Variation of carbon stock of Boca del Drago mangrove forests based on salinity and seaward proximity

Fiona Wyrtzen
*SIT Study Abroad*

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Variation of carbon stock of Boca del Drago mangrove forests based on salinity and seaward proximity

Fiona Wyrtzen
SIT Panama
Fall 2023
ABSTRACT

Mangrove forests, at the intersection of land and sea, are considered one of the most important marine environments for their variety of ecosystem services and their ability to sequester large amounts of carbon in their biomass and adjacent soils. With a changing climate, many of the abiotic and biotic factors influencing mangroves will begin to shift, potentially impacting resilience, growth capacity, and distribution of mangroves worldwide. This study aimed to examine the influence of changing salinity on the carbon stock capacity for *Rhizophora mangle* and *Laguncularia racemosa* forests, and the distribution of biomass in each species relative to salinity in mangrove forests in Bocas del Toro, Panamá. Understanding site-specific influence of abiotic factors is important for understanding mangrove resiliency in understudied areas. 15 radial plots were studied in mangrove forests near Ground Creek on Isla Colon, Bocas del Toro, Panamá to understand this relationship. Plots established represented three salinity zones (0-10 ppt, 10-20 ppt, and 20-30 ppt) and three sites (fringe forest, intermediate forests, and inland forest). DBH and height measurements were taken for all trees in each plot and used to calculate biomass and subsequently carbon stock per hectare. Carbon stock per hectare was related to salinity and site and no significant results were found, however significant differences were found between the individual biomass of *R. mangle* based on salinity zone (p = 0.0302). This indicates that overall carbon stock of mangrove forests in the Ground Creek could be resilient to future changes in sea level and land distribution, but rising salinity could have impact on individual growth parameters such as biomass, height, and DBH. Further inquiry is needed on the influence of salinity and site on individual tree carbon stock in the area to draw concrete conclusions.
ACKNOWLEDGEMENTS

Many individuals have given me the support and advice to make this project possible. I want to thank my research advisor, Gabriel Jacome for providing and guidance, information, and support every step of the way from refining my topic, to developing my proposal, to pulling together my research. Many thanks to Aly Dagang, my program advisor, for providing advice and consistent support throughout my project. Thank you to Yuritza Lara for coordinating and providing my equipment for this research, and Yariza Jiménez for coordinating logistics and helping me find a refractometer. Additionally, I would like to thank Dr. Eric Manzanae for providing feedback throughout the process.

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I would like to thank Ormelio Dixon and his family for showing me around the study area and letting me use the study site.

Lastly, I want to thank Marina Bazzano for making the daily kayak with me to my site, accompanying me into the mangrove forests, and helping with data collection. It would not have been possible for me to face the mangroves every day without her.

I could not have done this research without the support of all of these individuals, and I am so grateful for the wonderful human beings who made it possible.
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INTRODUCTION

Mangroves are classified as an association of halophytic trees, and sometimes additionally shrubs and other plants, growing on subtropical and tropical coastlines typically between 25°N and 25°S, in brackish to saline tidal waters. (Mitsch & Gosselink, 2007). The world-wide extent of mangroves is estimated to range from 14 to 24 million hectares (Giri et al., 2010). Mangroves are distinct from terrestrial trees due to their ability to survive in high salinity zones, and their gas exchange through above-ground root tissues such as stilt roots and pneumatophores (Kauffman & Donato, 2012). Mangroves provide a variety of ecosystem services including providing nurseries for fish, acting as a coastal defense and buffer to erosion and extreme weather events, and providing habitat for fish, birds, crustaceans, shellfish, reptiles, and mammals (Alongi, 2002). Mangrove ecosystems are considered one of the most threatened ecosystems across the tropics and face many immediate threats such as aquaculture, anthropogenic development, and pollution (Duke et al., 2007). In Latin America, anthropogenic activity accounted for 40.5% of regional occurrences in localized loss of mangroves between 1996-2010 (Thomas et al., 2017). Globally, the Atlantic and Pacific coasts of Central America have the highest proportion of threatened mangrove species (Polidoro et al., 2010).

Mangroves and Climate Change

Mangrove’s carbon pools are one of the highest among forest types, averaging at 1,023 metric tons of carbon per hectare and sequestering approximately 22.8 million metric tons of carbon each year worldwide (Donato 2011; Giri et al. 2011). Elevated carbon dioxide will change biomass allocation of mangroves through enhancements in growth and changes in productivity (Lovelock et al, 2016). Biomass, stem length, maturation rate, total leaf area, and photosynthetic rate of Rhizophora mangle seedlings have been shown to increase significantly at carbon concentrations of 700 ppt, about 300 more ppt than the current daily average (Farnsworth et al., 1996). Forests have been able to adapt to historic changes in temperature, freshwater availability, and changes in seal level but rapid changes caused by climate change may affect forest composition, productivity, and global distribution (Lovelock et al, 2016). Carbon capture and storage capacity can be reversed through dieback, degradation, and land use conversion, causing more greenhouse gas emissions (Bulmer et al., 2017; Sippo et al., 2020) Mangroves are considered particularly vulnerable to climate change-induced stressors such as sea-level rise that could cause increasing salinity in coastal ecosystems. However, the loss of wetlands depends more on anthropogenic influence than the individual influence of climate change or sea level rise (Kirwan & Megonigal, 2013). The resilience of coastal wetlands to climate change depends highly on the availability of space to adapt and expand which could be greatly influenced by increased anthropogenic activity encroaching on wetland habitat (Schuerch et al., 2018).

