The impact of human activity on sedimentary stored carbon levels within a mangrove forest

by

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Abstract

The objectives of this study were to examine the impact of human activity on organic content levels in mangrove sediment. Sediment samples and forest structure data from four sites in Utila, Honduras ranging in degradation levels were recorded and analyzed. Results indicated that forest structure differences are likely influenced more by environmental factors and setting differences than by human impacts and degradation. Additionally, the sediment from the most impacted sites had the greatest levels of organic content, while sediment from the least impacted, marine protected area, had a significantly lower average organic content level. These findings have noteworthy implications for conservation, as the sites that are being dredged and cleared are also those with the highest organic content levels. Ultimately, the findings of this study suggest an urgent need for the conservation of sites that have previously been overlooked and continuously degraded.

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Introduction

Mangrove forests are one of the most carbon rich forests in the world (Donato et al. 2011). Over the past several decades, scientific knowledge of these forests has increased tremendously. Despite their significance as one of the most carbon rich forests in the world, mangroves remain a relatively understudied topic in terms of their role in carbon storage. Mangrove degradation and the clearing of these habitats is a problem worldwide (Granek and Ruttenberg 2008, Alongi 2002), and many ramifications of the degradation of mangroves are still being discovered. Due to the rising atmospheric carbon levels, the role of mangrove forests in carbon sequestration is of heightened attention. Numerous studies have been published within the past decade attempting to improve what is known about their role as a carbon sink. A complicating factor in current knowledge of this topic, however, is the fact that within published findings there are methodological discrepancies that make interpreting available data difficult (DelVecchia et al. 2013).

Deforestation and land-use change are two of the main causal agents in the global rise in atmospheric carbon, second only to fossil fuel use (Sabine et al. 2004). Wetland ecosystems such as salt marshes and mangrove ecosystems play a vital role in the process of carbon sequestration (Whiting and Chanton 2001). Similar to terrestrial forests, deforestation is one of the main threats to mangrove forests.

Unlike terrestrial forests, mangrove forests store the majority of their carbon in their sediment (Kristensen et al. 2008). This study seeks to assess and examine the carbon content of the surface sediment within four sites that vary in terms of human impact, on the island of Utila, Honduras. Utila is one of the Bay Islands off of the Caribbean coast of Honduras. It houses a community that has traditionally relied on the fishing industry for commercial revenue, but recently has seen a shift to a tourism-based economy (Hogg et al. 2012, Korda et al. 2008). The vast majority of visitors to this island travel there to dive in the Meso-American Reef as well as to dive with the whale sharks that frequent the area seasonally (Graham 2007, Korda et al. 2008). Conserving mangroves is necessary to help maintain the influx of divers, as mangroves are vital in maintaining the health of the surrounding coral reef. Yet with increasing revenue from tourism, there is increased mangrove clearing for infrastructure construction.

The overall objective of this study is to assess the effects of human activities on organic content levels in mangrove forests. More specifically, this study aims to determine if human activity directly impacts the overall forest structure of these ecosystems, and therefore, indirectly impacts organic content levels. Organic carbon comprises a large portion of organic content, and the process of storing of organic carbon in soils is known as soil carbon sequestration (Chan 2008). If more carbon is stored in the sediment as organic content, this will decrease the amount of carbon being added to the atmosphere (Chan 2008). If human activities are significantly impacting carbon sequestration rates in mangrove forests, this will have negative repercussions on atmospheric carbon levels—especially when applied to a global scale.

Four sites are used in this study ranging from most impacted to least impacted. The objective is to identify any primary differences that occur between these sites that may be indicative of the organic content levels. It is predicted that human activities will have a negative impact on the overall forest structure as well as organic content levels. It is hypothesized that the more pristine sites will have greater amounts of organic content than the other, more disturbed sites.

Methods

<u>Study Site</u>

This study took place at four sites on the island of Utila, Honduras during an Operation Wallacea expedition in the summer of 2013.

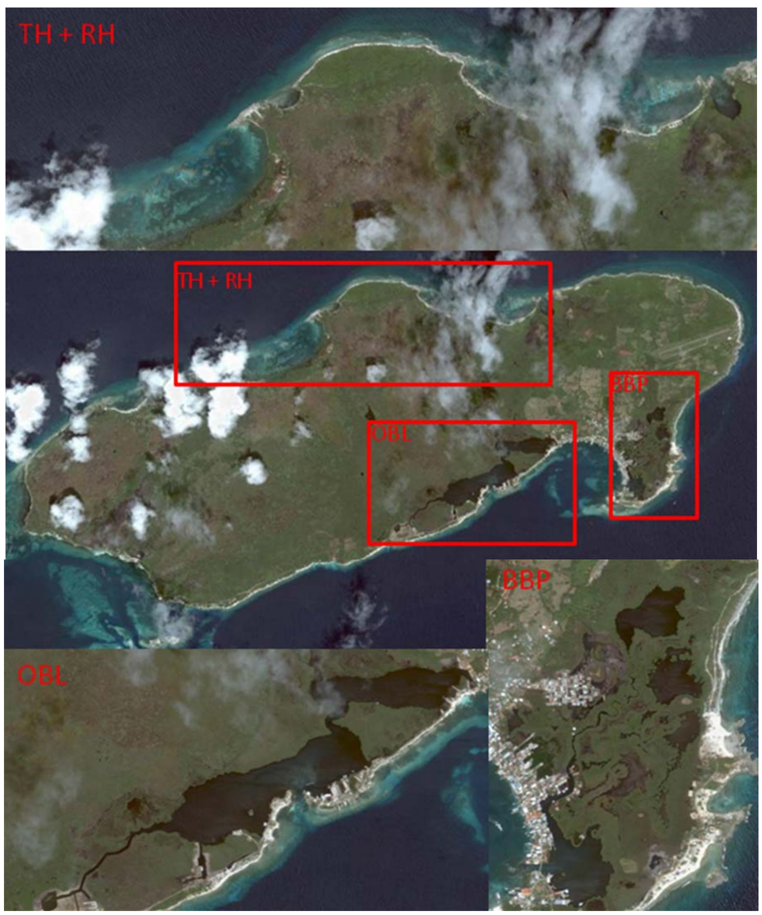

Figure 1: (Exton 2009) The four study sites on the island of Utila, Honduras labeled BBP (Big Bite Pond), OBL (Oyster Bed Lagoon), RH (Rock Harbor), and TH (Turtle Harbor).

