The effects of seaward distance on above and below ground carbon stocks in estuarine mangrove ecosystems

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Abstract

Background: Mangrove forests have gained recognition for their potential role in climate change mitigation due to the carbon sequestration of the productive ecosystems and storage in the sediments that are trapped by the mangrove tree roots and pneumatophores. Africa hosts about 19% of the world's mangroves, yet there are relatively few studies that have examined the carbon stocks of African mangroves, and the studies available report great differences among sites and amongst the different pools of carbon stocks, particularly between the above ground carbon stored in trees (AGC) and organic carbon stored within the sediment - ‘soil organic carbon (SOC)’ and none considered the effects of seaward distance. We investigate if AGC and SOC carbon stocks differ with increasing seaward distance for estuarine mangroves in Tanzania and, how our results compare to those reported elsewhere across Africa.

Results: AGC ranged between 10.9-54.9 Mg C ha\(^{-1}\), but was not significantly affected by seaward distance. SOC for 0-1m depth ranged from 153.7-483.6, with a mean of 301.7 Mg C ha\(^{-1}\). SOC was significantly negatively correlated with seaward distance, which is different from studies in Micronesia and the Indo-Pacific. Mangrove type (estuarine/oceanic), soil erosion and soil depth may explain these differences We note important methodological differences in previous studies on carbon stocks in mangroves in Africa.

Conclusion:

This study indicates that seaward distance has an important effect on SOC stocks in the Lindi region of Tanzania. There is the need to standardise methodological approaches for mangroves in Africa, to report seaward distance and to describe the type of mangrove stand to make results easily comparable across sites and to assess the true value of Blue Carbon in Africa. We recommend focusing on trees >10cm diameter for AGC, and sampling soils to greater than 1m depth for SOC, which would provide a more complete assessment of the potentially considerable mangrove carbon store.

Background

Mangroves are salt-tolerant forests that grow at the interface between land and sea in tropical and sub-tropical latitudes (1,2). Mangroves provide a number of important ecosystem services to humans; in addition to being an essential source of building materials and firewood, they act as irreplaceable nursery habitats for economically and ecologically valuable marine species (3–5) and provide coastal protection from waves and storms (6,7). Additionally, they improve water quality through nutrient recycling and sediment regulation (5,8). More recently, mangrove forests have gained recognition for their potential role in climate change mitigation due to the carbon sequestration in trees and storage in the sediments that are trapped by the mangrove tree roots and pneumatophores (8–10). Together with seagrass beds and salt marshes, mangroves form the ‘Blue Carbon’ ecosystems (11) which are attracting increased attention as one way to store carbon and reduce the speed of global warming. Although coastal vegetated habitats represent a much smaller area than terrestrial forests, their total contribution to long-term carbon sequestration is comparable to carbon sinks in terrestrial ecosystem types (10). Like many other forests and woodlands, because primary production exceeds respiration, mangroves are net autotrophic ecosystem and produce more energy than they utilise (12,13) and therefore function, if not degraded, as one of the most effective global CO\(_2\) sinks (14). Mangroves have the greatest carbon stock among the Blue
Carbon ecosystems, storing 6.5 Pg carbon globally, whilst saltmarshes and seagrass meadows stock 2.0 and 2.3 Pg carbon, respectively (15).

Despite their importance, over the past 60 years more than one third of the world’s mangroves have been lost (16), but the history of degradation extends through centuries (17). Coastal development, aquaculture expansion and overharvesting for boat building (timber and poles), building material and firewood are the primary anthropogenic drivers of loss of mangroves (5,18–20). Natural drivers of loss are also important and include hydrological dynamics and the impacts of extreme weather events, sea-level rise and salt water intrusion of coastal wells that used to be freshwater wells, which are projected to increase in frequency and magnitude due to climate change (6,20). As climate change mitigation has come to the fore of international scientific and political discussions (21), there has been an enhanced focus on conserving and restoring degraded ecosystems that are known to function as carbon sinks (10,21), through mechanisms such as Reducing Emissions from Deforestation and Degradation (REDD+) and other United Nations Framework Convention on Climate Change (UNFCCC) mechanisms increasingly aim to support livelihood developments and mitigate climate change impacts through Green Climate Fund investments (22). The significance of ‘blue’ carbon processes, pools and sinks need to be centrally factored into decision making at all scales – from global policy issues on climate change, through to resource management at sectoral (e.g. fisheries) and national levels, and even as a criterion in the selection of prospective Marine Protected Areas (23).

