The Codrington Lagoon Project, Barbuda, Antigua and Barbuda.

Investigating environmental parameters in the Codrington Lagoon with a focus on the fringing mangrove ecosystem.

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Section 1

Factors affecting the geographical distribution of commercially important reef fish in Codrington lagoon.

Abstract

There has been a rise in concern for the health of the global ocean and its biota as a consequence of the demand for food resources and the anthropogenic threat to this essential ecosystem. Scientific research is required into what constitutes a productive nursery, how nurseries can be managed viably and what factors improve juvenile fish abundance to provide sustainable fisheries for human consumption. This dissertation presents two factors - mangroves and substratum plant cover - associated with fish nurseries within a tropical lagoon, and shows how individual species within these two factors harbour different fish assemblages and interact with each other, demonstrating the harbouring potential for juvenile fish populations. There is a secondary emphasis on migratory patterns of commerically important fish and comparison of biodiversity between polluted and non-polluted sites within the lagoon. Results showed that the lagoon, mangroves and substratum plant cover provide areas for feeding, spawning and shelter of commercially important fish in Barbuda. There are no differences in the harbouring potential of juvenile fish between *R.mangle* and *L.racemosa* despite contrasts in mangal density. *R.mangle* and unpolluted sites have higher biodiversity than *L.racemosa* and polluted sites. Cuffy creek is an essential pathway for spawning and feeding of commercially important fish. Conserving the lagoon's habitat mosaic is essential for a sustainable fishery.

Results

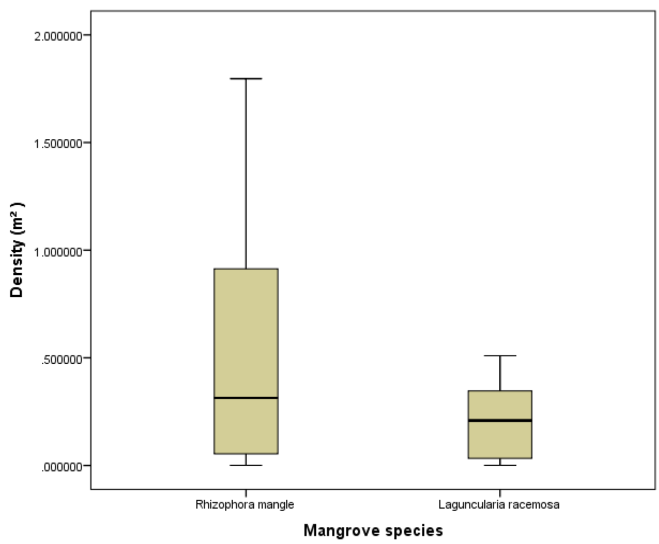

Figure 1: Box plot showing the range of densities of mangrove species.

Figure 1 shows that *R. mangle* has a greater range of densities and there is a higher variability as shown by the error bars. Meanwhile, *L. racemosa* has a smaller range and less variability amongst the values of density. In order to test if the difference of these densities for the mangrove species were statistically significant and not just through random sampling, an independent t-test was conducted.

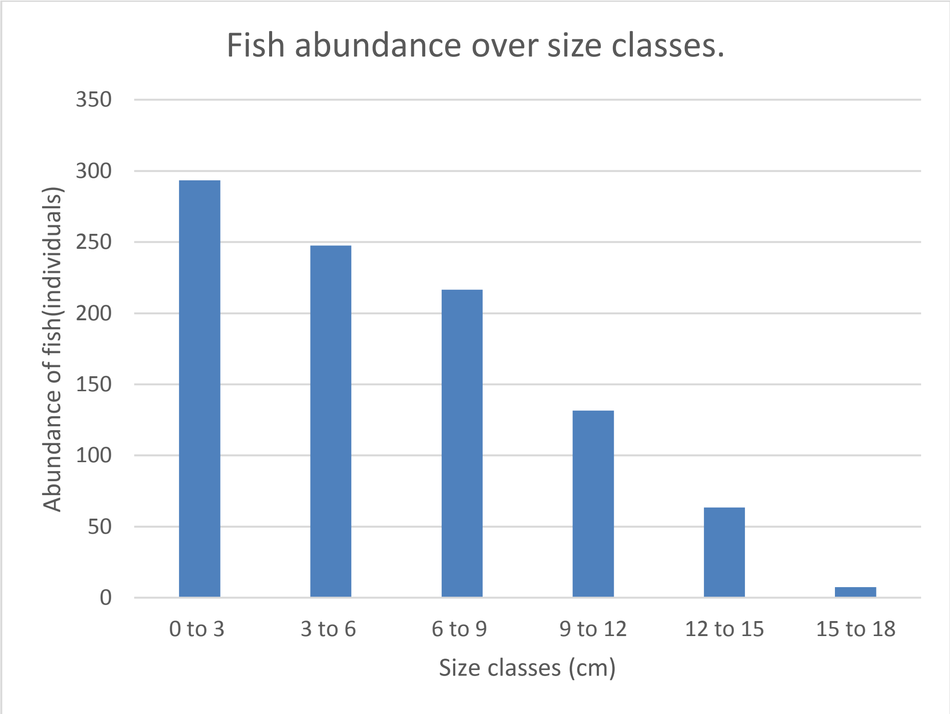

Figure 2: Fish abundance at each size class (truncated species).

Figure 2 shows the distribution of the shorter species of fish over all of the size classes that were found. The relationship between abundance and size class appears to be a negative one. As size class increases, abundance of fish decreases (shown by red line).The distribution of the abundance of fish was skewed towards the smaller size classes (0-6 cm), whilst the size classes that may be considered to be adult fish (12-18 cm) were low in abundance.