Each site ranged in its level of degradation. Site 1 (Big Bite Pond) and Site 2 (Oyster Bed Lagoon) are located on the southern region of the island, which has experienced significant amounts of development with the rising levels of tourism from the dive industry. Site 3 (Rock Harbor) and Site 4 (Turtle Harbor) are located on the northern shore of the island. Boat is the most feasible method of transportation to access these sites, and takes about an hour to reach from the town depending on conditions. Crossing the island by land is impractical due to the fact that there are no roads in this region and a large pond/swamp region creates impractical hiking conditions. Turtle Harbor, Site 4, is located within a marine protected area that is off limits to all except permitted researchers. Rock Harbor, Site 3, also remains undisturbed despite its lack of protection. As the latter two of all of the sites are the furthest from any human activity, they are considered the most pristine sites. Table 1 further details these sites.

Table 1: Site descriptions and details

Site	Proximity (km)[a]	Ease of Access[b]	Protected (Yes or No)[c]	Human Impact	Overall Ranking
Big Bite Pond (BB)	0.35	1	No	Sediment erosion and high levels of organic pollution from untreated waste and mangrove clearing. Close proximity to the "slums"[d]	Most Impacted
Oyster Bed Lagoon (OB)	1.5	2	No	High levels of physical destruction from dredging of lagoons for hotel projects	Medium Impacted
Rock Harbor (RH)	2.5	3	No	Relatively undisturbed, but littered with trash from tides	Low Impacted
Turtle Harbor (TH)	4	4	Yes	Little to no impact from development--off limits to all except permitted researchers, also littered with trash from tides	Least Impacted

[a] Proximity: the direct measured distance (straight-line route) from the town center to the site measured on a map. Proximity does not take into account any obstacles (i.e., swamps or bodies of water).
[b] Ease of access: takes into account the distance to the site as well as any obstacles that may create difficulty in reaching the site (i.e., swamps that need to be avoided or bodies of water). The ranking ranges from most accessible (1) to least accessible (4).
[c] Protected: whether or not the site is considered a marine protected area
[d] Slums – "urban development" – Limited or no waste removal. These slums formed as a result of the inflow of mainland Hondurans moving to Utila to find work in the tourism industry.

Big Bite Pond is the most heavily degraded site, plagued by pollution due to its close proximity to the “slums” of the community where waste goes untreated and mangroves are frequently cleared (Exton 2009). At this site, sampling was forced to end at both transects due to mangrove clearing from construction of condominiums.

Oyster Bed Lagoon is located further from the town and has been impacted in a different way than Big Bite Pond. It is impacted less by the local community and more by the building of hotels and resorts, which entails dredging of lagoons and frequent boat traffic. As a result, this site experiences less organic pollution than Big Bite Pond (Exton 2009). Physical disturbances, including dredging, are the primary threats to Oyster Bed Lagoon (Exton 2009).

Two transects were used at each site. At Big Bite Pond, Transect 1 was 200 meters and Transect 2 was 180 meters—this transect was shortened due to construction. Transects were 300 meters at Oyster Bed Lagoon, 100 meters at Rock Harbor, and 50 meters at Turtle Harbor. Each transect began at the shoreline and continued into the stand until the mangrove forest ended or transitioned into another forest type.

Data Collection

Sediment samples were collected from two transects at each site to observe below ground carbon content. Samples were collected with a push sediment corer every fifty meters, starting at the outskirts of the forest. After collection, the top two centimeters of the samples were used for analysis. The weights of the wet samples were recorded and then placed in the sun to air dry. Once dried, dry weights were recorded. The samples were then placed in a furnace at a temperature of 450° Celsius for four hours. At the end of the four hours, the samples were removed and weighed again for a final weight. Sediment Organic Content was calculated using the following equation:

$$\% \text{ Organic Content} = \frac{(Dry\ weight - Wet\ weight)}{(Dry\ weight)} \cdot (100)$$

As for determining the forest structure, data regarding tree density, species composition, and salinity were all collected. Tree density was determined using a densiometer, which measured canopy cover. Canopy cover (percent cover) measurements were recorded every ten meters along the transect line. Every ten meters, the canopy cover was measured two meters from the transect line on both sides. These two readings were then averaged to give an estimate of the percent canopy cover. Using two readings, rather than one, helped to provide a more accurate representation of the forest. As for species composition, each tree species along the transect line was recorded along with its height. Box plots (5x5 meters or 10x10 meters, depending on the site) were used along the transect lines at random intervals, within which measurements of diameter at breast height (DBH), height, and tree species were recorded for each tree. A total area of $50m^2$ or $100m^2$ was surveyed for each 50-meter section of the transects—the area of each box plot was dependent on the density of the trees. These data were used in the calculation of aboveground biomass. A salinometer was used to measure salinity—measurements were taken every two meters.

Aboveground biomass was calculated using formulas compiled from Komiyama et al. (2008). The following equations, originally from Imbert & Rollet (1989) were used to calculate the aboveground biomass for each of the corresponding species:

$$\textit{Rhizophora mangle:}\quad Wtop = .178(DBH)^{2.47}$$
$$\textit{Avicennia germinans:}\ Wtop = .0942(DBH)^{2.54}$$
$$\textit{Laguncularia racemosa:}\ Wtop = .209(DBH)^{2.24}$$

Once calculated, the biomass' for all of the trees within a boxplot was summed. Each boxplot sum was then normalized to m^2 and then averaged in order to compare sites on an area basis.

<u>Data Analysis</u>

To assess differences in organic matter content and vegetation between sites, Analysis of Variance (ANOVA) and Tukey's HSD tests were used. All analyses were performed in Minitab version 17 and considered significant at $\alpha = 0.05$. It should be noted that due to the fact that the Turtle Harbor transects were only 50 meters (mangroves ended and transitioned to mostly palm and other terrestrial vegetation), data were broken up to be analyzed from 0 to 50 meters (which included Turtle Harbor) and also 0 to 100 meters (from which Turtle Harbor was excluded). This was done to include the most data possible, in order to avoid skewing any results—as distance from the shoreline could have acted as a variable.

Results

Organic Content

The average organic content was different between sites (Fig. 2) (0 to 50 m: ANOVA; $F_{3,14}$=6.14; p=0.007; 0 to 100 m: ANOVA; $F_{2,15}$=5.38; p=0.017). Turtle Harbor had the lowest average organic content, while Oyster Bed Lagoon had the highest. Oyster Bed Lagoon had significantly higher organic content than both Rock Harbor and Turtle Harbor (Table 2). Organic content at Big Bite Pond, however, was not significantly different from any of the other sites.

Table 2: Results of Tukey HSD of Organic Content (%) of sediments from 0 to 50 meters. Sites listed from most impacted (BB) to least impacted (TH) sites. Sites that share a letter are not significantly different.

Site	N (Number of samples per site)	Mean (±SE) (%)	Tukey HSD grouping
BB	4	71.02 (1.75)	AB
OB	4	80.40 (0.82)	A
RH	4	45.89 (8.67)	B
TH	6	42.58 (7.59)	B

Table 3: Results of Tukey HSD of Organic Content (%) of sediments from 0 to 100 meters. Sites listed from most impacted (BB) to least impacted (TH). Sites that share a letter are not significantly different.

