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The Relationship between Large Herbivore Abundance and Algal Cover on Coral Reefs on West Coast Barbados

Abstract

Background: Over the past few decades, climate change and the intensification of coastal development significantly contributed to the degradation of coral reefs across the Caribbean Sea. Widespread increase in algal cover on coral reefs since the 1970s has made it difficult for the corals to recover. Thus, algae regulating factors, such as herbivorous grazers and groundwater nutrient concentrations, have important implications for the conservation of coral reefs. In this study we conducted a small-scale assessment of the relationship between the abundance of two families of herbivorous fishes, *Scaridae* and *Acanthuridae*, and algal cover on the coral reefs of West Coast Barbados was conducted, and we hypothesized that a direct negative correlation exists between them.

Methods: Herbivorous fish abundance and percent algal cover were quantified for three different coral reefs, and the data was analyzed using linear regressions and analyses of variance.

Results: We found that although there were no significant relationship between herbivorous fish abundance and algal cover, there was a significant difference between them across the three reefs studied. These results suggest the presence of other factors influencing algal cover. One such factor could potentially be groundwater input levels, which was found to differ at each of the three sites studied.

Limitations: The limited timeframe of this study did not allow for extensive sampling.

Conclusion: In order to effectively protect the coral reefs in Western Barbados, Further studies are needed to increase the understanding of the relationship between herbivory and algal cover in Western Barbados as well as to further investigate the role of groundwater seepage on algal growth.

Introduction

Many coral reef ecosystems around the world have shown a significant decline in coral cover and species diversity over the past four to five decades. Estimates suggest that 20% of the world's coral reefs are already lost, 20% are under imminent risk of collapse, and another 26% face threats of irreparable damage. (1) Such coral cover decline is attributed to indirect human disturbances including ocean warming, which cause coral bleaching and diseases the growth of human coastal populations, and overfishing of key herbivorous fishes, namely scarids and acanthurids. A loss of coral cover can result in a phase shift from coral to macroalgae dominance and cause further coral loss as coral death reduces competition for space, allowing algae to grow more easily. (2) In addition, excessive macroalgal cover is thought to harm coral reefs by reducing recruitment of juvenile corals from the plankton. (2)

Between 1983 and 1984, the entire Caribbean Sea experienced mass mortality of the sea urchin Diadema antillarum, an important algal grazer, due to a waterborne pathogen. Mortality rates ranged from 85% to 100%. (3) A significant decrease in herbivory on coral reefs and dramatic increases in algal cover ensued. (4) This event, combined with habitat loss as a result of increased coastal development, sedimentation, and eutrophication - the process by which excessive nutrients cause algal blooms and subsequent oxygen dead zones, was a strong contributor to the observed phase shift from corals to macroalgal-dominated reefs. Algal growth is promoted by eutrophication from groundwater seepage. Meanwhile, coral's ability to recover is hindered by many factors, including sedimentation, global warming, and reduced herbivory. The massive die offs of *Diadema*, and increased fishing pressure on herbivorous fish have therefore both con-

tributed to the lack of recovery of coral cover in Caribbean reefs. Herbivorous fishes are important in coral reef ecosystems because they reduce algal cover by grazing, contributing to the maintenance of reef health and the recovery of the reef from disturbances such as hurricanes. (5) Specifically, the families *Scaridae* (parrotfish) and *Acanthuridae* (surgeonfish) are thought to have the greatest impact on the regulation of algal cover via grazing, with adult scarids capable of maintaining 10% to 30% of a fore reef in a grazed state alone. (4)While damselfish (*Pomacentridae*) are also known grazers, their activity is confined to selectively maintaining algal "farms" in small territories, limiting their reef-wide impact on regulating benthic algae. (5)

In Barbados, the significance of herbivorous fishes' role as grazers in the coral reef ecosystem increased substantially with a 93.2% mortality of Barbadian *Diadema* populations from 1983 to 1984. (3) The increasing threats of overfishing and eutrophication on Barbados' reefs are bringing about lower numbers of herbivores and greater algal growth promotion, likely decreasing the health of the coral reef ecosystem. (6) To protect the reefs from algal dominance and loss of coral cover, one must first understand the extent of the top-down effects of herbivorous fish. The purpose of this study is to assess the relationship between the abundance of scarids and acanthurids and percent algal cover on the coral reefs of Western Barbados. We predict that a large abundance of scarids and acanthurids in an area will result in a low percent algal cover in that area.