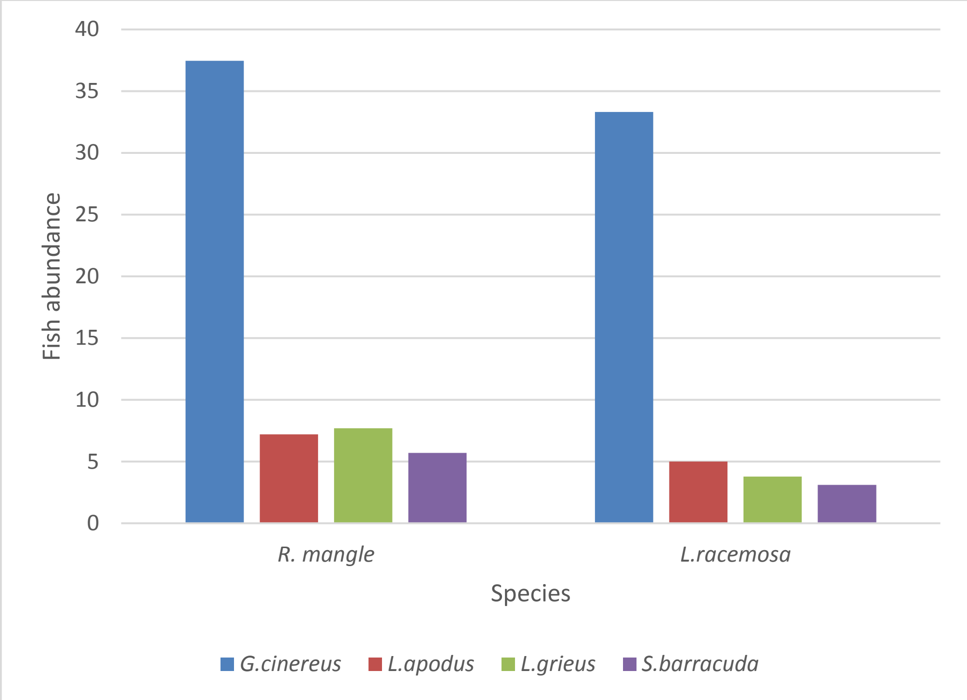

Figure 3: Fish abundance for *R.mangle* vs *L.racemosa*.

Figure 8 presents fish abundance of the target species identified in Table 6 over both of the mangrove species. *R.mangle* has a greater abundance of each fish species than *L.racemosa*. There are some similar patterns in the distribution of abundance of each fish species also. These similarities include the dominance of *G.cinereus*; the species least commonly observed is *S.barracuda.*There are also dissimilarities of the fish assemblage over each mangrove; *L.apodus* has lower abundance in *R.mangle* than *L.grieus* whereas in *L.racemosa*, *L.apodus* is higher.

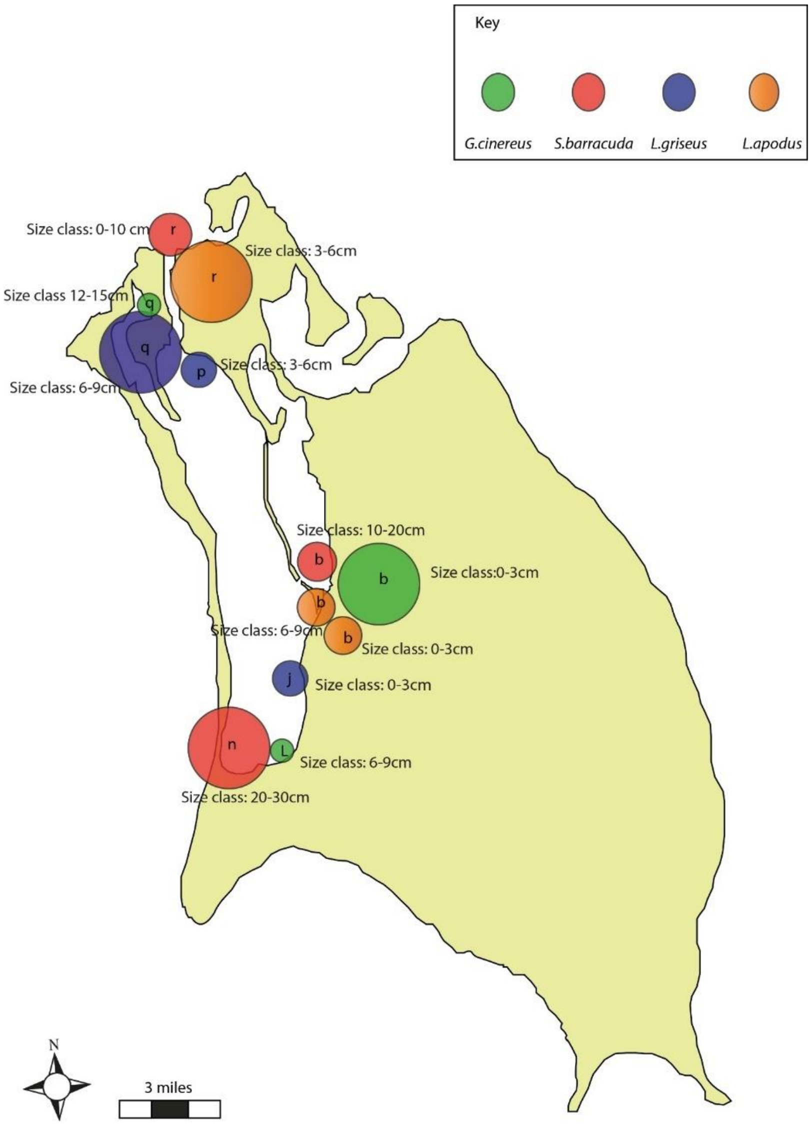

Figure 4: Target species' distribution across Barbuda's lagoon.

Figure 4 shows that there are a number of sites which appear to harbour the highest number of individuals at that size class. For example site B, located closed to Ratta wharf area harboured four size classes of the target species. Two of these being the smallest size class whilst one were the median size class and the other the largest size class. There is also a grouping of the circles at Cuffy creek, the channel that leads to the open ocean. Sites R, Q and P tend to harbour the median and largest size classes, with 1 out of 5 of these being the smallest size class. *L.griesus, G.cinerus* and *L.apodus* appear to begin their life cycle within the lagoon, two of the four at site B. These three species then appear to migrate towards the channel in order to leave the lagoon for the open ocean. *S.barracuda* however begins its life cycle at site R, before migrating into the lagoon; this may be for reducing its own predation, and also the potential of prey. These hypothetical migratory patterns are shown below in Figure 15.

Discussion and Conclusion

The sampling of the lagoon showed that there were higher quantities of *R.mangle* than *L.racemosa* within the wetlands in Barbuda. This resembles the idea proposed by West (1956) that *R.mangle* is tolerable to wetter swamp conditions and a wider salinity range than *L.racemosa*.

Results showed that the smallest size class had the greatest number of individuals. The trend is evidence of the nursery role that mangrove-lined lagoons provide for juvenile fish (Mumby et al., 2004; Dahlgren et al., 2006). The larger size classes also contained individuals and this may be a sign of adult fish returning to the lagoon to feed or spawn (Burton, 2001) and is indicative of the homing mechanism described by Huijbers et al., (2012).

