THE STATUS OF CORAL REEFS IN TOBAGO, 2020

SEPTEMBER 2022

PREPARED BY

DR. ANJANI GANASE, *Lead Research Officer, Coral Reef Ecology*

MS. HANNAH LOCHAN, *Research Officer*

INSTITUTE OF MARINE AFFAIRS

Hilltop Lane, Chaguaramas
Government of the Republic of Trinidad and Tobago
Tel: 1 (868) 634-4291/ 4 - Fax: 1 (868) 634-4433 or 2479
E-mail: director@ima.gov.tt - Website: www.ima.gov.tt
A Statutory body established by Act of Parliament, No. 15 of 1976

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Thank you to Dr Reia Guppy, Associate Professor University of Trinidad and Tobago, for reviewing this technical report.

PROJECT TEAM

LEAD RESEARCH OFFICER	-	Dr. Anjani Ganase
RESEARCH OFFICER	-	Ms. Hannah Lochan
CHEMISTRY OFFICERS	-	Mr. Kyle Williams
	-	Mr. Shane Ramsammy
TECHNICIANS	-	Mr. Jonathan Gomez
SENIOR SUPERVISOR	-	Mr. Addison Titus

EXECUTIVE SUMMARY

The Institute of Marine Affairs (IMA) conducts annual monitoring of Tobago's coral reef health using ecological and environmental metrics. In 2020, in addition to monitoring long-term trends in reef health, the IMA used existing monitoring methods to highlight the relative state of the reef health and resilience for coral reefs by compiling ecological measurements into a Cumulative Resilience Index. In 2020, of the ten sites monitored, Booby Island in north-east Tobago had the highest cumulative resilience score largely driven by the highest coral diversity, coral juvenile density and structural complexity. Conversely, Flying Reef, along the south coast, had the lowest reef resilience, driven by having the lowest coral cover and correspondingly high algae cover. Flying Reef also had relatively low coral diversity and juvenile density. Most coral reefs sites have hard coral cover less than 20 % with two sites (Flying Reef and Culloden East) having less than 10 % coral cover. Turf algae continue to be the dominant benthic species on all reefs, up to nearly 50 % at Culloden West. While sponge communities consisted of less than 2 % cover at most sites, the sponge cover at Blackjack Hole and Flying Reef were exceptionally high, 12.5 % and 8.6 % respectively. *Orbicella faveolata* remains the most prominent hard coral at eight out of the ten sites with Buccoo Outer having the highest cover of 15.2 %. However, recruit numbers were generally low, and commonly composed of species with weedy (*Agaricia spp., Porites astreoides*) and stress tolerant *(Siderastrea siderea, Pseudodiploria strigosa)* life histories. There were no records of *O. faveolata* recruits found across all sites. With respect to impacts to the health of corals, disease is the main source of impact infecting an average 8.6 % of corals across all sites. Dark spot disease and yellow band disease were the two most prevalent diseases observed across the sites. Yellow band disease mainly targeted *Orbicella faveolata* and infected ~ 3.4 % across sites, while dark spot disease was primarily observed on *Siderastrea siderea* infecting ~ 6 % across sites. By understanding which ecological components of the reef are being degraded, the cumulative reef resilience index can guide the type of management, marine spatial planning or restoration strategies needed to improve the resilience score of the reef and reduce the vulnerability of the reef to future disturbances.

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1.0 INTRODUCTION

Coral reefs provide an abundance of ecosystem services including but not limited to shoreline protection, food supply, and biodiversity. Reefs have a global asset value of 1 trillion USD (Hoegh-Guldberg et al. 2015). In a coastal valuation conducted for Tobago in 2006, coral reef fishing related activities brought in 0.7 – 1.1 million USD for Tobago, while protecting about 50 % of Tobago's coastline (Burke et al. 2008). The combined value of both direct and indirect coral reef related tourism in Tobago measured between 101-130 million USD (Burke et al. 2008). Therefore, coral reef ecosystem services are critical to livelihoods, namely the tourism and fishing industries of Trinidad and Tobago.

Regionally, coral cover in Tobago and the wider Caribbean have been chronically impacted by human activities, such as coastal development and unmanaged fishing. Coastal development results in increased nutrient run off and sediments that smother and pollute reefs (Lapointe et al. 2010). Coral reefs also have over a hundred years of fish exploitation that have resulted in significant declines in large fish species across the region (Jackson 1997). Over the last fifty years, a series of disturbance events have further impaired reef health throughout the Caribbean (Figure 1). This includes disease outbreaks that resulted in up to 97 % mass die off of a major branching coral group, *Acropora* species, across the region during the 1970s (Laydoo 1984; Goreau et al. 1998; Cramer et al. 2020), followed by the die off of a major grazer, *Diadema antillarum* in the 1980s (Lessios 1988, 2003; Hughes 1994; Aronson and Precht 2001; Jackson et al. 2014).

At the global scale, climate change, namely global warming and ocean acidification, threatens the survival of coral reefs. The IPCC Special Report 1.5 °C (Masson-Delmotte et al. 2018) states with high confidence that if there are not significant reductions in carbon emissions now, an increase in 1.5 °C will result in 70 - 90 % loss of coral reefs worldwide, while an increase in greater than 2 °C would result in 99 % loss. While local management can improve reef health and resilience to permit reef recovery following thermal bleaching events, climate change is an incontrovertible threat that cannot be managed at only a local scale (Hughes et al. 2003). Over the past five decades, Tobago's coral reefs have suffered two major coral reef bleaching events in 2005 and 2010 with little recovery (**Figure 1:**; Eakin et al. 2010; Mallela et al. 2010; Alemu I and Clement 2014; Ganase 2020). Corals can functionally withstand sea surface temperatures of up to 29.5°C as stated by NOAA, Coral Reef Watch (Alemu I and Clement 2014). In 2010, sea surface temperatures of greater than 29.5 °C were recorded over a sixty-four-day period with a maximum temperature recording of 30.5 °C resulting in mass bleaching of many coral species across multiple sites (Alemu I and Clement 2014).

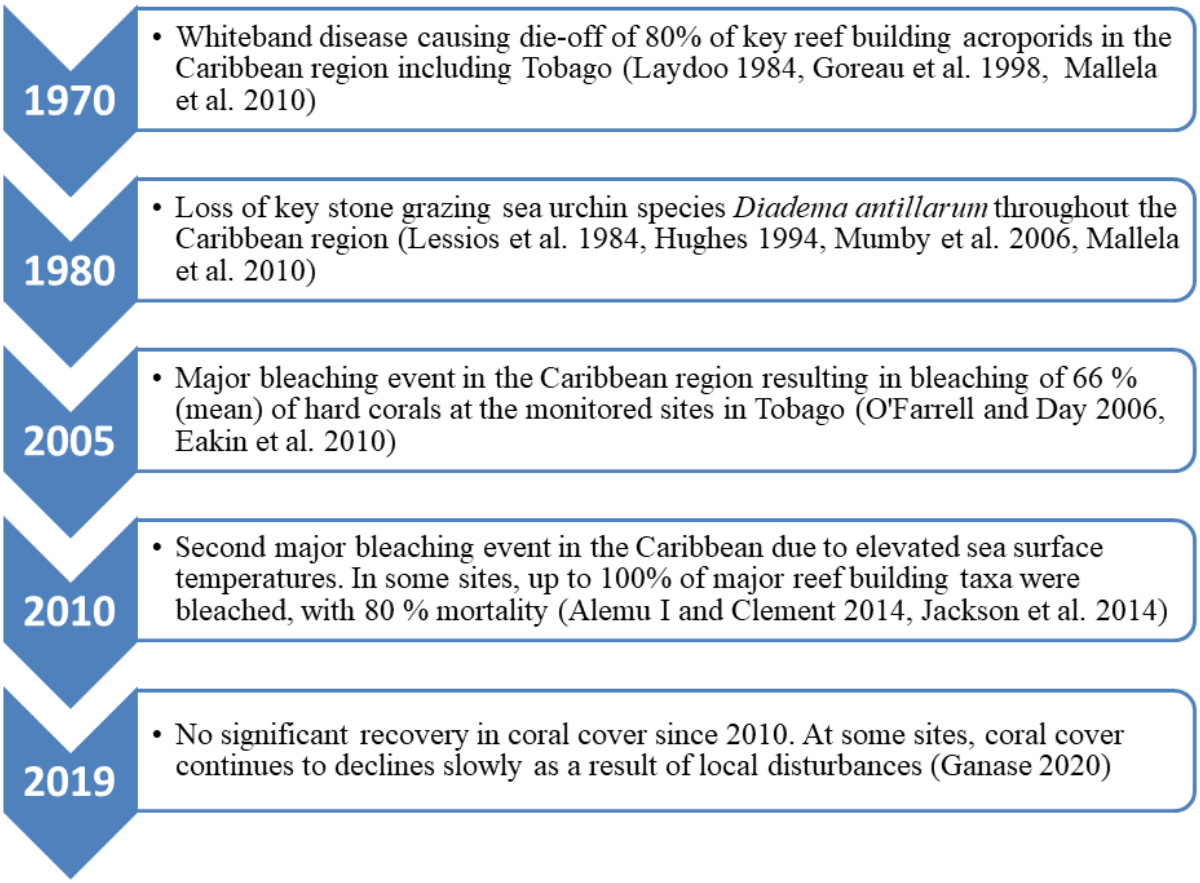

Figure 1: Timeline of disturbance events affecting coral reef health in Tobago.

1.1 REEF RESILIENCE INDEX

With disturbances to coral reef ecosystems, such as mass coral bleaching events, becoming more frequent, one of the most critical factors is assessing coral reef resilience (Maynard et al. 2017). Resilience refers to the coral reef's capacity to resist or recover from disturbances and degradation and maintain their ecological functions and ecosystem services (Marshall et al. 2006). Ecological indicators of coral reef resilience include hard coral cover and diversity of 'heat tolerant' coral species, coral recruitment, herbivore biomass, and algae cover (McClanahan et al. 2012). Environmental indicators of resilience include temperature variability, reef structural complexity, light (stress) along with anthropogenic stressors, such as nutrient pollution, sedimentation and fishing pressure (McClanahan et al. 2012). Since IMA began monitoring eleven years ago (2010), ecological data collected focused on coral cover and diversity, macroalgae cover with periodic assessments of fish biomass as indicators of reef health status. For 2020, additional metrics of measuring reef resilience, namely coral disease, recruitment, and structural complexity, have been added to the monitoring programme. The additional factors and the compilation into an index will more comprehensively inform on the state of reef resilience and can be used to guide reef managers and decision makers on the appropriate methods needed to prevent further reef degradation. The metrics will be scored to estimate the first cumulative resilience index for Tobago coral reefs based on the monitoring data.

2.0 METHODOLOGY

2.1 IMA SURVEY SITES

The IMA has ten coral reef monitoring sites geographically spread across Tobago. Sites were broadly selected based on geographical representation across Tobago. Four sites were established in 2010 (Buccoo Western, Buccoo Outer, Culloden East and Culloden West) representing two sites within a marine protected area (Buccoo) and two sites outside (Culloden). Angel Reef was added in 2014, Blackjack Hole in 2015, Castara, Plymouth and Charlotteville in 2016. In 2019, the tenth permanent monitoring site was added at Flying Reef along the south coast (**Figure 2**). At each site, there are ten permanent transects except for Castara reef which has eight transects owing to the limited area. Sites are monitored annually between the months of May – July when the conditions are calmest. In 2020, all ten sites (Table 1) were monitored for (i) benthic cover, (ii) coral recruit and juvenile density, (iii) prevalence of coral impacts, namely disease, predation, bleaching and growth anomalies, and (iv) water quality (2019 – 2020). Sampling was conducted between June 19 – 28, 2020 with one site surveyed per day.

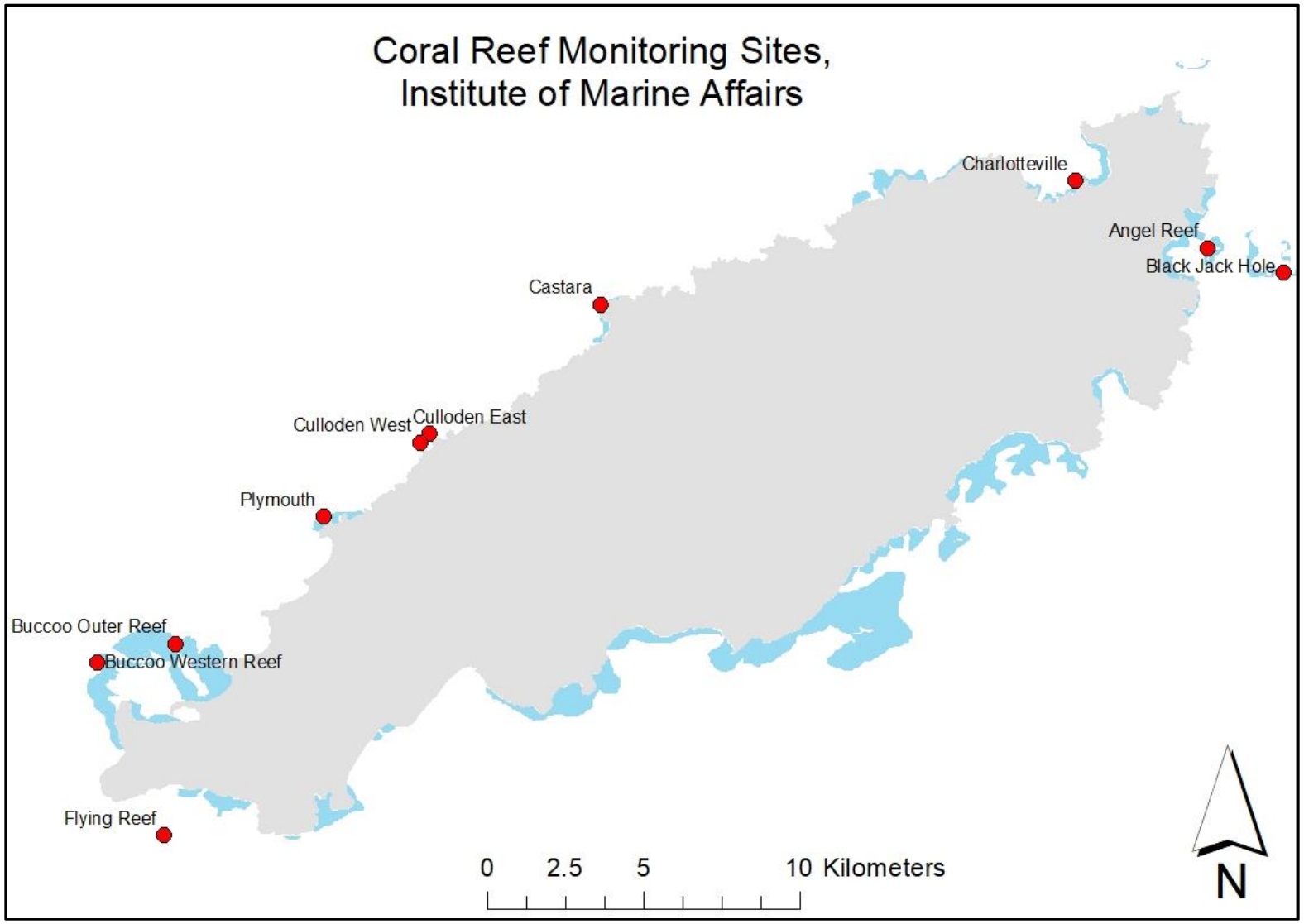

Figure 2: Map of coral reef baseline assessment locations around Tobago. Coral reef monitoring sites 2010 – 2020.

Table 1: Location of coral reefs monitoring sites in Tobago.

