PROJECTO CONSTRUINDO UM FUTURO AZUL PARA ECOSSISTEMAS

E PESSOAS NA COSTA LESTE AFRICANA

FUTURO AZUL

# ECOLOGICAL ASSESSMENT OF THE MANGROVE FORESTS OF MEMBA, NACALA-À-VELHA AND MOSSURIL

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## 1 Introduction

Mangrove forests are coastline ecosystems, and among the most productive in the world (Donato *et al.*, 2011). Despite a wide structural variability, the number of plant species is reduced, since mangrove ecosystem houses a typical vegetation adapted to the specific conditions of insolation, flooding regimes, salinity and oxygen in the soil (Santos *et al.*, 2019). They are ecologically and socioeconomically important (Carvalho and Jardim, 2017; Trettin *et al.*, 2015) as they help soil fixing, preventing erosion and balancing the coastline, reducing the effects of storms, cyclones and flooding on the coast (Macamo *et al.*, 2016). They are areas for the development and feeding of marine, estuarine, limnetic and terrestrial species (Carvalho and Jardim, 2017), and also providing various resources such as fuel (firewood), wood for construction, fishing resources and common utility services for local communities (Macamo and Sitoe, 2017) allowing the practice of agriculture, aquaculture and salt production (Nicolau *et al.*, 2017). Therefore, this ecosystem provides a whole range of services that are essential for coastal communities, particularly those of the East African coast, whose livelihoods are very dependent from coastal and marine ecosystems (Macamo *et* al., 2021; WWF, 2022).

In Mozambique, eight species of mangrove trees occur (Balidy and Laissone, 2011; Macamo and Sitoe, 2017): *Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal, Heritiera littoralis, Lumntzera racemosa, Rhizophora mucronata, Sonneratia alba*, and *Xylocarpus granatum* (Ferreira *et al.*, 2009; Balidy and Laissone, 2011; Macamo and Sitoe, 2017) being *A. marina* the most widely distributed species in the country (Macamo *et al.*, 2016). *Xylocarpus molluccensis* was also identified at the Zambezi delta and in the northern part of Nampula province (Trettin et al., 2015; Bandeira and Balidy, personal observation).

In the country, mangrove forests occupy an estimated area of 386 507 ha (Campira *et al.*, 2021; Barbosa *et al.*, 2001) being the 13$^{th}$ largest mangrove area in the world and the third largest in Africa (Giri *et al.*, 2010). They occur along the coast, at the mouths of major rivers and in sheltered areas such as bays (Macamo and Sitoe, 2017), extending from Rovuma to Maputo rivers (Barbosa et al., 2001; Macamo et al., 2016). The province of Zambézia, has the most extensive area of mangrove forest (150 769 ha), followed by Sofala (104 333 ha) and Nampula

(55 526 ha). The provinces of Cabo Delgado, Inhambane and Maputo account for 40 508 ha, 24 898 ha, and 10 078 ha respectively, and Gaza has the smallest area, estimated at 395 ha (Campira *et al.*, 2021; Barbosa *et al.*, 2001).

The main factors related to the loss of mangrove are deforestation, land use change, hydrological changes, chemical pollution and climate change (Santos *et al.*, 2019). Peri-urban forests, such as those around Maputo and Beira cities, are more threatened as they remain an important source of domestic fuel and timber to the communities (Barbosa et al., 2001; Macamo et al., 2016). Some cities are also growing at the expense of mangrove forests and other wetlands, as it was recorded in Maputo, Matola and Quelimane cities (Paula et al., 2014). The highest deforestation rates were recorded in Maputo, Beira, Quelimane and Nacala-à-Velha, which were considered priority areas for mangrove reforestation (Barbosa *et al.*, 2001).

A recent study from Macamo *et al.* (2021, unpub.), found crucial evidence of intensive and unsustainable mangrove logging in Nampula, showing the need of protecting the remaining mangrove communities and implementing activities to minimize the destructive impacts caused by human activities in order to secure a long-term provision of ecosystems services by mangroves.

Structural characterization of the mangroves can be explored to reveal the current state of mangrove forests, as well as the degree of damage caused to the forests by anthropogenic action (and not only) in specific locations (Fernando, 2020). Mangrove forests present a structural variability that may be associated with environmental characteristics and anthropogenic factors, and revealing the peculiarities of each site can emphasize the importance of preventive actions in the ecosystem conservation (Santos *et al.*, 2019).

This type of characterization of forests can be divided into two types: horizontal and vertical. The first is analyzed through quantitative parameters that indicate the occupation of individuals in forest horizontal space, which are density, frequency and dominance, in absolute and relative terms. The vertical characterization is intended to indicate the stage of successional species within the forest, which can be made by analyzing the upper, middle and bottom strata allowing the knowledge of the sociological position of existing species (Santos *et al.,* 2019)

The main objective of the present study is to describe the ecological characteristics of the mangrove, as well as the ecological condition and main threats to the forests in the districts of Memba, Nacala and Mossuril, in the province of Nampula, and identify the main areas of intervention for community restoration and conservation activities.

## 2 Objectives

The specific objectives of the current study are:

- To map mangrove occurrence and distribution in the districts of Memba, Nacala-à-Velha and Mossuril;
- To identify changes in forest distribution in the last 10 years;
- To describe the structural characteristics of the forest, including species composition, stand density, height and regeneration potential;
- To assess the ecological condition of the forests;
- To establish a baseline that will be used as a reference when comparing the results from the project interventions that will be achieved at the end of the project.
- To identify threats to the mangrove forests;
- To identify the most important areas to conserve, which need special attention under the development of the new sustainable use marine conservation area zoning plan;
- To identify 150 hectares of potential areas for mangrove restoration, to be implemented in partnership with local communities.

# 3 Scope of Work and Methodology

## 3.1 Study area

The coastal area of Mozambique has distinct characteristics and 3 major ecological systems are recognized. The southern area from Ponta do Ouro up to the Save river delta is predominantly sandy; the section between the Save river delta and Angoche is swampy; the north of the Angoche is the so-called rocky shore. This study was carried in the Nampula districts of Memba, Nacala-a-Velha and Mossuril, which are part of the rocky shore.

The climate of the region is tropical humid, characterized by two seasons: a warm and rainy summer that starts in November and ends in April, with frequent rains and thunderstorms, in which the precipitation represents about 80% of the total annual precipitation (Impacto, 2012a; Impacto, 2012b); and a dry and slightly fresher season that extends from May to October. The maximum temperature is 33.9º C and the minimum is 19º C, the average annual temperature is 25,5º C and the average annual precipitation ranges between 600 to 1000 mm (MIMAIP *et al*., 2019; Zacarias, 2019). Dominant winds in the region blow from east between January to March, and predominantly from South between April to August. Between September and December, the winds are predominantly from the east and southeast (MIMAIP *et al*., 2019).

The coastal area of Nampula province is one of the most known tourism destinations in Mozambique. Agriculture is the dominant activity and involves almost all households. The coastal strip is dominated by the production system based on the cassava crop, associated with grain vegetables such as cowpea and peanuts.

In the coastal districts of the province, the small local industry (fishing, carpentry and crafts) is predominant, emerging as an alternative to agricultural activity (Zacarias, 2019). Memba district is the northern most limit of Nampula province, were Lúrio river marks the border with Cabo Delgado province. It is divided into 4 administrative posts: Chipene, Memba, Mazua and Lúrio. The population of the district is estimated in 369 726 inhabitants in 2021 (INE, 2021). Mossuril district borders with Nacala and Nacala-a-Velha districts to the north, Monjicual to the south, Monapo to the West and the Indian Ocean to the east. The population was estimated in 199 246 in 2021 (INE, 2021). Nacala-a-Velha on its turn is bordered by Memba (Figure 1) Nacaroa, Monapo, Mossuril and Nacala Porto (Figure 1). Nacala-a-Velha has also an important port for coal, and has significant port and railway activities around. The total population was estimated in 199 246 inhabitants in 2021 (INE, 2021)  Mozambique Island is limited to the east by the Indian Ocean, to the north, south and west by Mossuril district. The District is divided in two parts: The Island which is composed by eight neighborhoods and the continental zone, constituted by 22 neighborhoods where the majority of the population live. The total population was estimated in 78 742 inhabitants in 2021 (INE, 2021)

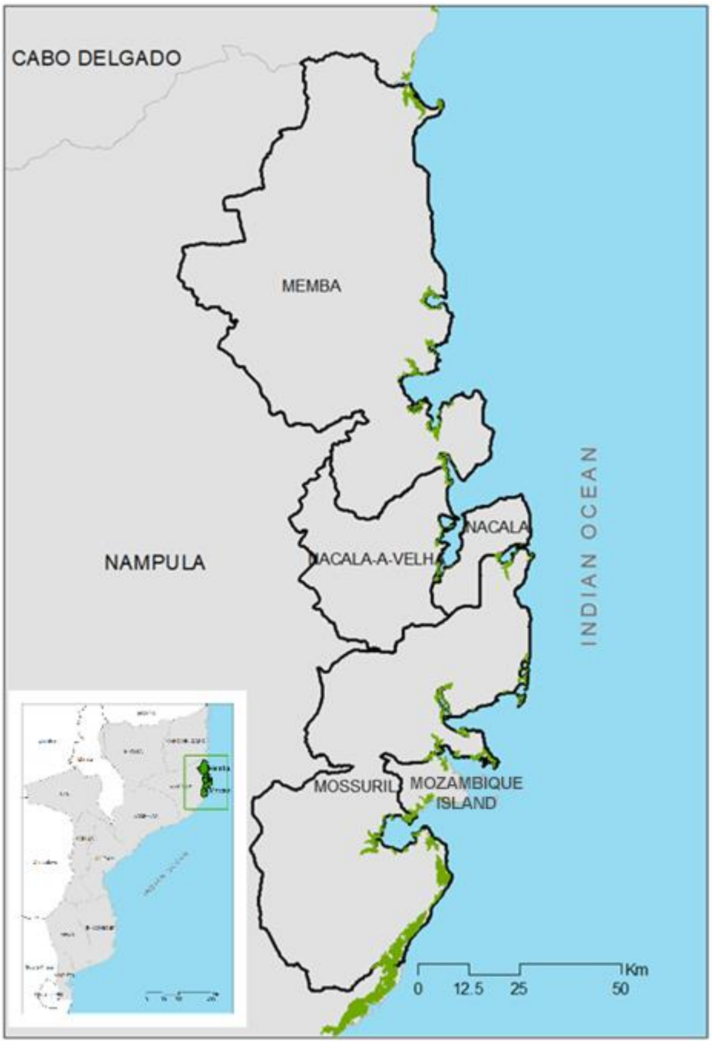


*Figure 1: Study area.*

## 3.2 Mangrove mapping

Sentinel-2 L2A multitemporal images were processed to produce mangrove distribution map of Mossuril and Memba districts between 2012 – 2022. The 10 m spatial resolution of visible and near-infrared bands of Sentinel-2 was selected as suitable for mangrove mapping and thus the 20 m short-wave infrared bands resampled to 10 m.

September and October have been selected as the best months per year to conduct the mapping due to the consistent availability of cloud-free Sentinel-2 images over the northern part of Nampula province in 2012 – 2022. To avoid seasonal variations that may affect the annual change detection of mangrove extent, images selection acquired in similar month each year.

To produce mangrove distribution map using Sentinel-2 images, supervised machine learning classification was performed. Random Forest (RF) algorithm for classifying mangrove and non-mangrove in the study area was applied. RF is a non-parametric machine learning classification algorithm that applies multiple decision trees and randomly selects training samples and variables in classification (Breiman, 2001), which is able to provide accurate classification results with relatively fast processing time, even when using large amounts of data (Belgiu & Dragut, 2016).

The non-mangrove class consisted of bare land and other vegetation to match the mangrove map of the study area produced by Shapiro et al. (2015) so that they could be compared. Water pixels were excluded from the analysis. To run the RF algorithm, reference data was obtained from the combined (human and machine) interpretation of very high spatial resolution image and field survey to train the RF algorithm.

The Sentinel-2 product L2A has been atmospherically corrected (at surface reflectance) and orthorectified, hence, directly comparable between dates for monitoring mangrove cover changes. The mangrove distribution map was produced once per year used to assess the change of mangrove areal extent annually from 2012 – 2022 (Figure 2).

After the mangrove distribution map was produced for each year, change detection analysis using simple raster operation was applied to identify the location where the mangroves occur. Mangrove area was classified as: stable, for those areas which had no change in cover and distribution; loss, for those areas where mangrove cover was lost and gain for new mangrove areas.

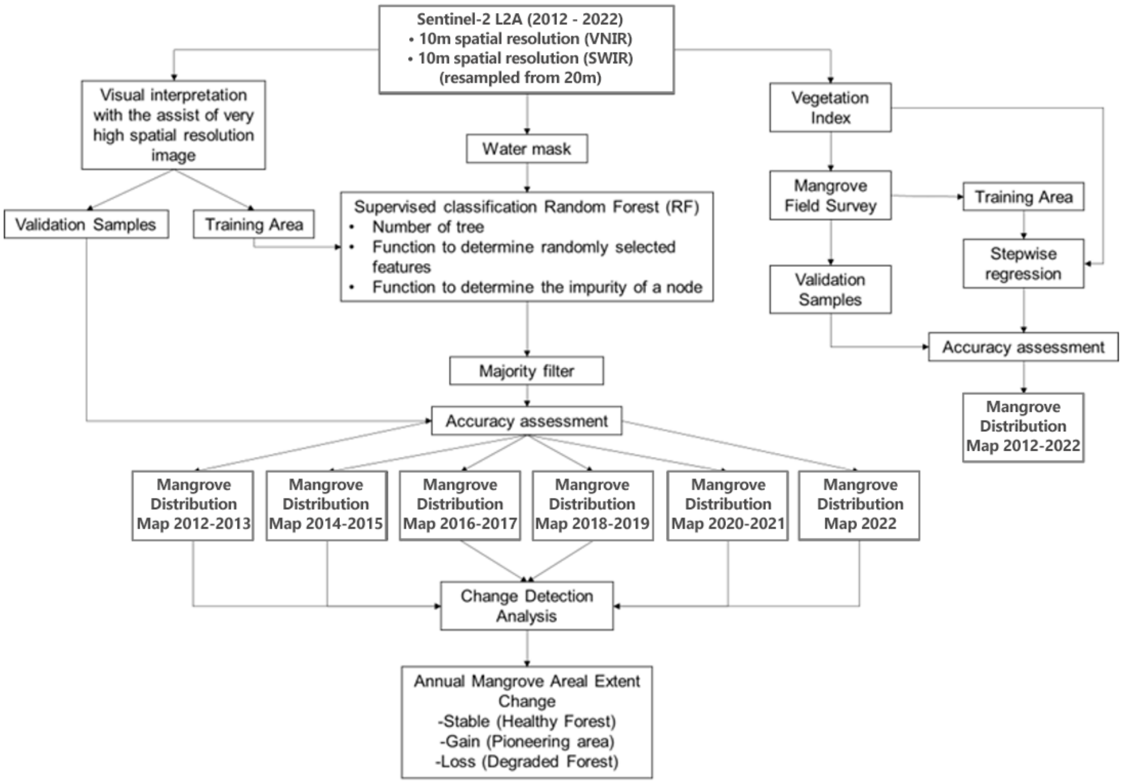


*Figure 2. Flowchart of mangrove mapping, distribution and change detection.*

During the field work, data for map validation were collected. This consisted in collecting GPS coordinates at every point where mangroves were sampled. Descriptive characteristics of the sampled point were also collected. These included: species occurrence, qualitative forest condition, mangrove threats, etc. Additionally, new coordinates were also collected in the field whenever needed. For instance, if a degraded site not selected for sapling was spotted in the ground, the respective coordinates were collected and a qualitative assessment (as described above) was conducted.

## 3.3 Field sampling design

Field sampling was undertaken between 21st February and 2nd March 2023 (10 days), following the combined methodology described by Kairo *et al.* (2002) and Kauffman and Donato (2012). The desktop mangrove distribution maps were used to identify sampling areas, considering important ground characteristics. A grid composed of 100 x 100 m plots was placed on the mangrove distribution maps of the study area, considering the 2022 distribution and cover, which indicated stable, degraded and new mangrove area. Another layer with data on main human settlements, roads and rivers was then added. Based on this, a representative number of plots was then selected, following the criteria:

- Access to the sampling points (by primary or secondary roads and rivers or channels);
- Near and far for human settlements, so that the influence of human pressure could also be captured;
- Stable, lost and new mangrove areas, in order to cover different forest conditions;
- Seaward, riverine/channel, landward and inner forest, so that all types of mangrove forest were covered;

The sampling plots were selected in order to form a transect perpendicular to the coastline, which allows observing any zonation pattern of the forest mangrove. A total of 28 sampling plots and 67 subplots were accessed in 12 sites as shown in the *Table* 1. The location of each sampling unit (subplot) is presented in the Figure 4.

*Table 1: Number of sapling plots and subplots sampled in the study area*

| Districts | Site | Plots | Subplots |
|---|---|---|---|
| **Memba** | Fungo | 1 | 4 |
| | Geba | 4 | 10 |
| | Nantaca | 2 | 6 |
| **Nacala-a-Velha** | Mussengua | 1 | 4 |
| | Pangane | 1 | 2 |
| **Mossutil** | Cabaceira Grande | 2 | 8 |
| | Lunga* | 5 | 7 |
| | Mingorine | 1 | 4 |
| | Quissanga-Nantoa | 1 | 4 |

| | | | |
|---|---|---|---|
| | Saua-Saua | 1 | 2 |
| | Sanhute | 2 | 7 |
| **Mz Iland** | Lumbo* | 7 | 9 |
| **Total (Study area)** | | 28 | 67 |

******These sites were sampled in 2020 and data was used to access the ecological condition of the forest.*

Two to four sub-plots were derived from each plot as indicated in Figure 3. 10x10 m subplots were placed within the plot, and separated by no less than 25 m. Figure 4 shows the geographic location of the subplots.

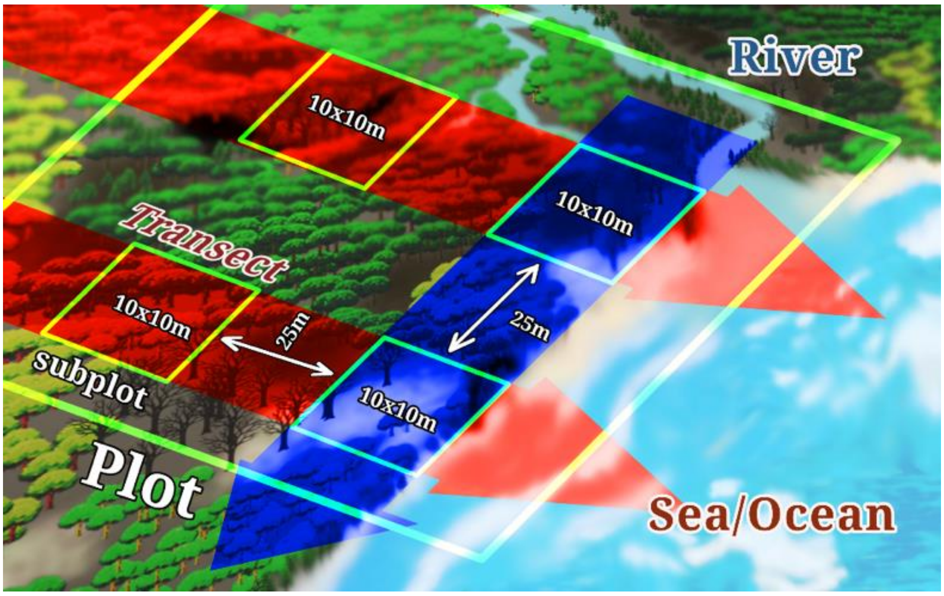


*Figure 3: Transects and subplots placement in the field. Red arrows represent transects perpendicular to Sea/ocean and blue arrow, transects perpendicular to main river. Minimum distance between plots must be 25 m, and surface area of each plot will be 100 m2 (10x10m).*

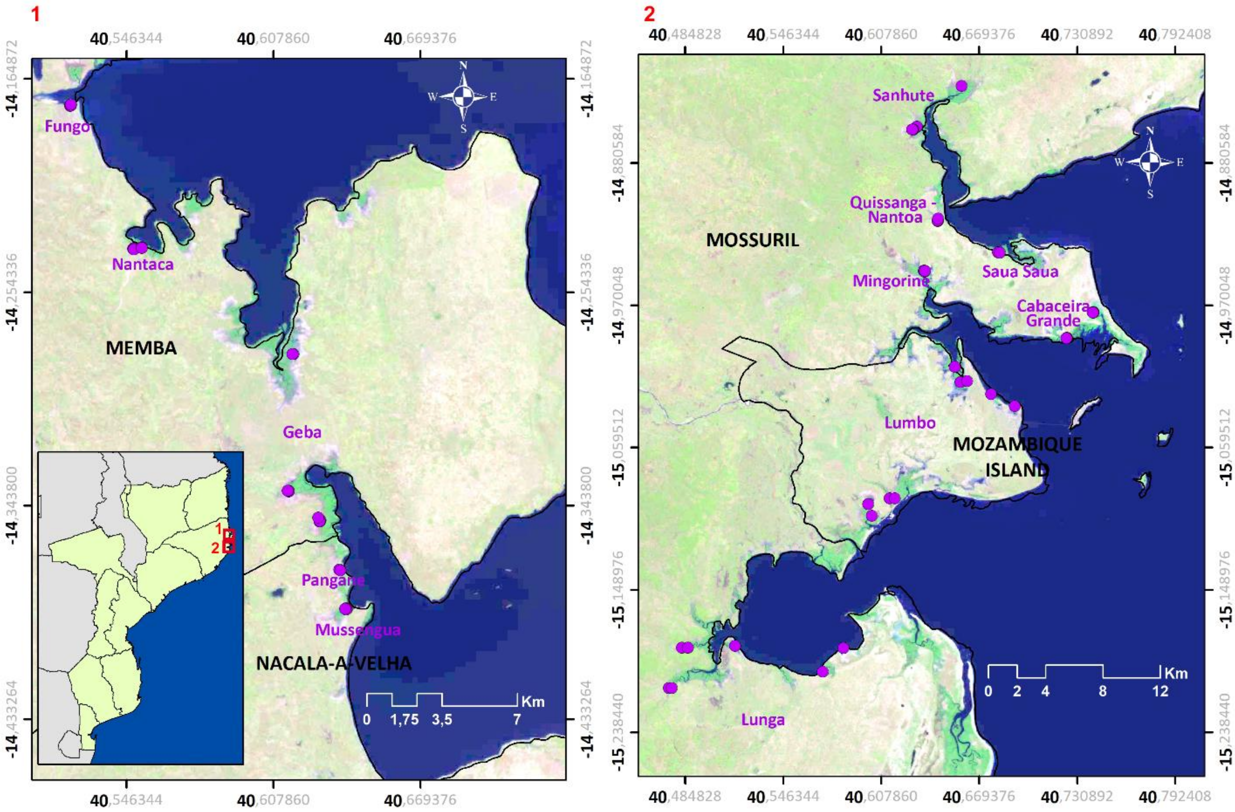


*Figure 4: Geographic location of the sampling subplots in the study area*

## 3.4 Forest structure: DBH and Height measurement

The forest structure indicates the successional stage of the forest (young *vs* mature), the species composition, average density and height. Forest structure can also indicate whether human interference has changed the natural patterns of the forest and can inform the need for human intervention. The sampling followed standard protocols adopted in other studies in Mozambique and in the region, which allows comparisons with other mangrove forests.

Within each 10x10 m subplot, a general description of the habitat was recorded, including: vegetation cover, inundation class, soil type, dominant species, phenology and other relevant habitat characteristics observed in the field and recorded in the sheets. This information is crucial to interpret the data and enrich the ecological knowledge of the forest and its functioning.

All adult trees (diameter above 2.5 cm) within the plot had their diameter at breast height (DBH) measured with a tree caliper (Figure 5), and the height was estimated with a graduated stick (Pérez-Pérez *et al.*, 2015).

Base diameter (BD) was measured for stumps and dead trees in stage 3 (explained in tree condition section of the methods) that not reach DBH because they were cut or naturally broken (Kauffman and Donato, 2012).

*Figure 5: DBH measurement in Rhizophora mucronata in Nantaca mangrove forest*

Different measuring protocols were followed (Malone *et al.*, 2009) to measure the DBH in trees which stems were in different situations (Figure 6):

- If the tree was growing on a slope, the DBH measurement was taken from the high side of that slope at a height of 1.37m.
- If the tree was leaning, DBH was measured from the top side of the tree

- For trees with a bifurcated stem at breast height, the DBH of each of the stems formed was measured and the measurements were summed. When the bifurcation starts at the base of the stem, these were considered as separate trees.
- If the tree had a deformed trunk at breast height, making the measurement inaccurate, the measurement was taken immediately above or below the deflection.
- When trees with flattened stems were found, the DBH measurement were performed at the angle that allowed for the smallest stem thickness to be measured.

