STATUS OF MANGROVE ECOSYSTEM CONSERVATION IN MOZAMBIQUE: CONTRIBUTION TO MINIMISING THE EFFECTS OF CLIMATE CHANGE

EZÍDIO DA LÚCIA CUAMBA

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THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE (PhD) IN FORESTRY ENGINEERING AND NATURAL RESOURCES

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ABSTRACT

Mangrove forests provide diversified ecosystem services, supporting plants, animals, microorganisms and community livelihood for subsistence. Mangroves and other blue carbon ecosystems sequester great quantities of carbon, becoming of relevant value to climate change adaptation and mitigation strategies. This study describes the mangrove forest structure, trees biomass pools and carbon stocks in different soil depth of Pemba Bay, in Northern Mozambique. We used a stratified random design, where the inventory considered three different mangrove strata: overstory, understory and dead trees, including soils, in five nested sub-plots in a 0,74 ha square plot. Biomass was calculated using allometric equations and carbon stock as a sum of the carbon per unit area of considered layers. All of the mangrove species reported to occur in Mozambique were found and measured in Pemba Bay. Understory, overstory, and dead standing trees, respectively dominated the stocking densities of mangrove forest. For the understory, the stocking densities were variable among the plots, averaging 6741 trees ha^{-1}, and ranging from 477 to 24192 trees ha^{-1}. The overstory stocking densities average was 695 trees ha^{-1}, and ranging from 299 to 1156 trees ha^{-1}, whereas, the dead standing trees averaged 126 trees ha^{-1}, and ranging from 13 to 325 trees ha^{-1}. The average soil carbon content (depth 0-150 cm) was estimated as 224.3 Mg ha^{-1}. The total carbon accumulated in mangrove system was of 309.11 Mg ha^{-1}, very high in the soil (71.4%); aboveground biomass contributes with 28.6% (overstory, understory and dead trees pools).

KEYWORDS: Mangrove characteristics, biomass, soil carbon storage, Pemba Bay

EXTENDED SUMMARY

Mangroves forests are among the most productive ecosystems in the world, providing nutrients to coastal waters and oceans, acting as nursing grounds and habitat for economically valued species. Mangroves are associated with highly productive fishing, and contributing to the mitigation of climate change effects due to amount of the carbon they fix.

Mangroves in Mozambique occur mostly in sheltered shorelines and river estuaries. The largest areas of mangroves mostly occur in central Mozambique, in the deltas and estuaries of large rivers. Indeed, about 28% of the mangrove area occurs in the Zambezi delta, which is the largest tract of mangrove forest in Africa; the provinces of Zambezia and Sofala accounts for about 55% of the global mangrove area in the country.

Even taking into account the importance of mangroves, there is a lake of studies regarding to produce consistent information to drive policies and to take a sustainable management in Mozambique, especially in the Northern. Thereby, this study brings a complete baseline of mangrove forest in Pemba Bay – Northern Mozambique, describing the forest status and composition, the biomass and accumulated soil carbon in the region.

A stratified random sampling design was used to inventory the mangrove vegetation and soils of Pemba Bay, where the location of the plots was based on remote sensing images. The forest inventory carried out, considered the different mangrove strata: overstory, understory, and dead trees. Sampling of the soil organic layer was carried out and soil samples were taken along a depth gradient. Samples were prepared in the laboratory to enable the description of the soil profile. The carbon stock of the mangrove forest of Pemba Bay was the sum of the carbon, determined per unit area, of the several layers considered.

Six mangrove species were found in Pemba Bay: *Avicennia marina*, *Bruguierra gymnorhiza*, *Ceriops tagal*, *Rhizophora mucronata*, *Sonneratia alba*, and *Heritiera litoralis*. *Avicennia marina* is the most frequent species, occurring in combinations with species *Sonneratia alba*, *Rhizophora mucronata* and *Ceriops tagal*, either for overstory and understory layers as well as for dead trees.

The stocking of the understory averaged 6741 trees ha^{-1}, and ranging from 477 to 24,192 trees ha^{-1}. The overstory stocking averaged 695 trees ha^{-1}, and ranging from 299 to 1,156 trees ha^{-1}, whereas the dead standing trees averaged 126 trees ha^{-1}, and ranging from 13 to 325 trees ha^{-1}. The organic carbon accumulated in the mangrove system of Pemba Bay was estimated in 309.11 Mg ha^{-1}, with 224.3 Mg ha^{-1} accumulated organic carbon in soils and 84.81 Mg ha^{-1} of above and belowground carbon pools in Pemba Bay.

KEYWORDS: Biomass pools, Mangrove forest, Northern Mozambique

RESUMO ALARGADO

As florestas de mangais estão entre os ecossistemas mais produtivos do mundo, fornecendo nutrientes às águas costeiras, atuando como habitat para espécies de valor económico. Os mangais estão associados a sistemas piscatórios altamente produtivos e contribuem para a mitigação dos efeitos das alterações climáticas devido à quantidade de carbono que fixam.

As maiores áreas de mangais ocorrem no centro de Moçambique, nos deltas e estuários dos grandes rios. De facto, cerca de 28% da área de mangal ocorre no delta do Zambeze, que é a maior área de mangal em África; as províncias da Zambézia e Sofala representam cerca de 55% da área global de mangal no país.

Mesmo tendo em conta a importância dos mangais, existe uma lacuna de estudos que produzam informação consistente para orientar políticas para uma gestão sustentável em Moçambique, especialmente na região Norte. Assim, este estudo constitui uma referência sobre a floresta de mangal na Baía de Pemba - Norte de Moçambique, descrevendo a composição da floresta mangal, a biomassa e o carbono acumulado no solo.

Foi utilizada uma amostragem aleatória estratificada para inventariar a vegetação e os solos da Baía de Pemba, onde a localização das parcelas foi baseada em imagens de deteção remota. O inventário florestal efetuado teve em conta os diferentes estratos do mangal: árvores adultas, árvores jovens e árvores mortas. A amostragem da camada orgânica do solo foi efetuada e as amostras de solo foram recolhidas ao longo de um gradiente de profundidade para permitir o conhecimento da variação do teor de carbono orgânico ao longo do perfil do solo.

Seis espécies de mangal ocorrem na Baía de Pemba: *Avicennia marina*, *Bruguierra gymnorhiza*, *Ceriops tagal*, *Rhizophora mucronata*, *Sonneratia alba* e *Heritiera litoralis*. A *Avicennia marina* é a espécie mais frequente, ocorrendo em combinação com as espécies *Sonneratia alba*, *Rhizophora mucronata* e *Ceriops tagal*, tanto para os estratos de sub-arbustivo e arbóreo, bem como para as árvores mortas.

A densidade das árvores jovens foi em média de 6.741 árvores ha^{-1}, variando de 477 a 24.192 árvores ha^{-1}, enquanto a das árvores adultas foi em média de 695 árvores ha^{-1}, variando de 299 a 1.156 árvores ha^{-1}, e a das árvores mortas em pé foi em média 126 árvores ha^{-1}, variando de 13 a 325 árvores ha^{-1}. O carbono orgânico acumulado no sistema de mangais da Baía de Pemba foi estimado em 309,11 Mg ha^{-1}, com 224,3 Mg ha^{-1} de carbono orgânico acumulado no solo e 84,81 Mg ha^{-1} na biomassa acima e abaixo do solo na Baía de Pemba.

PALAVRAS-CHAVE: Componentes da biomassa, Floresta de mangal, Norte de Moçambique

INDEX

LIST OF ABREVIATIONS AND ACRONYMS

	Species
Am	*Avicennia marina* (Forssk.) Vierh.
Bg	*Bruguierra gymnorhiza* (L.) Lamk.
Ct	*Ceriops tagal* (Perr.) C.B. Rob
Rm	*Rhizophora mucronata* (Lamk)
Sa	*Sonneratia alba* Sm.
	Others
CBD	Convention on Biological Biodiversity
CEPAM	Centro de Pesquisa do Ambiente Marinho e Costeiro
FAO	Food and Agriculture Organization
FCN	Faculdade de Ciências Naturais
INAHINA	Instituto Nacional de Hidrografia e Navegação
IUCN	International Union for Conservation of Nature
MAE	Ministério da Administração Estatal
MICOA	Ministério para Coordenação da Ação Ambiental
MPA	Marine Protected Areas
NDC	National Determined Contribution
PES	Payment of Ecosystem Services
PNQ	Parque Nacional das Quirimbas
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SADC	Southern African Development Community
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change

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CHAPTER I

1 INTRODUCTION

1.1 MANGROVE SYSTEMS

Mangroves forests are defined as woody trees and shrubs which flourish in mangrove habitats (or mangals), which is almost a tautology, where true mangroves are those which occur only in such habitats or rarely in different environment (Leal and Spalding, 2022). There is in addition a defined group of species described as mangrove associate or non-true mangrove species, which comprises numerous species typically occurring on the landward margin in non-mangrove habitats such as rainforest, salt marsh or lowland margin freshwater swamps (Figure 1) (Hogarth, 2015).

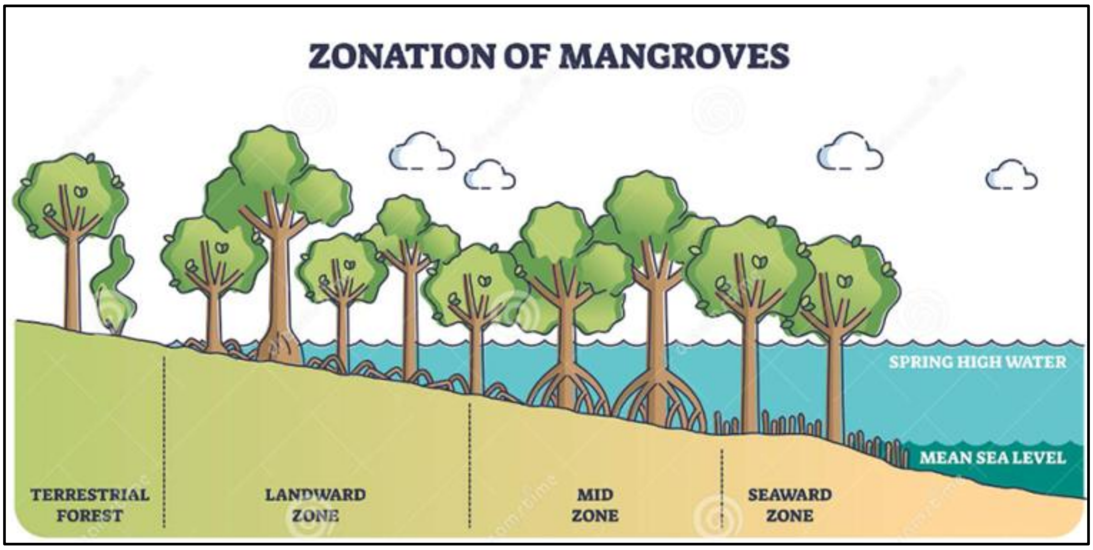


Figure 1 - General scheme of a mangrove zonation (adapted from Brown et al., 2016).

Tomlinson (2016) refers that the word “mangrove” has been used to refer either to the constituent plants of tropical intertidal forest communities or to community itself, arguing the need of using qualifications such as “mangrove plants” or “mangrove communities”. MacNae (1968) defines “mangal” as a term for the community, leaving “mangrove” for the constituent plant species, arguing that the expressions “mangal associate”, “mangrove associate” and “back mangal” may be used to distinguish species and communities. However, Machava-António et al. (2022) summarize the mangrove as tropical trees restricted to intertidal and adjacent communities, while Neely and Raymond (2023) describe mangal as a community that contains mangrove plants characterized by their fidelity to the ecotone influenced by tides which fluctuate, and inundate either the shoreline or river banks where the mangrove penetrate extensively. Hoff and Michel (2014) argue that mangroves are mostly defined by their ecology rather than their taxonomy.

Mangroves are among the most and distinctive coastal ecosystems (Ahmed et al., 2022). They colonize the area between land and sea of tropical and sub-tropical regions, making tidal forests, being one of the most productive and biodiverse ecosystems in estuaries, sea coasts and river mouths in the world (Chanda et al., 2016; Rovai et al., 2022). They create a habitat for economically valued fisheries and endangered species, stabilize shorelines, provide a number of direct and indirect services to human populations, including timber and non-timber products (Figure 2), being a subsistence source for local communities, protection of the coast against the effects of wind, swell and wave action (Kangkuso et al., 2015; Leal and Spalding, 2022). Mangroves provide protection from extreme weather events and regulate global climate (Ahmed et al., 2022).

Figure 2 - An example of uses of mangrove by the community of Pemba Bay (Mozambique): a cage made by mangrove poles to hunt crabs, for the subsistence, in *Rhizophora mucronata* community.

Mangrove plants may grow in different types of soil, and their vegetation species composition and structure may vary considerably at the global, regional and local scales (Hossain and Nuruddin, 2016). Soils of mangroves correspond to marine alluvium, transported as sediment and deposited by rivers and the sea (Sarker et al., 2020). Soils of mangroves are deep, show a wide variation in texture proportion of sand, silt, clay, are rich in organic matter and show low bulk density (Vasconcelos et al., 2014; Adame et al., 2013; Hossain and Nurunddin, 2016; Stringer et al., 2016; Nengi-Benwari et al., 2022). Usually, they are waterlogged, having little aeration, leading to accumulation of reduced compounds, which is associated with their dark grey and black color (Nengi-Benwari et al., 2022; Salvador et al., 2022). Soils of mangroves are characterized by the combination of various physical, chemical and biological factors, which may vary considerably among forest sites and within each site (Naidoo and Raiman, 1982; Brady and Weil, 2017). For instance, largest differences in soil character occur between the interior and seaward fringe settings (Stringer et al., 2016; Sasmito et al., 2020; Dewiyanti et al., 2021; Nengi-Benwari et al., 2022; Vivanco, 2009) related to salinity (Adame et al., 2013; Rahman, 2020; Ahmed et al., 2022; Nengi-Benwari et al., 2022), soil potential redox (Bomfim et al., 2018), iron sulphite content (Nengi-Benwari et al., 2022), nutrients (Andrade et al., 2018; Castellon et al., 2022) and organic matter (Castellon et al., 2022), determining mangrove species composition and structure, productivity and functions (Ball, 2002; Hossain and Nurunddin, 2016; Sarker et al., 2020; Poungparn et al., 2020).

Mangrove ecosystems are among the most carbon rich forests in the world and are vital for maintaining the global carbon cycle, given their ability to store carbon (Katherisan and Bingham, 2001; Jana et al., 2009; Bouillon, 2011; Alongi, 2012; Howard et al., 2014; Ahmed et al., 2022; Chatting et al., 2022). Although climate change has increased the interest in mangrove areas, as a result of their high capacity for carbon sequestration (Donato et al., 2011; Ricart et al., 2016; Salmo et al., 2019), studies regarding the quantification of biomass, species variability, soils or carbon changes, are still scarce (Mavie 2012; Tang et al., 2016; Amarasinghe and Balasubramaniam, 1992).

Mangroves have the highest carbon density among forested systems, as they can sequester a great amount of carbon, reaching up to 1,023 Mg ha^{-1} (Sitoe et al., 2014; Doughty et al., 2016), where the highest amount is allocated to the soil, depending on the species, the forest condition (Adame et al., 2017; Fernandes et al., 2020; Salvador et al., 2022). Covering only 0.5% of the global coastal area, the mangrove forests account for 11% of the total input of terrestrial carbon into the ocean, and 10% of the terrestrial dissolved organic carbon exported to the ocean (Giri et al., 2011; Howard et al., 2014; Serrano et al., 2016; Salvador et al., 2022).

Mangrove forests include wide a variety of trees and shrubs that have numerous adaptations to live in the challenging environmental gradient of the upper zone (less flooded), intermediate zone and lower zone (frequently flooded) (Figures 1, 3 and 4). They are home to a rich fauna, including 341 internationally threatened species, ranging from tigers to seahorses (Leal and Spalding, 2022). The structure and productivity of mangroves enables them to support rich fisheries. New research has estimated that, in many countries, over 80% of small-scale fishers rely on mangroves, and there are over 4.1 million mangrove fishers globally - each supporting a network or community of dependencies. Large-scale offshore fishing operations, notably for prawns, also have an often-overlooked dependency on mangroves for breeding or as nursery areas (Spalding and Leal, 2021).

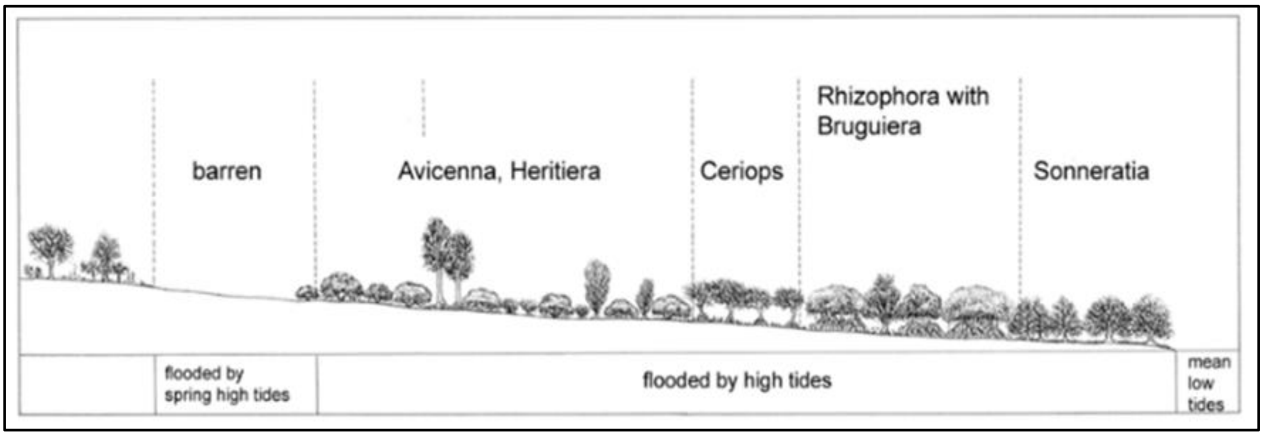


Figure 3 - Distribution of main species occurring in the different mangrove zones (adapted from Brown et al., 2016).

Since they are located where sea meets land, mangroves can reduce flooding and act as natural defenses from waves and wind. They also act as permeable dams, dampening storm surges and reducing damage (Shapiro et al., 2015). It has been estimated that mangroves prevent more than $65 billion in property damages and reduce flood risk to some 15 million people every year (Spalding and Leal, 2021). In the face of accelerating climate change, mangroves are particularly important contributors to ecosystem-based adaptation with a robust capacity to support lives and livelihoods, even in the changing settings predicted by many future climate models (Jones et al., 2014). A critical feature of mangrove forests is their ability to convert carbon dioxide to organic carbon at higher rates than almost any other habitat on earth. This ‘blue carbon’ is stored both in the living plants and in their thick peaty soils where it can remain, fixed, for centuries (Vasconcelos et al., 2015; Spalding and Leal, 2021; Salvador et al., 2022).

For mangroves, however, the most relevant components include changes in sea level, high water events, stormi-ness, precipitation, temperature, atmospheric CO_2 concentration and ocean circulation patterns. They are always associated with and subjected to saline seawater.

The effects of salinity on mangroves affects leaf structure, rates of transpiration, stomatal conductance and rates of photosynthesis (Bhattacharjee et al., 2013; Hogarth, 2015; Leal and Spalding, 2022). The rising sea level increases the salinity of the ambient water and soil, which poses a negative impact on the growth and physiological set-up of mangroves (McIvor et al., 2013; Bhattacharjee et al., 2013). Bhattacharjee et al. (2013) observed that the concentrations of chlorophyll decreased significantly with salinity in *Sonneratia apetala*, *Avicennia marina*, *Avicennia officinalis* and *Heritiera fomes*, but for *Rhizophora mangle,* a reverse situation was observed. The chlorophyll level also increased significantly with the increase of salinity. This confirms the adaptation of the species at biochemical level to high salinity related to rising sea level as was also observed by Richmond (2012) when described the specific pattern in the gradient of salinity and water availability as well as the way species cope through.

Figure 4 - Examples of the upper (A) and the lowest (B) zones of the Pemba Bay mangrove (Pemba, Mozambique).

Mangroves are facing several threats from human impact to natural phenomena (Feng et al., 2020; Leal and Spalding, 2022). Deforestation of mangroves results in a substantial increase in greenhouse gas emissions contributing with 17% of carbon emissions in the atmosphere (Jones et al., 2014). Most of the remaining mangrove is globally showing a slowed rate of loss. However, there are considerable hot spots in Asia. Therefore, monitoring the areas where these processes take place is essential (Salvador et al., 2022; Leal and Spalding, 2022). Updating information and describing the extent and conservation status of mangroves is crucial for effective management and decision-making (Jones et al., 2014; Salvador et al., 2022). Estimating the biomass and the amount of carbon sequestered or lost by mangroves is of great importance for climate change mitigation, allowing the benefit from economic incentives for conservation and preservation of mangroves, such as the Reducing Emissions from Deforestation and Forest Degradation (REDD+) (Akhand, 2016; Castellon et al., 2022).

The anthropogenic activities are responsible for over 60% of mangrove loss (Machava-António et al., 2022). Primary causes include conversion to farmland, aquaculture and urbanization. Natural or indirect human causes make up the remainder, including erosion, sea level rise, and storms, many of which are being exacerbated by climate change. Efforts to protect mangroves have risen globally and, currently, around 42% of all remaining mangroves are in designated protected areas. While this represents good progress, these are varied in distribution and, within these areas, degradation and loss still occurs due to natural causes, as well as failures of implementation of management programs worldwide (Kairo et al., 2021; Leal and Spalding, 2022).

1.2 MANGROVES IN THE WORLD

Mangroves are typically described to be much more concentrated throughout the tropics in suitable areas (Leal and Spalding, 2022). They colonize particular regions with large extensions, as a case of estuaries of large rivers that run over a shallow continental shelf of the Sundarbans, in Bangladesh, the rivers of Papua New Guinea and the Mekong Delta, in Vietnam (Hoff and Michel 2014; Hogarth, 2015). The Florida (USA) everglades is a drainage basin that changes from fresh water to an extensive mangrove at its seaward margin, differing from the two largest tropical rivers, the Amazon and Congo, that do not develop extensive estuarine mangrove for physiographic reasons (Tomlinson, 2016).

The location of mangroves in tropical regions, suggests a sea-surface temperature limitation. However, they can cope well in air temperatures approximately between 5 to 24ºC, but intolerant to frost. Therefore, community of species are differently distributed in the hemispheres (Hoff and Michel, 2014; Hogarth, 2015).

Mangroves worldwide cover an approximate area of 140,000 km^2 of sheltered coastlines, distributed within the tropics and subtropics (Figure 5), reaching their maximum development between 25°N and 25°S (Hoff and Michel, 2014). Figure 5 also shows the global distribution of mangrove over the two hemispheres - the Atlantic East Pacific and the Indo West Pacific. The largest area of mangroves occurs in Southeast Asia (43,767 km^2) and North, Central America, and the Caribbean (20,962 km^2). Globally, these regions account for 44% of the world mangrove area (Figure 6). They are followed by the West and Central Africa (19,767 km^2) and South America (18,943 km^2), which represent 26.2% of the global mangrove area in the world. These regions have more than two thirds of the global mangrove areas (Figure 6).

Besides differences in distribution areas, it is noteworthy the strong difference regarding the number of species occurring among the mangroves occurring in the different regions. Indeed, in the Southeast Asia and part of South Asia, Australia and Pacific Islands the number of species is much higher (17-47) than that reported for the other regions (Figure 5 and 6). Specifically, in parts of Southeast Asia the species number can range from 26 to 47. In contrast, the number of species in mangroves of Africa, South, North and Central (and the Caribbean) America, and in part of Pacific islands (East Pacific) is smaller, ranging from 1 to 12 (Hoff and Michel, 2014).

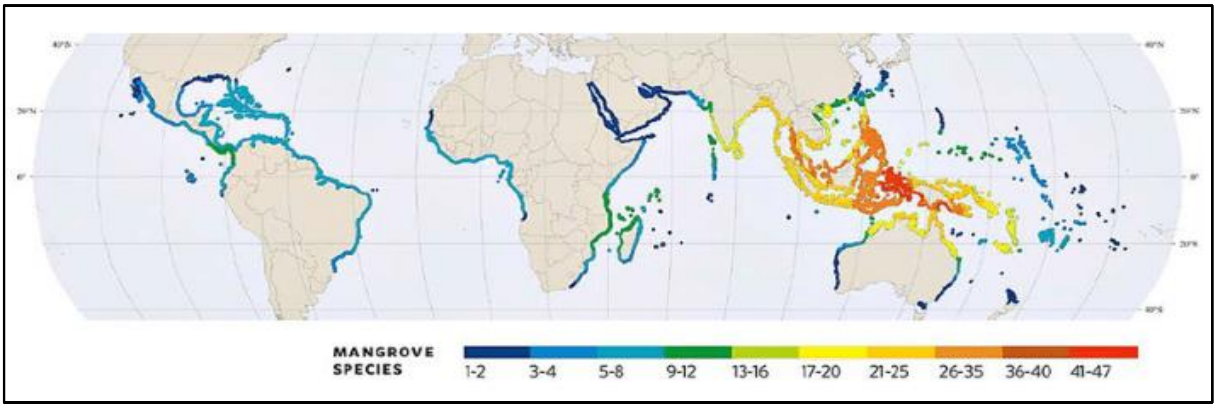


Figure 5 - World map of the mangrove distribution regions and the number of mangrove species along each region (Hoff and Michel, 2014).