Africa hosts about 19% of the world’s mangroves, yet there are relatively few studies that have examined the carbon stocks of African mangroves (24), and the studies available report great differences among sites and amongst the different pools of carbon stocks, particularly between the above ground carbon (AGC) stored in the trees and the organic carbon stored within the sediment - ‘soil organic carbon (SOC)’. For example, SOC estimates for 1m depth range from 122 Mg C ha\(^{-1}\) in Republic of Congo (25) to 342 Mg C ha\(^{-1}\) in Liberia (24). In a single estuary in Liberia, total ecosystem carbon stocks (AGC+ SOC) varied by over fourfold, ranging from 366 to 1,485 Mg C ha\(^{-1}\) (Kauffman et al. 2020).

In mangroves, high SOC is linked with slow decomposition of organic matter due to waterlogged saline environments which impedes microbial degradation (10,16,26,27). Differences in SOC can be explained by the differences in waterlogging, nutrients and salinity, linked to whether mangroves are classified as oceanic, estuarine, riverine or interior, and also to salinity/nutrient changes related to tidal inundation and seaward distance. Two recent reviews on SOC in mangroves pointed out at the importance of considering geomorphological processes in distinct coastal environmental settings (28,29). In Indonesia, Weiss et al. (2016) note the importance of both the relative seaward distance and the knowledge of the oceanic or estuarine nature of the mangrove ecosystem in estimating the SOC stocks (30). A recent meta-analysis of mangroves from 190 sites showed that lower mean porewater salinity (related to mangrove type and seaward distance ) also affects AGC (31), as in less saline environments more carbon is allocated to aboveground biomass than to roots (28). However, few available studies for Africa report the type of mangroves studied, and none mention seaward distance. The recent review by Kauffman et al. (2020) only included data from Senegal, Liberia and Gabon.

Considerable variation in above-ground carbon in mangroves (AGC, the part stored in aerial parts of trees) has been reported for Africa: from 26 C Mg ha\(^{-1}\) in Guinea-Bissau (32) to 237 Mg C ha\(^{-1}\) in Cameroon (25) (AGC estimated from above ground biomass using a conversion fraction of 0.47). Differences in AGC estimates among sites and countries may be related to structural attributes, such as variable stem density (e.g. ranging from <1000
stems ha\(^{-1}\) in Gabon South to >35,000 stems ha\(^{-1}\) in Senegal (24) but also to different sampling approaches, including minimum tree diameter sampled (33), or the equation used to estimate tree biomass (34). Again, waterlogging or salinity, which affects decomposition rates, and therefore nutrients available for plant growth, might also explain some of these differences. In Qatar, Son et al. (2018) (35) found that AGC increased as seaward distance increased.

This study is the first in Africa to investigate the effects of seaward distance on estuarine mangrove carbon stocks. We address four major research questions: do carbon stocks differ with increasing seaward distance? Are these differences only observed in AGC and SOC? What are the effects of using ≥ 5.0 or ≥ 10.0 cm diameter thresholds on AGC estimates? And, how do AGC and SOC compare to those reported elsewhere in in Africa? We hypothesized that AGC and SOC would increase with increasing seaward distance. We also hypothesized that the effects of using ≥ 5.0 or ≥ 10.0 cm diameter thresholds on AGC estimates would be highly significant, as current mangroves ecosystems are generally characterised by having numerous small stems due to historical and ongoing human use. Through this case study, we suggest standardised methods for future mangrove research in Africa.