Methods

Site Selection

Three individual coral reefs were selected along the West Coast of Barbados for sampling, which was done in May 2014. At each reef, scarid and acanthurid abundance and algal cover were measured. The sites were, from North to South: Mullin's Bay Beach, Folkestone Marine Reserve, and Sandy Lane Beach. The sites were chosen due to their proximity to one another (maximum distance of 11 km), as the focus of this study is to determine the small-scale effects of herbivore grazing on algal cover. This proximity enabled us to normalize the degree of coastal development, general oceanographic conditions, and physiography. One of our sites, the Folkstone Marine Reserve, is a Marine Protected Area in which fishing has been prohibited since 1981. (7) Fishing is permitted at the other two reefs.

Data Collection - Set Up

At each site, data were collected along five 30-meter long transects extended perpendicular to the shoreline. At each reef, the transects were positioned a short distance beyond the crest of the reef (Fig. 1). This was done to ensure rough standardization of the water depth in each reef studied. Throughout the reef area studied, water depth ranged from 1 to 3.5 meters. The start of each transect was positioned by a snorkeler swimming on their back - thereby assuring a haphazard assignment of each transect location. From this point, a 15-meter long weighted rope marked with tape at 5-meter intervals was laid along the reef. A dive buoy, attached to the rope, was used at Mullin's Bay and Sandy Lane as boats were prevalent in both places. Because the placement of the transects created a disturbance, our team waited five minutes to allow fish to return to the area before beginning data collection. One group of two observers (Team 1) assessed herbivore abundance and water clarity while the other group of two (Team 2) assessed percent algal cover - these teams remained constant throughout all the observations, and the same person assessed water clarity at each site. While collecting data along the transect, a minimum distance of 10 meters was maintained between the two teams to ensure minimal disturbance for the fish. Once both teams reached the end of the 15-meter rope, Team 2 displaced the rope so that it covered the second half of the transect (15-30 meters), and then the process explained above was repeated starting at the 20-meter point. Data was not collected at the 0-meter and 15-meter marks, as pilot studies showed that setting-up the buoy and transect disturbed algal cover.

Data Collection - Assessing Herbivore Abundance

At each five-meter mark, both observers of Team 1 completed two 360° turns on themselves, the first to count the number of acanthurids visible, and the second to count the number of scarids visible. All species within the two families were grouped together but juveniles of all of the species were ignored because they have been shown not to have a significant effect on algal abundance. (8) Both observers then recorded their results on slates with lead pencils. The number of scarids of three loosely defined and relative size ranges (small (~10cm), medium (~30cm), large (~50cm)) was recorded. Acanthurid abundance was recorded as the frequency of schools of 1, <10, 10-30, 30-50 individuals observed. This was done owing to acanthurids' proclivity for travelling in schools and the difficulty of recording exact number of fish in large schools moving away quickly. For data analysis, the number of observed acanthurids in a school was converted to a midpoint value (<10 was converted to 5, 10-30 to 20, and 30-50 to 40).