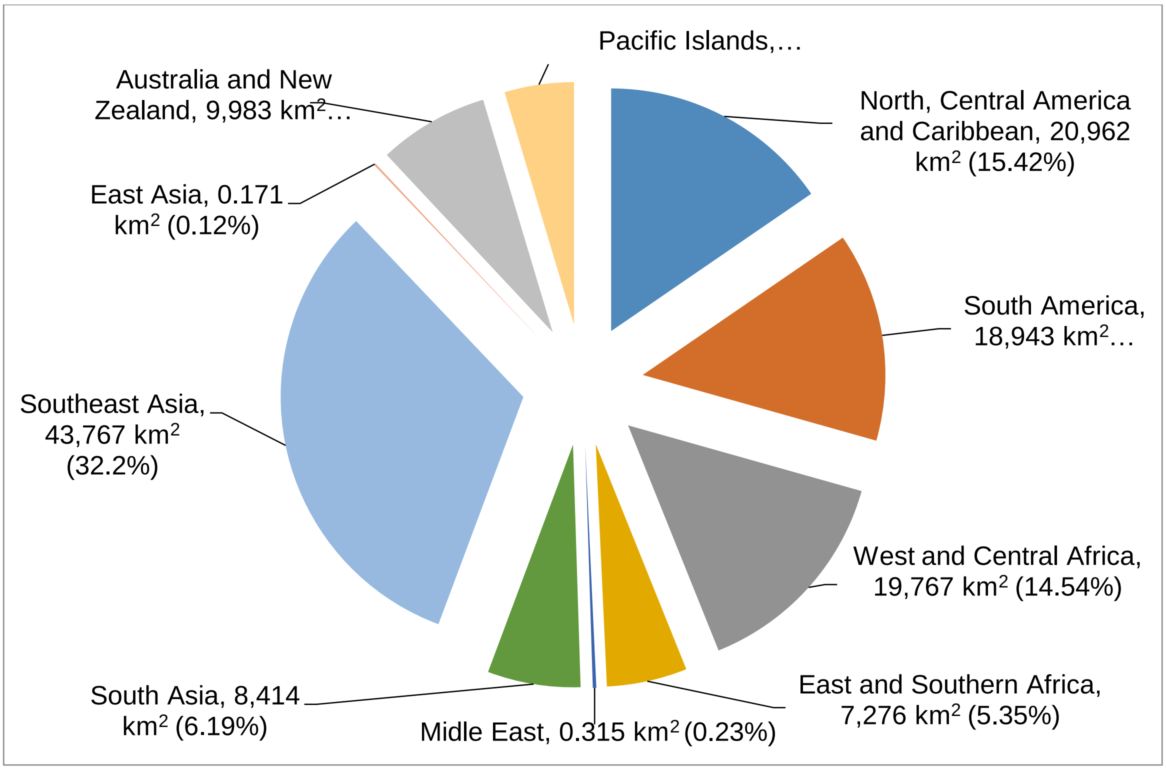


Figure 6 - Mangrove extent in the different regions of the world (from Leal and Spalding, 2022).

In the mangrove world regions, mangroves exhibited a diversified dynamic during the last twenty years (1996 to 2020). In the reference period is when the data was starting to be collected consistently (Leal and Spalding, 2022). However, the monitoring intervals were not consistent (12, 8 and 4 years). As is shown in Table 1, the mangrove area did not vary significantly in a general frame, East Asia where these forests were converted in aquaculture ponds as well as the relation with the over population in that region of the world. Even though, the loss of mangrove area around the mentioned area was about 4%.

Table 1 - Worldwide mangrove areas (km^2) and respective variation (km^2, and %) from 1996 to 2020 (adapted from Leal and Spalding, 2022).

Region	1996	2008	2016	2020	2008-1996	%Δ 2008-1996	2016-2008	%Δ 2016-2008	2020-2016	%Δ 2020-2016
North, Central America and Caribbean	23,949	23,167	22,684	22,827	-782	3.27	-483	2.08	143	0.63
South America	20,516	20,210	20,251	20,378	-306	1.49	41	0.20	127	0.63
West and Central Africa	22,090	21,937	21,816	21,715	-153	0.69	-121	0.80	-101	0.46
East and Southern Africa	7,902	7,733	7,681	7,630	-169	2.14	-52	0.67	-51	0.66
Midle East	344	331	284	285	-13	3.78	-47	14.20	1	0.35
South Asia	9,818	9,647	9,661	9,549	-132	1.34	14	0.15	-112	1.16
Southeast Asia	50,697	48,664	47,965	48,222	-2,033	4.01	-699	1.40	257	0.54
East Asia	257	231	232	228	-26	10.12	1	0.43	-4	1.72
Australia and New Zealand	10,945	10,618	10,426	10,467	-327	2.99	-192	1.81	41	0.39
Pacific Islands	6,104	6,107	6,070	6,058	3	0.70	-41	0.67	-12	0.20
Total	**152,622**	**148,645**	**147,070**	**147,359**	**-3,977**	**2.60**	**-1,575**	**1.06**	**289**	**0.20**

According to Hogarth (2015), mangroves comprise 55 species distributed in 20 genera, belonging to 16 families (Table 2). A small number of mangrove species represents most families, and non-mangrove species are usually present. From 30 species that represent the major components of mangrove communities, 25 belong to only two families: Avicenniaceae and Rhizophoraceae. These families dominate mangrove communities throughout the world (Hogarth, 2015). In the other hand, Hoff and Michel (2014) report that from a total of, approximately. 20 plant families containing mangrove species worldwide, only two, Pellicieraceae and Avicenniaceae, are comprised exclusively of mangroves, whereas, in the family Rhizphoraceae, only 4 of its 16 genera live in mangrove ecosystems.

Table 2 – Number of mangrove species and respective family and genus (Hogarth, 2015).

Family	Genus	Nº of species
Dominant species		
Avicenniaceae	*Avicennia*	8
Combretaceae	*Laguncularia*	1
	Lumnitzera	2
Palmae	*Nypa*	1
Rhizophoraceae	*Bruguiera*	6
	Ceriops	2
	Kandelia	2
	Rhizophora	8
Sonneratiaceae	*Sonneratia*	5
Secondary species		
Bombacaceae	*Camptostemon*	2
Euphorbiaceae	*Excoecaria*	2
Lythraceae	*Pemphis*	1
Meliaceae	*Xylocarpus*	2
Myrsinaceae	*Aegiceras*	2
Myrtaceae	*Osbornia*	1
Pellicieraceae	*Pelliciera*	1
Plumbaginaceae	*Aegialitis*	2
Pteridaceae	*Acrostichum*	3
Rubiaceae	*Scyphiphora*	1
Sterculiaceae	*Heritiera*	3

1.3 MANGROVES IN MOZAMBIQUE

In continental Africa, mangroves grow in coastal areas ranging from Mauritania (19º N), in the northwest, to Angola (10º S) in the southwest, and from South Africa (29º S), in the southeast, to Egypt (28º N) in the northeast, including Madagascar (Fatoyinbo and Simard, 2013). It is noteworthy the difference regarding mangrove distribution between the southwest and southeast African coast (Figure 6), which are mostly related to strong environmental contrasts (Machava-António et al., 2022). Indeed, the currents of the Mozambique Channel and of Agulhas push the warm tropical environments to higher latitudes in the southwestern Indian Ocean; in contrast, the Benguela current drives cool water to the north in the southeastern Atlantic, compressing the tropical region (Machava-António et al., 2022). This leads to higher mangrove species richness in the Indian Ocean as compared to the Atlantic, causing different forest structures.

On the Atlantic coast of Western Africa, the distribution limit of mangroves coincides with arid regions with rainfall below 30 mm year^{-1} (Saenger and Bellan, 1995). There are seven indigenous species, plus the introduced mangrove palm, *Nypa fruticans* (Thunb.), which are also found on the Atlantic and the Pacific coasts of the America continent (Spalding et al., 1997). The indigenous species are *Acrostichum aureum* L., *Avicennia germinans* (L.) L., *Conocarpus erectus* L., *Laguncularia racemose* (L.) C.F.Gaertn., *Rhizophora harrisonii* Leechman, *R. mangle* L., and *R. racemose* G.Mey.

On the Indian Ocean and Red Sea coastlines, the mangrove area is relatively small compared to the total length of the coastline, due to very arid conditions in areas north of the Equator. There are 14 species of mangrove present in this area, which differ from the west coast species. They are *Acrostichum aureum* L., *Avicennia marina* (Forssk.) Vierh., *Bruguiera cylindrica* (L.) Blume, *B. gymnorrhiza*, *Ceriops tagal* (Perr.) C.B. Robinson, *Excoecaria agallocha* L., *Heritiera littoralis* Aiton, *Lumnitzera racemosa* Willd., *Pemphis acidula* J.R.Forst. & G.Forst., *Rhizophora mucronata* Poir., *R. racemosa* G.Mey., *Sonneratia alba* Sm., *S. caseolaris* (L.) Engler, and *Xylocarpus granatum* J.Koenig. The largest diversity on the African continent occurs in Mozambique, where 9 of the species are present (Spalding et al., 1997).

According to Fatoyinbo and Simard (2013), the total area of mangrove cover in Africa is 25,960 km^2 (with 83% accuracy), which corresponds to about 21% of the mangrove area in the world (Giri et al., 2011; Murdiyarso et al., 2009). The largest mangrove areas, in decreasing order, occur in Nigeria (8,573 km^2), Mozambique (3,054 km^2), Guinea Bissau (2,806 km^2), Madagascar (2,059 km^2), and Guinea (1,889 km^2); the smallest mangroves area (0.4 km^2) occurs in Mauritania (Table 3). The mangrove area in Nigeria is the fourth largest in the world, after Indonesia, Brazil, and Australia (Fatoyinbo and Simard, 2013). Mozambique ranks 13th in mangrove area, with 2.3% of the world's mangrove area (Giri et al., 2011; Bosire et al., 2012), but ranks 2nd in African mangrove area (Tretin et al., 2016). Regarding mangrove biomass (Table 3), Mozambique ranks 3rd as the biomass per hectare is lower than the average for African continent.

Table 3 - Areas of mangrove cover and biomass per country in Africa (Fatoyinbo and Simard, 2013).

Country	**Area**	**Biomass**	
	(km^2)	**(Mg)**	**(Mg ha^{-1})**
Angola	154	1,441,200	94
Benin	18	137,719	76
Cameroon	1,483	25,334,900	171
Republic of Congo	15	267,603	178
Côte d’Ivoire	32	406,516	124
Djibout	17	1,653,170	90
DRC	183	51,570	140
Egypt	1	8,344	117
Equatorial Guinea	181	2,922,420	161
Eritrea	49	640,038	129
Gabon	1,457	23,840,000	162
Gambia	519	5,509,300	106
Ghana	76	742,925	97
Guinea	1,889	18,153,800	108
Guinea Bissau	2,806	31,712,300	113
Kenya	192	2,294,820	119
Liberia	189	2,141,860	113
Madagascar	2,059	24,856,900	121
Mauritania	0.4	4,156	95
Mozambique	**3,054**	**30,974,100**	**101**
Nigeria	8,573	94,788,000	111
Senegal	1,200	11,462,100	95
Sierra Leone	955	10,655,600	112
Somalia	30	436,907	143
Sudan	4	135,626	113
South Africa	12	40,018	100
Togo	2	15,861	78
Tanzania	809	11,037,800	136
Africa	25,960	301,665,553	116

Mozambique has a coastline of approximately 2,470 km and is ecologically divided into three distinct regions. Mangroves in Mozambique occur in sheltered shorelines and river estuaries (Figure 7). The largest areas of mangroves mostly occur in central Mozambique, in the deltas and estuaries of large rivers. Indeed, about 28% of the mangrove area occurs in the Zambezi delta, which is the largest tract of mangrove forest in Africa (Fatoyinbo and Simard, 2013). The provinces of Zambezia and Sofala accounts for about 55% of the global mangrove area in the country.

There are nine mangrove species in Mozambique, according to the last inventory (Barbosa et al., 2001; Shapiro, 2018).

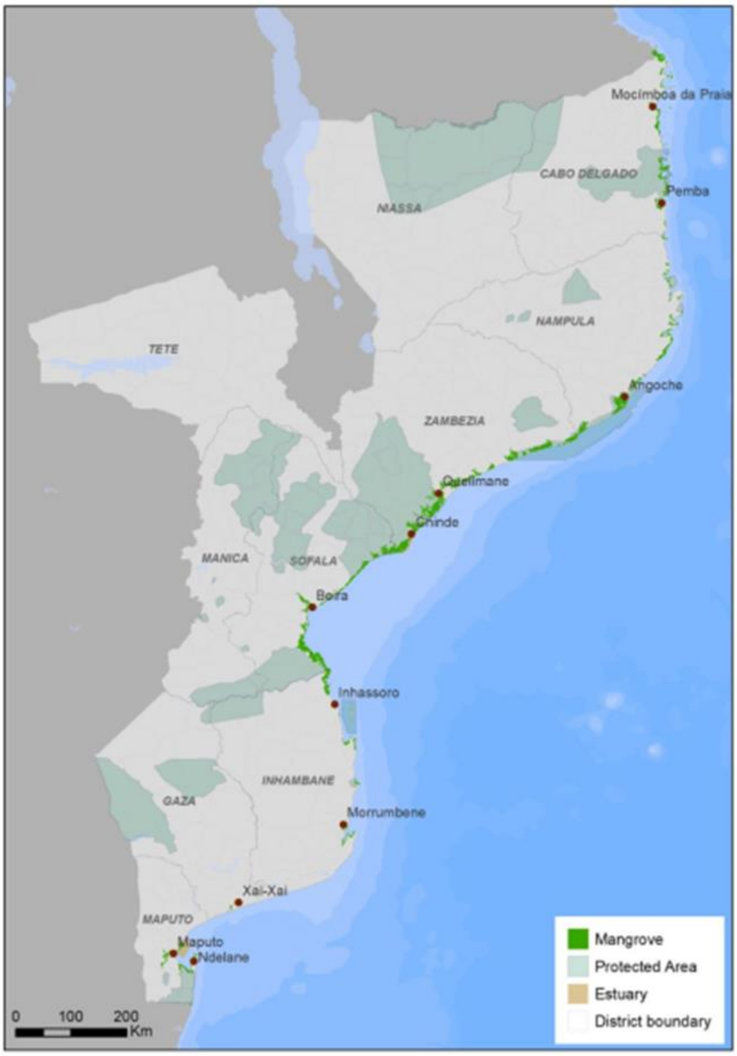


Figure 7 - Distribution of mangrove areas in Mozambique, in 2016 (Shapiro, 2018).

There is not a clear picture on the mangrove area in Mozambique, given de different dates of estimation and the differences in the used methodology. In fact, Fatoyinbo et al. (2008) estimated an area varying from 290,000 to 368,000 ha. Later on, Fatoyinbo and Simard (2013) estimated 300,000 ha (Table 3). Meanwhile, Shapiro (2018) reported a total area of 263,786 ha, in 2015.

As reported for the different mangrove areas in the World (Leal and Spalding, 2022), the mangrove area in Mozambique have strongly changed during the last two decades. For example, Marzoli (2007) reported to have decreased from 408,000 ha, in 1972, to 357,000 ha, in 2004. From 1994 to 2015, the trend of mangrove area variation (Table 4; Shapiro, 2018) followed that established for the worldwide mangrove areas for the period between 1996 and 2020 (Table 1; Leal and Spalding, 2022). It is notable that an average decreasing of 4.6% of the mangrove area from 1994 to 2001, occurring mostly in Zambezia and Sofala areas. Conversely, an increasing of mangrove area occurred during the period from 2001 to 2015 (Table 4). As a result, the net increment of mangrove area relative to 1994 was 19,098 ha (7.8%). It should be also emphasized that changes mostly took place in the centre of the country.

Causes of mangrove loss

Deforestation can lead to irreversible consequences for ecosystem goods, services and values, emphasized by the lack of material transfer into the marine systems and influence the atmospheric composition and climate (Kauffman and Donato, 2012; Shapiro et al., 2015). Tropical cyclones and floods in South (“Favio” - 2007; “Japhet” - 2003; “Eline” - 2000), Central (“Eloise” - 2021; “Chalane” - 2021; “Idai” - 2019) and Northern (“Kenneth” - 2019) regions of Mozambique have been responsible for the devastation of mangrove areas, endangering human life and contributing to environmental losses (Macamo et al., 2016; Charrua et al., 2021). The impact of such events is still poorly quantified, but it is known that the Eline, Japhet and Favio cyclones impacted about 6000 ha of mangrove in the Save delta while the Idai cyclone affected 2,500 ha in Beira, Búzi and Dondo (IUCN et al., 2021).

In Mozambique, studies regarding mangrove structure, conservation or carbon stock assessment are still scarce, due to lack of expertise or funding, and difficulty of field measurements due to extreme conditions like mud or tidal inundation (Kangkuso et al., 2015). Studies on mangrove structure and carbon stock have been developed (Bosire et al., 2012; Sitoe et al., 2014, Shapiro et al., 2015; Macamo et al., 2016; Charrua et al., 2021). However, the gap remains, considering the extension of the country and its distribution countrywide, especially in northern, which limits the planning for protection and sustainable use (Fu and Wu, 2011). The Mozambican mangroves may have some similarities with those in Kenyan, but local specificities, such as river flow, sedimentation, and tidal regime, may be responsible for differences between them.

Table 4 - Mangrove areas (ha) and respective variation (ha, %) from 1994 to 2015 in Mozambique by Province (adapted from Shapiro, 2018).

Province	1994	2001	2008	2015	2001-1994		2008-2001		2015-2008		2015-1994	
					Δ (ha)	Δ (%)	Δ (ha)	Δ (%)	Δ (ha)	Δ (%)	Δ (ha)	Δ (%)
Cabo Delgado	33,646	33,339	35,725	37,041	-307	0.9	2,386	7.2	1,316	3.7	3,395	10.1
Gaza	311	247	266	287	-64	20.6	19	7.7	21	7.9	-24	7.7
Inhambane	17,374	17,112	17,713	18,460	-262	1.5	601	3.5	747	4.2	1,086	6.3
Maputo	12,918	12,587	13,307	13,665	-331	2.6	720	5.7	358	2.7	747	5.8
Nampula	46,351	45,376	47,442	49,271	-975	2.1	2,066	4.6	1,829	3.9	2,920	6.3
Sofala	64,127	60,942	64,676	70,660	-3,185	5.0	3,734	6.1	5,984	9.3	6,533	10.2
Zambezia	69,961	64,409	69,678	74,402	-5,552	7.9	5,269	8.2	4,724	6.8	4,441	6.3
Total	**244,688**	**234,012**	**248,807**	**263,786**	**10,676**	**4.6**	**14,795**	**5.9**	**14,979**	**5.7**	**19,098**	**7.8**

Mangroves of Mozambique are very dynamic and change over time, either from human activities or natural accretion or erosion along the coasts (Charrua et al., 2021). The overall trends, however, onwards from 2001, show that mangrove, despite losses, are showing a net increase in many provinces, with the exception of Zambeze province, which shows a maximum net gain after 2008 (Shapiro, 2018) (Table 4).

In Mozambique, the major factors contributing for mangrove degradation, are divided in antropogenic, such as urbanization, woody fuel, poles for construction, logs for construction of boats, salt pans, agriculture and shrimp aquaculture, and natural phenomens. As natural phenomens, the most common are extreme events as cyclones, inundations, and floods (Charrua et al., 2021; Macamo et al., 2016). In Mozambique, mangrove destruction is reduced and stable. However, the development of the petrol and gas facilities and harbors extension including salt production (e.g. Pemba Bay) is threatening.

Efforts are being made to preserve the Mozambique mangrove and restore the destroyed areas (Vance et al., 1996), by introducing national policies and strategies related to mangroves or coastal ecosystem. Recognizing the social, economic and ecological value of the mangrove, and the growing concern for the maintenance of biological biodiversity at international level (14^{th} Sustainable Development Goal - ODS 14), as well as at national level, based on the principle of rational use and management of natural resources, the Government of Mozambique decided to draw up the National Strategy and Action Plan for Mangrove Management for the period 2020-2024.

In relation to mangroves, Art. 117 of the Constitution of the Mozambican Republic, referring to the “Environment and Quality of Life”, states that:

(1) The State promotes initiatives to ensure the ecological balance and conservation and preservation of the environment aiming at improving the quality of life of citizens.

(2) In order to guarantee the right to the environment in the context of sustainable development, the State shall adopt policies aimed at:

(a) prevent and control pollution and erosion;

(b) integrate environmental objectives into sectoral policies;

(c) promote the integration of environmental values into educational policies and programs;

(d) ensure the rational use of natural resources, safeguarding their capacity for renewal, ecological stability and the rights of future generations;

(e) promote spatial planning with a view to the correct location of activities and balanced socio-economic development.

Management strategy

The Mozambique Mangrove Management Strategy 2020-2024 is a document that constitutes a policy instrument designed to combat and reverse the degradation and destruction of the mangrove ecosystem in the country. As stated in the document "The objective of the Strategy is to maintain or increase the biodiversity, values and function of the mangrove ecosystem, in order to meet the needs of environmental protection in estuaries and coastal areas. It is also intended that this strategy will contribute to minimize the effects of global warming through the process of carbon sequestration and storage, absorbing carbon dioxide from the atmosphere and contribute significantly to the achievement of SDG 14. The implementation of the strategy can also open new avenues for self-employment, such as ecotourism, restoration and replanting, aquaculture and beekeeping, helping to improve the socio-economic conditions of coastal communities."

Mozambique is a signatory of International Conventions regarding to mangrove conservation and restoration such as: Ramsar Convention's (Resolution nº45/03, 5th November); World Heritage Convention (Resolution nº17/82, 13th November); Convention on Biological Diversity (Resolution nº2/94, 24th August); UNCLOS (Resolution nº21/96, 26th November); UNFCCC/Paris Agreement (Resolution nº23/17, 7th November), including Regional Agreements (SADC Forest Protocol). Some programs and policies listed as a contribution for mitigation may concur to relate indirectly to mangroves, e.g., the Decree nº23/2018, 3rd May, regarding the implementation of REDD+ Program states. In fact, one of the objectives is to promote the conservation and restoration of degraded ecosystems and natural resources and value their ecosystem services and environmental factors.

Mangroves sequester and store large quantities of carbon. When they are disturbed, they shift from important carbon sinks to sources of greenhouse gases, becoming ecosystems of great value and interest regarding to climate change adaptation and mitigation strategies (e.g. REDD+) (Leal and Spalding, 2022; Salvador et al., 2022; Kairo et al., 2021). Conservation of mangroves has been increasingly considered as a meaningful way to reduce emissions of GHG in the atmosphere. Participation in such mitigation/adaptation strategies requires accurate quantification of existing carbon stocks to meet required monitoring, reporting and verification standards (Kauffman and Bhomia, 2017; Jones et al., 2014; Salvador et al., 2022).

Globally, it is recognized that blue carbon ecosystems, especially mangroves, sequester large quantities of carbon and are of interest for inclusion in climate change mitigation strategies. While 19% of the world's mangroves are in Africa, they are among the least investigated of all blue carbon ecosystems (Fatoyinbo and Simard, 2013; Kauffman and Bhomia, 2017; Sanderman et al., 2018).

Therefore, intending to produce consistent information to drive protective policies throughout Mozambique mangrove ecosystems, this Thesis brings a deep characterization of the mangrove ecosystem in Pemba Bay, located in the Northern Mozambique. Pemba Bay area is facing population increase and industrial growing, either from creating saline facilities as well as from harbour construction for gas exploitation. These factors can anticipate a possible reduction of the mangrove area that affect all the associated ecosystem services. These include the conservation of species, biodiversity, economic production (fishing and shellfish), biomass for domestic use and carbon accumulation. Pemba Bay is also important to protect the Pemba area from extreme events, including cyclones. Nevertheless, scarce information exists on magnitude of potential effects, even taking into account the constitution on its Art. 102 (Natural Resources) – "The State promotes the knowledge, inventory and valorization of natural resources and determines the conditions of their use and exploitation in order to safeguard national interests".

1.4 OBJECTIVES

The National Strategy and Action Plan for Mangrove Management for the period 2020-2024 is structured into five Pillars of Intervention, being the "Research and knowledge management" one of them.

It is taken into account that forest carbon is stored in five pools (Hoover and Riddle, 2020):

- aboveground biomass, includes foliage, branches, stems and bark, stumps. Also includes living understory plants;

- belowground biomass, includes all living root biomass of trees and understory plants;

- deadwood, includes all dead woody biomass either standing, down or in the soil;

- forest floor litter, includes leaves, needles, twigs, and all other dead biomass. This includes small-sized dead biomass that is decomposed but has not yet become part of the soil; and

- soil, includes all carbon-based material in soil to a depth of 1.20 m.

Within this context, the work developed in that Doctoral Thesis it is intended to contribute to the fulfilment of the National Strategy, being objectives:

1. To describe the forest structure and the biomass pools in mangrove Pemba Bay.
2. To describe the soil profile according to texture, salinity, pH, and organic carbon concentration.
3. To determine the mangrove carbon stock in Pemba Bay.

CHAPTER II

2 STUDY AREA

The study was carried out in mangrove forest of Pemba Bay, which is located in the district of Pemba, in Cabo Delgado Province, Northern Mozambique, between the coordinates 12º51’48.55’’S and 13º04’53.66’’S and 40º23’18.10’’E and 40º30’44.17’’E (Figure 8 and 9).

