COASTAL CLIMATE CHANGE MITIGATION AND ADAPTATION THROUGH REDD+ CARBON PROGRAMMES IN MANGROVES IN MOZAMBIQUE: PILOT IN THE ZAMBEZI DELTA

COMPONENT: DETERMINATION OF CARBON STOCKS THROUGH LOCALIZED ALLOMERTIC EQUATIONS

DRAFT REPORT V1

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Summary

Resilient aquatic ecosystems not only play a crucial role in binding carbon, they are also important to economic development, food security, social wellbeing and provide important buffers against pollution, and extreme weather events. While mangroves support livelihoods of millions of people in the tropics, these blue carbon sinks also sequester about five times more carbon than any forest ecosystem. These ecosystems, however, are being degraded and disappear at rates 5–10 times faster than rainforests. The Zambezi mangroves have reduced in cover by 50% between 1972 and 2002, which is significant considering that the Delta has about 50% of the total mangrove cover in Mozambique. The objective of this work was to determine specific species densities of the mangroves at the Delta and apply these values in customizing global general allometric equations to facilitate determination of carbon stocks at the site.

Using unsupervised classified SPOT images, sampling transects were determined to run through the different assemblages and ensure a representative sample at the northern part of the Delta. Transects were also selected on the open sea side (oceanic) mid-zone adjacent to the northern arm of the Zambezi River (estuarine) and landward sites (Nhaimbo and Temane) to capture any gradients in carbon across the intertidal. Vegetation surveys were conducted using classical methodologies. From forest surveys, the species occurring and their respective diameters at breast height (dbh) were determined. Based on this, for each species, trees were selected at dbh intervals of 10cm starting from 5cm as the minimum. The number of trees harvested per a species depended on its diameter range from the forest surveys. The trees were felled at the base, branches removed and the trunks sliced to obtain respective wet weights, sub-samples taken and oven dried to obtain dry weights and respective volumes. This allowed determination of whole tree dry weights and volume from which respective densities were computed. Using global general equations, above ground biomass (AGB) and below ground biomass (BGB) of all species encountered in sampled plots were determined. Appropriate conversion factors were applied to obtain carbon. Soil organic carbon (SOC), which is a major pool was obtained by coring up to 100cm and sub-samples taken from pre-determined intervals. Sub-samples of the soil samples were oven dried and then ashed at 450^{o}C. A conversion factor was used to obtain carbon from organic matter.

Overall biomass in the area was 479.87±59.30 Mg/ha composed of 344.95±43.30 Mg/ha (72%) above ground biomass (AGB) and 134.92 ± 16.07 Mg/ha (28%) below ground biomass (BGB). Nhamacara had the highest biomass (819 Mg/ha), while Mwandua had the lowest (142 Mg/ha). The average quantity of soil organic carbon stored in the mangrove sediments in the entire study area amounted to 321.00±20.15 Mg/ha. The landward sites had the highest SOC, followed by the estuarine mangroves (Nhamacara), while the oceanic mangroves had the lowest SOC. Total organic carbon for the ecosystem under study was estimated at 534.12±29.19 Mg/ha, with 160.50±20.17 Mg/ha in the aboveground biomass, 52.62±6.27 Mg/ha in the root biomass and 321.00±20.15 Mg/ha in the soil pool. Soil carbon accounted for about 60% of the entire ecosystem carbon pools while above-ground stem and below-ground root carbon accounted for about 30% and 10%

respectively. The highest ecosystem carbon stock (672.29±54.08 Mg/ha) was estimated for the forest area in Nhamacara, and the least carbon density of 175.91±34.08 Mg/ha was estimated for the forest area in Mwandua, suggesting that estuarine mangroves had the highest carbon density.

Despite loosing about 50% of the mangroves for the last about 50 years, these mangroves still have high potential for carbon storage. The high rate of degradation offers high potential for additionality to motivate a REDD+ project. However, management regimes which reduce pressure on the forest and support recovery are recommended.

1.0 TERMS OF REFERENCE

WWF is preparing a suite of REDD+ mangrove carbon and other climate change initiatives in the Zambezi delta, Marromeu and Chinde Districts, Mozambique. WWF MCO needed to develop a means of measuring mangrove biomass throughout the Zambezi Delta mangrove stand, as well as to measure soil carbon content and volume in the same area. The lead consultant was responsible for the following:

1.1 Objective

Develop allometric equations (through determination of specific species densities) specific to the Zambezi mangroves, for above ground woody biomass. These equations can vary from country to country and even over smaller areas as well. The Kenya Marine and Fisheries Research Institute has been developing these for Kenya and thus was consulted to provide technical support to WWF MCO and institutional partners (government and university).

1.2 Results

1. Allometric equations to be used for carbon calculations in the Zambezi mangrove stand standardized and shared with in-country scientific community.
2. Mozambican teams with technical capacity to develop allometrics for other areas of Mozambique as well. To develop local capacity, the project worked hand in hand with the University of Eduardo Mondlane and the community at the project site.
3. Above ground biomass (AGB for the mangroves was determined by collecting structural data using standard mangrove survey methodologies and global/general mangrove allometric equations applied after determination of the density of local mangrove species. Determination and application of this density variable customized the global/general equations to the local site. Relevant conversion factors were used to convert the AGB to carbon. Mapping was done based on high resolution satellite imagery to determine total mangrove cover in terms of acreage and species to allow extrapolation of carbon storage potential to the whole forest.
4. Since sedimentary organic carbon forms (50 – 90% of above ground carbon) a major carbon pool in mangroves making this ecosystem generally sequester much more carbon than any terrestrial ecosystem per unit area, SOC was determined through loss on ignition (LOI) and total organic carbon (TOC) assessment.

1.3 Deliverables

1. Output 1 is a first draft digital copy in Microsoft Word format of project report containing:
    a. An outline of the process used to establish the allometric equations;
    b. High resolution satellite maps, in digital form and hard copy, showing sampling sites, strata, and any other important features of the project area relevant to the work at hand;
    c. The allometric equations themselves, with notes on how to apply them;
    d. Determination of mangrove biomass for the study area;
    e. Sedimentary organic carbon for the study site
2. Output 2 is a final draft, of the report, in two digital and two hard copies, incorporating comments and questions and feedback given by WWF during the draft one review.

2.0 INTRODUCTION

Mangrove forests provide an array of ecosystem goods and services, which support the livelihoods of millions of people in the tropics and sub-tropics (Siddiqi and Khan 1996, Kairo et al. 2002, Bosire et al. 2003, Mumby et al. 2004, Dahdouh-Guebas et al. 2005, Bosire et al. 2008). Total economic valuation (TEV) of mangroves based on both marketable and non-marketable ecosystem components (Constanza et al. 1997, Barbier 2000) to account for the ecosystem value of this spatially limited biotope suggest that mangrove ecosystems have very high TEV values of up to US$10 million ha^{-1} per year depending on site productivity and concomitant management regimes (Sathirathai and Barbier 2001, UNEP-WCMC 2006). In the context of climate change, the global role of mangroves as carbon sinks has become more appreciated as they sequester about five times more carbon per unit area than any forest ecosystem (Bouillon et al. 2008, Donato and Kauffman 2011).

Fig. 2.1. Global map showing mangrove distribution (FAO 2007)

According to the most recent estimates, mangroves globally cover about 15.2 million ha straddling coastlines in 123 tropical and subtropical countries (Spalding et al. 2010). Of these, about 1 million ha are in the western Indian Ocean region (FAO 2007) with most of the cover found in Mozambique (Zambezi delta), Madagascar (Mahajamba Bay), Tanzania (Rufiji delta) and Kenya (Lamu) in decreasing order (UNEP/Nairobi Convention Secretariat 2009). However, the decline of these spatially limited ecosystems due to multiple global and local pressures is increasing (Aksornkoae et al., 1993; MacKinnon 1997, Valiela et al. 2001; FAO 2007, Gilman et al. 2008), thus rapidly altering the composition, structure and function of these ecosystems and their capacity to provide ecosystem services essential for the livelihoods of people in most tropical countries (Kairo 2002, Bosire et al. 2004, Mumby et al. 2004, Dahdouh-Guebas et al. 2005, Duke et al. 2007). Deforestation rates of between 1-2% per year have been reported thus precipitating a global loss of 30-50% of mangrove cover over the last half century majorly due to overharvesting and land conversion (Alongi 2002, Duke et al. 2007, Giri et al. 2010, Polidoro et al. 2010).

Ecosystems that can no longer provide their full ecosystem goods and services have a social and economic "cost" to humanity, which can be felt even in areas far away from the degraded ecosystem (UNEP-WCMC 2006). In Thailand, the welfare losses associated with the impacts of mangrove degradation on coastal communities were estimated to be around

US$27,264 to US$35,921 ha^{-1} (Sathirathai and Barbier 2001). Overall, it is the local people who suffer most due to a shortage of wood products, compromised food security, water quality and loss of protection against catastrophic sea events.