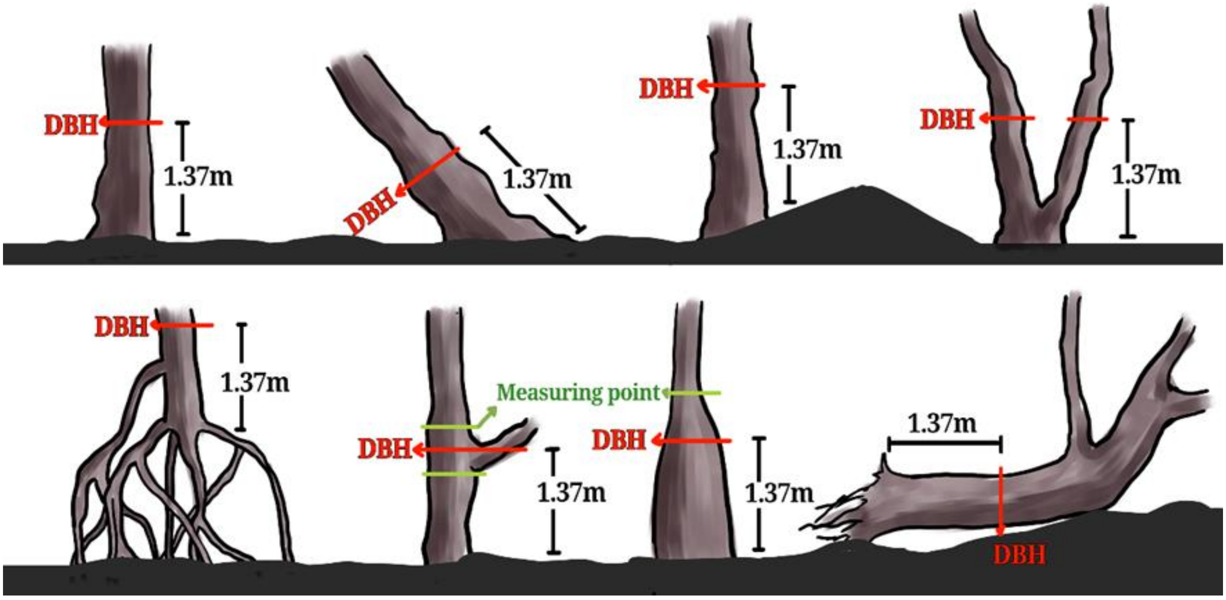


*Figure 6: Different possible situations to be found, regarding tree stems. Normal (1), inclined tree (2), on a slope (3), forked (4), trees with prop roots (Rhizophora mucronata) (5), in the presence of a deformation (6 and 7) and fallen tree (8)*

## 3.5 Stem quality class

The stem quality is simultaneously an indicator of human pressure and ecological conditions, as trees tend to grow straight in specific environmental conditions (e.g.: high stand density, rich soils) and dwarf and crooked in harsh environmental conditions (e.g.: high salinity). Human pressure also targets specifically on straight poles, so the over-abundance of crooked poles may also be perceived as a sign of overexploitation.

Stem quality was assessed for every adult tree with the subplot. Trunks were classified as Quality I, II and III, depending on the degree of stem bending and the way the trees grow (Figure 7) (Macamo, 2018).

- Quality I – trees with erect stems, useful for construction;
- Quality II – trees with semi-erect stems, which would need to be straightened for use in construction;
- Quality III – trees with crooked stems, not usable in construction. Dwarf adult trees whose stems had less than 1 m height were classified as Quality III.

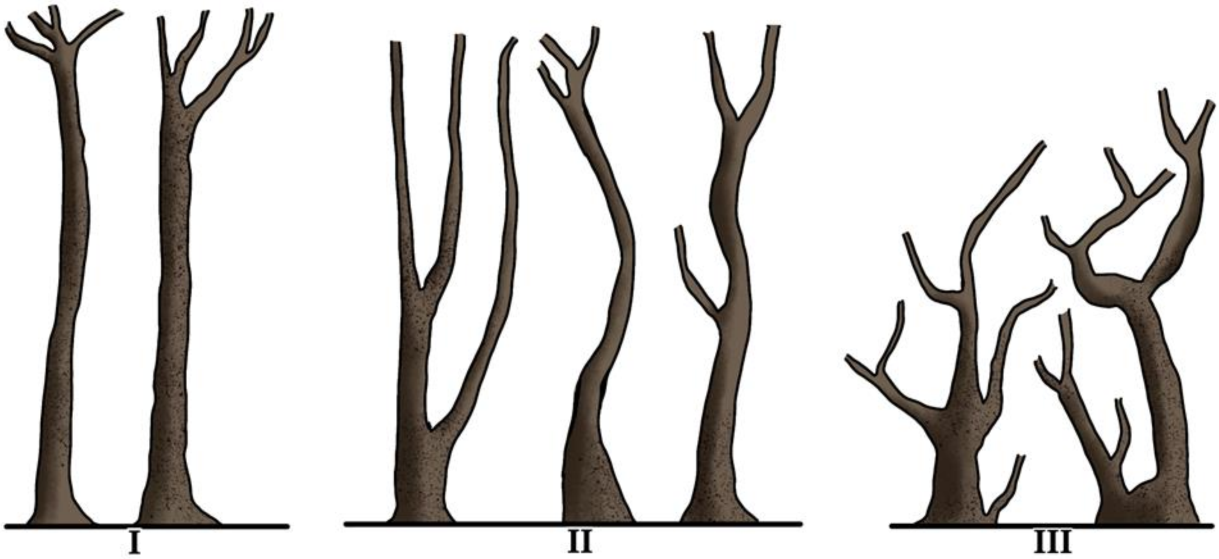


*Figure 7: Different tree stem qualities. Quality I, Quality II and Quality III*

DBH was used to calculate forest indices and biodiversity (Zimudzi and Chapano, 2016):

a) Basal area ($m^2$) = $\pi \frac{DBH^2}{4}$

Where DBH = diameter at breast height

b) Relative dominance = total basal area of Species Y / total basal area of all species X 100

c) Relative Density = number of trees of Species Y / total number of all trees X 100

Where “Y” is the species for which the density is to be determined

d) Frequency = number of squares where a certain species occurs / total number of squares in the location

e) Relative frequency = frequency of Species Y / sum of all frequencies X 100

f) The Importance Value Index (IVI): measures the share of each species relative to the other, and the verification of the form of their spatial distribution (Santos *et al.*, 2019). To calculate this Index, the following equation was used:

IVI = relative dominance + relative density + relative frequency

g) Complexity Index: is a reliable indicator of stand level biodiversity and rank stands in terms of their potential contribution to biodiversity (McElhinny, 2005). The mathematical expression used to calculate the complexity index combines the basal area, stand density, height and number of species (Macamo *et al.,* 2021):

$$CI = (Nr\ of\ species \times Mean\ height \times stand\ Basal\ area \times mean\ density)/10^{-5}$$

## 3.6 Tree condition

Tree condition is directly related to human pressure, as it indicates the intensity of wood harvesting. It also allows the identification of natural threats, such as diseases, sedimentation and other causes of tree mortality.

All adult trees within the subplot were classified according to their condition as: Intact, partially cut, severely cut, dead and stump, as described by Kairo *et al.* (2001) and Bandeira *et al.* (2009):

- Intact tree (I) – trees that did not show any sign of cutting;

- Partially cut tree (PC) – trees with one or a few cut branches corresponding to less than 50% of the branches or canopy cover, and with their main trunk intact;
- Severely cut tree (SC) – trees with many of their branches cut, in more than 50%;
- Stump – trees that were completely cut at the base, without stems and/or healthy branches;
- Die-Back – Naturally dead tree (with no signs of cutting).

Dead trees were classified at 3 different stages, stage 1 – trees recently dead that maintain many smaller branches and twigs; stage 2 – dead trees that lost small branches and twigs as well as a portion of large branches; stage 3 old dead trees that lost most of the branches and only the main stem remains or even broken (Kauffman and Donato, 2012).

## 3.7 Regeneration potential

The regeneration potential of the forest indicates its ability to continue as an ecologically functional unit. Low regeneration potential may indicate the presence of a disturbance, while high potential with plants of different categories, indicates a young thriving forest. The proportion 6:3:1 or 2500 seedlings.ha$^{-1}$ is desirable for a young forest (FAO, 1994).

The regeneration potential of the forest was estimated within the subplot and followed standard procedures. Seedlings, saplings and young plants (DBH less than 2.5 cm) were counted for each mangrove species (Kairo *et al.*, 2002), and classified into 3 regeneration classes depending on their height (Macamo *et al.*, 2016) where:

- Regeneration Class I (RCI) – seedlings with less than 40 cm high;
- Regeneration Class II (RCII) – seedlings between 40 cm and 1.5 m;
- Regeneration Class III (RCIII) – small plants with a height between 1.5 and 3 m (Kairo *et al.*, 2002; Komiyama *et al.*, 2005; Bandeira *et al.*, 2009; Kauffman and Donato, 2012).

In the case of forests with a high density of seedlings observed, a subplot of 5m x 5m (25 $m^2$) (Mchenga and Ali, 2014; FAO, 1994) or 2.5m x 2.5m (6.25 $m^2$) was set for seedling counting. In this case, the results obtained was used to estimate the number of seedlings in an area of 100 $m^2$ corresponding to the original subplot multiplying by 4 (for 5m x 5m) and 16 (for 2.5m x 2.5m (Mchenga and Ali, 2014).

The ecological proportions of the regeneration potential of each site were determined and compared with the minimum ecological potential determined by FAO (1994), dividing the total seedling density of all regeneration classes by the class with the lowest seedling density (Machana-António *et al,* 2022).

## 3.8 Biomass and Carbon

### 3.8.1. Live biomass and carbon

DBH data was also used to determine above and below ground Biomass (Indrayani *et al.*, 2021). The general formulas of Komiyama et al (2005 and& 2008) presented in the protocol by Kauffman and Donato (2012) were used:

$$AGB=0.251 \times \rho \times DBH^{2.46}$$

Where: AGB = Aboveground Biomass*;*

*P* = Specific wood density ($g.cm^{-3}$); DBH = Diameter of stem at breast height

$$BGB=0.199 \times 0.899DBH^{2.22}$$

Where:

BGB = Belowground Biomass

DBH = Diameter of stem at Breast Height

The specific wood density used in the determination of AGB and BGB was based on the densities determined by Bosire et al. (2012) for mangrove species from the Zambezi delta (Table 2. Specific wood densities for mangrove species which occur in Mozambique (Bosire et al., 2012).

*Table 2. Specific wood densities for mangrove species which occur in Mozambique (Bosire et al., 2012) and http://db.worldagroforestry.org/wd.*

| Species | Wood density ($g.cm^{-3}$) |
|---|---|
| *Avicennia marina* | 0.9 |
| *Bruguiera gymnorrhiza* | 0.1 |
| *Ceriops tagal* | 1.1 |
| *Rhizophora mucronate* | 1.1 |
| *Xylocarpus granatum* | 0.8 |
| *Sonneratia alba* | 0.8 |
| *Heritiera littoralis* | 0.8 |

The above ground biomass for dead trees, and below ground biomass for dead trees were adjusted by subtracting 15% of the biomass. A conversion factor of 0.01 was used to determine AGB and BGB per hectare as $kg.ha^{-1}$.

Biomass estimates were converted to Carbon ($Mg.ha^{-1}$) by multiplying by a conversion factor of 0.5 for AGB and 0.39 for BGB (Stringer *at al.,* 2015). BGB was calculated for stumps, because despite the tree has undergone a clear cut, the stump still has a root system that contributes to the total biomass of the forest (Kauffman and Donato, 2012).

### 3.8.2. Soil carbon

For Carbon data, a corer was used to take soil samples from mangrove at 4 different depths, in each plot. The corer was placed at the center of the plot. Figure 8 shows how to get the samples in the field.

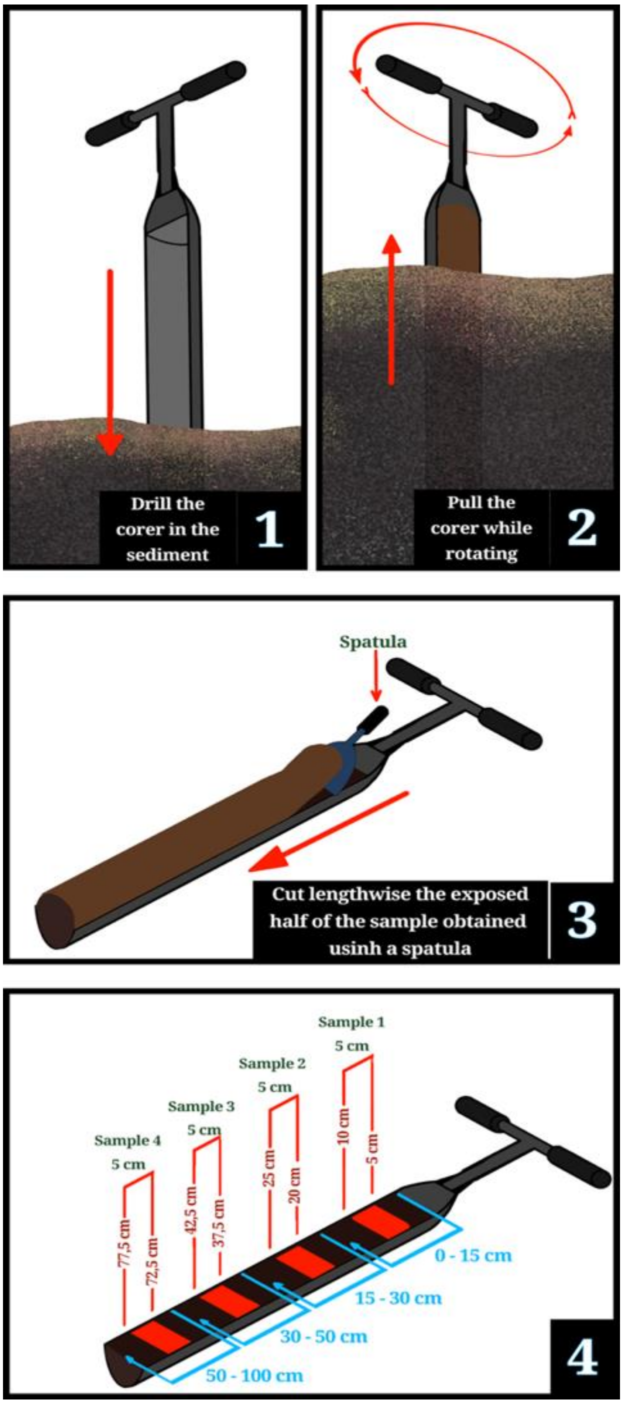


*Figure 8: Steps followed during soil sampling for carbon estimation.*

**Step 1:** The corer was placed vertically, and was introduced in the soil completely.

To avoid missing the last interval sample, the corer was drilled in different places inside the plot until the right spot was found where the corer could be completely introduced in the soil.

**Step 2:** The corer was rotated while pulled up, ensuring that an intact sample of the 4 layers was obtained.

**Step 3:** The exposed half of the sample was cut carefully, keeping all the elements (roots, leaves, rocks and other debris) in their respective place.

**Step 4**. 4 samples were taken in 4 different depths interval (0-15 cm, 15-30 cm, 30-50 cm and 50-100 cm) as illustrated in the figure. A 5 cm wide sample was collected in the middle of each depth interval.

Soil samples were processed in the laboratory to determine soil bulk density, carbon content and total soil organic carbon (Sakin, 2012). The Loss on ignition method (LOI) was used to estimate the organic carbon content of the soil (Kauffman and Donato, 2012). The method consists of weighing and incinerating the soil samples. The lost weight (ash) corresponds to the organic matter, from which the amount of carbon was calculated using allometric equations. The steps were as follows:

- Samples were weighed to determine wet weight. Then the samples were dried in a stove for 48H at 45°C;
- Then dry samples were weighed to determine dry weight;
- Next, samples were incinerated in a muffle for 3h at 550° C. After cooling in a desiccator, the weight of the ashes was determined.

Soil bulk density (g.cm$^{-3}$) was calculated for each sample by dividing the dried mass of the sample by the volume of the sample (Stringer *et al.*, 2015). This volume is calculated using core diameter and sample length which are 3 cm and 5 cm, respectively.

$$\text{Bulk density (g.cm}^{-3} = \frac{sample\ dried\ weight\ (g)}{Sample\ volume\ (cm^3)}$$

The carbon concentration in the soil was calculated by diving the ashes weight by the sample dried weight and multiplying by a hundred.

$$\%\ C = (\frac{sample\ dried\ weight - weight\ after\ ignition\ in\ the\ muffle}{sample\ dried\ weight}) \times 100$$

The soil carbon density was calculated by multiplying the bulk density by the depth interval and by carbon concentration.

$$\text{Soil carbon density } (C_S^n) = D_b \times d \times \%C$$

Where:

$C_S^n$ is the Carbon density in the soil expressed in Mg.ha$^{-1}$ for each depth interval (n);
*d* is the length of the depth interval; $D_b$ is the bulk density and
*%C* is the carbon concentration as an entire number.

### 3.8.3. Total Carbon

The total carbon of the system was obtained by summing all assessed carbon pools as the formula below indicates:

Total carbon = ABG + BGB+ Soil Carbon

Where:

ABG = Above ground biomass

BGB = Below ground biomass

## 3.9 Fauna – diversity and density

Fauna data were collected to provide baseline information on species occurrence, which will be used as reference in restored sited during the end-of-project assessments.

The fauna transects were set about 5 m away from the flora transects. This avoided the impact of disturbance (e.g.: noise, stepping, soil disturbance, etc.). Fauna transects were 10 m long (perpendicular to the coastline), along which 3 plots of 2 x 2 m were placed. The plots were 5 m away from each other. Mangrove fauna was then observed and counted with minimum disturbance as possible (no sound, slow movements) for 5 minutes at each plot. The abundance of benthic fauna was determined by the number of individuals counted (including emerging species such as crabs inside holes) and number of holes within each of the 4 $m^2$ plot. The fauna in the mangrove was identified at the surface of the ground and digging 2 cm below the ground to include any burrowing species. Gastropods, crabs and other fauna observed during sampling, were identified at species level. The Scientific names were confirmed and/or corrected (finding accepted names) using WoRMS (World Register of Marine Species) platform available at https://www.marinespecies.org/.

The abundance of fauna individuals was determined using the formula:

$$\text{Abundance} = \frac{Number\ of\ indivuduals}{area\ (m^2)}.$$

Abundance data was converted to density (ind.ha$^{-1}$) dividing the results obtained by 0.0001. Mean densities of the species identified were determined for each site.

Shannon and Simpson's diversity index was used to determine species diversity among sites. Then a Jaccard Similarity index was used to explore similarity of sites and the results were presented as heatmap graphic.

Relative frequency of each identified species was determined to identify the most common species for each site.

### 3.10 Lichens – diversity and density

Lichen studies in the mangroves of Mozambique are in their very initial stages, and this is one of the pilot areas in the country. To date, lichen composition of mangrove forests in Mozambique is only known for Maputo Bay and Sofala Bay. Lichen are important components of the forest and are potential indicators of the forest condition and pollution – either by the species composition or by the condition of the trees that they colonize. Being a preliminary study, this report will indicate the lichen composition of the mangroves and more detailed analysis will be conducted in future surveys.

Data for lichen density and diversity was collected on 5 trees with a DBH ≥ 6cm, randomly selected, as recommend for lichen assessment in forests with DBH below 20 cm (Dymytrova *et al.*, 2014). The applied method was adopted from Dymytrova *et al.* (2014) and Cáceres *et al.* (2007). A 6x6 cm plastic grid subdivided into 2x2 cm subunits (total of 9 subunits) (or 6x20cm subdivided into 2x2 cm subunits with a total of 30 subunits). The grid was placed on the stem, at a height of 1.3m above the ground, in such a way that the greatest lichen cover was observed. The relative lichen cover was determined by the number of subunits in which lichens of a given specie was present. The diversity of lichens was determined by the total number of species identified.

The relative cover of each lichen species on mangrove trees was determined using the following procedure:

The number of sub-unities of the plastic grid counted for each lichen specie was multiplied by the area of the sub-unity (4 $cm^2$). Then, the area of the mangrove stem where the lichen was observed was determined multiplying the stem circumference by tree height. The circumference at breast height (CBH) was determined using the formula (Hanifah and Eddiwan, 2018):

$$CBH = DBH \times 3.14$$

Where:

CBH = circumference at breast Height

DBH = Diameter at breast height

These data were used to determine which species have the higher cover in the mangrove, and which mangrove species is preferred for colonization by lichen.

## 3.11 Ecological condition of the mangrove forest

The ecological condition of the mangrove forest in the study area was classified based on the identification of impacts and through metrics that allow the determination of the Mangrove Conservation Index (MCI) proposed for the mangrove forests of Mozambique by Macamo et al. (2021). This method is currently under field validation, and has showed promising results.

The Mangrove Conservation Index consists of the combination of three different sub-indices:

### i. Sub-index 1: Adjusted Complexity Index (ACI)

The Adjusted Complexity Index (ACI) indicates how complex a forest is and assumes that more complex forests deliver better ecological services, such as coastal protection, nursery and carbon sequestration (Loria-Naranjo et al., 2014). The ACI is based on the structural characteristics of the forest such as the number of species, stand density, basal area and tree height. The formula for the ACI is as follows bellow:

$$ACI = Log_e (s*d*b*h)$$

where:

ACI = complexity index

s = number of species

d = stand density

b = basal area

h = mean height

The ACI ranges between 4.7 and 18.1, based on the minimum and maximum values of environmental factors found in the mangrove forests of Mozambique, as indicated in Table 3. Five intervals for the ACI where determined, each one corresponding to a score between 1 to 5 (Table 4).

*Table 3. Complexity index (CI) benchmarks for "the best" (highest) and "the worst" (lowest) mangrove forest in Mozambique.*

| **Structural parameter** | **Country benchmark** | | **Reference** |
|---|---|---|---|
| | **Lowest** | **Highest** | |
| **Number of species** | 1 | 6[1] | Bandeira et al., 2009; Macamo et al., 2015; Macamo et al., 2016; Amade et al., 2019 |

[1] Although there are 9 species of mangrove in Mozambique, most forests will have up to 6 species at once. Thus, this was considered the optimum number of species in a mangrove forest for Mozambique.

| Structural parameter | Country benchmark | | Reference |
|---|---|---|---|
| | Lowest | Highest | |
| Stand density (tree/ha) | 967 | 6 000 | Bandeira et al., 2009; Macamo et al., 2018; Amade et al., 2019 ; this study |
| Basal area ($m^2$/ha) | 0.11 | 60 | Bandeira et al., 2009; Amade et al., 2019 |
| Mean height (m) | 1 | 35 | Bandeira et al., 2009; Fatoyinbo et al., 2008; Bosire et al., 2012; Amade et al., 2019 |
| ACI | 4.68 | 18.14 | Proposed in the present study |

*Table 4. Benchmarks for the Adjusted Complexity Index in mangrove forests of Mozambique.*

| Adjusted Complexity Index | Range | Score |
|---|---|---|
| Very high | ]15.42 – 18.1] | 5 |
| High | ]12.74 – 15.42] | 4 |
| Average | ]10.06 – 12.74] | 3 |
| Low | ]7.38 – 10.06] | 2 |
| Very low | ]4.7 – 7.38] | 1 |

### ii. Sub-index 2: Forest Regeneration Potential sub-index (RFP)

This sub-index indicates whether the forest is producing a sustainable number of new plants, which will indicate the continuity of the forest. This sub-index is based on the ratio between seedlings (RCI), saplings (RCII) and young plants (RCIII), which should be 6:3:1 in a healthy/sustainable forest; or a minimum of 2500 seedlings per ha (FAO, 1994). Two scenarios can be found:

**Scenario A (RCIII> (RCII+RCI):** Low regeneration potentials are found in significantly disturbed forests, where environmental conditions are harsh for seedlings growth, or seedlings production is impaired by a reduced number of trees with reproductive capacity. Mature forests also have a low regeneration potential as the closed canopy does not allow seedling growth. In this case, the ration between regenerating classes (RC) is RCIII > (RCII+RCI). The RPI score is based on the density of RCI only, considering the minim sustainable stock density of 2500 seedlings/ha (FAO, 1994). Table 5 indicates the reference value and the corresponding scores for this scenario.

*Table 5. Reference values and scores for the Forest Regeneration Potential sub-index when RCIII > (RCIII+RCI) (Scenario A).*

| Seedling density (RCI only) | Benchmark RCI/ha | Score |
|---|---|---|
| **Sustainable** | > 2500 | 3 |
| **Worrying** | ]1000 – 2500] | 2 |
| **Unsustainable** | ]0 – 1000] | 1 |

**Scenario B (RCI>RCII>RCIII):** High regeneration potential is found in young and maturing forests, where RCI>RCII>RCIII. In these forests, seedlings production is very high, but as they establish and grow, they also tend to die in large numbers. Seedling mortality is related to the natural dynamic of mangrove forests, where seedlings are attacked by predators such as crabs. Seedlings are also very sensitive to high salinities and salinity fluctuations, to wave action and to sedimentation (Hoghart, 2015).  Therefore, only a few proportion of seedling make it to saplings, and a small proportion of saplings make it to young trees, which are then very likely to become adult trees. In this scenario, the FRP was calculated by the formula:

$$FRP = RCIII/(RCII+RCIII)$$

Where:

RPI = regeneration potential sub-index

RCIII = total number of young trees

RCII = total number of saplings

RCI = total number of seedings

FRP values and corresponding scores were then attributed as Table 6 indicates.

*Table 6. Benchmarks and scores for the Regenerating Potential Sub-Index in young forests.*

| RCIII:(RCI+RCII) | Benchmark | Score |
|---|---|---|
| **High** | ]0.088 – 0.110] | 5 |
| **Sustainable** | ]0.066 – 0.088] | 4 |
| **Worrying** | ]0.044 – 0.066] | 3 |
| **Unsustainable** | ]0.022 – 0.044] | 2 |
| **Low** | ]0.0 – 0.022] | 1 |

Figure 9 bellow shows the decision matrix for the Forest Regeneration Potential sub-index.