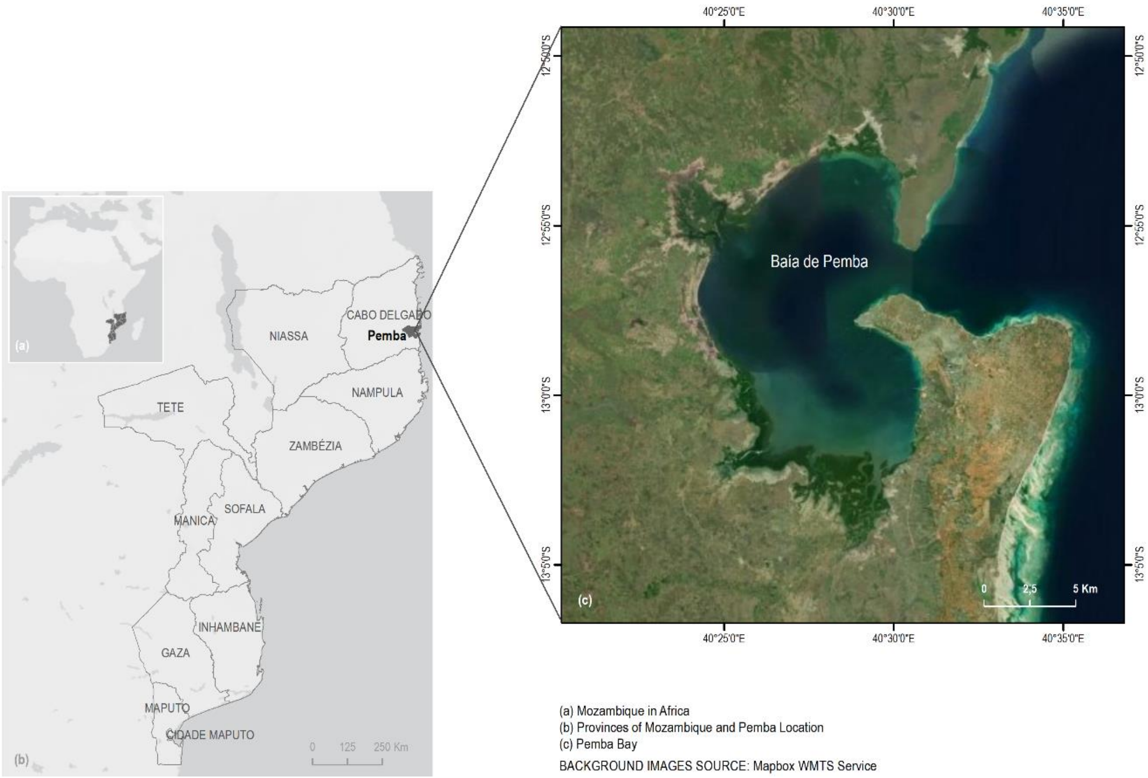


Figure 8 - Location of Pemba Bay in Mozambique.

According to Köppen-Geiger classification, the climate is tropical wet Savanna, with average annual precipitation between 800 and 1000 mm and mean annual temperature of 25ºC (MAE, 2005). The wet season occurs between November and April, corresponding to 85% of the annual precipitation, March being the wettest month. The dry period is from May to October with monthly rainfall averages below 50 mm (Impacto, 2012).

About 30% of the Pemba district is located in the coastal plains, with elevations below 25 m. In the transition to the inland areas, elevations are between 25 and 100 m. In the inland part of the district, land elevations are higher, ranging between 100 and 500 m.

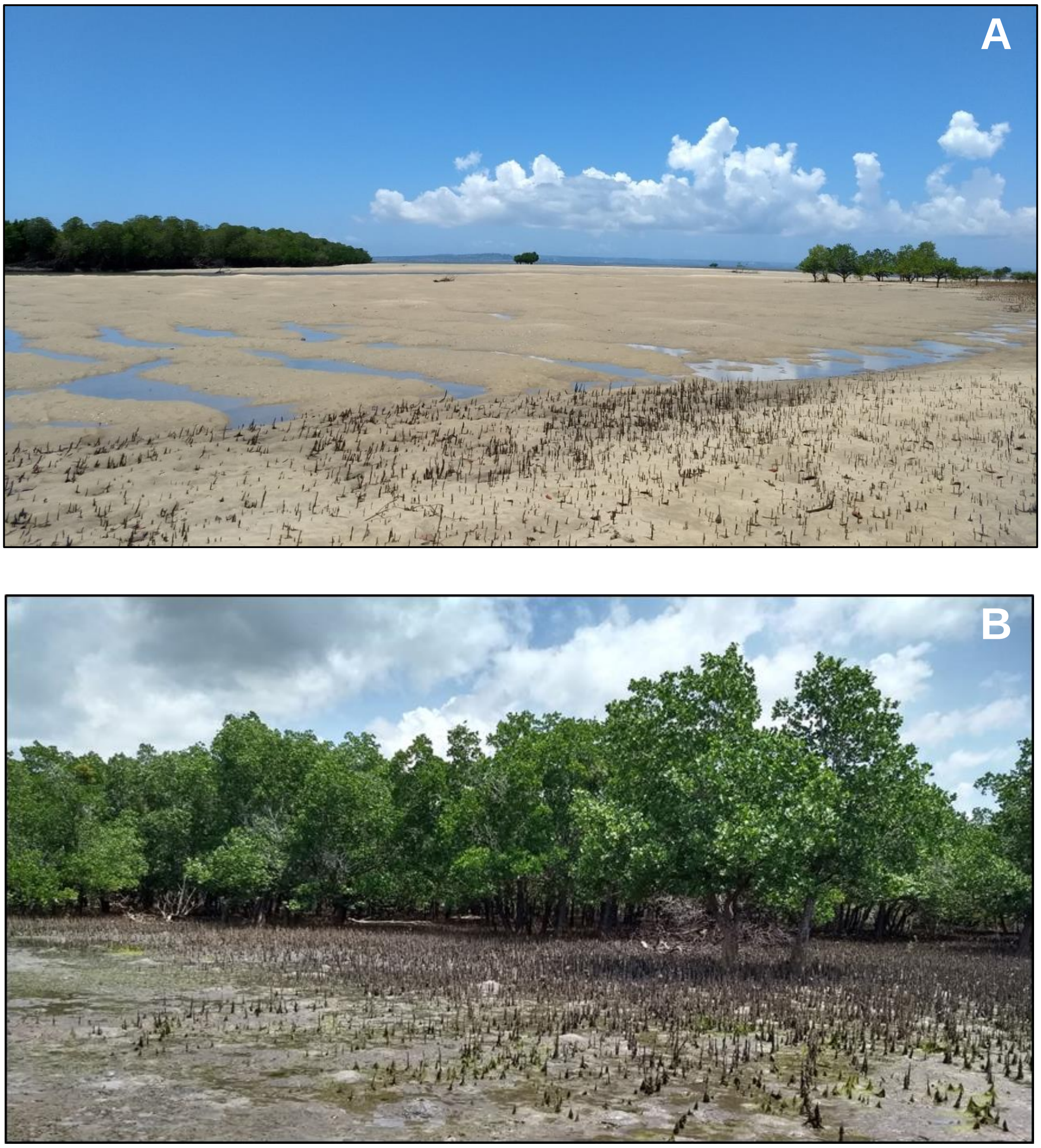


Figure 9 - Landscape of Pemba Bay (Mozambique) mangrove ecosystem communities during low tide: *Rhizophora mucronata* and *Avicennia marina* (A), *Sonneratia alba* (B) and its prop roots.

From the geological point of view, sandstone and claystone predominate in the district, followed by the granitic to tonalitic gneisses of the Meluco do Mesoproterozoic (Impacto, 2012). In the coastal zone, rocks from the Quaternary predominate. Namely recent alluvium, lamellae of sand with local gravel and an association of unconsolidated sand, sandstone and conglomerate from the Mikindani Formation. Alluviums are poorly developed, except along some sections of the main rivers. A small percentage of the coastal zone also has marine reefs, corals and bioclastic sediments from the Quaternary period (Impacto, 2012). In the coastal zone, rocks from the Quaternary predominate.

Pemba district shallow soils over non-calcareous rocks dominate, followed by sandy soils, medium-textured red soils (in association with brownish-grey sandy soils and lithic soils), and alluvial soils (Figure 10) (Impacto, 2012).

In the coastal zone, to the north of the district, the soils are essentially unspecified sandy soils. Coastal dune soils also occur but in a smaller percentage. In the southern part of the district there are non-calcareous rocks and, in smaller percentage, soils of marine soils of marine sediments. Alluvial soils occur along the main rivers. These are very fertile soils.

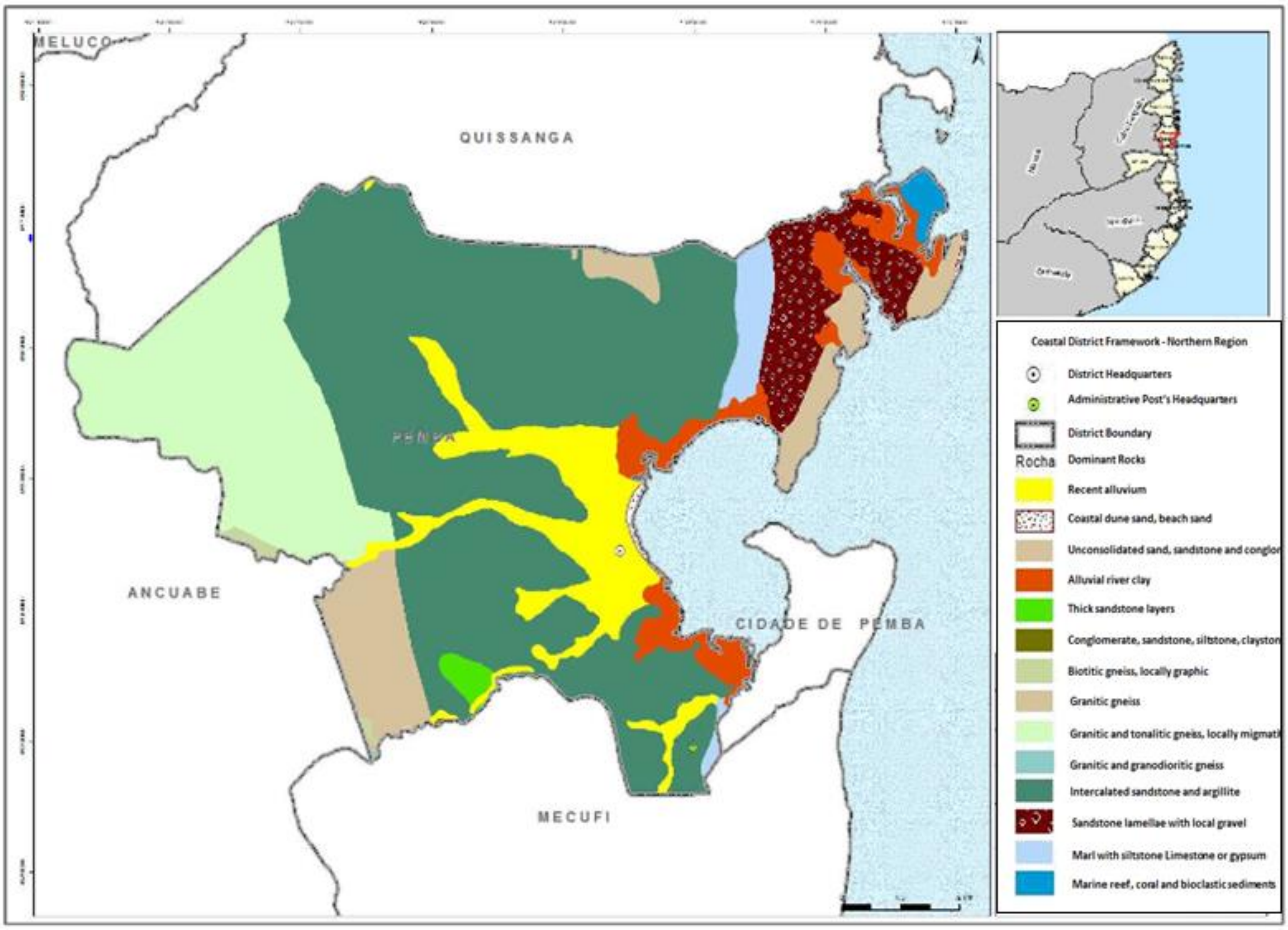


Figure 10 - Distribution of soils in the Pemba district (Impacto, 2012).

In Pemba district, the risk of soil erosion varies between low to moderate. However, this problem has been considered as less critical in an inventory carried out by MICOA (MICOA, 2008). Despite this, the Action Plan for the Prevention and Control of Soil Erosion for 2008-2018 (MICOA, 2008), foresees some priority actions for the district, namely, construction of infrastructures and planting of some species to stabilize steep slopes.

Half of the coastal zone of the district is inside Pemba Bay with depths that do not exceed 50 m. At the mouth of the Bay a canyon appears whose depth increases to 1,000 m. The Bay is one of the most propitious and sheltered bays against winds and swell, usable for vessels with large drafts. The Bay presents many banks and dangerous rocks and it is separated from the ocean by two peninsulas advancing from the coast. The bathymetric lines on the ocean coast are narrower, the 50 m class being only notable at the mouths of rivers. This narrowing occurs until the tip of Diabo in the north of the district (Impacto, 2012).

In Pemba there are aquifers with different productivities, predominating areas whose local aquifers (types C1 and C2) are superficial and limited productivity (extraction flows below 5 m^3/hour). There are still aquifers more productive, types A3 and B3, able to satisfy moderate extractions, between 3 and 10 m^3/hour. In the interior of the district, aquifers of type C2 and B3 predominate (Impacto, 2012). The underground water of these formations is, in general, of good quality. However, close to the coast, there is a high risk of seawater intrusion, which can occur as a result of overexploitation of the holes. In these aquifers, water can also have hardness levels high. In the Pemba district, mostly groundwater occur in sufficient reserves to satisfy only small-scale extractions, given that the average flows are less than 5 m^3/hour. However, aquifers still occur in the district where the extracted flow may be higher (Impacto, 2012).

Near the Pemba Bay, there are some water basins due to the impermeability of some soils and to the depth variations of their beds (MAE, 2014). Access to the Indian Ocean is made from the entrance of the bay, formed by the southern tip Ponta Maunhane and extreme north tip Said Ali (Banze and José, 2011). The continental shelf in the study area is extensive, the depth and volume of the water are variables, and the flat shape of the substrate can be a considerable influence, mainly the shape of the depression and the volume of water, from hundreds of meters from water.

The tides along the Mozambican coast are semi-diurnal, reaching between 0.2 and 7 m at high tides that may occur under medium weather conditions. The tidal range in Pemba is 3.9 m (average of the high tide) and 2.8 m (average of the neap tide). In this region, the tidal amplitude varies markedly during the month and can be as low as 0.6 m during neap tides (Hoguane, 2007).

Pemba Bay mangroves occupies an area of 159.3 ha (Figure 11). On the western side of the Bay, extensive and continuous areas are observed, while on the eastern side there are several natural clearings and areas where the forest has been felled for salt exploitation.

In the study area, there are mixed stands of seven true mangrove species, namely (Macamo et al., 2008; Banze and José, 2011) (Figures 12, 13 and 14):

- *Avicennia marina* (Forssk.) Vierh.

- *Lumnitzera racemosa* Wild (Combretaceae)

- *Ceriops tagal* (Perr.) C.B. Rob.

- *Rhizophora mucronata* (Lamk)

- *Xylocarpus granatum* Koenig.

- *Bruguiera gymnorrhiza* (L.) Lamk.

- *Sonneratia alba* Sm.

The common associate species *Pemphis acidula* Forst. (not true mangrove), ferns *Acrostichum aureum*, and shrubs of genus *Phoenix* can also be found.

The main characteristics of each of those species and its conservation status are presented in Annex 1, based on the IUCN red list (http://www.iucnredlist.org/), where all the species are Least Concern.

Macamo et al. (2008) developed a relevant study in two small patches of Pemba Bay mangrove (southwest part) using a different method, as it was based in belt transects, where was measuring the status of the tree poles and the level cutting. However, the author found results and the same species found in our study. The author observed that the species with the greatest ecological importance were *Avicennia marina* and *Sonneratia alba*, in Mieze and Muchara, respectively. Large individuals are less common in forests, most being between 2.5 and 5 cm diameter. Most poles are not straight (1,273 trees/ha at Mieze and 1,067 trees/ha in Muchara), but there is a considerable stock of straight and semi-straight stems of *Ceriops tagal* and *S. alba* species in Mieze. Muchara is more intensively exploited, judging by the high tree density with 25% and 75% of the branches cut (about 1,100 trees/ha) as well as by the high density of stumps (553 trees/ha, against 273 in Mieze). In both forests, most young plants were between 40.1 and 150 cm height. The total density of young plants was higher in Mieze.

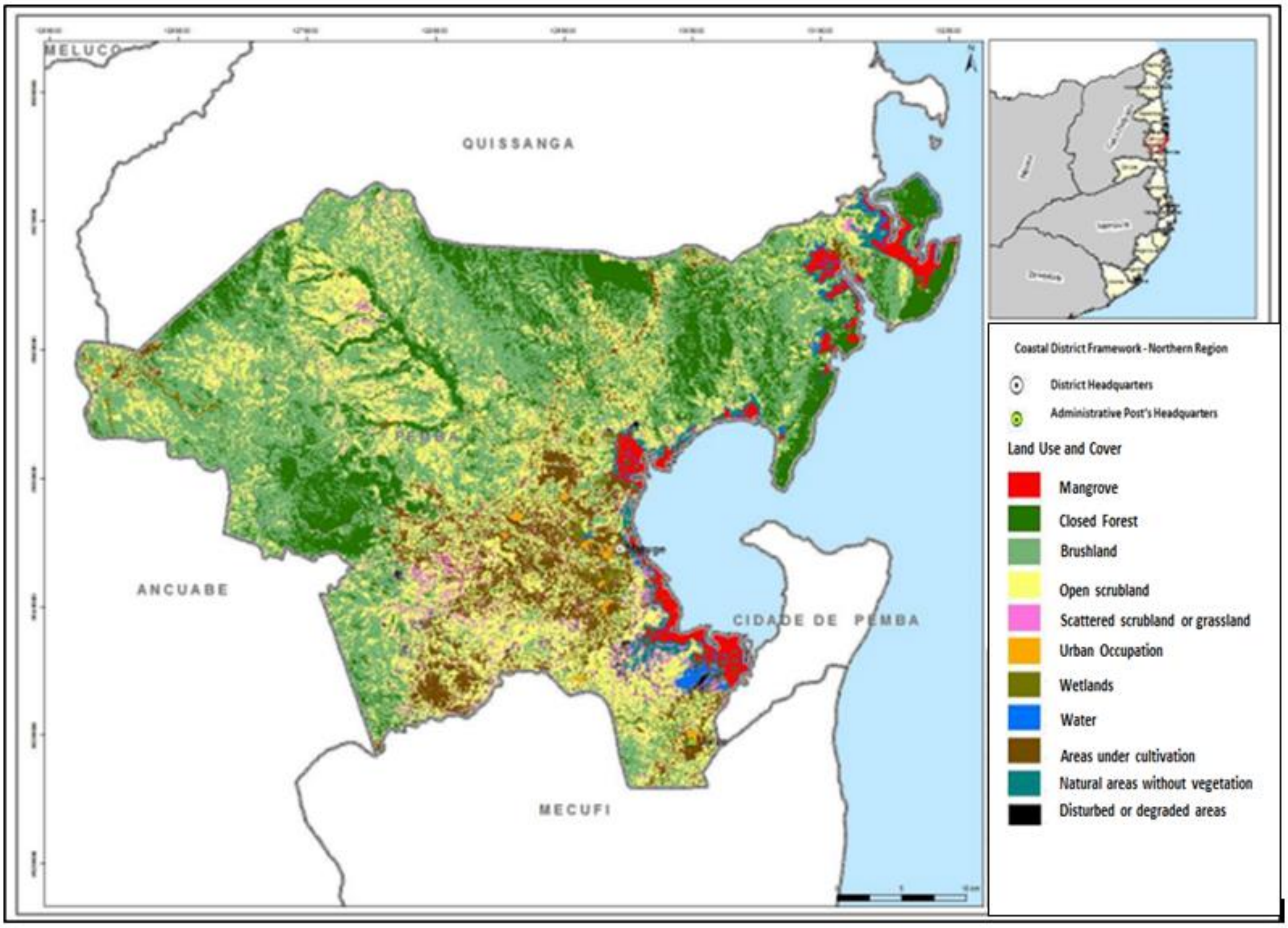


Figure 11 - Mangrove cover in Pemba Bay (Impacto, 2012).

Ferreira et al. (2012) produced an unofficially recognized map with the aim of enlighten about the extension and disturbance of coastal habitats, which included mangrove of Pemba. They had difficulty to access due to the rainfall signal along the period of study. However, they found that the area had grown in 3%. Even though, the authors suggest that data maybe misleading due to the miss of fieldwork data. In general, the authors show some doubts on making the results trustable (Ferreira et al., 2009) suggesting that is better be cautious on using the images due to the accuracy of ecological measurements.

Figure 12 - Mangrove species in the upper zone of the Pemba Bay mangrove: *Avicennia marina* (A) and *Ceriops tagal* (B).

Figure 13 - Mangrove species in the intermediate zone of the Pemba Bay mangrove: *Rhizophora mucronata.*

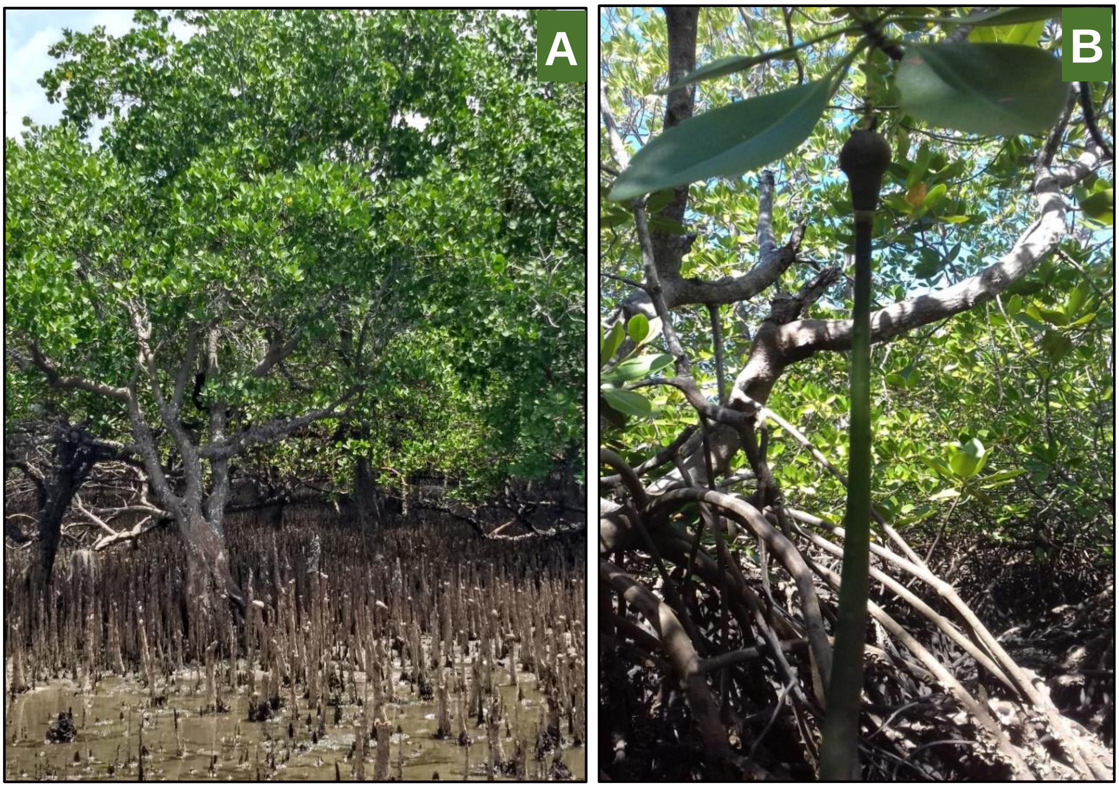


Figure 14 - Mangrove species in the lower zone of the Pemba Bay mangrove: *Sonneratia alba* (A) and *Rhizophora mucronata* (B), with pneumatophores.

CHAPTER III

3 METHODOLOGIES

To achieve the objectives, a methodology was defined and described in the sections below. Thus:

Objective 1. To describe the forest structure and the biomass pools in mangrove Pemba Bay.

A forest inventory was planned and carried out, considering the different mangrove strata: overstory, understory, and dead trees. The data collected in the inventory allowed the characterization of the several strata and the calculation of the variables at tree and stand levels. To estimate tree total biomass in the overstory stratum, allometric equations were used based on the literature related to mangrove. For the three most frequent species - *Avicennia marina*, *Rizophora mucronata*, and *Ceriops tagal* – tree wood biomass equations were fitted in order to analyze the accuracy of the equations used in the biomass estimation. For this purpose, a destructive sampling method was used and 55 trees were felled.

Objective 2. To describe the soil profile, including forest floor litter layer, texture, salinity, pH, and organic carbon concentration.

Sampling of the soil organic layer was carried out and soil samples were taken along a depth gradient. Samples were prepared in the laboratory to enable the description of the soil profile.