2.1 MANGROVES OF MOZAMBIQUE

Africa contains approximately 21% of the mangroves in the world (Murdiyarso and Kauffman, 2011), almost equivalent to the total mangrove cover in Indonesia (22%, Giri et al. 2011). The current estimate of mangrove forest area in Mozambique varies from 368,000 ha (Min.Coord. Env. Affairs, 2009) to 290,000 ha depending on year of assessment and source of information. Based on a recent assessment, 28% of these mangroves occur in the Zambezi delta (Fatoyimbo et al., 2008). Globally, Mozambique ranks 13th in mangrove coverage; equivalent to approximately 2.3% of the global mangrove forest area (Giri et al. 2011).

Mozambique has nine species of mangroves found along the 2,700 km coast having a mangrove cover of 290,000 ha (Fig 1), with the greatest concentration being along river estuaries (Fatoyinbo et al., 2008). The country has many trans-boundary rivers draining into the Indian Ocean thus making the mangroves highly productive. Largest blocks of mangroves are found within central Mozambique, and in deltas and large rivers estuaries (Barbosa et al., 2001), such as in Beira and the Save Rivers where mangroves cover extends up to 50 km inland. The southern coast of the country is characteristically sand-dune coastline, and mangroves are scanty, but well established stands occur on the estuaries of rivers such as Save, Incomati, and Maputo rivers as well as around larger bays such as Inhamabe and Maputo bay. *Avicennia marina* is the most widespread species, and colonises both inner and outer margins of the forests, however towards upper latitudes some inner parts are dominated by *Sonnerati alba and Rhizophora mucronata*, adapted to tolerate small variation in salinity. The northern coast is predominantly coraline, with coral reefs normally bordering the clear water subtidal areas of these locations. Mangroves are common and grow in the estuaries of the rivers, embayments and some areas protected from direct ocean currents. Extensive mangrove areas occurs in the extensive Quirimbas archipelago and several embayments near the archipelago (viz Palma, Ulombi, Mocimboa, Quiretajo). Other important mangrove areas are Pemba town bay with 33,600 ha (Ferreira et al 2009) and the coastline of Nampula. Approximately 50% of Mozambique's mangroves are located at the Zambezi delta (covering almost a 180 km of the coastline), which also represents the single-largest area of mangrove forests in Africa. Along the north and central coastlines, mangroves can be found growing in continuous forms Fig. 2.2), however mangroves are scanty in the southern areas (Taylor et al., 2003).

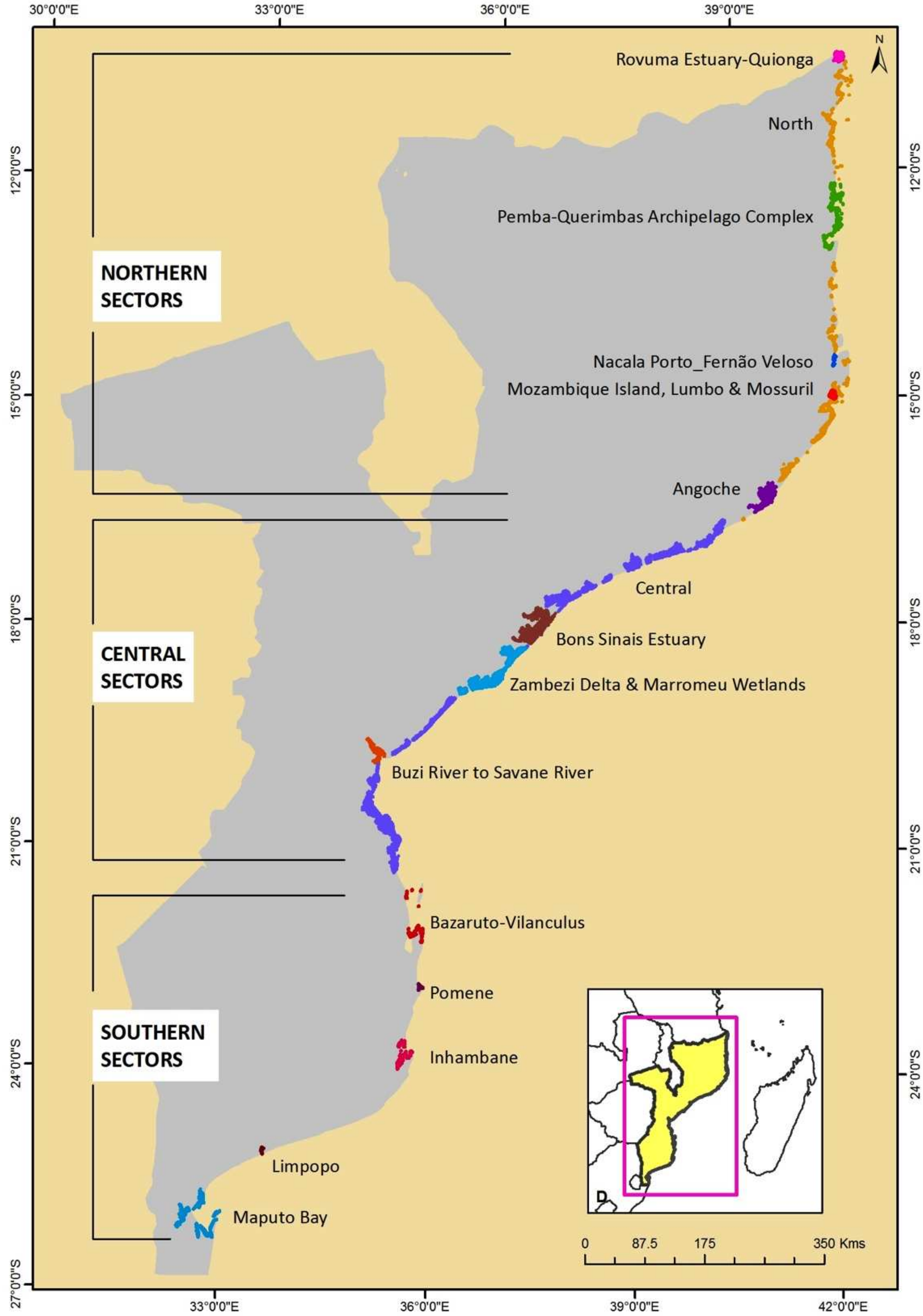

Fig. 2.2. Map of Mozambique showing mangrove locations grouped in sectors (and sub-sectors with different colours) along the coast.

The mangrove forest resource in Mozambique has exhibited substantial declines since 1972 (Fig. 2.3). This trend is particularly evident in the Zambezi delta where there has been an approximate 50% reduction in mangrove coverage, from 1,600 to 811 km^2, implying that based on the loss in mangrove cover at the delta, the country has lost 25% of mangroves over this period. Such a great loss has far reaching ramifications ranging from scarce wood products, coastal erosion, reduced fisheries, degradation of adjacent ecosystems (especially seagrasses due to smothering by sediments) and aggravated carbon emissions. Save for

Sofala and Inhambane areas, other mangrove locations have had relatively much less loss in cover.

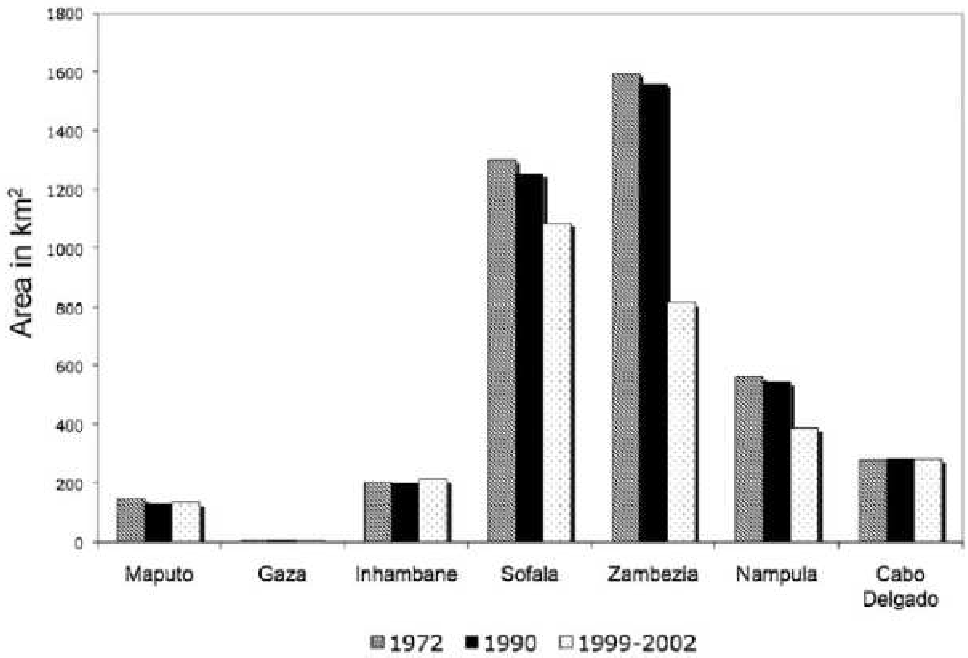

Fig. 2.3. Change in mangrove forest area between 1972 and 2002 (Fatoyimbo et al., 2008).

