology* 14:1377-1390.

Ben-Tzvi, O., S. Einbinder and E. Brokovich. 2006. A beneficial association between a polychaete worm and a scleranctinin coral? *Coral Reefs 25*: 98.

Birkeland, C., Ed. 1997. *Life and death of coral reefs*. New York: Chapman and Hall.

Boulon, R., M. Chiappone, R. Halley, W. Jaap, B. Keller, B. Kruczynski, M. Miller and C. Rogers. 2005. *Atlantic Acropora status review document*. Report to National Marine Fisheries Service, Southeast Regional Office.

Bruckner, A.W. 2002. *Proceedings of the Caribbean Acropora workshop*: *Potential application of the U.S. Endangered Species Act as a conservation strategy*. NOAA Technical Memorandum NMFS-OPR-24: 199pp.

Bruckner, A. W. and R. J. Bruckner. 2001. Condition of restored *Acropora palmata* fragments off Mona Island, Puerto Rico, two years after the Fortuna Reefer ship grounding. *Coral Reefs* 20: 235–243.

Bruckner, A. W., T. F. Hourigan, M. Moosa, S. Soemodihardjo, A. Soegiarto, K. Romimohtarto and S. Suharsono. 2002. Proactive management for conservation of *Acropora cervicornis* and *Acropora palmata*: application of the U. S. Endangered Species Act. *Proceedings of the International Coral Reef Symposium* 9: 661-665.

Connell, S. 2013. The west coast fringing reefs of Barbados: A broad-scale assessment of their ecological condition. Master of Philosophy Thesis, University of the West Indies, Barbados.

Gardner, T. A., I. M. Côté, J. A. Gill, A. Grant and A. R. Watkinson. 2003. Long-term region-wide declines in Caribbean corals. *Science* 301:958-960.

Grober-Dunsmore R., V. Bonito, and T. K. Frazer. 2006. Potential inhibitors to recovery of *Acropora palmata* populations in St. John, US Virgin Islands. *Marine Ecology Progress Series* 321:123-32.

Hernández-Delgado, E. A., B. Sandoz, M. Bonkosky, J. Norat-Ramírez and H. Mattei. 2008. Impacts of non-point source sewage pollution on elkhorn coral, *Acropora palmata* (Lamarck), assemblages of the southwestern Puerto Rico shelf. *Proceedings of the International Coral Reef Symposium* 11: 747-751.

Hughes T. P., A. H. Baird, E. A. Dinsdale, V. J. Harriot, N. A. Moltschaniwskyj, M. S. Pratchett, J. E. Tanner, B. L. Willis. 2002. Detecting regional variation using meta-analysis and large-scale sampling: latitudinal patterns in recruitment. *Ecology* 83:436–451.

Jackson, J. B. C. 1992. Pleistocene perspectives on coral reef community structure. *American Zoologist* 32:719-731.

Jackson, J., K. Cramer, M. Donovan and V. Lam, (eds). 2014. *Status and trends of Caribbean coral reefs: 1969–2012*. Switzerland: Global Coral Reef Monitoring Network, IUCN .

Japaud, A., C. Bouchon, J. L. Manceau and C. Fauvelot. 2015. High clonality in *Acropora palmata* and *Acropora cervicornis* populations of Guadeloupe, French Lesser Antilles. *Marine and Freshwater Research* 66: 847-851.

Larson E. A., D. S. Gilliam, M. L. Padiema and B. K. Walker. 2014. Possible recovery of *Acropora palmata* (Scleractinia:Acroporidae) within the Veracruz Reef System, Gulf of Mexico: a survey of 24 reefs to assess the benthic communities. *Revista de Biologia Tropical* 62:75-84.

Lessios, H. A. 1988. Mass mortality of *Diadema antillarum* in the Caribbean: what have we learned? *Annual Review of Ecology and Systematics* 19:371–393.

Lewis J. B. 1984. The *Acropora* inheritance: a reinterpretation of the development of fringing reefs in Barbados, West Indies. *Coral Reefs* 3:117-122.

Lewis J. B. and H. A. Oxenford. 1996. *A field guide to the coral reefs of Barbados*. Montreal: McGill University, 46pp.