Mangroves and Salinity

Salinity is one of the key controlling factors in mangroves and increasing salinity can impede mangrove forest growth and ecosystem function making tropical regions extremely
vulnerable (Chen and Wang, 2017; Ahmed et al., 2012). High salinity can disrupt normal homeostasis of the release of nutrients by microbial decomposers in soil, degrading soil quality and restricting normal mangrove forest function across species (Chowdhury et al., 2019). Rising levels in salinity can lead to reduction in tree height, leaf area index, and forests dominated by dwarf species that hold less biomass (Ahmed et al, 2022). In other areas of the world that have seen tide-dominated salinity gradients, mangrove species sensitive to salinity are gradually disappearing and species that are salt tolerant expand into degraded forests (Chowdhury et al., 2019).

For instance, in the widespread species *Rhizophora mangle*, individuals reduce their stomatal openings to conserve water when high evaporative demand exceeds the rate of salt exclusion and fresh water supply to leaves because of high salinity (Barr et al., 2009). In controlled study environments, *R. mangle* propagules show lower levels of plant growth, chlorophyll content, and net photosynthesis under drought and salinity stress, but do show mechanisms of resistance to these factors (Iwuala et al., 2023). Specific costs of salt in mangrove physiology include reduced survival in the shade, reduced growth rates, and loss of mechanical strength (Ball, 1988; Santini et al., 2012). Mangrove forests that experience sudden high salinity conditions may not show significant differences in biomass and ground carbon, but can quickly show reduction in plant physiology parameters within a year (Dittman et al., 2023). Although mangroves have high trait plasticity in terms of tolerance of salinity, aridity, and temperature change, it is important to understand these factors and their effect on local site adaptability in mangrove forests (Lovelock et al., 2016). Prior studies account for how salinity effects propagule growth (Iwauala et al., 2023) and carbon stock along solid salinity zones (Ahmed et al., 2023), but not how carbon stock of preexisting forest is affected along regular salinity gradients. Few studies have been done to look at *R. mangle* and *L. racemosa* in terms of carbon stock over a general salinity gradient.

**Mangrove Biomass and Carbon**

Factors influencing aboveground biomass of mangroves are relatively understudied but may depend on soil properties and nutrients after succession development. Stem, branch, leaf biomass are the components of aboveground biomass and prop roots and below-ground root biomass are the components of below-ground biomass (Komiyama et al., 2008). Biomass varies greatly across species, locality, age, and dominant species, and calculations can differ greatly due to the range of biomass equations that have been developed over multiple studies (Komiyama et al., 2008). Biomass can be converted to carbon stock using carbon equivalents for specific species and biomass components. Global mangroves have large variation in biomass, from over 500 Mg C ha⁻¹ in Indo-Pacific fringe and riverine forests, to 8 Mg C ha⁻¹ for dwarf stands (Kauffman and Cole, 2010; Kauffman et al., 2011). Generally, aboveground biomass in mangroves is low closer to the sea and increases inland (Komiyama et al., 2008). However, soil organic carbon is inversely related to seaward distance and decreases inland (de Jong Cleynhert, 2020). In *R. mangle*, aboveground prop root systems often have biomass equal to the roots. In mangroves, especially those with prop roots, belowground biomass is much more significant than in upland forests, and the ratio of above-ground to below-ground carbon stock is much lower (Komiyama et al., 2008). Beyond above-ground and below-ground carbon stock found
using biomass, mangrove carbon pools consist of carbon stock from dead trees, saplings and seedlings, downed wood, and total soil carbon, although these measurements are beyond the scope of this study (Kauffman & Donato, 2012).

Local mangrove species

Mangrove forest is a dominant ecosystem throughout Bocas del Toro, estimated to cover 28 km^2, over half of the mangrove area on the Panamanian Caribbean Coast, predominating Laguna de Chiriquí where they overwash islands because of terrestrial run-off from large rivers nearby (D'Croz, 1993). Mangrove forests in the area are dominated by red mangroves (Rhizophora mangle) due to its flooding tolerance, with white mangroves (Laguncularia racemosa) occurring as well in Boca del Drago and a few individuals of the black mangrove (Avicennia germinans) in other areas of the region (Lovelock et al., 2005). Rhizophora mangle is one of the most extensively distributed mangrove species in the Americas and are characterized by their aboveground prop roots and viviparous propagules, with a wide distribution ranging from fringe to more terrestrial soils (Tomlinson, 2016).

It is common for mangroves to have zonation patterns based on species, for instance in Caribbean forests the most common trend is to see Rhizophora mangle from the fringe to the land, overlapping with Avicennia germinans, Laguncularia Racemosa, and Conocarpus erectus, respectively (Rull, 2022). R. mangle has a wide distribution along seaward fringe to tidal creek banks to mouths of estuaries, typically occurring in salinities around 35 ppt (seawater), but can survive from 0-90 ppt, from freshwater to saline environments (Rull, 2022). L. Racemosa inhibits a smaller niche and does best in salinities of 15-20 ppt (intermediate), in zones of infrequent tidal flooding and frequent freshwater inputs (Rull, 2022). Because of R. mangle’s resilience across salinities and tidal zones, L. racemosa is unable to compete along salinity gradients. While R. mangle have aerial prop roots, L. racemosa has phumataphores (aerial roots) and pneumathodes (lateral roots) with high concentrations of lenticels. (Lonard et al., 2020).