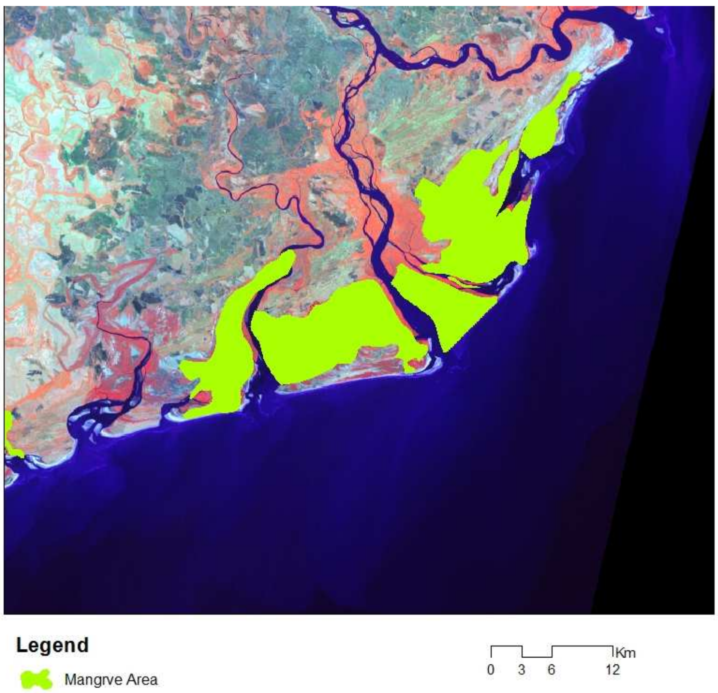

Fig. 2.4. Map of central Mozambique showing the Zambezi area (in green)

This high rate of degradation of these unique deltaic mangroves with enormous potential of providing vast ecosystem goods and services, can be turned into an opportunity under carbon financing schemes especially through reduced emissions from degradation and deforestation including enhanced forest conservation (REDD+). A loss of 50% of mangrove cover over 30 years period ranks on the upper rate (30 – 50%) of mangrove loss globally. Assuming that the same rate of mangrove loss at the delta continues unabated, the future trajectory looks less optimistic.

Fig. 2.5. Mangrove degradation in Central Mozambique due to cyclone (Bosire 2011)

2.2 MANGROVE CARBON

Mangroves and other coastal ecosystems are particularly vulnerable to global climate change. Climate related changes that are predicted to affect mangroves include rising sea levels, increased frequency and intensity of tropical cyclones (i.e., hurricanes, tropical depressions), increased storm surges, ocean acidification, increased severity and frequency of ENSO events and changes in freshwater flows. Coupled with the high rates of land conversion, mangroves are among the most vulnerable forest ecosystems in the world's tropics.

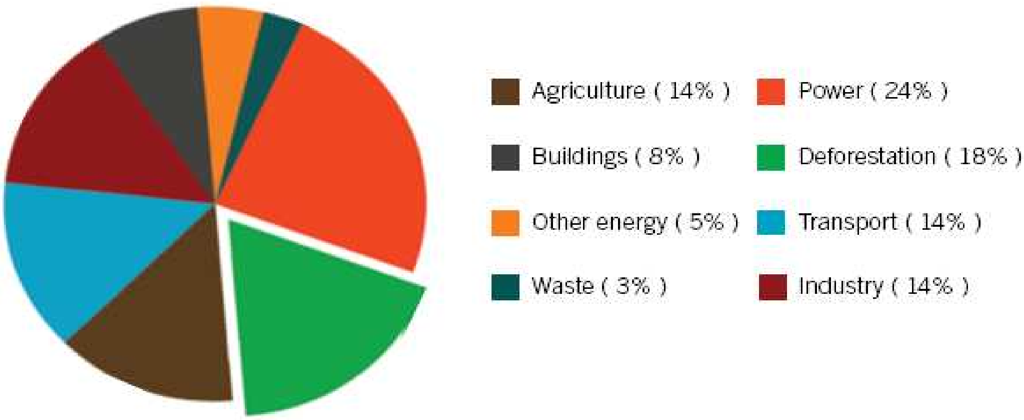

Fig. 2.6. Sector CO_2 emission contributions indicating that deforestation significantly (IPCC 2007)

Carbon pools of coastal wetlands (Blue Carbon) are poorly described at present. This is particularly true of African mangroves. In recent international Blue Carbon workshops (funded by UNESCO, IUCN and CI) African coastal ecosystems were noted as sites where the least information exists. Especially relevant is the potential role of mangroves in climate change mitigation strategies. The ocean's vegetated habitats, especially mangroves, salt marshes, and sea grasses cover <0.05% of the sea bed but account for >50% and as much as 71% of all C storage in ocean sediments. They comprise only 0.05% of the plant biomass on land but store a comparable amount of C per year as tropical forests, thus ranking among the most intense carbon sinks on the planet. Currently, on average, between 2-7% of blue carbon sinks are being lost annually. These are rates exceeding the loss of tropical upland forests. Halting degradation and restoring both the lost marine carbon sinks in the oceans, and slowing deforestation of tropical forests could result in mitigating emissions by up to 25%. Deforestation significantly contributes to CO_2 missions (Fig. 2.6) compared to other known sector (IPCC 2007).

The loss of the carbon sinks and their crucial role in managing climate health, food security, and economic development in the coastal zones is an eminent threat. Addressing these threats is a significant need to mitigate in climate change effects, especially in developing countries which are the most vulnerable to climate change due to low level of development, high dependence on vulnerable (sectors e.g. agriculture, tourism, fishing etc.) and low preparedness to disasters.

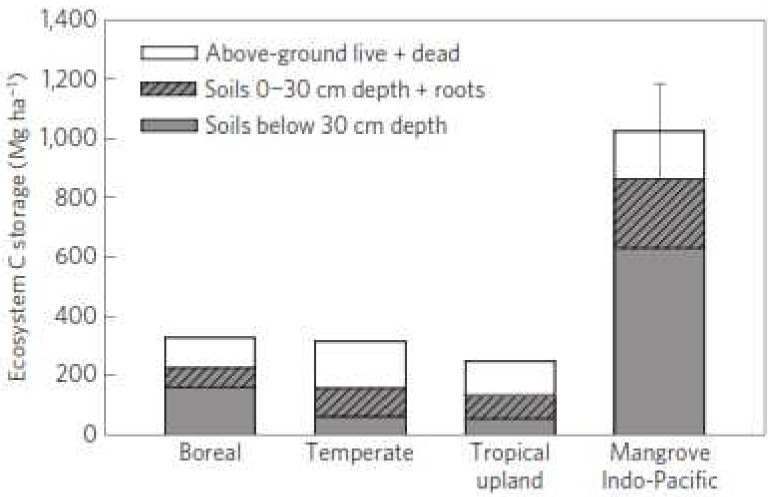

Fig. 2.7. Graphs showing ecosystem carbon storage per unit area in different forests (Donato et al. 2011).

Carbon emissions as a result of this high rate of degradation are highly uncertain. This is so true in mangroves where hitherto, total ecosystem carbon stocks have been scarcely assessed. However, recent assessments strongly suggest that mangroves sequester about five times much more carbon per unit area than all other forest ecosystems Fig. 2.7), thus making their contribution to carbon storage crucial despite their spatially limited extent. Most of this carbon is stored below ground in the sediments and this is the major carbon pool (Fig. 2.8), which is often ignored in many assessments due to attendant complications in sampling.

The high degradation rate reported for the Zambezi mangroves and the high potential of these deltaic mangroves as carbon sinks is a great opportunity to enhance conservation of these critical mangroves under payment for ecosystem services (PES) schemes especially carbon financing (REDD+).

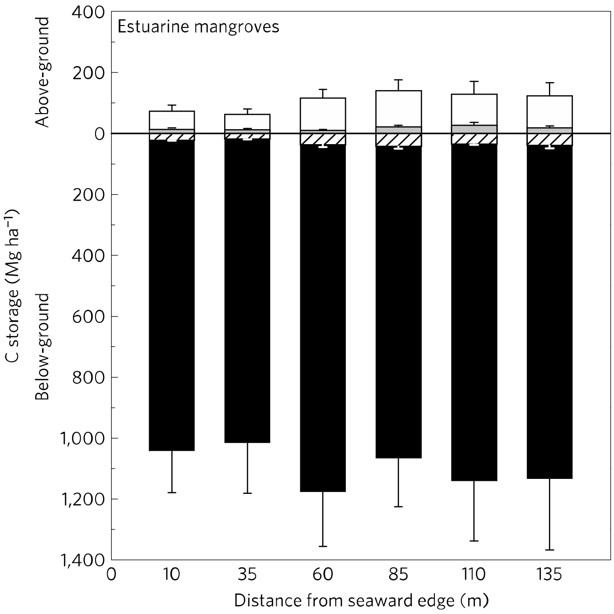

Fig. 2.8. Carbon storage at the Asia-Pacific showing the high contribution of sedimentary organic carbon to total ecosystem carbon (Donato et al. 2011)

The main objective of this work was to establish species-specific densities for the Zambezi mangroves and customize the global/general equations for the determination of biomass of mangroves at the Delta. This was then to facilitate a rapid assessment of carbon stocks at the Delta including sedimentary organic carbon.