Elongated species such as *S.barracuda* and *M.atlanticus* showed a tendency for the median size class to be more abundant, this may be an indicator of this fish being in a higher place in the trophic web (Chivers et al., 2014). This is because there is an important food source provided by the juvenile species within the lagoon.

The comparison between sites in section 4.3.1 that were dominated by *R.mangle* and those dominated by *L.racemosa* yielded important results. The combination of indicators used showed that *R.mangle* had a greater biodiversity than *L.racemosa*. This difference may be due to the difference in densities of the mangals that occurred: denser prop roots and stems that are more structurally complex may reduce predator efficiency by impeding movement or restricting predator vision (Huxham, 2004). The difference could also be attributed to chance, that a particularly high quantity of fish were observed during a certain day, although this is unlikely as two surveys were conducted on different days. It could also be attributed to the random selection of sites as a comparison for the rank-abundance plots. The sites for the *R.mangle* included site B which had the greatest number of individuals (see appendix E) which would have swayed the biodiversity measurements.

Historically Barbudans have relied on fish as a major constituent of their diet, and from a young age children are encouraged to fish for their own food in the lagoon for 'Silver' (*Gerres cinereus*), an easily caught and edible fish. The Barbudan population of approximately 1700 are supported by a fleet of 43 active fishing vessels, most of which are small skiffs with single outboard-motors for artisanal fishing families (Charles, 2014). Some people sell their catch within the community or to the hotels and others catch and export Spiny Lobster (*Panulirus argus)* commercially to other Caribbean islands. Fishing is often the sole source of income for most families on the island where there is limited alternative employment. Socio-economic issues contribute to this; lack of opportunity, isolation, political differences between Antigua and Barbuda and the overburdened Barbuda Council, which employs 75% of the population and is currently 21 weeks in payment arrears to its workforce (Malone, 2014).

In recent years Barbuda has been subject to Illegal, Unreported and Unregulated fishing (IUU) which has become more prevalent, with fishers from Dominica and Antigua who have more sophisticated equipment extracting fish in waters that are under the jurisdiction of the Barbuda Council. Section 4 of the 1959 by-law requires those acquiring fish within 1 maritime league (3.15 miles off the Barbudan coast) must obtain a permit. The Waitt Foundation (see appendix A) came to the government of Antigua and Barbuda in 2012 and began a consultation programme over two years that assessed Barbuda's fisheries. As a consequence of this the Blue Halo initiative (Blue Halo Initiative, 2013) has enforced a permanent 'no-fish' zone (appendix B) within the lagoon and established five marine sanctuaries around the island (see figure 16). Although these measures collectively protect 33% (139 km^2) of the coastal area, in spite of the consultation they have been met with concern by the fishing community. In order to restore the coral reefs to healthy status, catching parrotfish and sea urchins has been completely prohibited, as these herbivores are essential to lowering algae levels on reefs so coral can thrive and grow, however there has been no focus on the mangrove habitat which generates these herbivores (Mumby and Hastings, 2008; Korzen et al., 2011; Barbuda Fisheries Regulations, 2014). The sanctuaries are expected to increase fish populations and allow habitats to rebuild and recover but appear to penalise the local fishing community by forcing them to travel further distances for fish.

Marine protected areas are considered to be indispensable for conserving marine life and managing fisheries, and almost every marine nation has signed a United Nations treaty with the goal of protecting 10% of the world's ocean by 2020. However for many small scale fishing communities, MPAs highlight inequality, especially if the no-fish zone is located on the doorstep of the community.

Recommendations

1. The Codrington lagoon is an essential component of fisheries within Barbuda. The factors that comprise this system are optimal for the survival and regeneration of fish to the coral reefs surrounding the island (Figure 16) that support the fishing families of Barbuda. The lagoon, mangroves and substratum plant cover provide areas for feeding, spawning and shelter of commercially important fish.

2. There is no difference in the ability of mangrove species to harbour different densities of fish: mangroves in general are a great habitat for juveniles. It is indispensable to preserve the mangrove forests used by locals for charcoal burning.

3. There is an association between sea grasses and mangrove species and their ability to harbour fish although this is not shown by statistics.

4. *R.mangle* and unpolluted sites are more biodiverse in assemblage – this is based on a selection of indicators, more research should be focused here in the style of Huxham et al., (2004).

5. 'Cuffy creek' channel is an extremely important access point for juveniles and adult fish that use it to enter the lagoon for spawning and feeding. It may be a serious issue if the current construction of a hotel (appendix L) in the area of Cedar Tree point (Figure 2) continues – as frequent boat transport affects fish migrations negatively (Becker et al., 2013).

6. There needs to be a conservation perspective adopted by the Council with the priority of protecting a mosaic of habitats instead of single nursery habitats (Kimirie et al., 2013) as both mangrove and un-vegetated sites act as feeding grounds for fishes via pelagic and benthic food pathways (Shahraki et al., 2014).

Section 2

The Application of Ostracod and Foraminifera as an assessment of water quality within a mangrove environment.

Abstract:

Due to the recent increase in human population the islands of Antigua and Barbuda are undergoing rapid environmental change. Amongst many other Caribbean islands, Barbuda is classified as an SIDS (small island developing state) and thus faces a number of common sustainable development challenges. The island currently has no centralised sewage system and therefore relies on other methods of sewage waste disposal. Excessive Nitrogen and Phosphorous within aquatic environments can be the result of increased domestic sewage and can cause environmental implications such as eutrophication. The tolerance of aquatic biota is shown to be associated with the extent of heavy metals, pollutants and other hydrological parameters, which often coincide with anthropocentric activities. The distribution and composition of aquatic species, such as Ostracod and Foraminifera, can provide an important insight into the ecological integrity of a particular environment. The application of such methods provides the potential to highlight key areas that are undergoing environmental deterioration and thereby enables decision makers to provide evidence based decision making and prioritise the location of improvement plans. Within this study various ostracod and foraminiferal assemblages within Codrington Lagoon (Barbuda) were accomplished to determine the environmental status of Codrington Lagoon and the surrounding mangrove forest. Analysis of various water quality parameters and heavy metal contaminants were assessed to define their impact on the surrounding environment. The assemblage, composition and biodiversity of the individual species were correlated against water quality variables to ascertain their relationship between water quality and the flora/fauna within the lagoon. The study revealed that: (1) Ostracod and foraminiferal assemblages are significantly correlated to heavy metal contamination. (2) Miliolids are less tolerant to pollution than *Ammonia beccarii* and *Ammonia parkinsonian* species (spp.). (3) The ostracod species *Paranesidea harpago* is more opportunistic than *Caudites* spp. And *Xestolebris* spp. And managed to colonies a moderately polluted site. (4) The overall status of the lagoon was optimal. However it is apparent that anthropocentric activities within certain areas of the lagoon are compromising the ecological integrity and it is therefore suggested that regular monitoring of the surrounding wetlands should be implemented to ensure further degradation is prevented.