**Methods**

**Study area**

This study focused on the estuarine mangroves of the Lindi region in Tanzania. Lindi has approximately 4,000 ha of mangroves, of the 108,000 ha currently found in Tanzania (5) (Figure 1). Although this figure should be seen as an estimate as the area of mangroves is not fully known and depends on how these are accounted for; for example UNEP-WCMC estimated 127,200 ha, in 2000, Francis and Bryson estimated 133,500 ha in 2001 (36,37). The average annual temperature in Lindi is 25.7 °C, mean annual rainfall is 1200 mm yr\(^{-1}\), with a rainy season that extends from October to June (38). The coastal soils in the region consists of alluvial and sandy soils (39). Mangrove ecosystems in Tanzania have long been exploited by humans. Before and during the colonial era, poles and timber were used as building materials for boats and houses by Arabic traders (40,41). Mangroves continue to be exploited for firewood and poles, but large timbers requited for boats are no longer available. In some parts of Tanzania, such as the Rufiji Delta, mangroves are cleared to provide space for rice paddy production and shrimp farming (42). In the Lindi region, mangroves are mostly used as source of building poles for houses, and fuelwood for lime burning to create cement (42).

**Data collection and analysis of soil samples**

Four 1-ha plots were established along a gradient through the mangrove forest from land to sea (Figure 1). In each plot, the diameter at breast height (DBH; 1.3m), the species and the height were recorded for all stems ≥ 10.0 cm. The same variables were recorded for smaller stems (5.0-9.9 cm DBH) in five subplots of 20 x 20m (subplots 1, 5, 13, 21 and 25). Stem heights for the trees ≤ 10.0 m height were measured parallel to tree from the base to the highest point using a pole of known height (43). Heights of the trees above 10m were measured using a laser distance meter (Leica disto). For species which were not identified in the field, a voucher specimen was collected and then taken to the National Herbarium in Arusha for further identification. In total, we sampled 2071 stems ≥ 10.0 cm of seven species, and 970 stems 5-9.9 cm of the same seven species.
In each plot, litter biomass was recorded as follows: first, 1m$^2$ quadrats were established in the corners of subplots 1, 5, 21, 25 and at the centre of the subplot 13. Litter materials (excluding dead wood) were collected from the five (1 m$^2$) established quadrats and the total wet weight was taken. Sub-samples (50%) were taken from the whole sample, weighed before packing and transported to the lab (44,45). The wet combustion method was used to estimate percentage organic carbon from the dry mass of the litter (46). A portion (50%) of the litter was oven dried to constant weight at 70.0 °C to determine the dry mass (47) and grounded to fine powder for total organic carbon determination. The total organic carbon was determined using the wet combustion procedure as described in Nelson & Sommers (48). The amount of carbon in each sample was calculated as the product of percentage organic carbon and dry mass (47).

A pit of 1m depth was dug 15m away from each plot. Soil samples were collected using a metal ring (98.12 cm volume) inserted into the sediment in a pit dug from a profile at different depths: 0-15cm, 16-30cm 31-60cm and 61-100cm. Soil samples were transported to the lab, air dried, grounded and passed through a 2mm sieve to remove stones and gravel. SOC was determined based on the Walkley-Black chromic acid wet oxidation method (49) and the results were expressed as the % organic carbon. Computation of SOC density was based on soil mass per unit area obtained as the product of soil volume and soil bulk density determined from the bulk density samples in (g/cm$^3$).

**AGC estimations and Data Analysis**

Above ground biomass of all stems > 5.0cm DBH (AGB, Mg ha$^{-1}$) was computed using different biomass equations, including generic equations derived by Komiyama et al. (2008) and Chave et al. (2014) (50,51) (see Additional Information). We report here the values of AGB and below ground biomass (BGB) using the multispecies equations developed by Njana et al. (2015), as these equations were derived using species from coastal regions in Tanzania, including Lindi (34). AGC and BGC (Mg C ha$^{-1}$) stocks were determined by using a carbon fraction of 0.47 and 0.39, respectively (52–54). We computed AGC using stems $\geq$ 10.0cm (named AGC$_{10}$) and using stems $\geq$ 5.0cm (named AGC). For each plot we computed stem density (stems ha$^{-1}$), percentage of small stems (those 5.0-9.9cm DBH), basal area (in m$^2$ ha$^{-1}$), mean diameter (cm), mean height (m), species’ richness (number species present in the plot), species’ dominance (in terms of basal area), and species’ contribution to plot-level AGC (in percentage). We also investigated the conservation status of the species we found, using the IUCN Red list (https://www.iucnredlist.org/).