Site	N (Number of samples per site)	Mean (±SE) (%)	Tukey HSD grouping
BB	6	70.93 (1.55)	AB
OB	6	80.99 (0.66)	A
RH	6	56.91 (8.88)	B

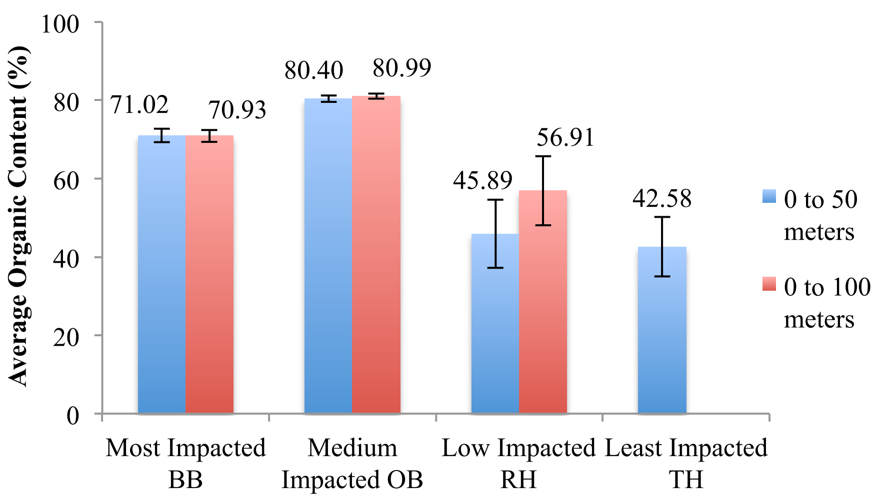

Figure 2: Results of average percent organic content of surface sediments from transects. Turtle Harbor transects end at 50 meters.

Canopy cover:

Results for canopy cover differences are shown in Figure 3, Table 4, and Table 5.

Canopy cover at Turtle Harbor was significantly higher than at Big Bite over 0 to 50 meters (0 to 50 m: ANOVA; $F_{3,44}$=3.09; p= 0.037) (Table 4, Figure 3), with almost 80% cover. Average canopy cover over 0 to 100 meters was similar at Big Bite Pond, Oyster Bed Lagoon, and Rock Harbor (0 to 100 m: ANOVA; $F_{2, 63}$=1.70; p=0.192) (Table 5). These results show that there was significant overlap in canopy cover between sites. Big Bite Pond and Turtle Harbor were the only sites with significantly different canopy cover means.

Table 4: Average percent canopy cover from 0 m to 50 m. Each site was sampled every 10 meters (starting at 0 meters and ending at 50 meters) on both of the two transects. Sites that share a letter are not significantly different.

Site	N (number of readings)	Mean (±SE) (%)	Tukey HSD grouping
BB	12	62.69 (4.07)	A
OB	12	65.98 (1.72)	AB
RH	12	65.85 (7.35)	AB
TH	12	79.98 (1.91)	B

Table 5: Average percent canopy cover from 0 m to 100 m. Each site was sampled every 10 meters (starting at 0 meters and ending at 100 meters) on both of the two transects. Sites that share a letter are not significantly different.

Site	N (number of readings)	Mean (±SE) (%)	Tukey HSD grouping
BB	22	66.46 (2.93)	A
OB	22	58.02 (2.64)	A
RH	22	65.94 (4.90)	A

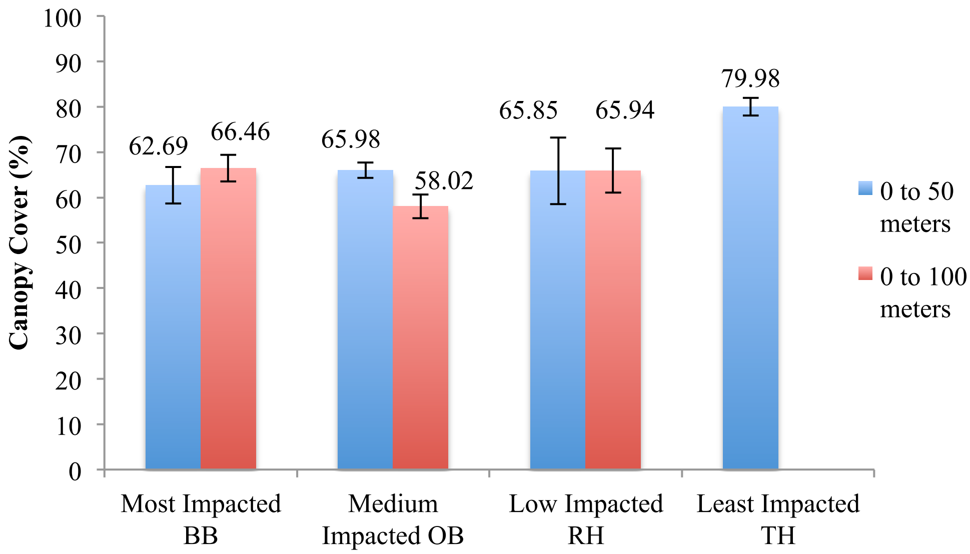

Figure 3: Average percent canopy cover for each site from both 0 to 50 meters (including Turtle Harbor) and 0 to 100 meters (excluding Turtle Harbor). Turtle Harbor transects end at 50 meters.

Number of Trees:

These results were significantly different between the number of trees between study sites (Figure 4) over the 0 to 50 meter range (0 to 50 m: ANOVA; $F_{2,4}$=7.57; p= 0.040) and over the 0 to 100 meter range (0 to 100 m: ANOVA; $F_{2,3}$=12.86; p=0.034). Oyster Bed Lagoon (OB) had significantly more trees than Turtle Harbor (TH) over 0 to 50 meters (Table 6). When analyzing 0 to 100 meters (Table 7) of the transects and excluding Turtle Harbor, significantly more trees were present in Oyster Bed Lagoon (OB) than in Rock Harbor (RH). In both the 0 to 100 meter test and the 0 to 50 meter test, Big Bite was not significantly different from any of the other sites. Oyster Bed Lagoon displayed the greatest number of trees. Additionally, results indicated a positive correlation (R^2=0.34, Figure 5) between the number of trees at a site and the percent organic content.