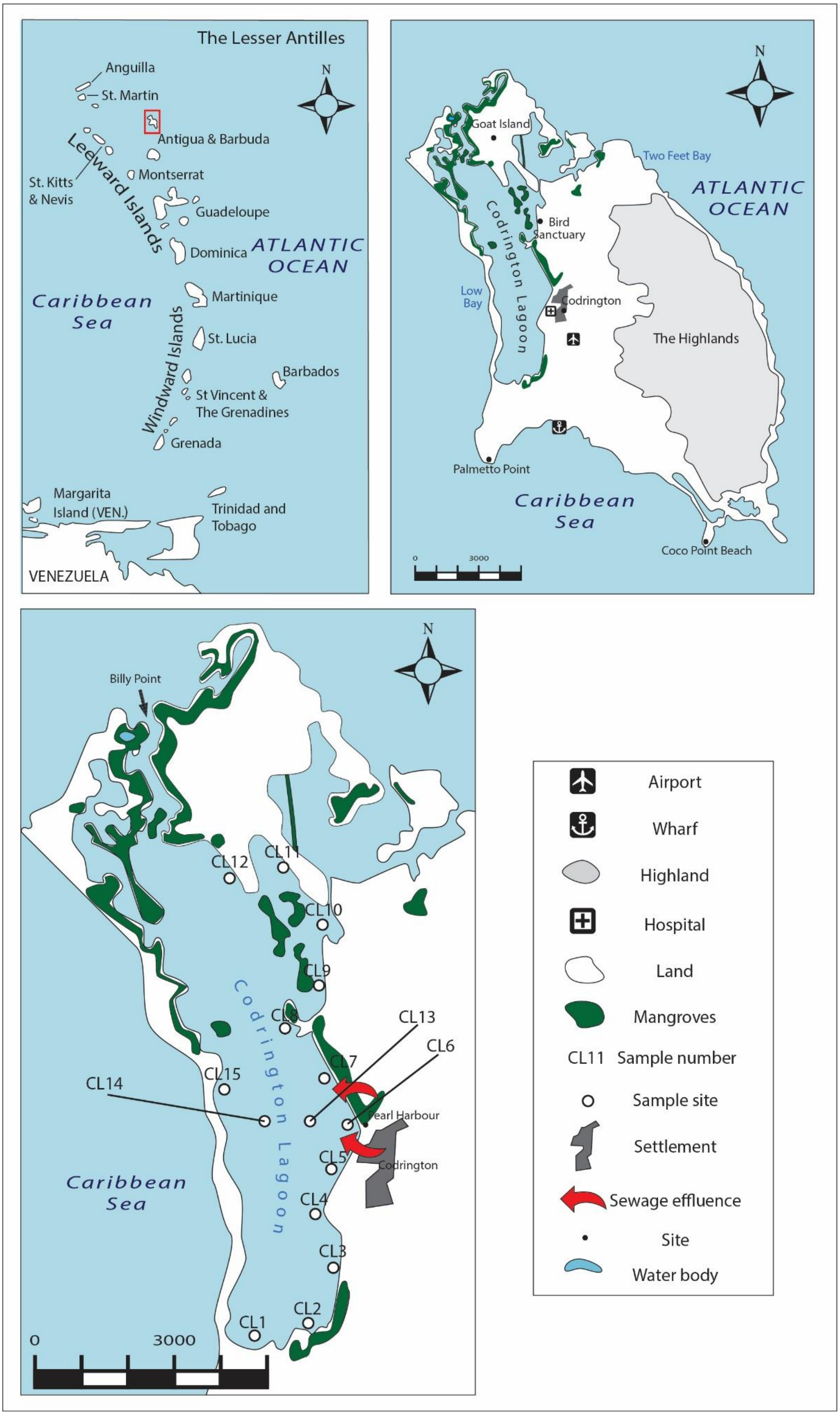

FIGURE 1. Top left – The islands which encompass the Eastern Caribbean and the Lesser Antilles. Top right – Map of Barbuda and the numerous sites situated on the island. Bottom left – An overview of Codrington Lagoon and the surrounding settlement of Codrington. Sites where samples were taken are signified by CL followed by the sample number i.e. CL1 represents the site where sample 1 was extracted. Sources of pollution are denoted by the input of effluence at site CL6 and CL7.

Water Quality Parameters	Sample														
	CL1	CL2	CL3	CL4	CL5	CL6	CL7	CL8	CL9	CL10	CL11	CL12	CL13	CL14	CL15
Salinity (‰)	42	42	40	40	40	39	36	39	38	37	37	37	39	40	40
Dissolved Oxygen (mg/l)	7.2	7.5	7.2	7.3	7.1	6.2	4.3	7	7.1	7.1	7.9	8	7	7.2	6.9
Temperature (°C)	29.0	27.5	27.1	27.2	28.0	27.4	28.3	27.6	27.4	27.5	27.1	27.3	27.5	27.1	27.9
pH	8.5	8.5	8.4	8.3	8.2	8.2	8.0	8.3	8.3	8.3	8.3	8.3	8.5	8.5	8.6
Phosphate (μ g Po_4/l)[1]	43.2	41	51.2	43.4	45.7	78.1	276.3	57	49.1	42.7	43.5	46.1	51.1	38	40
Nitrite + Nitrate (μ g N_{o4}/l)[1]	10.9	11.7	11.4	15.2	17.1	35.2	80.7	20.1	15.9	13.6	12.9	11.4	11.9	12.6	13.2

Table 1. The physio-chemical characteristics of Codrington Lagoon. Triplicate readings were collected at each site and collated with Nitrogen and Phosphorous data

Site	Contaminant (ppm)[2]				
	Pb	Cu	Cr	Zn	Cd
CL1	0	0	0	0	0
CL2	0	0	0	0	0
CL3	0	0	0	0	0
CL4	0	0	0.1	0	0
CL5	0	0	0.1	0	0
CL6	0.4	0.1	3.9	4	0.2
CL7	4.7	1.2	8.7	9.2	0.5
CL8	0.1	0	0.6	0.6	0
CL9	0	0	0.1	0	0
CL10	0	0	0.1	0	0
CL11	0	0	0	0	0
CL12	0	0	0.2	0	0
CL13	0	0	0	0	0
CL14	0	0	0.1	0	0
CL15	0	0	0	0	0

Table 2. The concentrations of selected contaminants/pollutants within the sediments of Codrington Lagoon.