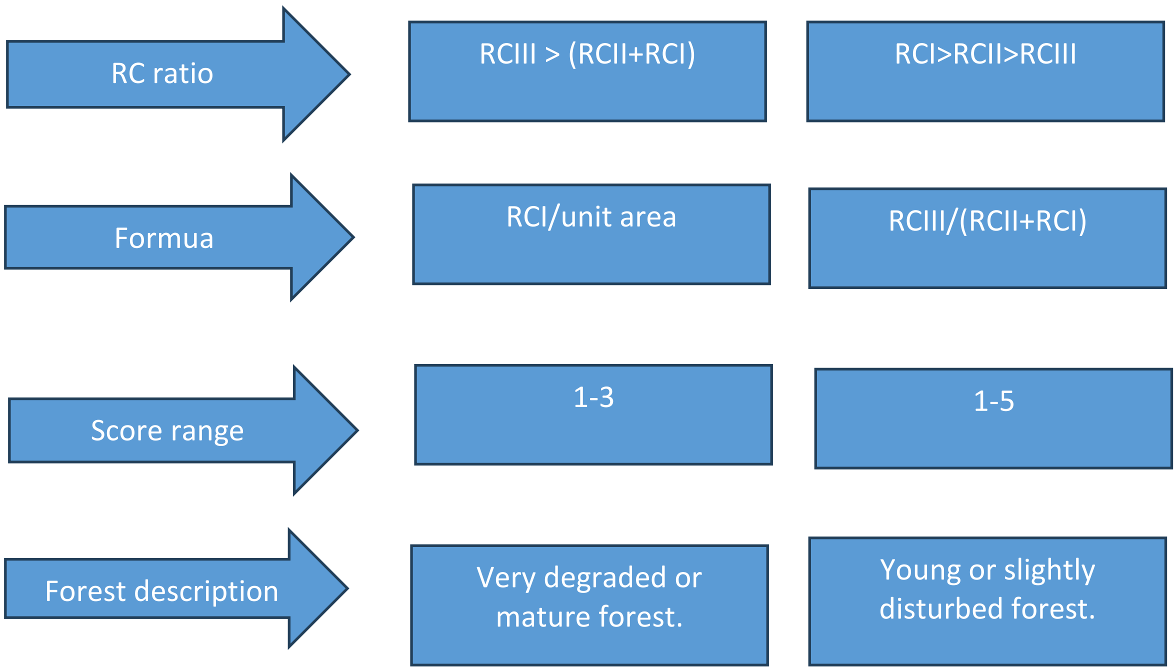


*Figure 9. Decision matrix for the Forest Regeneration Potential sub-index.*

### iii. Sub-index 3: Forest Integrity

This index classifies the forest in order to understand the level of human pressure (logging) and the natural death of trees in the mangroves. The sub-index considers severely cut (more than 50% of the tree canopy), stumps and naturally dead trees to assess the forest integrity. It indicates the level of human exploitation of a forest as well as the presence of natural threats that cause tree mortality. A mangrove forest that has a large percentage of intact individuals is under little pressure, while the dominance of stumps reflects high anthropogenic pressure. On the other hand, the predominance of naturally dead trees can indicate disease or sudden changes in environmental conditions that can be caused events such as floods, cyclones or accelerated sedimentation (Macamo et al., 2021). The formula for the Forest Integrity sub-index is presented below:

$$FII = \Sigma \%S+\%Sc+\%Nd$$

Where:

FII = Forest integrity sub-index

%S = percentage of stumps

%Pc = percentage of severely cut trees

%Nd = percentage of naturally dead trees

The FII considers 5 forest categories, which are:

**Semi-intact** (assuming that there are no intact mangrove forests in Mozambique, as all of them will have some degree of use). These forests have very low density of stumps and naturally dead trees, and are able to deliver ecological services at its best. These forests do not need further management interventions.

**Healthy forests**, with a significant level of use which allows them to still provide ecological services with little or no impact. These forests usually require little management intervention to reduce the pressure. These may include community awareness and other activities that reduce the pressure.

**OK** – these forests have a significant human and/or natural impact but are still able to provide the critical ecological services at a minimum level. Combined interventions may be required in these forests, such as raising awareness, reducing the cutting pressure and eventually some planting.

**Unhealthy** – unhealthy forests have the ability of delivering critical ecological services significantly impacted. For instance, coastal protection, nursery and biofiltering may be significantly reduced. These forests need combined intervention, which may include awareness, reducing pressures, mangrove planting and other specific measurers.

**Degraded** – these forests are no longer able to provide critical services. For instance, degraded forests do not protect the coast line and are heavily eroded. Nursery, carbon sequestration, and provision of wood and poles are no longer delivered. These forests usually need heavy intervention that includes planting and restoration (Macamo et al., 2021).

The ranges and scores of the Forest Integrity sub-index are indicated in Table 7.

*Table 7. Reference values and scores for the Forest Integrity index.*

| Forest category | Sum of % of severely cut, stumps and naturally dead trees | Weight in the final formula | Assumptions |
|---|---|---|---|
| **Semi-intact** | [0 – 5[ | 5 | Degraded forests have high density of cut trees or die back, and are unable to deliver key ecosystem services such as biodiversity, nursery and coastal protection |
| **Healthy** | [5 – 10[ | 4 | |
| **OK** | [10 – 15[ | 3 | |
| **Unhealthy** | [15 – 25[ | 2 | |
| **Degraded** | >25 | 1 | |

#### iv. Combined Mangrove Conservation Index

The Mangrove Conservation Index resulted from the combination of the 3 sub-indices, the final formula presented below:

$$MCI = ACI + RPI + FII$$

Where:

MCI – Mangrove Conservation Index

ACI = Adjusted Complexity Index

FRP = Forest Reproduction Potential

FI = Forest Integrity

MCI varied between 1 and 15. A qualitative assessment of the forest was also made, based on this scale, where:

1 – 5 indicated a poor forest condition;

5 – 10 indicated moderate forest condition;

11 – 15 indicated good condition.

## 3.12 Potential areas for planting and restoration

The identification of potential areas for restoration considered the forest ecological condition, the extension of the rehabilitation area and the reversibility of the impact. Other qualitative aspects, such as proximity to villages and accesses should also be considered prior to site selection, therefore information regarding these aspects was also collected. The areas for restoration where then ranked based on the ecological condition, the extent of the degraded area and the reversibility of the impact.

**Criteria 1: Ecological Condition of the forest**

Ecological condition of the forest was determined through the Mangrove Conservation Index (MCI) (Macamo et al., 2021). The lower the MCI, the more degraded the forests. Forests with low MCI were prioritized for restoration. MCI varies between 0 and 15. Table 8 below shows the conversion of MCI to calculate the ranking for restoration priorities.

*Table 8. Conversion of MCI to restoration scores*

| MCI score | Restoration score | Ecological significance |
|---|---|---|
| **1-5** | 15-10 | Mangrove in bad ecological condition. Priority for restoration |
| **5-10** | 10-5 | Mangrove in average condition. In need of intervention, but restoration may not be a priority |
| **10-15** | 1-5 | Good mangrove. Does not need restoration. Other interventions to prevent further degradation may be required. |

**Criteria 2: The size or extent of the degraded area (EDA)**

The size or extent of the degraded area is a very important factor to consider when restoring mangrove ecosystems (Lewis III, 2009). Due to logistics, it is advisable to prioritize the restoration of larger areas in relation to smaller areas (Teutli-Hernández et al., 2021). Restoring large areas was also prioritized because they contribute more to biodiversity conservation and provision of ecological services than small degraded areas (Lewis, 2009). Therefore, a higher score was attributed to the largest degraded areas, as Table 9 below indicates.

*Table 9. Restoration scores attributed to the extent of areas in need for restoration.*

| Extent of the degraded area (ha) | Score | Ecological significance |
|---|---|---|
| **]00 – 01]** | 0 | Insignificant degraded area. Demands high logistical effort. The ecological benefits are small. Not worth restoring |
| **]01 – 05]** | 1 | Small degraded area. Demands high logistical effort, but there are some ecological benefits. |
| **]05 – 10]** | 2 | Medium degraded areas. The logistical effort is concentrated and compensated by the extent of the area. Significant ecological and socio-economic benefits to reap from the mangrove restoration. |
| **>10** | 3 | Large degraded areas. High ecological and socio-economic benefits to reap from the mangrove restoration |

**Criteria 3: The reversibility of the impact (RoI)**

The reversibility of impacts and land tenure issues are key to decide whether an area is restorable or not. If the cause and impact of mangrove degradation is hardly avoidable or reversible, such area must not be selected for restoration. Unavoidable impacts include natural causes of mangrove degradation, such as erosion at river banks, and degradation near sand dunes or areas with high sediment dynamics. Salt pans are also very difficult to restore, but long-time abandoned ponds are restorable, especially if there are signs of mangrove colonization in (Crisman *et al.,* 2009; Kairo and Mangora, 2020). Macamo et al. (2021b) reported that in Mozambique, restoration of abandoned salt pans as initiated a few years ago in Mecufi, Cabo Delgado. Moreover, if the degraded area is owned by private entities, restoration requires permissions. Negotiation processes may be complex. Therefore, these areas are to be avoided in the course of this project. Table 10 shows how these criteria were scored to rank the restoration areas.

*Table 10. Restoration scores for the reversibility of impacts*

| Reversibility of the impact | Restoration score | Ecological significance |
| --- | --- | --- |
| **Reversible** | 1 | Cumulatively the threat is avoidable and the impact is reversible during the course of the project |
| **Irreversible** | 0 | The threat cannot be avoided or the impact is not reversible during the course of the project |

The combined formula to rank the restoration potential was as follows:

$$\text{Potential for mangrove restoration} = (MCI + EDA)*RoI$$

Where:

MCI = Restoration score for the Mangrove Conservation Index

EDA = Extension of degraded area

RoI = Reversibility of the Impact

The potential for mangrove restoration ranged between 0 and 18, where the areas with the highest scores were considered priority areas for restoration.

### 3.13 Data Analysis

Collected data were organized in Microsoft Office Excel 2019 sheets, from which the databases were generated to be used in static programs such as R-studio, Jamovi 2.3.9 and IBM SPSS Statistics 25.0.

Shapiro-Wilk Normality tests were performed to test normality of the data (tree height, DBH, tree condition, stem quality, regeneration data, soil carbon, fauna density and lichen cover). Normal data were tested with ANOVA, and non-normal with Kruskal-Wallis (95% significance).

# 4 Results and discussion

## 4.1 Mapping and change detection

It was estimated that mangroves occupied 2525.78 ha of the study area in 2022, Mossuril contributing 25.5% to this area (Table 11). When compared to 2012, 217.96 ha of forest were lost. This corresponds to about 7% of the initial area. Most losses were recorded at Mossuril, which also experienced more mangrove growth (about 13ha) (**Erro! A origem da referência não foi encontrada.** to Figure 15). Even though the area has experienced 7% loss in mangrove cover, the vast majority of the forest remained intact.

*Table 11: Mangrove dynamics in the study area between 2012 and 2022.*

| District | Mangrove cover (ha) | | Mangrove change 2012-2022 (ha) | | |
|---|---|---|---|---|---|
| | 2012 | 2022 | Loss | Gain | Net change |
| **Memba** | 1507.32 | 1468.08 | -44.0 | +4.76 | -39.24 |
| **Nacala** | 374.4 | 358.93 | -17.0 | +1.26 | -15.74 |
| **Mossoril** | 861.75 | 698.77 | -176.68 | +13.7 | -162.98 |
| **Total** | 2743.47 | 2525.78 | -237.68 | +19.72 | -217.96 |

Mangrove forests are dynamic systems and gains and losses are always expected throughout the years, however human interference can change the natural dynamic of the system and cause unforeseen losses. Studies in other parts of Mozambique show a general trend of loss in rates between 1.05 and 3.79 ha/year. For instance, Macamo et al., (2018) found loss annual rates of 1.05 and 1.15 at Pemba Bay and Olumbi, respectively, while Nicolau et al. (2017) found increase rates at the Querimbas National Park of 0.44 ha/year. Mangrove extension was also observed at the Zembezi delta, at a rate of 0.53 ha/year. Meanwhile, major losses were recorded at the Save delta between 1999 and 2014 (Macamo et al., 2016). Here an annual rate loss of 3.79 ha was estimated in a period where the Save delta was hit by 3 major cyclones. Globally, recent estimated indicate loss rates of between 0.26% and 0.66% (Hamilton and Casey, 2016).

In our study area the annual change rate was estimated at -2.17 ha, or a loss of 7.94% of the initial area, which corresponds to an annual loss rate of 0.79%. These figures are high when compared to those of Olumbi and Pemba and to the global estimates (Hamilton and Casey, 2016; Macamo et al., 2018). Field work observation do not suggest the occurrence of any major extreme event such as cyclone or floods, although it is known that recently the area was impacted by a number of extreme events including: Tropical storm Jasmin in April 2022; cyclone Gombe in March 2022; tropical storm Ana in January 2022; storm Iman in March 2021; cyclone Eloise in January 2021 and cyclone Idai in March 2019 ( https://www.dadosmundiais.com/africa/mocambique/ciclones.php). These events may have had none or little impact on the mangrove forests. Mangrove logging, salt pans expansion and natural sedimentation on the other side were observed in several parts during the field work. It is, therefore expectable that human interference played a key role in the loss of these areas.

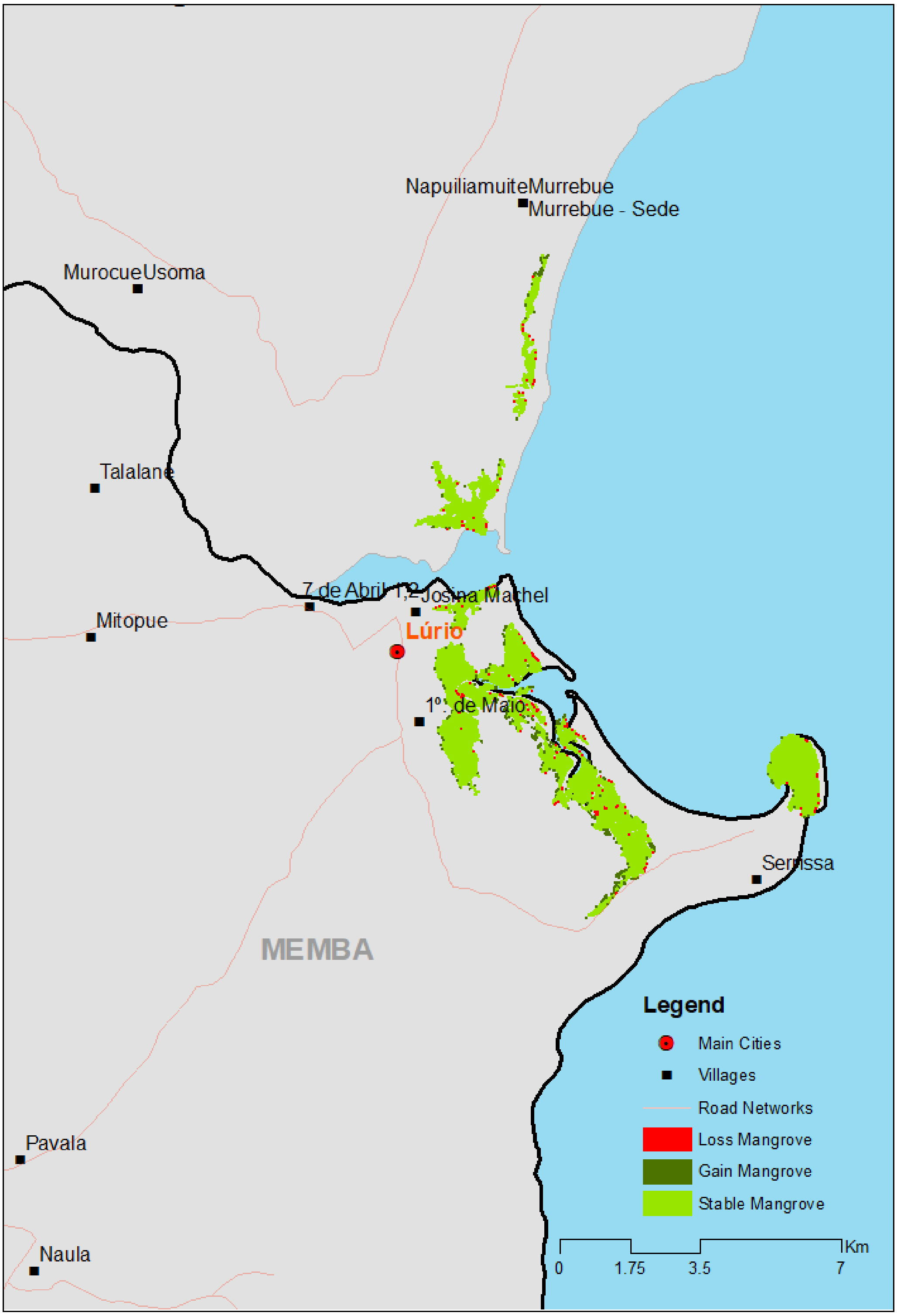


*Figure 10. Change detection in mangrove forests at Lurio and Serissa.*

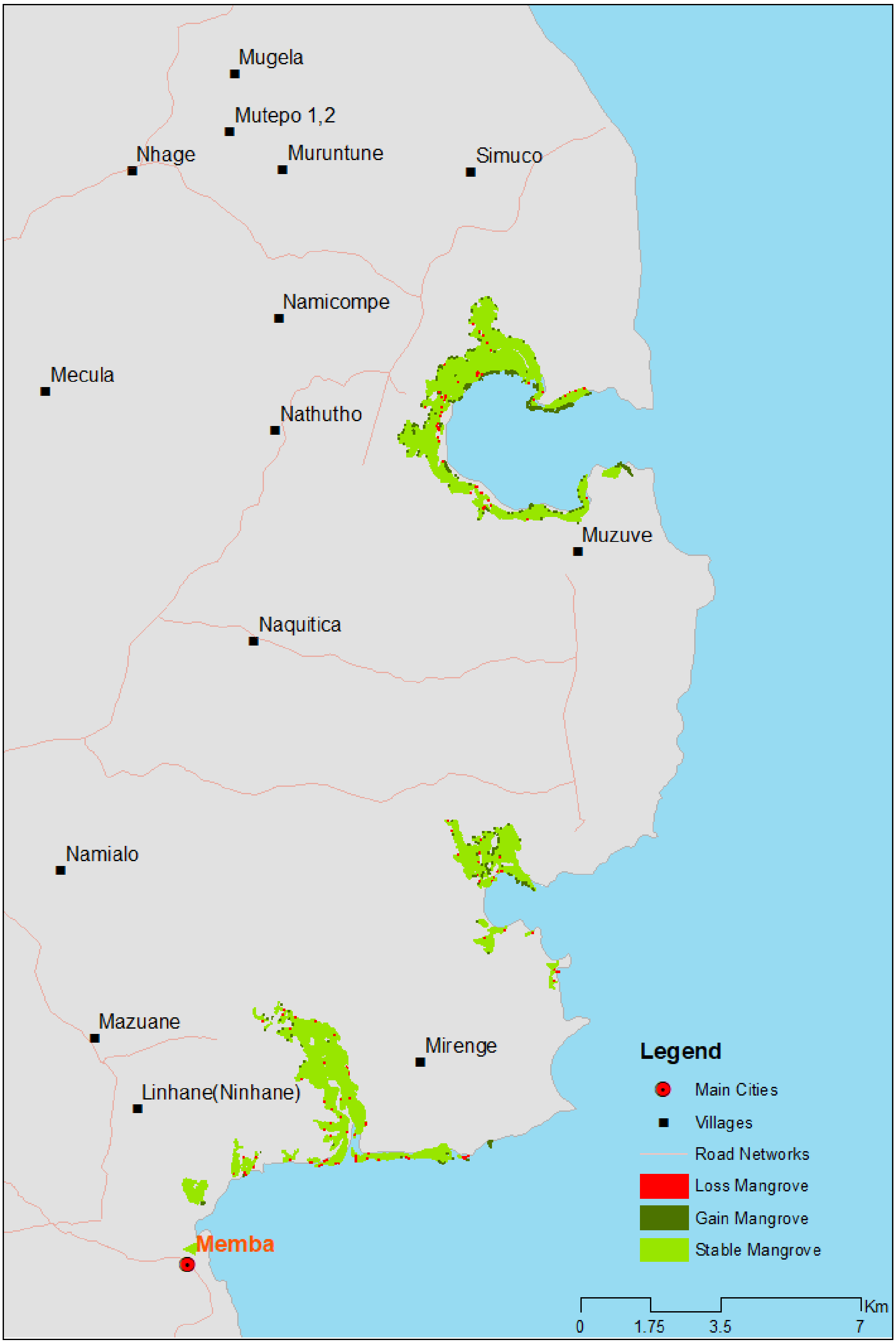


*Figure 11. Change detection of mangrove forests in the northern part of Memba*

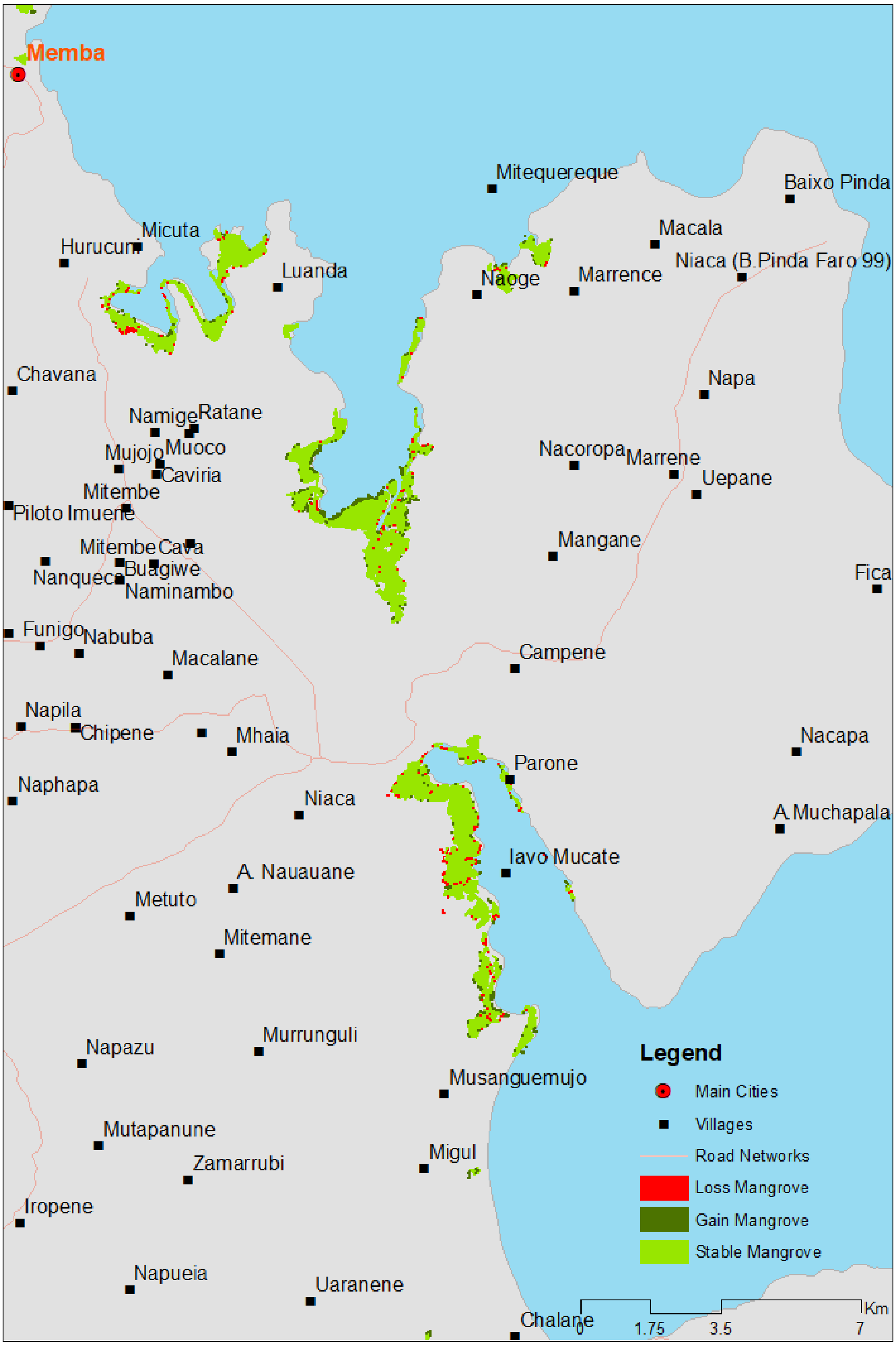


*Figure 12. Change detection of mangrove forests in the southern part of Memba.*

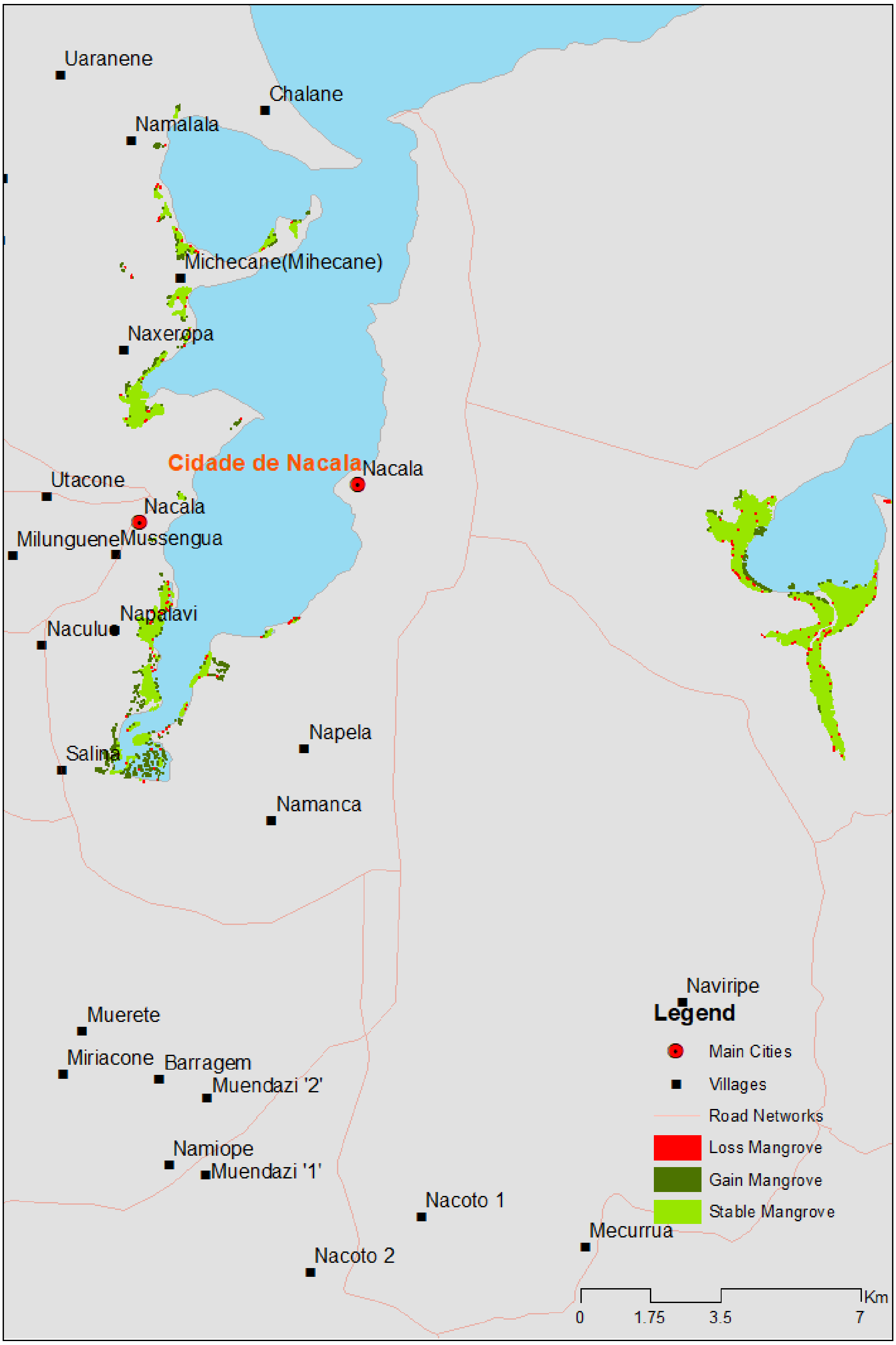


*Figure 13. Change detection of mangrove forests in Nacala Bay*


*Figure 14. Change detection of mangrove forests in Matibane, Mossoril, Lumbo and Mozambique Island.*