Lighty R. G., I. G. Macintyre and R. Stuckenrath. 1982. *Acropora palmata* reef framework: a reliable indicator of sea level in the Western Atlantic for the past 10,000 years. *Coral Reefs* 1:125-30.

Lirman, D. 1999. Reef fish communities associated with *Acropora palmata*: relationships to benthic attributes. *Bulletin of Marine Science* 65:235-252.

Lirman, D. 2000. Fragmentation in the branching coral *Acropora palmata* (Lamarck): growth, survivorship, and reproduction of colonies and fragments. *Journal of Experimental Marine Biology and Ecology* 251:41-57.

Lirman, D. 2003. A simulation model of the population dynamics of the branching coral *Acropora palmata*. Effects of storm intensity and frequency. *Ecological Modelling* 161:169-182.

Lohr K. E., S. L. Bejarano, D. Lirman, S. Schopmeyer and C. Manfrino. 2015. Optimizing the productivity of a coral nursery focused on staghorn coral *Acropora cervicornis. Endangered Species Research* 27:243-250

Macintyre, I. G. and M. A. Toscano. 2007. The elkhorn coral *Acropora palmata* is coming back to the Belize Barrier Reef. *Coral Reefs* 26: 757.

Macintyre, I. G., P. W. Glynn and M. A. Toscano. 2007. The demise of a major *Acropora palmata* bank–barrier reef off the southeast coast of Barbados, West Indies. *Coral Reefs* 26:765-773.

Muller, E. M., C. S. Rogers and R. van Woesik. 2014. Early signs of recovery of *Acropora palmata* in St. John, US Virgin Islands. *Marine Biology* 161:359-365.

Office of Research. 2014. *The Barbados Coral Reef Monitoring Programme: Changes in Coral Reef Communities on the West and South Coasts 2002-2012*. University of the West Indies, Barbados, 92pp.

Precht, W. F. and R. B. Aronson. 2004. Climate flickers and range shifts of reef corals. *Frontiers in Ecology and the Environment* 2:307-314.

Precht, W. F., A. W. Bruckner, R. B. Aronson and R. J. Bruckner. 2002. Endangered acroporid corals of the Caribbean. *Coral Reefs* 21: 41-42

Precht, W. F., M. L. Robbart and R. B. Aronson. 2004. The potential listing of *Acroporid* species under the US Endangered Species Act. *Marine Pollution Bulletin* 49:534-536.

Tomascik, T. 1991. Settlement patterns of Caribbean scleractinian corals on artificial substrata along a eutrophication gradient, Barbados, West Indies. *Marine Ecology Progress Series* 77:261-269.

Tomascik, T. and F. Sander. 1987. Effects of eutrophication on reef-building corals. II. Structure of scleractinian coral communities on the fringing reefs, Barbados, West Indies. *Marine Biology* 94: 53-75.

Valles, H., D. Gill and H. A. Oxenford. 2015. Parrotfish size as a useful indicator of fishing effects in a small Caribbean island. *Coral Reefs* 34:789-801.

Van Oppen M. J. H., B. L. Willis, H. W. J. A. Van Vugt and D. J. Miller. 2000. Examination of species boundaries in the *Acropora cervicornis* group (Scleractinia, Cnidaria) using nuclear DNA sequence analyses. *Molecular Ecology* 9:1363-1373.

Vollmer, S. V. and S. R. Palumbi. 2002. Hybridization and evolution of coral reef diversity. *Science* 296:20203-2025.

Williams, D. E. and M. W. Miller. 2005. Coral disease outbreak: pattern, prevalence and transmission in *Acropora cervicornis*. *Marine Ecology Progress Series* 301:119-128.

Young, C. N., S. A. Schopmeyer and D. Lirman. 2012. A review of reef restoration and coral propagation using the threatened genus *Acropora* in the Caribbean and Western Atlantic. *Bulletin of Marine Science* 88:1075–1098.

Zubillaga, A. L., C. Bastidas and A. Cróquer. 2005. High densities of the elkhorn coral *Acropora palmata* in Cayo de Agua, Archipelago Los Roques National Park, Venezuela. *Coral Reefs* 24:86.

Zubillaga, A. L., L. M. Márquez, A. Cróquer and C. Bastidas. 2008. Ecological and genetic data indicate recovery of the endangered coral *Acropora palmata* in Los Roques, Southern Caribbean. *Coral Reefs* 27: 63-72.