	Sample Number														
	CL1	**CL2**	**CL3**	**CL4**	**CL5**	**CL6**	**CL7**	**CL8**	**CL9**	**CL10**	**CL11**	**CL12**	**CL13**	**CL14**	**CL15**
Foraminifera species															
Ammonia beccarii	0	0	3	0	3	20	107	9	6	3	0	0	0	0	0
Ammonia parkinsonia	31	48	21	21	28	20	12	12	19	21	13	25	21	25	29
Ammonia tepida	0	0	0	0	3	9	118	9	6	6	0	0	0	3	0
Archaias angulatus	16	18	12	15	11	9	1	4	9	12	20	18	19	17	26
Clavulina angularis	2	2	1	2	0	0	0	0	0	0	0	0	0	0	0
Elphidium spp.	16	23	21	33	28	49	29	26	22	15	25	16	27	16	23
Miliolinella subrotunda	24	43	39	31	41	15	2	17	28	40	38	37	29	33	42
Triloculina oblonga	28	27	31	24	10	18	1	23	36	17	30	32	25	32	30
Quinqueloculina spp.	108	127	68	99	96	76	12	28	89	94	80	87	87	82	100
Quinqueloculina subpoeyana	94	49	99	70	100	51	16	60	101	103	86	120	74	93	57
Ostracod species															
*Cauditess*pp.	6	11	0	5	0	0	0	0	0	6	0	12	0	4	3
Paranesidea harpago	6	6	12	0	0	0	0	5	0	0	12	7	0	0	0
Xestoleberis spp.	21	22	13	14	12	0	0	0	0	14	10	18	14	15	11

TABLE 3. *The counted individuals of foraminifera and ostracod within each sample. As shown, Quinqueloculina subpoeyeana and Quinqueloculina spp. dominate the lagoon in most areas with the exception of site 7 which is largely dominated by Ammonia spp. The least abundant species of foraminifera is Clavulina angularis,* a large textularid foram species, which has few individuals situated amongst various sites within the lagoon

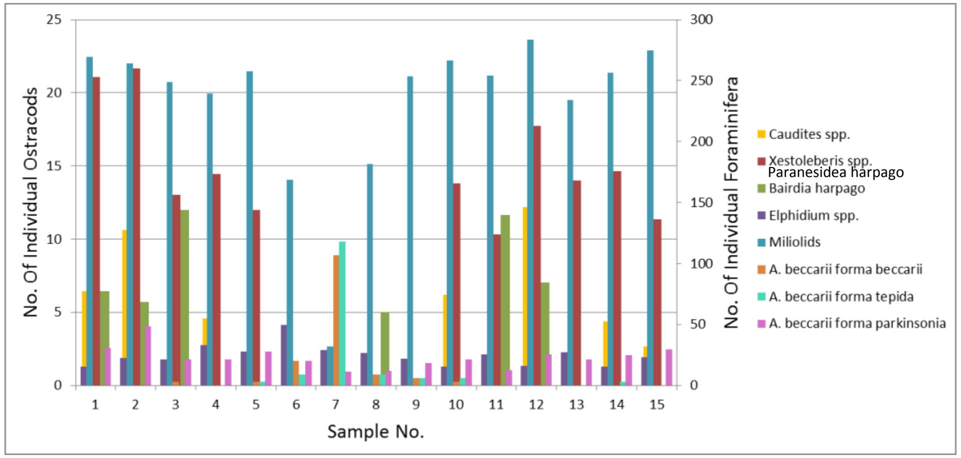

FIGURE 2. The counted individuals of foraminifera and ostracod are represented by the above graph, which displays the variation in dominant species throughout the lagoon.

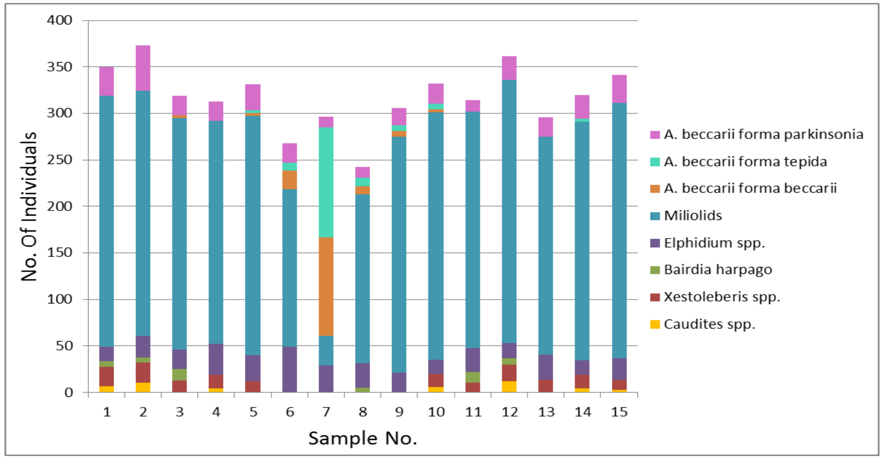

FIGURE 3. The ratio of individual species within the individual samples is demonstrated by the bar graph above.