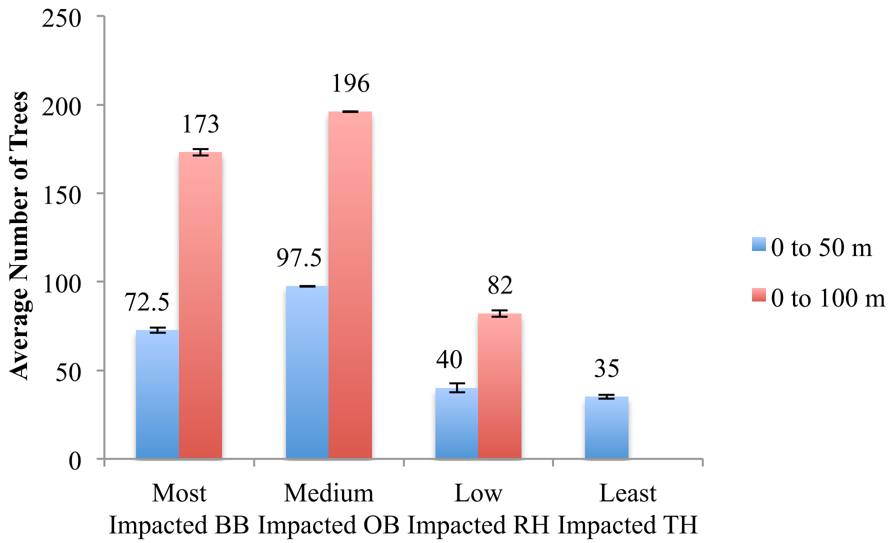

Fig 4: Average number of trees per transect at each site over 0 to 50 meters (for each site) and 0 to 100 meters (each site except Turtle Harbor). Turtle Harbor transects end at 50 meters.

Table 6: Average number of trees per transect (0 m to 50 m). Sites that share a letter are not significantly different.

Site	Mean (± SD)	Tukey HSD grouping
BB	72.50 (1.47)	AB
OB	97.50 (0.25)	A
RH	40 (2.53)	AB
TH	35 (1.01)	B

Table 7: Average number of trees per transect (0 m to 100 m). Sites that share a letter are not significantly different.

Site	Mean (± SD)	Tukey HSD grouping
BB	173 (1.82)	AB
OB	196 (0.29)	A
RH	82 (1.77)	B

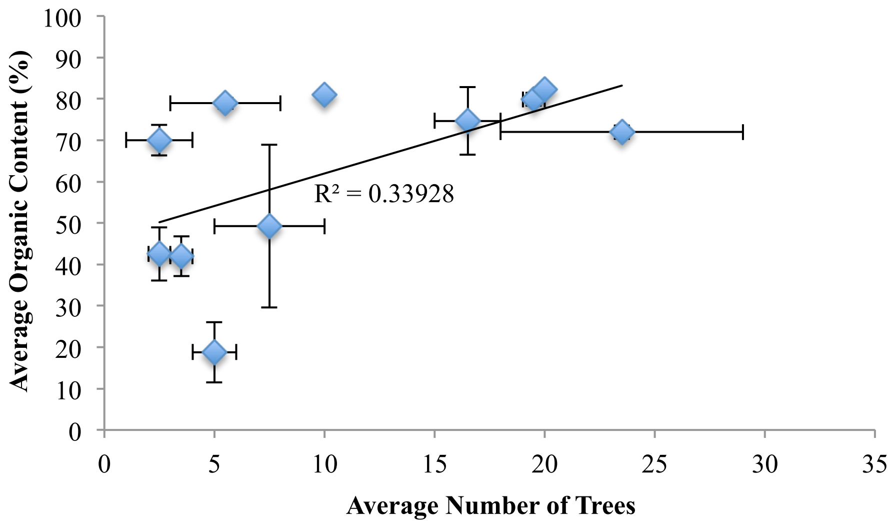

Fig 5: Average number of trees per transect at each site compared to the average percent organic content at all 4 of the sites sampled.

Tree Height:

There was a significant difference between tree height at all four of the sites (0 to 50 m: ANOVA; $F_{3,483}$=343.27; p=0.000; 0 to 100 m: ANOVA; $F_{2,897}$=399.36; p= 0.000). All four sites were grouped separately (Table 8 & Table 9), with the least impacted site, Turtle Harbor (TH), having the greatest average tree height and the medium impacted site, Oyster Bed Lagoon (OB), having the lowest. Average tree heights are displayed in Figure 6. Additionally, these results indicated a negative correlation (R^2 = 0.52) between average organic content and average tree height (Figure 7). It was also found that there is a strong negative correlation (R^2=1.0 and R^2=0.91, Figure 8) between number of trees and tree height. With a decrease in number of trees, there is an increase in tree height.

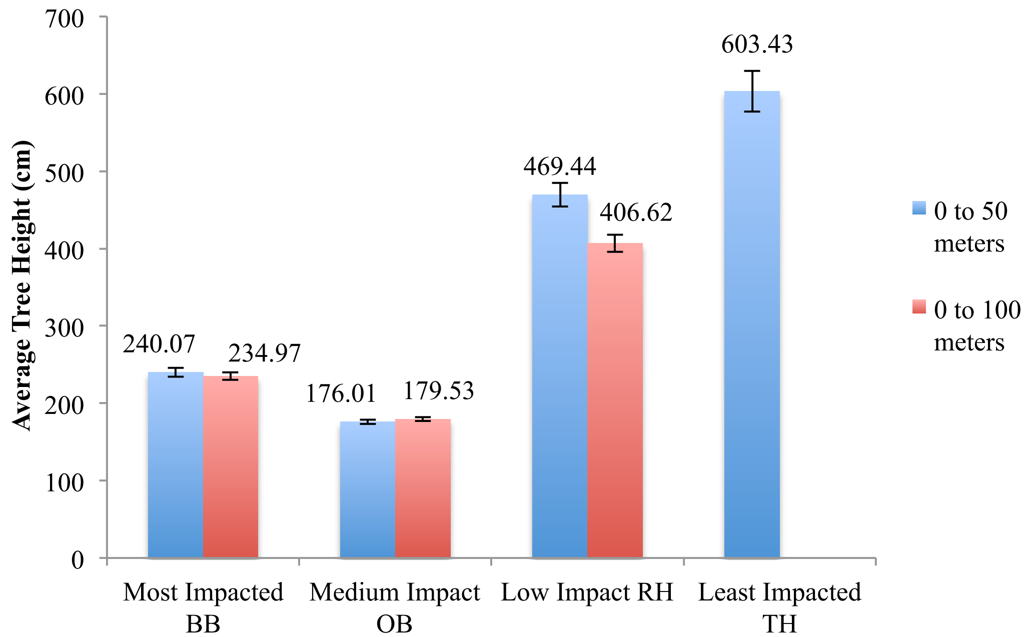

Figure 6: Average tree height (cm) from 0 m to 50 m (including Turtle Harbor) and 0 to 100 m (excluding Turtle Harbor). Turtle Harbor transects ended at 50 meters.

Table 8: Average tree height over 0 to 50 meters. Heights were averaged over two transects. Sites that share a letter are not significantly different.