# 9 APPENDICES

## 9.1 Appendix 1

**Sample of the Excel database containing the reef, location, GPS coordinates, size, presence/absence of predators and borers, and whether or not the colony was overturned for each of the 707 colonies found along the west coast of Barbados during a survey from June 13th to August 22nd, 2015.**

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Colony | Reef # | Location | Colony ID# | Waypoint | FID | Lat_DEC | Long_DEC | Height (cm) | Colony Area (m2) | Size Class | Christmas tree worms | fire worms | snails | lesions | upside dow |
| 2 | 1 | 3 | Port St. Charles | 1 | 89 | 0 | 13.26285 | -59.64498 | 21 | 0.735479007 | x-large | n | n | n | y | n |
| 3 | 2 | 3 | Port St. Charles | 2 | 90 | 1 | 13.2637 | -59.64504 | 55 | 1.770342857 | x-large | y | n | n | y | n |
| 4 | 3 | 3 | Port St. Charles | 3 | 91 | 2 | 13.26381 | -59.64501 | 80 | 1.155103625 | x-large | n | n | n | y | n |
| 5 | 4 | 4 | Almond Bay | 1 | 84 | 3 | 13.2616 | -59.64398 | 25 | 0.235244091 | x-large | n | n | y | y | n |
| 6 | 5 | 4 | Almond Bay | 2 | 84 | 4 | 13.2616 | -59.64398 | 28 | 0.076561426 | small | n | n | n | n | n |
| 7 | 6 | 4 | Almond Bay | 3 | 84 | 5 | 13.2616 | -59.64398 | 26 | 0.169724302 | x-large | y | n | n | n | n |
| 8 | 7 | 4 | Almond Bay | 4 | 85 | 6 | 13.26215 | -59.64394 | 26 | 0.037917662 | x-large | y | n | n | n | n |
| 9 | 8 | 4 | Almond Bay | 5 | 86 | 7 | 13.2609 | -59.64421 | 18 | 0.075049107 | large | n | n | n | n | n |
| 10 | 9 | 4 | Almond Bay | 6 | 86 | 8 | 13.2609 | -59.64421 | 7 | 0.954216479 | large | y | n | n | n | n |
| 11 | 10 | 4 | Almond Bay | 7 | 87 | 9 | 13.26102 | -59.6442 | 60 | 0.474351197 | medium | n | n | n | n | n |
| 12 | 11 | 4 | Almond Bay | 8 | 87 | 10 | 13.26102 | -59.6442 | 19 | 0.351295914 | large | n | n | n | n | n |
| 13 | 12 | 4 | Almond Bay | 9 | 87 | 11 | 13.26102 | -59.6442 | 18 | 0.015785276 | medium | n | n | y | y | n |
| 14 | 13 | 4 | Almond Bay | 10 | 87 | 12 | 13.26102 | -59.6442 | 6 | 1.290155908 | medium | n | n | n | n | n |
| 15 | 14 | 4 | Almond Bay | 11 | 88 | 13 | 13.26104 | -59.64455 | 50 | 0.042785849 | x-large | n | n | n | y | n |