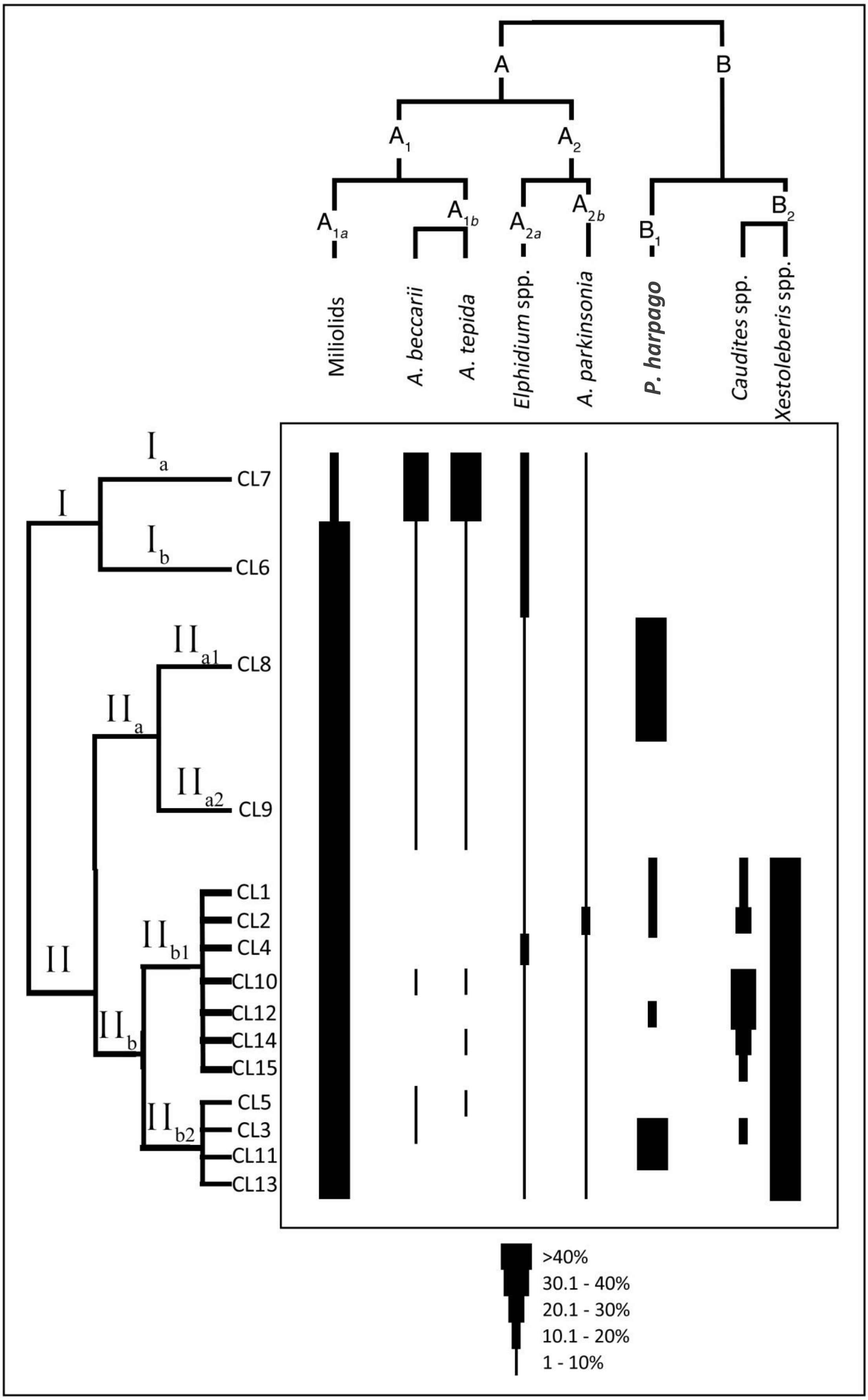

FIGURE 4. The above dendrogram image represents the various samples of the lagoon (left of the diagram) and the percentage of each species within the given samples (top of dendrogram). CL = Codrington Lagoon samples. Miliolids display continuous dominance throughout the individual sites, excluding sample 7 which is dominated by *A. tepida* and sub-dominance of *A.beccarii*. Ostracod assemblages are dominated mainly by *Xestoleberis* spp. and sub-dominated by *P. harpago*. *Caudites* spp. also show moderate frequencies throughout the lagoon, alongside *Xestoleberis* spp. this species are also non-existent in the polluted areas, including the sites situated closely to the polluted sites.