Objective 3. To determine the mangrove carbon stock in Pemba Bay.

The carbon stock of the mangrove forest of Pemba Bay is the sum of the carbon, determined per unit area, of the several layers considered.

3.1 SAMPLING DESIGN

A stratified random sampling design (Kauffman and Donato, 2012) was used to inventory the mangrove vegetation and soils of Pemba Bay. The location of the plots was based on remote sensing images. The area was stratified taking into account mangrove species and density, resulting in eight strata. Over the area, a square grid was laid out. The center of each grid cell corresponded to the location of the inventory plots. Most of the plots were distributed in the western and eastern side of the Bay, following the starting direction (clockwise) according the furthest accessible region to the main town, due to logistical constrains. Thirty plots were identified.

In the field, it was not always possible to install the plots in the previously defined locations. There were several causes: tide variation, presence of bees, and mostly water shads crossing the forest. Alternative nearest points in a distance of, at least, 1 km were defined. Of the initial 30 inventory plots, only 15 could be installed (Figure 15, Table 5), resulting in two groups of plots: plots 1 to 8, and plots 9 to 15. The other 15 plots were not accessible due to military attacks over the region alongside the established period for sampling. However, the number of plots installed was considered as reasonable and the plots were representative to the area. The total sampled area corresponded to 4.9% of the mangrove area of Pemba Bay.

Figure 15 - Location of the inventory plots in Pemba Bay.

Each square inventory plot has 0.52 ha of area (Figure 16). Within each plot, and in order to accommodate inherent spatial variation, 5 circular subplots with 153.9 m^2 of area (7 m radius) were considered, distributed in the four corners and one in the centre of the square (Kauffman and Donato, 2012). The 7 m radius subplot contained a nested 2 m radius circle for measuring natural regeneration (saplings). The closed symbol in the center of each subplot was used for soil samples.

Table 5 - Coordinates of the centres of the inventory plots located in the mangrove of Pemba Bay.

Plots	Latitude	Longitude	Plots	Latitude	Longitude
P1	12°53'54.31"S	40°26'14.16"E	P8	12°54'9.84"S	40°23'42.30"E
P2	12°54'21.31"S	40°25'40.60"E	P9	12°59'20.26"S	40°30'45.76"E
P3	12°54'53.24"S	40°25'34.51"E	P10	13°0'28.31"S	40°30'46.41"E
P4	12°55'15.01"S	40°25'11.45"E	P11	13°1'16.77"S	40°30'40.10"E
P5	12°55'24.43"S	40°24'49.37"E	P12	13°2'51.18"S	40°29'21.87"E
P6	12°55'0.19"S	40°23'49.02"E	P13	13°3'14.21"S	40°28'44.23"E
P7	12°54'15.70"S	40°24'24.57"E	P14	13°3'32.82"S	40°29'23.71"E
			P15	13°3'17.32"S	40°27'42.44"E

Table 6 – Main inventory plots characteristics in the mangrove of Pemba Bay.

Plot	Main plot characteristics
P1 P2 P3 P4 P5 P6 P7 P8	Plots located in western side of the Pemba Bay. This region is little disturbed. It is a remote area with less anthropogenic disturbance. Tree density is high.
P9 P10 P11 P12 P13 P14 P15	Plots located in eastern side of the Pemba Bay. This region is close to the urban area. Signs of anthropogenic activities are visible. Pure mangrove is common. Plots 13, 14, and 15 are surrounded by salt pans; Plot 11 is a clearing, as a result of the high salinity level.

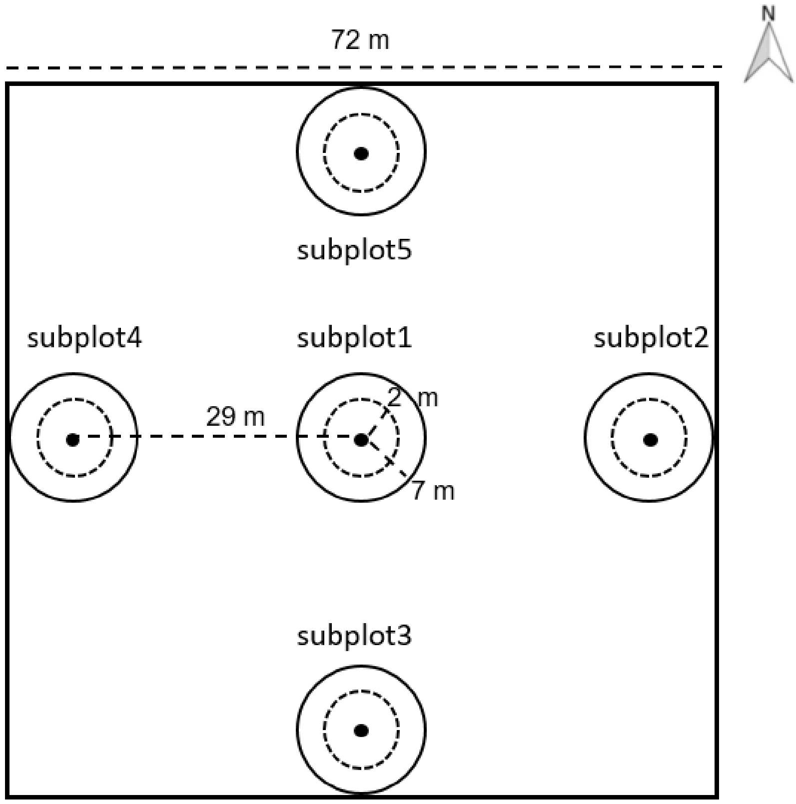


Figure 16 - Design of the inventory plot, with the location of circular subplots and nested circular plots (adapted from Kauffman and Donato, 2012).

3.2 TREE MEASUREMENTS

A field protocol was prepared to guide the inventory work. In this protocol were defined:

- variables to be measured in each of the layers considered - overstory, understory, dead trees, and soil;

- rules of measurement of the variables;

- the measuring equipment.

The information collected was used to:

- characterize the mangrove in the Pemba Bay;

- select trees to be felled (species and number of trees/species) to develop stem biomass equations;

- quantify the carbon in the mangrove layers.

Overstory layer

In each square inventory plot (Figure 16), the diameter at breast height (dbh) was measured for all live trees with a dbh greater than 50 cm. In each circular subplot (7 m radius), dbh was measured for all live trees with a dbh greater than 5 cm (overstory layer). Dbh was measured at 1.3 m height except in the case of *Rhizophora mucronata* tree species when the highest prop root occurred above 1.3 m height. In that case, diameter was measured at 30 cm above the highest prop root. Total height was measured for all trees. Heights were measured with a 4 m bamboo pole and the diameters with a caliper to nearest 0.1 cm (Figures 17 and 18).

Figure 17 - Measuring diameter of *Rizophora mucronata* with a caliper at 30 cm above the last pneumatophore.

Figure 18 - Measuring tree height with a bamboo stick.

Understory layer

In the nested circular subplots (2 m radius) (Figure 16), natural regeneration (saplings) with diameter - taken at the base - smaller than 5 cm was counted and height was measured. Heights were measured with a measuring ruler and the diameters with a diameter taper.

Dead trees

The dead standing trees were recorded in the 7 m radius subplots and classified according to a decay class (Figure 19): 1 – tree presents leaves, branches and stem; 2 - tree presents branches and stem; 3 – tree presents only stem. In addition, dbh measurements were adjusted to accommodate different mangrove morphologies, just above the highest prop root and above buttresses (Kauffman and Donato, 2012; Trettin et al., 2016).

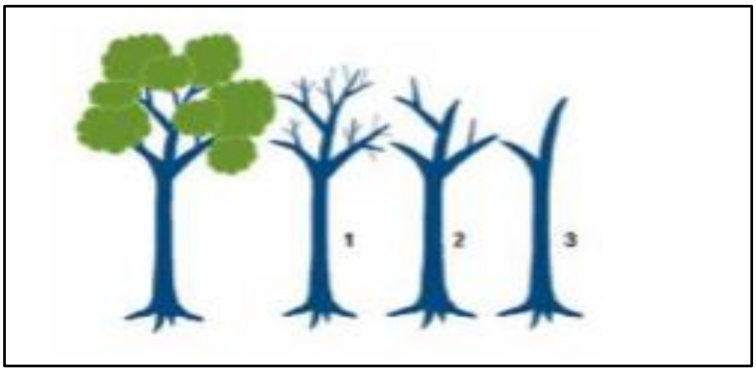


Figure 19 - Dead trees classes according to Kauffman and Donato (2012).

Felled trees

Tree felling was restricted to the most abundant species in the Bay - *Avicennia marina, Rizophora mucronata*, and *Ceriops tagal*. Moreover, it was only done in five plots located in the lower part of the Bay (Figure 16), since the insecurity due to terrorist actions shortened the period in which fieldwork could be conducted.

To select the trees to be felled, the information collected in the inventory was used. Trees were distributed over 10 dbh (over bark) classes of 6.3 cm range. The range classes was determined according Finger (1992), for the entire study area. However, it was only possible to fell trees from five dbh classes (Table 7), because for the larger trees it was not possible to get a chainsaw to do the felling. In each of the dbh classes of each plot, the trees to be felled were selected as they were measured in the field.

Table 7 - Number of felled trees by dbh class and species.

dbh class (cm)	Number of felled trees	Number of felled trees		
		A. marina	*C. tagal*	*R. mucronata*
[6.0-12.3[	22	12	5	5
[12.3-18.6[	12	9	1	2
[18.6-24.9[	13	12	-	1
[24.9-31.2[	6	4	-	2
[37.5-43.7[	1	1	-	-
Total	54	38	6	10

Trees were felled using a chainsaw (Figure 20). Each tree was debranched and the stem was cut in three logs (upper, middle, and lower) of equal length, therefore, there was no experimental information about the weight of branches, leaves and pneumatophores, including the roots. Each log was weighed using a 100 kg dynamometer. A 5 cm width disc was cut in the middle of each section. Discs were weighed in the field and taken to the CEPAM Laboratory in order to determine the moisture content. For each sample disc, the plot number, species, tree number, the corresponding stem log, the log weight and the sample disc weight were recorded.

Figure 20 - Cutting and sampling of felled trees.

3.3 SOIL SAMPLING

To sample the forest floor litter layer, all the decomposing material contained in a 50 cm x 50 cm square was collected in the centre of each of the five circular subplots (Figure 21). This material was weighed in the field and taken to the Laboratory for dry weight determination. From the dry material, a 100 g sample was taken, which was ground and sent to the ISA Laboratory for determination of carbon and chemical elements.

Soil samples were taken in the center of each 7 m radius subplot of each square plot (Figure 16) to assess soil characteristics up to 150 cm depth. Samples were collected by using a soil sample probe (Figure 21). A soil core or section was extracted at specified depth intervals: 5-10, 20-25, 35-40, 70-75, and 145-150 cm. The depth of the samples was referenced to the soil surface. Soil samples were stored in labelled plastic bags and taken to the Laboratory.

Figure 21 - Soil sampling in the upper (A), middle (B) and lower (C) zone of mangrove in Pemba Bay. (D) Structure for sampling the forest floor litter layer.

3.4 LABORATORY PROCEDURES

In the Laboratory, the samples (stem+bark) were identified and their respective weights were taken. Samples were placed in an oven at 60ºC until constant weight (Figure 22). The number of days in the oven varied between 3 and 16 days. At the end, the samples were weighed. The percentage moisture content per log was used to calculate the dry biomass of each of the felled trees.

Figure 22 - Drying sample discs in the oven.

The material correspondent to forest floor litter layer was ground to pass a 1 mm screen before the chemical analysis was carried out. For chemical analysis, two replicates were used. Carbon content was determined by wet oxidation method (De Leenheer & Van Hove, 1958). The mineral nutrients were determined after ashing (6 hours at 450ºC) and dissolving ash in HCl. Ca, Mg and K were measured by atomic absorption spectrophotometry, and P by the ascorbic acid method (Watanabe and Olsen, 1965). Total N was determined by Kjeldahl digestion (Digestion System 40, Kjeltec Auto 1030 Analyser).

In the Laboratory, soil samples were dried in an oven at 70ºC. A 100 g subsamples were sent to the ISA Soil Laboratory, to pass a 2 mm mesh sieve. Soil analyses were carried out on the fine earth fraction (<2 mm). Particle size analysis was determined by the pipette method (clay <2 µm, and silt 2-20 µm), sedimentation and decantation (fine sand 20-200 µm) and by wet sieving (coarse sand 200-2000 µm), after H_2O_2 oxidation of organic matter and dispersion with a mixture of sodium hexametaphosphate and sodium carbonate. Total organic C was measured as above for the organic material. Soil pH was determined by potentiometry using a 1:2.5 soil/water and soil/KCl suspensions. The pH and the electrical conductivity of the samples were measured in a suspension of soil: distilled water in the ratio 1:2.5 by digital pH meter.

3.5 CALCULATIONS

Total tree biomass and stand variables

Tree above and belowground biomass were estimated by species. Considering the fact that local species-specific allometric equations have not yet been developed for the study area, and that the equations of Komiyama et al. (2005, 2008) have been used in previous studies in the mangroves of Mozambique (Trettin et al., 2016), those were selected to estimate above and belowground biomass:

$$w_{ag} = 0.251\ \rho\ dbh^{2.46} \qquad \text{eq (1)}$$

$$w_{bg} = 0.199\ \rho^{0.899}\ dbh^{2.22} \qquad \text{eq (2),}$$

where w_{ag} is the tree aboveground biomass (kg); w_{bg} is the tree belowground biomass (kg); ρ is the wood density (g cm^{-3}); and dbh is the diameter at breast height (cm). Species-specific wood density values published by Bosire et al. (2012) for Zambeze Delta (Table 8) were used.

Table 8 - Wood density of mangrove common species in Mozambique (Bosire et al., 2012).

Species	**Wood density (g cm^{-3})**
Avicennia marina	0.9
Bruguiera gymnorrhiza	1.3
Ceriops tagal	1.1
Heriteira littoralis	0.8
Rhizophora mucronata	1.1
Sonneratia alba	0.8
Xylocarpus granatum	0.8

For standing dead trees, particularly decay classes 1 and 2, eq (1) was used with a wood density value of 0.69 g cm^{-3} (Kauffman and Donato, 2012; Trettin et al., 2016). The loss of leaves and branches (Figure 19) were compensated by subtracting 2.5 and 15% of the biomass estimates for each one of these two classes, respectively (Kauffman and Donato, 2012; Trettin et al., 2016). For decay class 3, aboveground biomass was estimated by applying the formula of a cone volume multiplied by 0.69 g cm^{-3}. Belowground biomass for all classes of standing dead trees was estimated with equation (2), assuming a wood density value of

0.69 g cm^{-3}. Consideration was made for the swift loss of fine roots once a tree dies, correcting the estimates by subtracting 46%, a conservative estimate within the ranges of fine root biomass (Komiyama et al., 1987, 2000).

For the understory, as the diameter was measured at the tree base, the aboveground biomass was estimated assuming a cone; volume was multiplied by the wood density of each species (Table 8).

Biomass estimates were converted to carbon mass by using 0.50 and 0.39 for above and belowground estimates, respectively (Kauffman and Donato, 2012; Trettin et al., 2016).

To analyse the accuracy of the aboveground biomass equations used (eq. 1), 54 trees were felled as described in section 3.2 and allometric equations were fitted to estimate the wood biomass for the most abundant species in the Pemba Bay: *Avicennia marina*, *Rhizophora mucronata*, and *Ceriops tagal*.

The moisture content (MC) of the log samples discs was determined by (Sitoe et al., 2014):

$$MC = \frac{w_g - w_d}{w_g} \times 100 \qquad \text{eq (3)}$$

where MC is the moisture content (%); w_g is the disc green weight; w_d is the disc dry weight.

A graphical analysis was made to analyze the relationship between tree stem biomass and dbh. Finally, allometric equation were fitted to estimate tree stem biomass as a function of dbh. The coefficient of determination was used to select the equation that best fits the dataset. The analysis was done by species.

The fitted equations were applied to the total dataset (from the inventory), to obtain stem biomass estimate for each tree of each species (*Avicennia marina*, *Rhizophora mucronata*, and *Ceriops tagal*). The percentage of stem biomass in relation to total aboveground biomass, estimated with eq (1), was calculated. The values obtained were compared with literature values for the same species (Slim et al., 1996; Rakotomavo, 2018), although for different locations, due to the inexistence of equations for mangroves in the study area.

For each of the inventory plots, stand variables were calculated separately for the overstory and understory layers and for dead trees (Table 9).

Table 9 – Calculation of the stand variables.

Mean tree variable	
dg, quadratic mean dbh (cm)	$\sqrt{\sum_{i=1}^{n} \frac{dbh_i^2}{n}}$
Stand variables	
N (ha^{-1}), number of trees	$\frac{n \times 10,000}{\text{plot area}}$
G (m^2 ha^{-1}), basal area	$\frac{\pi}{40,000} \sum_{i=1}^{n} dbh_i^2 \times \frac{10,000}{\text{plot area}}$
W_{ag} (Mg ha^{-1}), aboveground biomass	$\frac{1}{1,000} \sum_{i=1}^{n} w_{ag} \times \frac{10,000}{\text{plot area}}$
W_{bg} (Mg ha^{-1}), belowground biomass	$\frac{1}{1,000} \sum_{i=1}^{n} w_{bg} \times \frac{10,000}{\text{plot area}}$
W (Mg ha^{-1}), total biomass	$W_{ag} + W_{bg}$
C (Mg ha^{-1}), total carbon	$0.5 \times W_{ag} + 0.39 \times W_{bg}$

where n is the number of trees in each inventory plot; dbh is the diameter measured at 1.30 m height (cm); plot area (m^2); w_{ag} is the tree aboveground biomass (kg); w_{bg} is the tree belowground biomass (kg).

Carbon accumulated in the soil

The soil carbon (Mg·ha^{-1}) per sampled depth interval was calculated using eq (4), as suggested by several authors (e.g., Adotey et al., 2022):

$$\text{Soil carbon} = [\text{bulk density} \times \text{soil depth interval} \times \%C] \times \frac{1}{100} \qquad \text{eq (4)}$$

where Soil carbon in Mg ha^{-1}, bulk density in g·cm^{-3}, soil depth interval in cm, and carbon in %.

As this study did not carried out undisturbed soil samples for the determination of the bulk densities in each of the five depths, the values estimated by Sitoe et al. (2014) in a mangrove area, with similarities in terms of soil characteristics and species abundance, in center Mozambique (Sofala Bay), were used. However, the authors used only three depths (0-30, 30-60 and 60-100 cm), what obliged us to adjust our depths intervals to the proposed bulk densities as medium values.

Total carbon stock in the mangrove of Pemba Bay

The total carbon stock in the mangrove was calculated as the sum of the aboveground carbon pools (understory, overstory, and dead standing trees), the belowground carbon pool, the floor litter layer carbon, and the soil carbon.

CHAPTER IV

4 RESULTS

4.1 STAND COMPOSITION AND STAND VARIABLES

Total tree biomass and stand variables

Table 10 presents the main characteristics of the inventory plots where the trees were felled. The relationship between tree stem biomass and dbh, by species, is presented in Figure 23. The fitted tree stem biomass equations as a function of dbh are also presented as well as the respective coefficient of determination. The selected function expresses an allometric relationship often used to estimate tree biomass. Because the height of the felled tree was not measured, it was not possible to analyze the effect of adding tree height to the allometric model.

Table 10 - Characteristics of the plots where trees were felled, by species, considering the overstory layer of the mangrove of Pemba Bay.

values per plot			values per species					
Plot	**N (ha^{-1})**	**G (m^2ha^{-1})**	**N (ha^{-1})**	**G (m^2ha^{-1})**	**dg (cm)**	**hmed±SD (m)**	**dmin (cm)**	**dmax (cm)**
			Avicennia marina					
P10	299	1.41	299	1.41	7.7	3.4±0.55	6.9	8.8
P12	585	4.78	585	4.78	12.0	5.2±1.49	10.2	40.0
P13	364	3.93	117	0.70	8.7	4.3±1.12	6.0	22.0
P15	702	20.10	208	3.69	15.0	2.8±0.91	11.0	23.5
			Ceriops tagal					
P13	364	3.93	26	0.14	8.3	3.0±0.71	6.0	8.5
P14	702	20.10	39	0.32	10.3	3.8±0.29	9.3	17.0
			Rhizophora mucronata					
P13	364	3.93	91	1.01	11.9	4.6±0.61	7.0	15.5
P14	702	20.10	637	19.43	19.7	6.4±1.97	10.5	28.0

where N is the number of trees per ha; G is the stand basal area; dg is the quadratic mean dbh; hmed is the mean total height; dmin is the minimum tree dbh; dmax is the maximum tree dbh; SD is the standard deviation.

The average moisture contents (MC) obtained, at tree level, and for each species, are 37.7% for *Avicennia marina*, 34.3% for *Ceriops tagal*, and 34.0% for *Rhizophora mucronata*.

The equations presented in Figure 23 were applied to the dataset (from the inventory), to estimate stem biomass for each tree of each species (*Avicennia marina*, *Rhizophora mucronata*, and *Ceriops tagal*). The percentage of stem in relation to the total aboveground biomass - estimated with equation (1) - was calculated. Results are, on average:

- *Avicennia marina* stem biomass corresponds to 19.0% of aboveground biomass;

- *Rhizophora mucronata* stem biomass corresponds to 17.1% of aboveground biomass;

- *Ceriops tagal* stem biomass corresponds to 14.1% of aboveground biomass.

These values are much lower than those referred to in the literature (e.g., Rakotomavo, 2018), leading to suggest that the aboveground biomass is overestimated.

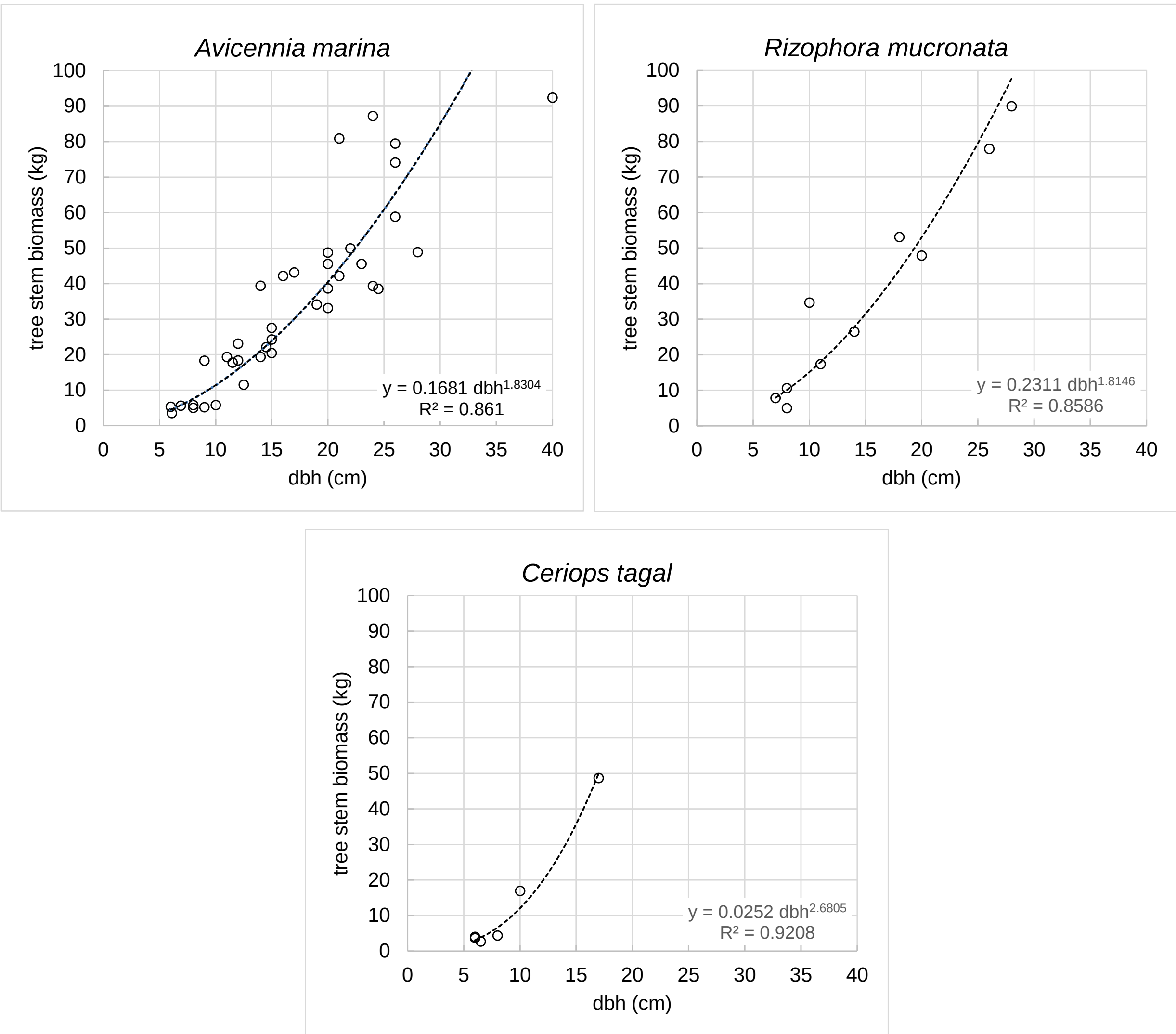


Figure 23 - Relationship between tree stem biomass and dbh for the felled trees, by species, considering the overstory layer.