Data Collection - Assessing Percent Algal Cover

Percent algal cover and grazing pressure at each 5-meter point along transects was estimated with a one square foot (929.03 cm^2) quadrat. The quadrat was placed first to the left and then to the right of the rope at each meter mark (ignoring the 0-meter mark). At each position, a visual assessment of the percent algal cover and number of grazer marks observed in the quadrat was recorded by both observers on their own slates. This was done to ensure two independent assessments of each replicate. Grazer marks are sometimes left by scarids (but not by acanthurids), therefore the number of marks is an additional indication of the level of grazing pressure on algae. Grazer marks were recorded as being either absent (n/a),
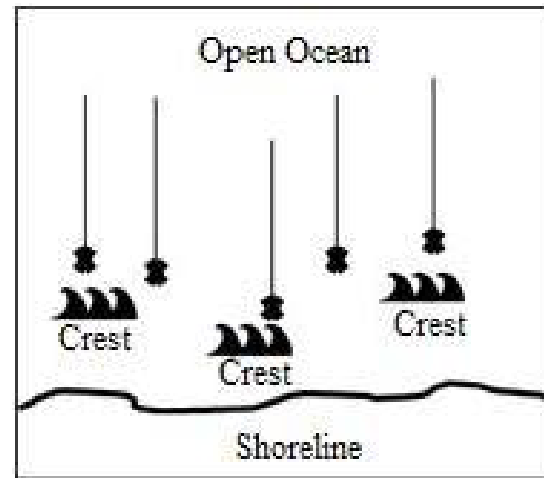

Fig. 1. Transect selection design

a single mark (1), few (2-9) and many (≥10). These values were then analyzed in pivot tables to assess the frequency of each category of bite in each site. In cases when the reef surface did not allow easy viewing of the quadrat, a picture was taken and later examined by both of the original observers. A final estimate of algal cover and number of grazer marks for each 5-meter point was obtained by taking the average of the independent assessments for each side and subsequently taking the average of the left and right mean value.

Data Collection - Assessing Groundwater Input into the Reef

Conductivity and salinity were assessed at each reef using a salinity meter. Salinity, the total concentration of all dissolved salts in water, is a strong contributor to conductivity, a measure of water's capability to pass electrical flow. Measurements were taken every 5 meters along the shore of each site, starting 20 meters before the onset of the reef and, from that point, continuing for 100 meters down the coast.

Data Analysis - Statistical Analyses

Null hypotheses that algal cover and herbivorous fish abundance were independent of the reef being measured were tested using one-way analysis of variance (ANOVAs). Additionally, pairwise comparisons of the three sites were conducted using Bonferroni confidence intervals. To test our null hypothesis that herbivorous fish abundance negatively affects algal cover, we used a simple linear regression model using data combined from all sites. Additional linear regressions were performed to evaluate the individual relationships of acanthurid abundance and scarid abundance versus algal cover both at the reef scale and across all reefs. Additionally, an analysis of covariance (ANCOVA) was used to test the effect of reef (grouping variable) on algal cover (response variable), while controlling for the effect of herbivore abundance (independent continuous co-variable).

Mean conductivity was computed for each site in order to determine which site had the highest groundwater input. Conductivity values were plotted respective to distance from the start of the reef (South end on the shore) in order to locate groundwater input (if any).

Results and Discussion

Algal cover (ALCO) was found to be significantly different between reefs (ANOVA, Falco=4.107, Palco=0.0198). Similarly, mean herbivorous fish abundance (HAB) significantly differed between reefs (ANOVA, F_{hab}=11.6700, P_{hab}=3.2400e^{-05}) (Table 1).

Pairwise comparisons revealed that mean algal cover in Folkstone was not significantly different from Sandy Lane or Mullins Bay at α=0.05, with Bonferroni confidence intervals of [-2.46, 16.07] and [-13.90, 5.1]) respectively. However, Sandy Lane's mean algal cover was significantly less than

Site	Mean algal cover (%)	Standard deviation	Mean herbivorous fish abundance	Standard deviation
Folkstone	76.15	11.67	5.92	4.50
Sandy Lane	69.08	20.57	4.23	6.36
Mullins Bay	80.51	12.99	12.60	9.50

Table 1. Summary for ANOVA

that of Mullins Bay CI[-20.97, -1.89]. Folkstone mean herbivorous fish abundance was found to be significantly less than Mullins Bay, CI[-2.64, 6.02], but not significantly different from Sandy Lane, CI[-2.64, 6.02]. Sandy Lane herbivorous fish abundance was significantly less than Mullins Bay CI[-12.7, -4.04].