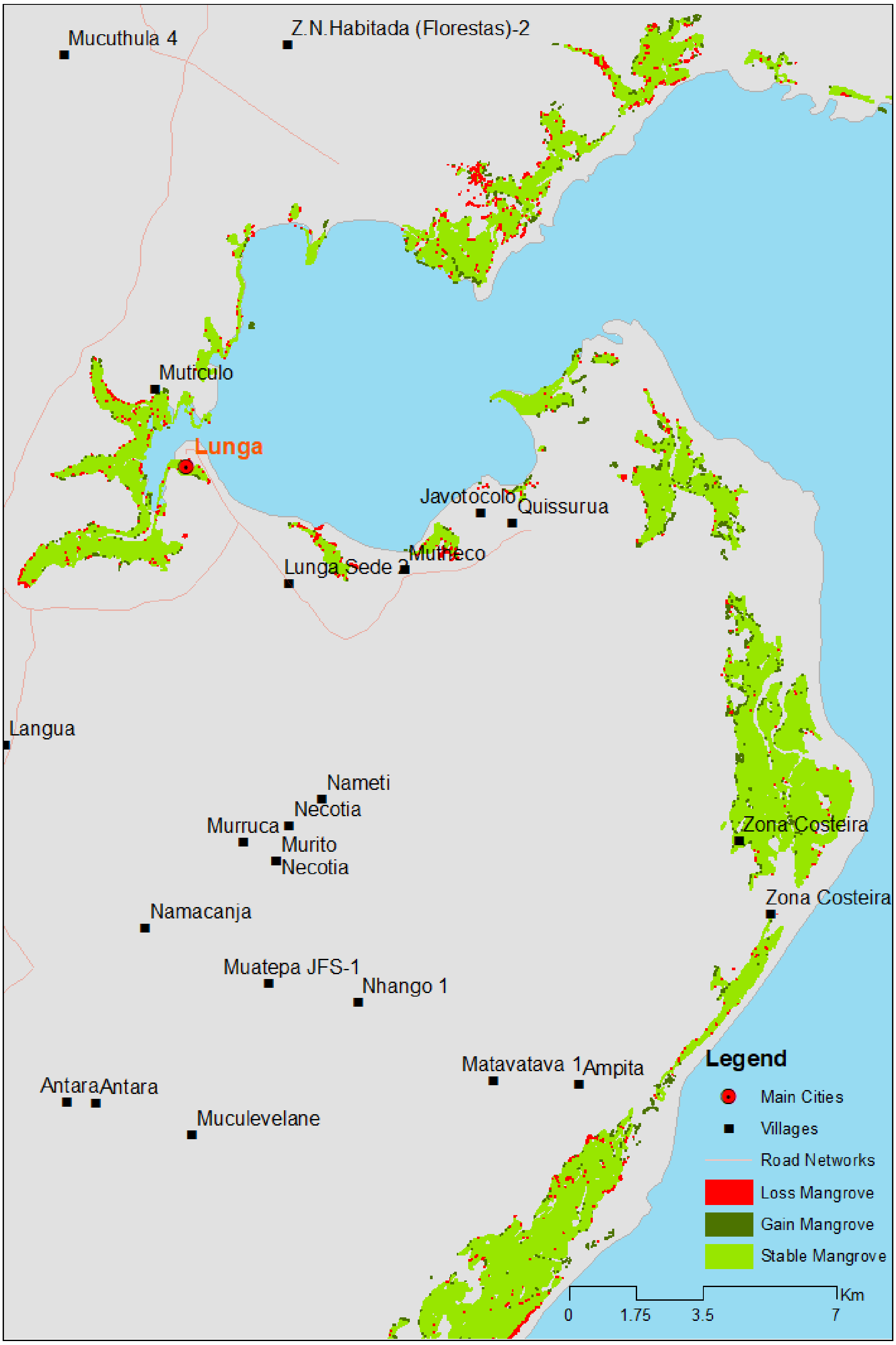


*Figure 15. Change detection of mangrove forests in Lunga.*

### 4.1.1 Mangroves general characterization

The soil of most sampled sites is composed by sand, clay and peat, or a combination of the three, forming mostly firm and somehow loos (intermediate) soils (Table 12). The forests were either basin or riverine.

*Table 12: Characterization of mangrove forests in the study area*

| District | Site | Soil Composition | Inundation Classes | Soil Type | Forest type |
|---|---|---|---|---|---|
| **Memba** | **Fungo** | Sand<br>Sand/Clay | All spring tides<br>Extreme high tides | Firm<br>Intermediate | Riverine |
| | **Geba** | Clay<br>Peat<br>Sand<br>Sand/Clay | All neap tides<br>All spring tides | Firm<br>Intermediate | Basin |
| | **Nantaca** | Sand | All spring tides<br>Extreme high tides | Firm | Basin<br>Riverine |
| **Nacala-a-Velha** | **Mussengua** | Peat/Clay<br>Sand<br>Sand/Clay | All spring tides | Firm | Riverine |
| | **Pangane** | Sand | All spring tides | Firm | Basin |
| **Mossuril** | **Cabaceira Grande** | Peat<br>Sand | All spring tides | Firm<br>Intermediate | Basin |
| | **Lunga** | Clay<br>Peat/Clay<br>Peat/Sand<br>Sand | All neap tides<br>All spring tides<br>High spring tides | Firm | Basin<br>Riverine |
| | **Mingorine** | Peat<br>Sand/Clay | All spring tides | Firm<br>Intermediate | Basin |
| | **Quissanga-Nantoa** | Sand | All spring tides | Firm | Basin |
| | **Saua-Saua** | Sand<br>Sand/Clay | All spring tides | Firm | Basin |
| | **Sanhute** | Clay | All spring tides | Firm<br>Intermediate | Basin<br>Riverine |
| **Mz Iland** | **Lumbo** | Clay<br>Peat/Clay<br>Sand<br>Sand/Clay | All neap tides<br>All spring tides | Firm<br>Intermediate<br>Soft | Basin<br>Fringe |

This description is common to other forests of Mozambique, such as those of Maputo Bay, Querimbas National Park and Pemba Bay (Bandeira et al., 2009; Nicolau et al., 2017; Macamo et al., 2018; Amade et al., 2019).

## 4.2 Mangrove Structure

### 4.2.1 Stand density

Tree density varied along all 12 sampled sites in the study. Saua Saua, Lumbo and Mussengua had the highest average tree density (Figure 16) with 4550±2487 trees.ha$^{-1}$ (mean±Standard errosr), 3680±2359 trees.ha$^{-1}$ and 2790±1148 trees.ha$^{-1}$, respectively.

Sanhute, Geba, Fungo and Nantaca had the lowest average tree densities in the mangrove forest. Density ranged from 1562±364 trees.ha$^{-1}$ to 967±248 trees.ha$^{-1}$, but these differences were not statistically significant [p>0.05 (Kruskal-Wallis: H(N=145):11.596; df=11; p=0.395)].

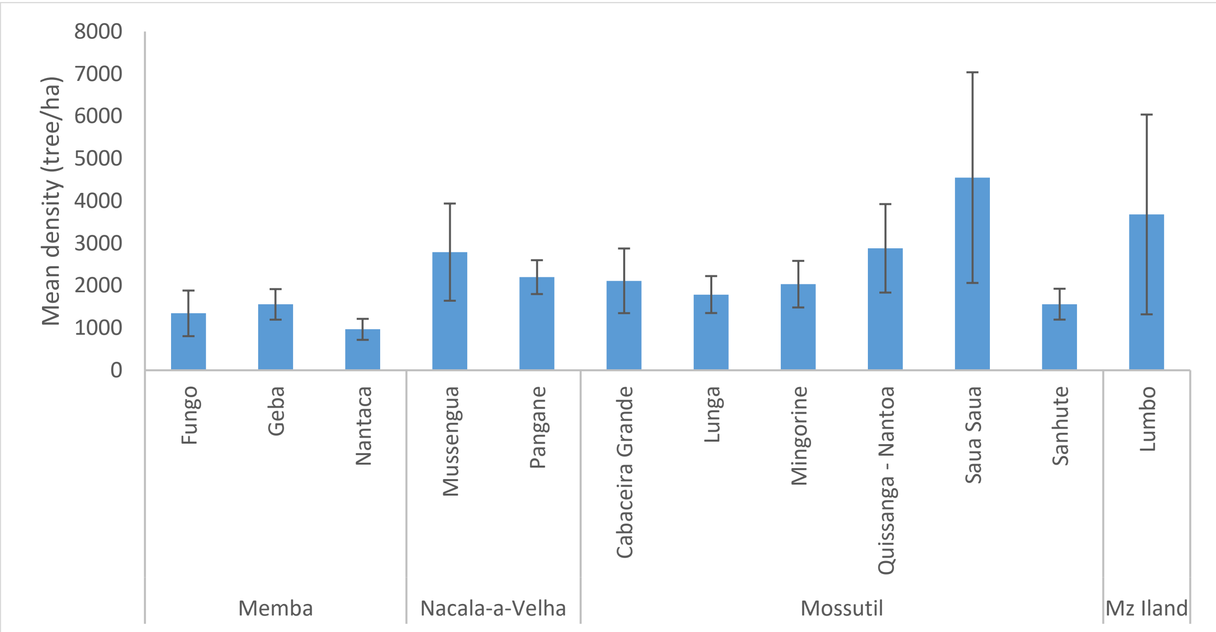


*Figure 16: Mangrove tree density along all sampled sites*

A total of 7 species were observed in the study area, however not all species occur at all sites. Six species were observed in Nantaca, Lunga and Lumbo, 5 species in Cabaceira Grande, 4 species in Fungo, Mussengua and Sanhute, 3 species in Geba, 2 species in Mingorine, Quissanga – Nantoa and Saua Saua and 1 species in Pangane (Table 13 and Table 14).

Mean densities of the species showed significant statistical differences [p>0.05 (Kruskal-Wallis: H(N=145):16.863; df=6; p=0.010)]. *Ceriops tagal* was the species with the highest density of trees in the study area, followed by *A. marina* and *R. mucronata* (Figure 17).

*R. mucronata* had the highst density of individuals, followed by *A. marina and C. tagal* in Sanhute. *A. marina* had the highest density In Fungo, Geba and Quissanga (Table 13).

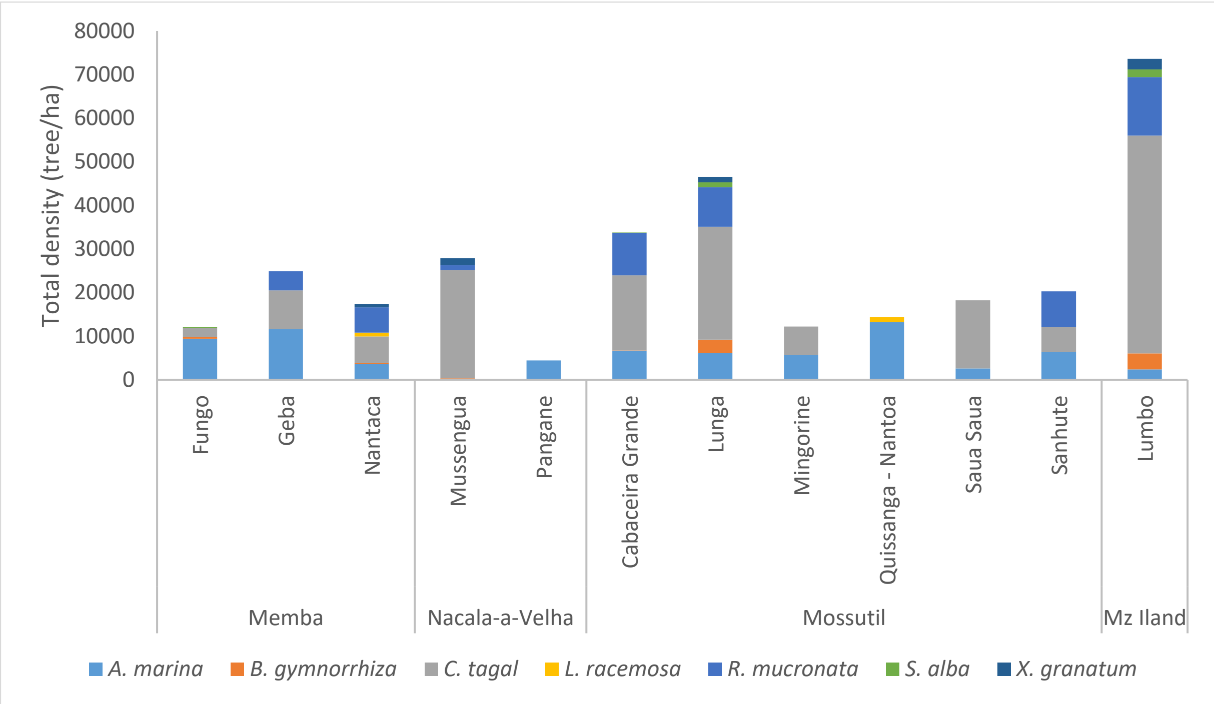


*Figure 17: Distribution of tree densities by mangrove species in all sampled sites*

### 4.2.2 Tree diameter at breast height (DBH)

Pangane and Nantaca had the highest mean tree diameters (DBH), being 10.61±1.48 cm and 12.21±0.87 cm, respectively (Figure 18), while Saua Saua and Cabaceira Grande presented the lowest mean DBH, with 3.27±0.28 cm and 3.28±0.10 cm, respectively. These differences were statistically significant (Kruskal-Wallis: H(N=3033):628.828; df=11; p=0.00).

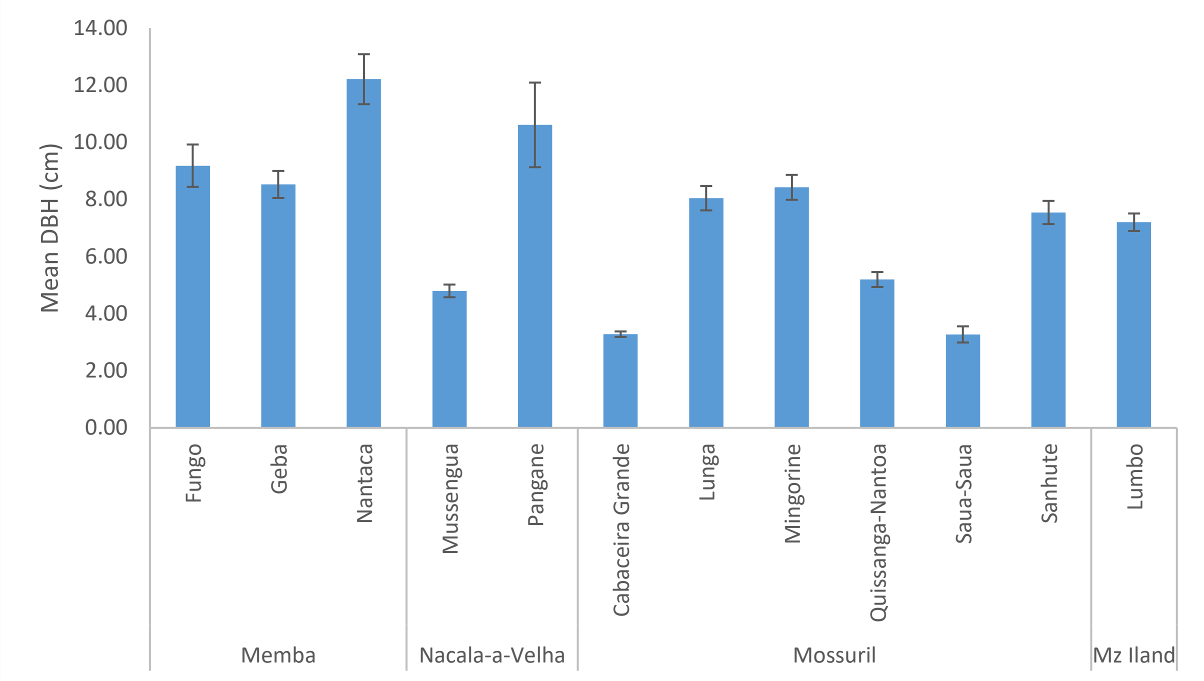


*Figure 18: Mean DBH of the trees in the mangrove forests*

#### 4.2.2.1 Size-class distribution

The majority of trees had DBH between 2.5 and 5 cm, while bigger trees were less common. There were missing size classes in sites like Nantaca, Mussengua, Pangane and Cabaceira Grande, which can be the result of human pressure.**Erro! A origem da referência não foi encontrada.** Young intact (or semi-intact) mangrove forests tend to have an inverted J curve for DBH size distribution classes, and missing size classes are usually and indicative of selective logging. Therefore, Fungo, Mingorine and Sanhute size-class structures are closer to that of young intact forests, where there is a gradual reduction in the density of trees from the lower to the higher size classes. However, the structure of Geba, Nantaca and Saua Saua (Figure 19) are markedly different due to the missing size-classes. This is usually an indicative of high harvesting pressure. The other forests have an in-between structure, compatible with a semi-intact forest.

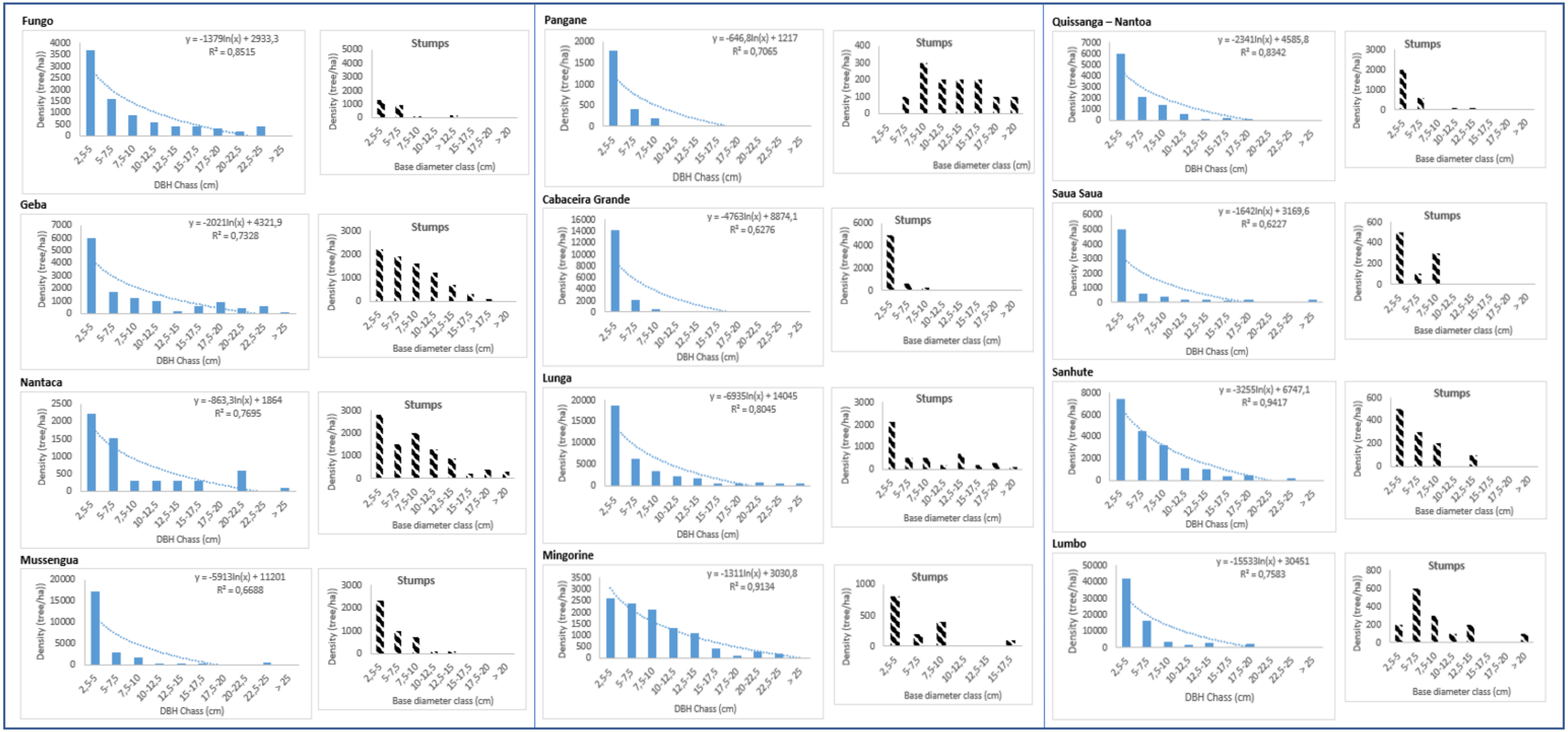


*Figure 19: Size-class distribution of mangrove trees at the different surveyed sites*

Most stumps had a diameter between 2.5-5 cm, except for Lumbo, where the majority of stumps were 5-7.5 cm wide. These results corroborate with the observation that mangrove logging is selective and but availability and accessibility play an important role on the most targeted groups. Smaller poles are more abundant; therefore, it makes sense that this is the most targeted size. However, targeting all size class may indicate a very high demand for poles. That was the case of Geba, Nantaca, Mussengua, Pangane, Lunga (although the smaller poles are much more targeted), Sanhute and Lumbo. At Cabaceira Grande, Quissanga and Saua Saua only one or two classes are targeted.

### 4.2.3 Tree height

The mean height for the whole study area was 2.44±0.03 m, ranging from 1,36±0,03 m at Cabaceira Grande to 3.99±0.38 m at Nantaca (Figure 20).

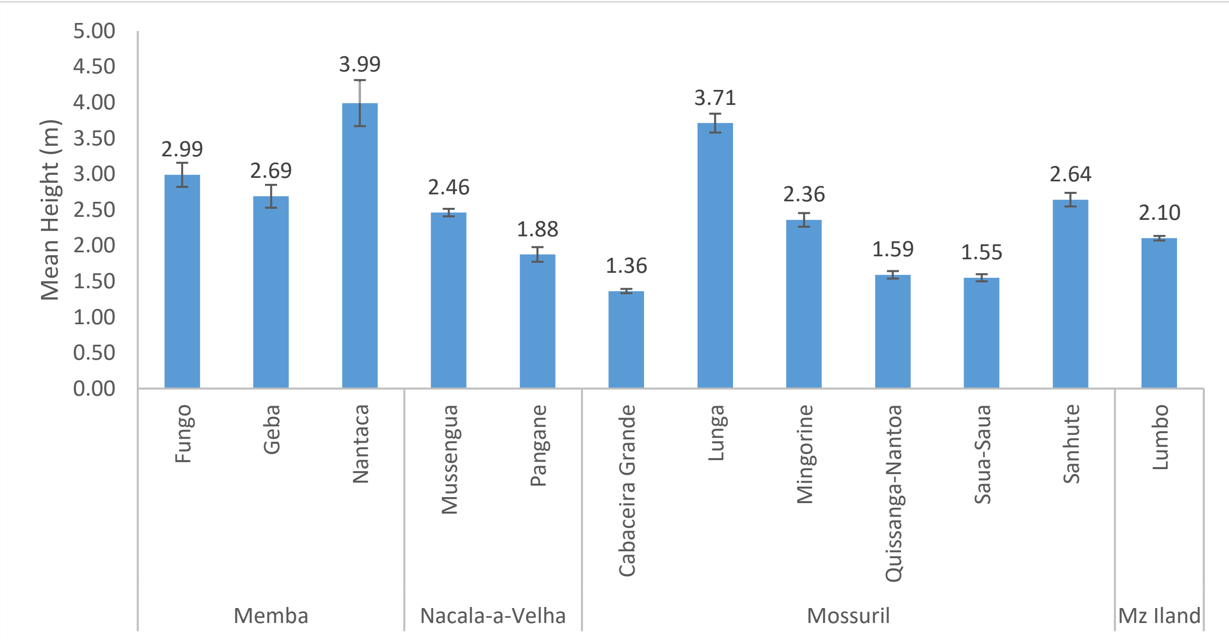


*Figure 20: Mean thee heights the mangrove forest*

Mean height was significantly different when comparing all sampled sites (Kruskal-Wallis: H(N=2516):767.594; df=11; p=0.00).

### 4.2.4 Basal area

Mean basal area was 0.82±0,05 $m^2$ $ha^{-1}$, ranging from 0.11±0.01 $m^2$ $ha^{-1}$ at Cabaceira Grande and 2.19±0.37 $m^2$ $ha^{-1}$ at Nantaca (Figure 21).