All of the mangrove species reported to occur in Mozambique were found and measured in Pemba Bay (Barbosa et al., 2001; Beentje and Bandeira, 2007; Sitoe et al., 2014) (Table 11 and 12, and Figure 24). In Figure 24, the graph of the total tree height/dbh for *Bruguierra gymnorhiza* is not presented because only 17 trees were identified in the overstory in all 15 inventory plots. The relation between tree total height and dbh varied significantly with the species (Figure 24); however, it can be influenced by the distribution of some species acording to the gradient, either from the land with common low diameter (*Aviccenia marina* and *Ceriops tagal*) including low occurancy.

The ratio between below and aboveground biomass, estimated with eq (1) and (2) respectively, was relatively similar for the different species, with average values changing between 42.9% for *Rhizophora mucronata* and 49.2% for *Ceriops tagal*. This small variation in values is related to the fact that the biomasses at the tree level were estimated with allometric equations only as a function of dbh and this does not vary much between the inventoried trees; the wood density values of the various species are also identical.

Table 11 - Characterization of the species, considering the overstory layer, in the mangrove forest of Pemba Bay.

Species	Nobs	$\overline{dbh}$±SD (cm)	dmin (cm)	dmax (cm)	$\bar{h}$±SD (m)	hmin (m)	hmax (m)
Avicennia marina	268	10.0±5.0	2.3	44.6	4.4±1.9	1.6	13.5
Sonneratia alba	208	15.5±9.6	5.0	68.9	4.5±1.6	2.0	12.0
Ceriops tagal	152	7.5±2.9	5.0	21.5	4.7±1.2	2.5	8.0
Rhizophora mucronata	103	14.3±6.6	5.0	28.0	5.4±1.9	2.0	16.5
Bruguierra gymnorhiza	17	13.0±6.5	5.5	23.0	4.5±1.3	3.0	8.0

Where Nobs is the number of observations; $\overline{dbh}$ is the mean dbh; SD is the standard deviation; dmin and dmax are the minimum and maximum values of dbh, respectively; dmax is the maximum value of dbh, $\bar{h}$ is the mean height, hmin and hmax are the minimum and maximum values of tree total height, respectively.

In the study area, *Avicennia marina* is the most frequent species, occurring in combinations with all other species, but remarkably with *Sonneratia alba*, *Rhizophora mucronata*, and *Ceriops tagal*, either for overstory and understory layers as well as for dead trees (Tables 13-15 and Figure 24-28).

Understory, overstory, and dead standing trees, respectively dominated the stocking of mangrove forest. For the understory, the density was inconsistent among the plots, averaging 6,741 trees ha^{-1}, and ranging from 477 to 24,192 trees ha^{-1}. The overstory density averaged 695 trees ha^{-1}, and ranging from 299 to 1,156 trees ha^{-1}, whereas the dead standing trees averaged 126 trees ha^{-1}, and ranging from 13 to 325 trees ha^{-1}.

Table 12 - Representativity of overstory species in the inventory plots in the mangrove of Pemba Bay.

Plot	Species	Species representativity (%)
P1	Sa **Am**	33.1 - **68.9**
P2	Ct Sa **Am** Rm	10.2 - 30.7 - **44.3** - 14.8
P3	Am Rm **Sa**	16.7 - 11.1 - **72.2**
P4	Am Bg **Ct**	1.6 - 3.3 - **95.1**
P5	**Ct** Bg Rm	**64.6** - 17 - 18.5
P6	**Ct** Bg Rm	**71.7** - 1.9 - 26.4
P7	**Sa** Am Rm	**61** - 36 - 3.1
P8	**Sa** Am	**60** - 40
P9	**Am** Sa	**64.3** - 35.7
P10	**Am**	**100**
P11	-	-
P12	**Am**	**100**
P13	**Am** Bg Ct Rm **Sa**	**32.1** - 3.6 - 7.1 – 25 - 12.9 - **32.1**
P14	Bg Ct **Rm**	3.7 - 5.6 - **90.7**
P15	Am **Sa**	42.1 - **57.9**

Bold are the species with the highest representativity per plot. Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba*

Among the inventory plots, the understory stocking was less pronounced in plot 9 (with two species) and plot 1 (with three species), whereas in overstory the stocking was less in plot 10 (one species), plot 9 (two species) and plot 13 (five species). In dead standing trees the stocking was less in plots 1 and 15 (both with one specie), and plots 3 and 5 (with three species) (Tables 13-15).

Overstory tree diameter averaged 13.5 cm, ranging from 7.2 to 24.8 cm, whereas the mean height averaged 4.5 m, ranging from 3.4 to 6.2 m. Small diameter was pronounced in plots 10 and 7, with a little variation among the inventory plots. The tree mean height less pronunciation was observed in plots 10 and 15, but with a relatively little variation among the plots (Table 14).

Aboveground biomass for overstory averaged 119.9 Mg ha^{-1}, ranging from 10.5 to 449 Mg ha^{-1}, while the belowground biomass averaged 46.2 Mg ha^{-1}, ranging from 5.1 to 155.6 Mg ha^{-1}. The inventory plots 10 (with one species) and 6 (with three species) showed less pronounced above and belowground biomass, respectively (Table 14).

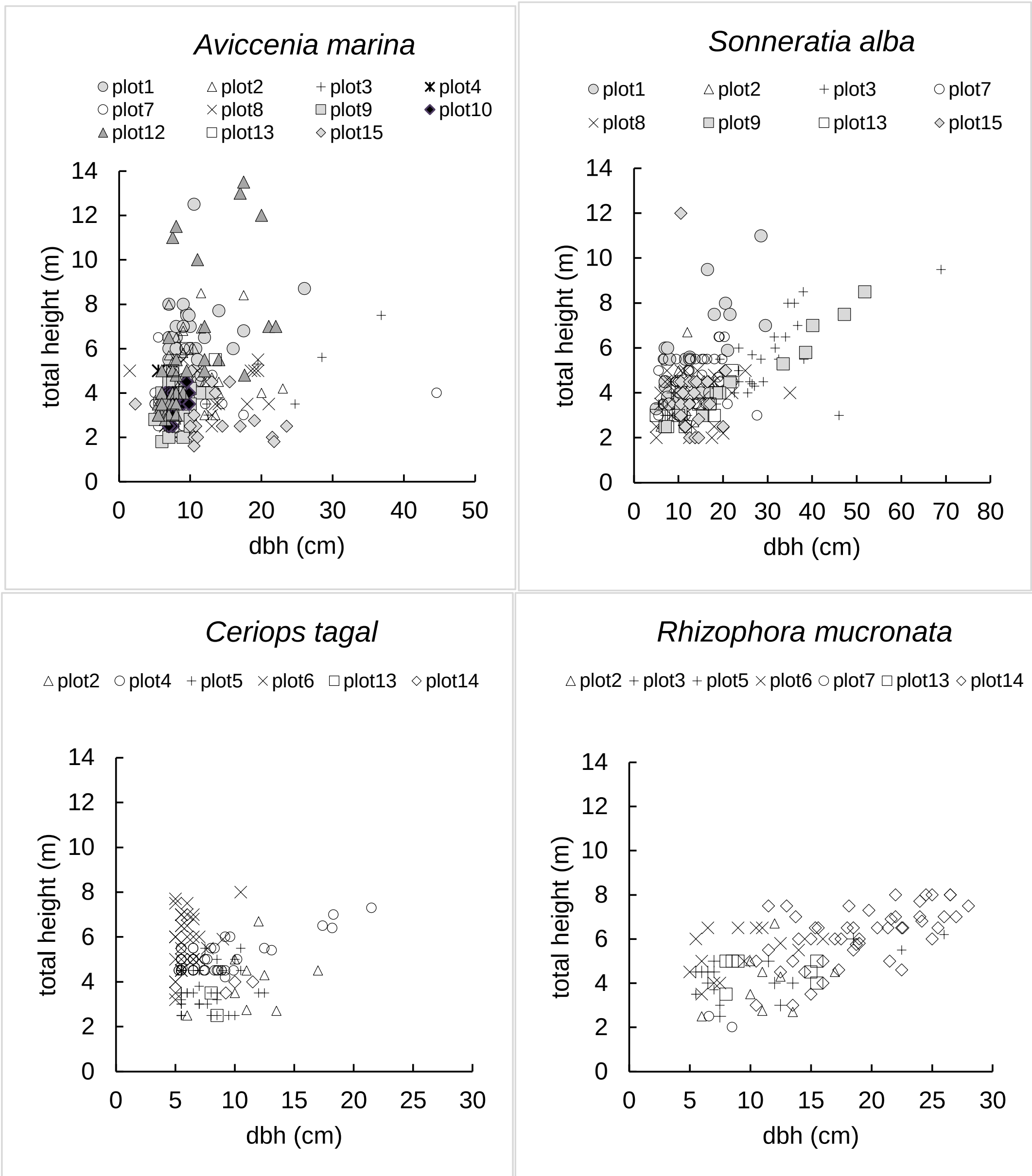


Figure 24 - Relationship between total tree height and dbh for the 4 most represented species in the mangrove of Pemba Bay. The graphs are ordered from top to bottom and from left to right according to the highest number of measured trees in the indicated plots.

Table 13 - Species and variables regarding the **understory layer** in each inventory plot in the mangrove of Pemba Bay. Stocking (N), basal area (G), quadratic mean dbh (dg), mean height (h), and above (Wa) and below (Wb) ground biomass.

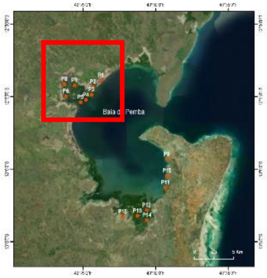
Plot	Number species	Species	N (ha^{-1})	G (m^2 ha^{-1})	dg (cm)	hmed (m)	Wa (Mg ha^{-1})	Wb (Mg ha^{-1})
1	3	Sa Am Rm	955	0.6	2.7	0.3	0.058	0.034
2	4	Ct Sa Am Rm	4,138	2.6	2.8	0.3	0.305	0.180
3	3	Ct Am Rm	2,546	0.4	1.5	1.2	0.172	0.102
4	2	Ct	13,687	4.4	2.0	0.7	1.108	0.654
5	4	Ct Bg Am Rm	12,096	2.2	1.5	0.4	0.254	0.150
6	3	Ct Bg Rm	24,192	7.4	2.0	1.1	3.995	2.357
7	4	Ct Sa Am Rm	3,342	0.7	1.7	1.0	0.331	0.195
8	4	Ct Sa Am Rm	1,273	0.8	2.8	1.4	0.628	0.370
9	2	Ct Am	477	0.4	3.1	2.5	0.346	0.204
10	1	Am	6,048	1.1	1.5	1.0	0.534	0.315
12	1	Am	2,069	1.4	2.9	0.9	0.511	0.302
13	3	Ct Am Rm	10,504	1.8	1.5	1.3	1.123	0.6627
14	2	Ct Rm	7,480	0.6	1.0	0.9	0.200	0.113
15	4	Ct Sa Am Rm	5,570	0.4	1.0	0.6	0.104	0.062

Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba*

Table 14 - Species and variables regarding the **overstory layer** in each inventory plot in the mangrove of Pemba Bay. Stocking (N), basal area (G), quadratic mean dbh (dg), mean height (h), and above (A_{GB}) and below (B_{GB}) ground biomass.

Plot	Number species	Species	N (ha^{-1})	G (m^2 ha^{-1})	dg (cm)	hmed (m)	A_{GB} (Mg ha^{-1})	B_{GB} (Mg ha^{-1})
1	2	Sa Am	1,130	11.1	11.2	5.4	103.313	43.437
2	5	Ct Sa Am Rm Hl	1,156	10.4	10.7	4.4	98.697	42.674
3	3	Sa Am Rm	702	34.0	24.8	4.5	449.001	155.641
4	3	Ct Bg Am	793	5.0	8.9	5.1	56.051	23.950
5	3	Ct Bg Rm	844	6.3	9.7	4.0	77.682	32.359
6	3	Ct,Bg,Rm	689	2.8	7.2	5.6	26.143	12.259
7	3	Sa Am Rm	832	12.6	13.9	4.1	131.396	51.683
8	2	Sa Am	780	11.8	13.9	3.8	116.487	47.219
9	2	Sa Am	364	12.0	20.5	3.9	159.100	54.569
10	1	Am	299	1.4	7.7	3.4	10.483	5.114
12	1	Am	585	4.8	10.2	5.2	45.092	19.330
13	5	Ct Bg Sa Am Rm	364	3.9	11.7	3.9	38.214	16.270
14	3	Ct Bg Rm	702	20.1	19.1	6.2	286.210	108.300
15	2	Sa Am	494	8.3	14.7	3.4	80.902	33.385

Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba;* Hl, *Heritiera littoralis*



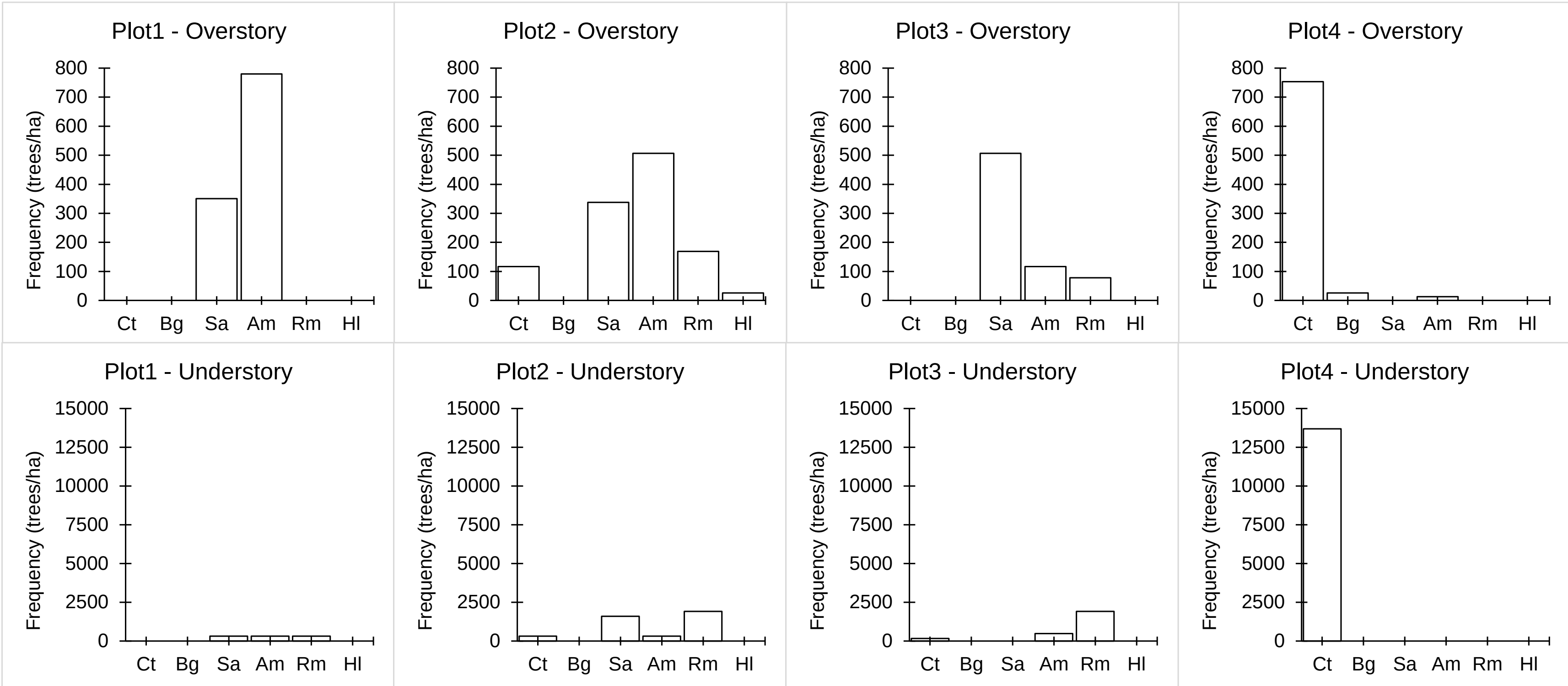


Figure 25 - Distribution of species in the overstory and understory for all plots located in the northern part of the mangrove forest of Pemba Bay. Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba;* Hl, *Heritiera littoralis*

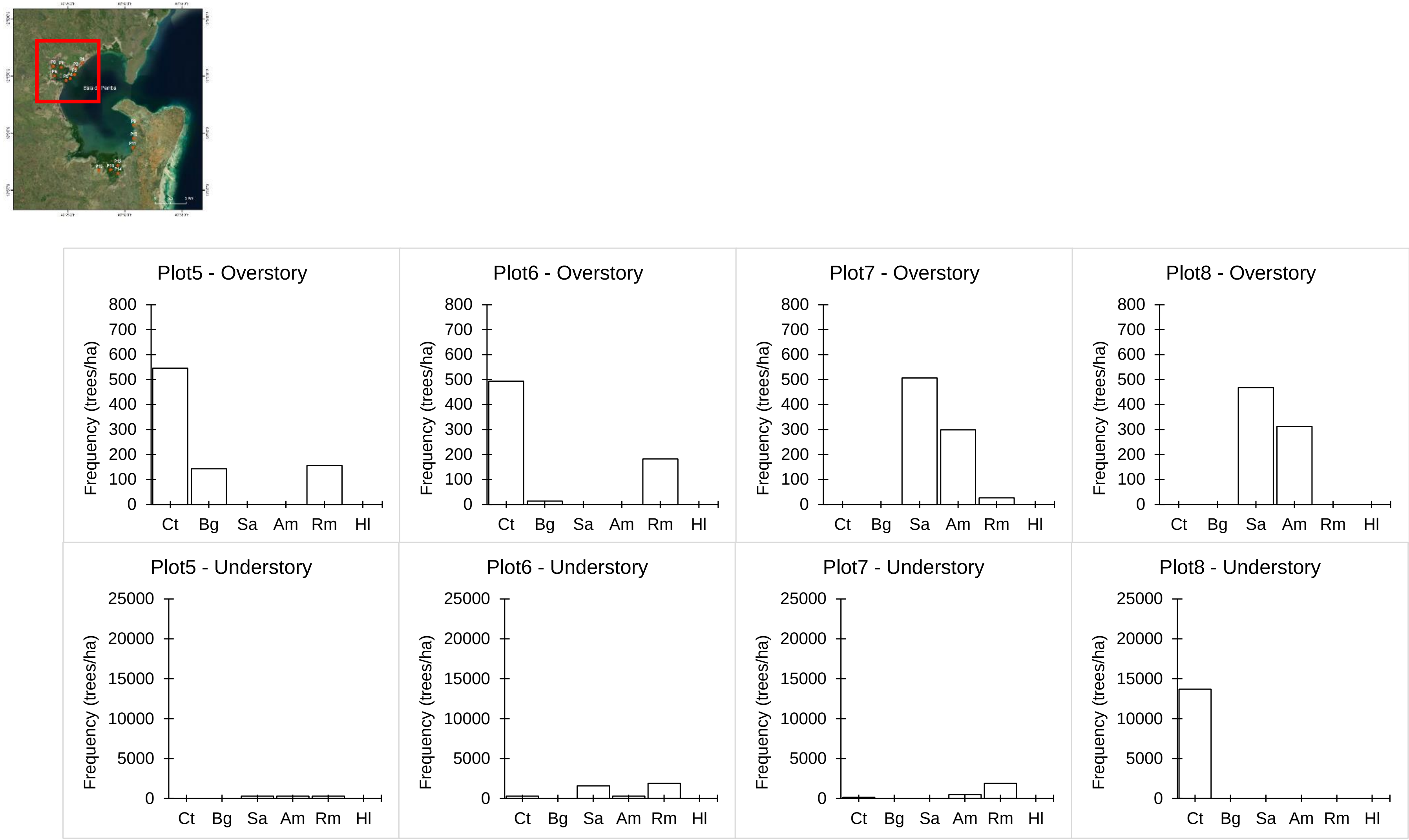


Figure 26 - Distribution of species in the overstory and understory for all plots located in the northern part of the mangrove forest of Pemba Bay. Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba;* Hl, *Heritiera littoralis*

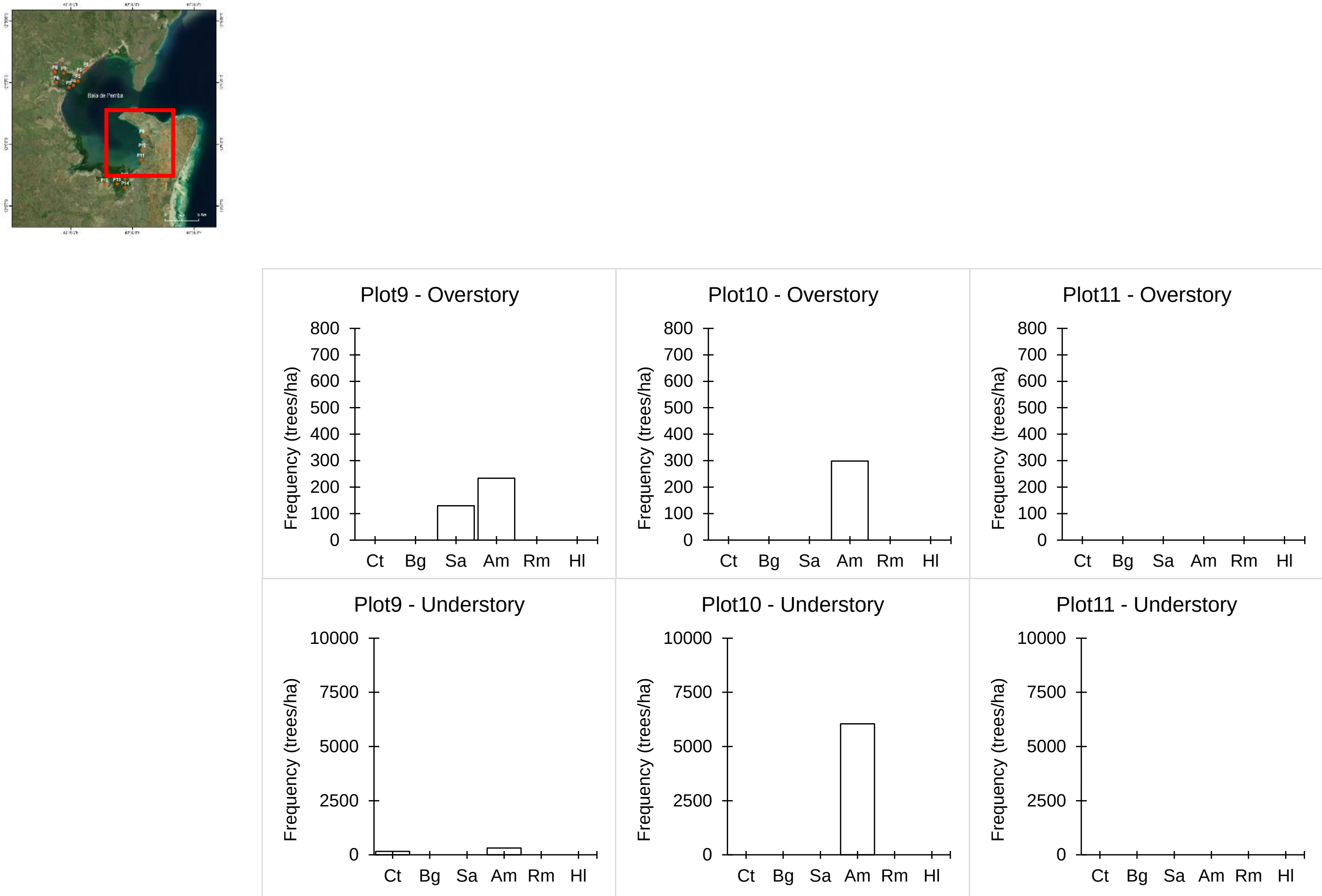


Figure 27 - Distribution of species in the overstory and understory for all plots located in the southeast part of the mangrove forest of Pemba Bay. Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba;* Hl, *Heritiera littoralis*

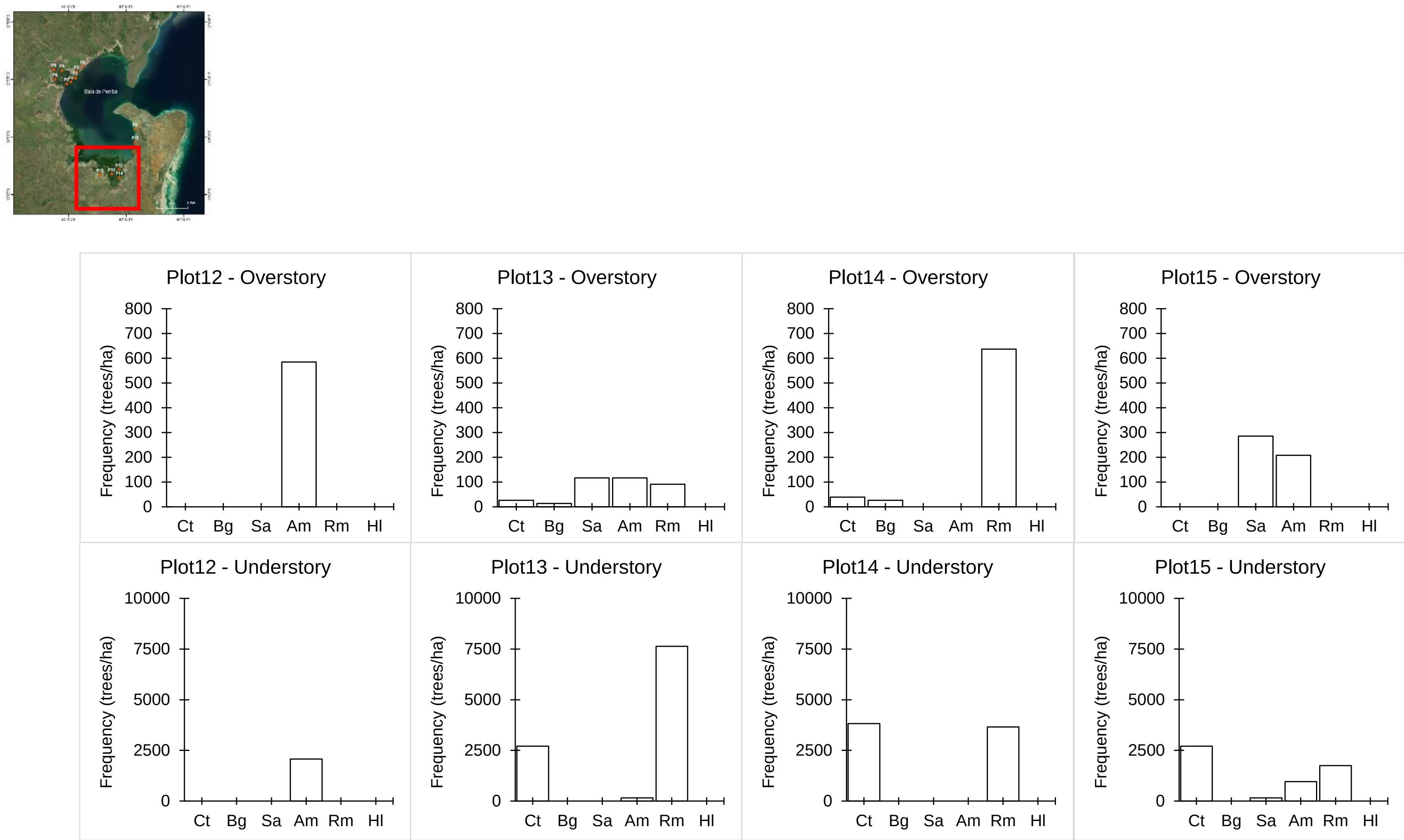


Figure 28 - Distribution of species in the overstory and understory for all plots located in the southwest part of the mangrove forest of Pemba Bay. Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba;* Hl, *Heritiera littoralis*

Dead trees above and belowground biomass, averaged 9.7 and 3.8 Mg ha^{-1}, respectively, having shown insignificant minimum values (Table 15).