Threats to mangroves in Bocas del Toro

Boca del Drago Beach was identified as a vulnerable area to sea level rise from projections of flood maps up to 2080, putting mangroves at risk (Grajales Saavedra et al., 2021). In addition, the tourism industry has increased by 70% in the previous decades in Bocas del Toro due to an increase in restaurants and hotels, creating more demand for cleared land and putting more pressure on mangrove forests (Sellier, 2009). Although the area has low mangrove species diversity, there is a large variation in forest structure and soil conditions in terms of salinity, phosphorus concentration, and sulfide concentration (Lovelock et al., 2005). Understanding the patterns that cause forest structure are necessary to scale up ecosystem services provided by the mangroves (Lovelock et al., 2005). Identifying how future increases in salinity will influence biomass allocation and forest distribution will be imperative to predict impacts on the mangrove forest of Boca del Drago with a changing climate.

Boca del Drago and Ground Creek

Boca del Drago (9°24'47"N 82° 19' 23"W) lies on the northwest corner of Isla Colón in the Bocas del Toro Archipelago on Panama’s Caribbean coast near the border with Costa Rica.
The archipelago includes six main islands, Isla Colón, Bastiementos, Solarte, Cristóbal, Popa, and Cayo Aqua (Collin, 2005). Isla Colón is the largest of such islands and serves as the most populated and developed island in the archipelago, with the tourist center, the town of Bocas del Toro, lying about 18 km southeast of Boca del Drago on the major peninsula of Isla Colón (Moody, 2005).

The Islands separate two bays, the Bahía Almirante and Laguna de Chiriquí, consisting of a diverse patchwork of mangrove, seagrass bed, and coral reef coastal ecosystems (Collin, 2005). Diverse tropical rainforests are directly adjacent to mangrove forests. Boca del Drago sits at the edge of Bahía Almirante and the Caribbean Sea, around 2,000 m away from the mainland of La Gloria, Changuinola (Figure 1). It is located on top of a stabilized beach ridge that consists of coralline sands created from reef erosion. Elevation of this area lies at sea level and temperature average around 27°C with little variation. Rainfall in this region is high ranging from 3-5 m annually with little seasonality, with common occurrences of flooding due to high rainfall and passing hurricanes far to the north. (Lovelock, 2005).

There are abundant mangrove forests along the coastline south of Boca del Drago, specifically in an area called Ground Creek. This area is slightly south of Starfish Beach, a highly frequented tourist beach that used to be a mangrove forest, but was cleared of the fringe mangroves and remains highly affected. The mangrove forests of Ground Creek surround three small bays and typically remain fringe forests, with some areas of the forest extending farther inland. There is little infrastructural development in this area except for a few residential plots of land owned by local families. Cuts have been made through the mangrove forest for access to land by boat, and there is frequent daily passage of small boats through the bay and mangrove forest.
RESEARCH QUESTION

Is there variation in carbon stock capacity of *R. mangle* and *L. racemosa* mangrove forests near Boca del Drago based on water salinity and proximity?

METHODS

*Site Selection*

A site was selected at beginning at 9°23'56.09"N 82°18'34.82"W due to easy access to the inland forest and little interruptions by human infrastructure and activity (Figure 2). The study site is along a clear-cut path through the fringing mangrove forest that has been there for over 50 years. Multiple sites in the area were generally tested for salinity gradients and this site showed the highest gradient. The only users of the path through the mangrove are residents of the land adjacent, who take small boats through daily. In some areas of the forest, it is evident that there is human influence due to the presence of trash and other anthropogenic objects, however the forest remains largely undisturbed compared to others in the area.

![Figure 2: Boca del Drago and Ground Creek area of Isla Colón highlighting location of mangrove forests and study site.](image)

Methods for measuring carbon stocks for mangrove forest were largely based off Kauffman and Donato’s 2012 protocols for mangrove measurement, consistent with recommendations from the Intergovernmental Panel on Climate Change, to stay congruous with
recent monitoring of mangrove forests (Kauffman & Donato, 2012). Accessible study area extended about 280m inland. Study area was split into three sampling sites spanning approximately 90m (1/3 of the study area) each; closest to the water was be classified as fringe, followed intermediate or middle, and ending with most inland forests classified as back. It is necessary to sample different distances from the seaward edge of mangrove forest since characteristics will vary due to slight changes in relative elevation and tidal influence, therefore establishing shoreline-to-upland gradients (Kauffman et al. 2011).

In each site, 5 radial plots of 3m radius were randomly established along the stream in each site for a total of 15 plots. Linear plot arrangement will capture variation in mangroves and circular plots will be easy to establish and measure (Kauffman & Donato, 2012). Distance between plots was fairly consistent between sites but depended on accessibility of the mangrove forest due to hard to navigate prop roots and access from the stream. Since it was predicted that some parts of the project area will have a higher carbon content, systematic sampling is recognized as credible (Pearson et al., 2007). Each plot was identified with site classification, A representing fringe closest to the mainland, B representing middle, and C representing Back closest to the mainland, and a number (1-5) (Figure 5).