Site	N (total number of trees measured over two transects)	Mean (± SD) (cm)	Tukey HSD grouping
BB	143	240.07 (5.76)	A
OB	194	176.01 (2.72)	B
RH	80	469.44 (15.07)	C
TH	70	603.43 (26.34)	D

Table 9: Average tree height over 0 to 100 meters. Heights were averaged over two transects. Sites that share a letter are not significantly different.

Site	N (total number of trees measured over two transects)	Mean (± SD) (cm)	Tukey HSD grouping
BB	344	234.97 (4.68)	A
OB	392	179.5 (2.56)	B
RH	164	406.6 (10.85)	C

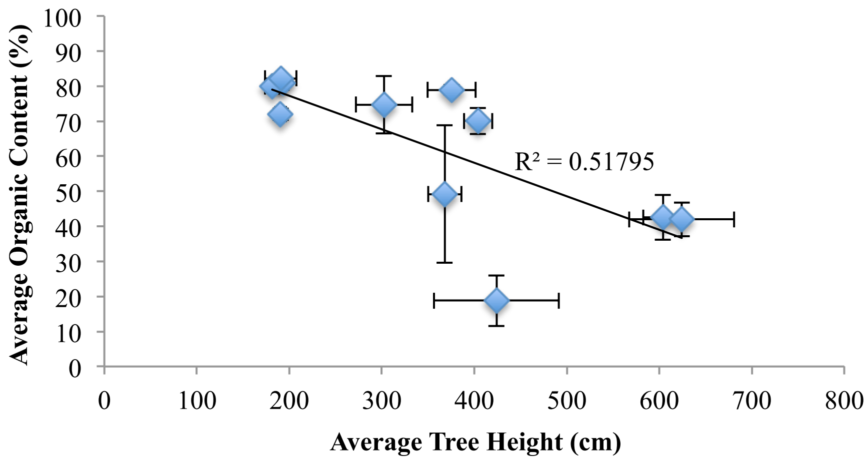

Figure 7: Average tree height compared to average organic content of sample point—trees within 10 meters of sediment sample location were averaged. Data were used from every 50 meters of each transect from all 4 of the sample sites.

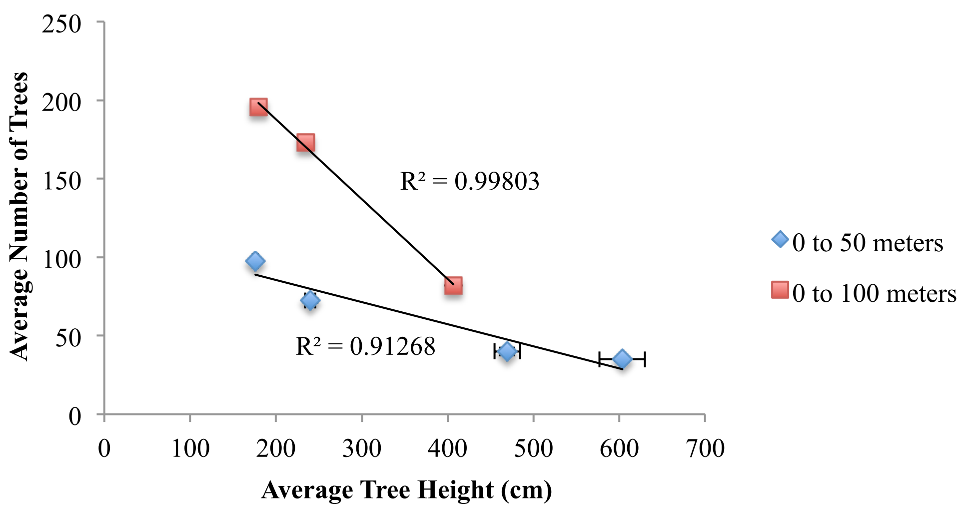

Figure 8: Average tree height (cm) versus the average number of trees at each site.

Figures 9a through 9d plot the number of trees along with average tree height *versus* the distance from shore. At Big Bite Pond there is not much variation in tree height, however the number of trees follows a bimodal trend. At Oyster Bed Lagoon there is a slight increase in tree height further into the stand.