| 16 | 15 | 4 | Almond Bay | 12 | 88 | 14 | 13.26104 | -59.64455 | 13 | | | | | | | |
| 17 | 16 | 7 | Almond Bay | 1 | 80 | 15 | 13.25626 | -59.64516 | 37 | 0.026821228 | large | n | n | n | y | n |
| 18 | 17 | 7 | Almond Bay | 2 | 81 | 16 | 13.25641 | -59.64485 | 6 | 0.214052347 | large | n | n | n | y | n |
| 19 | 18 | 7 | Almond Bay | 3 | 82 | 17 | 13.2564 | -59.64494 | 17 | 1.057604692 | small | n | n | n | n | n |
| 20 | 19 | 7 | Almond Bay | 4 | 82 | 18 | 13.2564 | -59.64494 | 40 | 0.150572076 | x-large | n | n | n | y | y |
| 21 | 20 | 7 | Almond Bay | 5 | 83 | 19 | 13.25735 | -59.64486 | 15 | 0.13643194 | medium | n | n | n | n | n |
| 22 | 21 | 8 | Speightstown | 1 | 79 | 20 | 13.25379 | -59.6455 | 26 | 0.643056698 | x-large | y | n | n | n | n |
| 23 | 22 | 9 | Cobblers Cove | 1 | 71 | 21 | 13.24605 | -59.6463 | 38 | 0.250533705 | x-large | n | n | n | y | y |
| 24 | 23 | 9 | Cobblers Cove | 2 | 72 | 22 | 13.24591 | -59.64593 | 27 | 0.153833267 | large | n | n | n | y | n |
| 25 | 24 | 9 | Cobblers Cove | 3 | 73 | 23 | 13.24662 | -59.6462 | 90 | 2.459446259 | x-large | n | n | n | y | n |
| 26 | 25 | 9 | Cobblers Cove | 4 | 74 | 24 | 13.24672 | -59.64583 | 20 | 0.712695882 | x-large | y | y | n | y | n |
| 27 | 26 | 9 | Cobblers Cove | 5 | 74 | 25 | 13.24672 | -59.64583 | 8 | 0.075498322 | medium | y | n | n | y | n |
| 28 | 27 | 9 | Cobblers Cove | 6 | 75 | 26 | 13.24764 | -59.64607 | | 0.066067054 | medium | y | n | n | n | n |
| 29 | 28 | 9 | Cobblers Cove | 7 | 76 | 27 | 13.24766 | -59.64575 | 29 | 0.246422953 | large | n | n | n | n | n |
| 30 | 29 | 9 | Cobblers Cove | 8 | 77 | 28 | 13.24745 | -59.64568 | 22 | 0.26855 | x-large | n | n | n | n | n |
| 31 | 30 | 9 | Cobblers Cove | 9 | 77 | 29 | 13.24745 | -59.64568 | 4 | 0.048132932 | small | n | n | n | n | n |
| 32 | 31 | 9 | Cobblers Cove | 10 | 77 | 30 | 13.24745 | -59.64568 | 2 | 0.018539218 | small | n | n | n | y | n |
| 33 | 32 | 9 | Cobblers Cove | 11 | 77 | 31 | 13.24745 | -59.64568 | 3 | 0.032159203 | medium | n | n | n | y | n |
| 34 | 33 | 9 | Cobblers Cove | 12 | 77 | 32 | 13.24745 | -59.64568 | 2 | 0.061676032 | small | y | n | y | y | n |