![Figure 3: Subplot distribution based on site location.](image)

The center of each plot was recorded, and four digital pictures were taken in each cardinal direction. Carbon stock calculations in this study were limited to aboveground and belowground biomass of live vegetation, due to time and resource constraints. Status 1 dead and standing trees, or trees that resemble live trees with the absence of leaves, were included in the calculation of biomass due to the ability to use live tree allometric equations, although all other statuses will be omitted (Kauffman & Donato, 2012). Small trees can often dominate the stand composition, so
all mangrove trees over 3 cm DBH were considered (Kauffman & Cole, 2010). Each individual was identified by species and DBH was measured using diameter tape taken at 1.37m above the ground, or 1.37 m above the highest prop or stilt root for *R. mangle* when practical (Komiyama et al., 2005). If 50% of the main stem of the root was inside the plot perimeter was included (Donato & Kauffman, 2012). The height of each mangrove sampled was taken with an extendable measuring stick, or rangefinder if height exceeded 16 ft (Jones et al., 2020).

Limitations on access to labs and equipment required measurement of salinity with a salinity refractometer from tidal waters. Water salinity in mangrove ecosystems can vary greatly with tide height and season making it difficult to get consistent readings of salinity, so salinity was measured inside of mangrove forest rather than open water for more accurate readings (Wang et al. 2023). Although there are daily fluctuations in salinity, general salinity levels play a larger role than salinity fluctuation. Water was collected with 1m PVC pipes with small holes 20cm high secured into the soil cap-side down allowing water to collect and fluctuate with tides. Each pipe was left in the ground during the sampling period of each plot to allow time for tide and salinity fluctuations, with a minimum of 20 minutes for each measurement. Water collected was poured into a clean container and brought back from the field and measured with a refractometer in ppt. Pipes and containers were cleansed with freshwater samples. Samples were attempted to be collected at synonymous cycles in the tide to mitigate tidal fluctuation in salinity, as most samples were taken in the morning.

The allometric equation specifically developed to calculate the biomass of tropical mangroves gathered by Komiyama et al (2008) were used to estimate above-ground, below-ground, and total carbon storage by specimen.

**Rhizophora mangle:**

Above ground (kg): \( W_{\text{top}} = 0.178(DBH)^{2.47} \) \( r^2 = 0.98, n = 17 \), \( D_{\text{max}}: \) unknown (Imbert & Rollet, 1989)

Below ground (kg): \( W_R = 0.00974((DBH)^2H)^{1.05} \) (Tamai et al., 1989)

**Laguncularia Racemosa:**

\( W_{\text{top}} = 0.102DBH^{2.50} \) \( r^2 = 0.97, n = 70 \), \( D_{\text{max}} = 10 \text{ cm} \) (Fromard et al., 1998)

Generally, the highest proportion of biomass is found in the stem (31.28%), along with below-ground roots (23.40%), and twigs, branches, and foliage (collectively 38.81%). Pneumatophores have the smallest concentration at 6.51% (Kusama et al., 2018). Adding tree heights and wood density to allometric calculation can help with accuracy but do not provide significantly different results than only using DBH. Since *R. mangle* has such a large proportion of prop roots and well-established equations, below-ground biomass was calculated into the total biomass. However, due to a lack of credible below-ground equations for *L. Racemosa* and such a small proportion of biomass lying in pneumatophores, below-ground biomass was omitted for the species. Specific carbon pools of above-ground biomass can be determined by multiplying biomass of individual components by a specific carbon concentration per species, but due to lack of species-specific data, 0.48 will be used (Donato & Kauffman, 2012).

Data was analyzed with one-way and two-way ANOVA tests to understand the significance of salinity and site on carbon stock per hectare and carbon stock per tree for the
collective mangrove forest, *R. mangle* trees, and *L. racemosa* trees. Carbon stock was calculated in metric tons per hectare and kg per tree. Salinity classes were defined as 0-10ppt, 10-20ppt, and 20-30ppt and site classes were defined as previously stated. One-way ANOVA tests were performed to test the significance of salinity and site with carbon site for Above-ground (AG), below-ground (BG), and total biomass, and two-way ANOVA tests were performed to test the combined significance of site and salinity (Rahman et al., 2014). The tests were repeated for specific species when applicable with AG biomass, along with carbon stock per tree for the same factors.

**ETHICS**

This study was ecological with no human subjects and no samples were removed from the environment so ethical implications were low. Special care was taken not to break any branches, step on or damage any pneumatophores or prop roots, or trample any propagules. However, on some occurrences roots or branches were broken due to misjudgment of step. No materials were taken out of the forests and all materials brought in were be taken out. Flagging tape was left in the environment for the study period but was removed at the conclusion of fieldwork. Efforts were made to cause minimal disturbance to wildlife in the area and to keep noise to a minimum to not disturb birds, crabs, or mammals. Manual modes of transportation to study sites by kayak were prioritized over gas-powered vehicles to reduce environmental impact, with 11 out of 12 site trips achieved manually. Permission of use of study sites was pre-established with the nearby owner’s family, although the mangroves themselves are public land. Before research began, an Institutional Review Board (IRB) Form was submitted with a research proposal. Research permission was approved due to lack of human subjects and use of ethical methods.