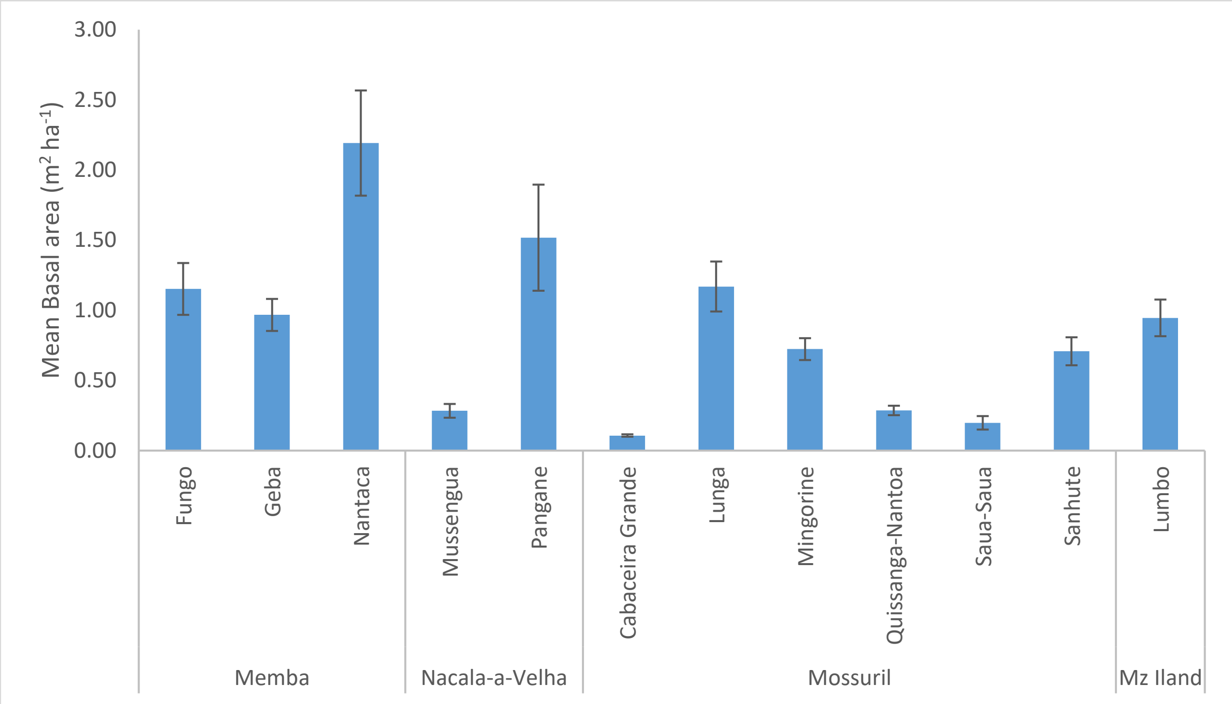


*Figure 21: Mean basal area of the trees in the mangrove forest*

These averages where significantly different when comparing all sampled sites $p<0.05$ (Kruskal-Wallis: H(N=3057):624.668; df=11; p=0.00).

Nantaca and Pangane presented the highest mean basal area 2.19±0.37 $m^2.ha^{-1}$ and 1.52±0.38 $m^2.ha^{-1}$, respectively.

**DBH-height relationship**

The DBH-Height distribution of all forests showed that many of them are shrubby or young (with small trees). At Fungo, Geba, Nantaca, Lunga, Sanhute and Lumbo large trees were also observed and sampled (despite not being the majority), which indicates that these are more mature forests.

The relationship between tree DBH and tree height (Figure 22) in Fungo, Geba, Nantaca, Mussengua, Lunga, Sanhute and Lumbo, showed a similar pattern found at the semi-intact to degraded forests of the Incomati estuary in Maputo Bay (Macamo *et al.* (2015), ie., short to medium trees, with average height up to 4 m. On the other hand, the height-diameter distribution of Pangane, Cabaceira Grande, Mingorine, Quissanga – Nantoa and Saua Saua are more similar to that of dwarf, new mangrove and mangrove degraded with reeds. Large trees are virtually absent from these stands. Mangrove trees usually grow dwarf as a response to stressful environmental conditions, such as high salinity, low temperatures and poor shallow soils. In these case, high salinity (due to the proximity to salt pans and to natural salt deserts)[2] and poor sandy soils seem to be the case.

[2] Salt deserts are natural unvegetated salty areas that occur within the mangrove forest (in higher areas) or near the terrestrial margin of the forest. These areas are only rarely inundated by salt water, thus tend to be highly saline. Succulent salt tolerant species usually grow in these areas. Salt deserts are mostly suitable for *Avicennia marina*, which grows crooked and stunted (Hoghart, 2015).

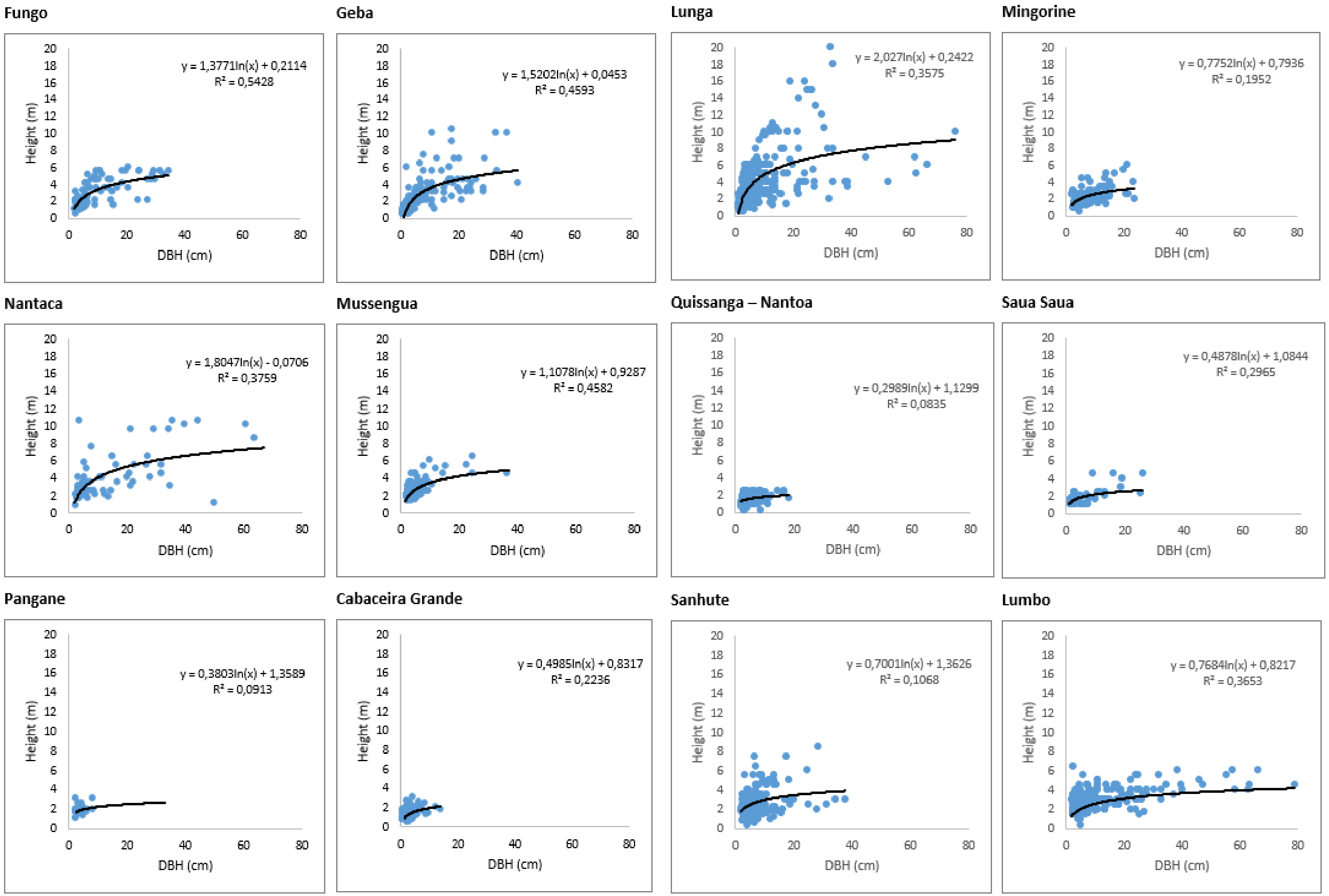


Figure 22: Height-diameter relationship of the mangrove forests

### 4.2.5 Importance Value Index (IVI)

Table 13 presents the Importance Value Index of each species identified in all sampled sites. The results show that *A. marina* is the most important species in mangrove forests in Fungo, Geba, Pangane, Quissanga – Nantoa and Sanhute. In other mangrove forests such as Mussengua, Cabaceira Grande, Lunga, Mingorine, Saua Saua and Lumbo, *C. tagal* was the most important, while, *R. mucronata* was the most important species in Nantaca.

*Table 13: Importance Value Index of all species identified in the study area*

| District | Site | Espécies | Relative Dominance | Relative Density | Relative Frequency | IVI |
|---|---|---|---|---|---|---|
| **Memba** | Fungo | *A. marina* | 84.38 | 77.69 | 44.44 | 206.51 |
| | | *B. gymnorrhiza* | 4.00 | 3.31 | 11.11 | 18.42 |
| | | *C. tagal* | 9.77 | 17.36 | 33.33 | 60.46 |
| | | *S. alba* | 1.85 | 1.65 | 11.11 | 14.61 |
| | Geba | *A. marina* | 78.13 | 46.59 | 56.25 | 180.97 |
| | | *C. tagal* | 7.09 | 35.74 | 25.00 | 67.83 |
| | | *R. mucronata* | 14.78 | 17.67 | 18.75 | 51.20 |
| | Nantaca | *A. marina* | 40.37 | 20.69 | 27.78 | 88.84 |
| | | *B. gymnorrhiza* | 0.12 | 1.15 | 5.56 | 6.83 |
| | | *C. tagal* | 5.63 | 35.06 | 22.22 | 62.91 |
| | | *L. racemosa* | 3.31 | 5.17 | 11.11 | 19.59 |
| | | *R. mucronata* | 48.42 | 33.33 | 27.78 | 109.53 |
| | | *X. granatum* | 2.15 | 4.60 | 5.56 | 12.30 |
| **Nacala-à-Velha** | Mussengua | *B. gymnorrhiza* | 0.26 | 1.08 | 10.00 | 11.34 |
| | | *C. tagal* | 77.34 | 89.25 | 40.00 | 206.59 |
| | | *R. mucronata* | 9.36 | 3.94 | 30.00 | 43.30 |
| | | *X. granatum* | 13.04 | 5.73 | 20.00 | 38.77 |
| | Pangane | *A. marina* | 100.00 | 100.00 | 100.00 | 300.00 |
| **Mossuril** | Cabaceira Grande | *A. marina* | 39.07 | 19.53 | 25.00 | 83.60 |
| | | *B. gymnorrhiza* | 0.09 | 0.30 | 6.25 | 6.63 |
| | | *C. tagal* | 30.57 | 50.89 | 31.25 | 112.71 |
| | | *R. mucronata* | 29.80 | 28.99 | 31.25 | 90.04 |
| | | *S. alba* | 0.48 | 0.30 | 6.25 | 7.02 |
| | Lunga | *A. marina* | 37.39 | 13.33 | 19.23 | 69.96 |
| | | *B. gymnorrhiza* | 10.08 | 6.45 | 15.38 | 31.91 |
| | | *C. tagal* | 18.95 | 55.70 | 26.92 | 101.58 |
| | | *R. mucronata* | 13.70 | 19.57 | 26.92 | 60.20 |
| | | *S. alba* | 11.53 | 2.37 | 7.69 | 21.59 |
| | | *X. granatum* | 8.34 | 2.58 | 3.85 | 14.76 |
| | Mingorine | *A. marina* | 36.35 | 46.72 | 66.67 | 149.74 |
| | | *C. tagal* | 63.65 | 53.28 | 33.33 | 150.26 |
| | Quissanga – Nantoa | *A. marina* | 87.22 | 91.67 | 80.00 | 258.88 |
| | | *L. racemosa* | 12.78 | 8.33 | 20.00 | 41.12 |
| | Saua Saua | *A. marina* | 78.36 | 14.29 | 50.00 | 142.65 |
| | | *C. tagal* | 21.64 | 85.71 | 50.00 | 157.35 |
| | Sanhute | *A. marina* | 53.28 | 31.03 | 36.36 | 120.67 |
| | | *B. gymnorrhiza* | 0.03 | 0.49 | 9.09 | 9.62 |
| | | *C. tagal* | 18.76 | 28.08 | 27.27 | 74.11 |
| | | *R. mucronata* | 27.93 | 40.39 | 27.27 | 95.60 |
| **Mozambique Island** | Lumbo | *A. marina* | 6.65 | 3.26 | 20.00 | 29.91 |
| | | *B. gymnorrhiza* | 1.74 | 4.89 | 10.00 | 16.63 |
| | | *C. tagal* | 23.07 | 67.93 | 25.00 | 116.00 |

| District | Site | Espécies | Relative Dominance | Relative Density | Relative Frequency | IVI |
|---|---|---|---|---|---|---|
| | | *R. mucronata* | 41.74 | 18.21 | 25.00 | 84.95 |
| | | *S. alba* | 7.03 | 2.45 | 10.00 | 19.47 |
| | | *X. granatum* | 19.78 | 3.26 | 10.00 | 33.04 |

Similar results were found in other mangrove forests across the country (Bandeira et al., 2009; Macamo et al., 2018; Amade et al., 2019). *Avicennia marina* is the most widespread mangrove species in Mozambique. The species occurs from south to north and colonizes both the terrestrial and marine margins of the mangrove forest. Additionally, *A. marina* is an *environmentally smart species*, which means it can adapt to a wide range of harsh environmental conditions, include those of high salinity, poor soils, sedimentation and human pressure (Hoghart, 2015; Macamo et al., 2016). *Rhizophora mucronata* is more sensitive and tends to grow on muddier and saline stable soils, thus its occurrence is somehow restricted in the mangrove forest (Paula et al., 2014). *Ceriops tagal* is somewhere in the of the two in terms of environmental sensitivity and distribution (Paula et al., 2014).

### 4.2.6 Complexity Index (CI)

The mangrove forests of Nantaca, Lumbo and Lunga were structurally more complex as shown by higher CI. These forests had high tree DBH, height, higher stand density and more species (Table 14). High complexity index indicates that the forest is in better condition of providing ecological services, such as coastal protection, carbo sequestration and nursery. For instance, Pangane has wide trees and relatively high density stands, but the forest has one species only, hence the low complexity index. Higher species richness creates more micro habitats and enhance important functions such as nursery and protection against predators. Nantaca, on the other side, has similar mean DBH and much lower stand density, but the complexity index is much higher due to the number of species, which was 6.

*Table 14: Structural parameters of the mangrove forests in the study site (Mean values ± Standard Error). CI = Complexity Index*

| District | Site | DBH (cm) | Basal area ($m^2$ $ha^{-1}$ ) | Height (m) | Density (ind.$ha^{-1}$) | Nr of species | C.I. |
|---|---|---|---|---|---|---|---|
| **Memba** | Fungo | 9.18±0.74 | 1.15±0.18 | 2.99±0.17 | 1344±538.55 | 4 | 1.9 |
| | Geba | 8.52±0.47 | 0.97±0.11 | 2.69±0.16 | 1556±360.67 | 3 | 1.2 |
| | Nantaca | 12.21±0.87 | 2.19±0.37 | 3.99±0.32 | 967±248.13 | 6 | 5.1 |
| **Nacala-a-Velha** | Mussengua | 4.80±0.22 | 0.28±0.05 | 2.46±0.05 | 2790±1147.60 | 4 | 0.8 |
| | Pangane | 10.61±1.48 | 1.52±0.38 | 1.88±0.10 | 2200±400.00 | 1 | 0.6 |
| **Mossuril** | Cabaceira Grande | 3.28±0.10 | 0.11±0.01 | 1.36±0.03 | 2113±763.43 | 5 | 0.2 |
| | Lunga | 8.04±0.43 | 1.17±0.18 | 3.71±0.13 | 1788±436.61 | 6 | 4.7 |
| | Mingorine | 8.42±0.44 | 0.72±0.08 | 2.36±0.10 | 2033±549.95 | 2 | 0.7 |
| | Quissanga-Nantoa | 5.19±0.26 | 0.29±0.03 | 1.59±0.05 | 2880±1044.7 | 2 | 0.3 |
| | Saua-Saua | 3.27±0.28 | 0.20±0.05 | 1.55±0.05 | 4550±2487.47 | 2 | 0.3 |
| | Sanhute | 7.54±0.41 | 0.71±0.10 | 2.64±0.10 | 1562±364.36 | 4 | 1.2 |
| **Mozambique Iland** | Lumbo | 7.20±0.31 | 0.95±0.13 | 2.10±0.03 | 3680±2358.65 | 6 | 4.4 |

The CI of these forests is relatively low when compared to that of Pemba-Metuge and Bons Sinais Estuary, but are similar to that of Costa do Sol (Amade et al., 2019). Pemba-Metuge and Bons Sinais forests grow in completely different environments, with a lot of fresh water input and nutrients that come with the water.

## 4.3 Stem quality

Crooked stems (Quality III) were dominant at all sites, and the only type of stem at Pangane and Saua Saua. Quality III poles represent 80.1% of the forest in the whole study area, corresponding to an overall mean density of 1542±376 stems.$ha^{-1}$ while straight poles accounted for 4.8% and semi-straight poles for 15% of the sampled trees, with 456±78 stems.$ha^{-1}$ and 577±103 stems.$ha^{-1}$, respectively (Figure 23). The test results indicate that the average density of all types of poles were not significantly different: (Kruskal-Wallis: H(N=27):9.154; df=5; p=0.103) for straight poles; (Kruskal-Wallis: H(N=66):12.882; df=9; p=0.168) for semi-straight poles; and (Kruskal-Wallis: H(N=132):18.525; df=11; p=0.07) for crooked poles.

Dominance of crooked poles (Quality III) is a common feature in many mangrove forests across the country (Amade et al., 2019; Macamo et al., 2018; Nicolau et al., 2017; Bandeira et al., 2009), which is usually an indicative of environmental stress or of selective logging. This was observed, for instance, in parts of Maputo Bay, where mangrove growth is limited by temperature (being a subtropical area), shallow soils and high salinity in areas where salt water inundation is rare (Magalhaes, 2018; Adams and Rajkaran., 2021). Additionally, straight poles are specifically targeted during mangrove logging, as construction is the main use of mangrove wood. This selective logging results in straight poles being rare.

In our study the dominance of crooked poles could be the result of a combination of natural environmental and human pressure through selective logging. This result was the opposite of what was reported in Zambeze Delta, where straight poles dominate as result of the combination of exceptionally good environmental conditions, forest high productivity and low human pressure (Torres *et al.,* in prep). Indeed, Nampula province is part of a rocky system, which can be a limiting factor for mangrove growth, even though they occur in several parts of the province. Additionally, these areas are very densely populated, and mangroves constitute an important source of wood resources for these communities.

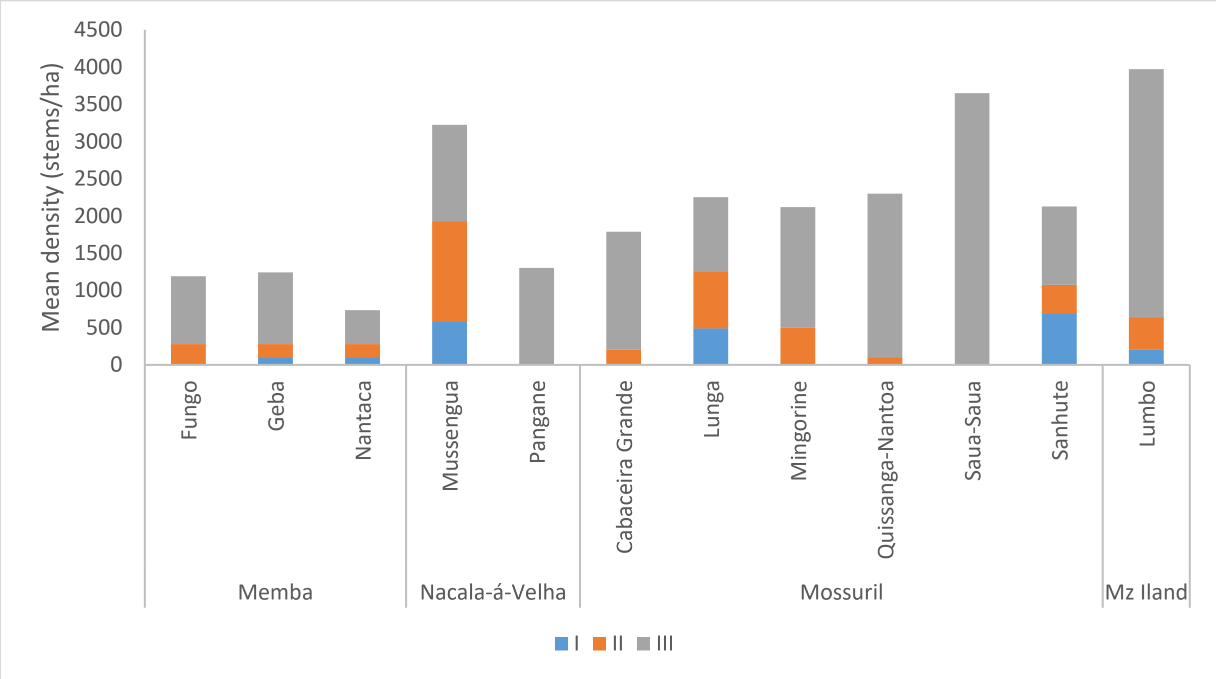


*Figure 23: Relative density of mangrove trees of the three qualities for each site of the study area*

## 4.4 Tree condition

The mangrove forests at all visited sites were dominated by intact trees (66.2% of all sampled trees), with an average density of 1620±396 tree.ha$^{-1}$. Still, human exploitation was recorded in several sites, particularly on those forests near human settlements. The densities of partially and severally cut trees were 379±39 tree.ha$^{-1}$ and 206±27 tree.ha$^{-1}$ (12.4% and 2.3%) respectively. Total density of stumps was 602±84 tree.ha$^{-1}$ (16.9%) and dieback trees 283±90 tree.ha$^{-1}$ (2.1%).

Intact trees are dominant at Mussengue, Pangane, Cabaceira Grande, Lunga, Saua Saua, Sanhute and Lumbo (Figure 24). At Fungo, Geba, Nantaca, Quissanga-Nantoa and Mingorine, the other categories compose more than 50% of the forest, which indicates that the forests were negatively impacted by mangrove logging (**Erro! A origem da referência não foi encontrada.**). Differences on average densities of naturally dead trees were not significant when the sites were compared (Kruskal-Wallis: H(N=23):4.451; df=9; p=0.814). Tree mortality seemed to be related to:

- Sedimentation, which occurred mainly on the mouth of Muntua river;
- Changes in hydrological regimes, mainly caused by the built of dykes that diverted or blocked channels. These dykes were built for salt pans and fishing ponds[3];

*Table 15. Proportion of stumps to dead trees at the study sites*

| District | Site | Proportion Stumps:live |
|---|---|---|
| **Memba** | Fungo | 1:4 |
| | Geba | 1:2 |
| | Nantaca | 1:1 |
| **Nacala-a-Velha** | Mussengua | 1:5 |
| | Pangane | 1:1 |
| **Mossuril** | Cabaceira Grande | 1:3 |
| | Lunga | 1:8 |
| | Mingorine | 1:7 |
| | Quissanga-Nantoa | 1:3 |
| | Saua-Saua | 1:4 |
| | Sanhute | 1:17 |
| **Mozambique Island** | Lumbo | 1:47 |

Fungo, Pangane and Saua Saua had high mean densities for stumps (500±352 $tree.ha^{-1}$, 900±700 $tree.ha^{-1}$ and 1200±737 $tree.ha^{-1}$ respectively), but differences in stump means were not significant between all sampled sites [p>0.05 (Kruskal-Wallis: H(N=86):13.44; df=11; p=0.265)].

[3] A common practice in Nampula province is that people build dykes or other types of barriers during the high tide that trap water and fish when the tide goes down. This way people can easily fish in the pond. In the long term, however, if such ponds have no communication with sea water for a long time, the mangroves can be negatively impacted and die.

Mangrove clear cut (i.e., with clustered stumps) was observed at Geba, Cabaceira Grande and Lunga **Erro! A origem da referência não foi encontrada.**, respectively.

Mean density of intact trees was high in Saua Saua, Lumbo and Mussengua (Figure 24). The distribution of intact trees densities did not show significant differences between all sampled sites p>0.05 (Kruskal-Wallis: H(N=125) = 13.166; df=11; p=0.283).

The distribution of severely cut trees densities and partially cut trees densities did not present significant differences between all sampled sites p>0.05: Kruskal-Wallis: H(N=34):5.139; df=9; p=0.822 and Kruskal-Wallis: H(N=100):13.910; df=11; p=0.238, respectively.

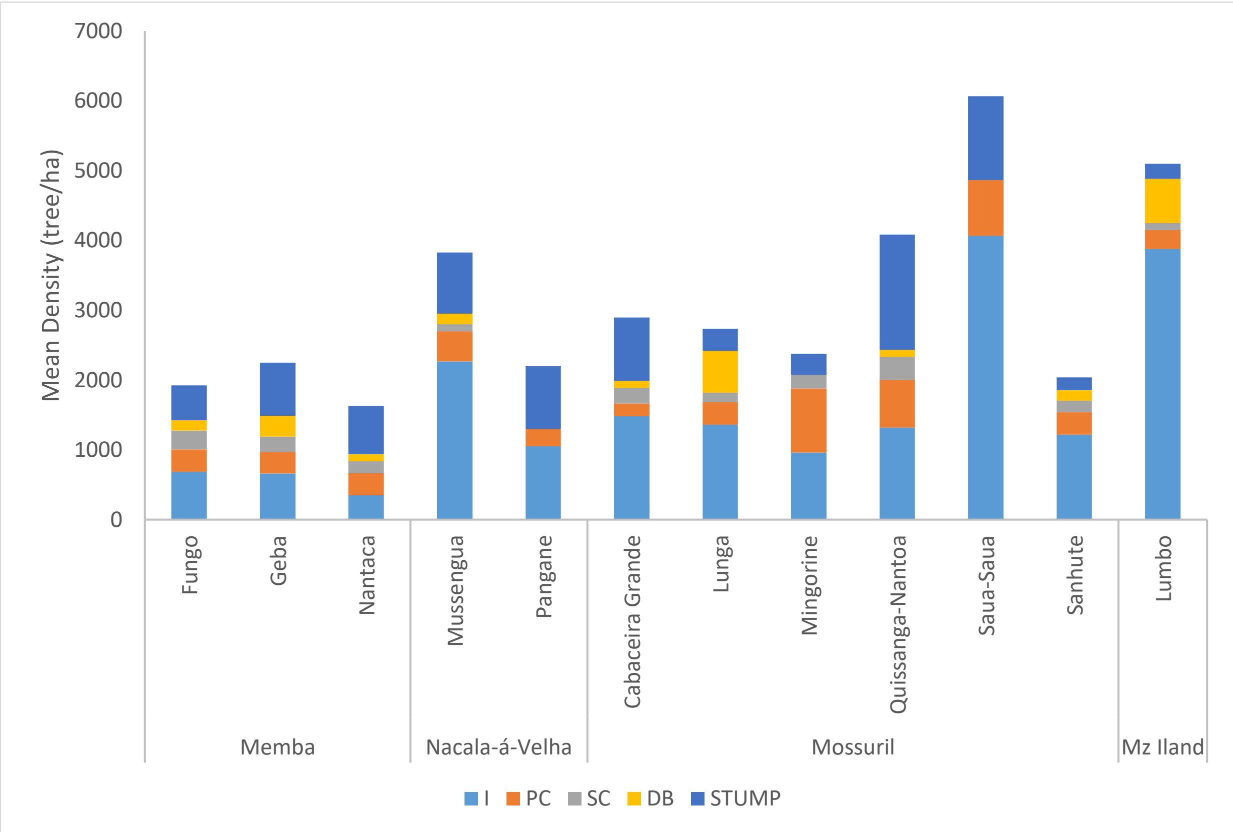


Figure *24*: *Relative density of* Mangrove trees *various* condition *at each site of* the study area

## 4.5 Regeneration Potential

Seedling density was estimated at 1 426 000 seedlings.$ha^{-1}$ and mean density of 4583±1463 seedlings.$ha^{-1}$ in the study area. The majority of seedlings belonged to Regeneration Class I (RCI), with a mean density of 10514±4243 seedlings.$ha^{-1}$, followed by RCII with 2848±898 seedlings.$ha^{-1}$ and RCIII with 386±143 seedlings.$ha^{-1}$ .