To compare our findings with those reported elsewhere across Africa, we carried out a literature review searching for mangrove carbon estimates across Africa Statistical analysis was carried out using R Studio (version 3.6.0). Pearson correlation coefficient was used to determine correlation between seaward distance and AGC or SOC. Paired t-tests were used to compare significant differences between AGC and AGC$_{10}$.

**Results**

**Above ground carbon stocks**

AGC ranged between 10.9 and 54.9 Mg C ha$^{-1}$, the mean being 26.8 Mg C ha$^{-1}$ (Table 1). AGC was not significantly positively correlated with seaward distance (Pearson's correlation, $r^2=0.4$ p=0.3, df=2), nor was BGB (Pearson's correlation, $r^2=0.4$ p=0.4, df=2). Stem density, basal area, mean diameter and mean height increased
with increasing distance to the sea (Table 1). The percentage of small stems (5.0-9.9 cm DBH) was greatest closest to shore (58%, see Table 1). Using a 5.0 cm diameter threshold significantly affects AGC estimates (paired t-test, df = 3, p-value = 0.02), although in plots 2 and 4 there was less than a 10% difference in AGC & AGC10. The contribution of litter to the total carbon stocks was negligible in all plots (Table 1). Species’ richness and dominance, and contribution to AGC changed with distance from the sea (Figure 2). Overall, only four species were observed (Table 1), and there were no differences in species richness if a 5.0 cm or a 10.0 cm diameter threshold was used. All the species found are considered Least Concern according to IUCN Red List.

**Soil organic carbon stocks**

Soil Organic Carbon for 0-1m depth ranged from 153.73 to 483.63 Mg C ha⁻¹, the mean being 301.7 Mg C ha⁻¹ (Figure 3). Contrary to AGC, SOC was significantly negatively correlated with distance towards the sea (Pearson’s correlation, r²=1.0 p<0.05, df=2). SOC in each layer (0-15cm, 15-30cm, 30-60cm and 60-1m) decreased with increasing distance from the sea (Figure 3).

**Carbon change with distance to the sea**

Overall carbon stocks were significantly negatively correlated with distance to the sea (Pearson’s correlation, r²=0.9 p<0.05, df=2), with 510.1 Mg C ha⁻¹ in plot 1, closest to the sea and 251.9 Mg C ha⁻¹ in plot 4, furthest from the sea (Table 1).

**Comparison with other studies in Africa**

The literature review of available mangrove studies across Africa is presented in Table 2. Important differences were observed in plot shape and size sampled, minimum tree diameter recorded, the equations used to estimate biomass and the soil depth sampled. Few studies report if mangroves sampled were estuarine or oceanic and none reported seaward distance. Overall, our estimates of AGC (10.9-54.9 Mg C ha⁻¹) are similar to those reported elsewhere in Tanzania (33.5 and 40.5 Mg C ha⁻¹, Table 2), but our estimates of SOC (153.7-483.6 Mg C ha⁻¹) are significantly higher than those previously reported for Tanzania, (98.6 Mg C ha⁻¹) as we sampled at a greater depth (1m compared to 60cm).