**RESULTS**

There were 98 trees surveyed across 15 plots, with *R. mangle* dominating with 88 individual trees and only 10 *L. racemosa* trees. Salinity measurements did not line up exactly with sites, causing some variation in the variables (Figure 4). Tree counts decreased from fringe to back sites, with 41 *R. mangle* trees and no *L. racemosa* trees in the fringe, 26 *R. mangle* and 6 *L. racemosa* in the middle, and 21 *R. mangle* and 4 *L. racemosa* in the back. Tree counts were highest in 20-30 ppm and 0-10 ppt salinity zones, with tree counts in 20-30 ppt equal to fringe count, 19 *R. mangle* and 2 *L. racemosa* in 10-20 ppt, and 28 *R. mangle* and 8 *L. racemosa* in 0-10 ppt.
Figure 4. Salinity gradient along the subplots from refractometer readings. Salinity groups are not completely aligned with site, although some are (for instance, 20-30 ppt plots are all in fringe site).

**Carbon Stock per Hectare**

<table>
<thead>
<tr>
<th>Carbon Stock</th>
<th>Site</th>
<th>p-value</th>
<th>μ Fringe</th>
<th>μ Middle</th>
<th>μ Back</th>
<th>p-value</th>
<th>μ 0-10</th>
<th>μ 10-20</th>
<th>μ 20-30</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above-ground, R. mangle</td>
<td></td>
<td>0.968</td>
<td>45.47 ± 16.42</td>
<td>41.01 ± 16.05</td>
<td>45.87 ± 11.8</td>
<td>0.352</td>
<td>28.84 ± 7.07</td>
<td>58.03 ± 15.58</td>
<td>45.47 ± 16.4</td>
<td>0.412</td>
</tr>
<tr>
<td>Above-ground, L. racemosa</td>
<td></td>
<td>0.128</td>
<td>0</td>
<td>3.9 ± 3.9</td>
<td>269.91 ± 170.94</td>
<td>0.587</td>
<td>109.48 ± 104.66</td>
<td>164.34 ± 163.56</td>
<td>0</td>
<td>0.959</td>
</tr>
<tr>
<td>Above-ground (R. Mangle + L. racemosa)</td>
<td></td>
<td>0.101</td>
<td>45.47 ± 16.43</td>
<td>44.91 ± 16.05</td>
<td>315.78 ± 11.80</td>
<td>0.525</td>
<td>138.33 ± 7.08</td>
<td>222.37 ± 15.59</td>
<td>45.47 ± 16.4</td>
<td>0.9 ±</td>
</tr>
<tr>
<td>Below-ground (R. mangle)</td>
<td></td>
<td>0.234</td>
<td>1.16 ± 0.30</td>
<td>0.966 ± 0.24</td>
<td>1.84 ± 0.49</td>
<td>0.348</td>
<td>1.03 ± 0.30</td>
<td>1.77 ± 0.48</td>
<td>1.16 ± 0.30</td>
<td>0.874</td>
</tr>
<tr>
<td>Total (Above-ground + Below-ground, R. mangle)</td>
<td></td>
<td>0.961</td>
<td>46.64 ± 16.7</td>
<td>41.97 ± 16.2</td>
<td>47.71 ± 12.26</td>
<td>0.348</td>
<td>29.88 ± 7.36</td>
<td>59.8 ± 15.91</td>
<td>46.83 ± 16.64</td>
<td>0.671</td>
</tr>
</tbody>
</table>
Table 1. Significance of carbon stock differences (Mg C ha⁻¹) based on site and salinity. All p-values have df = 2. All averages are in units of Mg C ha⁻¹ and include standard error. *L. racemosa* is excluded from Below-ground carbon stock and Total Carbon Stock. Due to a lack of belowground biomass data. One-way ANOVA tests were used to test differences in carbon stock based on site and salinity individually. Two-way ANOVA tests were used to test differences in carbon stock based on site and salinity cumulatively. No p-values were significant.

Figure 5. Above-ground carbon stock based on site and salinity range depending on species. Carbon Stock in Mg C ha⁻¹ was found based on all trees in site or salinity zone.

*R. mangle* AG (above-ground) carbon stock per hectare stayed fairly consistent throughout site, with 45.47 Mg C ha⁻¹ in the fringe site, 41.01 Mg C ha⁻¹ in the middle site, and 45.87 Mg C ha⁻¹ in the back site. *L. racemosa* AG carbon ranges from zero in fringe sites to 269.91 Mg C ha⁻¹ in back sites, largely overshadowing carbon stock of *R. mangle* across all sites. *R. mangle* carbon stock per hectare varied more by salinity, with the highest amounts of AG carbon stock (58 Mg C ha⁻¹) in the 10-20 ppt salinity zone and lowest amounts of AG carbon stock in 0-10 ppt (28.95 Mg C ha⁻¹). *L. racemosa* AG carbon stocks per hectare varied somewhat by salinity, with 60 more Mg C/ ha in the 10-20 ppt zone (164.34 Mg C ha⁻¹) than the 0-10 zone (105.57 Mg C ha⁻¹).