Site #	Common Name	Latitude (UTM WGS84 m)	Longitude (UTM WGS84 m)	Depth Profile	Coastline Profile
1	Buccoo Western Reef	735175	1237188	3m – 15m	Sandy Bay
2	Buccoo Outer Reef	737665	1237811	10m – 30m	Sandy Bay
3	Culloden Western Reef	745493	1244256	3m – 15m	Sandy Bay
4	Culloden Eastern Reef	745822	1244533	3m – 15m	Sandy Bay
5	Castara	751274	1248667	3m – 30m	Sandy Bay
6	Plymouth	742463	1241814	3m -15m	Rocky Shore
7	Charlotteville	766598	1252635	3m – 30m	Sandy Bay
8	Angel Reef	770732	1250446	3m – 20m	Sandy/Rocky Shore
9	Blackjack Hole	772912	1249743	15m – 40m	Rocky Shore
10	Flying Reef	738659	1232756	3m – 20m	Rocky Shore

2.1.1 Data Collection Water Quality

Water quality refers to the physical, chemical and biological state of the water environment surrounding coral reefs. Poor water quality is reflected, for example by low dissolved oxygen, heavy metals, hydrocarbons, pesticides, litter, microplastics, higher turbidity, nutrient loads, and phytoplankton and microbial communities in the water column. Poor water quality drives deleterious impacts on coral reef health, such as light limitations, smothering from sedimentation and microbial infections that result in declines in hard coral health. In this study, water quality parameters included dissolved inorganic nitrogen (ammonium (NH_3-N) and oxidised nitrogen (NO_2-N + NO_3-N)) and soluble reactive phosphorus (RPO_4) (nutrient loads), chlorophyll *a* concentration (biological loads)[1], and total suspended solids (TSS) to estimate water clarity. More specifically, Dissolved Inorganic Nitrogen (DIN) is a measure of the total amount of nitrogen present in the water column that is available for phytoplankton, and an overabundance can have adverse ecological and health effects. Phosphorus, as a limiting nutrient, is indicative of eutrophication which results in algal blooms (Carpenter 2008). Chlorophyll *a* concentration is an indicator of the phytoplankton biomass present in the water column which is a proxy for productivity and nutrient availability (Brodie et al. 2007; Lønborg et al. 2016). TSS is an indicator of water clarity which can be influenced by oceanographic conditions, such as waves and currents, as well as the influence of coastal rivers and runoff (Lønborg et al. 2016).

[1] Chlorophyll *a* results not included in results owing to lab processing errors

For one year from July 2019 to June 2020, quarterly water sampling was conducted at each monitoring site. The COVID-19 Pandemic prevented sampling at regular three-month intervals to assess seasonal water quality conditions. Therefore, the last time point, March 2020, was sampled in June 2020 as Trinidad and Tobago was under national lockdown from March to June 2020. Water samples were collected at one-metre below the surface and one-metre above the bottom along the 10 m contour at the start of the first transect on each site using one-litre Nalgene bottles. A CTD (conductivity, temperature, and dissolved oxygen) profile was obtained to determine any temperature, conductivity, salinity and dissolved oxygen variability at the top and bottom of the water column. Dissolved oxygen (DO) is a measure of how much oxygen is available to support marine life, and declines of DO is indicative of the level of respiration from the growth and reproduction of microbes in the water column. Generalised linear regression analyses were used to assess significances between sites and sampling times.

Benthic surveys

Benthic surveys were conducted over two weeks at the end of July 2020. Along each transect, a 1 m^2 quadrat was laid over the adjacent reef on the right-hand side of the transect at each metre mark, and the photo was taken. A total of ten images per transect were collected per site, giving a total of 100 images per site except for Castara which has 80 images.

Coral juveniles

Coral juveniles, defined as corals < 5 cm in diameter, were counted using a belt transect survey method on the right-hand side of the transect line. For each 10 m transect, the belt width was 0.34 m (width of a dive slate) giving a survey area of 3.4 m^2. For each juvenile encountered, the colony was identified to the lowest possible taxonomic level (species/ genus) and measured for its maximum diameter. Coral juveniles were further classed as *recruits* if they were $\leq$ 2 cm in diameter.

Coral Impacts Prevalence

The prevalence of coral impacts was recorded using a transect belt survey along each of the 10 m transect surveys and a width of 2 m giving a 20 m^2 survey area. Encountered hard corals larger than 5 cm in diameter were observed for being healthy or not (yes/ no). Unhealthy corals were placed into one of the following "impact" categories (i) bleaching, (ii) disease, (iii) predation, (iv) overgrowth, (v) growth anomaly, and (vi) unknown. Where possible, type of disease and predation, and what was overgrowing the coral were identified. For any bleaching, the percentage of the colony that was bleached or pale was recorded. For impacts that resulted in partial coral mortality, the percentage of recent and old mortality was recorded.

2.1.2 Post Processing and Analysis

Semi-Automated Image Annotation

To analyse the benthic percent cover, the CoralNet Platform (coralnet.ucsd.edu) was used. Images were uploaded to the IMA's CoralNet database and the metadata was inputted. For the image analysis, a virtual quadrat was drawn over the photographed $1m^2$ quadrat. CoralNet randomly generated 60 points for each quadrat annotated. CoralNet is a deep-learning annotation tool where the trained machine (on image annotations for previous years) automatically annotated points with greater than 75 % confidence. For confidences lower than 75 %, the machine gives taxonomic recommendations to guide the annotators in their identification process. All annotators are experts in the field of coral taxonomy and use guides to assist identifications. Annotated images were then compiled to give the benthic cover for each of the labels used and exported as a csv file. Please refer to the Appendix of (Ganase 2020) for details on the CoralNet training and annotation process. Data annotations were exported to Microsoft Excel 2019, to determine the sum, mean and standard error for each (i) benthic functional group and (ii) hard coral species cover per site. This data was tabulated and exported into R (software ver. 3.2.4) for generation of the visual graphic representations. Species richness and Shannon Weiner's Diversity Index were calculated in R.

Long-Term Trends

The percentage cover for each site assessed between 2010 and 2020 was plotted to visualise the long-term trends of major functional groups (hard coral, algae, octocoral, sponge and other). Changes in hard coral cover and octocoral cover over the years were assessed across all sites using a Generalised Least Squares (GLS) analysis for repeated measures across sites and years (R; non-linear mixed effect (nlme) package, significant p-value < 0.05). Hard coral and octocoral percentage covers were transformed using a fourth square root prior to modelling. Transect number was represented in the model as a random variable and year variable was included for autocorrelation structure analysis. Model residuals were assessed for normality and homogenous variance (Zuur et al. 2010).

Coral Juvenile Density

The total coral juvenile (< 5 cm in diameter) and recruitment ($\leq$ 2 cm in diameter) densities were calculated by adding up the number of colonies and dividing by the survey area – 3.4 m^2. To compare the number of juveniles across sites, Kruskal- Wallis non-parametric test was used as the data was not normality distributed (Shapiro-Wilke test). A pairwise Wilcoxon test was then done to determine which sites had significantly different juvenile densities (R software ver. 3.2.4).

Coral Health Prevalence

The percentage (for a survey area of 20 m^2) of unhealthy corals for each site was calculated by dividing the number of unhealthy corals by the total number for each transect. The site average was then calculated by averaging across all the transects. This calculation was also used to assess the prevalence of disease and bleaching. The types of diseases and numbers of infected corals present per site were collated and were graphically represented as disease prevalence per site.

Structural Complexity

Surveys for structural complexity were collected for IMA's previous monitoring survey at the same ten sites in 2019. Photogrammetry surveys were carried out by two divers. Along each 10 m transect, two replicate 2 x 2 m^2 quadrats were recorded using a GoPro Hero 6 along alternating sides of the transect tape at the 2 m and 6 m marks. For each recording, the diver took a video of the reef substrate at a consistent height above the substrate i.e. at 1.5 m above the highest part of the reef framework. The diver ensured at least 5 – 6 overlapping passes and criss-crosses of the quadrat to obtain full coverage of the quadrat. Camera orientation remained consistently face down to the substrate recording in one plane. The 3D model generation was processed using the methodology from Young et al. (2017) by Dr Kathryn Whittey, Cardiff University. Rendered models were used to calculate reef rugosity, a common metric of reef 3D structural complexity, using Rhino 3D programme. Rugosity is a relative measure of how rough or structured a surface is compared to a straight line. Rugosity was measured as the distance that a virtual chain fell along the reef surface (3D rendered model) divided by the straight length of the virtual chain (1 m). Rugosity was averaged to each monitoring sites. Six replicate measurements of rugosity were calculated per quadrat (Young et al. 2017) and then averaged for each quadrat and transect to obtain a site average.

2.1.3 Relative Resilience Index

The use of Relative cumulative resilience index follows the methodology suggested by Maynard et al (2017) and has been generated from six benthic ecological metrics: hard coral diversity, hard coral cover, algae cover, coral disease, coral juveniles and structural complexity averaged to site to determine overall reef status (Maynard et al. 2017). Coral diversity was calculated using species richness of hard coral species. Each metric was first normalised to range between 0 -1 and made unidirectional so that all values closer to 1 mean better health. Therefore, a higher resilience index means greater coral cover, juveniles, diversity, greater absence of algae, lower coral impact and higher structural complexity. A cumulative score was

calculated by summing individual metrics, normalising and ranking the values for all sites. Index categories were derived as follows: low resilience (x < average score – standard deviation), medium-low resilience (average score – standard deviation > x <average score), medium-high resilience (average score < x < average score + standard deviation), high resilience (> average score + standard deviation) (Maynard et al. 2017).

3.0 RESULTS

3.1 WATER QUALITY

3.1.1 Temperature, Salinity and Dissolved Oxygen

Temperatures averaged 28 ºC across all sites and ranged from 26. 1 to 30. 1 ºC. Water temperatures showed significant temporal variation for all sites (Date: t-value = -2.629, p = 0.02). The highest temperatures occurred in September 2019 at (28.5 – 30.1 ºC), while the lowest were in June 2020 (26.2 – 27.6 ºC) reflecting natural seasonal temperature variation. pH conditions ranged from 7.47 – 8.74 with most of the significant variation occurring across dates (Date: t-value = -6.621, p = 1.18e-07), where the mean pH condition of most sites were significantly lower in June 2020 (8.21 ± 0.3) compared to July 2019 (9.69 ± 0.1). Salinities showed small, and non-significant, temporal variations with the lowest salinities occurring in in June 2020 (33.58 - 35.01) salinities occurred in December 2019 (35.57 – 35.11) at most sites. Dissolved oxygen also displayed small and non-significant variations across dates and sites (mean: 6.92 ± 0.129 ppm, range: 5.74 - 8.63 ppm) (**Figure 3**).

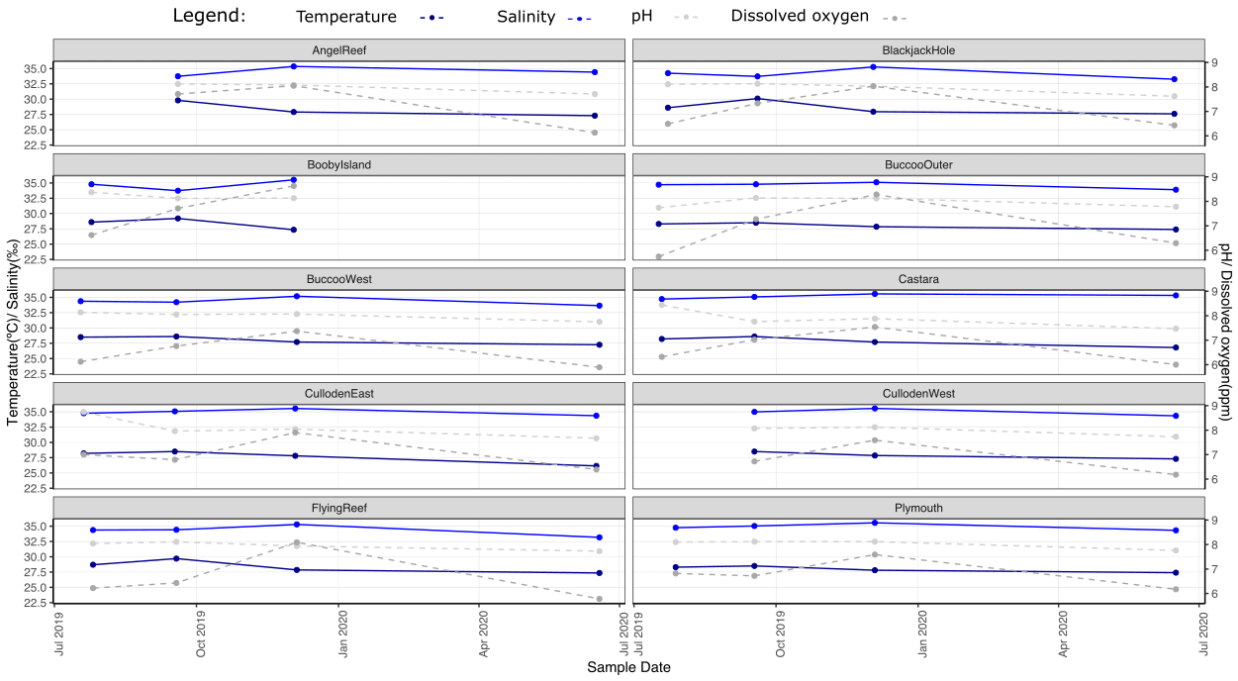

Figure 3: Compiled plot of average temperature, salinity, pH and dissolve oxygen profiles for each site and sample date.

Dissolved Inorganic Nitrogen (DIN) concentrations averaged 2.36 (± 0.13) µM across all sites, depths and sampling times (**Figure 4**). The highest concentrations at each site and depth were found in June 2020, except for Castara and Plymouth. At both Castara and Plymouth, the DIN values in July 2019 and June 2020 were similarly high and the DIN values were at its lowest in September and December 2019 (**Figure 4**). The largest component of the DIN (averaged across sample depths) was ammonium (NH3-N), which was much higher when sampled in June 2020 compared to the sampling times July to December 2019. Note that NH3-N was below the detectable range (< 0.7 µM) for Buccoo West, Flying Reef and Angel Reef in July 2019 for both top and bottom samples. DIN only showed significant variations in concentrations across sampling dates and sites, but not among sampling depths (Date: t-value = 2.721, p = 0.01). Castara had significantly lower DIN concentrations compared to the other sites on the sampling date of June 2020 (t-value -2.277, p = 0.03). The lowest DIN concentrations were found on Angel Reef (top – 0.71 µM) and Flying Reef (top – 0.74 µM and bottom – 0.75 µM) in July 2019 but Flying Reef (top- 5.77 µM) had the highest concentration one year later in June 2020.