Mean percent algal cover (Fig. 2A) was found to be the highest at Mullins Bay (80.51%) and the lowest at Sandy Lane (69.08%). Though total and mean herbivore abundance was highest at Mullins Bay (5.92) and lowest at Sandy Lane (4.23) the most scarids were observed at the Folkstone Marine Reserve (Fig. 2B). Of the 79 scarids observed, 25 were judged to be larger than the acanthurids observed around them. In total, around ten times more acanthurids were observed than scarids.

Simple linear regression models comparing the pooled herbivorous fish abundance and algal cover across all reefs indicated an insignificant relationship at all scales . More specifically, non-significant positive relationships were observed between total herbivore abundance and algal cover at Sandy Lane and at Mullins Bay and a non-significant negative relationship was observed at Folkstone Marine Reserve (Table 2A).

Linear regressions comparing scarid abundance and algal cover were even less conclusive (Table 2B) - P values were all greater than 0.05 and the slopes closer to zero. A non-significant positive relationship was observed between scarid abundance and algal cover for pooled sites and at the Mullins Bay reef specifically. The relationship was also non-significant but negative for Sandy Lane and Folkstone. Comparing acanthurid abundance with algal cover at Sandy Lane and Mullins Bay showed a positive relationship - with a very high P value, as when the two herbivore families were combined. Lower P values, negative slopes and slightly higher R2 values were observed for the linear regressions performed at Folkstone Marine Reserve and pooled sites (Table 2C).

In the first ANCOVA model (with an interaction effect between reef (the grouping variable) and herbivore abundance (the independent continuous co-variate)), herbivore abundance was not found to significantly predict algal cover at the reef scale (ANCOVA with interaction, $F_{hab}=1.892$, $P_{hab}=0.1726$). However, algal cover significantly differed between reefs, which in this case could be interpreted as a significant difference in intercepts between the regression lines of Folkstone, Sandy lane and Mullins Bay (ANCOVA, $F_{reef}=3.138$, $P_{reef}=0.0485$). Furthermore, no interaction between reef and herbivore abundance was found (ANCOVA, $F_{hab:reef}=0.944$, $P_{hab:reef}=0.3933$) (Fig. 3). Therefore, on the small scale the effect of herbivore abundance on algal cover does not depend on the reef. These results suggest that the slope of the regression lines between herbivore abundance and algal cover did not vary across reefs. The results of a second ANCOVA model (without interaction) confirmed that there was no significant difference in the slopes of the regression lines of each reef (ANCOVA without interaction, $F_{hab}=1.895$, $F_{reef}=3.142$, $P_{hab}=0.1722$, $P_{reef}=0.0482$). A subsequent comparison of both models using a one-way ANOVA showed that the effect of reef and herbivore abundance on algal cover are independent of one another (ANOVA(mod1,mod2), F=0.9436, P=0.3933).

Overall, the analysis shows that algal cover and herbivorous fish abundance significantly differ between the three sites. However, herbivorous fish abundance does not significantly predict algal cover, suggesting that other factors may be responsible for the regulation of algal growth on these reefs.

Bite Mark Analysis

Bite marks in the coral from scarids were observed at Folkestone, but neither at Sandy Lane nor at Mullins Bay. Out of the observations at Folkestone, 0 bite marks were observed 20 times, a single bite mark was observed 8.5 times, 2-15 bite marks were observed 20 times, and 15+ bite marks were observed 11.5 times.
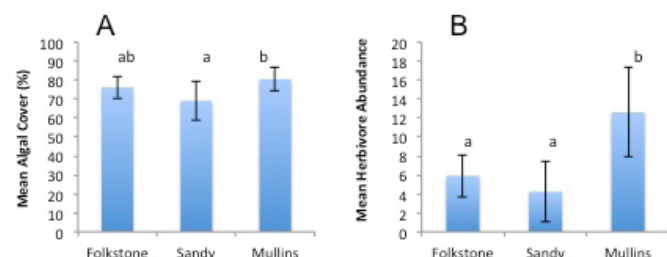

Fig. 2. (A) Mean Algal Cover, (B) Mean Herbivore Abundance; error bars represent standard deviation by sites. If two sites have the same letter above them that means that their means are not significantly different.