No significant difference in above-ground carbon stock was found between *R. mangle* and *L. racemosa* across all plots (t-test, df = 14.455, p = 0.4672) between a mean of 44.12 Mg C ha⁻¹ for *R. mangle* and 91.27 Mg C ha⁻¹ for *L. racemosa*. However, large differences are seen between the two.
**Figure 6.** Below-ground carbon stock based on site and salinity range. *L. racemosa* is excluded due to a lack of belowground biomass data. Carbon Stock in Mg C ha$^{-1}$ was found based on all trees in site or salinity zone.

*R. mangle* below-ground carbon stock per hectare varied somewhat throughout site but increased towards the back, with 1.16 Mg C ha$^{-1}$ in the fringe site, 0.966 Mg C ha$^{-1}$ in the middle site, and 1.837 Mg C ha$^{-1}$ in the back site. Tree heights tended to be lower in the middle site, possibly contributing to the decrease in BG carbon stock. *R. mangle* carbon stock per hectare also varied somewhat by salinity, with 1.16 Mg C ha$^{-1}$ in the 20-30 ppt site, 1.77 Mg C ha$^{-1}$ in the 10-20 ppt site, and 1.03 Mg C ha$^{-1}$ in the 0-10 ppt site.

**Figure 7.** Total carbon stock (above-ground + below-ground) based on site and salinity range. *L. racemosa* is excluded due to a lack of belowground biomass data. Carbon Stock in Mg C ha$^{-1}$ was found based on all trees in site or salinity zone.

*R. mangle* total carbon stock per hectare was fairly consistent throughout site, with 46.63 Mg C ha$^{-1}$ in the fringe site, 41.98 Mg C ha$^{-1}$ in the middle site, and 47.70 Mg C ha$^{-1}$ in the back site. *R. mangle* total carbon stock per hectare was the lowest in salinity zones of 0-10 (29.88
Mg C ha$^{-1}$), and highest in salinity zones of 10-20 ppt (59.80 Mg C ha$^{-1}$), followed by zones of 20-30 ppt (46.63 Mg C ha$^{-1}$).

**Carbon Stock per Tree**

In order to further understand significance in results of carbon per hectare relationships, relationships between the carbon stock of individual trees and site/salinity were pursued. Because *L. racemosa* was omitted for BG and total carbon stock, only AG stock was used in this analysis. Although not insignificant, BG carbon stock contributes only a fraction of total carbon stock compared to AG biomass.

<table>
<thead>
<tr>
<th>Carbon Stock per Tree</th>
<th>Site &amp; Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Site</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
</tr>
<tr>
<td>Above-ground R. Mangle</td>
<td>0.388</td>
</tr>
<tr>
<td>Above-ground L. racemosa</td>
<td>0.342</td>
</tr>
<tr>
<td>Total Above Ground</td>
<td>0.0414</td>
</tr>
</tbody>
</table>

**Table 2.** Significances of above-ground carbon stock differences (Mg C) per tree based on site and salinity.

There are significant differences between total AG carbon per tree depending on site (df=2, p=0.0414), and *R. mangle* above-ground biomass based on salinity (df=2, p=0.0341). Remaining differences AG carbon per tree based on site and salinity are statistically insignificant.
Figure 8. Average above-ground carbon stock per *R. mangle* trees (kg C) based on site and salinity. Error bars based on standard error. Significant differences are seen between *R. mangle* tree carbon stock based on salinity (df=2, p=0.032).

Average AG carbon stock appears to increase from fringe to back sites for *L. racemosa*, and is highest in 10-20 ppt versus 0-10 ppt and 20-30 ppt.

![Graph](image)

Figure 9. Average above-ground carbon stock per *L. racemosa* tree (kg C) based on site and salinity. Error bars based on standard error. No significant differences were found.

Average AG carbon stock appears to increase from fringe to back sites for *L. racemosa*, and is highest in 10-20 ppt versus 0-10 ppt and 20-30 ppt, congruent with *R. mangle*.

DISCUSSION

**Overall Carbon Stock Assessment**

The studied mangrove forest was dominated by *R. mangle* further supporting its dominance in the Bocas del Toro area (Lovelock et al., 2005). The presence of 10 *L. racemosa* trees made accurate assessment of trends in carbon stock per species less significant due to small sample size, but compared to other areas of Isla Colón and Bocas del Toro, there is a high proportion of *L. racemosa* species indicating relative levels of success of the species in this area.

Carbon stocks ranged from around Mg C ha\(^{-1}\) to 315 Mg C ha\(^{-1}\), with largest variations coming from the presence of *L. racemosa*. Similar carbon assessments have been done in other areas of the Neotropics with similar species. In Sian Ka’an, Yucatán, *L. racemosa* forests accounted for 84.6 Mg C ha\(^{-1}\), and *R. mangle* accounted for 69.6 Mg C ha\(^{-1}\), for trees over 5cm DBH (Adame et al., 2013). In El Sargento, Mexico, mangrove forests of predominantly *L. racemosa* were estimated to be between 181.1 and 316.78 Mg C ha\(^{-1}\) based on multiple allometric equations including those mentioned in Komiyama (2008), which was used in this study (Baustista-Olivas et al., 2018). A study in Panamá indicated that a primary *Rhizophora* forest had 279.2 Mg C ha\(^{-1}\) (Golley et al., 1975). This indicates that mangrove forests around
Ground Creek have carbon stock fairly congruent with other areas of similar species. However, carbon stock of *R. mangle* in the area tend to be lower than shown in other studies at around 45 Mg C ha$^{-1}$, and somewhat higher for *L. racemosa*.