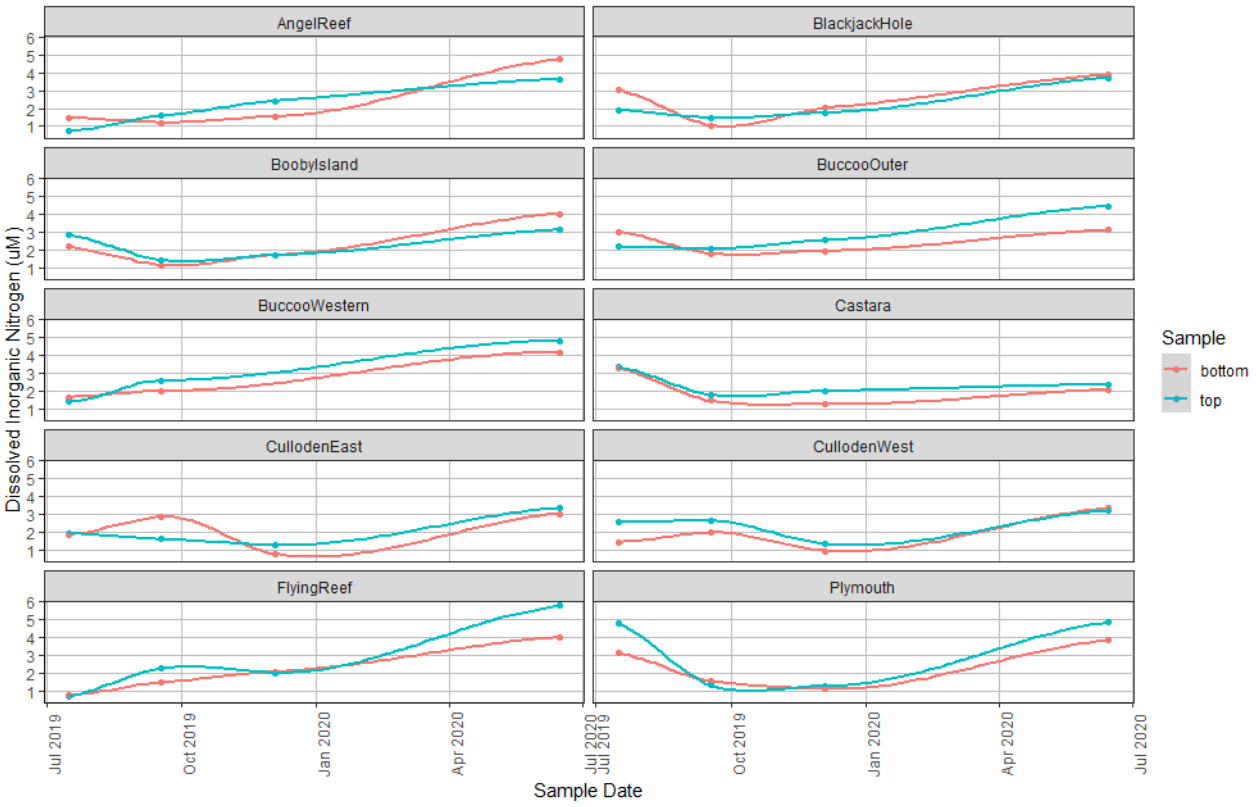

Figure 4: **Average Dissolved Inorganic Nitrogen (DIN) concentrations for water samples collected at the top (one metre below the surface) and bottom (one metre above the reef substrate) at each coral reef site between 2019 and 2020.**

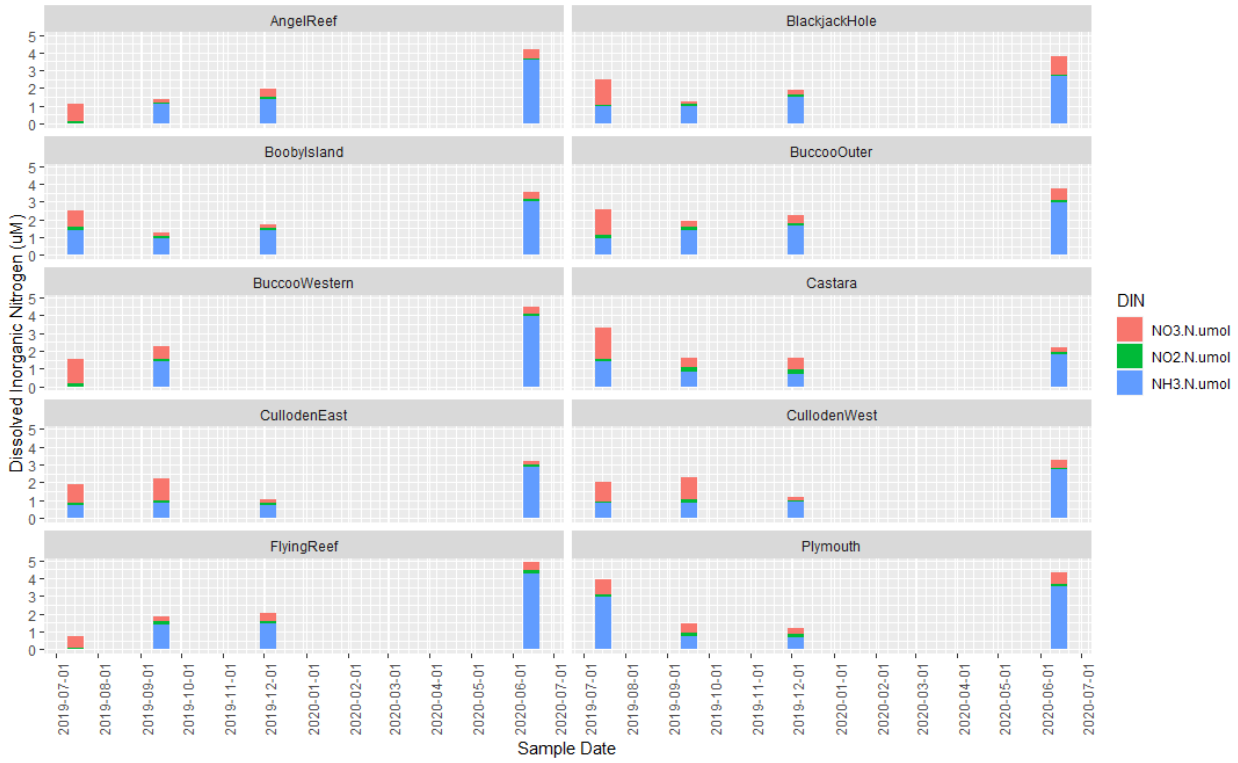

Figure 5: Components of Dissolved Inorganic Nitrogen (DIN) concentrations averaged to each site sampled between 2019 and 2020.

Soluble Reactive phosphate (SRP) averaged at 0.12 (± 0.1) µM across all sites, sampling depths and times. The lowest SRP concentrations were found on Flying Reef in December 2019 (bottom: 0.01 µM) and Plymouth in September 2019 (bottom: 0.012 µM) (Figure 5). No significant variation across the top and bottom samples. There was significant interactive variations in the SRP concentrations between some sites and dates, where Culloden East (bottom: 0.57 µM; t-value = 2.538, p = 0.01) and West (bottom: 0.6 µM; t-value = 3.214, p = 0.002) both had significantly higher concentrations of SRP of all sites and dates on the June 2020 sampling time (**Figure 6**).

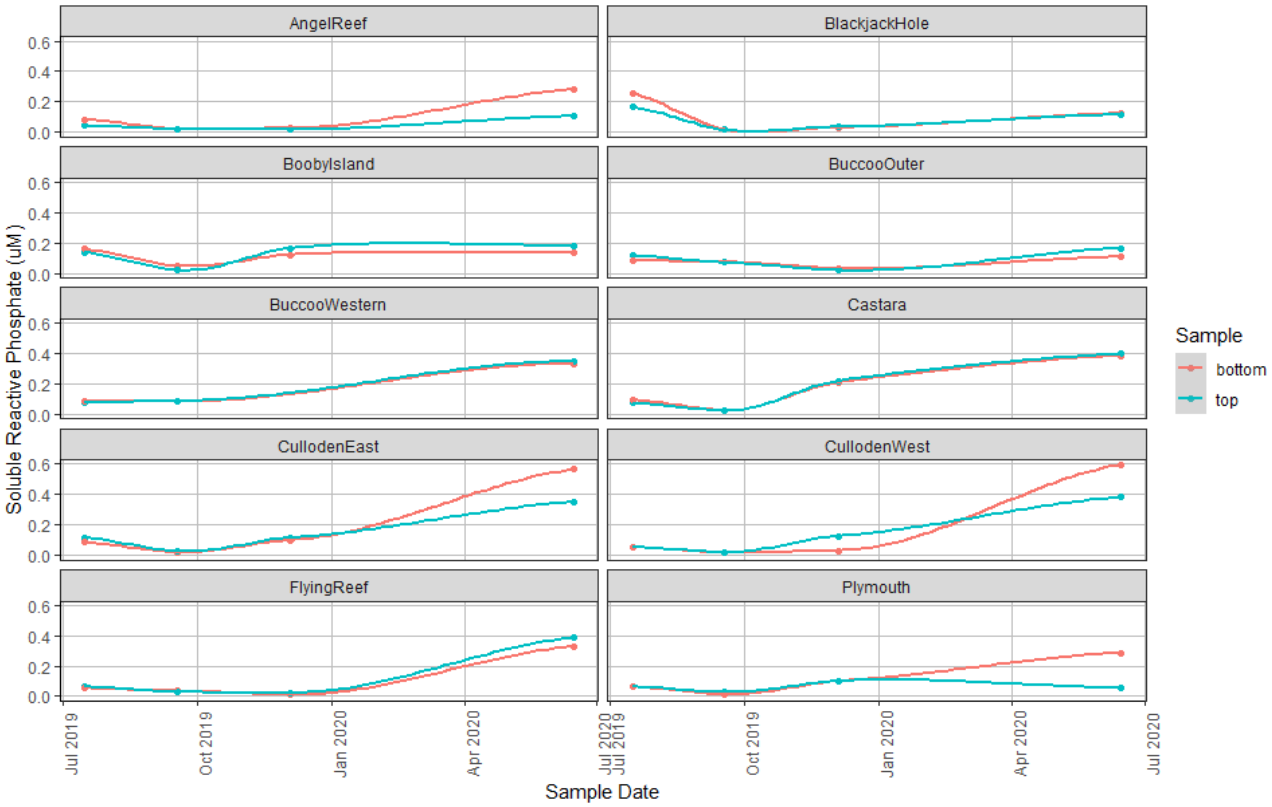

Figure 6: **Average Soluble Reactive Phosphate (SRP) concentrations for water samples collected at the top (one metre below the surface) and bottom (one metre above the reef substrate) at each coral reef site across sampling times.**

Nutrient ratios (DIN: SRP) looks at any potential nutrient limitations. Average ratio across all sites, sampling depths and sampling time is ~ 41.4 (± 4.5). Sites along the Caribbean coast, Culloden and Castara, appear to only fall below the nutrient limitation threshold (< 15) in December 2019 and June 2020. The lowest ratio was Castara (bottom: 5.32) and Culloden East (bottom: 5.35) both sampled in June 2020 (**Figure 7**). Sites with the highest ratio were Flying Reef (bottom: 196.6), followed by Angel Reef (top: 144.1), both sampled in December 2019 (**Figure 7**). There were no significant variations among the sites, sample depth and sampling times.

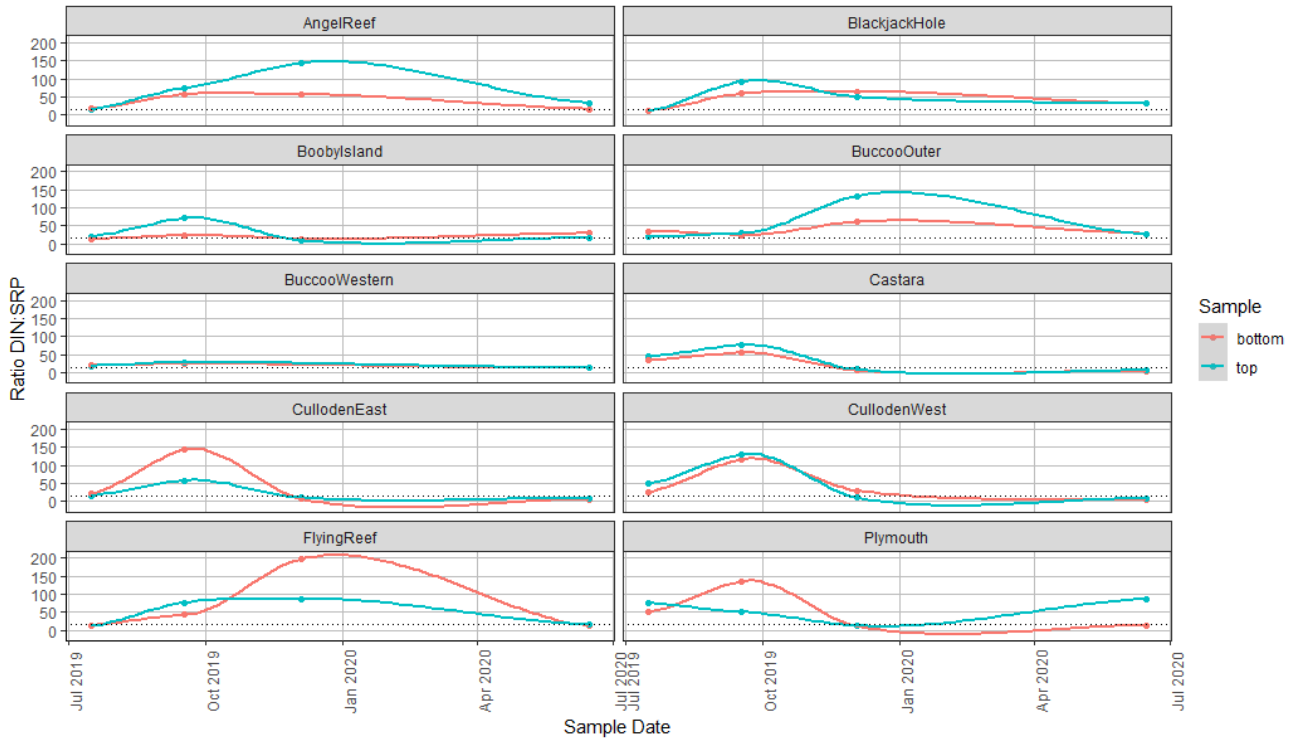

Figure 7: **Ratio of Dissolved Inorganic Nitrogen: Soluble Reactive Phosphate (DIN: SRP) for water samples collected at the top (one metre below the surface) and bottom (one metre above the reef substrate) at each coral reef site as an indicator of nitrogen limitation. Dotted line represents the 15: ratio that is indicative of N-limitation (Lapointe et al 2003).**

Total Suspended Solids (TSS) is indicative of water clarity around surveyed coral reefs in Tobago. The variations in TSS across sites between 2019 to 2020 appears to be site specific. The overall mean TSS was 18.1 (± 0.51) mg/l. Generalised linear regression analysis identified significant interactions among some sites and dates, where the highest TSS occurred at Buccoo Western Reef in June 2020 (bottom: 34.3 mg/l; t-value = 2.408, p = 0.02). The sites with the lowest TSS values occurred in September 2019 at Culloden East (bottom: 13.6 mg/l) and Flying Reef (top: 13.6 mg/l). There was no significantly different variation among sampling depths across sites, (**Figures 8** and **9**).