Table 15 - Species and variables regarding **dead trees** in each inventory plot in the mangrove of Pemba Bay. Stocking (N), basal area (G), quadratic mean dbh (dg), mean height (h), and above (Wa) and below (Wb) ground biomass.

Plot	Number species	Species	N (ha^{-1})	G (m^2 ha^{-1})	dg (cm)	hmed (m)	Wa (Mg ha^{-1})	Wb (Mg ha^{-1})
1	1	Sa	13	0.13	11.5	3.0	0.093	0.226
2	4	Ct Sa Am Rm	169	1.88	11.9	4.3	11.882	3.373
3	3	Sa Am Rm	52	1.94	21.8	5.0	3.976	4.080
4	2	Ct Bg	117	1.05	10.7	4.6	3.221	1.830
5	3	Ct Bg Rm	78	0.54	9.4	4.0	2.049	0.888
6	1	Ct	130	0.61	7.7	5.4	2.842	0.947
7	1	Sa	156	1.43	10.8	3.3	4.999	2.416
8	1	Sa	169	1.30	9.9	3.9	7.576	2.181
12	1	Am	195	2.69	13.3	3.3	6.254	4.907
13	3	Ct Sa Am	325	9.04	18.8	4.0	64.027	17.691
14	2	Sa Rm	91	3.48	22.1	4.5	9.518	6.853
15	1	Sa	13	0.12	11.0	1.4	0.040	0.205

Am, *Avicennia marina*; Bg, *Bruguierra gymnorhiza*; Ct, *Ceriops tagal*; Rm, *Rhizophora mucronata*; Sa, *Sonneratia alba*

Specifically, *Avicennia marina* (11 plots), *Rhizophora mucronata* (10 plots), and *Ceriops tagal* (11 plots) are the most prominent species in the understory around the sampling site. *Ceriops tagal* stocking ranged from 159 to 22,759 trees ha^{-1} and a large mean basal area of 1.3 m^{2}ha^{-1} (Table 16).

Stocking of *Avicennia marina* varied from 159 to 6,047 trees ha^{-1}, being the second highest mean basal area (0.4 m^{2}ha^{-1}). *Rhizophora mucronata*, presented the third high stocking with a mean of 2,016 trees ha^{-1}, a basal area varying from 0.02 to 1.1 m^2 ha^{-1}. *Bruguierra gymnorhiza* had the lowest contribution in the stocking and biomass content in the understory.

Overstory or live trees presented a particular paradigm, where *Sonneratia alba*, *Rhizophora mucronata* and *Avicennia marina* were subsequently the most influent species. *Sonneratia alba* was not found only in plots 4, 5 and 6 (out of 15), and the stocking averaged 338 trees ha^{-1}, ranging from 117 to 507 trees ha^{-1}. This species also presented highest values in all parameters: high quadratic mean diameter (18 cm) varying from 9.8 to 32.2 cm and mean height of 4.5 m (Table 17).

Table 16 - Stocking (N), basal area (G), quadratic mean dbh (dg), mean height (h), and above (Wa) and below (Wb) ground biomass **by species** for **understory** in the mangrove of Pemba Bay.

Plot	Species	N (ha^{-1})	G (m^2 ha^{-1})	dg (cm)	hmed (m)	Wa (Mg ha^{-1})	Wb (Mg ha^{-1})
1	*Avicennia marina*	318	0.36	3.8	0.3	0.039	0.023
2		318	0.24	3.1	0.4	0.025	0.015
3		477	0.06	1.2	1.6	0.044	0.026
5		477	0.02	0.7	0.4	0.002	0.001
7		318	0.04	1.3	1.9	0.024	0.014
8		796	0.39	2.5	1.2	0.316	0.186
9		318	0.36	3.8	3.0	0.344	0.203
10		6,048	1.07	1.5	1.0	0.534	0.3150
12		2,069	1.39	2.9	0.9	0.511	0.302
13		159	0.05	2.0	1.1	0.017	0.010
15		955	0.04	0.7	0.7	0.010	0.006
5	*Bruguierra gymnoriza*	318	0.04	1.3	0.6	0.012	0.007
6		159	0.03	1.5	1.6	0.019	0.011
2	*Ceriops tagal*	318	0.08	1.8	0.2	0.008	0.005
3		159	0.01	1.0	1.1	0.005	0.003
4		13,687	4.38	2.0	0.7	1.108	0.654
5		10,345	1.71	1.5	0.4	0.201	0.119
6		22,759	7.26	2.0	1.1	3.959	2.336
7		318	0.01	0.5	0.3	0.001	0.000
8		159	0.14	3.3	2.0	0.100	0.059
9		159	0.00	0.5	1.5	0.002	0.001
13		2,706	0.67	1.8	1.0	0.410	0.242
14		3,820	0.40	1.2	0.9	0.152	0.090
15		2,706	0.17	0.9	0.4	0.041	0.024
1	*Rhizophora mucronata*	318	0.07	1.7	0.2	0.007	0.004
2		1,910	1.06	2.7	0.3	0.152	0.090
3		1,910	0.36	1.6	1.1	0.123	0.073
5		955	0.24	1.8	0.8	0.039	0.023
6		1,273	0.06	0.8	0.7	0.017	0.010
7		1,592	0.16	1.1	0.8	0.055	0.032
8		159	0.02	1.1	0.5	0.003	0.002
13		7,639	1.07	1.3	1.4	0.697	0.411
14		3,661	0.18	0.8	0.9	0.048	0.028
15		1,751	0.18	1.2	0.6	0.049	0.029
1	*Sonneratia alba*	318	0.13	2.3	0.4	0.012	0.007
2		1,592	1.24	3.1	0.4	0.121	0.071
7		1,114	0.52	2.4	1.4	0.251	0.148
8		159	0.25	4.5	3.1	0.209	0.124
15		159	0.01	1.0	1.5	0.005	0.003

Table 17 - Stocking (N), basal area (G), quadratic mean dbh (dg), mean height (hmed) and above (Wa) and below (Wb) ground biomass **by species** for **overstory** in the mangrove of Pemba Bay.

Plot	Species	N (ha^{-1})	G (m^2 ha^{-1})	dg (cm)	hmed (m)	Wa (Mg ha^{-1})	Wb (Mg ha^{-1})
1	*A. marina*	780	5.52	9.5	5.4	48.487	21.593
2		507	4.71	10.9	4.6	43.676	18.936
3		117	3.85	20.5	4.4	49.795	18.136
4		13	0.03	5.5	4.0	0.194	0.104
7		299	3.83	12.8	3.7	49.014	17.768
8		312	3.96	12.9	3.8	39.992	16.595
9		234	1.42	8.8	3.2	11.447	5.352
10		299	1.41	7.7	3.4	10.483	5.114
12		585	4.78	10.2	5.2	45.092	19.330
13		117	0.70	8.7	4.3	5.587	2.617
15		208	3.69	15.0	2.8	39.238	15.849
4	*B. gymnorhiza*	26	0.56	16.6	6.3	9.510	3.528
5		143	2.58	15.2	4.0	41.091	15.680
6		13	0.03	5.5	4.0	0.281	0.144
13		13	0.08	9.0	3.5	0.943	0.430
14		26	0.35	13.1	6.0	4.831	1.992
2	*C. tagal*	117	1.28	11.8	4.1	14.372	6.137
4		754	4.36	8.6	4.9	46.346	20.318
5		546	2.41	7.5	3.6	22.237	10.528
6		494	1.44	6.1	5.8	11.918	5.985
13		26	0.14	8.3	3.0	1.291	0.611
14		39	0.32	10.3	3.8	3.348	1.498
2	*H. litoralis*	26	0.53	16.1	4.2	4.916	2.036
2	*R. mucronata*	169	1.37	10.2	4.4	14.747	6.444
3		78	1.38	15.0	4.2	19.875	7.435
5		156	1.29	10.3	4.3	14.353	6.151
6		182	1.31	9.6	5.4	13.944	6.130
7		26	0.12	7.6	2.3	1.066	0.512
13		91	1.01	11.9	4.6	11.573	4.889
14		637	19.43	19.7	6.4	278.031	104.810
1	*S. alba*	351	5.55	14.2	5.4	54.826	21.844
2		338	2.52	9.8	4.7	20.986	9.121
3		507	28.78	26.9	4.8	379.331	130.071
7		507	8.68	14.8	4.5	81.316	33.403
8		468	7.81	14.6	3.8	76.495	30.624
9		130	10.56	32.2	5.1	147.653	49.217
13		117	2.00	14.8	3.3	18.819	7.723
15		286	4.65	14.4	3.9	41.664	17.536

The dead standing trees were found in almost all the plots. Five of the six identified species comprised dead trees. *Sonneratia alba* presented the highest stocking, varying from 13 to 247 trees ha^{-1}, basal area ranging from 0.1 to 7.3 m^2ha^{-1}. This species also presented high mean biomass values of aboveground (9.5 Mg ha^{-1}) and belowground (3.2 Mg ha^{-1}). *Rhizophora mucronata* and *Ceriops tagal* presented slightly similar values in stocking, being from 13 to 65 trees ha^{-1} (*R. mucronata*) and 13 to 130 trees ha^{-1} (*C. tagal*). The mean aboveground biomass was lower for *Ceriops tagal* (2.8 Mg ha^{-1}) than *Rhizophora mucronata* (3.2 Mg ha^{-1}). Being the same for belowground biomass, 1.87 Mg ha^{-1} for *Rhizophora mucronata* and 0.96 Mg ha^{-1} for *Ceriops tagal* (Table 17).

Table 18 - Stocking (N), basal area (G), quadratic mean dbh (dg), mean height (h), and above (Wa) and below (Wb) ground biomass **by species** for **dead trees** in the mangrove of Pemba Bay.

Plot	species	N (ha^{-1})	G (m^2 ha^{-1})	dg (cm)	hmed (m)	Wa (Mg ha^{-1})	Wb (Mg ha^{-1})
2	*Avicennia marina*	39	0.26	9.3	4.6	1.413	0.426
3		26	0.23	10.5	3.8	0.193	0.371
12		195	2.69	13.3	3.3	6.254	4.907
13		52	0.79	13.9	3.4	5.516	1.434
4	*Bruguiera gymnorhiza*	13	0.06	7.5	5.0	0.066	0.088
5		13	0.08	9.0	3.5	0.067	0.131
2	*Ceriops tagal*	13	0.05	7.0	8.0	0.237	0.075
4		104	0.99	11.0	4.5	3.155	1.743
5		39	0.15	7.1	3.7	0.739	0.235
6		130	0.61	7.7	5.4	2.842	0.947
13		26	0.92	21.3	5.3	7.035	1.778
2	*Rhizophora mucronata*	26	0.94	21.5	4.1	7.595	1.856
3		13	0.12	11.0	3.8	0.670	0.205
5		26	0.31	12.3	4.8	1.243	0.521
14		65	2.48	22.1	3.5	3.302	4.921
1	*Sonneratia alba*	13	0.13	11.5	3.0	0.093	0.226
2		91	0.62	9.4	3.8	2.637	1.016
3		13	1.59	39.5	8.5	3.113	3.504
7		156	1.43	10.8	3.3	4.999	2.416
8		169	1.30	9.9	3.9	7.576	2.181
13		247	7.33	19.4	4.0	51.475	14.479
14		26	1.00	22.1	7.0	6.216	1.932
15		13	0.12	11.0	1.4	0.040	0.205

Avicennia marina dead trees were also representative. The stocking ranged from 26 to 195 trees ha^{-1}, while basal area varied from 0.2 to 2.7 m^2 ha^{-1}.

The relashionship between stand aboveground biomass and stand basal area, considering the 14 inventory plots, was strong (R^2=0.97, Figure 29).

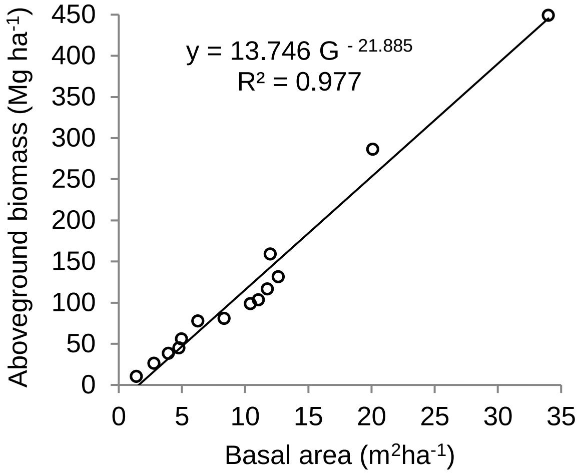


Figure 29 - Relationship of stand aboveground biomass and stand basal (G) area in the mangrove forest of Pemba Bay.

The understory frequency distribution showed a decrease in frequency with increasing diameter (Figure 30). Overstory diameter distribution followed an inverted “J” pattern (Figure 31) and the standing dead trees followed the same pattern (Figure 32).

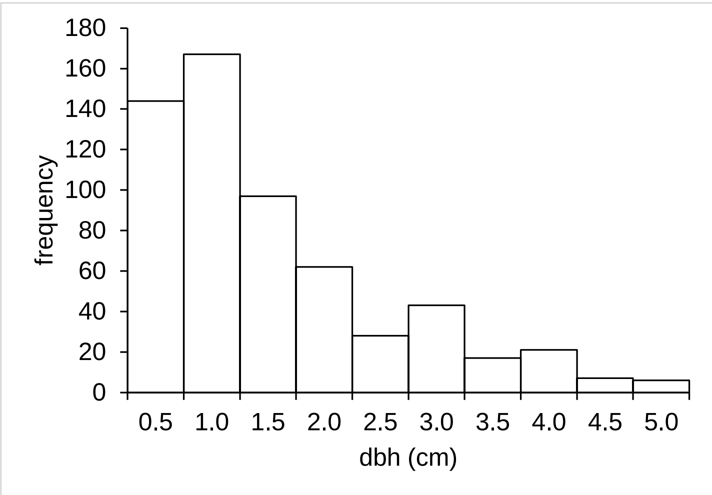


Figure 30 – Diameter frequency distribution of **understory** within mangrove forest of Pemba Bay.

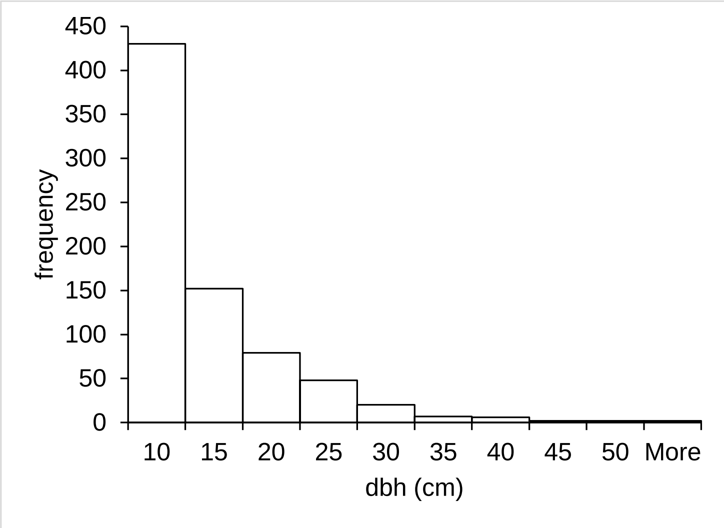


Figure 31 – Diameter frequency distribution of **overstory** within mangrove forest of Pemba Bay.

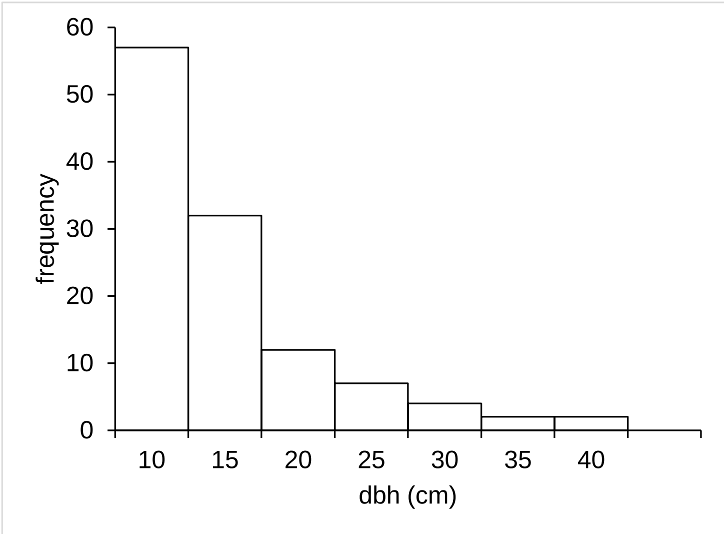


Figure 32 – Diameter frequency distribution of **dead trees** within mangrove forest of Pemba Bay.

4.2 SOIL CHARACTERISTICS

Forest floor litter layer

The mass of the forest floor litter layer showed a wide range (5.6 - 16.6 Mg ha^{-1}) (Table 18). The organic residues occurring in such layer may be extremely variable, given the variation of concentration of most of the nutrients, and the variation of the C/N (42-104) and N/P (7.7-27.5) ratios. The amount of organic carbon accumulated also had a wide variation and values ranged 1.48-5.40 Mg ha^{-1}. In spite of the wide variation, it is notable the quantity of N, Ca and Mg accumulated in the forest floor litter layer. The quantity of K is mostly lower than that corresponding to Mg.

Particle size distribution

The particle size distribution of soil samples taken in some inventory plots are shown in Table 19 were randomly determined in five plots (1, 3, 4, 6 and 9) where the fine sediments were the most dominant in all the depth profile, particularly in the layer 5 – 10 cm. Overall, the sand (coarse sand plus fine sand) fraction was largely predominant, reaching 864-967 g kg^{-1}, whereas the concentration of silt (1-134 g kg^{-1}) and clay (12-179 g kg^{-1}) fractins are much lower. Therefore, the texture is mostly sand, but sometimes is loamy sand or sandy loam.

The coarse sand was the second most predominant sediments, however, the high quantities were observed on the botom, in the layer 145 - 150 cm. The plot 9 did not vary significantly in all the depth profile for all the soil granulometry classes, however, the coasre and fine sediments were the most predominant in the region.

Table 19 - Forest floor litter layer characteristics in inventory plots considered in the mangrove forest of Pemba Bay.

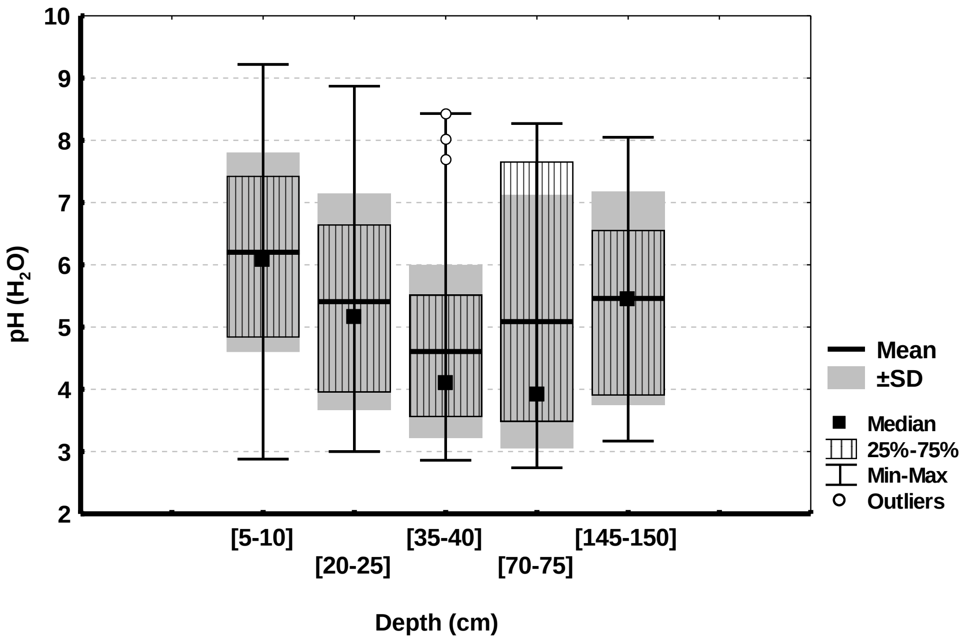
Plot	FFLL	C_{org}	N	P	Ca	Mg	K	Mn	C	N	P	Ca	Mg	K	Mn
	Mg ha^{-1}	g kg^{-1}	---------------------mg g^{-1} --------------------						Mg ha^{-1}	kg ha^{-1}					
1	13.67	227.5	4.65	0.42	29.82	7.44	2.43	0.08	3.11	63.5	5.7	407.5	101.7	33.2	1.09
2	8.75	288.6	4.41	0.22	16.97	5.98	1.35	0.04	2.53	38.6	1.9	148.5	52.3	11.8	0.35
3	6.41	393.1	5.72	0.37	12.09	5.13	2.55	0.04	2.52	36.7	2.4	77.5	32.9	16.4	0.26
4	8.00	439.3	4.67	0.17	16.67	7,31	1,06	0,01	3.51	37.3	1.4	133.3	58.5	8.5	0.08
5	13.64	154.8	3.13	0.16	19.23	3.93	2.06	0.04	2.11	42.7	2.2	262.3	53.6	28.1	0.55
6	12.58	181.5	3.27	0.23	17.94	5.33	1.64	0.03	2.28	41.1	2.9	225.7	67.1	20.6	0.38
7	6.59	451.4	4.32	0.24	15.83	5.68	1.22	0.04	2.97	28.5	1.6	104.3	37.4	8.0	0.26
8	7.70	251.7	5.53	0.56	12.62	6.31	4.34	0.23	1.94	42.6	4.3	97.2	48.6	33.4	1.77
9	10.59	329.9	6.02	0.61	8.36	5.66	6.01	0.31	3.49	63.7	6.5	88.5	59.9	63.6	3.28
12	5.59	265.1	3.88	0.34	12.33	6.51	2.20	0.10	1.48	21.7	1.9	68.9	36.4	12.3	0.56
13	9.89	360.4	3.71	0.27	18.20	7.08	2.13	0.08	3.56	36.7	2.7	179.9	70.0	21.1	0.79
14	16.60	325.0	4.86	0.54	10.08	6.40	3.25	0.08	5.40	80.7	9.0	167.3	106.2	54.0	1.33
15	12.68	167.1	3.99	0.52	6.73	5.65	4.30	0.34	2.12	50.6	6.6	85.3	71.6	54.5	4.31

Table 20 - Values of pH, organic carbon concentration (Corg) and electrical conductivity (EC), and particle size distribution according to soil depth in some plots considered in the Pemba Bay mangrove.