Combined Herbivore Abundance			
All	0.0201	0.2894	0.1820
Folkestone Marine Reserve	0.0835	-0.1113	0.1215
Sandy Lane	0.0085	0.0285	0.6279
Mullins Bay	0.0086	0.0678	0.6258
Scarid Abundance			
All	0.0014	0.0025	0.7276
Folkestone Marine Reserve	0.0353	-0.0191	0.3204
Sandy Lane	0.0003	-0.0004	0.3212
Mullins Bay	0.0378	0.0129	0.3032
Acanthurid Abundance			
All	0.0195	-0.0670	0.1898
Folkestone Marine Reserve	0.0684	-0.0923	0.0317
Sandy Lane	0.0089	0.0290	0.6478
Mullins Bay	0.0061	0.0549	0.6811

Table 2. Linear Regression Models – Herbivore Abundance vs. Algal Cover
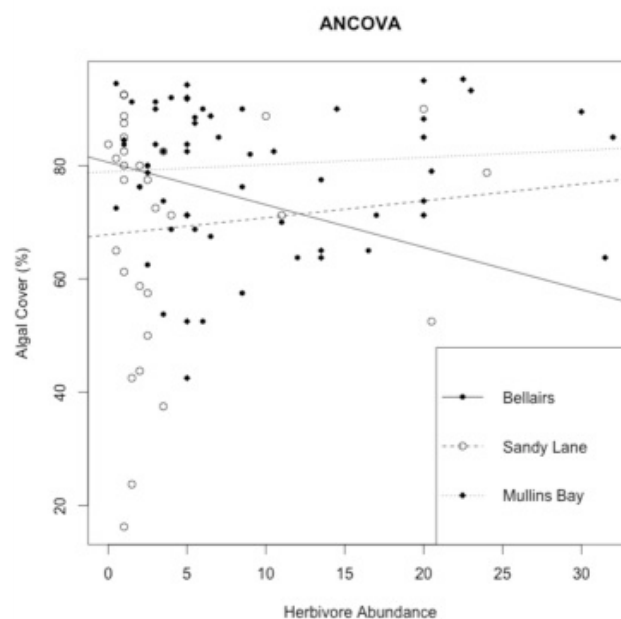

Fig. 3. Results of the ANCOVA – Reef (REEF) was used as the grouping variable and is dimensionless. Herbivore abundance (HAB) was used as the continuous predictor and is in units of individual fish. Algal cover (ALCO) was used as the response variable and was recorded as a percentage.

Conductive Value Analysis

The highest mean conductivity, 56163 μS/cm, was found at Sandy Lane, while the lowest was recorded at Folkestone Marine Reserve, which had a conductivity value of 56163 μS/cm. Mullins Bay had an intermediate conductivity value of 56455 μS/cm. Important drops in conductivity were observed in front of the Bellairs Research Institute (located near the shore where the Folkstone reef is found), before the reef at Mullins Bay and 20 meters after the start of the reef at Sandy Lane (Fig. 4).

Discussion

While a negative relationship between scarid and acanthurid abundance and algal cover has been observed and confirmed in previous studies (12, 16) (Table 2), only the relationship between acanthurid abundance and algal cover in the Folkstone Marine Reserve was found to be significant ($P<0.05$). No inferences can therefore be made from our data concerning whether acanthurids or scarids had a more significant impact on algal cover, as neither were found to have a strong impact. From the linear regression analysis performed, we saw that herbivore abundance does not affect algal cover, irrespective of the reef analyzed.