Mean density of seedlings differs between regeneration classes [$p<0.05$ (Kruskal-Wallis: H(N=309):60.905; df=2; p=0.00)], but did not differ significantly across sites [$p>0.05$ (Kruskal-Wallis: H(N=309):15.194; df=11; p=0.174)] (*Table* 16). The high seedling density at Mussengua was largely influenced by a number of sub-plots along the margin of the main channel. However, it is likely that a large majority of these seedlings will die due to competition for space as well as by shading caused by the mostly closed canopy. This is evidenced by the sharp decrease of the density of seedlings to saplings.

*Table 16.: Men density of seedlings in the study area*

<table>
<tr><th>Districts</th><th>Site</th><th>Mean</th><th>S.E</th></tr>
<tr><td rowspan="3">Memba</td><td>Fungo</td><td>1638</td><td>952</td></tr>
<tr><td>Geba</td><td>3154</td><td>1619</td></tr>
<tr><td>Nantaca</td><td>419</td><td>199</td></tr>
<tr><td rowspan="2">Nacala-a-Velha</td><td>Mussengua</td><td>41200</td><td>17160</td></tr>
<tr><td>Pangane</td><td>783</td><td>373</td></tr>
<tr><td rowspan="6">Mossutil</td><td>Cabaceira Grande</td><td>2185</td><td>998</td></tr>
<tr><td>Lunga</td><td>826</td><td>249</td></tr>
<tr><td>Mingorine</td><td>517</td><td>239</td></tr>
<tr><td>Quissanga-Nantoa</td><td>2411</td><td>1397</td></tr>
<tr><td>Saua-Saua</td><td>3892</td><td>2589</td></tr>
<tr><td>Sanhute</td><td>440</td><td>121</td></tr>
<tr><td>Mz Iland</td><td>Lumbo</td><td>1270</td><td>429</td></tr>
<tr><td colspan="2">Total (Study area)</td><td>4583</td><td>1463</td></tr>
</table>

All forests produce seedlings (RCI) (Figure 25), which indicates that there is enough stock density to ensure the continuity of the forests. However, saplings density decreases sharply in places like Saua Saua, Quissanga-Nantoa and Mussengua (Table 17). This sharp decrease is usually an indicator of harsh environmental conditions. Moreover, Fungo, Geba, Pangane, Cabaceira

Grande, Quissanga-Nantoa and Saua Saua mangrove forests did not show any young plants (RCIII). This result could be interpreted in two ways:

i. Mature forests tend to have low regeneration potential, as close canopies do not favor the growth of new plants. This is the case of parts of Lumbo, Nantaca and Lunga, where large trees with wide canopies occur;
ii. Environmental conditions such as high salinity and predation by crabs cause high mortality of seedlings and saplings. This was the case of most of the forests.

*Table 17: Regeneration potential of the mangrove in the study area*

| District | Site | Ratio RCI:RCII:RCIII |
|---|---|---|
| **Memba** | Fungo | 10:1:0 |
| | Geba | 7:1:0 |
| | Nantaca | 3:1:1 |
| **Nacala-a-Velha** | Mussengua | 61:15:1 |
| | Pangane | 1:1:0 |
| **Mossuril** | Cabaceira Grande | 2:1:0 |
| | Lunga | 7:4:1 |
| | Mingorine | 3:2:1 |
| | Quissanga-Nantoa | 7:1:0 |
| | Saua-Saua | 11:1:0 |
| | Sanhute | 9:9:1 |
| **Mozambique Island** | Lumbo | 2:1:1 |

Given the high level of exploitation of most of our sites, and the presence of salt pans, it is more likely that the regeneration potential is being negatively affected by the environmental conditions. It is estimated that the ideal ration of seedlings:saplings:young plants in a young healthy forest should be 6:3:1 (FAO, 1994). In our study, only Lunga had a regeneration proportion similar to that, which was 7:4:1.

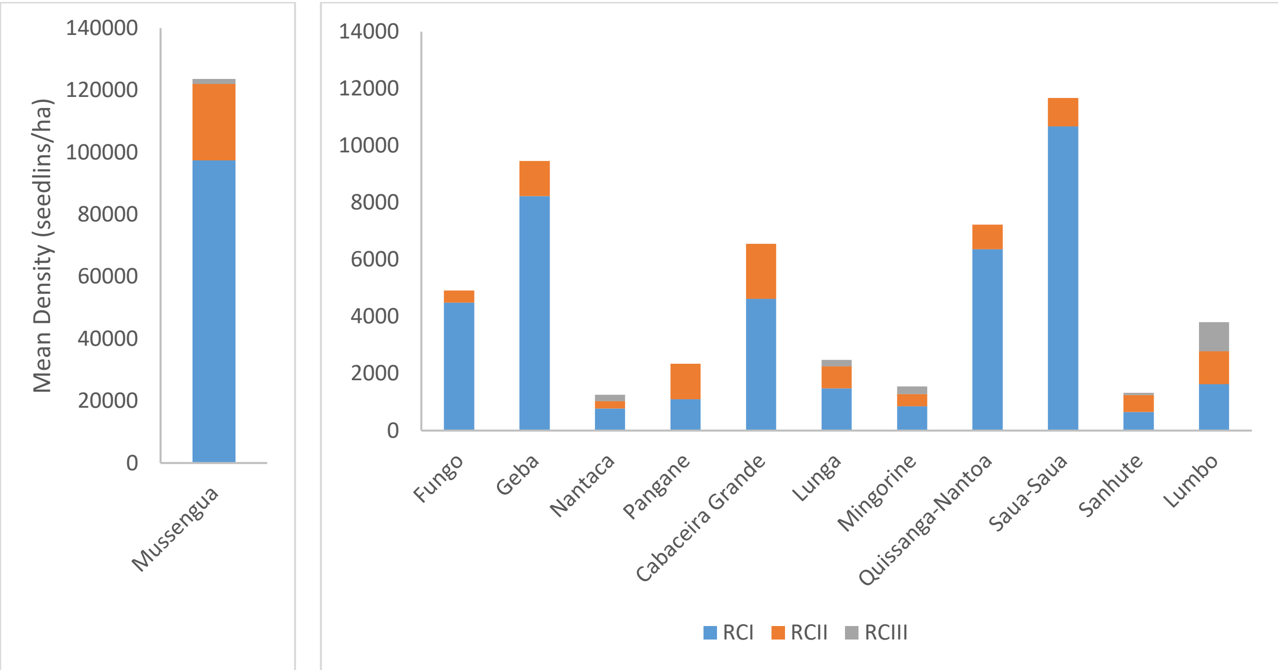


*Figure 25: Density of seedlings for each regeneration class*

## 4.6 Biomass and Carbon

### 4.6.1 Above and below ground biomass

The mean above ground biomass (AGB) ranged from 12,33±11.204 $Mg.ha^{-1}$ at Pangane, to 382.37±148.19 $Mg.ha^{-1}$ at Lumbo while the mean below ground biomass (BGB) ranged from 16.66±3.51 $Mg.ha^{-1}$ at Cabaceira Grande, to 164.78±66.19 $Mg.ha^{-1}$ at Lumbo. Lumbo, Lunga, Fungo and Mingorine had the highest total biomass, while the lowest biomass was found at Pangane, Quissanga – Nantoa,and Cabaceira Grande (Figure *26*). Average AGB and BGB were significantly different when comparing sites [$p<0.05$ (Kruskal-Wallis: H(N=68):30.687; df=11; p=0.001)] for above ground biomass; $p < 0.05$ (Kruskal-Wallis: H(N=68):27.427; df=11; p= 0.004) for below ground biomass].

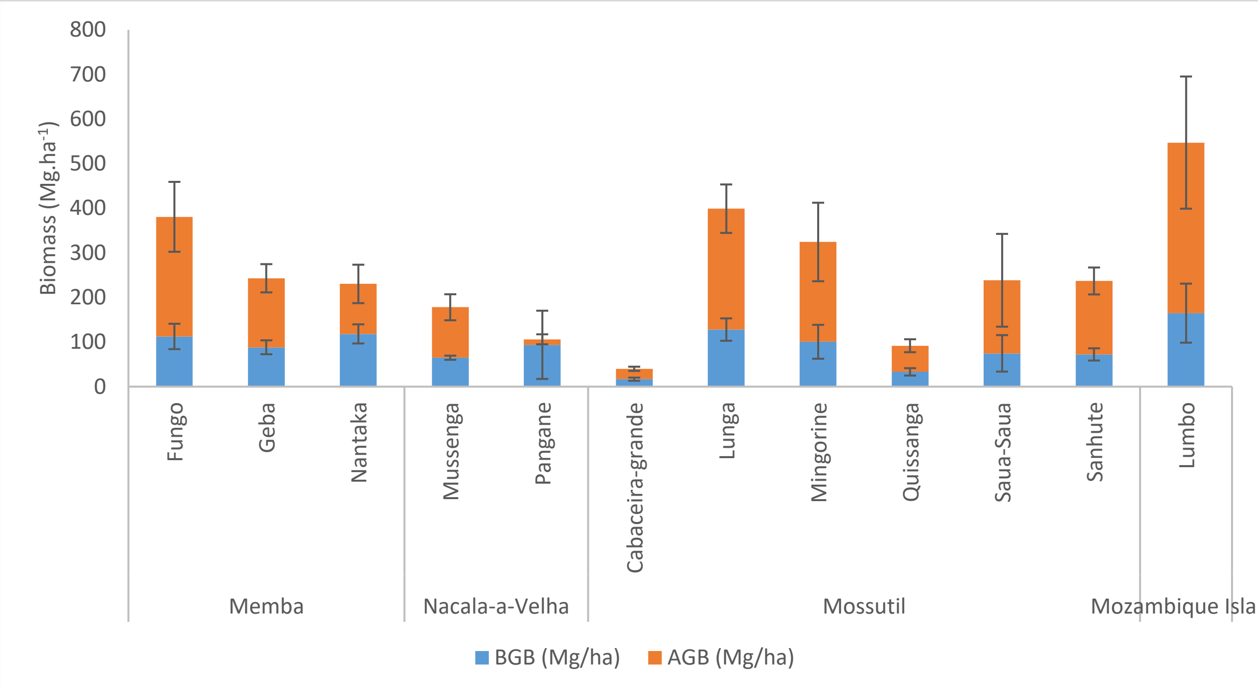


Figure 26: Above ground and Below ground Biomass

These figures are way below those of the Zambezi delta, where above ground biomass was estimated at 111 to 483 Mg ha$^{-1}$ (Stringer et al., 2015; Trettin et al., 2015). The Zambezi delta is a much more productive systems with taller and wider trees, but also more biomass pools were assessed in this study (e.g., understory, litter and debris). This study only considered the main biomass pools (Stringer et al., 2015), but it is also clear that the Nampula mangrove forests are structurally much smaller than those of the Zambezi delta (Trettin et al., 2015).

### 4.6.2 Soil carbon

The mean bulk density for the whole study area was 1.33±0.24 g.cm$^{-3}$, and ranged from 1.29±0.043 to 1.42±0.53 g.cm$^{-3}$ (15 – 30 cm and 30 – 50 cm depths, respectively). In the 0 – 15 cm and 15 – 30 cm depths, mean bulk density was 1.30±0.40 g.cm$^{-3}$ and 1.29 ±0.43 g.cm$^{-3}$, respectively (Figure 27: A). Soil bulk density did not differ significantly with depth [$p>0.05$ (Kruskal-Wallis: H(N=195):4.83; df=3; $p=0.184$) and did not differ significantly across sites [$p>0.05$ (Kruskal-Wallis: H(N=195):19.0; df=11; $p=0.062$). Pangane and Quissanga have shown slightly higher mean bulk density, with 1.45±0.78 $g.cm^{-3}$ and 1.54±0.71 $g.cm^{-3}$, and Saua Saua, the lowest bulk density 0.95±0.74 $g.cm^{-3}$.

The mean bulk density of the soil in the study area was similar to the soil bulk density in Maputo City mangrove forest, where Magalhaes (2018) reported to be 1.22 $g.cm^{-3}$. This high mean bulk densities observed in the study area is as indicator of a low soil porosity caused by soil compaction, according to Gnanamoorthy et al. (2019), results in a decreasing in the soil permeability. This result was greater than the bulk density reported in the mangroves within Zambeze River Delta where Stringer *et al.* (2015), found that the mean bulk density ranged from 0.7 to 0.9 $g.cm^{-3}$ with no statistically significant differences with depth. Studies on mangrove soils on Indo-Pacific region, Donato *et al*. (2011), found even lower soil bulk densities ranging from 0.35 to 0.55 $g.cm^{-3}$. Gnanamoorthy et al. (2019) states that natural and wealthy forests, tend to have lower bulk density and that leads to a high porosity and high gas exchanges.

Mean soil carbon concentration in the study area was 2.73±0.17%, ranging from 1.82±0.15% to 3.29±0.43%, and did not differ significantly with depth [$p>0.05$ (Kruskal-Wallis: H(N=195):4.41; df=3; p=0.220). Carbon concentration decreased with depth from the 15-30 cm to the 50-100 cm depth, while increasing from the 0-15 cm to the 15-30 cm depth (Figure 27: B).

In general, Soil carbon increases with depth in the study area (Figure 27), although there are differences on the variation of soil carbon on each site (Table 18). This variation aligns with those reported by Stringer et al. (2014) in the Zambeze River Delta Mangrove Carbon Project where she found that the Soil Carbon Density ($Mg.ha^{-1}$) increased between depths 0 – 15 to 110 – 185 within the 5 (five) canopy height classes in the study.

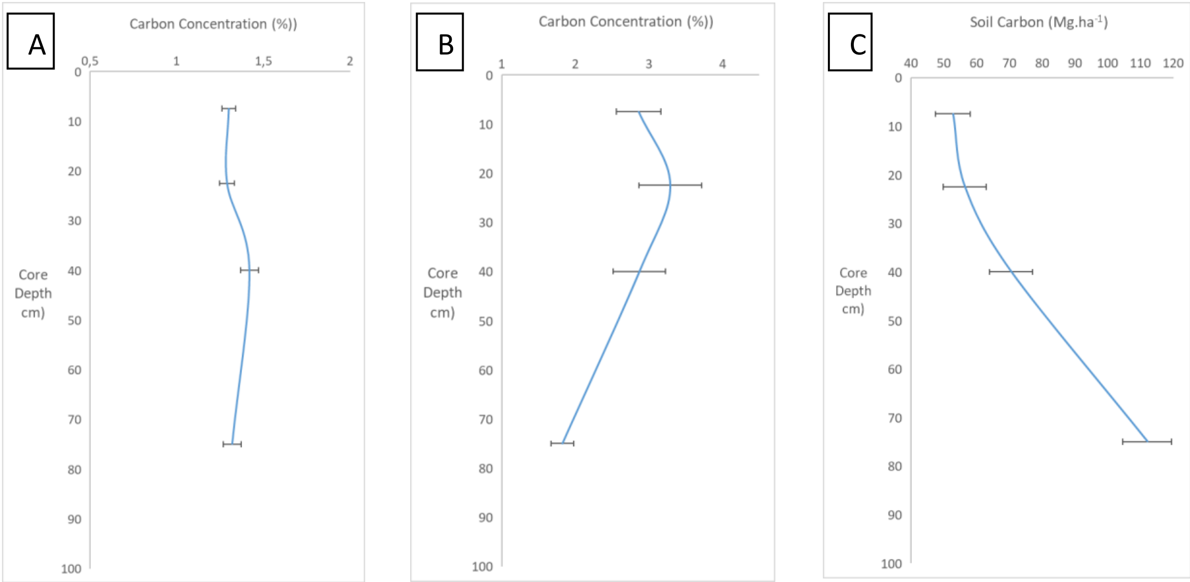

*Figure 27: Mean bulk density, Carbon concentration and Soil Carbon with depth (error bars represent standard error)*

Table 18 presents the variation on Bulk density, Carbon concentration (%) and Soil carbon within the four core depths sampled in each site.

*Table 18. Bulk density, carbon percentage and Carbon density means*

| Site | Depth | Bulk Density (g.m$^{-3}$) | | %Carbon | | Soil C (Mg.ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| Fungo | 0 – 15 | 1,26 | 0,25 | 3,95 | 2,05 | 66,80 | 23,60 |
| | 15 – 30 | 1,33 | 0,17 | 1,69 | 0,20 | 34,20 | 8,41 |
| | 30 – 50 | 1,58 | 0,10 | 1,07 | 0,75 | 32,40 | 21,40 |
| | 50 – 100 | 1,50 | 0,07 | 0,96 | 0,82 | 75,40 | 65,20 |
| Geba | 0 – 15 | 1,42 | 0,06 | 2,21 | 0,32 | 46,40 | 5,51 |
| | 15 – 30 | 1,31 | 0,09 | 4,07 | 1,24 | 74,40 | 21,60 |
| | 30 – 50 | 1,35 | 0,11 | 3,26 | 1,37 | 78,70 | 28,60 |
| | 50 – 100 | 1,18 | 0,14 | 1,06 | 0,28 | 68,80 | 24,20 |
| Nantaka | 0 – 15 | 1,30 | 0,13 | 2,80 | 1,51 | 62,80 | 39,90 |
| | 15 – 30 | 1,35 | 0,09 | 3,41 | 1,53 | 72,70 | 34,70 |
| | 30 – 50 | 1,44 | 0,15 | 1,37 | 0,34 | 40,40 | 11,90 |
| | 50 – 100 | 1,37 | 0,15 | 0,93 | 0,16 | 63,90 | 15,30 |
| Mussenga | 0 – 15 | 1,36 | 0,08 | 4,09 | 2,17 | 85,80 | 48,80 |
| | 15 – 30 | 1,07 | 0,28 | 6,93 | 5,05 | 90,00 | 52,10 |
| | 30 – 50 | 1,53 | 0,18 | 1,46 | 0,02 | 44,80 | 4,72 |
| | 50 – 100 | 1,49 | 0,11 | 1,64 | 0,31 | 120,00 | 14,70 |
| Pangane | 0 – 15 | 1,25 | 0,02 | 0,80 | 0,24 | 15,00 | 4,82 |

| Site | Depth | Bulk Density (g.m$^{-3}$) | | %Carbon | | Soil C (Mg.ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| | 15 – 30 | 1,45 | 0,31 | 1,07 | 0,51 | 20,80 | 6,03 |
| | 30 – 50 | 1,53 | 0,03 | 2,82 | 0,68 | 85,70 | 19,20 |
| | 50 – 100 | 1,59 | 0,05 | 1,00 | 0,44 | 80,10 | 37,30 |
| Cabaceira-grande | 0 – 15 | 1,25 | 0,15 | 3,37 | 0,84 | 61,40 | 15,40 |
| | 15 – 30 | 1,20 | 0,18 | 6,00 | 1,92 | 93,50 | 24,20 |
| | 30 – 50 | 1,25 | 0,18 | 4,18 | 0,94 | 98,30 | 21,10 |
| | 50 – 100 | 1,09 | 0,12 | 1,85 | 0,21 | 102,00 | 17,30 |
| Lunga | 0 – 15 | 1,16 | 0,11 | 4,81 | 0,89 | 77,80 | 11,50 |
| | 15 – 30 | 1,23 | 0,11 | 4,07 | 1,05 | 69,40 | 17,40 |
| | 30 – 50 | 1,28 | 0,17 | 5,53 | 1,16 | 118,00 | 15,90 |
| | 50 – 100 | 1,41 | 0,14 | 2,07 | 0,34 | 131,00 | 12,60 |
| Mingorine | 0 – 15 | 1,12 | 0,20 | 2,19 | 0,40 | 34,50 | 3,57 |
| | 15 – 30 | 1,46 | 0,24 | 1,24 | 0,18 | 25,90 | 1,51 |
| | 30 – 50 | 1,38 | 0,17 | 1,34 | 0,26 | 36,00 | 6,48 |
| | 50 – 100 | 0,96 | 0,08 | 3,10 | 0,71 | 144,00 | 25,70 |
| Quissanga | 0 – 15 | 1,44 | 0,08 | 1,30 | 0,35 | 27,50 | 7,12 |
| | 15 – 30 | 1,47 | 0,08 | 1,32 | 0,29 | 29,70 | 7,14 |
| | 30 – 50 | 1,69 | 0,19 | 1,22 | 0,31 | 38,00 | 6,16 |
| | 50 – 100 | 1,55 | 0,20 | 1,68 | 0,44 | 117,00 | 16,40 |
| Sanhute | 0 – 15 | 1,40 | 0,24 | 0,66 | 0,19 | 15,70 | 5,03 |
| | 15 – 30 | 1,41 | 0,24 | 0,98 | 0,35 | 17,30 | 2,92 |
| | 30 – 50 | 1,52 | 0,24 | 0,97 | 0,51 | 33,00 | 18,60 |
| | 50 – 100 | 0,97 | 0,20 | 2,51 | 0,90 | 119,00 | 44,00 |
| Lumbo | 0 – 15 | 1,35 | 0,11 | 3,40 | 0,68 | 61,90 | 9,06 |
| | 15 – 30 | 1,19 | 0,09 | 3,64 | 0,95 | 58,00 | 12,80 |
| | 30 – 50 | 1,48 | 0,15 | 3,19 | 0,64 | 79,50 | 8,30 |
| | 50 – 100 | 1,49 | 0,09 | 2,03 | 0,26 | 144,00 | 13,00 |

### 4.6.3 Total carbon

Total carbon for the whole sampled forest was 384.70±31.93 Mg.ha$^{-1}$, ranging from 244.33±102.8 Mg.ha$^{-1}$ to 598.85±99.91 Mg.ha$^{-1}$ (Table 19). This variation was relatively lower compared to the carbon stocks determined in the Zambezi River Delta where carbon stocks ranged from 374 Mg.ha$^{-1}$ to 621 Mg.ha$^{-1}$ (Stringer *et al.*, 2015) and very low than the range reported by Taberima *et al*. (2014) in Eastern Indonesia where carbon stocks in mangrove areas within 3 sites ranged from 853.2 Mg.ha$^{-1}$ to 1311.6 Mg.ha$^{-1}$.

The range found in this study was also lower than the range reported by Kauffman *et al.* (2011) and Donato *et al*. (2012) in the Indo-West-Pacific where carbon stocks range from 830 $Mg.ha^{-1}$ to 1218 $Mg.ha^{-1}$.

*Table 19: Total soil Carbon density, above ground biomass and below ground biomass means*

| District | Site | Soil Carbon ($Mg.ha^{-1}$) | | BG Carbon ($Mg.ha^{-1}$) | | AG Carbon ($Mg.ha^{-1}$) | | Total ($Mg.ha^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | S.E. | Mean | S.E. | Mean | S.E. | Mean | S.E. |
| Memba | Fungo | 208,80 | 118,61 | 43,88 | 11,09 | 134,11 | 39,17 | 386,79 | 168,88 |
| | Geba | 268,30 | 79,91 | 34,40 | 6,08 | 77,38 | 15,83 | 380,08 | 101,83 |
| | Nantaka | 239,80 | 101,80 | 46,11 | 8,36 | 56,04 | 21,54 | 341,94 | 131,70 |
| Nacala-a-Velha | Mussenga | 340,60 | 120,32 | 25,30 | 1,82 | 56,54 | 14,60 | 422,44 | 136,74 |
| | Pangane | 201,60 | 67,35 | 36,57 | 29,85 | 6,17 | 5,60 | 244,33 | 102,80 |
| Mossuril | Cabaceira-grande | 355,20 | 78,00 | 6,50 | 1,37 | 11,68 | 2,36 | 373,38 | 81,73 |
| | Lunga | 396,20 | 57,40 | 49,89 | 9,79 | 135,52 | 27,18 | 581,61 | 94,37 |
| | Mingorine | 240,40 | 37,26 | 39,21 | 14,84 | 111,90 | 44,00 | 391,51 | 96,09 |
| | Quissanga | 212,20 | 36,82 | 12,93 | 3,22 | 29,28 | 7,26 | 254,41 | 47,30 |
| | Saua-Saua | 230,40 | 0,00 | 29,11 | 15,95 | 81,90 | 52,01 | 341,41 | 67,95 |
| | Sanhute | 185,00 | 70,55 | 28,17 | 5,35 | 82,33 | 15,10 | 295,50 | 63,61 |
| Mozambique Island | Lumbo | 343,40 | 43,16 | 64,26 | 25,82 | 191,19 | 74,10 | 598,85 | 99,91 |

The differences between the ranges found in this study compared to the referred studies could be due to the fact that these forests are amongst the most productive in the world. However, the figures are within the global range of 55–1376 $MgC.ha^{-1}$ (Howard et al., 2014). In warm temperate systems, such as that of Nxaxo estuary in Sout Africa, the total carbon of the system was estimated at 234.9 ± 39.16 $MgC.ha^{-1}$, while in New Zeland carbon estimates went as low as 106.23 $MgC.ha^{-1}$ (Bulmer et al., 2016). Moreover, sampling approaches may have also influenced in some results. In this study, only 4 core depths were considered for soil sampling at intervals of 0–15 cm, 15–30 cm, 30–50 cm and 50–100 cm, while Stringer *et al*. (2015) have considered 6 slightly different core depths intervals (0 -15 cm, 15–30 cm, 30–45, 45–110, 110–185 and 185–200cm) and Zakaria *et al*. (2018), considered 5 core depths 0–20, 20–40, 40–60, 60–80 and 80–100 cm.