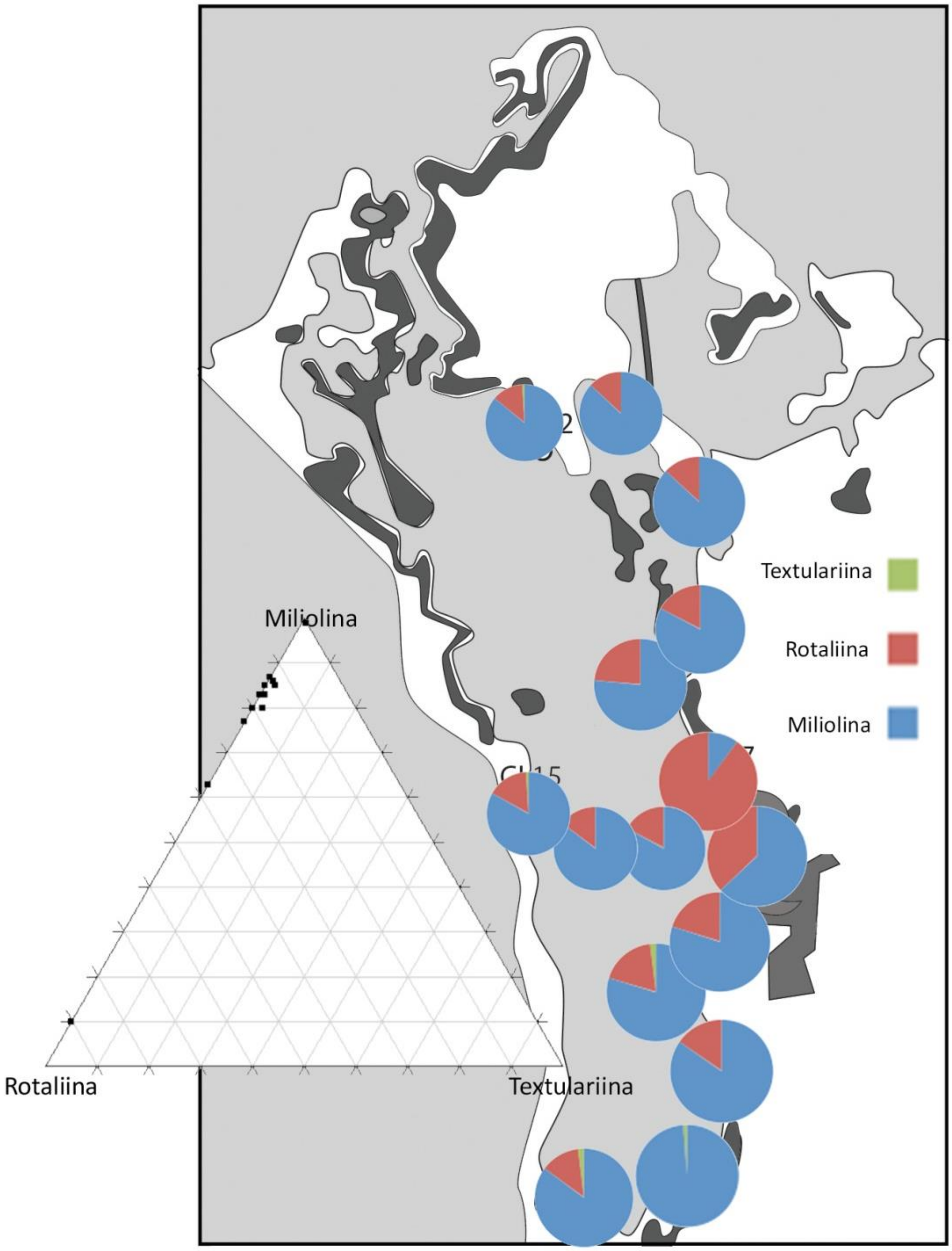

FIGURE 5. The above image comprises a triangular diagram alongside pie charts. The diagrams compare three forms of foraminifera (textularid, miliolid and rotalid) which were discovered within the sediment samples at each site. The site is dominated by miliolid foraminifera, with exemption to sample 7 which is dominated largely by rotalid species of foraminifera. Few examples of textularid foraminifera species (<1% of total individuals) are demonstrated within sites CL1, CL2, CL3 and CL4. These forms are non-existent in the remaining samples.

Variables	Salinity (‰)	Dissolved Oxygen (mg/l)	Temperature (°C)	pH	Phosphate (μ g Po4/l)	Nitrite + Nitrate (μ g No4/l)	Pb	Cu	Cr	Zn	Cd
Caudites spp.	.220	.431	.026	-.384	-.276	-.330	-.232	-.227	-.288	-.297	-.279
Xestoleberis spp.	**.524***	**.593***	.069	**-.575***	-.497	**-.599***	-.447	-.437	**-.573***	**-.571***	**-.536***
Bairdia harpago	.071	.453	-.159	-.218	-.209	-.298	-.214	-.216	-.271	-.263	-.265
Elphidium spp.	-.049	-.406	-.118	.388	.258	.412	.202	.199	.454	.451	.425
Miliolids	.430	**.915****	-.242	**-.924****	**-.925****	**-.956****	**-.899****	**-.892****	**-.944****	**-.947****	**-.931****
A. beccarii forma *beccarii*	-.492	**-.926****	.350	**.960****	**.997****	**.987****	**.992****	**.991****	**.967****	**.969****	**.973****
A. beccarii forma *tepida*	-.501	**-.901****	.364	**.933****	**.992****	**.963****	**.996****	**.995****	**.931****	**.933****	**.941****
A. beccarii forma *parkinsonia*	**.726****	.355	.170	-.383	-.400	-.419	-.364	-.356	-.386	-.384	-.362

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

TABLE 4. The correlation between foraminifera/ostracod and various water quality parameters (including both natural and anthropogenic qualities) are displayed within the above data. It is clear that the various parameters influence the assemblage and structure of both Foraminifera and Ostracoda. However, it should also be made apparent that the species of both ostracod and foraminfera respond contrarily to one another; *Xestoleberis* spp. for example are significantly inversely correlated to most natural parameters and also heavy metal pollution and contamination, perhaps signifying lower tolerance of change. Adversely, *Bairdia harpago* demonstrates a lower correlation to all water quality parameters perhaps signifying a greater degree of tolerance and/or opportunistic traits for this particular species. Foraminifera show also show a varying degree of response and correlation to the various pollutants/paramters. The Miliolid species within all samples show a highly negative correlation between individual abundance and the presence of heavy metals. Alternatively, *A. beccarii* and *A. tepida* are significantly positively correlated to all heavy metals and excess organic pollutants within each sample. The results above signify that *A. beccarii* are most tolerable to stressed conditions and would therefore inhabit and dominate the polluted sites within Codrington Lagoon. This adverse reaction to each variable signifies differences within the varying species of foraminifera.

Summary and Conclusions

The environmental status of Codrington Lagoon and the surrounding mangrove forests was established thoroughly assessing the assemblage, composition and diversity of ostracod and foraminifera within the lagoon. Certain sites within the lagoon (site CL6 and CL7) were shown to attain elevated levels when compared to the remaining sites. Various water quality parameters (salinity, temperature, phosphorous, nitrate etc.) and heavy metal contaminants (Pb, Zn, Cd, Cr and Cu) were therefore evaluated to define their influence on the surrounding environment. Based on various qualitative and quantitative methods, the following conclusions were presumed:

1. The presence of heavy metals has a greater impact upon the assemblage of foraminifera and ostracod, in comparison to the effects from natural water quality parameters. Most species were therefore negatively correlated against the individual heavy metal pollutants, with the exception of *A. beccarii* and *A. tepida* which generally shown a positive correlation with most heavy metal contaminants.
2. The variability and composition of foraminifera and ostracod are consequently affected along the pollution gradient. Milliolids are seen to dominate throughout the non-polluted sites, whereas *Ammonia* species are dominant throughout the more polluted areas (excluding *A. parkinsonian*).
3. *Quinqueloculina* spp. was the most dominant species of foraminifera throughout the lagoon. Nevertheless, this species was unable to occupy polluted areas of the lagoon. This also applied to *Xestoleberis* spp. which was the most dominant ostracod species but was also unable to colonise the polluted regions.
4. Overall the lagoon does provide a stable habitat for the marine flora and fauna. However, sites such as Pearl Harbour and The Jetty situated close to Codrington Village should be regularly monitored to avoid further contamination and degradation of the mangrove forest. Proposed development along the Frigate Bird Sanctuary should also be regulated and assessed to ensure the condition of the lagoon is optimum.
5. ‘Dumping’ of sewage and waste should be prohibited amongst all regions of the along and the region may benefit from the implementation of a sewage treatment network to reduce the amount of organic pollutants within the lagoon.

Section 3

Assessing Mangrove Carbon Storage for Conservation Management Scheme in Barbuda.

Mangrove forests are greatly threatened worldwide, and their loss could potentially impact their functioning and significant carbon stocks. There is currently a lack of broad-scale knowledge on the amount of carbon stored in the ecosystem (Donato *et al*., 2011), hence an accurate quantification of the current status of carbon stocks is necessary for suitable conservation management schemes that prevent the degradation and CO_2 emissions of this carbon-rich ecosystem.

This study assessed the amount of above and belowground carbon within an unstudied environment of degraded and pristine lagoons, and their distinct environmental parameters of water pH, water salinity, and air temperature, as well as species composition and soil decomposition for management schemes in Barbuda **Figure 1**.