We interpret dips in conductivity values as marking sources of groundwater input into the reef. In our study, we found groundwater input sources near each of our three reefs, with the most significant being that found in the Folkestone Marine Reserve. Since it is likely that the nutrient levels within the groundwater inputs at all three sites are comparable, it can be said that the Folkestone Marine Reserve receives the highest amount of

Fig. 4. (A) Folkstone Marine Reserve conductivity measurements. The red boxes indicate position of landmarks relative to the conductivity measurements.(B) Sandy Lane conductivity measurements recorded along the beach. The zero point represents the starting point of the reef, and the negative values before it indicate groundwater measurements taken north of the reef. (C) Mullins Bay conductivity measurements recorded along the beach.

nutrient input via groundwater discharge.

It is important to take into account the limitations of our data arising from the limited time of our study and the small sample size. Due to time constraints, we only analyzed a small number of reefs and transects at each reef. The small sample size reduces the power of the statistical tests used, making it harder to make any inference about our data. Furthermore, multiple factors affected the process of data collection. For example, fish counts as well as algal cover measurements, could be affected by differing abilities among researchers to correctly identify fish families and algae. The researchers in our study had limited experience in identifying fish prior to this experiment. While the observers usually made similar fish counts in this study, additional experience in fish identification would likely have decreased the frequency of divergent results between individuals. These factors may have resulted in higher variance across replicates, reducing the significance of our data. Further studies could therefore be done with greater replication in the number of sites and transects, and additional training given to the people collecting data, both of which would act to reduce the limitations of our data

Despite seeing a direct impact of herbivorous fish on algal cover in the form of grazing marks, we found in our analysis that there is no significant correlation between the abundance of said fish and algal cover. This suggests that herbivorous fish do not have a significant effect on algal growth in the coral reef ecosystems of Western Barbados. However, other factors may be responsible for algal covers that were not addressed in our experiment.

Some other factors that were not assessed but observed and could therefore be influential were: *(1)* the presence of *Diadema* in certain reefs; *(2)* biological interactions between fish; and *(3)* varying structural complexity of our study reefs. Many reefs across the Caribbean have yet to recover their *Diadema* populations. (9) We noticed higher numbers of *Diadema* on the Sandy Lane and Mullins Bay reefs than in Folkstone Marine Reserve reefs. Thus, *Diadema* grazing could be replacing the low grazing of scarids in Sandy Lane and Mullins Bay. In addition, interactions between fish that were not accounted for in our analysis may have had an impact on the data we collected. For example, damselfish (*Pomacentridae*) are territorial, and attack other fishes entering their territories. (10) This behavior may have contributed to lower scarid and acanthurid sightings; however, we did not assess the presence of damselfish across sites in this study. Finally, structural complexity has been documented as positively affecting coral reef fish population density and species richness. (11) The variation in topography across sites could not only have contributed to varying fish abundances, but also affected our range of visibility. Furthermore, differences in topography may also have caused a variation in our estimates of algal cover across the different sites, with a flat reef surface being much easier to visualize than a quadrat placed on a more uneven surface, for example.

We interpreted all of the scarids and acanthurids as being equivalent but there are various reasons why that might not have been a valid assumption, since both groups are of different sizes and display different feeding behaviors. Firstly, roughly one third of the scarids observed were found to be larger than the observed acanthurids. The relationship between scarid size and volume of algae consumed was found to be roughly curvilinear, with larger fish consuming more algae. (12) Intuitively, it makes sense that a similar relationship between fish size and algal biomass consumed exists across all herbivores. It is then reasonable to assume that scarids should not be considered equivalent grazers to acanthurids. Larger scarids have also been shown to make deeper grazing marks and therefore change both the algal cover and the underlying substratum resulting in new colonization sites on the reef. (12) This implies that the larger scarids may play a more significant role in the reduction of algal cover and subsequent resurgence of coral than the acanthurids and smaller scarids. We recommend that further studies investigating the effect of herbivore abundance on algal cover should carefully record scarid size and account for it in the analysis.