2.3 CARBON POOLS IN MANGROVES

Similar to most forest types, mangroves can be roughly divided into five carbon pools: 1) aboveground biomass of live vegetation; 2) belowground biomass of live vegetation; 3) dead wood; 4) forest floor (litter); and 5) soil. A pool should be measured if it is large, if it is likely to be affected by land use, or if the land-use effects or size of the pool are uncertain. Small pools or those unlikely to be affected by land use may be excluded or sampled less frequently. In mangroves, non-tree vegetation and litter are usually minor ecosystem components and can often be excluded from measurements without compromising the accuracy of the sample.

Trees are always included since they are relatively easy to measure, good scaling equations exist, and they are heavily affected by land use. Many mangroves have deep organic-rich soils (peat) resulting in large carbon pools. The large size of these belowground pools and their poorly understood vulnerability to land-use change makes their measurement relatively important. Once species-specific equations are established, then below ground living biomass can also be determined. For this rapid assessment, the major carbon pools investigated are: above ground biomass (AGB) for adult trees, sedimentary organic carbon (SOC) and below ground biomass (BGB) for the roots (Fig. 2.9).

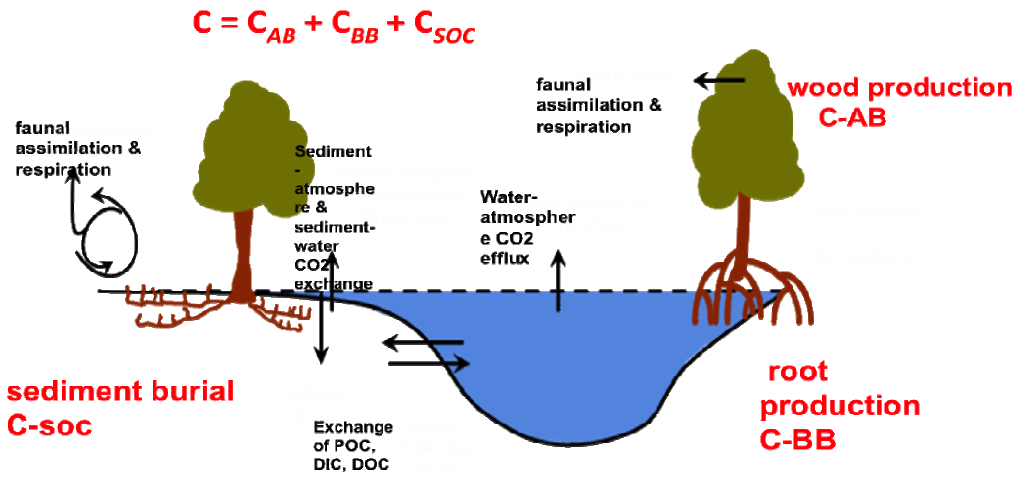

Fig. 2.9. Different carbon pools in mangroves

3.0 SAMPLING METHODOLOGIES

3.1 Vegetation structure for above ground biomass

One of the important divisions of carbon stocks in mangroves is the aboveground component. Trees dominate the aboveground carbon pool and are an obvious indicator of land-use change and ecological condition. Stem diameter and sometimes height are used to estimate tree biomass and carbon stocks using allometric equations. Stem diameter is measured at D130 (dbh) or 30cm above the highest prop root for Rhizophora spp (Fig. 9).

Fig. 3.1. Different structures of mangrove roots (Bosire 2011 Zambezi, 2010 Cameroon)

3.1.1 Sampling

Using SPOT satellite images, the project area boundary was defined to cover the northern Zambezi and restricted to the mangrove ecosystem only. These acquired SPOT images were classified using unsupervised classification to establish strata of different mangrove assemblages at the study site based mainly on assumed species/classes and mangrove structure. For details on mapping, refer work submitted separately under the mapping component under the Project.

Within the strata delineated above, transects were established running perpendicular to the shoreline. Using the plot method, along each transect, plots of 10m x 10m spaced at 50m from each other were made. Within each plot measurement of dbh and height of all trees with diameter greater than 5cm was done, canopy cover and plot density for adult trees recorded. For determination of natural regeneration, within the plots above, 1m x 1m or 5m x 5m sub-plots depending on density were made. Use linear regeneration sampling (LRS), species, size class and density of all seedlings or saplings were recorded. All sampled plots were geo-referenced to facilitate supervised classification of the mangroves and production of a vegetation map (Fig 3.3).

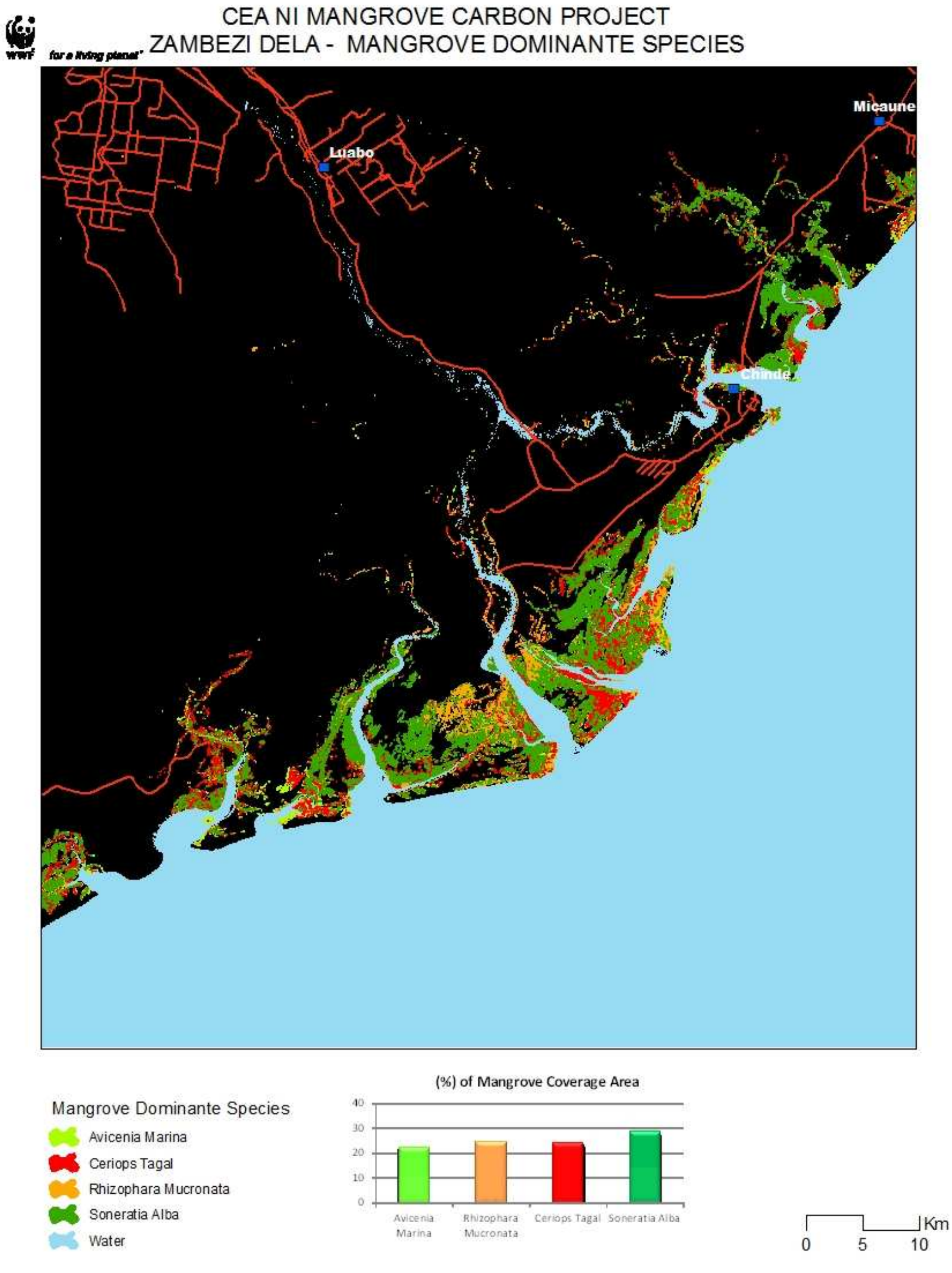

Fig. 3.3. Classified map of the study area showing the main mangrove species.

3.2 Specific species density

Locally generated allometric equations are best suited for estimating biomass from which C concentration can be determined. This is because mangrove vegetation structure varies greatly among sites, hence biomass. While global general allometric equations can be applied across sites, one very important variable, which is very site specific and must thus be determined to customize application of the general equations is species density.