## 9.2 Appendix 2

**Summary of data shown separately for each of the 46 reefs surveyed along the west coast of Barbados from June 13th to August 22nd, 2015. Data included are reef numbers, their location, their latitude and longitude coordinates and the reef zone areas (calculated from the benthic habitat map in ArcGIS).**

| Reef # | Location | Latitude | Longitude | Area of reef / zone ($m^2$) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Spur & groove | Reef crest | Reef flat | Total reef |
| 1 | Six Mens Bay | 13°16'06.23 | 59°38'43.12 | 6412 | 0 | 8744 | 15156 |
| 2 | Six Mens Bay | 13°15'29.11 | 59°38'10.65 | 5984 | 0 | 8952 | 14936 |
| 3 | PSC | 13°15'48.91 | 59°38'41.03 | 0 | 0 | 0 | 300 |
| 4 | Almond Bay | 13°15'37.74 | 59°38'39.16 | 0 | 13976 | 4116 | 18092 |
| 5 | Almond Bay | 13°15'31.57 | 59°38'40.20 | 0 | 6276 | 92 | 6368 |
| 6 | Almond Bay | 13°15'28.77 | 59°38'39.78 | 0 | 3380 | 4920 | 8300 |
| 7 | Almond Bay | 13°15'23.47 | 59°38'41.39 | 0 | 5432 | 6900 | 12332 |
| 8 | Speightstown | 13°15'15.12 | 59°38'42.22 | 0 | 20560 | 14832 | 35392 |
| 9 | Cobblers Cove | 13°14'43.88 | 59°38'42.49 | 19196 | 19892 | 27120 | 66208 |
| 10 | Godings Bay | 13°14'34.50 | 59°38'40.43 | 5600 | 0 | 0 | 5600 |
| 11 | Godings Bay | 13°14'25.24 | 59°38'44.09 | 10712 | 18992 | 18004 | 47708 |
| 12 | Godings Bay | 13°14'20.06 | 59°38'41.94 | 2396 | 2908 | 5297 | 10601 |
| 13 | Godings Bay | 13°14'14.67 | 59°38'40.43 | 2580 | 5752 | 8114 | 16446 |
| 14 | Godings Bay | 13°14'09.83 | 59°38'37.35 | 0 | 3096 | 10692 | 13788 |
| 15 | Mullins | 13°13'57.01 | 59°38'39.89 | 21412 | 9921 | 3862 | 35195 |
| 16 | Gibbs Bay | 13°13'47.80 | 59°38'38.38 | 7572 | 16327 | 6238 | 30137 |
| 17 | Gibbs Bay | 13°13'31.79 | 59°38'38.65 | 6520 | 15028 | 10560 | 32108 |
| 18 | Reeds Bay | 13°13'20.43 | 59°328'32.78 | 6884 | 5880 | 648 | 13412 |
| 19 | Tropicana | 13°13'08.96 | 59°38'34.55 | 13064 | 7900 | 6464 | 27428 |
| 20 | Weston | 13°13'03.92 | 59°38'33.06 | 1640 | 2480 | 4620 | 8740 |
| 21 | Weston | 13°12'52.05 | 59°38'31.00 | 2624 | 3304 | 5852 | 11780 |
| 22 | Weston | 13°12'42.83 | 59°38'28.97 | 7284 | 3336 | 6904 | 17524 |
| 23 | Alleynes | 13°12'26.39 | 59°38'26.46 | 6956 | 3796 | 2420 | 13172 |
| 24 | Alleynes | 13°12'17.09 | 59°38'26.37 | 868 | 2112 | 3888 | 6868 |
| 25 | Alleynes | 13°12'06.55 | 59°38'32.07 | 15592 | 1296 | 1052 | 17940 |
| 26 | Bachelors | 13°11'57.29 | 59°38'34.80 | 9364 | 2488 | 7588 | 19440 |
| 27 | Bachelors | 13°11'48.85 | 59°38'34.43 | 7984 | 9712 | 9516 | 27212 |
| 28 | Bachelors | 13°11'44.89 | 59°38'31.14 | 844 | 1432 | 2308 | 4584 |
| 29 | North Bellairs | 13°11'33.01 | 59°38'30.05 | 8888 | 4740 | 3036 | 16664 |
| 30 | South Bellairs | 13°11'26.69 | 59°38'28.99 | 20608 | 12092 | 7472 | 40172 |
| 31 | Holetown | 13°'11'09.11 | 59°38'21.81 | 5216 | 0 | 3324 | 8540 |
| 32 | Holetown | 13°10'59.03 | 59°38'21.84 | 4772 | 4008 | 4988 | 13768 |
| 33 | Holetown | 13°10'51.53 | 59°38'23.23 | 8508 | 4752 | 9956 | 23216 |
| 34 | Vauxhall | 13°10'41.39 | 59°38'23.24 | 5692 | 7076 | 13172 | 25940 |
| 35 | Vauxhall | 13°10'33.23 | 59°38'22.70 | 4468 | 4724 | 13452 | 22644 |
| 36 | Sandy Lane | 13°10'17.27 | 59°38'19.40 | 7012 | 8936 | 8264 | 24212 |
| 37 | Paynes Bay | 13°10'07.16 | 59°38'17.67 | 3152 | 2672 | 14300 | 20124 |
| 38 | Tamarind | 13°09'48.54 | 59°38'20.19 | 3152 | 3104 | 5920 | 12176 |
| 39 | Mahogany Bay | 13°09'38.75 | 59°38'17.75 | 5072 | 3916 | 4884 | 13872 |
| 40 | The Cliff | 13°09'23.19 | 59°38'28.15 | 14236 | 884 | 1528 | 16648 |
| 41 | Crystal Cove | 13°09'07.69 | 59°38'19.05 | 960 | 2968 | 12408 | 16336 |
| 42 | Fitts Village | 13°08'52.34 | 59°38'19.92 | 376 | 7376 | 16052 | 23804 |
| 43 | Waves | 13°08'37 | 59°38'19.84 | 0 | 5520 | 15596 | 21116 |
| 44 | Waves | 13°08'24.21 | 59°38'15.88 | 2300 | 1196 | 6892 | 10388 |
| 45 | Batts Rock | 13°08'15.9 | 59°38'14.25 | 3724 | 3964 | 760 | 8448 |
| 46 | Batts Rock | 13°08'06.62 | 59°38'13.54 | 15408 | 8036 | 1152 | 24596 |