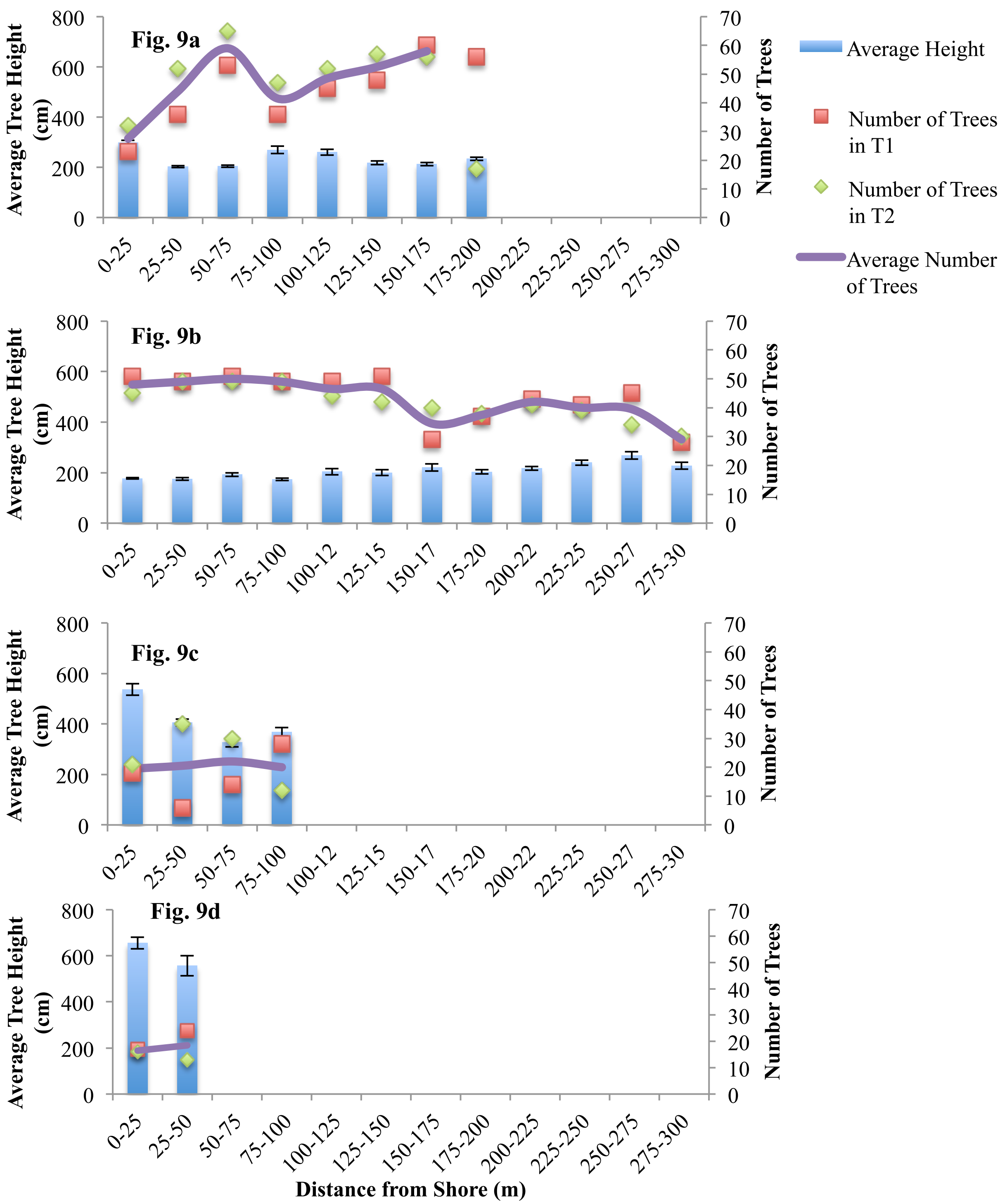

Figure 9: Displays average tree heights and number of trees compared to the distance from the shore at each site. Figures descend from most impacted sites to least impacted sites (Fig. 9a: Big Bite Pond; Fig. 9b: Oyster Bed Lagoon; Fig. 9c: Rock Harbor; Fig. 9d: Turtle Harbor). In Fig. 9a, average number of trees line ended at 175 due to an outlier on

Transect 2, which skewed the data. Removing this outlier allowed for a more accurate representation of the pattern that the average number of trees followed.

Aboveground Biomass

There were significant differences in the amount of aboveground biomass over 0 to 50 meters (0 to 50 m: ANOVA; $F_{3,12}$= 11.38; p=0.001) with Turtle Harbor significantly higher than all other sites (Table 10). Over 0 to 100 meters there were no differences in aboveground biomass between Big Bite Pond, Oyster Bed Lagoon, or Turtle Harbor (0 to 100 m: ANOVA; $F_{2,21}$=.21; p=0.814) (Table 11). Turtle Harbor had the greatest aboveground biomass (Figure 10). Results also indicated a negative correlation between aboveground biomass and organic content (R^2 = 0.67, Figure 11).

Table 10: Average aboveground biomass at each site for 0 to 50 m. N is the total number of boxplots used at each site (includes boxplots from both transects). Sites that share a letter are not significantly different.

Site	**N (Number of boxplots)**	**Mean (±SE) (kg/m^2)**	**Tukey HSD grouping**
BB	4	5.68 (3.37)	A
OB	4	1.72 (0.35)	A
RH	4	11.88 (3.43)	A
TH	4	27.86 (4.81)	B

Table 11: Average aboveground biomass for 0 to 100 m (Turtle Harbor excluded- see methods). N is the total number of boxplots used at each site (includes boxplots from both transects). Sites that share a letter are not significantly different.

Site	**N (Number of Boxplots)**	**Mean (±SE) (kg/m^2)**	**Tukey HSD grouping**
BB	8	8.52 (4.63)	A
OB	8	5.96 (3.25)	A
RH	8	8.87 (2.06)	A

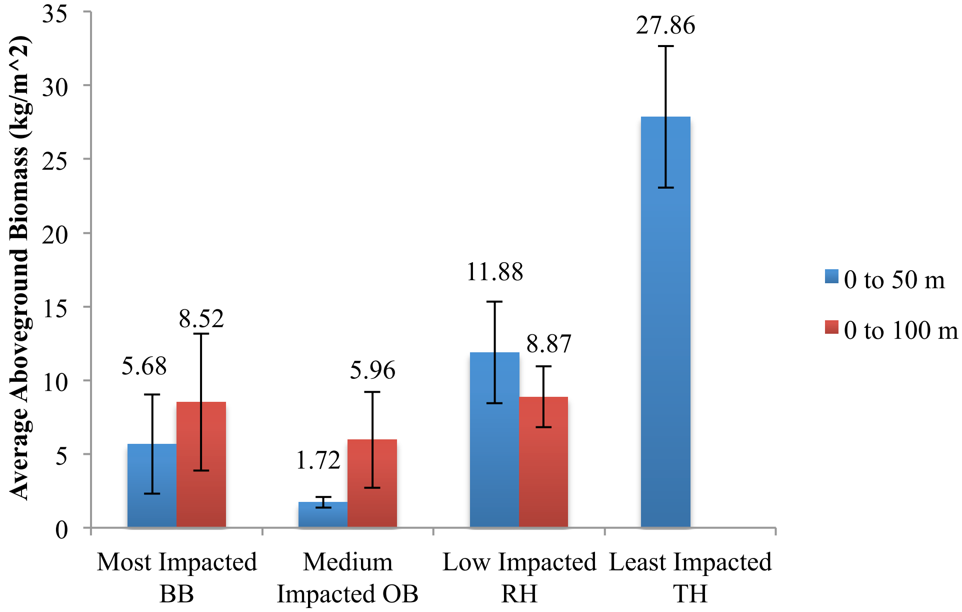

Figure 10: Average aboveground biomass per meter for each site.

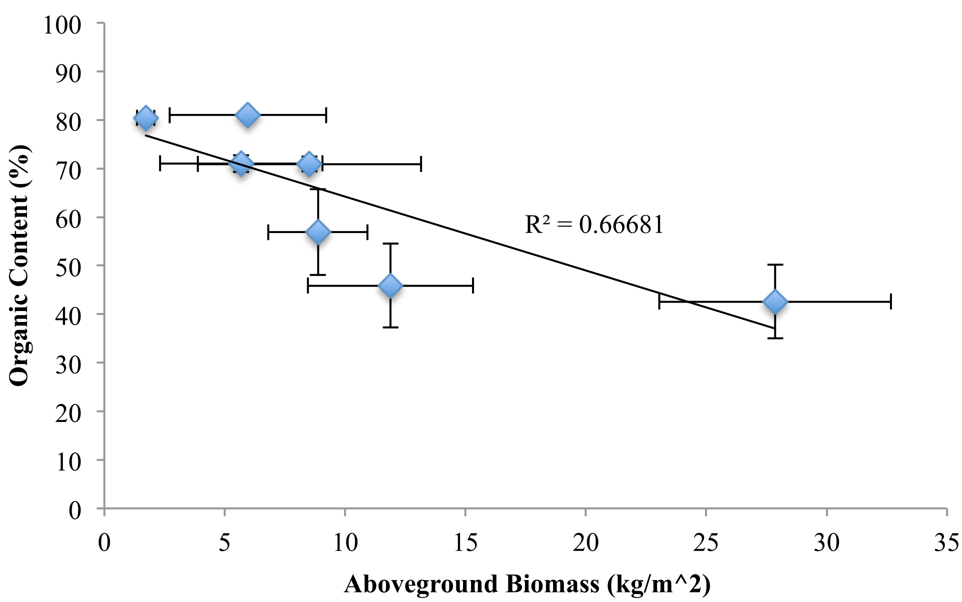

Figure 11: Average aboveground biomass at each site compared to the mean organic content at all of the sites. The data from 0 to 50 meters were used for all four sites as well as the data from 0 to 100 m, which excluded Turtle Harbor. (Total of 7 data points).