**Site and Carbon Stock**

Differences in carbon stock based on site were insignificant for above-ground, below-ground, and total carbon stock. These results were unexpected due to trends of above-ground biomass, and subsequently aboveground carbon stock, increasing inland for mangrove forests (Komiyama et al., 2008). Trends in mangrove biomass based on seaward distance, especially for Caribbean species, are somewhat understudied. These results may reveal evidence towards little effect of seaward distance on carbon stock in the Ground Creek area even though carbon stock varied from 12.64 Mg C ha$^{-1}$ to 838.88 Mg C ha$^{-1}$. In mangrove carbon stocks of Tanzania, for instance, there is not a significant relationship in above-ground carbon and seaward distance even though above-ground carbon ranged from 11 and 55 Mg C ha$^{-1}$ (de Jong Cleyndert et al., 2020). Carbon stock calculations in this study were fairly consistent with a previous study in Bocas del Toro that used 64 10 x 10 m plots over four locations that showed 59 Mg C ha$^{-1}$ at the fringe, 22 Mg C ha$^{-1}$ in seaward areas, 8.3 Mg C ha$^{-1}$ in dwarf forests, and 194.3 Mg C ha$^{-1}$ in landward forests (Lovelock et al., 2005). This study found variation in forest structure was predictable depending on intertidal zone, revealing that similar relationships may be found with a larger sample size. There are many limitations to data on Ground Creek due to a small sample size of 15 plots and limited access to the mangroves. Allocation of *fringe*, *middle*, and *back* sites were arbitrary based on study area as it was impossible to access the full extent of the inland mangrove forest.

Although data is not statistically significant, the absence of *L. racemosa* in the *fringe* area is apparent. This is consistent in zonation patterns of Caribbean mangroves, as *R. mangle* often inhibits the niche along the seaward edge (Lonard et al. 2020). The *back* site has over 600 times more average Mg C ha$^{-1}$ in above-ground carbon stock than *fringe* or *middle* sites, largely due to the presence of *L. racemosa*, shown by only 1 Mg C ha$^{-1}$ increase in average carbon stock between *fringe* and *back* sites when looking only at total carbon stock, which excludes *L. racemosa* (Table 1). *L. racemosa* carbon stock is highest in the *back* site with over 265 more Mg C ha$^{-1}$ than the *middle* site, although there were only 4 individual trees in the *back* compared to 6 in the *middle* site (Figure 5). *L. racemosa* carbon stock per tree appears to be much higher in *back* sites, largely due to the presence of two multiple-trunked large individuals in the *back* site. *R. mangle* tree counts ranged from 41 in *fringe* to 21 in *back* sites, but *R. mangle* above-ground, below-ground, and total carbon per hectare stayed fairly consistent throughout site (Table 1). Although there was no significant difference in individual carbon stock of *R. mangle* based on carbon stock, average carbon stock per tree generally increased from *fringe* to *back* (Figure 8). *BG* biomass for *R. mangle* is highest in the *back* site as well. As tree counts decrease from *fringe* to *back* sites, carbon stock of individual trees increase, possibly showing that *R. mangle* compensates for loss in numbers by increasing biomass (Lovelock et al., 2005). More inquiry is needed into the relationship of tree abundance and biomass for *R. mangle*, as carbon stock per hectare remains unchanged across sites zones, possible due to increasing biomass. Significant
differences in AG carbon stock based on site further support physiological compensation dynamics for *R. mangle* and niche partitioning for *L. racemosa* (Table 2).

**Salinity and Carbon Stock**

The distribution of plot salinity as seen in Figure 4 show a high salinity zone at the fringe areas with all measurements of salinity lying between 20-30 ppt. More variation follows between following plots, which do not show a consistent salinity gradient beyond that point. Variation in sampling days, tides, and rainfall may have limited the accuracy of this gradient, or salinity may be constantly fluctuating in these areas and influenced by many factors. Long term site-specific salinity data for Ground Creek mangrove forest creeks is unavailable, adding limitations to accurate assessment of salinity gradients.

Differences in Carbon Stock based on salinity were insignificant for above-ground, below-ground, and total carbon stock. Salinity generally has a direct negative influence on carbon stock, but variables can vary on environmental conditions (Ahmed 2023). Many studies have looked at the influence of salinity on growth parameters but few examine the direct influence of salinity carbon stocks per hectare. Previous study found significant difference in AG, BG, and total carbon stocks across distinct salinity gradients of oligohaline (<14 ppt), mesohaline (14-25 ppt), and polyhaline (>25 ppt) zones using 60 sample plots in Bangladesh (Ahmed et al., 2022). Similar relationships may be found using more sample plots, or possibly the more subtle salinity gradients of Isla Colón could have less direct effect on mangrove carbon stocks.