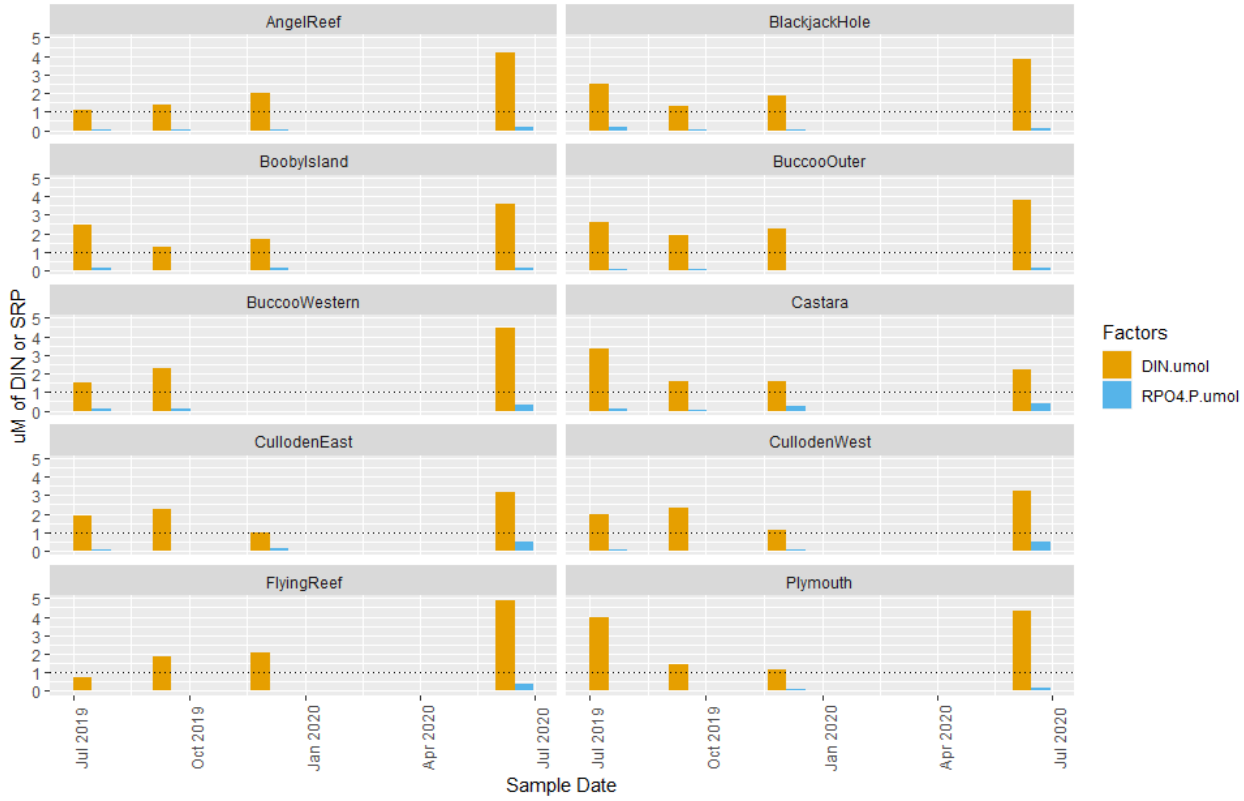

Figure 8: **Bar plot display of the proportional concentrations of dissolved inorganic nitrogen to soluble reactive phosphate averaged across depths for each site and for each sampling time.**

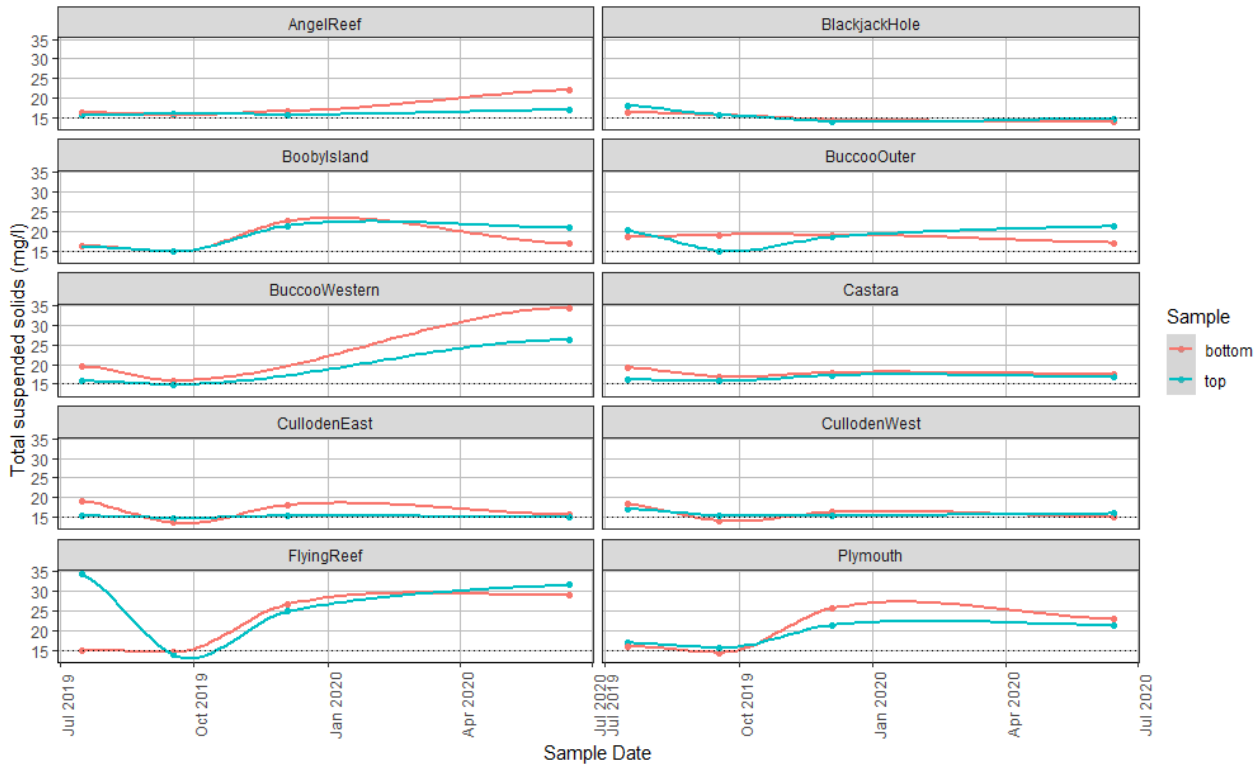

Figure 9: **Total suspended solids (TSS) for water samples collected at the top (one metre below the surface) and bottom (one metre above the reef substrate) at each coral reef site for four time points between 2019 and 2020.**

3.1.2 Benthic Functional Group

Hard coral cover was highest at Angel Reef (20.1 ± 1.1 %) and Buccoo Outer (19.9 ± 3.0 %) and lowest at Flying Reef (3.0 ± 0.4 %) and Culloden East (8.90 ± 1.3 %) (Figure 10). Octocorals were abundant on all ten reefs with Culloden East (29.0 ± 3.2 %), Buccoo Western (25.3 ± 3.0 %), Castara (23.2 ± 2.2 %) and Plymouth (22.6 ± 2.4 %) having the largest coverages. Octocoral cover was lowest at Buccoo Outer (3.9 ± 0.8 %) and Blackjack Hole (4.5 ± 2.4 %) (Figure 10). The sponge population was generally very low accounting for less than 2 % benthic cover at eight of the monitoring sites, again except for Blackjack Hole (12. 5 ± 1.5 %) and Flying Reef (8.6 ± 1.3 %) where sponge assemblages were more prominent (**Figure 10**).

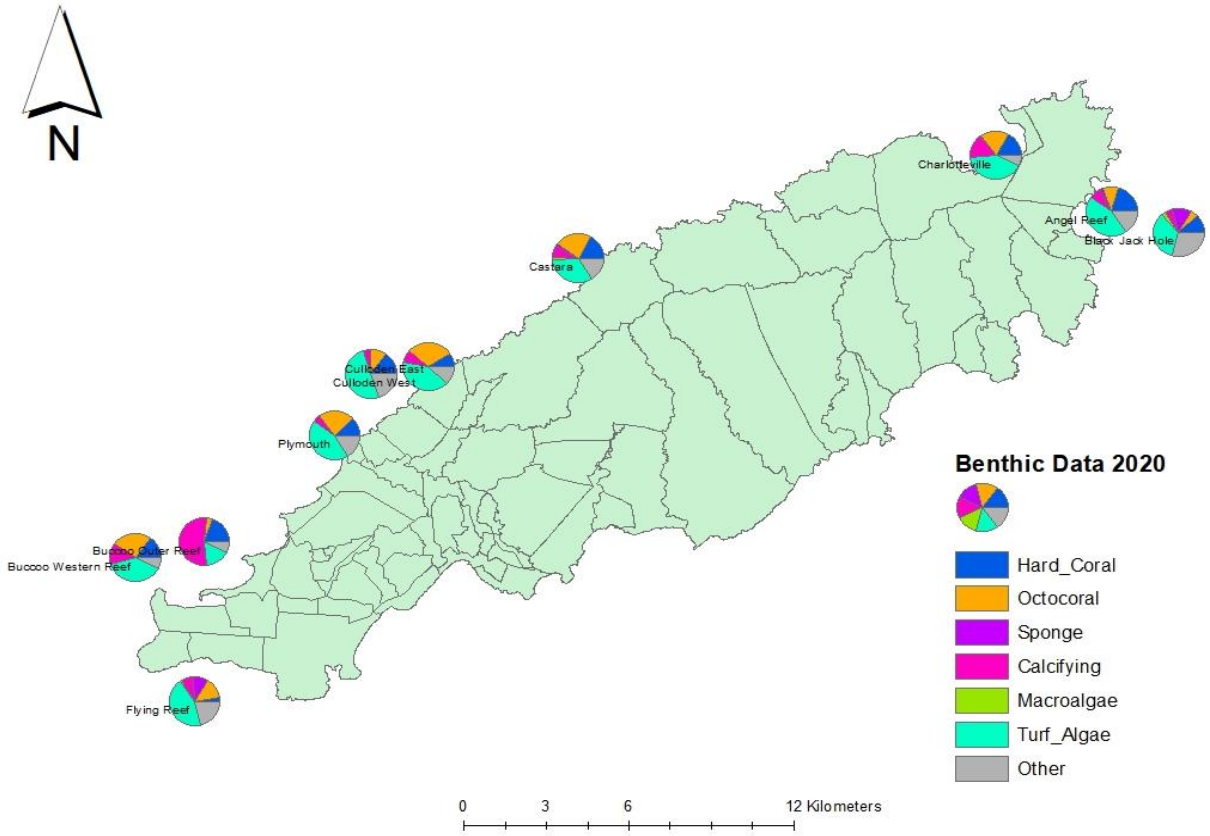

Figure 10: Benthic covers of the main functional groups found at the ten IMA coral reef monitoring sites around Tobago surveyed in 2020

All monitoring sites were dominated by turf algae with Culloden West registering the highest percent cover of turf algae (49.7 ± 2.8 %) (**Figure 11**). Conversely, Buccoo Outer reef was dominated by calcareous algae (51.8 ± 2.8 %), and the second highest percent cover of calcareous algae was at Booby Island (15.6 % ± 2.5) (**Figure 11**). Macroalgae cover was highest at Blackjack Hole (3.1 ± 0.8 %) with the remaining sites recording cover less than 2 %. Blackjack Hole had the highest soft substrate cover (18.5 ± 5.5 %), and Booby Island had the lowest soft substrate cover (0.02 % ± 0.02) (**Figure 11**).

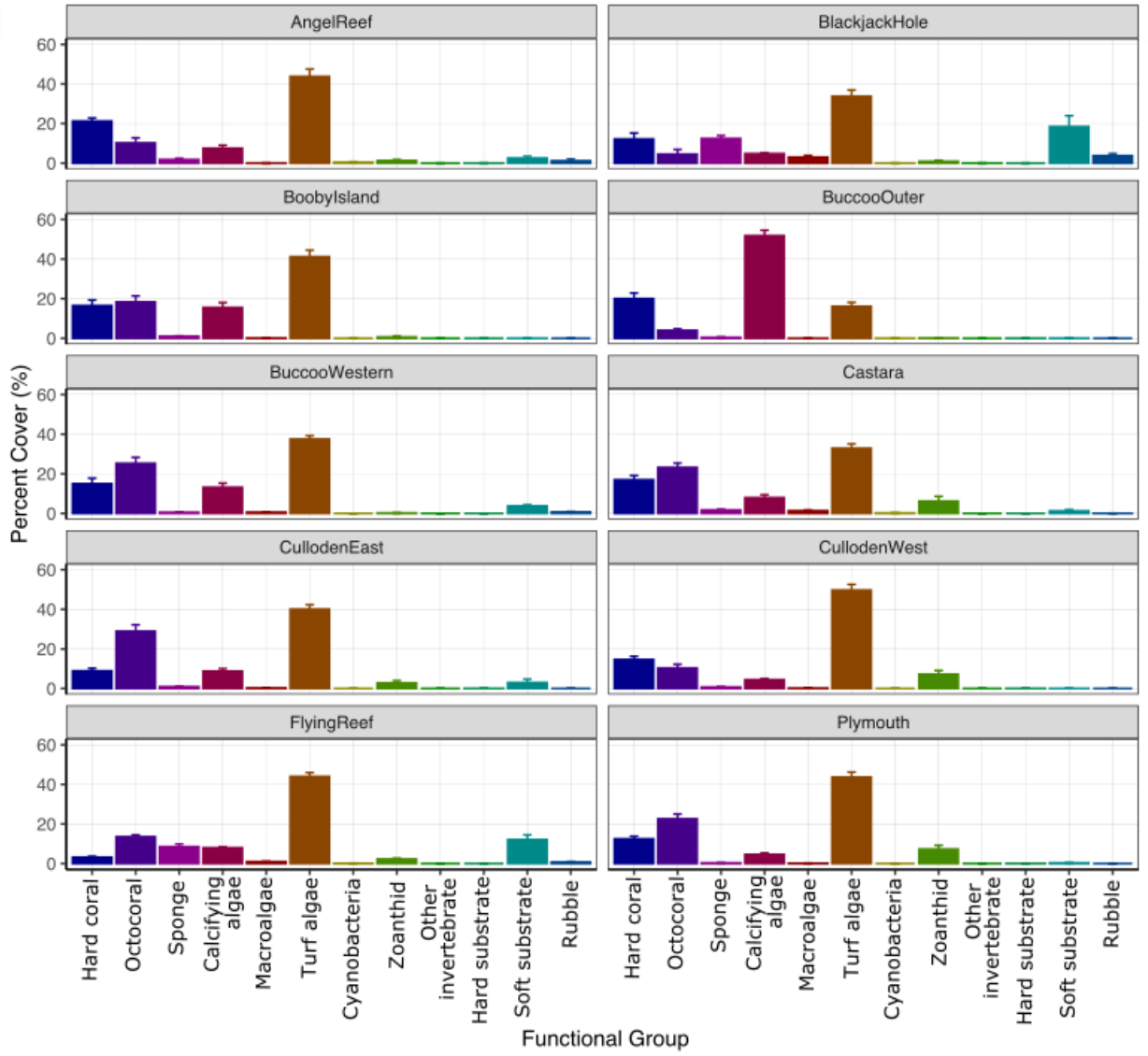

Figure 11: Percentage cover of twelve main functional groups for ten monitoring sites across Tobago in 2020.

3.1.3 Hard Coral Species

Orbicella faveolata continues to be the most dominant reef-building hard coral species at eight out of ten sites. Buccoo Outer has the highest *O. faveolata* cover at 15.2 (± 2.3) %, while Blackjack Hole (0.2 ± 0.1 %) and Flying reef (0.02 ± 0.02 %) both have the lowest cover (**Figure 12**). Massive coral growth forms were also common throughout the ten sites. These included *Montastraea cavernosa*, *Colpophyllia natans*, *Pseudodiploria strigosa* and *Siderastrea siderea*. *M. cavernosa* was most dominant at Castara (1.4 ± 0.6 %) (**Figure 12**). Booby Island had the highest cover of *S. siderea* (2.5 ± 0.6 %), and Buccoo Outer had the highest cover of *C. natans* (2.1 ± 0.8 %) (**Figure 12**).