Under this campaign, density of various species within the Zambezi delta falling under the defined project boundary were determined:

3.2.1 Sampling

The diameter range of trees extracted was determined from the structural data collected above. Trees extracted for density estimation per species had diameter interval of 10cm. Therefore for each species within the project boundary, extract one tree from each diameter range: 5 - 15cm, 15 – 25cm, 25 - 35cm, 35 - 45cm etc. Each selected tree was felled at the base, all branches removed and the trunk sliced into sections which were weighed in the field using a 50kg weighing balance (Fig 3.3).

Fig. 3.3. Steps in extracting/slicing and weighing wood samples (Bosire 2011).

From each tree, wood samples of about 0.5kg were extracted each from the base, mid section and top section. The samples were then labeled in terms of species, dbh of the main tree and section (i.e. b for base, m for mid-section and t for top section). The wet weight of the respective wood samples was record in the field. In the lab, wood samples were dried to constant dry weight and their weights recorded respectively.

For volumetric analysis, a graduated bucket filled with water to a recorded level was used to determine the volume of each wood sample dried above using the displacement method and record individual volumes against each respective sample.

Using the relationship between oven DW and wet weight to obtain a conversion factor, the DW of the individual trees extracted in the field was determined. Using the respective volume and weight of wood samples, the respective volumes of all individual trees felled in the field were determined. With the DW and volume of each individual trees for all species now obtained, the density of each species was determine for biomass (and subsequent C concentration) estimation.

$$Density\left(gcm^{-3}\right) = \frac{Mass(g)}{Volume(cm^3)}$$ ....Equation 1

3.3 Sedimentary organic carbon determination

Soil organic carbon has been found to be highly concentrated in the upper 1m of the soil profile (Donato et al. 2011). This layer is also the most vulnerable to land-use change, thus contributing most to emissions when mangroves are degraded. Sediment core sampling was thus limited to a depth of 100cm with a core being taken from the center of each plot surveyed for vegetation structure above at low tide (Fig. 3.4). Soil cores were extracted from each sample point using a corer of 6cm diameter and systematically divided into different depth intervals (0–15 cm, 15–30 cm, 30–50 cm, and 50– ca. 100 cm), with minimum soil disturbance during core extraction (Kauffman *et al.,* 2010; Donato *et al.,* 2011).

a b c

Fig. 3.4. Sediment sampling: a). Driving the corer into the soil on hard substrate; b). retrieving corer with sample and c). sediment core which has been sectioned and samples extracted.

a b

Fig. 3.5. a). Sediment core sectioning and b). sample storage in pre-labeled plastic bag

A total of 168 soil samples were collected from 42 sample points across the study site. A sample of 5cm length was extracted from the central portion of each depth interval to obtain a standard volume for all sub –samples (Fig.3.5). In the field, these samples were placed in pre-labeled plastic bags. In the lab, they were placed in pre-weighted crucibles and oven-dried to constant mass at 70^{o}C for 48 hours and the weight was taking after drying (Kauffman and Donato 2012). Bulk density was calculated as follows:

$$\text{Soil bulk density } (\text{gm}^{-3}) = \frac{\text{Oven-dry sample mass (g)}}{\text{Sample volume } (\text{m}^3)} \text{.............................Equation 2}$$

Where, Volume = cross-sectional area of the corer x the height of the sample sub-section

Of the dried soil samples, 5-10g subsamples were weighed out into crucibles and set in a muffle furnace for combustion at 550^{o}C for 8 hours through the process of Loss- On-Ignition (LOI), and cooled in desiccators before reweighing. The weight of each ashed sample was recorded and used to calculate organic matter.

4.0 RESULTS

4.1 Specific species densities

Specific species densities for seven species out of nine were determined at the Delta, presenting the first ever such work done in the (Western Indian Ocean (WIO) region. The species who densities were not determined are *Lumnitzera racemosa* and *X. molucensis* which aren't common and ideally don't contribute much to stand structure and productivity. Species in the Rhizophoracea family had the highest densities with *B gymnorrhiza* leading, while *C. tagal* and *R. mucronata* had the same density. These were followed by A. marina, while *X. granatum, S. alba* and *H. littoralis* had the same and lowest density (Table 4.1).

Table 4.1. Specific species densities of various species at the Zambezi Delta

Species	**DW (Kg)**	**SE**	**Vol (cm^3)**	**SE**	**Density (g/cm^3)**	**SE**
C. tagal	56.3	29.9	47,242	24,393	1.1	0.0
B gymnorrhiza	72.5	32.2	52,061	20,417	1.3	0.1
X. granatum	41.6	21.5	44,327	18,583	0.8	0.1
S. alba	140.9	69.3	160,602	69,785	0.8	0.0
A. marina	119.7	50.0	129,276	54,605	0.9	0.0
R. mucronata	52.6	23.8	46,892	19,687	1.1	0.1
H. littoralis	52.5	25.5	54,648	23,614	0.8	0.1

4.2 Live biomass Distribution

The results of this study estimated the overall mean live biomass in the area to be 479.87±59.30 Mg/ha (Table 4.2). This composed of 344.95 ± 43.30 Mg/ha above ground biomass (AGB) and 134.92 ± 16.07 Mg/ha below ground biomass (BGB).

Table 4.2: Summary of mean live biomass distribution in the sites in the study area

Site	AGB Mg/ha	SE	BGB Mg/ha	SE	Total Biomass Mg/ha	SE
Nhaimbo II	441.66	96.55	172.05	37.56	613.71 [a]	103.6
Nhaimbo	236.69	52.79	97.01	19.05	333.70 [ab]	56.12
Temane	330.59	89.18	124.1	30.35	454.69 [ab]	94.2
Mwandua	99.9	44.87	42.41	18.13	142.31 [b]	48.4
Nhamacara	592.87	106.18	226.45	33.22	819.32 [a]	111.25
Mean	344.95	43.3	134.92	16.07	479.87	46.19

Sites whose total live biomass share either one or two similar letter superscripts are not significantly different from each other.

The AGB contributed the most to the total live biomass of the area (72%), BGB was 28% of the total live tree biomass. The overall ratio of AGB to BGB in the forest averaged at 2.56, this ratio did not differ statistically from the ratio in individual sites (P > 0.05). This ratio ranged from 2.36 in Mwandua to 2.66 in Temane.

There results indicated a statistical difference in the mean total live biomass in different zones (P = 0.0029) maybe due to large variations within each zone. On further seperation of means, NhaimboII (613.71±103.60 Mg/ha) and Nhamacara (819.32±111.25 Mg/ha) showed a significantly different total live biomass from Mwandua which recorded the least amount of mean total live biomass of 142.31± 48.40 Mg/ha (Table 4.2, Fig 4.1).

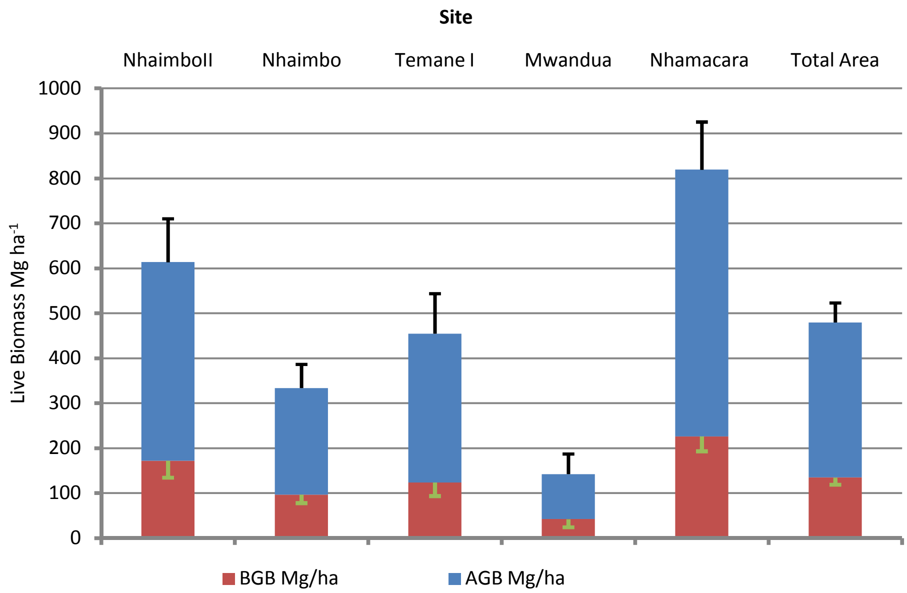

Fig 4.1: Distribution of biomass across the sites in the study area

4.3 Bulk density

Table 4.4: Soil bulk density (g/cm^3) in different sites across the sampled sites in the forest

	Location			
Depth (Cm)	NhaimboII [ab]	Nhaimbo [ab]	Mwandua [a]	Nhamacara [b]
0-15	0.52±0.03	0.51±0.05	0.58±0.11	0.46±0.03
15-30	0.56±0.04	0.54±0.03	0.80±0.14	0.52±0.05
30-50	0.60±0.05	0.64±0.05	1.07±0.05	0.48±0.01
50-100	0.61±0.04	0.62±0.05	0.58±0.11	0.54±0.02

Sites that share one or more similar letter superscripts are not significantly different from each other in terms of overall mean bulk density.