Plot	**Subplot**	**Depth (cm)**	**Corg**	**pH**	**CE**	**Particle size composition (g kg^{-1})**				**Texture**
			g kg^{-1}	**H_2O**	**dS m^{-1}**	**Coarse sand**	**Fine sand**	**Silt**	**Clay**	
1	**S1**	[5-10]	2.68	5.84	6.013	399	565	24	12	Sand
		[20-25]	3.14	5.48	4.156	515	438	10	37	Sand
		[35-40]	8.02	4.95	5.167	604	345	14	37	Sand
		[70-75]	4.96	4.09	4.424	744	223	14	19	Sand
		[145-150]	2.18	4.55	4.344	782	158	39	20	Sand
3	**S2**	[5-10]	13.49	4.78	7.587	387	524	27	61	Sand
		[20-25]	16.24	4.10	8.975	452	443	33	72	Sand
		[35-40]	12.59	4.70	9.017	470	448	12	71	Sand
		[70-75]	5.42	5.03	5.786	547	376	29	48	Sand
		[145-150]	7.72	5.95	6.238	548	399	7	47	Sand
4	**S4**	[5-10]	40.40	5.68	10.500	397	446	63	95	Loamy sand
		[20-25]	48.62	4.21	17.390	371	428	134	68	Sandy loam
		[35-40]	48.19	3.42	18.110	342	422	56	179	Sandy loam
6	**S4**	[5-10]	5.61	7.23	3.334	99	865	1	34	Sand
		[20-25]	5.66	6.64	2.917	84	866	9	41	Sand
		[35-40]	10.49	5.89	2.482	111	827	20	42	Sand
		[70-75]	35.92	3.28	7.574	291	625	19	64	Sand
		[145-150]	30.64	3.17	13.130	285	581	8	126	Loamy sand
9	**S4**	[5-10]	4.15	4.77	7.588	474	472	7	46	Sand
		[20-25]	5.98	4.80	3.591	475	491	1	34	Sand
		[35-40]	5.04	5.77	6.028	406	524	12	58	Sand
		[70-75]	9.16	7.80	6.358	446	470	6	78	Sand
		[145-150]	6.93	5.30	1.533	450	482	4	64	Sand

Values of pH measured (in H_2O)

The pH values showed a wide difference among the inventory plots, regarding to its behavior in the depth profile in mangrove forest of Pemba Bay. However, almost all the plots tended to have values distant from neutral (Figure 33). Plots 1, 6, 7 and 8 were the only ones to have had values in all the depth profile, differing from plots 2, 3, 5, 9 and 12 with values up to 75 cm depth, and plots 4, 10, 11, 14 and 15 reaching up to 35 cm depth. Plots 10, 15, 11, and 12 showed the same tendency of decreasing their alkaline values on the surface, to acid on the bottom, reducing from 8.5, 9, 7.5 and 7.5, respectively, to lower than 6 (being acid) at the depth ranging from 10 to 40 cm.



Sampling depth interval	Depth (cm)	Valid N	pH (H_2O)			
			Mean	Q25	Median	Q75
[5-10]	**7.5**	69	6.20	4.83	6.09	7.43
[20-25]	**22.5**	65	5.41	3.95	5.17	6.65
[35-40]	**37.5**	60	4.61	3.56	4.10	5.52
[70-75]	**72.5**	31	5.09	3.48	3.92	7.66
[145-150]	**147.5**	10	5.46	3.90	5.46	6.56

Figure 33 – Box-plot regarding the values of pH measured (in H_2O) at different depth soil layers. Each sampling depth interval is represented by the respective average.

The surface pH of plots 1, 6 and 7 slightly decreased from 6 to 4 at 30 cm depth, and maintained markedly constant acidity values up to the bottom (150 cm), differing plot 8 which was markedly acid at 75 cm depth and decreased to become neutral at the bottom (Figure 34). The surface pH of plots 1, 6 and 7 slightly decreased from 6 to 4 at 30 cm depth, and

maintained markedly constant acidity values up to the bottom (150 cm), differing plot 8 which was markedly acid at 75 cm depth and decreased to become neutral at the bottom (Figure 34).

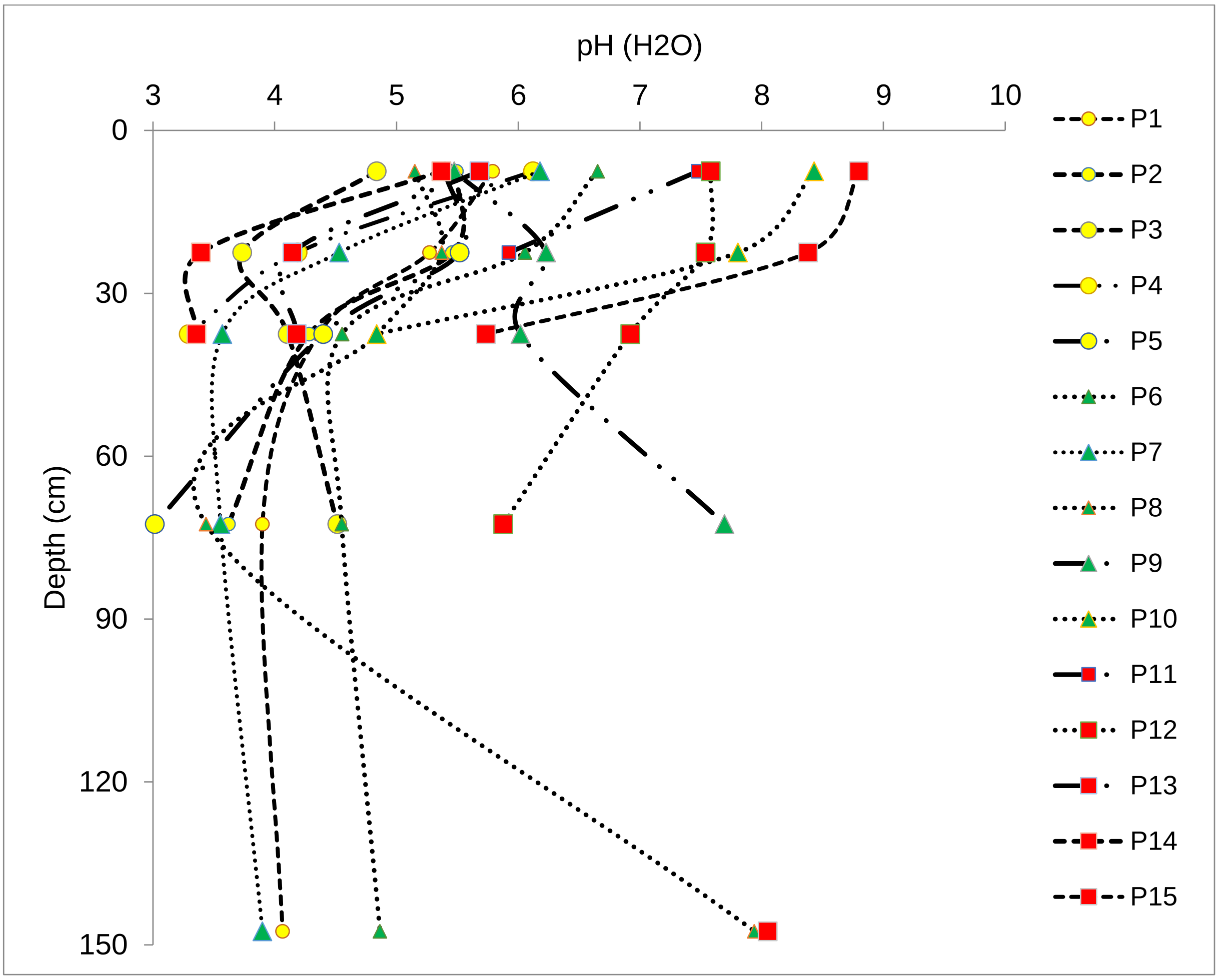
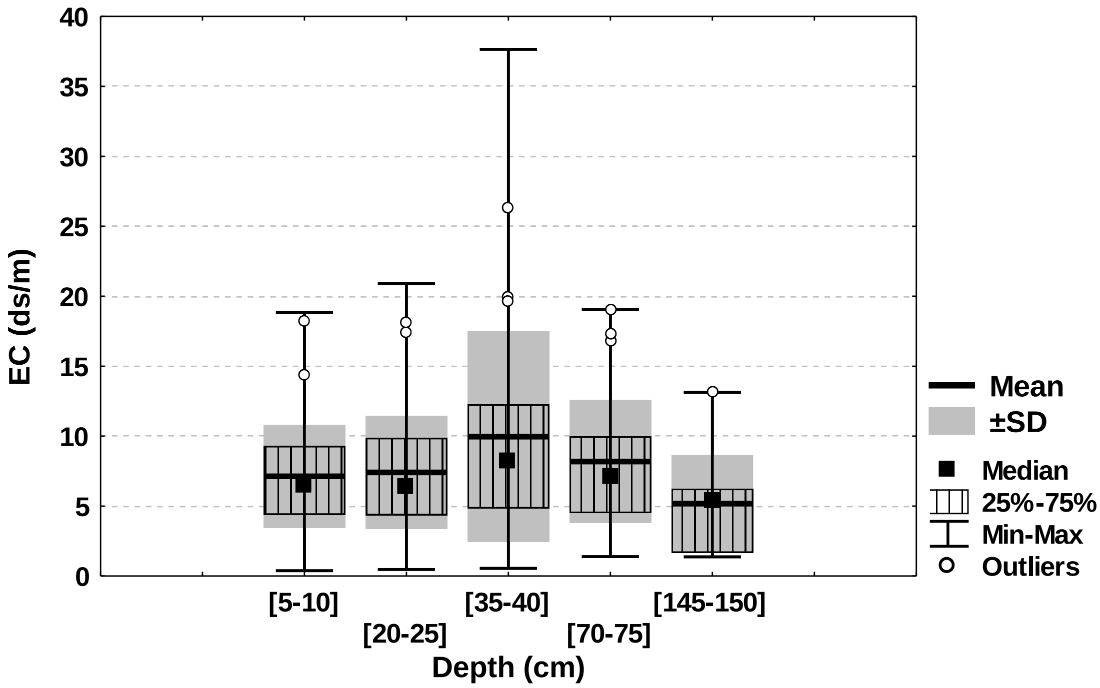


Figure 34 - Values of pH along soil depth in the different inventory plots considered in the mangrove forest of Pemba Bay

Electrical conductivity

The variability of electrical conductivity was in the range of 3.5 to 17 dS m^{-1} form the sampled plots, except plot 11, where it followed a particular pattern, showing a group of plots behaving in a cerntain manner (Figure 35). Plots 1, 6, 7, 8 and 15 showed almost the same configuration, possessing values in the hole depth gradient, however, plot 7 tended to have a slite decrease from 5 to 2 dS m^{-1} at the interval depth of 30 to 90 cm, but remaining constant (5 dS m^{-1}) at the range depth of 90 to 150 cm. In the order hand, plot 8 tended to increase the conductivity values at the same interval plot 7 decreased. Plots 1 and 6 tended to maintain constant values from the surface to the bottom, not increasing more than 1 ds/m or reducing less than 2 dS m^{-1} from the base value of 5 dS m^{-1} in the hole gradient profile.



Sampling depth interval	Depth (cm)	Valid N	EC (dS m^{-1})			
			Mean	Q25	Median	Q75
[5-10]	**7.5**	69	7.13	4.38	6.47	9.29
[20-25]	**22.5**	65	7.41	4.35	6.37	9.87
[35-40]	**37.5**	60	9.96	4.84	8.23	12.27
[70-75]	**72.5**	31	8.19	4.51	7.06	9.98
[145-150]	**147.5**	10	5.17	1.66	5.33	6.24

Figure 35 - Box-plot regarding the values of electrical conductivity (EC, dS m^{-1}) measured at different depth soil layers. Each sampling depth interval is represented by the respective average.

Plot 10 has showed a great variance at the depth gradient with low values up to 25 cm (4.5 dS m^{-1}), but increased radicaly between 25 to 35 cm, reaching 17 dS m^{-1}. a tendency of having high values on the surface and keep increasing in the depth was markedly observed in plots 11 and 13, however plot 11 was isoledetly the one with highest values on the first 20 cm, and manteined increasing at gange depth of 25 to 40 cm, to a constant value of 28 dS m^{-1} (Figure 36).

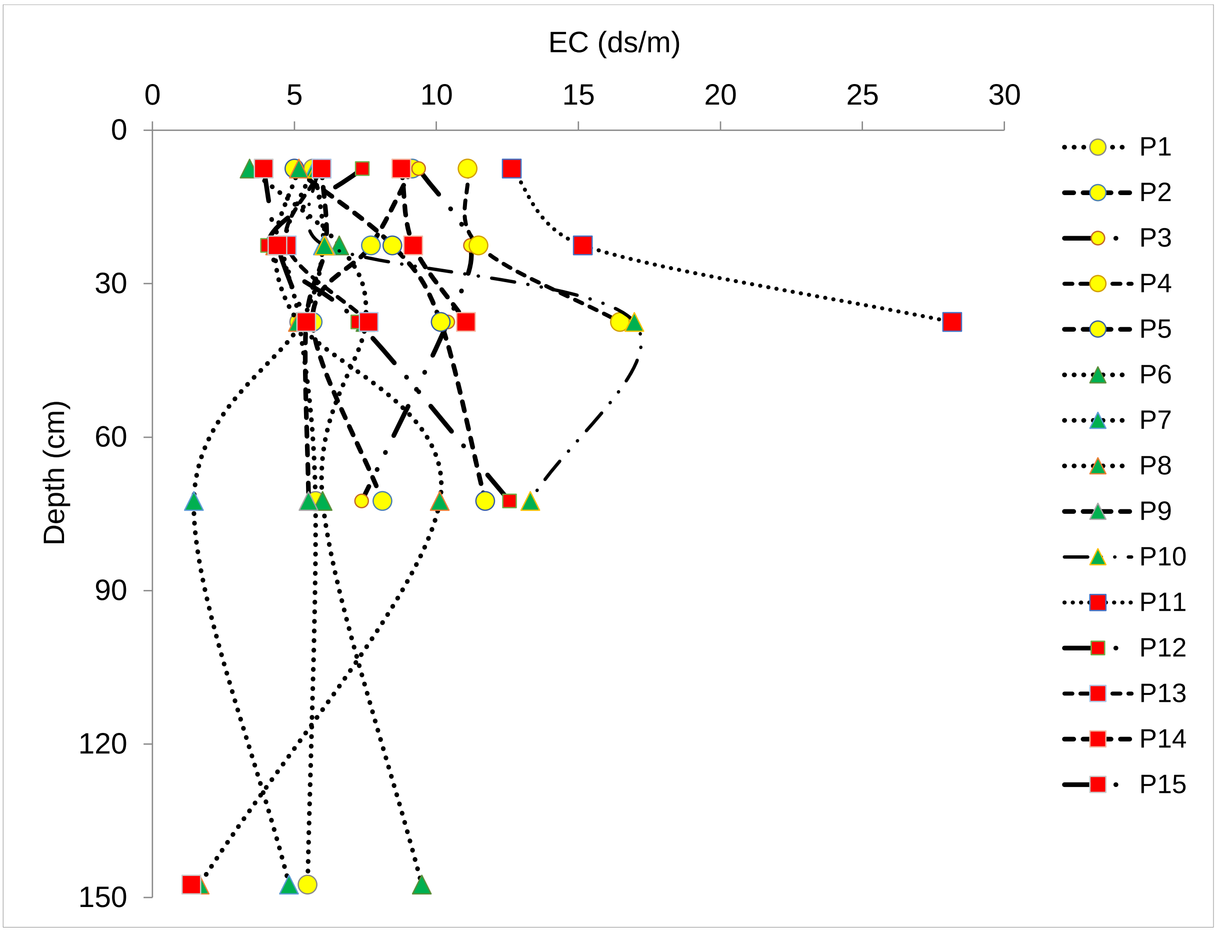
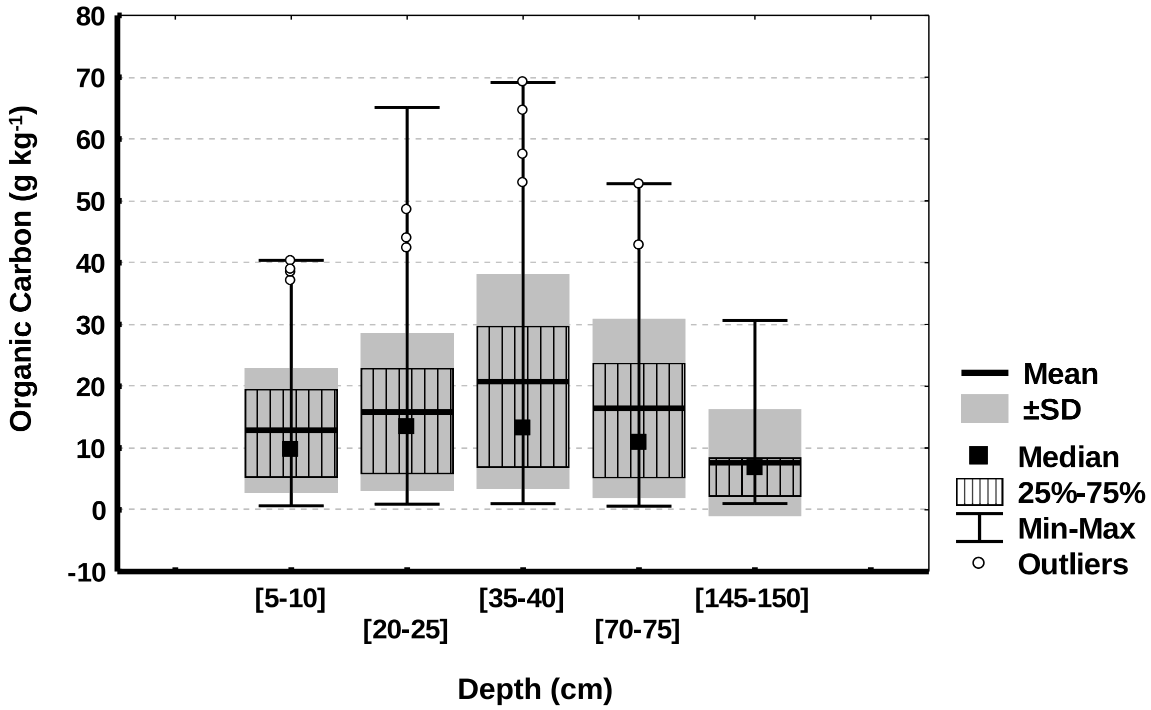


Figure 36 - Values of electric conductivity (EC) along soil depth in each of the different study plots considered within the mangrove forest of Pemba Bay.

Organic carbon concentration

The concentration of organic carbon showed a range with soil depth, and differed among soils from the different inventory plots considered in Pemba Bay mangrove (Figures 37 and 38). Overall, the highest values were measured in the 35-40 cm soil layer, while the lowest occurred in the 145-150 cm depth soil layer.

Eastern plots showed high organic carbon concentration and distributed in all the depth profile (0-150 cm). Plot 1 presented constant values of organic carbon concentration along the depth gradient, 5 g kg^{-1}, differing from plot 7, which had high Corg in the first 20 cm (12 g kg^{-1}), tending to decrease from depth 30 cm (9 g kg^{-1}) up to the lowest value in depth 150 cm (3 g kg^{-1}). Plot 8 accumulated high organic carbon concentrations from depth 55 to 85 cm (14 g kg^{-1}), whereas, either on the surface or the bottom it was lower (5 g kg^{-1}). The same tendency was observed in plot 6, having high concentration in depth 35 cm (25 g kg^{-1}), and maintaining constant up to the bottom (15 g kg^{-1}), (Figure 37).



Sampling depth interval	Depth (cm)	Valid N	Corg (g kg-1)			
			Mean	**Q25**	**Median**	**Q75**
[5-10]	**7.5**	69	12.88	5.23	9.85	19.55
[20-25]	**22.5**	65	15.84	5.77	13.45	22.95
[35-40]	**37.5**	60	20.75	6.83	13.14	29.76
[70-75]	**72.5**	31	16.42	5.12	10.90	23.78
[145-150]	**147.5**	10	7.62	2.18	6.70	8.41

Figure 37 - Box-plot regarding the concentration of organic carbon (Corg, g kg^{-1}) measured at different depth soil layers. Each sampling depth interval is represented by the respective average.

All of other plots did not have any organic carbon concentration after the depth of 75 cm, where plots 4, 10 and 11 tended to high Corg concentrations on the bottom. Plots 5, 14 and 4 presented the highest concentrations among all the plots, maximum of these values in plot 4 with 50 g kg^{-1} at the depth 30 cm. plot 10 tended to have increasing concentration from the surface to the bottom, ranging from 20 to 48 g kg^{-1}, respectively (Figure 38).

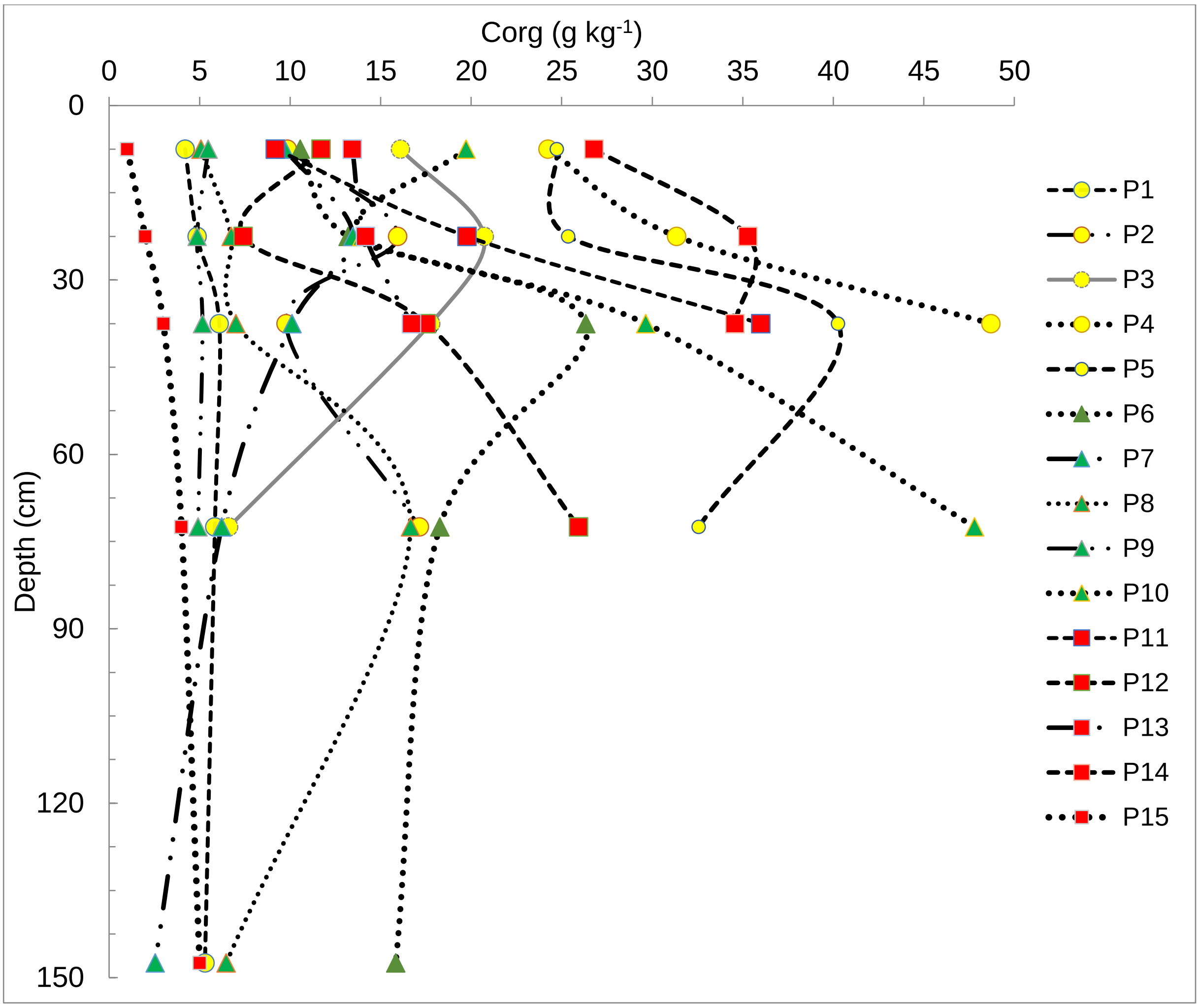


Figure 38 - Soil organic carbon concentration along soil depth in each of the different study inventory plots considered in mangrove forest of Pemba Bay.

4.3 ACCUMULATED ORGANIC CARBON IN THE MANGROVE SYSTEM

The average soil organic carbon content (depth 0-150 cm) was estimated as 224.3 Mg ha^{-1} in the sampled plots of Pemba bay. The carbon stock content in the region was slightly similar in the first two depth layers (0 – 30 and 30 – 50 cm), following an increasing pattern allong the depth. The highest carbon content was observed in the layer of 50 – 100 cm (95.9 ± 79.4 Mg ha^{-1}) and being lower it the layer 100 – 150 cm (32.3 ± 23.7 Mg ha^{-1}) (Table 22).

The organic carbon accumulated in the mangrove forests of Pemba Bay was of 309.11 Mg ha^{-1} (summed values of Table 21 and Table 22). The apportioning of organic carbon in mangrove system of Pemba Bay, including both above and belowground is shown in Figure 39.

Table 21 – Aboveground and belowground biomass and carbon pools in the mangrove Pemba Bay.