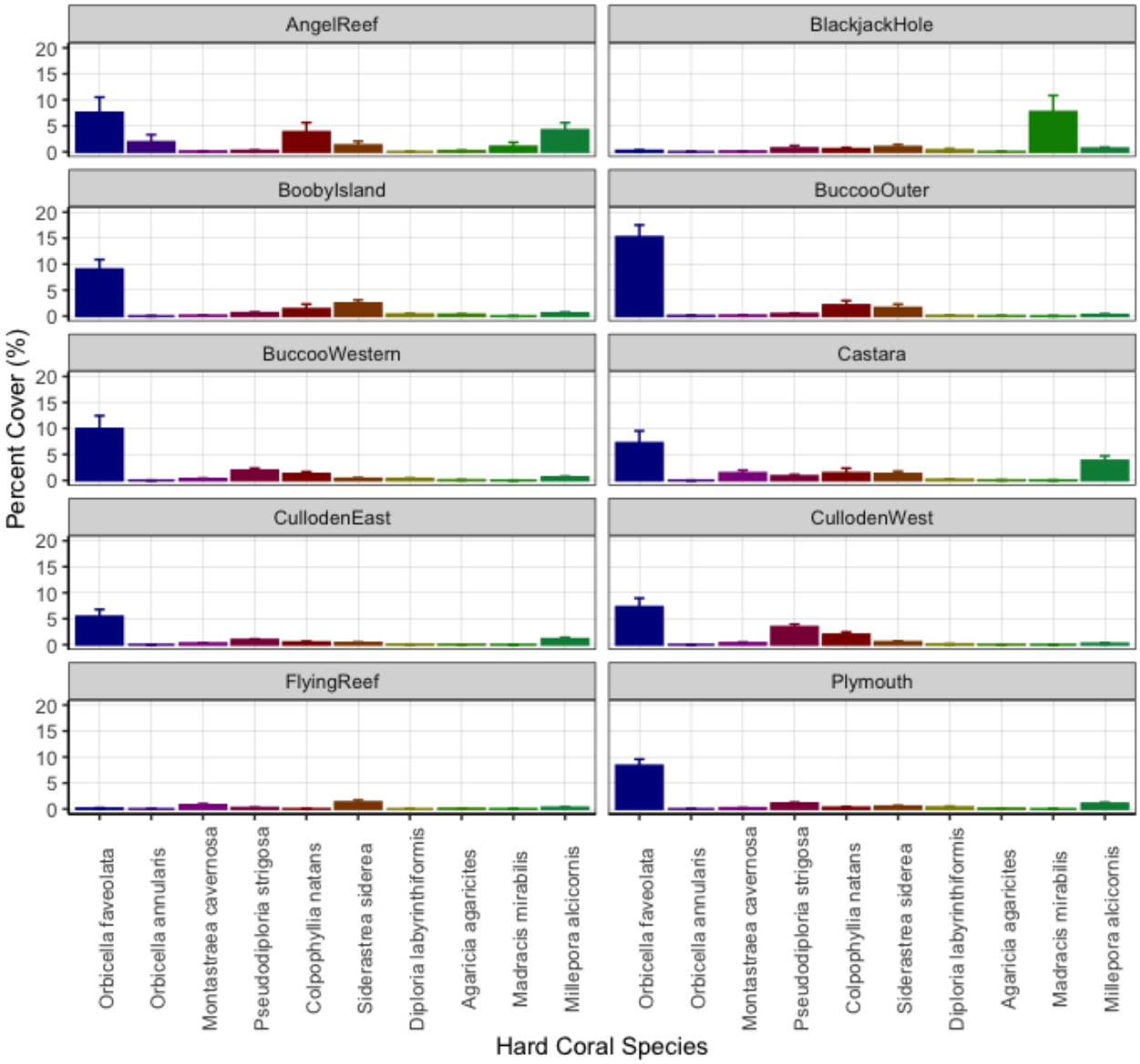

Figure 12: Ten most prominent hard corals present across ten coral reef monitoring sites in Tobago in 2020.

3.1.4 Benthic Diversity

Species Richness

The highest benthic species richness occurred at Castara (20.1 ± 0.6) (**Figure 13**) with the second highest species richness at Flying Reef (17.8 ± 0.3) followed by Blackjack Hole (17.7 ± 0.8) (**Figure 13**). Buccoo Outer had the lowest species richness (11.3 ± 0.4) (**Figure 13**). The remaining sites all had values ranging between 15.5 to 17 species.

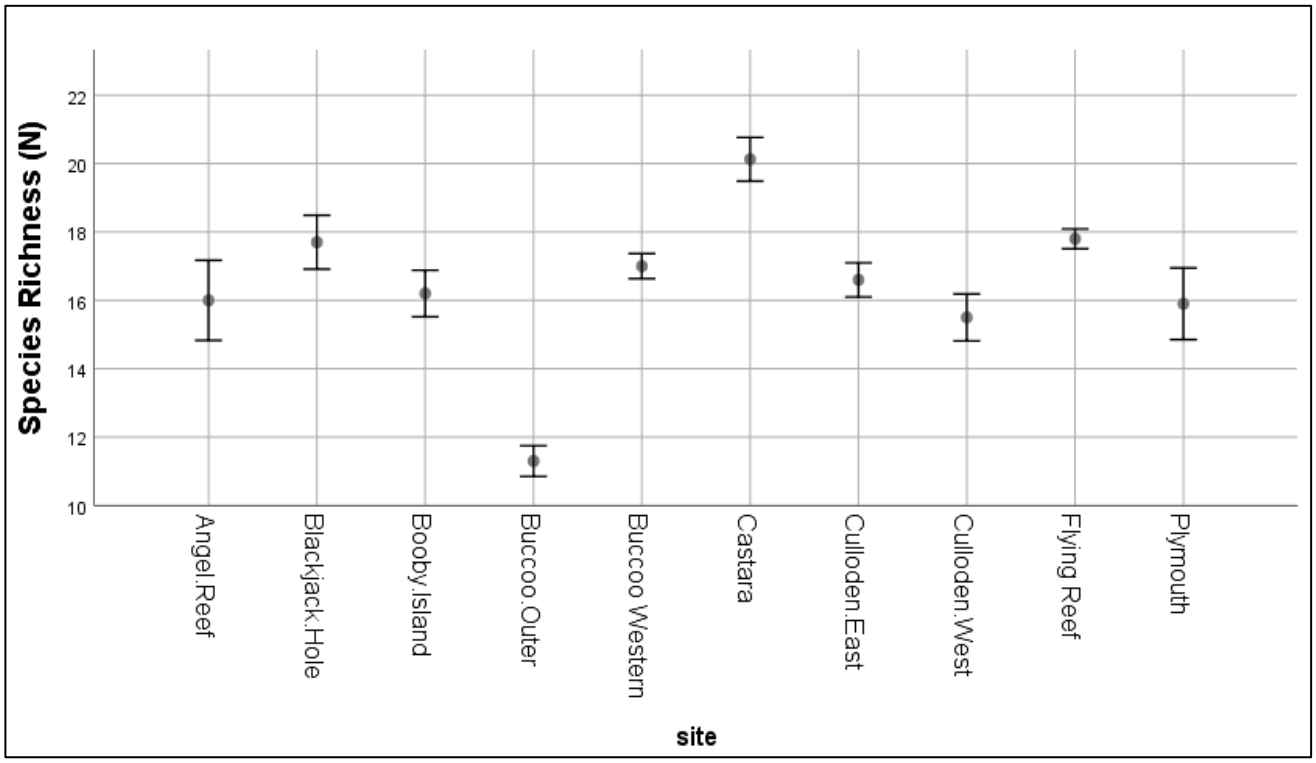

Figure 13: Mean species richness (+/- standard error of mean) of benthic species for each of the ten monitoring sites around Tobago in 2020.

Shannon-Diversity Index

Similar to the species richness, the site with the highest benthic species diversity was Castara (8.0), followed by Buccoo Western (6.9) and Flying Reef (6.9) (**Figure 14**). Buccoo Outer (3.8) had the lowest diversity and Plymouth (4.6) had the second lowest diversity (**Figure 14**). Of the remaining sites, Angel Reef, Blackjack Hole, Booby Island in the northeast had 6.3, 6.3 and 5.7 respectively, while Culloden West and Culloden East along the Caribbean coast had similar indices of 5.1 and 4.9 (**Figure 14**).

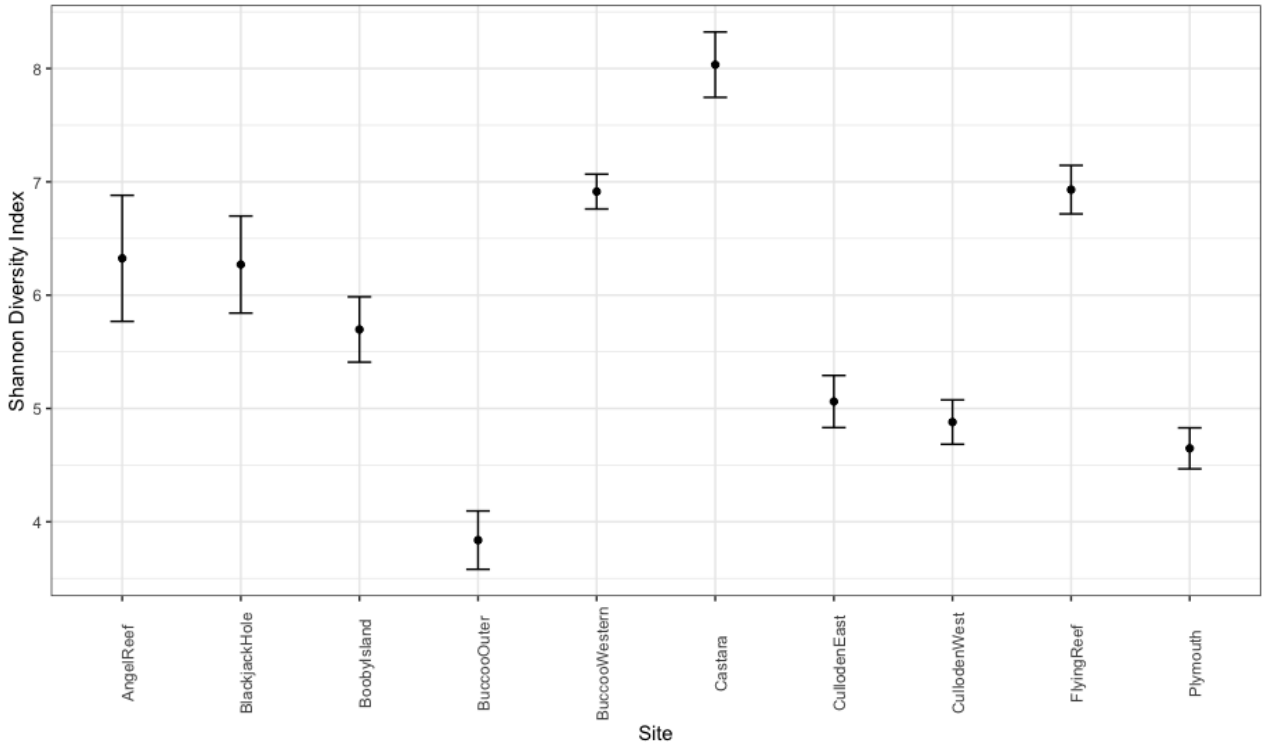

Figure 14: Species diversity for each monitoring site in 2020 according to the Shannon Diversity Number.

3.1.5 Structural Complexity

Three-dimensional structural complexity was estimated using a rugosity index. Booby Island has the highest structural complexity followed by Angel Reef and Buccoo Outer Reef. Conversely, sites with relatively low structural complexity include Buccoo West, Plymouth Reef and Culloden East and West (**Figure 15**).

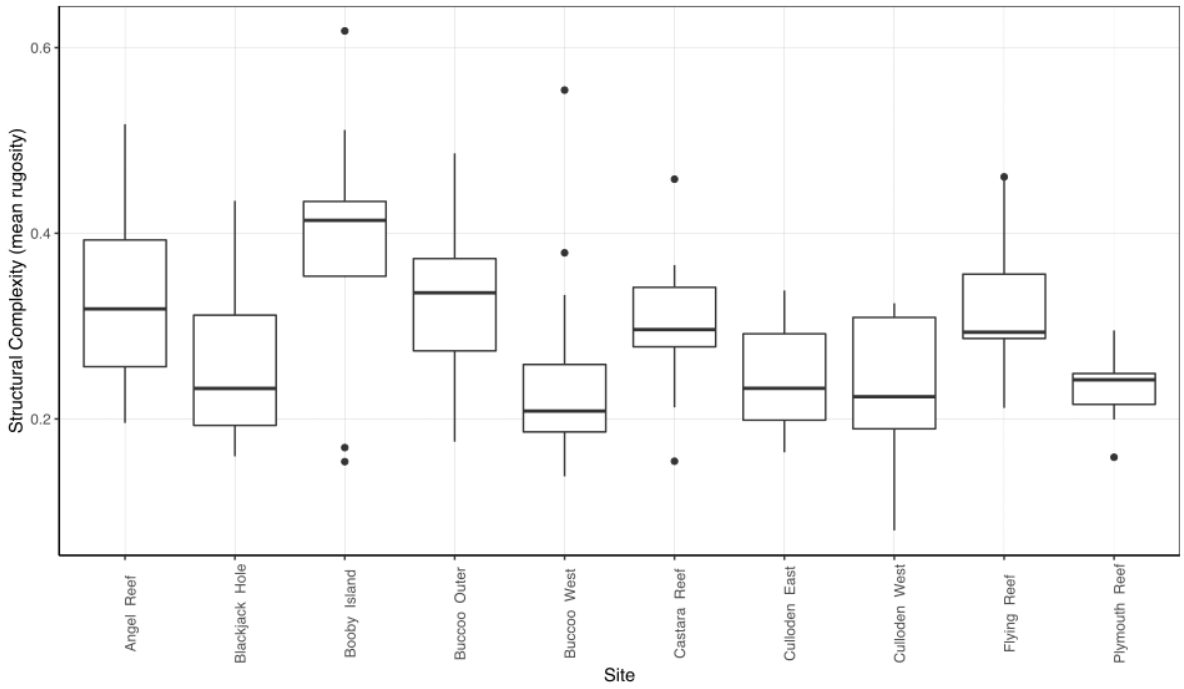

Figure 15: Structural complexity measured as mean rugosity across all survey sites in 2020.

3.1.6 Long-Term Trends

There was significant variation across sites and years where sites surveyed since 2010 exhibited a significant decline in coral cover after the 2010 bleaching event (t-value = -2.58, p = 0.010), but with no significant change in the hard coral cover in the years following (t-value = -1.545, p = 0.123) (**Figure 16**). While GLS analysis showed no significant change in octocoral cover across all sites over the years, there were significant site-specific changes in octocoral over time (ANOVA year: site, Chisq. = 42.5, p-value = 1.08×10^{-6}). More specifically, there was a significant rise in octocoral cover at Buccoo Western Reef, Booby Island and Culloden East from 2016 to present day. Furthermore, turf algae showed significant increase in percent cover between 2010 and 2020 (t-value = 2.447, p = 0.017). Conversely, coralline algae showed a significant decline from 2011 to 2020 (t-value = -2.973, p = 0.004). Across all sites, the fluctuations between turf algal and calcifying algae seem apparent over the years at Buccoo Western and other sites. However, coralline algae maintain the highest cover at Buccoo Outer over the years (**Figure 16**). Macroalgal cover is consistently low at all sites throughout the years except for Blackjack Hole where there was an increase in cover in 2019 followed by a decline in 2020 (**Figure 16**). Sponge cover remains consistently low for all sites except for Blackjack Hole, which consistently had ten times more sponge cover than the other sites over the years (**Figure 16**).