Table 4.5: Mean Soil bulk density (g/cm^3) in various soil depths in the forest

Soil Depth	Bulk density (g/cm^3)	SE
0-15	0.52 [a]	0.02
15-30	0.59 [ab]	0.03
30-50	0.61 [ab]	0.03
50-100	0.61 [b]	0.03

Mean bulk densities that share one or more similar letter superscripts are not significantly different from each other.

As presented in Table 4.3 below, bulk density of the soil sediment across the sampled sites varied from an average of 0.46±0.03 g m^{-3} in the 0-15cm layer of Nhamacara to 1.07±0.03 g cm^{-3} in the 30-50cm layer, recorded in Mwandua. The overall average soil bulk density increased with depth and attained a maximum of 0.70 ±0.05 g cm^{-3} at the 30-50cm layer after which it decreased to an average of 0.59 ±0.04 g cm^{-3} at the 50-100 layer. This was the general trend in all the sample sites except Nhamacara where the 50-100cm layer had the highest bulk density. However, it suffices to note here that the overall mean bulk density per depth (Table 4.4) increased steadily with depth. All the sites did not have statistically different bulk densities in their various layers with an exception of Mwandua and Nhamacara which differed significantly in overall mean bulk density (P = 0.035).

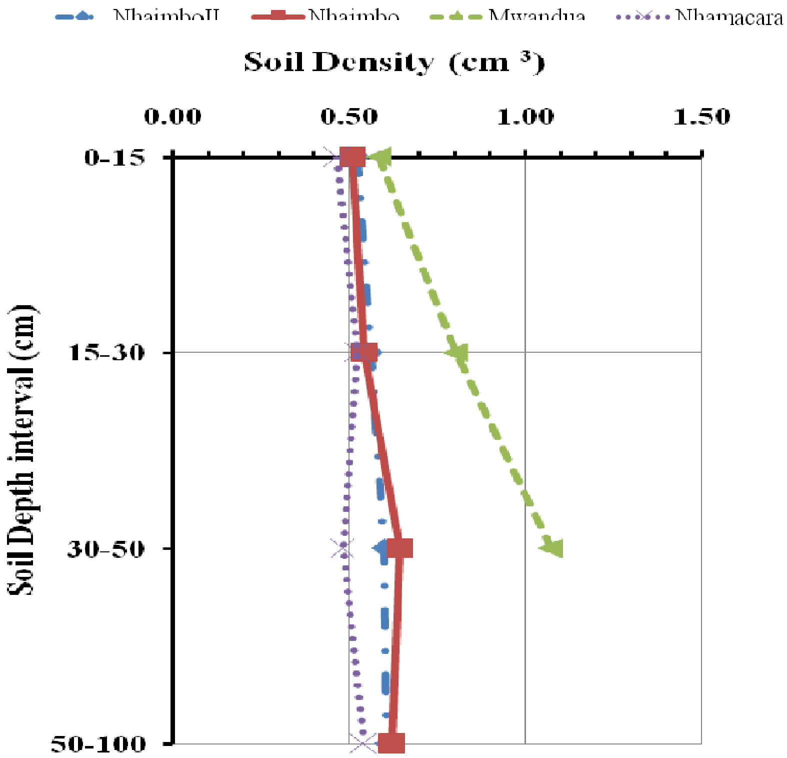

Figure 4.2: Distribution of soil density along the soil profile in the different sites of the study area

4.4 Soil organic carbon

For the entire study site, the highest average percentage carbon was 6.18%±0.3 which was estimated at the 50-100 cm layer.followed by 6.16% ± 0.29 in the 0-15 cm layer, 5.83% ± 0.38 in the 15-30cm. The least overall average percent carbon for the study area was recorded for the 30-50cm layer as 5.76%±0.46 (Table 4.6). The overall percentage carbon concentration in the various soil depths in the forest did not differ statistically (P = 0.8075).

Table 4.6: % Carbon concentration along the different sampled soil depths in the study area.

Depth	% Carbon concentration	SE
0-15	6.16	0.29
15-30	5.83	0.38
30-50	5.76	0.46
50-100	6.18	0.3

Percentage carbon concentration varied slightly along the different soil depth layers within the sites in the study area although there was no statistical significant difference (P = 0.8075) in percentage carbon throughout the depths within a site. Nhaimbo II had the highest carbon concentration in the study area of 6.98 % ± 0.64 estimated in the 30-50cm soil layer. Mwandua registered the lowest percentages of carbon concentration with a low of 1.6% ± 0.74 in the 30-50cm soil depth layer (Figure 4.3). There was a significant difference (P<0.05) in the overall mean percentage carbon concentration among the sites.

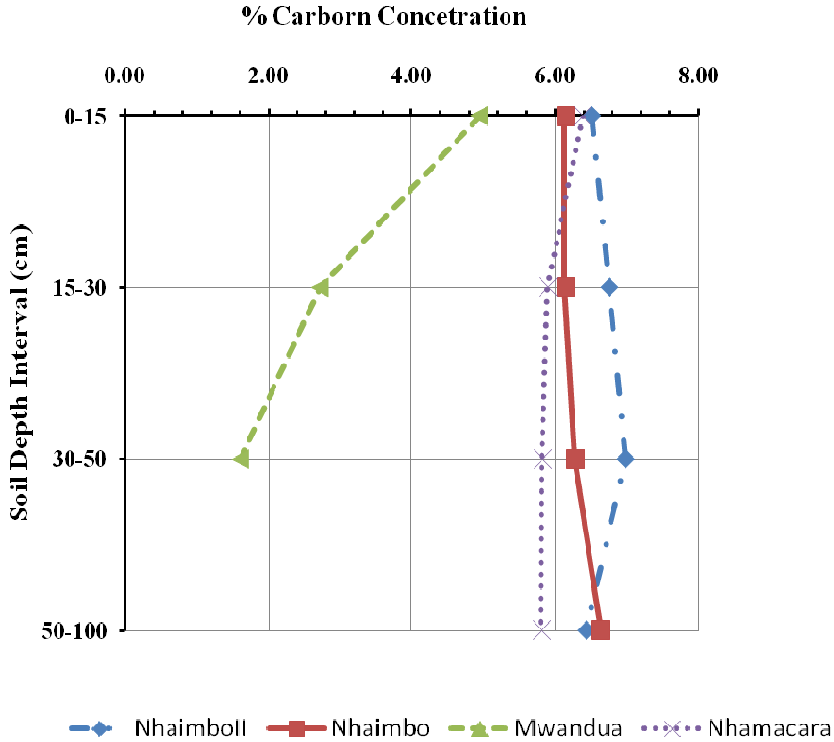

Figure 4.3: Distribution of % Carbon concentration along the soil profile in the different sites of the study area

Table 4.7: Soil Organic Carbon (SOC) along the different sampled sites in the study area.

Site	Soil C (Mg ha^{-1})	SE
Nhaimbo II	373.91a	19.92
Nhaimbo	376.75^{a}	26.98
Mwandua	112.42^{b}	25.76
Nhamacara	306.30a^{b}	15.12
Mean	321	20.15

Sites whose soil carbon share one or more similar letter superscripts are not significantly different from each othe in terms of soil carbon.

The average quantity of soil organic carbon stored in the mangrove sediments in the entire study area amounted to 321.00±20.15 Mg/ha. There were significant differences in soil organic carbon among the sites (P = 0.0014). Nhaimbo recorded the highest amount of average SOC of 376.75 ± 26.98 Mg/ha (Table 4.7), followed by NhaimboII which had an average SOC of 373.91±19.92 Mg/ha. These were statistically significantly different (P<0.05) from the average SOC recorded on Mwandua of 112.42±25.76 Mg/ha. This value recorded in Mwandua for SOC was also the lowest recorded for the study area.

4.5 Total ecosystem carbon

The total carbon pool/carbon density was estimated by adding all the component pools. The component pools are; carbon from tree above ground biomass, carbon from tree below ground biomass and the soil organic carbon.

Table 4.8: Summary of total ecosystem carbon for the study site

Site	Trees Mg/ha	SE	Roots Mg/ha	SE	SOC (Mg/ha)	SE	Total Ecosystem Carbon	SE
NhaimboII	204.93	44.8	67.1	14.65	373.91	19.92	645.95	51.17
Nhaimbo	109.89	24.5	37.83	7.43	376.75	26.98	524.47	37.2
Temane I	153.53	41.35	48.4	11.84				
Mwandua	46.95	21.17	16.54	7.07	112.42	25.76	175.91	34.08
Nhamacara	277.68	50.28	88.31	12.96	306.3	15.12	672.29	54.08
Mean	160.5	20.17	52.62	6.27	321	20.15	534.12	29.19

Carbon pools of trees (above ground) were calculated as the product of tree biomass multiplied by wood carbon content: B. gymnorrhiza=46.3%, S.alba=47.1%, and an average of all species of 46.4%. Carbon pools of trees (below ground) was calculated using wood carbon content of 39% for all species.