Salinity

Rock Harbor (RH) had the highest salinity and Turtle Harbor had the lowest salinity (Figure 12) (0 to 50 m: ANOVA; $F_{3,140}$= 14.68; p=0.000; 0 to 100 m: ANOVA; $F_{2,167}$=3.95; p=0.021). Salinity at Big Bite Pond was significantly different from both Rock Harbor and Turtle Harbor, while Oyster Bed Lagoon's salinity was significantly different from that of Rock Harbor (Table 12 and 13). There were no sites that had salinities that were significantly different from all of the other sites.

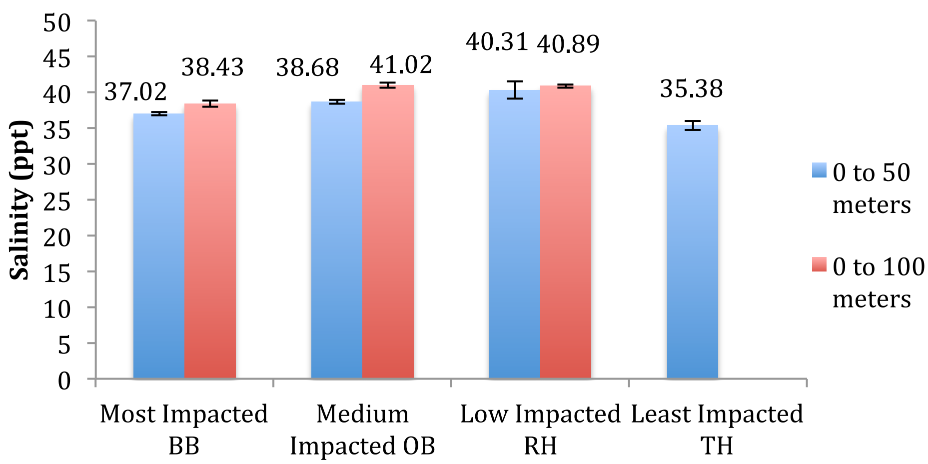

Fig 12: Average salinity from 0 to 50 meters for all four sites and 0 to 100 meters for all sites except Turtle Harbor.

Table 12: Average salinity over 0 to 50 meters. Sites that share a letter are not significantly different.

Site	N (Number of samples)	Mean (±SE) (ppt)	Tukey HSD grouping
BB	43	37.02 (0.23)	AB
OB	22	38.68 (.27)	AC
RH	42	40.31 (1.21)	C
TH	37	35.38 (0.64)	B

Table 13: Average Salinity over 0 to 100 meters. Sites that share a letter are not significantly different.

Site	N (Number of samples)	Mean (±SE) (ppt)	Tukey HSD grouping
BB	74	38.43 (0.44)	A
OB	42	41.02 (0.38)	AB
RH	54	40.89 (0.24)	B

Discussion

1.Correlation between number of trees and organic content

There is a positive correlation between number of trees and organic content (Figure 5). From Figure 9, it appears that there may be a connection between tree height and number of trees. An increase in number of trees is often associated with a slightly lower tree height at the same distance. Figure 8 provides more definitive support that there is a very strong negative correlation between the number of trees present and the tree height.

With greater numbers of trees, despite potentially having lower average heights, there could be a greater amount of leaf litter. It was observed in previous studies that estuarine mangroves have high rates of primary productivity due to increased litter fall and above-ground woody biomass growth (Amarasinghe & Balasubramaniam, 1992). This increased primary productivity would lead to an increase in the organic content present in the sediment, as was seen in the results.

Additionally, it should be noted that a drastic decrease in the number of trees at Big Bite Pond’s transect 2 was the result of construction activity. Sampling at this transect was stopped due to mangrove clearing that had taken place as a result of condominium construction. There was a sharp decline in number of trees at 180 meters into the stand, and this decline was a direct effect of human activity.

2. Correlation between tree height and organic content.

As apposed to the number of trees, tree height resulted in a negative correlation with organic content. There was a significant difference between tree heights at all 4 sites. Average tree heights were greatest at Turtle Harbor, the marine protected area, which also had sediment with the lowest organic content. Despite being a marine protected area and having greater tree heights, the carbon stored in the sediment at this site was still lower. This could indicate that a variety of factors, including tree height, play an important role in the amount organic content present. However, it is plausible that tree height, combined with other factors such as number of trees and exposure to tidal action, is responsible for the amount of organic content (as apposed to solely tree height determining organic content).

The estuarine sites, Big Bite Pond and Oyster Bed Lagoon, had smaller trees compared to the oceanic sites, Rock Harbor and Turtle Harbor. With a lower average height, there is opportunity for a greater number of trees, which may be why sites with lower heights often times had a greater number of trees. Dwarfed mangroves are commonly associated with sites that have suboptimal conditions, such as limited nutrients and tidal inundation (Naidoo 2006), however there is variation among causes of mangrove dwarfing.

Dwarfing in mangroves occurs naturally, and is often associated with conditions of high salinity, poor aeration (Davies 1940), waterlogging and salinity (Egler 1952), and limited nutrients(Lugo and Snedaker, 1974). Although the results from this study indicate a higher organic content is associated with lower tree height, it has also been found that highest C stocks can also be associated with taller mangroves (Adame et al. 2013). This indicates that there are other factors contributing to the amount of organic content that is stored in mangrove sediments. Previous studies have also found that soil organic content is highest in the surface horizon and decreases with depth—especially in dwarfed mangrove habitats (Adame et al. 2013). As this study focused on surface sediments, this could offer an explain for the negative correlation between tree height and percent sedimentary organic content.

3. Lower aboveground biomass at more impacted sites

The more impacted sites, Big Bite Pond and Oyster Bed Lagoon, had the lowest average aboveground biomass. There was a negative correlation between aboveground biomass and sedimentary organic content. Despite having greater aboveground biomass, the sediments in the less impacted sites, Turtle Harbor and Rock Harbor, had lower organic matter content.

It is possible that having smaller and a greater number of roots combined with less exposure to tidal action is responsible for the greater sedimentary organic content at Big Bite Pond and Oyster Bed Lagoon. Because mangrove roots act as sediment stabilizers (Carlton, 1974), it is possible that having a greater number of roots reduces the outflow of organic content. Mangroves' elaborate root structures are an important characteristic that allows them to slow water flow and create more suitable conditions for the settling of clay and silt particles (Wolanski 1995, Young and Harvey 1996).