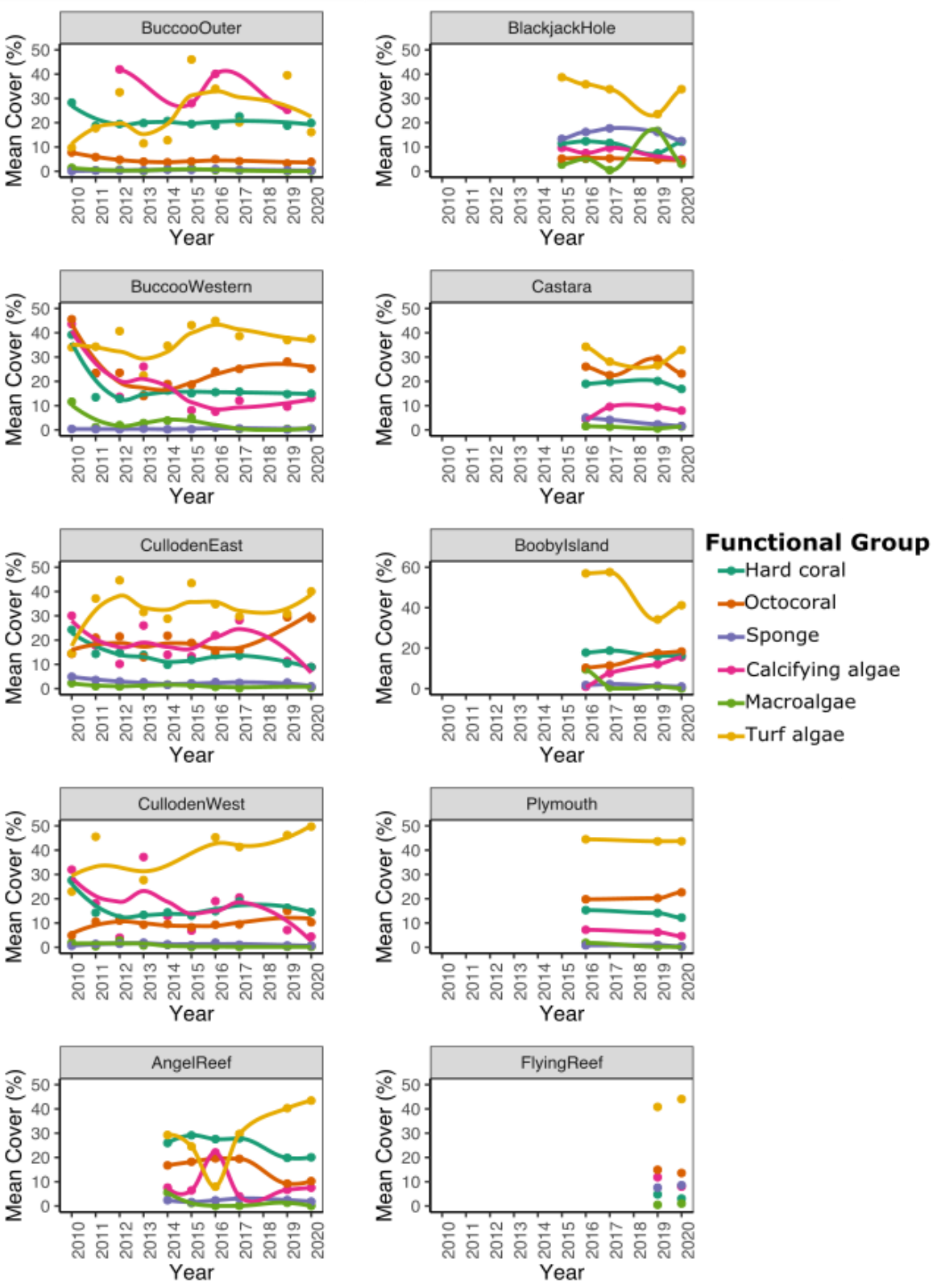

Figure 16: Trends in coral reef functional groups for ten monitoring sites in Tobago.

3.1.7 Coral Juveniles

For all coral juveniles (< 5 cm in diameter), Booby Island recorded the highest average density of coral juveniles (4.15 ± 0.56 n/m^2) and was significantly higher compared to Castara (0.92 ± 0.21 n/m^2), Plymouth (1.77 ± 0.23 n/m^2) and Flying Reef (1.47 ± 0.22 n/m^2) (Kruskal-Wallis chi^2 test, p = 2e-05) (Figure 17). Buccoo Western (3.71 ± 0.61 n/m^2) had the second highest density of juveniles followed by Buccoo Outer (3.38 ± 0.37 n/m^2) (**Figure 17**) and were both significantly higher than Flying Reef (Buccoo Outer, p = 0.02; Buccoo Western, p = 0.04) and Castara (Buccoo Outer and Buccoo Western; p = 0.02) (Figure 17). With respect to the coral recruits (corals < 2 cm in diameter), the mean number of recruits per metre squared observed across sites were all low (< 1 n/m^2). The sites with the highest density of recruits were Buccoo Outer reef (0.92 ± 0.19 n/m^2) followed by Booby Island (0.74 ± 0.11 n/m^2) and Culloden East (0.63 ± 0.10 n/m^2) (Figure 17). Castara, Culloden West, Flying Reef and Plymouth all have the lowest coral recruitment density across sites (all: 0.29 n/m^2) (Figure 17).

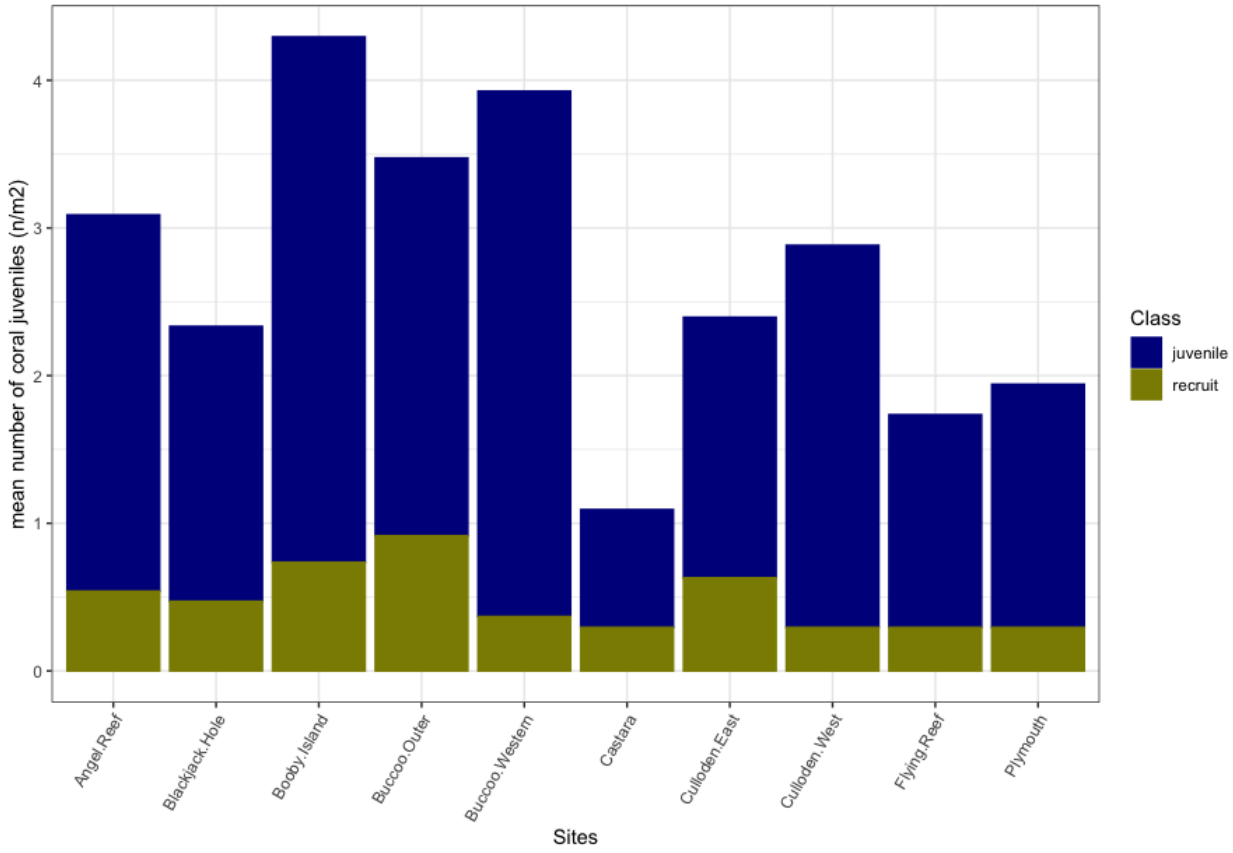

Figure 17: Density of coral juveniles recorded per metre squared. Juveniles less than 2 cm in diameter are classified as recruits in 2020.

With respect to species richness of coral juveniles, Booby Island (n = 11) had the highest species richness, followed by Castara (n = 10). Buccoo Outer reef (n = 4) and Buccoo Western (n = 5) reefs had the lowest species richness (Figure 18). The most common species recorded at most sites were *Agaricia agaricites*, *S. siderea* and *Pseudodiploria strigosa* (all except Buccoo Outer). Reef building *O. faveolata* juveniles were rare and only observed on Booby Island and Castara (Figure 18).

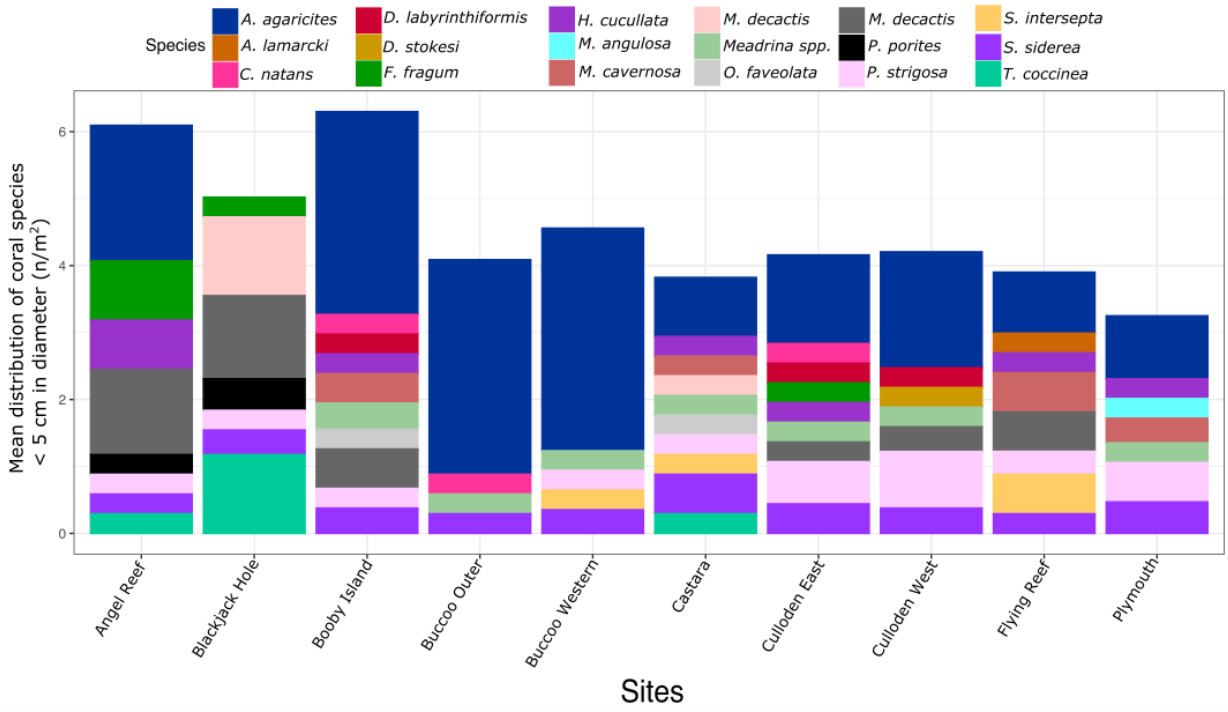

Figure 18: The average species density distribution of coral juveniles (< 5 cm in diameter) per site in 2020.

Observing only the species richness of coral recruits, Culloden East had the highest coral recruit richness with six species observed, albeit in low numbers, including *Agaricia spp., S. siderea, P. astreoides* and *P. strigosa* (**Figure 19**). However, Buccoo Outer and Flying Reef had the lowest species richness with only *Agaricia spp.* present at Buccoo Outer, and *P. strigosa* at Flying Reef (**Figure 19**). *Agaricia spp.* were the most observed species among the recruits at different sites.

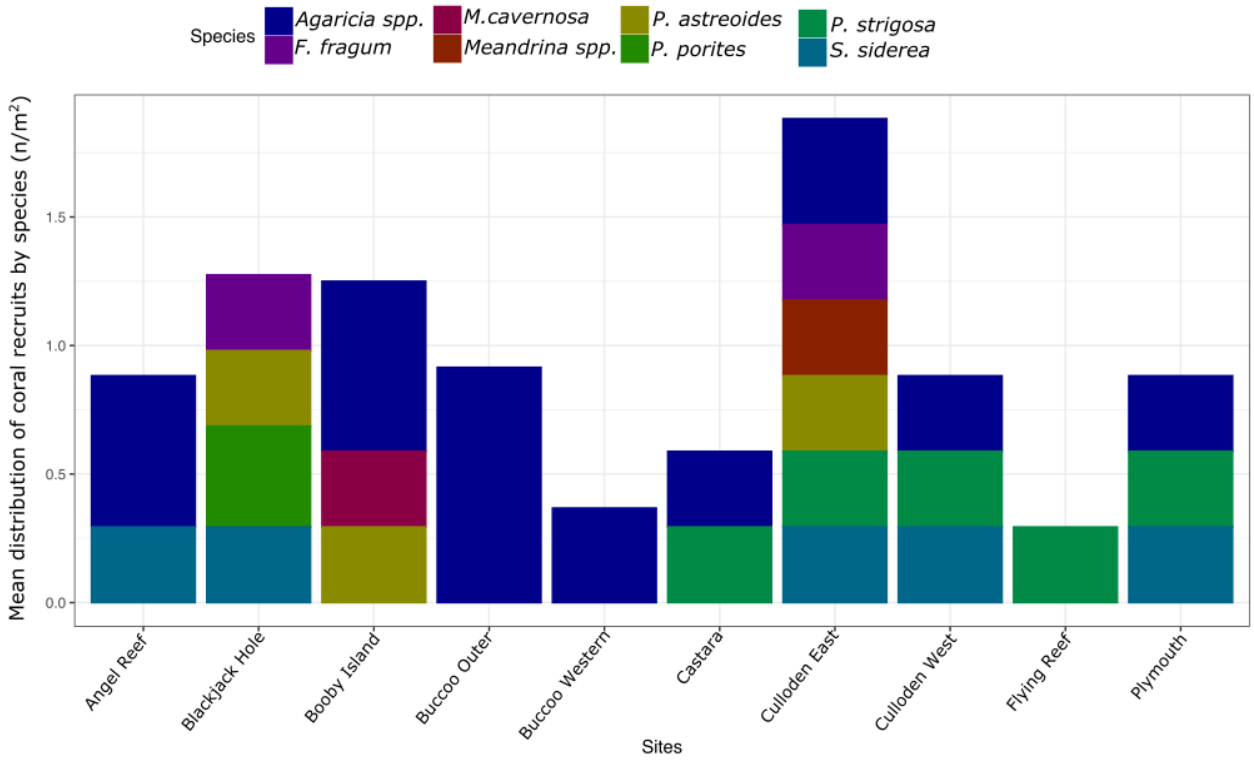

Figure 19: Mean number of coral recruits (n/m^2), defined as colonies < 2 cm in maximum diameter, for each monitoring site in 2020.

3.1.8 Coral Health Prevalence

The prevalence of healthy corals across all sites averaged ~ 73.6 (± 6.6) %, while the prevalence of impacted corals was ~ 26.4 (± 6.6) %. Buccoo Outer Reef had the highest percentage of impacted corals (82.1 ± 10 %, n= 4), followed by Plymouth (31.8 ± 2.1 %, n = 41), while Buccoo Western had the lowest proportion of impacted corals (5.3 ± 2.5 %, n = 33) (**Figure 20**). Coral impacts largely consisted of disease, bleaching and predation, with some occurrence of growth anomalies and overgrowth from competition (**Figure 20**). Divided into impact categories, the average prevalence across all sites is as follows: disease – 8.6 (± 3.5) %, predation – 5.3 (± 0.8) %, bleaching – 3.7 (± 2.3) %, overgrowth – 0.3 (± 0.1) %, growth anomaly – 1.0 (± 0.6) % and unknown – 2.8 (± 1.0) % (**Figure 20**).