Polls		**Biomass (Mg ha^{-1})**	**Carbon (Mg ha^{-1})**
Aboveground	Overstory	119.90 ± 117.3	59.96 ± 58.64
	Understory	0.69 ± 1.01	0.35 ± 0.50
	Sub-total	**120.6**	**60.31**
Belowground	Overstory	46.16 ± 40.44	18.00 ± 15.77
	Understory	0.41 ± 0.59	0.16 ± 0.23
	Dead trees	3.80 ± 4.81	1.48 ± 1.88
	Sub-total	**50.4**	**19.64**
Aboveground	Dead trees	**9.71** ± 17.48	**4.86** ± 8.74
	Total	**180.7**	**84.81**

Table 22 - Accumulated organic carbon in the Pemba Bay mangrove soils.

Depth (cm)	Plots	Bulk density * ($g{\cdot}cm^{-3}$)	Carbon ($Mg\ ha^{-1}$)
0-30	All 15 plots	1.12	47.7 ± 28
30-50	All 15 plots	1.07	45.5 ± 31.1
50-100	11	1.05	95.9 ± 79.4
100-150	5	1.05	32.3 ± 23.7
0-150		-	**221.43**
Forest floor litter layer		-	2.85 ± 1.0
		Total	**224.3**

* Sitoe et al. (2014)

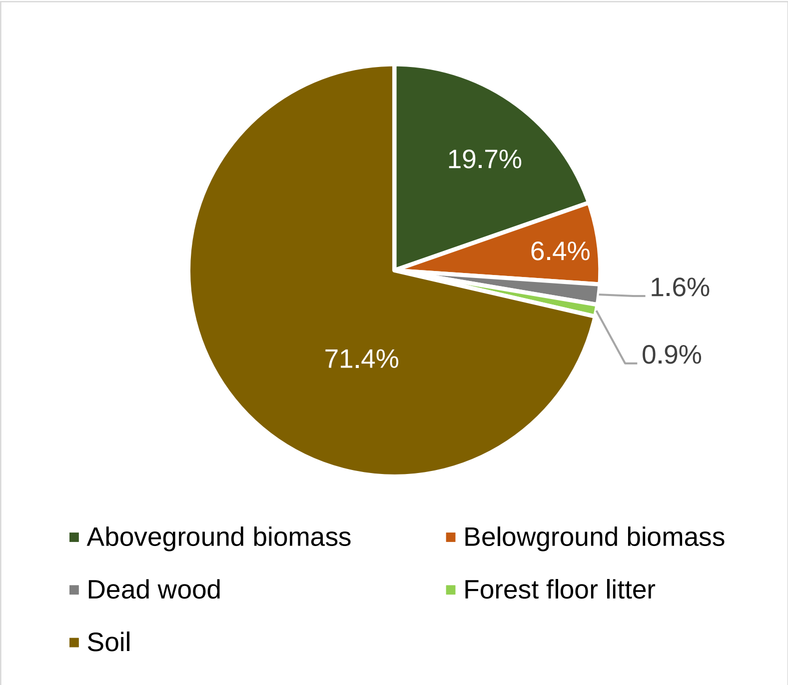


Figure 39 - Apportioning of different organic carbon pools (in percentage) in the mangrove of Pemba Bay.

CHAPTER V

5 DISCUSSION

5.1 MANGROVE FOREST DIVERSITY AND STRUCTURE

This study found six mangrove species, namely: *Avicennia marina*, *Bruguierra gymnorhiza*, *Ceriops tagal*, *Rhizophora mucronata*, *Sonneratia alba*, and *Heritiera litoralis*, being conglomerated in four communities: (i) *Avicennia marina/Rhizophora mucronata/Sonneratia alba*; (ii) *Avicennia marina/Ceriops tagal/Rhizophora mucronata/Sonneratia alba*; (iii) *Avicennia marina/Ceriops tagal/Rhizophora mucronata/Avicennia marina/Bruguierra gymnorhiza/Ceriops tagal*, and (iv) *Rhizophora mucronata*.

Those species are similar to identified in previous studies in Cabo Delgado (Nicolau et al., 2017; Amade et al., 2018) and in other regions of mangrove occurrence in Mozambique (e.g. Macamo et al., 2016; Sitoe et al., 2014; Trettin et al., 2016).

These species are commonly described in eastern Africa (Kairo et al., 2021), Western India Ocean (der Stocken et al., 2021), differing from the West and Central Africa (Kauffman and Bhomia, 2017). Out of 73 mangroves species occurring globally (Spalding et al., 2010), nine occur in Mozambique (Macamo, 2018).

This local, regional or global difference of the species distribution is associated with physical-chemical conditions, climate, latitude and longitude, availability of river flow nutrient, sediment supply and yield, including tidal variation and precipitation (Ellison, 2021).

Mangrove species zonation in Pemba Bay was according to the pattern described by Brown et al. (2016), through tolerance to tidal variation, where *Sonneratia alba* dominated the lower layer with the intermediate and most diverse layer composed by *Bruguierra-Rhizophora-Ceriops* community, followed by *Avicennia marina* in upper layer. However, presenting double zoning (Reef and Livelock, 2015), including the general pattern in Mozambique (Macamo, 2018).

The pattern of species distribution, especially to the same genius and families are similar to those observed in another regions, regarding to distribution from landward, middle and seaward (Pazi et al., 2016; Ragavan et al., 2014) in South-east Asia, Kauffman and Bhomia (2017) in West Central Africa, almost in the generality of Western Indian Ocean (Leal and Spading, 2022).

The stand density in Pemba Bay ranged from 299 to 1,156 trees ha^{-1} for overstory trees, and from 477 to 24,192 trees ha^{-1} for understory trees. Those records are among the values from the previous studies in Cabo Delgado (Nicolau et al., 2017; Cuamba et al., 2019), but lower than other Mozambican mangrove forest, Zambezi Delta (Trettin et al., 2016), Sofala Bay (Sitoe et al., 2014), including other Eastern Africa (Jones et al., 2014; Kairo et al., 2021; Kairo et al., 2002; Kairo et al., 2008) and higher than Maputo Bay and Principe island (Machava-António et al., 2022). These values are also similar to ones found by Adotey et al. (2022) in Western Africa, however the similarities a summarized in the same species genius.

This observed difference could be attributed to the characteristics of each region, species composition, and tendency of logging or an existence of a certain management regime (Kairo et al., 2021). Machava-António et al. (2022) and Sitoe et al. (2014) who observed high human interference though cutting in all the sites of Maputo Bay and Sofala, respectively.

The sample size and the methodological approach can be a key factor to estimate the approximate real density and the coverage of the species, as most the studies in Eastern Africa (Macamo et al., 2016; Nicolau et al., 2017; Amade et al., 2018; Kairo et al., 2021; Machava-António et al., 2022) have been sampling in quadrates of 100 m^2 in a perpendicular belt transect, and Ren et al. (2020) used algorithms, and Marshall et al. (2012) used elevation.

The methodologies can also influence the quantities of a certain group of trees, as case of Adotey et al. (2022) who consider the dbh from 1.37 cm while generality of literature it stands at 1.30 cm. Even using the same reference for the sampling, the author does not consider the saplings (understory) or the dead trees; however, these components have a considerable contribution, or (Henri and Randiansyah, 2022) who consider an adult tree with minimum dbh of 8 cm, either de Cleynder et al. (2020) who consider 1 ha sampling plot and ignore standing dead trees.

This study was based in a method proposed by Kauffman and Donatto (2012), somehow comparable to the procedure applied in Eastern Africa (Jones et al., 2014; Sitoe et al., 2014; Trettin et al., 2016), West Central Africa (Kauffman and Bhomia, 2017) and in Central Asia (Salvador et al., 2022).

Pemba Bay aboveground biomass for overstory ranged from 10.5 to 449 Mg ha^{-1} (table 14), values which are significantly lower than ones found in Zambezi Delta (Trettin et al., 2016; Fatoyinbo et al., 2018), but comparable to those found by Sitoe et al. (2014) all in Mozambique, and comparable to found in West Central Africa (Kauffman and Bhomia, 2017), and in Central Asia (Salvador et al., 2022).

The belowground biomass (5.1 to 155.6 Mg ha^{-1}), followed the same pattern with aboveground biomass considering the measurements in the same regions, in exception to Fatoyinbo et al.

(2018) who only accessed the aboveground biomass content based on satellite imagery and had high values.

The highest proportion of below and aboveground biomass was found in live tree, followed by standing dead trees, based on estimations by general allometric equations. Fatoyinbo et al. (2008) suggest that studies including all plant components are scarce, as most have limited the focus to aboveground live tree biomass, not including roots, dead trees, litter, and wood debris. This limitation may be on behalf of resources or the accesses to the fieldwork as mangrove forest occur in a complex environment; however, is acceptable that neglected components could comprise added biomass and organic carbon in mangrove ecosystems. Cleynder et al. (2020), when performing the study on Mangrove carbon in Tanzania, identified the same species and values of above and belowground biomass were approximate to our intervals; however, the author found more biomass as far as the trees were sampled from the shore.

The fact that small stems are found close to the shore may be related to the new colonization by some mangrove invasive species (e.g. *Ceriops tagal*) in new seaward formed by sediment trapped (Fatoyinbo et al., 2018).

Pemba Bay mangrove forest are basin and overwashed. Therefore, the most relevant species in biomass in the region *Avicennia marina* (779 trees ha^{-1}; aboveground biomass (Wa) = 49.8 Mg ha^{-1}; belowground biomass (Wb) = 21.6 Mg ha^{-1}); *Rhizophora mucronata* (637 trees ha^{-1}; Wa = 278 Mg ha^{-1}) and *Sonneratia alba* (507 trees ha^{-1}; Wa = 379 Mg ha^{-1}; Wb = 130 Mg ha^{-1}), are characteristic of

This fact may be related to anthropogenic activities, as in the present study the biomass was higher in a regularly inundated and in remote area (in the northern part), where is less disturbed, trees with large basal area and height, different from the southeast part of mangrove forest of Pemba Bay, which is an urban region and there are some salt pans (Chatting et al., 2020).

Dead trees aboveground and belowground biomass content showed low values if compared to earlier studies in Mozambique (Trettin et al., 2016), including in the regional scenario (Eastern Africa). The methodological approach can be a differential factor, as many studies on carbon stocks, do not take into account the dead trees biomass (Adotey at al., 2022; Kairo at al., 2021; Salvador et al., 2022), so, is worth harmonizing the methodologies.

Measuring the dead standing trees could be fundamental, as they contribute to the productivity of the ecosystem, from either the leaves, downed wood or the decomposition of dead trees of level 3, which is supposed to be or become decomposed. However, the regime of inundation can also play an important role on salinity and lower decomposition rates (Komiyama et al., 2008; Lourenço et al., 2009; Mugi et al., 2022).

It is also relevant to describe the sampling site, as a Bay, a River or an Estuary, as the characteristics of each one of these environments can affect the behavior of each specie, as the water flow and nutrient availability, are different in those environments.

5.2 SOIL CHARACTERISTIC

This study has observed a significant contribution of organic carbon litter (2.85 ± 1.0 $Mg \cdot ha^{-1}$). Studies in Mozambique generally neglect these components. However, the only studies that consider those components had similar litter values (Sitoe et al., 2014). Those values are very low, if compared to a Bornean (Malasia) mangrove forest (Sukardjo et al., 2013).

Studies on mangrove carbon stocks focus only on the aboveground biomass, considering that litter layer insignificant, while it can contribute and become any indicator of the health of the ecosystem (Along, 2014; Rovai et al., 2018). Litter is one of the three components of net forest primary production, especially so in tropical forests where litter is rapidly produced and recycled. Mangrove litter is rapidly assimilated into food webs and either eventually buried in soil or exported by tides to adjacent coastal waters (Mackey and Smail, 1995; Sukardjo et al., 2013).

The abundant carbon that mangrove forests provide facilitates the development of soil microbial communities. Studies have shown that the microbial genus Bacteroidetes is abundant in the mangrove rhizosphere, which may be due to the high particulate organic matter in the environment. Furthermore, the abundant root systems of mangrove plants may create environmental niches for Proteobacteria, one of the important microbial genera for N and S cycling in mangrove ecosystems (Shiau and Chiu., 2020).

Three soil texture classes have been identified in the study area, namely: sand (82.6%), loamy (8.7%), and loamy sand (8.7%), showing significant differences. However, the sand was found in all the depth profile (0-150 cm) and the loamy and loamy sand being found in the first depth interval (5-10 and 20-25 cm). These soil texture classes are similar to those found by Alsunati and Shahibi (2018) in a mangrove forest of Meadle Asia; however, the author still found much mode texture diversity, as performed the study in a Lagoon.

The geomorphological characteristics of the study area region are formed by Coral coast. This coast is dominated by shallow, reef forming hermatypic corals (Macamo, 2018), a common feature within Pemba Bay and most of the northern Mozambique.

Particle size was dominated by coarse sand, fine sand, silt, and clay. The same results were found by Alsunati and Shahibi (2018), however, in a depth interval of 0-50 cm. The fine sand which is dominant in Pemba Bay mangrove forest may be related to the sediment trap by the costa, as the frequency of waves in this Bay is semi-diurnal (Hoguane, 2007).

Environmental parameters are one of the factors that can affect each organism; this can also affect a Mangrove forest ecosystem (Matthijs et al., 1999; Marchand et al., 2004). The environmental parameters measured have a direct influence on the mangrove forest ecosystem, including Salinity, pH, and electrical conductivity.

The pH value in the study area was categorized under acidic conditions, stated that pH 6-7 is suitable for mangrove growth. The low pH value is caused by a reshuffle as if the vegetation is rove by soil microorganisms that produce organic acids that can lower the pH of the water (Dewi and Herawatiningsih, 2017). The physic-chemical properties of sediments are most likely control the reforestation success as well as the nutrient recycling in mangrove sites (Gomes et al., 2016; Sahoo et al., 2017). For mangroves, however, the most relevant components include changes in sea level, high water events, stormi-ness, precipitation, temperature, atmospheric CO2 concentration, ocean circulation patterns; they are always associated with and subjected to saline seawater. The effects of salinity on mangroves affects leaf structure, rates of transpiration, stomatal conductance and rates of photosynthesis (Bhattacharjee et al., 2013; Hoghart, 2015; Leal and Spalding, 2022).

Soil composition in mangroves is very less known and studded, as most of the studies (as referred) do not expressively detail methodologic aspects through it treatments and collection. However, Kauffman and Donato (2012), Mustapha et al. (2016), and Samuel et al. (2022) suggest the methods. Earlier studies regarding to mangroves conservation and status, including carbon stocks use to determine soil characteristics visually (on the surface). Comparatively, Maputo Bay is dominated by clay followed by the combination of sand/clay and peat/clay, which is different from Pemba Bay sedimentary structure.

This scenario may have to be with the influence around the regions, regarding to river influences, variation of tides and inundation classes (Machava-António et al., 2022). The structural aspect of the trees can also be determinant due to the mangrove capacity of retaining the soil according to the species and its physiognomy.

Mangrove growth is mostly limited by its capacity of coping with salinity resistance, where species like *Avicennia marina* are able to cope, survive and regenerate in low, medium or high saline environment (Richmond, 2002; Beentje and Bandeira, 2007).

In the present study, we observed a scenario that is similar to the one observed by Kamruzzaman et al. (2018) when studied the structure and carbon in oligohaline zones of

India. This author reports that it is not mandatory that the identified species will be an indicator of being more or less saline zones, however, these species are very important for mangrove research and can be useful to understand the salinity level and their occurrence.

Salinity, which affects decomposition rates, and therefore nutrients available for plant growth, might also explain some of these differences. For example, it has previously been predicted that estuarine mangroves where there are lower salinities, usually have greater aboveground stature (Kauffman et al., 2020).

The pH condition of the water in the mangrove forest ecosystem of Baskara Bakti Village, ranged from 6.67-6.93. This result is the same as research in the mangrove forest of Nusapati Village, West Kalimantan, which has an average pH of 6.65 and is higher than the result in the mangrove forest on the East Coast of North Sumatra, which is 6.50. This pH value is categorized under acidic conditions, stated that pH 6-7 is suitable for mangrove growth. The low pH value is caused by a reshuffle as if the vegetation is rove by soil microorganisms that produce organic acids that can lower the pH of the water.

5.3 CARBON ACCUMULATED IN THE SYSTEM

The total carbon accumulated in magrove system of Pemba Bay was estimated in 306 Mg ha^{-1}, 71% found in the soil, 20% in abovegroung and 6% in belowground. Values and proportions which are similar to intervals described by Kairo et al. (2021) in Kenya, Sitoe et al. (2014) in Mozambique and Ren et al. (2020) in China.

Mangroves retain large amounts of carbon, an important function for climate change mitigation (Friess et al., 2020). At the Zambezi Delta, for example, it was estimated that 1.4 x 107 Mg C are stored in the system (Trettin et al., 2016), ranging from 99.2 Mg C/ha to 341.3 Mg C/ha. This amount is comparable to that found in other productive forests such as the Bangladeshi Sundarbans (Rahman, 2020), Madagascar (Jones et al., 2014), Peninsular Malaysia (Sofawi et al., 2017), Indonesia (Nehren and Wicaksono, 2018), and in Kuran Estuary (Hamzeh and Hamid, 2022).

Mozambique estimates indicate 30,974,100 Mg of carbon for the whole country (101 Mg/ha), making it the African country with the second highest amount of mangrove carbon (Fatoyinbo and Simard, 2013).The highest carbon content was observed in the layer of 50-100 cm, being lower in lower on the bottom layer (depth 100 - 150 cm).

The pattern of organic carbon accumulated in Pemba Bay is slightly different from many other studies - Sitoe et al. (2014) in Central Mozambique, and Salvador et al. (2022) in Philippines, who found large amount of soil carbon in the interval depth of 0-30 cm.

The variability of the organic carbon accumulated in the system is related to the forest coverage and the structure and composition of the forest (Kida and Fujitake, 2020), as it was observed in this study that the most vegetated sampled plots, the quantity is higher. Kauffman and Bhomia (2017) observed the same pattern when studying carbon stocks in Western-Central Africa. The same with Castellon et al. (2022) in Southern America.

The carbon accumulated in a forested system can be lost as long as there is logging, according to Leal and Spalding (2022), and Sanjay et al. (2014). Trettin et al. (2016) have found high amount of carbon than this study in above and belowground of Zambezi Delta, due to fact that the area is huge, the number of plots were superior and is a remote area that it is unvegetated.

Considerable variation carbon in mangroves carbon among sites and countries may be related to structural attributes, such as variable stem density but also to different sampling approach, as for the soil sampling.

As climate change mitigation has come to the fore of international scientific and political discussions, there has been an enhanced focus on conserving and restoring degraded ecosystems that are known to function as carbon sinks. Therefore, knowing the potential of a mangrove forest to sequester and store carbon, 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 (Huxham et al., 2015; Valdés et al., 2020; Chatting et al., 2022).

Using standardized methods is a helpful approach as it makes the comparison of results more flexible and establishes a frame of basic work, mainly if the goal is to monitor and access the REDD+ programs.

CHAPTER VI

6 CONCLUSIONS

Mangrove forests covers relatively a small area in comparison to theirs counterpart terrestrial vegetation but their footprint in carbon sequestration is far very significant. This study proposed to document trees biodiversity, structure, biomass pools as well as soil profiling, carbon concentration and stock including environmental parameters. The underlying outcomes of this study, on the first of its kind to be carried out in Pemba Bay, will help awareness and undertake carbon pathways of mangrove forests in Pemba and beyond in Mozambique and Africa.

The forest structure and the biomass pools

This study showed that the six mangrove species were found in Pemba Bay, namely: *Avicennia marina*, *Bruguierra gymnorhiza*, *Ceriops tagal*, *Rhizophora mucronata*, *Sonneratia alba*, and *Heritiera litoralis*. Those are conglomerated in four communities: (i) *Avicennia marina - Rhizophora mucronata - Sonneratia alba*; (ii) *Avicennia marina - Ceriops tagal - Rhizophora mucronata - Sonneratia alba*; (iii) *Avicennia marina - Ceriops tagal - Rhizophora mucronata - Avicennia marina - Bruguierra gymnorhiza - Ceriops tagal*, and (iv) *Rhizophora mucronata*.

Avicennia marina is the most frequent species, occurring in combinations with all other species, but remarkably with *Sonneratia alba*, *Rhizophora mucronata* and *Ceriops tagal*, either for overstory and understory layers as well as for dead trees.

The stocking of the understory was inconsistent in the area, averaging 6741 trees ha^{-1}, and ranging from 477 to 24,192 trees ha^{-1}. The overstory stocking averaged 695 trees ha^{-1}, and ranging from 299 to 1,156 trees ha^{-1}, whereas the dead standing trees averaged 126 trees ha^{-1}, and ranging from 13 to 325 trees ha^{-1}.

Stocking of *Avicennia marina* changed from 159 to 6,047 trees ha^{-1}, being the second highest basal area 0.36 m^2 ha^{-1}, contributing with 19.3% of aboveground (1.86 Mg ha^{-1}) and belowground (1.1 Mg ha^{-1}), respectively.

Rhizophora mucronata presented the third high stocking with a mean of 2,016 trees ha^{-1}, a basal area varying from 0.02 to 1.1 m^2 ha^{-1}, contributing with aboveground (1.18 Mg ha^{-1}) and belowground (0.70 Mg ha^{-1}) correspondent to 12.3% to both. *Bruguierra gymnorhiza* had the lowest contribution in the stocking and biomass content in the understory.

Dead trees aboveground and belowground biomass was 10.0 and 4.0 Mg ha^{-1}, respectively. High values of dead trees biomass content were pronounced in aboveground (116.47 Mg ha^{-1}) and less to belowground (45.59 Mg ha^{-1}), corresponding to 71.9 and 28.1%, respectively.

The dead standing trees of *Sonneratia alba* presented the highest stocking, varying from 13 to 247 trees ha^{-1}, basal area ranging from 0.12 to 7.3 m^2 ha^{-1}. The aboveground biomass was higher for *Ceriops tagal* (10.9 Mg ha^{-1}) than *Rhizophora mucronata* (10.9 Mg ha^{-1}), being opposite for belowground biomass, 16.4 Mg ha^{-1} for *Rhizophora mucronata* and 10.5 Mg ha^{-1} for *Ceriops tagal*.

Soil profiling, organic carbon concentration and physical parameters

The salinity (ds/m^3), pH (H2O), and carbon accumulated (g kg^{-1}) present slight differences in the area, suggesting an influence of site factors. In general, in the mangrove forest of Pemba Bay, the large amount of carbon is accumulated in the soil and belowground. The presence of the same species in the overstory and the understory (natural regeneration) suggests that the succession in the region is secure; however, the species *Avicennia marina*, *Ceriops tagal* and *Rizophora mucronata* showed high density, ranging from 159 to 22,759 trees ha^{-1}.

Soil profiling has indicated that the texture is mostly sand, with high quantities being observed in the layer 145-150 cm. In the southwest plots, there was no significant difference in the depth profile variability for all the soil granulometry classes. Coarse and fine sediments were the most predominant.

The pH values showed a wide difference among the inventory plots, regarding to high density in Western and low density in the southwest part mangrove forest of Pemba bay.

The salinity showed the same configuration in the hole depth gradient, with a tendency to have a slight decrease from 5 to 2 dS m^{-1} at the interval depth of 30 to 90 cm, but remaining constant (5 dS m^{-1}) at the range depth of 90 to 150 cm. The northeast part region tended to maintain constant salinity values in the whole gradient profile.

The concentration of organic carbon showed slight variations, being higher in the northeast part than the southwest, due to the vegetal coverage.

The mangrove carbon stocks

The organic carbon accumulated in the mangrove system of Pemba Bay was estimated in 309.11 Mg ha^{-1}. Highest organic carbon content was observed in the soil layer of 50-100 cm, being lower in the southwest part of the Bay and higher in northeast part. The southwest part showed high organic carbon content on the bottom (depth 100 - 150 cm) than the northeast part.

Mangrove management considerations and recommendations

These results of this Thesis documented relevant aspects for management and conservation of mangrove forests within Pemba Bay. Highlight to the contribution for payment for ecosystem services (PES) such as REDD+ strategy, creating a strong possibility of potential incentive for conservation and sustainable use of intact mangroves under the same strategies. Also, this study created the bases for wider actors engagement including researchers/biologists, students and the community who benefit direct and indirectly of mangroves.

Considering that this study produced baseline data, including the establishment of permanent monitoring or study plots in Pemba Bay, future actions may need to cover the following activities:

1. To describe the relationship and influence of physical-chemical parameters among the mangrove species distribution (such as pH and salinity) according soil depth;

2. To determine the variability of biomass due to plant coverage as well as to document mangrove degradation, change detection and root cause analysis;

3. Assess through a socio-ecological and/or socio-anthropological study the communities' dependence on mangrove forests, its fishing activity and develop a livelihood PES scheme so that mangrove recovery can be assisted and measured.

Further recommendation, for future studies, is to align mangrove stocks and mangrove sequestration studies within Pemba Bay and beyond in Mozambique and the Western Indian Ocean. Since mangroves in Mozambique covers extensive areas as most of the Pemba Bay is surrounded by mangroves forests, this area can be subjected for implementation of Mozambique carbon commitments such as mangrove restoration strategies, NDCs climate commitments as linked with mangroves forests as well as extension of Mozambique marine protected areas (MPA) to cover most of Pemba Bay. MPAs extension will satisfies therefore the recently CBD proclaimed Global Biodiversity Framework 30 by 30. Mozambique has only attained 2.1% of MPA and, committing part of mangrove areas may help the country attaining such commitments. Local legislation already states protection for critical shallow habitats such as mangrove forests. Combining PES schemes together would mangrove protection and restoration will strengthen the role of mangrove forests in climate mitigation and provision of livelihoods.

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