It may be possible that despite impaired growth parameters, the collective forest compensates by more concentrated forest in areas of high salinity (Chowdhury et al., 2019). Total above-ground biomass is highest in 10-20 ppt, largely dominated by *L. racemosa*, and lowest in 20-30 ppt, which is congruent with the idea that higher salinities can reduce biomass, although not statistically significant (Table 1 and Figure 5). The absence of *L. racemosa* in the highest salinity zone is consistent with a decline of salt-intolerant climax species and dominance of the salt tolerant *R. mangle* (Ahmed et al. 2022). *L. racemosa* success may depend more on zonation than salinity when salinity ranges from 0-20 ppt, as they did not inhibit salinity zones of over 20 ppt and showed more differences of carbon stock based on site than salinity (Table 1). Research has been established indicating that large-diameter trees loose tolerance to salinity as they grow, which may explain slight differences in carbon stock and tree size over salinity zones (Ahmed et al. 2023).

Salinity is also known to lower canopy height, nutrients, and growth dominance (Ahmed et al. 2022). These parameters were not examined in this study, and these factors may have more of a statistical significance and be more consistent with the prior literature. Poor site quality favors smaller trees, but this may not lower overall biomass of the area depending on concentration of trees (Ahmed et al. 2023). *R. mangle* carbon stock per hectare was highest in the salinity zone of 10-20 ppt, and significant differences were found between sites in terms of individual tree carbon stock (Table 1, Table 2). BG biomass is highest for *R. mangle* in the 10-20 ppt zone as well. It is possible that *R. mangle* trees find a balance of biological trade-offs in mid-range salinity (Iwuala et al. 2023). Prior studies show that salinity can actually enhance
below-ground carbon stocks, which is not congruent with this study due to the lowest below-ground carbon stocks from the 20-30 ppt zone (Rahman et al. 2014). Tendencies in AG carbon stock per tree between site and salinity zones tend to be consistent on a relative basis for *L. racemosa* and *R. mangle*, showing that trees may thrive under similar factors under certain conditions (Figure 8 & Figure 9). Overall, salinity may not be a determining factor into the carbon stock per hectare of Ground Creek mangrove forests, but further inquiry into the data and research is needed especially due to significant differences for carbon stock per tree.

**Limitations**

The largest limitations of this study were time, sample size, equipment, and forest access. Because only 15 plots were sampled in one study area, data may not be representative of the studied mangrove forest or those in close distance. Plots were only accessible by boat which allowed a limited daily sampling period. With a 3 m radius, plots are smaller than in a typical study of carbon stock and no subplots were established. Only mangroves of over 3 cm DBH were counted so there may be a lack of representation in carbon stock figures of younger or dwarfed species. Access to the forest was limited along a cut pathway through the mangroves and the full inland extent of the mangrove forest could not be reached. Fully random sampling was difficult in this area due to thick mangrove roots and morphology of mangrove path.

Measurement of salinity values was very limited by equipment and time. Salinity measurements were taken on different days and during different tide cycles which may have had a large impact on individual salinity readings. Although plots taken on different days were taken at similar times, tide cycles change daily. Frequent rains during the study period may have caused water to be less saline than normal on certain days. Since saline was a large determining factor in the study, these differences may have highly influenced the statistical results. Long-term and consistent salinity data would be useful for future study.

Lack of a below-ground biomass equation for *L. racemosa* also caused a lack of ability to fully compare the total biomass of the mangrove forest in this area.

**CONCLUSION**

The objective of this study was to see if there is a variation in the carbon stock capacity of *R. mangle* and *L. racemosa* mangrove forests near Boca del Drago based on water salinity and coastline proximity. Results from this study are a first step in understanding future impacts of sea-level rise and changing wetland distribution in mangrove forests around Boca del Drago and Ground Creek. No statistically significant differences in carbon stock per hectare were found based on salinity and coastline proximity, suggesting that changing salinity levels may not be a threat to mangrove forests in the area, and that forests may compensate for the biological tradeoffs of increased salinity levels. Large numerical differences were seen across carbon stock based on site, salinity, and species suggesting that relationships may be found with further study.

Further support for this theory comes from significant differences in *R. mangle* carbon stock per tree based on salinity zone, suggesting that salinity may have some impact on carbon stock on an individual tree level. *R. mangle* trees may find a balance of biological trade-offs in
mid-range salinity. More inquiry is needed into the relationship of tree abundance and biomass for *R. mangle*, as carbon stock per hectare remains unchanged across sites zones, possible due to increasing biomass. Physiological setbacks of individual trees in high salinities may be compensated for in terms of carbon stock per hectare because of increased concentration of trees, although these relationships should be examined further. *L. racemosa* showed the most sensitivity too salinity zone and site suggesting it may be most at risk for future changes in land distribution and salinity levels. Overall carbon stock is similar to other comparable Neotropical mangrove forests, but *R. mangle* carbon stock tends to be low, possibly pointing to a prohibiting factor that could be examined in the future.

Future study is needed to draw further conclusions about impacts of sea level rise and land change on forests in this area. There is a need for more assessment of carbon stocks per hectare of mangrove forests in the area, especially looking at the direct influence of salinity. Future studies should look at a wider study area, including an extension of the study area in Ground Creek and other forests in the area. Further information on salinity gradients and rate of salinity rise over time in Bahía Almirante and inland mangrove forests need to be evaluated. More research on individual biological parameters in relation to total carbon stock of mangrove forests in the area is necessary to further inquire into consistencies in carbon stock across the study site. Future study should account for other influencing factors on carbon stock such as nutrient availability and anthropogenic influence.
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