## 9.3 Appendix 3

**Summary of reef health indicators available from previous studies. Reef health index refers to the classification given by Connell (2013) by combining the scores of experts where 1 = very bad, 2 = bad, 3 = medium, 4 = good, and 5 = very good overall health. The coral diversity, mean % macroalgae cover, mean % live coral cover and *Diadema antillarum* abundance were taken from the Government's long-term reef monitoring programme data collected in the summer of 2012. These data were collected from a 10x20 m permanent reef monitoring plot on each reef comprising ten 10 m point-intercept transects and ten 10x1 m belt transects. Means represent the mean value across the ten transects.**

| Reef # (this study) | Reef Health Index | Coral Diversity Index | Mean % live coral cover | Mean % macroalgae cover | Mean Diadema density (no. $10m^{-2}$) |
|---|---|---|---|---|---|
| **1** | 2.6836 | - | - | - | - |
| **2** | 2.7438 | - | - | - | - |
| **3** | - | - | - | - | - |
| **4** | 2.7988 | - | - | - | - |
| **5** | 2.8486 | - | - | - | - |
| **6** | 2.8486 | 10 | 11.68 | 5 | 0 |
| **7** | 2.8932 | - | - | - | - |
| **8** | 2.9326 | 13 | 9.68 | 8.68 | 0 |
| **9** | 2.9668 | 13 | 6.09 | 18.95 | 0 |
| **10** | - | - | - | - | - |
| **11** | 2.9958 | 14 | 12.72 | 13.48 | 0.2 |
| **12** | 3.0196 | - | - | - | - |
| **13** | 3.0196 | - | - | - | - |
| **14** | 3.0382 | - | - | - | - |
| **15** | 3.0516 | 11 | 28.51 | 2.28 | 10.4 |
| **16** | 3.0598 | - | - | - | - |
| **17** | 3.0628 | 20 | 26.85 | 4.96 | 0 |
| **18** | - | - | - | - | - |
| **19** | 3.0606 | 15 | 29.63 | 2.73 | 0.1 |
| **20** | 3.0532 | - | - | - | - |
| **21** | 3.0406 | - | - | - | - |
| **22** | 3.0228 | 13 | 16.61 | 17.99 | 0.1 |
| **23** | 2.9998 | - | - | - | - |
| **24** | 2.9716 | 9 | 3.42 | 8.97 | 0 |
| **25** | 2.9382 | - | - | - | - |
| **26** | 2.8996 | 10 | 18.98 | 7.29 | 0.2 |
| **27** | 2.8558 | 10 | 9.95 | 12.62 | 0.1 |
| **28** | - | - | - | - | - |
| **29** | 2.8068 | - | - | - | - |
| **30** | 2.8068 | 15 | 9.75 | 6.03 | 0 |
| **31** | - | - | - | - | - |
| **32** | 2.7526 | - | - | - | - |
| **33** | 2.6932 | - | - | - | - |
| **34** | 2.6286 | - | - | - | - |
| **35** | 2.6286 | - | - | - | - |
| **36** | 2.5588 | 11 | 7.52 | 9.53 | 0.2 |
| **37** | 2.4838 | - | - | - | - |
| **38** | 2.4036 | 14 | 13.13 | 12.52 | 0 |
| **39** | 2.3182 | - | - | - | - |
| **40** | - | - | - | - | - |
| **41** | 2.1318 | 10 | 4.85 | 15.14 | 0 |
| **42** | 2.0308 | - | - | - | - |
| **43** | 1.9246 | 7 | 6.32 | 11.27 | 0 |
| **44** | 1.8132 | - | - | - | - |
| **45** | 1.8132 | - | - | - | - |
| **46** | 1.6966 | 12 | 15.96 | 12.29 | 0.2 |