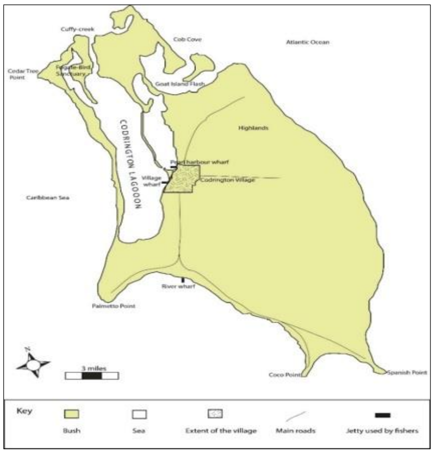

Figure 1: Map of Barbuda, located on the Leeward islands, Caribbean.

The results showed a minor variance between the environmental parameters of all lagoons, yet were within an appropriate range for ecosystem functioning **Table 1**.

Table 1: Mean and Standard Error of the mean of Water Salinity, Air Temperature, and pH in Lagoons.

		Water Salinity (%)		Temperature (ºC)		Water pH	
		Mean	SE Mean	Mean	SE Mean	Mean	SE Mean
Degraded	Lagoon 1	16.2	1.84	29.5	0.89	7.1	0.08
	Lagoon 2	18.2	0.31	30.3	0.78	6.9	0.06
Pristine	Lagoon 3	15.0	0.00	28.1	0.90	6.8	0.07
	Lagoon 4	17.5	1.00	27.9	0.85	7.2	0.08

Rhizophora mangle was the most dominant species in all lagoons (77%), followed by *Laguncularia racemosa* (21.6%). A third species, *Avicennia germinans* was only identified in Lagoon 2 (degraded) **Figure 2**.

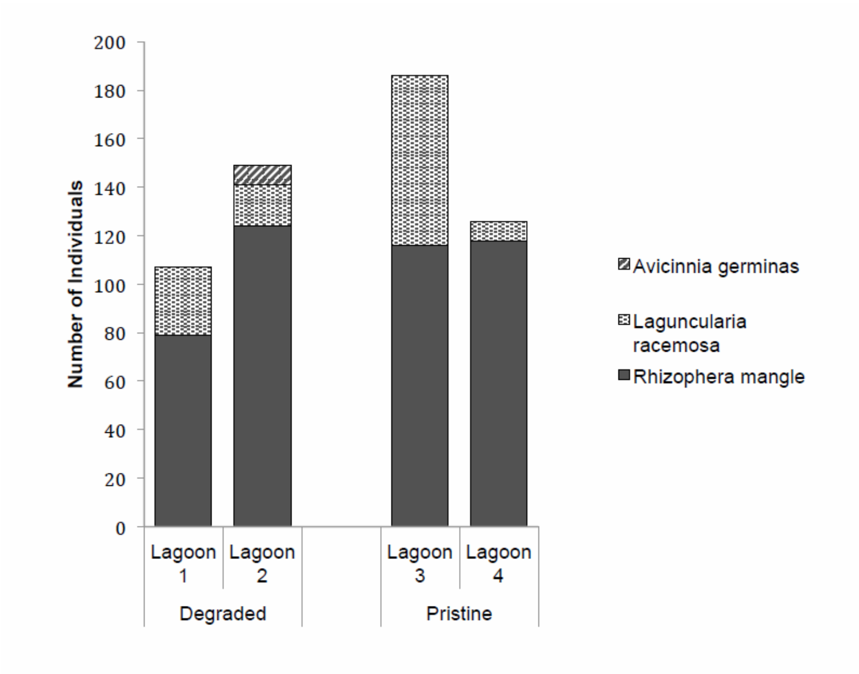

Figure 2: Mangrove species composition in Barbuda.

Heights and diameter at breast heights (DBH) of all species were significantly different in all lagoons ($p < 0.05$), and were greater in pristine lagoons. The below ground carbon stock was much greater than aboveground stock in lagoons, yet both were again greater in pristine lagoons. However, degraded Lagoon 2 contained the greatest C t ha_{-1} (60.76 ± 6.46), resulting in the total carbon in all lagoons being 116,720.18 t C **Figure 3**.

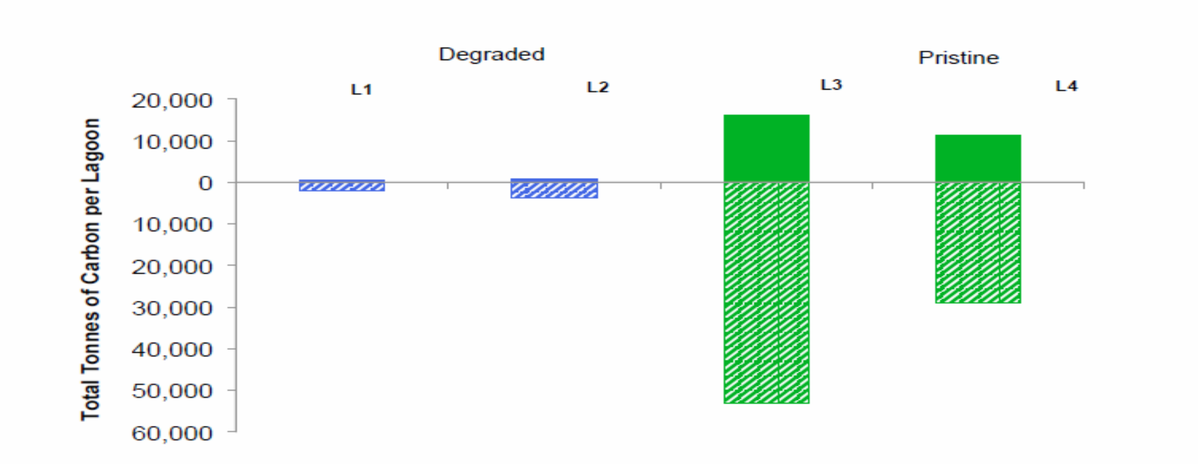

Figure 3: Above and belowground carbon (tC) in degraded and pristine lagoons in Barbuda.

It can be concluded that degraded lagoons contained a smaller carbon stock than pristine lagoons, and the reasons why it is so should be addressed in the future, yet the total amount of carbon in the lagoon ecosystem and its carbon credit value using REDD+ is outstanding at £875,401.35. Therefore management schemes to conserve and protect the mangroves in Barbuda from future development should be implemented.