Despite using the same procedure and allometric equations, differences in core depths and number of samples can affect the final result, as soil is the main carbon pool in the mangrove forest (Kauffman and Donato, 2012; Stringer *et al*., 2015; Zakaria *et al*., 2018). Other differences on the methodologies used by other authors that can be the reason of this differences in biomass and soil carbon, is that they made the evaluation of carbon stocks looking on different canopy height classes (Stringer et al., 2015) or mangrove canopy cover (Dai et al., 2022), while this study considered classes of lost, gain or stable mangroves, not discriminating canopy height or canopy cover classes.

The lower AG Carbon and BG Carbon was in line with the observations on the sampling areas in most of the areas such as Pangane, Cabaceira Grande (Figure 39 and Figure 40) and Quissanga were the majority of the plots were sampled in degraded mangrove areas with 0 – 20% and 21 – 40% cover percentage. When compared to sites such Lumbo, Fungo, Lunga and Mingorine where the mangrove cover percentage was majority around (41 – 60, 61 – 80 and 81 – 100%)

Soil carbon usually represents the main carbon pool in mangrove ecosystems with contribution that range between 53.98% and 95% of the system carbon (Figure 28). Above ground biomass accounts for 2.52 % to 34.67% and below ground biomass 1.74% to 14.97% and. In degraded forests biomass contribution can reduce significantly (Kauffman *et al.* (2011) and Donato *et al*., 2012; Taberima *et al*., 2014; Stringer *et al*., 2015). In the present study, soil carbon represented 69.86% of the total carbon while BG carbon and AG carbon represented 9.03 % (6.34% and 21.12% respectively).

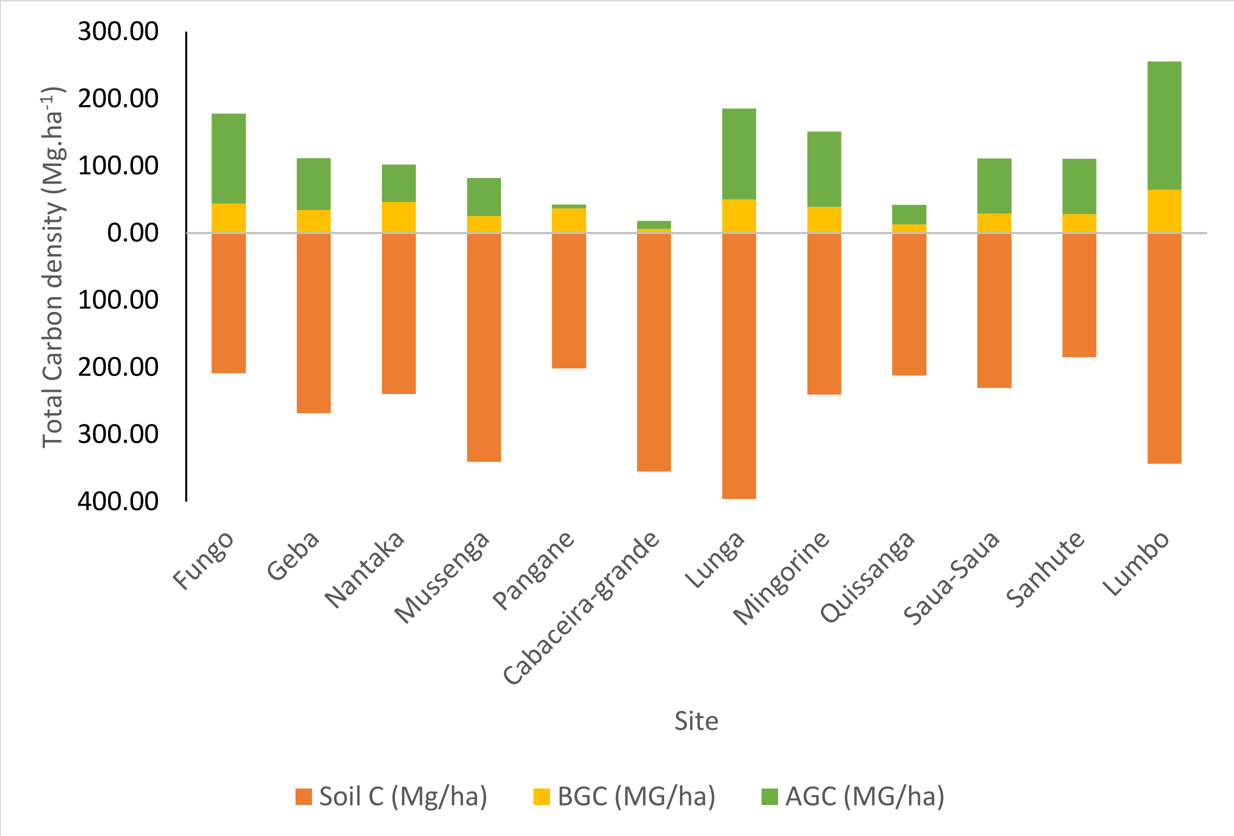


*Figure 28: Contribution of biomass and soil carbon to the mangrove forest ecosystem in the study area*

## 4.7 Fauna – diversity and density

A total of 19 species of fauna were identified in the study area, including crabs, gastropods and barnacles (Figure 29). This Number of species is lower compared to 31 species identified at Zambeze River Delta (Taimo *et al.*, in prep.) and 40 species identified between Mombasa and Sajá mangrove forests at Primeiras and Segundas Archipelago (de Abreu *et al.*, 2007). The diversity of species in mangrove forests very correlated to the age and condition of the forest. In general, in mature and well-preserved forests, the diversity and density of species is high compared to degraded forests as found in most of the sites in this study.

The distribution of species density was not similar among sampling sites. Figure 30 shows the distribution of the species recorded at each site.

*Figure 29: Population of Tubuca annulipes. Mangrove forest of Pangane*

The mean density of the fauna ranged from 496 ind.ha$^{-1}$ in Sangute, to 969 ind.ha$^{-1}$ in Quissanga (Figure 30).

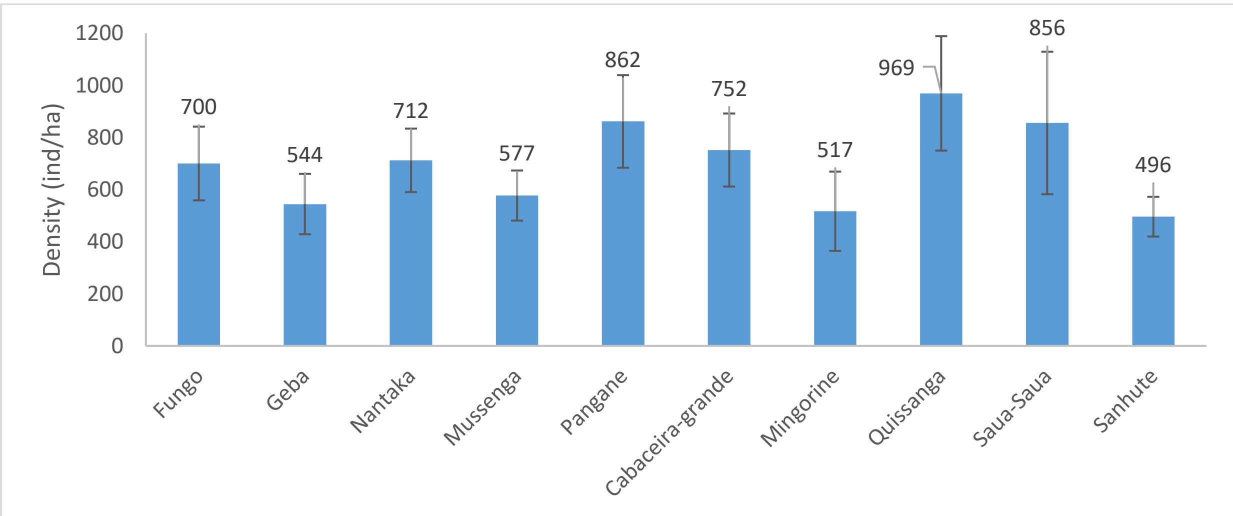


*Figure 30: Total Mean density of fauna in the study area*

The diversity of species was similar among all sites, but it was slightly higher at Sanhute, Geba and Nantaca, were it ranged from 2.07 to 2.23 (Shannon Index) (Figure 31). Simpson Index showed even stable values but indicated that Pangane, Mingorine, Quissanga – Nantoa and Saua Saua were the sites with the lower diversity (Figure 31).

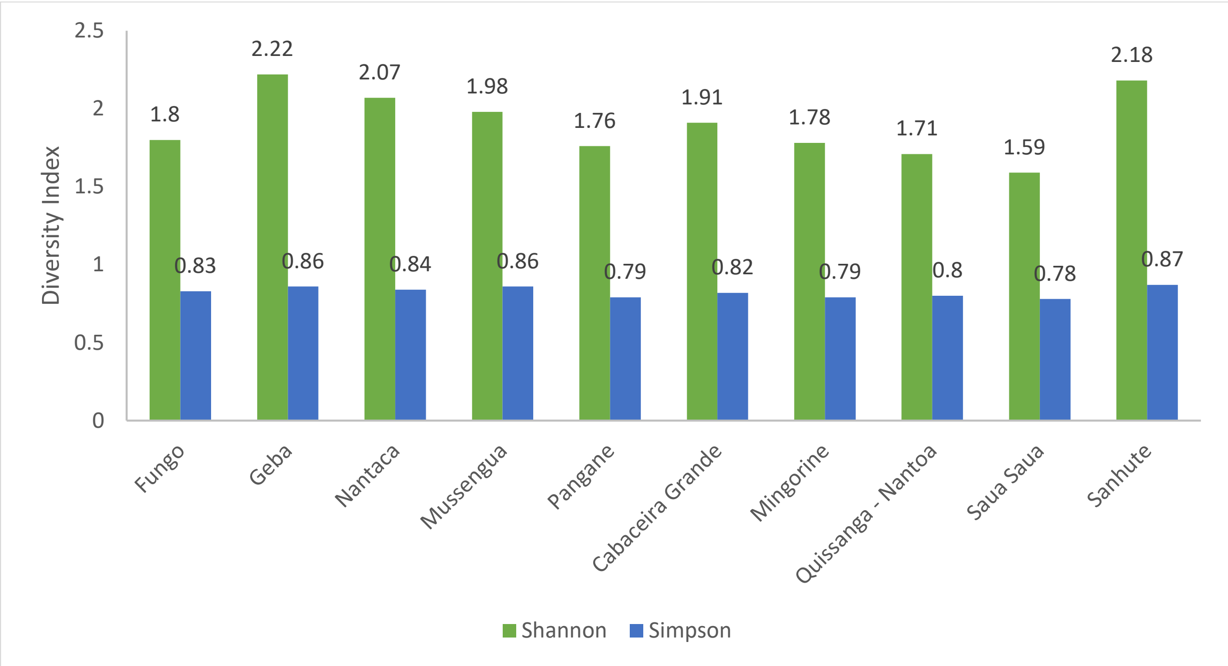


*Figure 31: Shannon and Simpson'sDiversity Index of the fauna in the study area*

The distribution of fauna density did not show significant differences between all sampled sites $p<0.05$ (Kruskal-Wallis: H(N=185):16.123; df=9; p=0.064).

Figure 32 shows the similarities found between each forest regarding the fauna. Sites with similar fauna were Mussengua, Saua Saua and Mingorine on which Jaccarrd's Index range from 0.55 to 0.86.

Sites with less similarities, on which Jaccard index was below 0.4, were, Cabaceira Grande – Geba (0.33), Cabaceira Grande – Sanhute (0.33), Pangane – Fungo (0.33), Geba – Mingorine (0.31) and Geba – Sanhute (0.38).

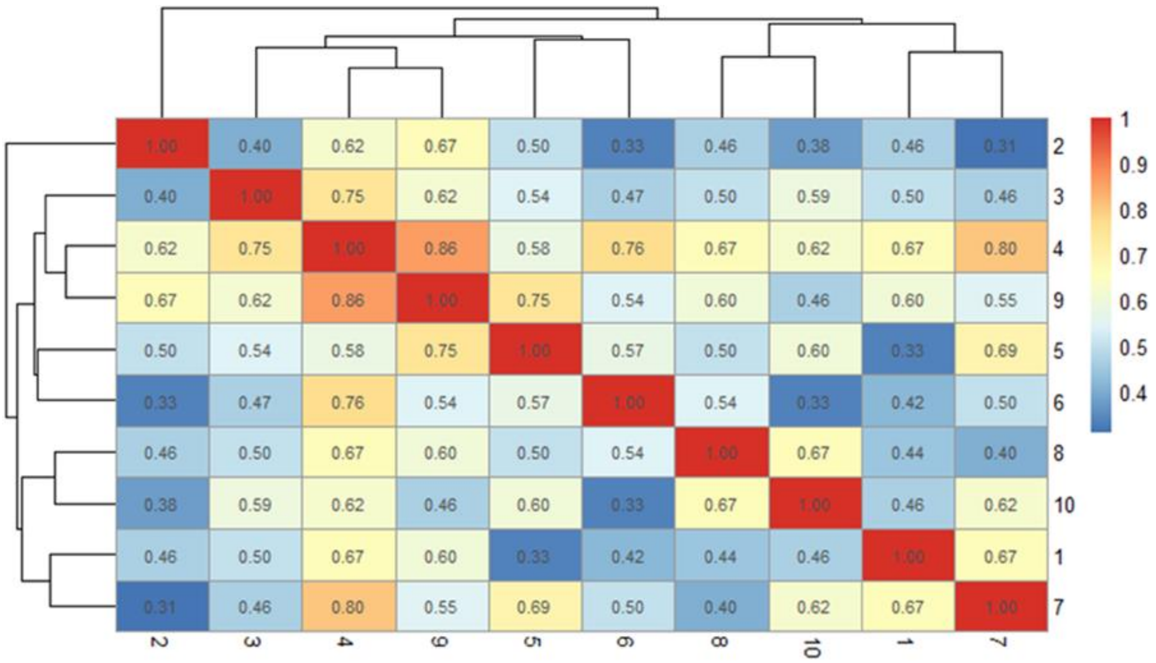


*Figure 32: Jaccard's Similarity index of the habitats in the study area: Sites are represented by numbers: 1- Fungo; 2- Geba; 3- Nantaca, 4- Mussengua; 5- Pangane; 6- Cabaceira Grande; 7- Mingorine; 8- Quissanga – Nantoa; 9- Saua Saua and 10- Sanhuute.*

The main faunal groups observed in this study are Molluscs (Gastropodes), Crustacea (crabs) and fish (Table 20). Other studies (Maputo National Park, Inhambane province and Zambezi delta) (Macamo et al., unpublished) show similar results, with crabs and gastropods being the most conspicuous groups. However, mangrove fauna studies are relatively scarce in Mozambique, and the basis for comparison are restricted. Notable exception is Maputo Bay, where mangrove fauna groups have been described in detail (Paula et al., 2014). The species found at the present study sites have already been recorded in the above-mentioned areas.

Table 20: Fauna species identified in the study area

| Class | Group | Family | Species |
|---|---|---|---|
| **Molluscs** | Barnacles | Balanidae | *Amphibalanus amphitrite (Darwin, 1854)* |
| | | Chthamalidae | *Chthamalus dentatus (Krauss, 1848)* |
| | Gastropods | Potamididae | *Cerithidea decollata (Linnaeus, 1767)* |
| | | | *Terebralia palustris (Linnaeus, 1767)* |
| **Crustacea** | Crabs | Grapsidae | *Grapsus fourmanoiri (Crosnier, 1965)* |
| | | Macrophthalmidae | *Chaenostoma boscii (Audouin, 1826)* |
| | | | *Macrophthalmus (Mareotis) depressus Rüppell, 1830* |
| | | | *Macrophthalmus (Macrophthalmus) grandidierii* (A. Milne-Edwards, 1867) |
| | | Ocypodidae | *Ocypode ceratophthalmus (Pallas, 1772)* |
| | | | *Austruca annulipes (H. Milne Edwards, 1837)* |
| | | | *Paraleptuca chlorophthalmus (H. Milne Edwards, 1837)* |
| | | | *Cranuca inversa (Hoffmann, 1874)* |
| | | | *Tubuca urvillei (H. Milne Edwards, 1852)* |
| | | | *Gelasimus vocans (Linnaeus, 1758)* |
| | | Portunidae | *Portunus pelagicus (Linnaeus, 1758)* |
| | | | *Scylla serrata (Forskål, 1775)* |
| | | Sesarmidae | *Parasesarma guttatum (A Milne-Edwards, 1869)* |
| | | | *Neosarmatium meinerti (De Man, 1887)* |
| **Teleostei** | Fish | Gobiidae | *Periophthalmus argentilineatus Valenciennes, 1837* |

### 4.7.1 Species composition

Species composition varied at each site. Geba had more species (13), of which *Cranuca inversa* was dominant (Figure 33**Erro! A origem da referência não foi encontrada.**). Fungo was the site with less species (7), where *Tubuca urvillei* was dominant.

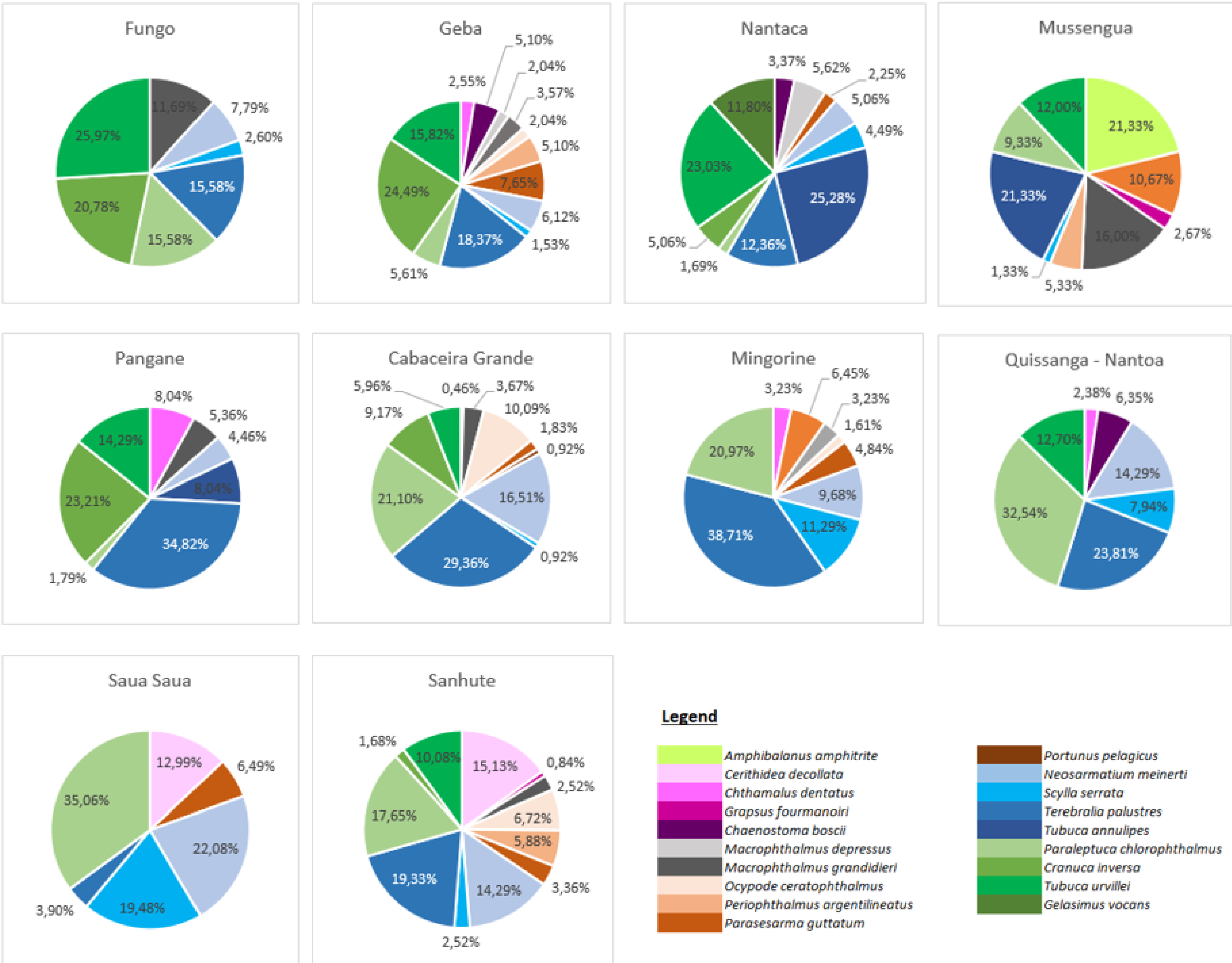


*Figure 33: Distribution of fauna species by sampling site*

*Paraleptuca chlorophthalmus, Tubuca annulipes, Tubuca urvillei and Cranuca inversa* were respectively, the dominant species at more sites. Those are a very common species in mangrove forests and occurs naturally in several micro-habitats within the forest.

## 4.8 Lichen – density and diversity

A total of 5 species of lichens from 5 families were identified in the study area. Table 21 presents the species and Families of the lichens.

This number is lower when compared to the number of species found in mangrove forests from Maputo National Park and Sofala Bay where 9 different species occur (Nicolau *et al.* in prep.; Fernando *et al*., in prep.) (Figure 34). The ecological meaning of these differences is not fully understood yet, but it could related to:

- Species composition. Data from Sofala Bay, Maputo Bay and Zambezi delta indicate that lichen are highly selective in terms of substrate species. A study in Maputo Bay shows clearly that *A. marina* and *B. gymnorhiza* are far less colonized when compared to *C. tagal* and *R. mucronata* (the last one even more colonized than *C. tagal*). The same study shows that *Rocella montagnei* prefers A. marina over other species while *Dinaria picta* prefers *R. mucronata* (Fernando et al., in prep.).
- Forest structure characteristics. Studies in terrestrial habitats indicate that lichen have preference for specific size diameters, and usually wider trees are preferred (Nascimbene et al., 2009).

Other factors such as tree condition and the overall environmental conditions of the forest may also have influence on lichen diversity. More studies to understand the relationship between lichen are being undertaken in Mozambique. The results of this study will be added to the nation database and contribute to understand whether lichen can be used to asses mangrove forests ecological condition.

Table 21: Lichen species identified in the study area

| Family | Species |
|---|---|
| **Graphidaceae** | *Graphis scripta* (L.) Ach. |
| **Opegraphaceae** | *Opegrapha sp* |
| **Lecanoraceae** | *Lecanora sp* |
| **Ramalinaceae** | *Ramalina farinacea* (L.) Ach. (Figure 34) |
| **Parmeliaceae** | *Parmotrema perlatum* (Hudson) M. Choisy |

Lichen occurrence is not similar at all sites: 1 species was identified at Cabaceira Grande, 2 species at Nantaca, 3 species at Quissanga – Nantoa, 4 species in Geba and 5 in Sanhute. The ecological significance of such differences is still to be investigated, and the results of this study will be added to a national data base and contribute to a better understanding of the relationship between lichen and mangroves.

*Figure 34: Ramalina farinacea, lichen growing on Rhiziphora mucronata in Geba.*

*Parmotrema perlatum* was the species with the higher mean relative cover, followed by *R. farinacea* with 22.53±8.32 $cm^2.ha^{-1}$ and 14.83±6.96 $cm^2.ha^{-1}$, respectively. For *G. scripta*, lichen cover ranged from 6.71±1.89 $cm^2.ha^{-1}$ to 22.53±8.32 $cm^2.ha^{-1}$ (Figure 35).

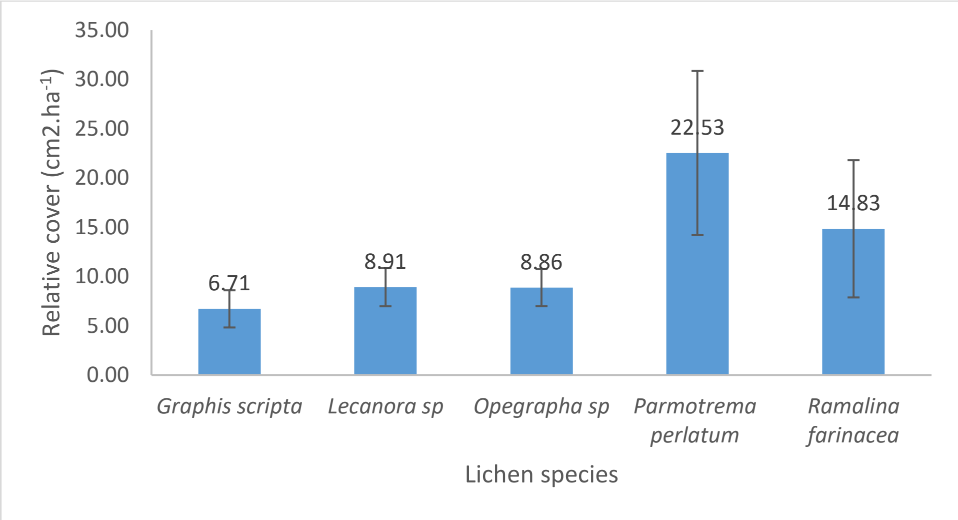


*Figure 35: Relative cover of the lichens species identifies in the study area.*

*Lumnitzera racemosa* was the preferred species for lichen colonization, with the higher relative lichen cover of 29.31±12.50 $cm^2.ha^{-1}$ , and the least preferred species was *R. mucronata,* with 3.36±0.67 $cm^2.ha^{-1}$ (Figure 36).