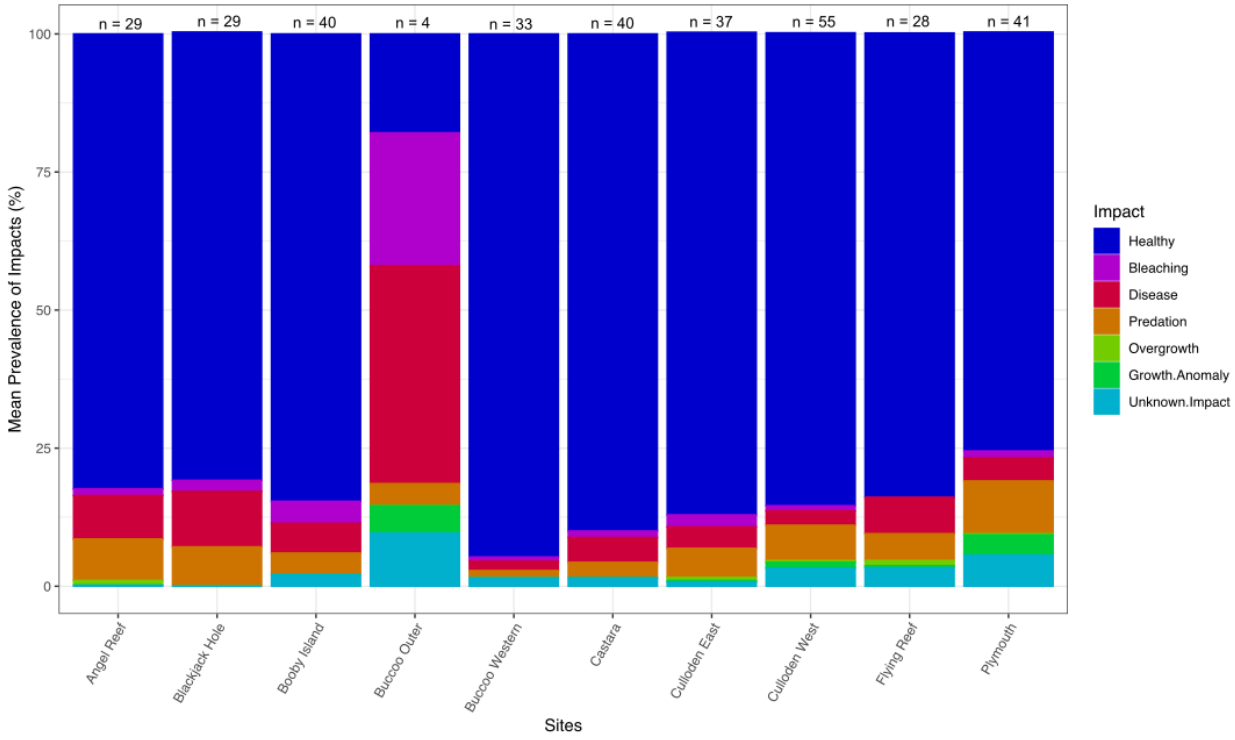

Figure 20: Percentage of healthy corals (blue) vs impacted corals present at each of the ten IMA monitoring sites in 2020.

Coral Disease

The highest/greatest presence of disease was recorded at Buccoo Outer Reef (39.4 ± 11.5 %, n = 4) (**Figure 21**). Of the remaining sites, Culloden East had the second highest prevalence of diseased corals (6.0 ± 1.0 %, n = 37). The disease that were observed most often were dark spot disease (DSD) that targets *S. siderea*, and yellow band disease (YBD) that targets *O. faveolata*. DSD was the most prevalent disease across all ten sites with Flying Reef having the highest DSD percentage (11.8 ± 2.7 %, n = 28) (**Figure 21**). Blackjack Hole had the third highest percentage of DSD (8.2 ± 1.6 %, n = 29) along with the highest prevalence of Black Band Disease (BBD) (2.9 ± 1.8 %, n = 29). Both diseases were observed on *S. siderea* (**Figure 21**). YBD was the second most prevalent disease across most sites with the largest proportion of *O. faveolata* infected occurring in Angel Reef (4.2 ± 2.2 %, n = 29) and Castara (3.1 ± 1.6 %, n = 40). Culloden East had the highest diversity of coral diseases with four diseases present (except white band disease), however the prevalence of BBD and white plague disease were present in < 1 % of the corals (**Figure 21**).

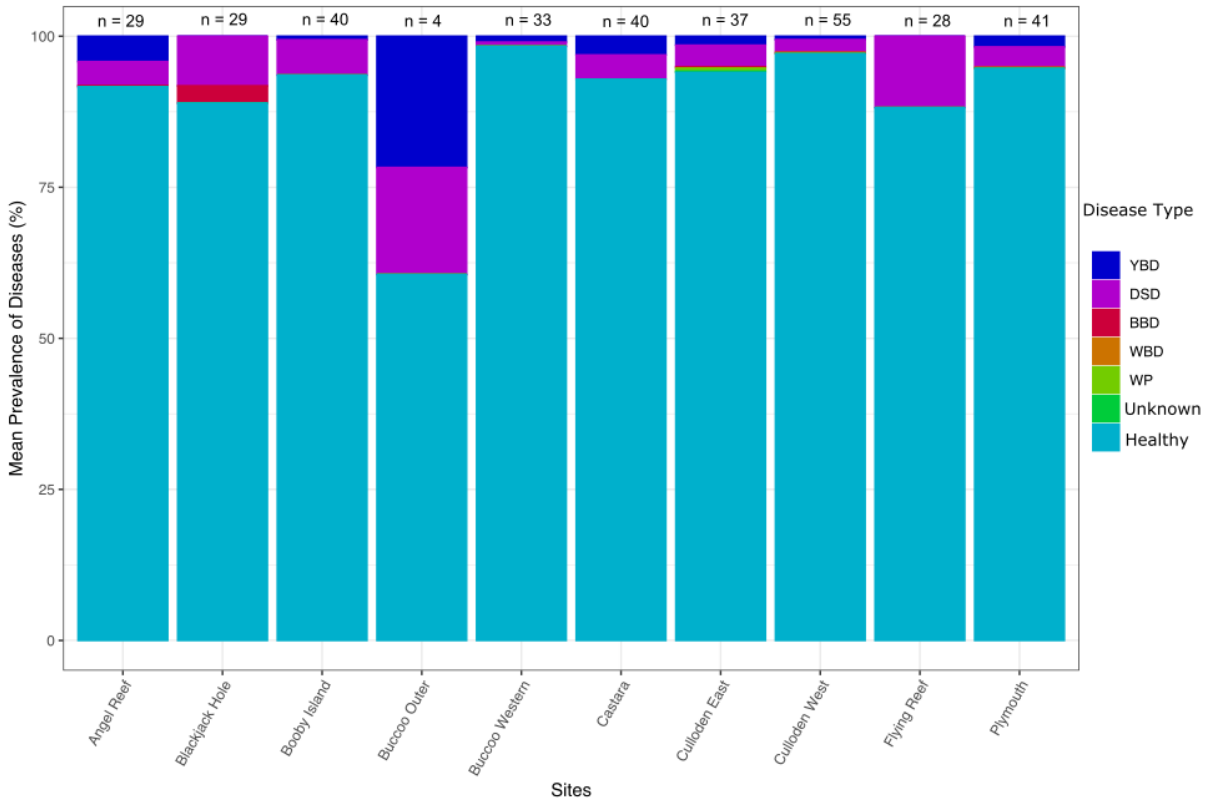

Figure 21: Mean prevalence (%) of corals infected by different types of diseases across the ten monitoring sites in 2020. YBD: yellow-band disease; DSD: dark-spot disease; BBD: black-band disease; WBD: white-band disease; WP: white plague disease.

3.1.9 Cumulative Reef Resilience Index

Overall, Booby Island had the highest relative cumulative resilience index of all monitoring sites. This was followed by Angel Reef and Buccoo Western (**Table 2**). Booby Island had the highest coral diversity, coral juveniles, and structural complexity compared to the other sites, while Angel Reef had the highest coral cover. Buccoo Western had the second highest density of coral juveniles and the highest prevalence of healthy corals. Castara and Buccoo Outer reefs scored in the medium to high category. Castara had relatively high coral cover, diversity, and lower coral impact. Buccoo Outer had the highest score for algae absence and a relatively high score for coral cover but had the lowest coral diversity and coral health. Conversely, Flying Reef had the lowest resilience index of all the sites because it had the lowest hard coral cover, diversity, and the second highest algae cover. Unfortunately, at least four other sites scored in the medium to low resilience range, including Culloden (East and West), Plymouth and Blackjack Hole. Culloden West had the highest algae cover and the lowest structural complexity.

Table 2: Cumulative coral reef health index based on six parameters of coral health.

Site	Coral Diversity	Hard Coral Cover	Coral Juveniles	Coral Impact	Structural Complexity	Absence of Algae	Normalised Score	Rank	Score Category
Booby Island	1.00	0.74	1.00	0.83	1.00	0.25	1.00	1	High
Angel Reef	0.56	1.00	0.62	0.81	0.50	0.18	0.76	2	Medium to High
Buccoo Western	0.53	0.65	0.86	1.00	0.25	0.35	0.76	3	Medium to High
Castara	0.77	0.76	0.00	0.84	0.50	0.46	0.69	4	Medium to High
Buccoo Outer	0.00	0.93	0.76	0.00	0.50	1.00	0.66	5	Medium to High
Culloden West	0.53	0.63	0.56	0.84	0.00	0.00	0.53	6	Medium to Low
Plymouth	0.67	0.51	0.26	0.66	0.25	0.18	0.52	7	Medium to Low
Blackjack Hole	0.23	0.50	0.31	0.81	0.25	0.39	0.51	8	Medium to Low
Culloden East	0.42	0.31	0.40	0.80	0.25	0.28	0.51	9	Medium to Low
Flying Reef	0.26	0.00	0.17	0.67	0.50	0.14	0.36	10	Low

4.0 DISCUSSION

4.1 SUMMARY OF RESULTS

Between 2019 and 2020, even though water quality sampling time points were affected by the COVID-19 pandemic, the high DIN to SRP ratio across most sites and times, is indicative of reefs that are not nitrogen limited. Additionally, most of the nitrogen on the reefs came from ammonium. Turf algae remained the dominant functional group at all sites with nine sites having > 30 % turf algal cover (except for Buccoo Outer which was dominated by calcifying algae) and hard coral cover ranged between 3 and 20 % across most sites. Coral disease plagued ~ 8 % of hard corals across sites where hard corals already make up only between 3 to 20 % of the reefscape. The relative cumulative coral health index confirms this by categorizing six sites with a medium to low, and low score in comparison to Booby Island which ranked as the most relatively resilient of all the monitored sites.

4.1.1 Water Quality

Previous research showed a correlation between concentrations of total suspended solids and coral degradation at TSS concentrations of 50 mg/l and more (Parwati et al. 2013). While such concentrations were not observed at our sites (max 34.3 mg/l), higher concentrations do occur episodically during the rainy season (June – December) in Tobago (Pers. Obs.). Past assessments of the nutrient conditions of Tobago's coral reefs have shown that the majority of the coral reefs present in Buccoo and surrounding reefs were all nutrient enriched (Lapointe et al. 2010). DIN concentrations that averaged 2.36 µM (range: 0.71 - 5.77 µM) across sites and sampling time points (taken primarily in the rainy season) was above the threshold of ~ 1 µM, indicative of eutrophication (Lapointe 1997; Lapointe et al. 2010). Lapointe et al (2010) in 2001 recorded a mean DIN of 2.4 µM during the rainy season, and a much lower mean of 0.7 µM during the dry season. Lapointe et al (2010) also observed lower DIN concentrations at sites farther from urban areas, however the high DIN concentrations in this study occurred at all reef sites across Tobago and were especially high during the summer periods (June/ July). In Lapointe et al (2010), the increase in DIN from dry to wet season was primarily related to increase in ammonium, similar to what was observed in this study as the largest component of DIN was ammonium. Ammonium stems from agricultural fertilizers and can end up in coastal waters through municipal effluent discharge, and land and river runoff from agricultural lands (US-EPA). Ammonium and phosphate even in very low concentrations can impair fertilization in coral, while nitrates also impair coral calcification (Marubini and Atkinson 1999; Harrison and Ward 2001; Pait et al. 2015). SRP concentrations averaged around 0.12 µM for our study across and time points, lower in concentration compared to ~ 0.23 µM measured in 2001 by Lapointe et al (2010). The threshold concentration of SRP for eutrophication is ~ 0.1 µM (Lapointe et al 1997, 2003). The high average value was driven mainly by the high SRP

concentrations across most sites recorded in June 2020. With respect the ratio of DIN: SRP, Lapointe et al (2003) suggested that < 15: 1 year-round is indicative of N-limitation and prevents algae growth on Tobago's reefs (Figure dotted line). Unfortunately, all reef sites appear to surpass this threshold, especially during the rainy season, again similar to findings of Lapointe et al (2003).

4.1.2 Benthic Composition

All monitoring sites have ~ 20 % or less hard coral cover with Flying Reef, Culloden East and Blackjack Hole having less than 10 % hard coral cover. This is in contrast to surveys conducted in 2001, which showed that Blackjack had some of the highest coral cover (~ 60 %) on the island, while Culloden reefs averaged ~ 50 % (Lapointe et al 2003), implying twenty years of significant hard coral loss with no recovery. This is a concerning trajectory for the hard coral health across Tobago. Hard corals provide a myriad of ecological services including habitat provision, coastal protection and dissipation of large waves by the rigid 3D framework formed by the scleractinian species (Moberg and Folke 1999). The suggested coral cover (%) target as an indicator of healthy reefs for the Mesoamerican region is ≥ 30 % with significant signs of recovery or further significant degradation seen by the respective increase or decrease in coral cover by 5 % (McField and Kramer 2007; Mcpherson and Mcfield 2007). Between 2017 and 2020, a further decline in hard coral cover of 5 % at Culloden (East and West) was observed. This is indicative of further disturbance to the area. Hard coral covers of ~ 10 % or less are thought to exhibit a potential net negative carbonate budget resulting in reef erosion, thus further jeopardizing the habitat functions of the coral reef (Perry et al. 2013). Many of Tobago's coral reefs are precipitously close to this 10 % threshold with three sites already below the threshold.

Apart from the dominance of turf algae on Tobago's coral reefs, many reef sites have also seen increases in octocorals and sponge communities in recent years, showing a further ecological shift in their benthic composition as a result of shifting environmental conditions (Lasker et al. 2020). While the stability in the shift in hard coral to sponge dominance at Blackjack Hole is unknown, coral - sponge regime shifts have been observed on many reefs in the Caribbean, and to the extent where sponges become the main contributor of reef complexity (Norström et al. 2009; Pawlik et al. 2013; Villamizar et al. 2014). Such a regime shift may also be more likely with further warming and ocean acidification as sponge communities have experimentally been shown to have a higher tolerance to these conditions, and have a high natural prevalence along carbon seeps (Schönberg and Suwa 2007; Morrow et al. 2015). However, while octocorals and sponges do contribute to 3-D matrix, their contribution to reef biodiversity does not compare to the complexity contributed by large long-lived hard coral colonies that also provide substrate to sponge and octocorals (Alvarez-Filip et al. 2009; Newman et al. 2015).