While we predicted that herbivore abundance would significantly affect algal cover, other ecological elements, such as eutrophication, may be used to help explain the variation of our results from those hypothesized. Eutrophication has been shown to contribute significantly to high algal cov-
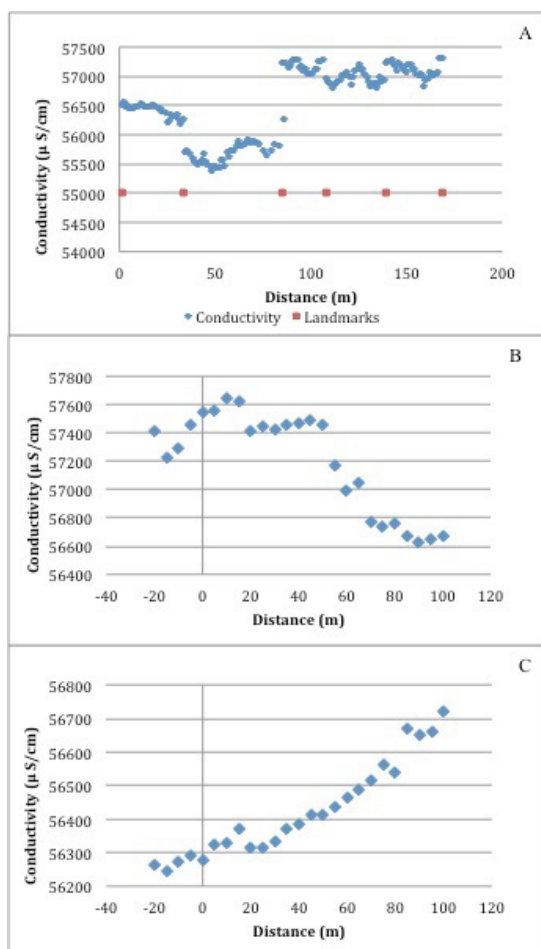
er. (13) Therefore, it is possible that the nutrient input from groundwater seepage is impacting the growth of algae in the coral reefs that we examined, thereby accounting in part for the high algal cover across our three chosen sites and potentially overshadowing the effect of herbivorous grazing on algal growth. While we did not directly measure nutrient concentrations, our conductivity data indicated the presence of a large amount of groundwater input, which may have affected levels of algal cover. This relationship is consistent with previous research on the bottom-up effect of eutrophication on algal growth in coral reef ecosystems. Studies have determined that nutrient input has a strong effect on algal cover, both in Barbados as well as worldwide. (14) However, it is important to note that groundwater input is directly related to tidal level, as can be seen in our study of Folkestone Marine Reserve conductivity. (15) Consequently, our results could have been influenced by the variance in sampling time in relation to the closest high tide across sites. We attempted to account for this since we observed a clear difference, but in order to avoid possibly over or under-compensating for this factor, salinity and conductivity values should be taken at the same time at all sites.

Conclusion

While our data does not indicate a strong relationship between algal cover and herbivorous fish abundance, many previous studies do demonstrate that a negative relationship exists between the two. It is therefore important to conduct a similar study with greater replication both within and across sites in order to foster a greater understanding of the relationship between herbivory and algal cover in Western Barbados. This additional knowledge of the importance of the role of herbivorous fish in Barbados could be used to support more ecological fishing regulations (i.e. restrictions on fishing of large scarids). However, in the scientific community, there remains a debate over whether the top-down effects of herbivory on algal growth are significant in comparison to the bottom-up effects of eutrophication. (14) Thus, further studies should be performed to quantify the amount of groundwater seepage, its nutrient composition, and its effect on algal growth. The results of this research would then demonstrate the importance of limiting groundwater discharge and pollution in Barbados. Coral reef ecosystems worldwide are expected to face further threats from such coastal development and climate change over the next few decades. It is thus crucial for conservation efforts that we understand these mechanisms behind algal regulation to prevent coral loss and algal dominance in the future.

Acknowledgements

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