Total organic carbon for the ecosystem under study was estimated at 534.12±29.19 Mg/ha, with 160.50±20.17 Mg/ha in the aboveground biomass, 52.62±6.27 Mg/ha in the root biomass and 321.00±20.15 Mg/ha in the soil pool (Table 4.8). This shows that soil carbon accounted for about 60% of the entire ecosystem carbon pools while above-ground stem and below-ground root carbon accounted for about 30% and 10% respectively. The highest ecosystem carbon stock (672.29±54.08 Mg/ha) was estimated for the forest area in Nhamacara, and the least carbon density of 175.91±34.08 Mg/ha was estimated for the forest area in Mwandua (Figure 4.4).

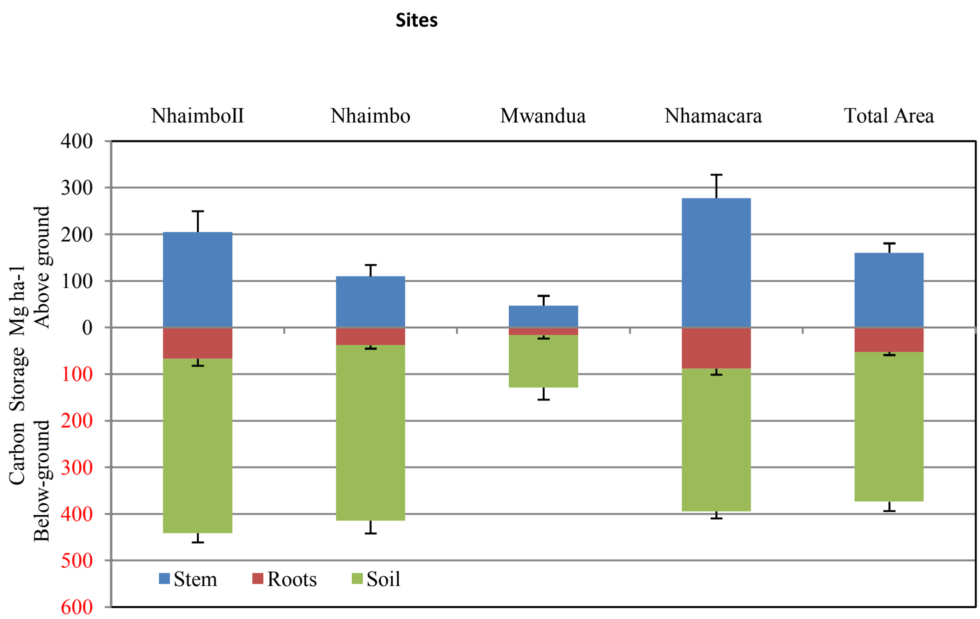

Fig 4.4: Total Ecosystem Carbon Pools for the sites in the study area

4.6 Intertidal gradients in ecosystem carbon

The mangroves in the study area were further classified into Oceanic, Esutuarine and Landward mangroves. These are already well established classifications of mangroves that have been adopted and they are based on the position of mangroves relative to the sea. The forest area in Mwandua was classified as oceanic mangroves, Nhamacara had estuarine mangroves as the area was adjacent to the one of the morthern arms of the R. Zambezi; and Nhaimbo II had Landward mangroves.

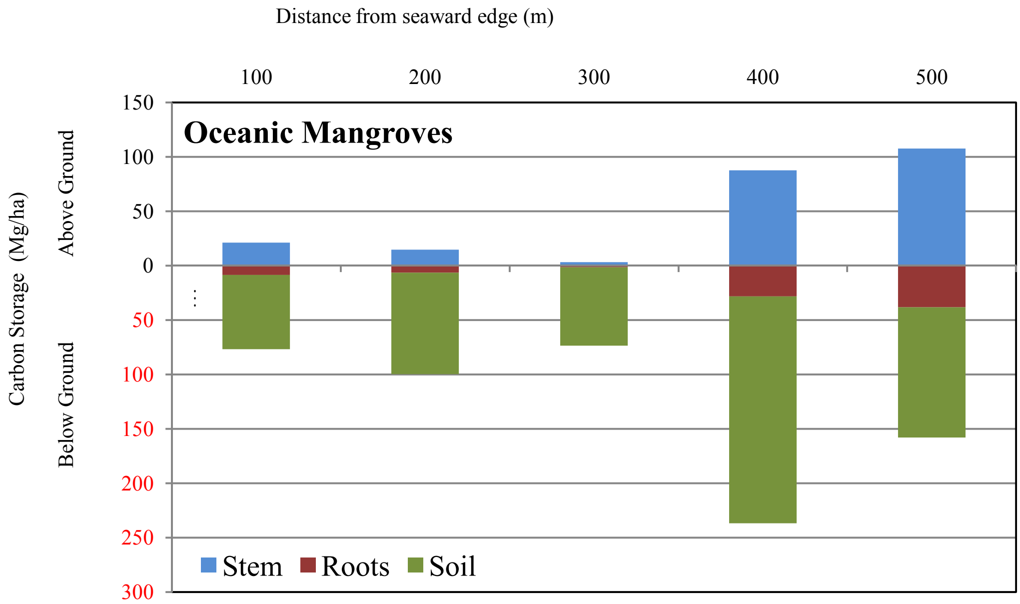

Fig 4.5: Above ground and below ground Carbon pools in oceanic mangroves in the study area

Overall carbon storage did not vary significantly with distance from the seaward edge in the various mangrove classifications over the area sampled (P>0.05). This was the case for above ground, below ground and soil carbon (Figures 4.5, 4.6 & 4.7).

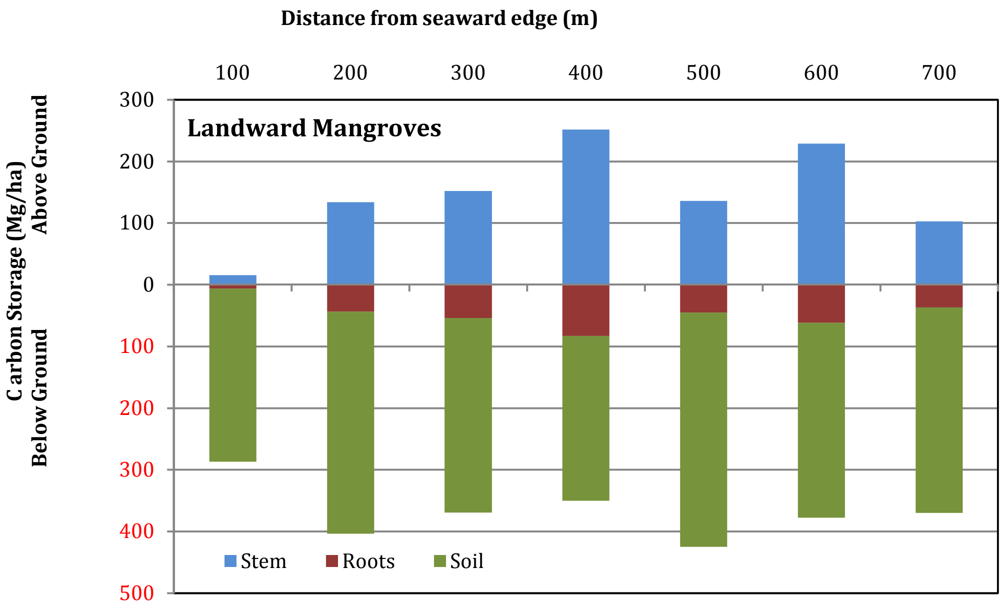

Figure 4.6: Above ground and below ground Carbon pools in landward mangroves in the study area

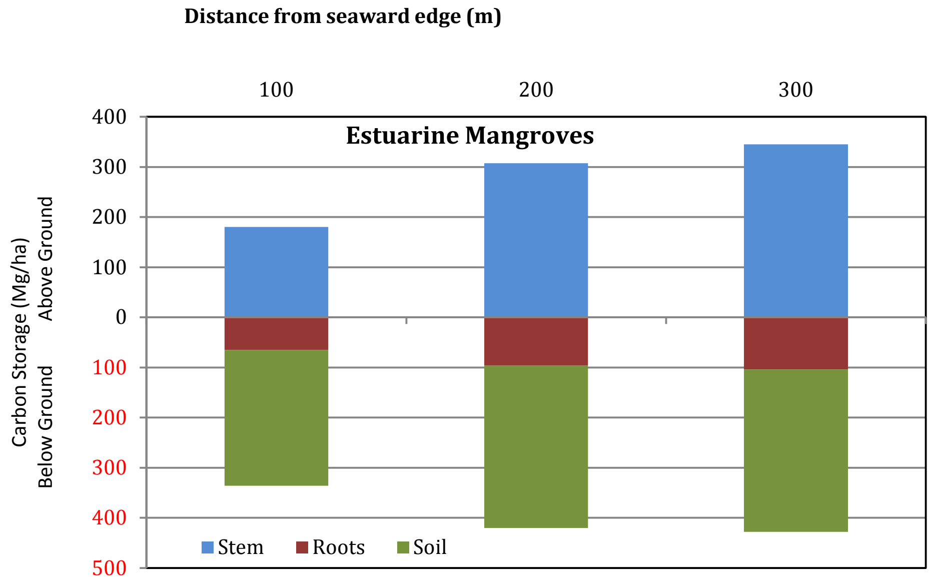

Fig 4.7: Above ground and below ground Carbon pools in estuarine mangroves in the study area

The total carbon stock was statistically significantly different in the classified mangroves (P= 0.0038). On further seperation of the means, it was evident that the carbon density in the Oceanic mangroves (with the lowest amount 175±49.9 Mg/ha) was significantly different from the landward and estuarine mangroves. The estuarine mangroves had the highest carbon storage of 672 ±77.12 Mg/ha (Table 4.9).