Another fundamental benthic functional group monitored are crustose coralline algae (CCA). Some species of CCA contribute to reef calcification, cementation and play an essential role in inducing settlement of coral larvae (Heyward and Negri 1999; Fabricius and De'ath 2001). The successful induction of larval settlement is governed by the bacterial community that resides on the CCA (Siboni et al. 2020). However, previous studies have also shown that peysonnelid algal crusts also outcompete and overgrow hard corals, and even promote the growth of octocorals on some Caribbean reefs (Edmunds et al. 2019). Buccoo Outer recorded the highest coverage of crustose coralline algae (> 50 %) in 2020, but with no exceptional coral recruitment or juvenile community compared to other sites. Whereas, Booby Island had the highest recruit abundance and the second highest coralline algae cover. Further studies to determine the species composition of CCA communities and their bacterial communities across Tobago's coral reefs is critical to understand the community distribution of CCA as natural inhibitors or promoters of coral recruitment. It must be noted that there is some discrepancy among annotations across the years in deciphering turf algae from calcifying algae through image annotation (**Figure 16**). This may also be triggered by variations in the length of turf algae growing over calcifying algae that may make it hard to be consistent in the image annotation.

4.1.3 Coral Structural Complexity

Present-day Caribbean reefs with the highest structural complexity are typically associated with *Orbicella d*ominant reefs (Alvarez-Filip et al. 2011; Williams et al. 2015). Most monitoring sites of Tobago are *Orbicella* reefs with the exception of Flying Reef and Blackjack Hole. Buccoo Outer and Angel Reefs both have relatively high structural complexity compared to the other sites attributed to the high *Orbicella* cover, and hard coral covers of both sites. However, Flying Reef with the lowest hard coral cover had moderate structural complexity compared to the other sites. This is likely a result of the dead coral skeletons that continue to contribute the reef framework. Structurally complex reefs are associated with higher biodiversity (greater biomass of fish and invertebrates), and is known to facilitate the recovery of hard corals after a disturbance (Graham and Nash 2013). While there is no regional target for structural complexity, forereef environments (e.g. long-term monitoring sites of Tobago) have relatively "good" states compared to the shallower reef zones that have undergone a significant loss in structure from storm damage and disease outbreaks, namely white-band disease in *Acropora spp.* (McField and Kramer 2007).

4.1.4 Coral Recruitment and Juvenile Density

Coral recruitment is the process whereby reefs replenish coral stocks to maintain coral populations. The successful recruitment on a coral reef is dependent upon the environmental and ecological conditions of the reef substrate that supports coral spawning and the survival of coral juveniles (Ritson-Williams et al. 2009). McField and Kramer (2007) defined the target

benchmark for coral recovery to be 5 recruits per m^2 for the Mesoamerican Region. A red flag is raised when recruitment drops to ≤ 2.5 recruits per m^2 (Mcpherson and Mcfield 2007). In 2020, the recruitment at sites of Tobago averaged less than 1 per m^2 across most sites. Considering that the Mesoamerican reef recruitment average is 4.5 recruits per m^2 (McField and Kramer 2007), coral recruitment across Tobago appears to be significantly impaired and therefore too low for sufficient recovery of coral cover. Drivers that impair coral recruitment and the maintenance of a healthy juvenile coral population include environmental stressors, such as algae overgrowth, space pre-emption, and predation (Mumby et al. 2014).

Throughout the Caribbean, many coral reefs are largely composed of key reef builders critical for maintaining the 3-D matrix of the reef. Many of these corals have competitive lifestyles (*Acropora spp.*) or are stress-tolerant species largely composed of the *Orbicella* species, boulder and brain corals (Darling et al. 2012). In this study, the species of coral juveniles observed were not reef framework builders of competitive or stress-tolerant life histories. Rather most juveniles observed have a weedy life history strategy (*Agaricia agaricites, Porites astreoides*) and would generally remain small in colony size (*Favia fragum, Madracis decactis and Porites porites*). Corals with weedy life histories tend to occur in disturbed environments. They have a brooding reproductive cycle, a high population turn over and a rapid growth rate as a survival strategy to survive disturbances (Szmant-Froelich et al. 1985; Darling et al. 2012; Madin et al. 2016). Such weedy recruits (*Agaricia* spp., *Porites porites)* were also observed on reefs of Tobago in 2016 following the 2010 bleaching event (Buglass et al. 2016).

Most notably, no recruitment of the main reef builder *Orbicella faveolata* was observed at any site, and very low densities of coral juveniles were found at few monitoring sites. (Mallela and Crabbe 2009) showed that coral recruitment rates on Tobago's reefs significantly declined in the years following disturbance events. This survey shows that recruitment continues to be poor thirteen years later. Mallela and Crabbe (2009) highlighted that an already slow recovery process in Tobago will become even more impaired as it is projected that future climate related disturbances are expected to be more frequent and severe in the future. The reasons for low recruitment across most sites may also be associated with Tobago's already marginal conditions and isolated location in the Caribbean serving as a barrier to recruitment with poor connectivity to external sources (Mallela and Crabbe 2009; Schill et al. 2015). At the reef level, there are many possible causes for low coral recruitment ranging from the settlement and post-settlement ecology, such as the lack of suitable substrate to settle and grow on, owing to high sedimentation or overgrowth of algae (McCook et al. 2001; Mumby et al. 2007; Wakwella et al. 2020). Other reasons for limited recruitment success may be related to limited larval availability because of poor connectivity or spawning impairment because of disease or a breakdown of spawning synchrony among colonies (Ritson-Williams et al. 2009).

4.1.5 Coral Impacts

Prevalent coral impacts on the surveyed reefs were disease, bleaching and predation where coral diseases seem to have the highest prevalence in corals. For most sites, coral bleaching was minor but present on at least one colony at most sites. This may be indicative of low-level stress conditions present on the reef. As Buccoo reef has a history of poor water quality, further investigations into whether the deleterious conditions are causing an increase in localized bleaching at this site (Lapointe 2003).

Coral Disease

According to the Healthy Reefs Initiative for the Mesoamerican Region, the target for disease prevalence should be less than 1 %, and reefs with greater than 5 % disease prevalence are a cause for concern (McField and Kramer 2007). Tobago's reefs have a disease prevalence average of ~ 8 % across all sites, which is a major concern for the trajectory of reef health. Diseases observed in these surveys – yellow band disease, dark spot disease and white plague – are common across the Caribbean region. Yellow band disease prevalence was first documented on *O. faveolata* on Tobago reefs following the 2005 mass-bleaching event at most surveyed locations (Mallela and Parkinson 2008; Mallela et al. 2010).

In this study, yellow band disease was observed on *Orbicella faveolata* colonies at eight out of ten sites, and its prevalence averaged 3.4 % across all the reefs. This poses a critical problem for Tobago's reefs which are primarily dependent on *O. faveolata* as a major reef framework provider. While yellow band disease has a relatively slow infection rate of 0.5 cm to 1 cm per month (Cervino et al. 2001), such slow rate of spread is competitive to the slow growth of *Orbicella spp.* that ranges 0.04 – 2.0 cm/ year on shallow reefs (< 12 m) (Hubbard and Scaturo 1985; Runnalls and Coleman 2003). Growth rates are even slower at greater depths and at polluted sites (Hubbard and Scaturo 1985; Runnalls and Coleman 2003). Yellow band disease may also hinder the reproduction of *O. faveolata* in five main mechanisms: (i) loss of reproductive polyps, (ii) diminished fecundity in diseased portions, (iii) reduction of live tissue where remaining healthy coral is too small to be able to carry out reproduction, since *O. faveolata* are sexually mature at >100 cm (Szmant-Froelich et al. 1985), (iv) loss of fecundity due to "edge" polyps being physiologically responsible for tissue growth over reproduction and (v) decline in the coral energy budget because of zooxanthellae mortality (Weil et al. 2009). Disease succession often results in coral mortality, exposure of coral skeleton and algal overgrowth.

There was a mean prevalence of 6.1% of dark spot disease infecting *Siderastrea siderea*. While the causative agent of dark spot disease is still unknown, it spreads at a relatively faster rate of

4 cm per month (Cervino et al. 2001). The disease results in patches of tissue necrosis and tissue depressions on *Siderastrea siderea* and *Stephanocoenia michellinii* (Cervino et al. 2001). The corals do not recover and dead areas are often colonized by algae (Cervino et al. 2001). It is important to note that other diseases such as black band disease, white band disease and white plague were also observed on Tobago's reefs albeit only a few coral colonies.

Worsening oceanic conditions because of climate change, such as increased sea surface temperatures and ocean acidification is expected to exacerbate coral disease spread (Sokolow 2009; Maynard et al. 2015). There is a clear link between higher sea surface temperatures and nutrient enrichment, and coral disease (Bruno et al. 2003, 2007; Jones et al. 2004).

4.2 RESEARCH AND MANAGEMENT RECOMMENDATIONS

4.2.1 Monitoring, The Next Steps

Climate change projections highlight an increase in frequency of annual severe thermal bleaching events for most of Tobago by 2042 (van Hooidonk et al. 2016), as well as an increase in severe storms events regionally (Masson-Delmotte et al. 2018). Additionally, existing impacts such as pollution, overexploitation and habitat destruction chronically degrade coral reefs and limit recovery. Realigning coral reef monitoring to focus on reef resilience relates the biological and physical health of the reef to its ability to withstand or recover from future climate relate disturbances events that have a very high certainty of occurring (IPCC 2021). Assessing reef resilience of Tobago's coral reef will enable us to identify areas of ecological vulnerability to climate impacts as well as the socio-economic vulnerability of dependent communities. Reef resilience can support decision making that can be scaled and prioritised to specific areas of differing vulnerabilities. While we currently measure most components of reef resilience there are a few additional metrics that will make our index more robust. Recommended additional metrics for reef resilience that should be added to the annual monitoring includes fish herbivore composition (biomass and diversity) and indicators of anthropogenic stress. Examples of stressors include a more comprehensive assessment of nutrient pollution, sedimentation (assessed seasonally) and fishing pressure. Fishing pressure can be estimated with the use of proxies, such as the proximity to fishing depots or the density of fishing boats until fish catch data becomes more freely available (Burke et al. 2011). Management authorities can then track changes, prioritise action, and guide zonation strategies for marine management and protection (Maynard et al. 2017).

As it appears that corals are significantly impaired in their recovery efforts, in addition to managing the reef to reduce algae cover, further investigation should be done to determine the

reproductive health of the hard corals during their spawning and recruitment phases of the reproductive cycle. To date, little is known about when corals spawn in Tobago. Research on the coral spawning times, and spawning quantities for reef builder species will provide insight into the success of coral sexual reproduction and determine the need for coral larval propagation to improve coral cover. Combined with the management action, coral larval propagation is an intervention method for rearing coral. With the capacity to increase genetic diversity, new coral recruits are grown ex-situ and outplanted on the reef when they are big enough and have a greater chance of survival. Another fundamental component for successful coral reproduction is the availability of suitable substrate for successful larval recruitment. Calcifying algae species are known to encourage coral recruitment and reef cementation, while sedimentation on reefs can result in loss of the CCA community (Barnes 1990; Fabricius and De'ath 2001). The exploration into the community composition of crustose coralline algae across Tobago sites will allow us to determine the best way forward to encourage the increase in cover of calcifying algae species naturally and on recruitment tiles for restoration purposes through management of sedimentation and pollution.

4.2.2 Implementation of Reef Resilience into Marine Spatial Planning and Management

There is a need to design a clear path for decision making for the protection and conservation of reef building coral communities and the biodiversity housed, especially considering the high reliance of Tobagonians on coral reefs (Burke et al. 2008). Marine spatial planning (MSP) allocates zones for different levels of resource use and protection based on the ecological state of health of the reef. Within MSP, designated marine protected areas should be protected to its full extent to conserve coral stock that may seed or replenish other reef zones managed for rehabilitation, recreation, cultural or tourism purposes. Marxan is a known strategy for designing MSP with all conservation, cultural and environmental considerations included (Ball et al. 2009). It is an algorithm that produces possible MSP solutions based on the goals of the marine management team and the activities of local community. Marxan can create zones that maximise biodiversity or minimize user conflict and moderate resource availability (Maynard et al 2017). Here are some recommendations for the use of MSP and decision making based on the reef resilience measures based on Maynard et al (2017).

4.2.3 Conservation

It is recommended that sites of both high and low reef resilience be designated Marine Protected Areas (MPA) but with site specific forms of management (Maynard et al. 2017). This includes Booby Island in Charlotteville, Angel Reef (Goat Island) in Speyside, in addition to the already established Buccoo Reef MPA. Both sites, have high algae cover and therefore requires special effort to conserve parrotfish and sea urchins, and more intense monitoring and management of

nutrient pollution. As Flying Reef scored the lowest in its reef resilience, it should also be designated an MPA, but with active management that caters for rehabilitation, such as coral restoration, in addition to the baseline management of water quality and exploitation to conserve biodiversity.

4.2.4 Land-based Sources of Pollution

As most sites are impacted by land-based sources of pollution, the recommended strategy is to work with partner government agencies, such as Water and Sewage Authority, Town and Country Planning Division, to regulate and manage human activities in watersheds. This includes activities to improve wastewater management, enforce responsible construction and land use regulations to limit and mitigate soil erosion and run off, especially during the rainy season, as well as regulate the types of construction. Collaborations can be developed with the Ministry of Agriculture, Land and Fisheries and farmers within upstream watersheds on limiting the excess use of fertilizer and potentially a transition to organic farming where possible. Targeted activities with Town and Country Planning Division, Coastal Protection Unit on the importance of integrated coastal zone management and the need to limit coastal construction is also crucial. Other issues that require cross-government collaborations include irresponsible land-clearing and reforestation activities, and cohesive and integrated government planning to limit downstream degradation of coral reefs.

4.2.5 Fisheries Management

For fisheries management on coral reefs, the overarching implementation and enforcement of restrictions on fish species, sizes and quantities, and fishing methods in legislature (Draft Fisheries Management Bill 2020) goes hand in hand with marine spatial planning and MPA designation to manage coral reef fish stocks. More specifically the recovery of herbivorous fish populations is a high priority for Tobago's reefs as all sites are dominated by algae. Full fishing restrictions can be prioritised for MPAs, while other sites can be protected for specific species, namely parrotfish. Fishing methods should be and not over exploitative. The inclusion of fish herbivore biomass into the reef resilience index will assist in assessing the effectiveness of the management strategies.

4.2.6 Bleaching Monitoring and Recovery

Sites with low bleaching resistance because of the low prevalence of stress-tolerant corals (e.g. boulder brain corals) can be monitored more frequently based on NOAA's Coral Watch alerts. Bleaching management will accompany the monitoring to reduce the risk of bleaching and facilitate the recovery in the wake of bleaching events. This should include activities, such as the temporary closure of impacted zones to any human activities to limit any additional stressors that may prevent recovery.

4.2.7 Reef Restoration

Target sites for restoration activities are sites with a high or low reef resilience driven largely by low coral cover and diversity (Maynard et al. 2017). Based on the parameters of the resilience index for Tobago, this includes Flying Reef, Blackjack Hole, Culloden Reef and Plymouth. Prior to any restoration activities, these sites must be managed for water quality and exploitation. Specific restoration methods, such as sexual or asexual propagation, are largely dependent on the ecological knowledge on coral reproduction in Tobago, the target coral species, as well as expertise and funding.

4.2.8 Tourism Outreach and Stewardship

Coral reefs recommended for tourism, conservation, education and outreach should be accessible and with relatively high coral cover and diversity, and a healthy fish community. Sites for such activities can include Booby Island, Angel Reef and Castara. These sites can be visited for educational trips, citizen science and outreach clean-up activities. Facilitations for such activities include safe mooring sites and calm conditions. Active stakeholder participation and inclusion should be encouraged regarding protection of the environment.

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