**Discussion**

**Above ground carbon stocks**

AGC increased with increasing seaward distance, as has been reported in Qatar and Micronesia and in worldwide reviews (35,50). However, the correlation between AGC and seaward distance was not significant, possibly due to the low number of plots or because of the lower AGC value in plot 3 which may have experienced greater exploitation pressure. Plots closest to shore are likely to experience greater tidal inundation and salinity, lower decomposition rates, and therefore, less nutrients being available for tree growth (50). With increasing seaward distance, increasing mean diameter and height at plot level, stem density and basal area, and a change in species composition and abundance, translated into increased AGC.
Although there was a difference using a 5.0 or 10.0 cm diameter threshold which agrees with savannah ecosystems (55) but differs from flooded forest and lowland terra firma rainforests (33,56), the difference was particularly small when compared to SOC and the total carbon stock. Despite having little effect on AGC, some authors have highlighted the importance of using 5.0cm thresholds when studying tree diversity patterns (56) as some species are only found in small diameter classes (55). In mangroves this effect of small diameter classes on species richness is unlikely to be relevant, because of the limited number of species found in mangrove ecosystems (we only report seven). Therefore, for mangrove ecosystems with numerous stems > 10.0cm, a 10.0cm diameter threshold is recommended, which is a less time-consuming approach during fieldwork. Note that numerous studies across African mangrove ecosystems have used smaller diameter thresholds (Table 2).

The AGC values reported in this study are similar to other Tanzanian studies but lower than for example in the Democratic Republic of Congo (25). This could be attributed to the combination of: i) different methods used to sample AGC (Table 2), ii) different environmental characteristics (e.g. ocean vs estuarine, different rainfall patterns, impacts of cyclones), but particularly important is likely to be iii) the long and pervasive history of exploitation of mangroves in Tanzania (40,41). Although the plots sampled are relatively inaccessible from nearby villages, it is likely that they are recovering from a past disturbance, as the whole coast of East Africa has a long and pervasive history of mangrove exploitation dating back through the evolution of the Swahili coast over the last millennium, with e.g. mangrove wood extensively used for boat building, construction and export into the Middle East [17]. This historical disturbance is likely to be the reason why we found few stems > 30.0cm diameter with all the large mangrove trees being removed. This is quite a key finding as it suggests that that current AGC quantified is significantly below the potential and could be significantly increased with appropriate control of mangrove timber harvesting combined with future management of the mangrove ecosystem that focuses on maintaining integrity of the sedimentary environment.

**Soil organic carbon stocks**

SOC stocks decreased with increasing distance from the sea, which is different from studies in Micronesia, where SOC increased with increasing seaward distance because of greater soil depth (57). Donato et al. (2011) found no change in SOC with increasing seaward distance in estuarine and oceanic mangroves in the Indo-Pacific – but all their plots were within 200m from the seaward edge. Soil erosion and soil depth are other important factors determining SOC along seaward gradients (19). In our study area the first plot we sampled was 4 km from the shoreline where soil erosion was not an issue. Beyond the zone of soil erosion, plots closest to the shore, which experience greater tidal inundation (and salinity), have slower decomposition rates, and therefore, higher SOC stocks. Mangrove's sediments can store high amounts of carbon due to complex root structures, high sedimentation rates and waterlogged conditions which impedes microbial degradation and slows decay [16, 25].

SOC stocks reported in this study are significantly higher than other studies in Tanzania (which only sampled 60cm depth (58)), but they are within the range reported by other studies in Africa (Table 2). Similar to AGC, there are no standardised methods for sampling carbon stocks in mangrove sediments: variable depths have been sampled, using different approaches. Given the high amount of carbon stored in soils (as SOC), we recommend sampling mangrove sediment at least up to 1m. Jones et al (2015) reported about 100 Mg C ha\(^{-1}\) in the sediment layer 1 to 1.5m in Madagascan mangroves (20), which suggests that sampling to greater depths would yield a true assessment of the extent of the SOC. Kauffman *et al.* (2020) also highlighted the importance of including soil profiles >1m depth in carbon stock estimates (31). Indeed, palaeoecological investigations from Tanzanian
mangrove systems clearly demonstrate that the sediment layer extends up to c. 4.0 meters (59,60); thus the high SOC value currently recorded down to 1m is likely to be much greater if the full sediment system is assessed and the true value of mangling the mangrove SOC realised by targeting above ground interventions to minimise any below ground disturbance. As SOC stocks were much greater than AGC, even further from the seashore where AGC increased, we recommend focusing on more extensive sampling of SOC so that the major repositories of carbon though soils can be quantified and feed into initiatives such as REDD+.