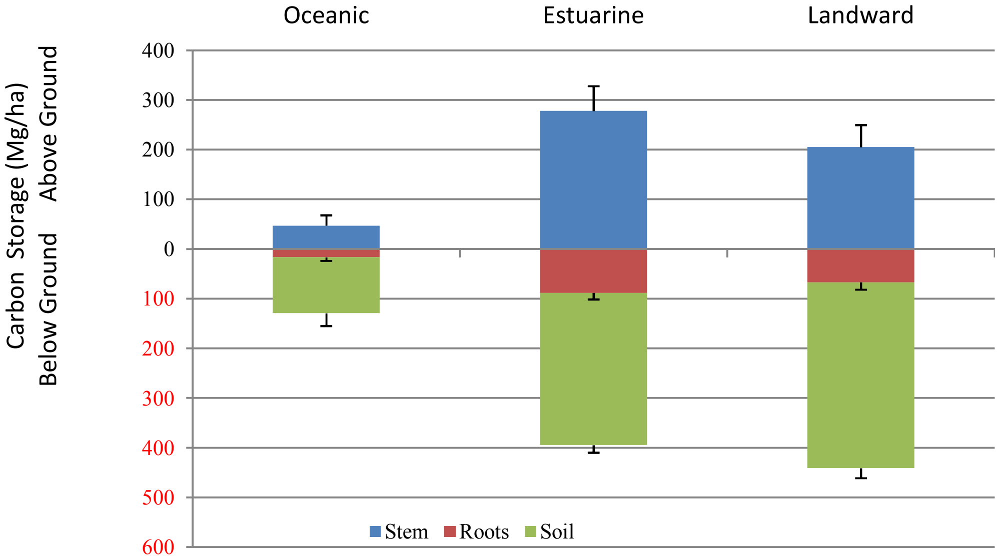

Fig 4.8: Above ground and below ground Carbon pools in Landward, Oceanic and Estuarine mangroves in the study area.

Table 4.9: Carbon Storage in Landward, Oceanic and Estuarine mangroves of the study area

	Carbon Density (Mg/ha)							
	Trees	**SE**	**Roots**	**SE**	**SOC**	**SE**	**Total Carbon**	**SE**
Landward	204.93[a]	44.8	67.1[a]	14.7	373.91[a]	19.9	645.95[a]	64.0
Oceanic	46.95[b]	21.2	16.54[b]	7.1	112.42[b]	25.8	175.91[b]	49.9
Estuarine	277.66[a]	50.3	88.31[a]	13.0	306.3[ab]	15.1	672.29[a]	77.1

Similar alphabetical superscripts indicate no significant differences in columns

5.0 DISCUSSION

This study indicates that the delta has high biomass potential with variations across the different zones. The variation in AGB and BGB in the different zones of the forest is likely due to soil nutrient availability which is often implicated as the principal factor determining variation in mangrove biomass and productivity (Chen and Twilley 1999). Nhamacara being an estuarine site recorded the largest amounts of AGB and BGB because fresh water and sediment input increases nutrient supply (Roy 1997, Wafar et al. 1997) that consequently invigorate mangrove productivity. In addition, reduced tidal flushing causes an increase in nutrient uptake and plant growth (McKee et al. 2002).

The mangroves in Nhamacara (estuarine mangroves) were the most productive in the study area giving the highest amount of biomass (819.32 ± 139.34 Mg/ha). Mwandua (oceanic mangroves) recorded the lowest biomass, even lower than Nhaimbo II (landward mangroves) contrary to what is expected of mangroves that receive water at all times since mangrove trees generally achieve optimum growth at low to moderate salinity levels (Ball, 2002). Hypersalinity has been implicated as a major factor limiting mangrove forest development (Lugo et al. 1981, Saintilan 1997) resulting in reductions in biomass. It is important to note here that the oceanic mangroves were young mangroves with recent colonization on newly deposited sediments and thus this might also explain the very low amounts of biomass recorded. However, this study concurs with the report in Kauffman et al. (2011) that estimated a higher biomass in the landward zone in comparison to the seaward edge.

The overall biomass of this forest (479 Mg ha^{-1}) was higher than the global range estimated at 7-440 Mg ha^{-1} (Saenger and Snedaker 1993) and 41-460 t ha^{-1} (Komiyama et al. 2008), but within the biomass of 700 t ha^{-1} reported by Clough (1992). The estuarine mangroves had the highest biomass of 819 Mg ha^{-1}, emphasizing the importance of the mighty Zambezi River in nutrient supply.

The results indicated variable amounts of carbon concentration throughout the soil profile consistent with the findings of Kauffman et al. (2011). In fact, the deepest soil profile layer had the highest overall % C of 6.18% ±3.0. These unique characteristic in mangrove soil is one of the factors that distinguishes mangroves from other forests in terms of their ability to store carbon.

The carbon concentration was lowest in the oceanic mangroves and highest in the landward mangroves with the estuarine site in-between. This was contrary to results from a study on Indo-Pacific mangroves (Donato et al. 2011) where they reported lower amounts of carbon concentration in estuarine as compared to oceanic mangroves. For sedimentary organic carbon (SOC), sediment samples were taken only up to a depth of 50cm for the oceanic mangroves because below this depth, it was sold coral rock reinforcing the fact these were new mangroves with poorly developed soils.

Consequently as a result of these % C concentrations, it followed that the landward mangroves recorded the highest amount of SOC and the oceanic mangroves the least. It is also hypothesized in this study that since the oceanic mangroves experience the highest exposure to strong wave energy, most of the dead wood and fallen litter are washed away by tidal activities unlike in the landward mangroves where these are left on site and are eventually incorporated into the soil. Due to exposure of seaward fringe mangroves to high tidal/wave activity, the amount of mangrove carbon in the form of litter and leaves exported into offshore areas is immense, resulting in over 10% of the ocean's dissolved organic carbon originating from mangroves (Dittmar et al. 2006).

In conformity to past studies (Ceron-Breton et al. 2011, Kauffman et al. 2011, Donato et al. 2011), this study has reaffirmed that carbon stored in the mangrove sediments (soil) contributes the most to the total carbon density of the forest. Overall, carbon storage in the study area did not vary significantly with distance from the sea in individual mangrove classifications, although there were variations by order of magnitude. SOC for the study area ranged from 46% to 72%, which falls within the range reported by Donato et al. (2011). It is very likely that SOC for these mangroves is much higher than observed because only 1m depth was sampled and yet deltaic mangroves can have deep sediments accumulating over many years, with higher SOC content. The top 1m was considered in this baseline assessment because normally it is most the most susceptible to land-use change and accumulates most of the carbon.

The Zambezi delta has lost 50% of its mangrove cover between 1972 and 2002 (Fatoyimbo et al. 2008), representing a 1.7% annual mangrove loss. This rate of loss is closer to the upper rate of loss globally. With the current estimated carbon of 534 Mg ha^{-1}, this suggests that conservatively, the delta may have lost more than 500 Mg ha^{-1} of carbon since 1972. While this is negative in as far forest production and provision of other ecosystem goods and services is concerned, it avails a great opportunity for such a forest to be a good candidate for a REDD+ project. This is due to the high potential of carbon storage and high opportunities for additionality through restoration of degraded areas and enhanced management. The proposed field campaign by the United States Forest Service (USFS), which will create great synergy with this preliminary work through specific species densities for seven species of the delta have been determined, and baseline carbon stocks assessed. The USFS, which intends to establish permanent plots for monitoring, reporting and verification (MRV) and sample sediment cores up to 3m, will have great value addition to this initial assessment.

By halting or slowing degradation of “green” and “blue” carbon binding ecosystems, this will represent an emission reduction equivalent to 1–2 times that of the entire global transport sector – or at least 25% of the total global carbon emission reductions needed, with additional benefits for biodiversity, food security and livelihoods. It is becoming increasingly clear that an effective regime to control emissions must control the entire “spectrum” of carbon, not just one “colour” (UNEP 2009). In addition to restoration of degraded areas at the Delta, use of energy efficient stoves, provision of alternative energy sources and a rational management plan for these unique mangroves will enhance their potential to not only sequester substantial carbon relative to other regional mangroves, but also support critical livelihoods.

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