It was observed in a previous study (Kristensen et al., 2008) that some mangroves lose a large portion of their net primary production to the adjacent coastal waters—

largely from tidal action (Kristensen et al., 2008), resulting in decreased organic matter. At the less impacted oceanic sites, there are fewer, although larger, roots that may be less efficient at reducing organic content loss. This combined with the greater tidal activity than in estuarine sties would create conditions that may allow for greater flushing rates. This combination of factors offers a possible explanation for the lower organic content levels at these sites.

4. Major factor in mangrove forest structure and organic content is environmental setting, not human impacts

Although sediment at Big Bite Pond and Oyster Bed Lagoon have greater organic content, they are also the most impacted by humans. It is also true that in this case, both of the most impacted sites are estuarine mangroves—meaning that there is less flushing (Wolanski & Ridd 1986), more likelihood for dwarfed mangroves (Naidoo 2006), and a greater ability to retain the organic content than in the oceanic sites . Naturally, an estuarine setting leads to more human activity because there is reduced tidal action. These bays are convenient for a variety of human activities, including fishing, docking boats, construction, etc. Many of the human activities in these bays are degrading to mangrove habitats, as is the case for Oyster Bed Lagoon and Big Bite Pond.

In a previous study looking at anthropogenic disturbances to mangroves in the Caribbean (Ellison and Farnsworth, 1996), wastewater was associated with higher aquatic N_2O concentrations. Heavy metal ions from sewage accumulated in *Rhizophora mangle* roots, which also affected the primary and secondary consumers relying on these plants (Ellison and Farnsworth, 1996).

As for the direct removal of mangroves, previous studies have suggested that the clearing and draining of mangroves is related to a decrease in mangrove soil carbon (Kristensen et al. 2008, Eong 1993, Sjöling et al. 2005, Strangmann et al. 2008, Granek and Ruttenberg 2008). The suboxic soils of mangroves and other wetlands that are exposed to draining and oxidizing conditions also impact the deeper layers (Hooijer et al. 2006). This draining results in a decrease in the overall organic carbon, as oxidized carbon is more likely to be lost to the atmosphere, and therefore, this carbon is less likely to transfer to the deeper soils. This differs from upland forests where only the top 30 cm are affected (Hooijer et al. 2006). This difference suggests that there would be a more drastic decrease in soil carbon in mangroves than in upland forests in this scenario. This scenario highlights how sensitive mangrove ecosystems are to disturbance when compared to terrestrial forests.

Ultimately, the results of my study suggest that mangrove forest structure and organic content is based largely on the setting it is found in (estaurine, riverine, oceanic, etc.). This is not to say that human activity does not influence mangrove forest structure and carbon storage, however, I found that human activity was not the major influencing factor in these living mangrove stands. It is likely that results are strongly influenced by the type and extent of pollution and degradation taking place. If this study were performed on a different island that had a far greater population density and pollution in the form of petroleum, it is possible that results would have differed. On Utila, the greatest threat from human activity is the actual destruction and removal of mangroves.

5. Implications for conservation

From this study, it can be recommended that construction at Big Bite and dredging at sites such as Oyster Bed lagoon should be minimized and strictly regulated because of their significance as sinks for organic carbon. Minimizing and regulating mangrove loss has been a problem in nations such as Honduras, which have laws protecting mangroves—but no regulation or enforcement. Solely looking at organic content in these sites, Oyster Bed Lagoon and Big Bite Pond should be the highest priorities—especially due to the fact that they currently have no protection status and continue to be degraded.

It is not the case that estuarine sties are more important for carbon storage than oceanic sites, because oceanic sites such as Turtle Harbor and Rock Harbor likely play an important role in the amount of organic content that is exported to the ocean. It is the case, however, that the estuarine sites in this study are currently more threatened by direct human activities. The results of my study suggest that there is greater organic content at these impacted sites, and therefore continued destruction and degradation will result in a net loss of stored organic content from the mangroves of Utila—indicating that there will be a loss of carbon from the soil to the atmosphere.

Overall, the results of my study indicate a low impact from human activity on the living mangroves and their stored organic content. The differences that were observed between the most impacted and the least impacted sites are predominantly due to environmental factors such as setting (bay area *versus* coastal), rather than direct impacts from human activity. A major exception to this finding is the direct effect on mangroves stemming from construction leading to complete mangrove removal. It is an obvious cause of the overall net decrease in organic content of the mangroves, however, this does not have any observable impacts on mangroves that are not cleared.

My study showed a significant level of organic content in the most impacted sites, and this warrants protection. The types of human activities that are taking place include both indirect and direct impacts, however, the direct loss of mangroves from clearing for construction will continue to have severe impacts by significantly reducing the amount of organic content that is stored by these mangroves.

Conclusion

The issue of mangrove clearing is not only a local issue for the island of Utila, but also an issue throughout the rest of the tropics worldwide. Global losses of mangroves are currently about 1-3% (Alongi 2002, Bouillon et al. 2008, Donato et al. 2011), and about 35% have been lost within the past two decades (Valiela et al. 2001). It is very likely that the clearing of mangroves on a large-scale basis is a significant contributing factor to the crisis of rising atmospheric carbon levels. It has been established that mangroves are critical in the marine carbon cycle and act as a carbon sink (Sabine et al. 2004). Additionally, the clearing of mangroves can ultimately result in the release of carbon from the sediment that has been stored for up to 1,000 years (Eong 1993). When cleared, the rate of carbon release from the sediment can be about 50 times the carbon-sequestering rate (Eong 1993). These land-use changes unfortunately force these ecosystems to shift from acting as a carbon sink, to acting as a carbon source.

The findings of this study have major implications for the conservation of mangroves. It is clear that the construction taking place at Big Bite Pond and the dredging in Oyster Bed Lagoon should be taken into consideration when determining future conservation plans for the island. The results of this study suggest that these sites have been overlooked in previous conservation efforts, which perhaps may have been due to a desire to conserve the more pristine sites of the island for their ecosystem services other than carbon storage. These more impacted sites have fallen by the wayside in terms of protection, and are being polluted and degraded with no regard for any laws or regulations. Due to the levels of degradation that these sites have faced, they should be considered a high priority for conservation. Despite their close proximity to the community center and tourism hot spots, these sites should not be overlooked or viewed as lost causes. This study provides significant incentive for protecting these sites as well as incentive for future studies at these same sites. Ultimately, I would suggest that there is a need for a paradigm shift in the current prioritizations for conservation. When studying these ecosystems from a carbon storage perspective, more attention and efforts are needed and should be focused on the heavily degraded sites.

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