**Conclusion**

This study has shown that seaward distance has an important effect on both AGC and SOC stocks in the Lindi region of Tanzania. It has also highlighted that mangrove carbon studies available for Africa do not describe type of mangrove (estuarine, oceanic), or consider seaward distance, and that there are no standardised sampling methods for AGC or SOC, which makes comparisons across sites challenging, and the true value of the Blue carbon store difficult to assess (19). Although more research on the environmental factors behind seaward distance are needed (e.g. salinity, flooding tidal periodicity, nutrients and soil porosity), we highlight that seaward distance should be reported in mangrove studies in the continent. We also recommend focusing on trees >10.0cm diameter, and sampling soils to greater than 1m depth which would provide a more complete assessment of the mangrove carbon store. Using large plots, which reduce sampling uncertainties (61), and sampling tree height in the field, which is known to improve AGC estimates (61), are also advised. Preferably, permanent plots should be established, so that forest dynamics and response to droughts or cyclones, can be monitored. The plots in Lindi are established as permanent sample plots and should be monitored to allow for insights on carbon sequestration in the nearby future.

Overall, mangroves in Lindi store a substantial amount of carbon, particularly, in the sediment. Once disturbed, SOC cannot be regained over meaningful human timescales because mangrove sediment deposits take thousands of years to form (16,59,60). Because SOC is protected by the above ground vegetation, mangrove tree conservation is of key importance. Although current efforts have been made to integrate mangroves into Tanzanian REDD+ readiness assessments, their full potential has not been recognised as the Forest Reference Emission Level Assessment (FREL, an assessment for the REDD+ readiness phrase, submitted by Tanzania to the UNFCCC in early 2018) does not include SOC in its estimations (62). If Tanzania - and other African nations - are to fully benefit from carbon offsetting schemes, it is essential that the contribution of mangrove sediment carbon is considered.

**Declarations**

**Ethics approval and consent to participate**

All permits were granted from the Tanzania Commission for Science and Technology (COSTECH)

**Consent for publication**

Not applicable

**Availability of data and material**

The datasets analysed during the current study available from the corresponding author on reasonable request
Competing interests

The authors declare that they have no competing interests

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Authors' contributions

- Conceived and designed the study: RAM and GDJC
- Data collection in the field: HS
- Analysed the data: GDJC, ACS, HS
- Contributed reagents/materials/analysis tools: GDJC, ACS, HS
- Wrote the paper: GDJC, ACS, RAM
- Provided input on manuscript: all co-authors

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Abbreviations

| Abbreviation | Explanation |
|--------------|-------------|
| AGC          | Above ground carbon |
| GB           | Below ground biomass |
| DBH          | Diameter at breast height |
| REDD+        | Reducing Emissions from Deforestation and Degradation |
| OC           | Soil organic carbon |
| UNEP WCMC    | United Nations Environment Programme World Conservation Monitoring Centre |
| UNFCCC       | United Nations Framework Convention on Climate Change |

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Figures
Figure 1

(a) Tanzanian coastline with mangroves highlighted in green; (b) Close-up of Lindi estuarine mangroves with study plots (black circles); (c) Study area in Tanzania; Mangrove coverage extracted from Bunting et al., (2018).

Figure 2

Contribution to plot level above ground carbon (AGC) (kg) of the different species found in each plot (there is increasing seaward distance from a-d). SA: Sonneratia alba, AM:Avicennia marina, RM: Rhizophora mucronata, BG:Bruguiera gymnorhiza, LR: Lumnitzera racemose, CT: Ceriops tagal, XG: Xylocarpus granatum.
Figure 3
Soil carbon stocks across the four plots sampled along a seaward gradient.

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