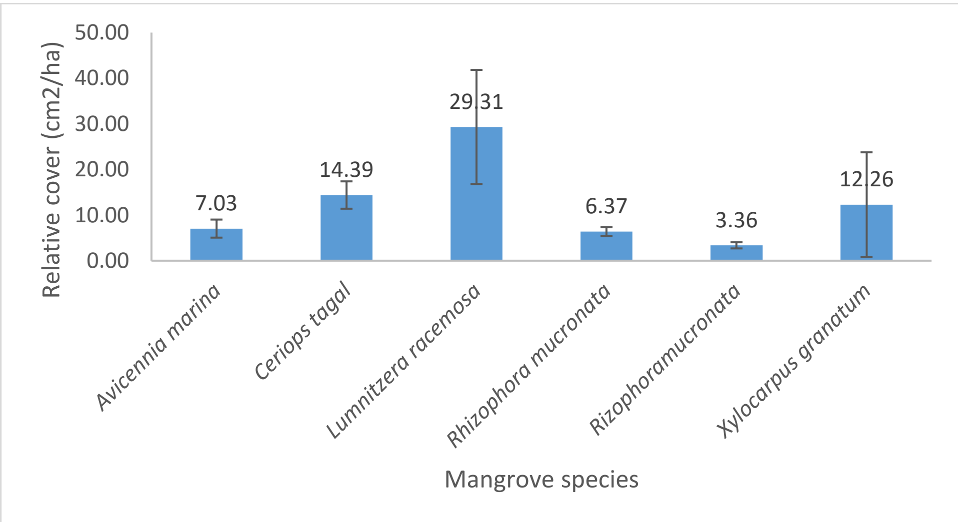


*Figure 36: Relative lichen cover on different mangrove species in the study area.*

These results found on lower number of lichens can be an indicator of the poor mangrove conservation on the sampled sites. Thormann, 2006; Vicol, 2016; Mikhaylov, 2020 have reported that lichens species tend to be more diverse and denser in healthy forests compared to degraded ones due to their sensibility to minor change in forest conditions, pollution and climate change.

## 4.9 Ecological condition of the mangrove forests in the study area

### 4.9.1 Main Impacts on mangroves

The main threats to mangrove observed at the sampled sites were mangrove logging for wood and poles (e.g.: construction, firewood) and salt pans. Erosion and sedimentation were also observed in specific sites within the study area.

#### 4.9.1.1 Mangrove logging

Mangrove logging was intense in the study area which was observed by the high percentage of not intact trees (Stumps, severely cut and partially cut trees). During sampling, large canopy gaps were observed in some areas at Geba (Figure 37), Nantaca (Figure 38), Cabaceira Grande (Figure 39 and Figure 40) and Lunga (Figure 41) far from areas with salt pans.

*Figure 37: Clear cut of mangroves in Geba*

*Figure 38: Cutting of mangroves and die back trees at Nantaca*

*Figure 39: Clear cut in a Rhizohpora mucronata area at Cabaceira Grande*

*Figure 40: Clear cut of mangrove trees in a Sonneratia alba area at Cabaceira Grande*

*Figure 41: Mangrove clear cut at Lunga*

Other forms of mangrove resources exploitation were also observed. For instance, at Cabaceira Grande human presence in the forest is frequent, as indicated by the presence of fishing traps and signs of trampling (Figure 42).

A

B

Figure 42. A and B: Fishing traps and trampling made with mangrove sticks

A socio-economic assessment should be made on the area to better understand the historical uses of the mangrove in these areas. The Solidariedade Moçambique (online) have reported that mangrove forest in Fungo was ravaged over time through indiscriminate logging for coal production, firewood, construction of boats and houses.

### 4.9.1.2 Salt pans

Salt pans were present at all sampled sites (Figure 43 to Figure 46). Salt pans are amongst the most destructive human activities in these mangrove forests, since the area has to be clear cut (old mangrove stumps were observed near and inside salt pans). Salt production is an important economic activity in Nampula coastal area and in the Nacala-Mossoril complex in particular (Macamo et al., 2016b), being one of the main drivers to mangrove degradation in the country. Salt production is detrimental to mangroves because it increases local salinity and soil temperature as a result of hard pans formation which prevent infiltration and mixing up of water. These leads to adverse environmental conditions (Liingilie et al., 2015) that affect negatively the growth, regeneration and development of mangrove trees. Indeed, the construction of salt pans and huts to store salt has been shown to reduce mangrove natural regeneration (Liingilie et al., 2015).

*Figure 43: Stumps in a salt pan showing signs of clear cut in at Geba*

*Figure 44.: Sat pan area in Sanhute*

Figure 45 and Figure 46 show the location of salt pans in the study area. It was estimated that salt pans occupy around 1 283,7 ha in the area, but it is difficult to say whether all of them were built in previous vegetated mangrove area.

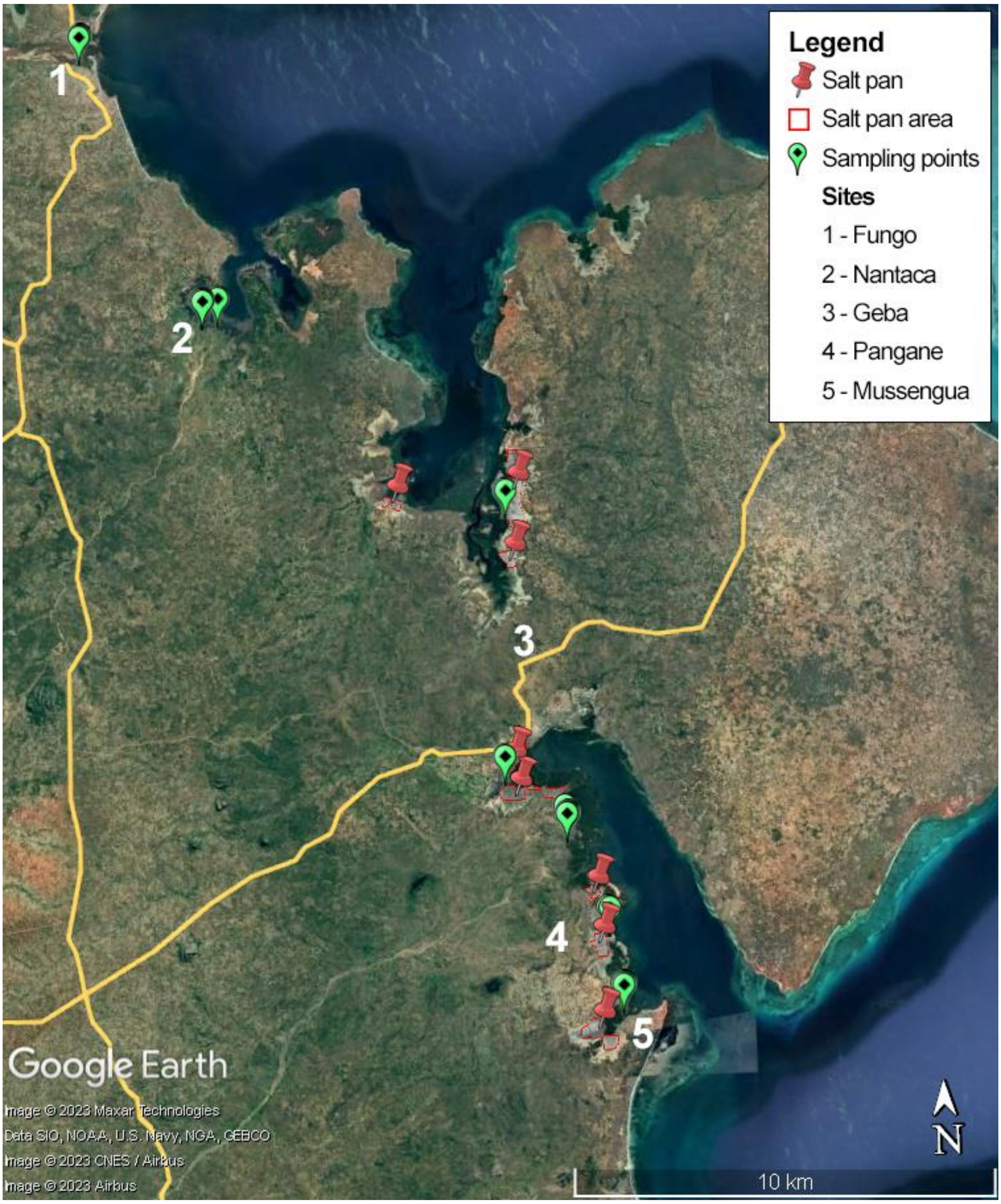


*Figure 45: Location of salt pans identified in the North part of the study area (Memba and Nacala-A-Velha districts)*

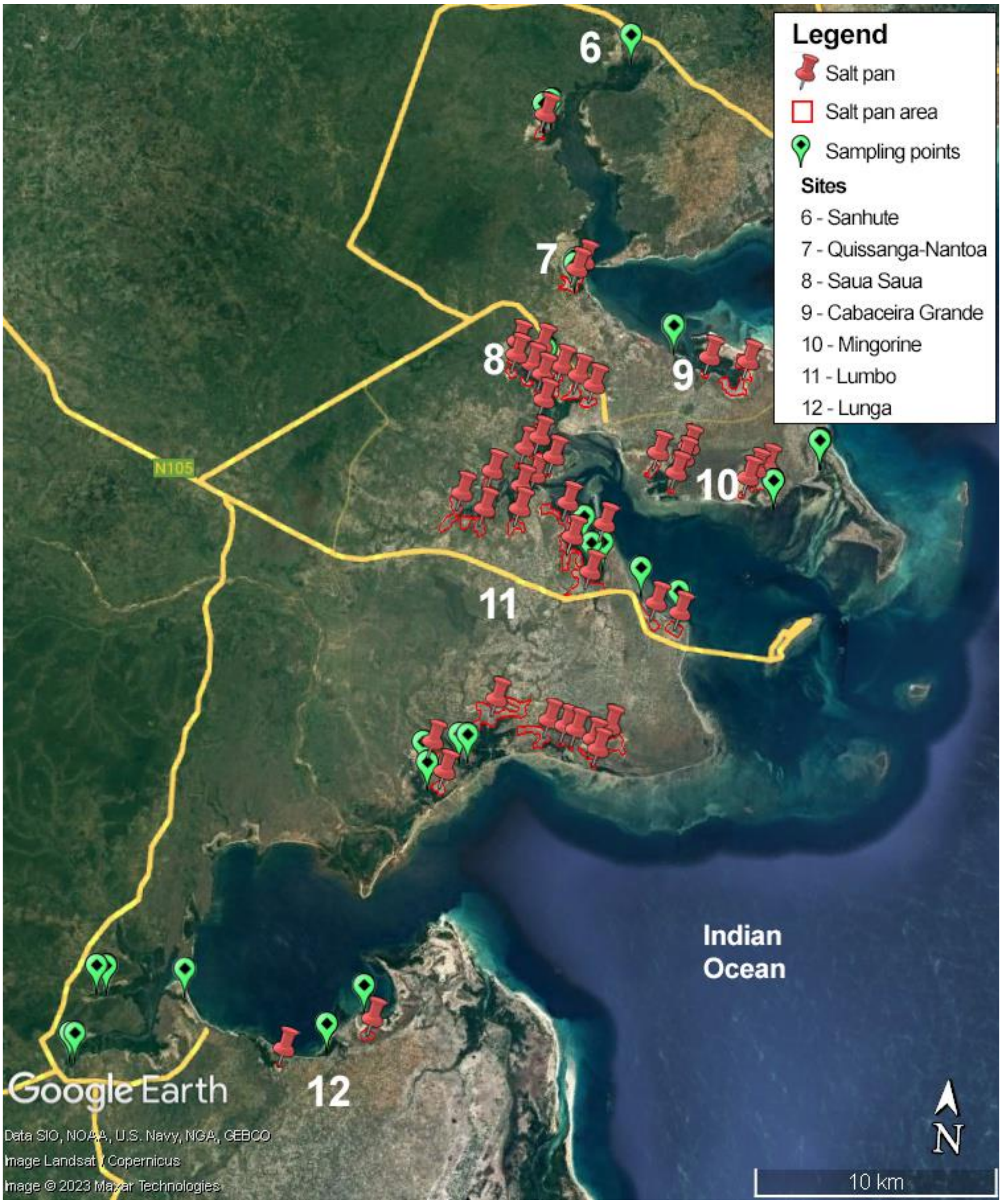


*Figure 46: Location of salt pans identified in the South part of the study area (Mossril and Ilha de Mozambique districts)*

### 4.9.1.3 Erosion and sedimentation

Erosion and sedimentation were observed in Nantaca, where mangroves are heavily influenced by the Muntua River (Figure 47). Water runoff causes severe erosion on one side, and brings large amounts of sediment that burry mangrove roots leading to mangrove trees death (Figure 48). However, it is important to note that this particular survey took place during the wet season and during the peak rain in 2023. It is thus likely that the effect of the river was exacerbated by the recent flood, meaning that during the dry season such effect is probably less significant. New sediment deposition has long-term damaging effects on mangroves, however.

*Figure 47: River runoff causes erosion and subsequent mangrove mortality at Nantaca*

Mangrove-associated species, such as *Cyperus alternifolius*, *Sporobolus virginicus* and *Sorghum sp*. are colonizing the newly stablished sediment brought by the river (Figure 48). These species are indicative of stress and habitat disturbance (e.g.: sedimentation and reduced salinity), as they are supposed to colonize the terrestrial margins of the forest.

*Figure 48: Dead Avicennia marina at Nantaca. Death was caused by sediments burry mangrove roots and stress due to changes on soil characteristics.*

The influence of the river reduces significantly inside the forest. In these areas, the most evident type of impact is tree clear cut in association with natural die back.

#### 4.9.1.4 Other impacts

Mangroves are also used as toilet (open defecation) at Fungo and possibly other places, as this is a cultural habit in the region. The impacts of open defecation include eutrophication and mangrove death due to trampling since many people get inside the forest frequently.

### 4.9.2 Mangrove Conservation Index

The mangrove ecological condition of the forest was, according to MCI, Bad at many sampled sites in the study area, which includes Fungo, Geba, Mussengua, Pangane, Cabaceira Grande, Quissanga – Nantoa and Saua Saua (Table 22). These sites had Low Adjusted Complexity Index (Table 23) and low Regeneration Potential Index (Table 24). On these mangroves, the Intactness Index (FII) show that the human impact and natural death (Die Back – DB) was high enough to Degrade the forest (Table 25). Nantaca, Mingorine and Sanhute presented moderate ecological conditions due to a high RPI combined with an Average ACI. Mangrove forest at Lumbo presented a good ecological condition when compared to all sampled sites. This site presented an Average ACI, a High FRP and had characteristics of a semi-intact forest.

*Table 22: Mangrove Conservation Index and Ecological condition of mangrove forests in the study area*

| District | Site | ACI | RPI | FII | MCI | Ecological condition |
|---|---|---|---|---|---|---|
| Memba | Fungo | 2 | 1 | 1 | 4 | Bad |
| | Geba | 2 | 1 | 1 | 4 | Bad |
| | Nantaca | 3 | 5 | 1 | 9 | Moderate |
| Nacala-a-Velha | Mussengua | 2 | 1 | 2 | 5 | Bad |
| | Pangane | 2 | 1 | 1 | 4 | Bad |
| Mossuril | Cabaceira Grande | 2 | 1 | 1 | 4 | Bad |
| | Lunga | 3 | 5 | 2 | 10 | Moderate |
| | Mingorine | 2 | 5 | 2 | 9 | Moderate |
| | Quissanga-Nantoa | 2 | 1 | 1 | 4 | Bad |
| | Saua-Saua | 2 | 1 | 2 | 5 | Bad |
| | Sanhute | 2 | 3 | 1 | 6 | Moderate |
| Mz Iland | Lumbo | 3 | 5 | 5 | 13 | Good |

Table 23: *Adjusted Complexity Index for mangrove forest in the study area*

| District | Site | Nr of species | Stand Density (ind.ha$^{-1}$) | Basal area (m$^2$.ha$^{-1}$) | Height (m) | ACI | Score | Category |
|---|---|---|---|---|---|---|---|---|
| **Memba** | **Fungo** | 4 | 1344 | 1,15 | 2,99 | 9,82 | 2 | Low |
| | **Geba** | 3 | 1556 | 0,97 | 2,69 | 9,41 | 2 | Low |
| | **Nantaca** | 6 | 967 | 2,19 | 3,99 | 10,83 | 3 | Average |
| **Nacala-a-Velha** | **Mussengua** | 4 | 2790 | 0,28 | 2,46 | 8,95 | 2 | Low |
| | **Pangane** | 1 | 2200 | 1,52 | 1,86 | 8,75 | 2 | Low |
| **Mossuril** | **Cabaceira Grande** | 5 | 2113 | 0,10 | 1,36 | 7,67 | 2 | Low |
| | **Lunga** | 6 | 1788 | 1,17 | 3,71 | 10,75 | 3 | Average |
| | **Mingorine** | 2 | 2033 | 0,72 | 2,36 | 8,84 | 2 | Low |
| | **Quissanga-Nantoa** | 2 | 2880 | 0,29 | 1,59 | 7,88 | 2 | Low |
| | **Saua-Saua** | 2 | 4550 | 0,198068 | 1,549 | 7,95 | 2 | Low |
| | **Sanhute** | 4 | 1561,54 | 0,707798 | 2,641 | 9,37 | 2 | Low |
| **Mz Iland** | **Lumbo** | 6 | 3680 | 0,94597 | 2,102 | 10,69 | 3 | Average |

Table 24: *Regeneration Potential Index for mangrove forest in the study area*

| District | Site | RCI | RCII | RCIII | RPI | Score | Caregory |
|---|---|---|---|---|---|---|---|
| **Memba** | **Fungo** | 31400 | 3000 | 0 | 0,000 | 1 | Low |
| | **Geba** | 65800 | 9900 | 0 | 0,000 | 1 | Low |
| | **Nantaca** | 5400 | 1800 | 1600 | 0,222 | 5 | High |
| **Nacala-a-Velha** | **Mussengua** | 779200 | 196800 | 12800 | 0,013 | 1 | Low |
| | **Pangane** | 2200 | 2500 | 0 | 0,000 | 1 | Low |
| **Mossuril** | **Cabaceira Grande** | 74000 | 30900 | 0 | 0,000 | 1 | Low |
| | **Lunga** | 20700 | 10900 | 3100 | 0,098 | 5 | High |
| | **Mingorine** | 3400 | 1700 | 1100 | 0,216 | 5 | High |
| | **Quissanga-Nantoa** | 19100 | 2600 | 0 | 0,000 | 1 | Low |
| | **Saua-Saua** | 42700 | 4000 | 0 | 0,000 | 1 | Low |
| | **Sanhute** | 6500 | 6000 | 700 | 0,056 | 3 | Worrying |
| **Mz Iland** | **Lumbo** | 32500 | 23200 | 20500 | 0,368 | 5 | High |

*Table 25: Forest Intactness Index for mangroves in the study area*

| District | Site | %SC | %Stumps | %DB | soma | score | Category |
|---|---|---|---|---|---|---|---|
| Memba | Fungo | 13,22% | 20,66% | 2,48% | 36,36% | 1 | Degraded |
| | Geba | 5,22% | 33,73% | 3,61% | 42,57% | 1 | Degraded |
| | Nantaca | 2,87% | 59,77% | 1,15% | 63,79% | 1 | Degraded |
| Nacala-a-Velha | Mussengua | 0,72% | 15,77% | 1,08% | 17,56% | 2 | Unhealthy |
| | Pangane | 0,00% | 40,91% | 0,00% | 40,91% | 1 | Degraded |
| Mossuril | Cabaceira Grande | 2,66% | 24,26% | 0,30% | 27,22% | 1 | Degraded |
| | Lunga | 0,86% | 10,97% | 3,87% | 15,70% | 2 | Unhealthy |
| | Mingorine | 3,28% | 12,30% | 0,00% | 15,57% | 2 | Unhealthy |
| | Quissanga-Nantoa | 6,94% | 22,92% | 0,69% | 30,56% | 1 | Degraded |
| | Saua-Saua | 0,00% | 19,78% | 0,00% | 19,78% | 2 | Unhealthy |
| | Sanhute | 2,46% | 5,42% | 4,43% | 12,32% | 2 | Unhealthy |
| Mz Iland | Lumbo | 0,27% | 2,04% | 2,58% | 4,89% | 5 | Semi-intact |

## 4.10 Mangrove planting and restoration

The potential areas for restoration identified based on observations in the field combined with mapping and change detection were located in Geba, Nantaca, Pangane, Sanhute, Quissanga-Nantoa, Mingorine, Cabaceira Grande, Lunga and Mossuril sede. Restorable areas were:

- Areas where mangrove was lost due to logging. The aim is to restore the mangroves to their previous condition before clear cut logging. Logged areas are near human settlements and the restoration in most of them may just require planting and monitoring.
- Abandoned salt pans, and/or salty plains where mangroves are taking over. In these areas, the aim is to support the mangrove expansion or natural regeneration and restore the areas were mangroves occurred previously trough passive restoration;

Areas that were not considered restorable included active salt pan areas and areas strongly affected by erosion.

- In areas at Nantaca which are under the influence of Muntua river, mangroves are severely affected by erosion and sedimentation. Seedlings may not thrive under these conditions, as they cannot cope with excessive sediment deposition nor stop erosion

(Ellison, 2000). Noahiro *et al*. (2011) suggested that inducing rapid growth of plants in the initial stages of development could benefit restoration in eroding areas. In a mangrove rehabilitation project in Samut Sakhon in Thailand, three types of soil amendment (NPK, Humic acid and coconut fiber) were applied. Monitoring studies in 4 years showed that the growth rate of *Rhizopora apiculata* in the plots subjected to this type of treatment was higher when compared to the control plots that were not amended. Soil amendment is not an option in this project however, due to financial and technical constraints, but we do recommend further studies in to better understand the Muntua system and explore the options to address erosion in this area.

- The restoration of salt pan areas may involve issues of land use right, as DUATs (Rights of Use of Land) may have been attributed to the salt pan owners. Additionally, salt pans are challenging to restore due to the ecological changes that they bring. In East Africa, mangrove rehabilitation attempts on abandoned salt pans areas in Tanga, Tanzania failed because the abrupt changes that these structures caused to the environmental factors (Kiprono, 2021). To increase the probability of success in the restoration, a combination of methods needs to be considered. Mangrove plantation in combination with a hydrological restoration will be crucial in sites where the tidal exchange was compromised. The hydrological restoration allows the pioneer mangrove species such as *Avicennia marina* to rapidly colonize the site by creating and maintaining channels to allow water to enter in the ecosystem (Ellison *et al.,* 2020).

The methods proposed for mangrove restoration include:

- Active restoration – direct planting of mangrove trees on degraded areas and it will be necessary the creation of nurseries in order to increase the survival potential of the planted seedlings and active monitoring of the planted area (Kairo and Mangora, 2020) this method of restoration was proposed to areas degrades affected by logging.
- Passive restoration – hydrological restoration, will be used to recover natural tidal regime of the affected area through digging of canals that mimic natural water flow Kairo

and Mangora, 2020; Teutli-Hernández *et al.,* 2021). Passive restoration also involved removing the threat and simply allowing the forest to recover alone.

- In large areas will be necessary to combine both methods to increase the rates on success in the restoration.

### 4.10.1 Potential restoration areas

#### 4.10.1.1 Geba

At Geba, a total of 66,1 ha of potential area for restoration was identified, however only 16,2 ha was considered restorable (Table 26). Active restoration (Planting) can be used to restore this area.

*Table 26: Potential areas for restoration at Geba*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Extent of Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| **Geba-A** | -14.333715° | 40.615293° | 16 | Salt pan | 4 | 3 | 0 | 0 |
| **Geba-B** | -14.336943° | 40.614998° | 11 | Logging | 4 | 3 | 1 | 7 |
| **Geba-C** | -14.339986° | 40.616250° | 33,6 | Salt pan | 4 | 3 | 0 | 0 |
| **Geba-D** | -14.347900° | 40.626700° | 3 | Logging | 4 | 1 | 1 | 5 |
| **Geba-E** | -14.349055° | 40.628513° | 2,5 | Logging | 4 | 1 | 1 | 5 |
| **Total restorable** | | | 16.5 | | | | | |

At Geba B, hydrological restoration is required to increase the rate of success for a large area, since it is located between two large salt pan areas.

#### 4.10.1.2 Nantaca

At Nantaca, a total of 7.82 ha of potential area for restoration was identified, however only 1.4 ha found in 2 areas (0.4ha and 1ha) was considered restorable. In these areas, restoration can be made through direct planting (Table 27).

Table 27: Potential areas for restoration at Nantaca

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| Nantaca-A | -14.234927° | 40.547849° | 4,91 | Erosion and sedimentation | 9 | 1 | 0 | 0 |
| Nantaca-B | -14.236014° | 40.550229° | 1,51 | Erosion and sedimentation | 9 | 1 | 0 | 0 |
| Nantaca-C | -14.236002° | 40.549361° | 0,4 | Logging | 9 | 0 | 1 | 9 |
| Nantaca-D | -14.235001° | 40.550877° | 1 | Logging | 9 | 0 | 1 | 9 |
| Total restorable | | | 1.4 | | | | | |

#### 4.10.1.3 Pangane

At Pangane, a total of 1.53 ha of potential area for restoration was identified (Table 28). Mangrove can be restored through direct planting.

Table 28: Potential areas for restoration at Pangane

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| Pangane | -14.370838° | 40.635810° | 1,53 | Logging | 4 | 1 | 1 | 5 |
| Total restorable | | | 1.53 | | | | | |

#### 4.10.1.4 Sanhute

At Sanhute, a total of 34,7 ha of potential area for restoration was identified (Table 29). However, only one of the areas was classified as restorable. 20,3 ha were salt desert, where mangroves don’t grow naturally due to environmental conditions. By opening channels, the salinity of the area can be lowered and the area can become suitable for mangrove growth (Barik *et al.*, 2018).

*Table 29: Potential areas for restoration at Sanhute*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| **Sanhute-A** | -14.855348° | 40.629907° | 20,3 | None (Salt desert) | 6 | 3 | 1 | 9 |
| **Sanhute-B** | -14.859726° | 40.626130° | 14,4 | Salt pan | 6 | 3 | 0 | 0 |
| **Total restorable** | | | 20.3 | | | | | |

### 4.10.1.5 Quissanga – Nantoa

The area identified at Quissanga was 6.56 ha of salt pan area (Table 30), thus a non-restorable area.

*Table 30: Potential areas for restoration at Quissanga-Nantoa*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (há) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| **Quissanga-Nantoa** | -14.915437° | 40.643459° | 6,58 | Salt pan | 4 | 2 | 0 | 0 |
| **Total restorable** | | | 0 | | | | | |

### 4.10.1.6 Mingorine

At Mingorine, was identified 7 ha of potential area for restoration (Table 31). This area is an abandoned salt pan where mangroves are starting to colonize. Restoration of these area must be through direct planting and Hydrological restoration.

*Table 31: Potential areas for restoration at Mingorine*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (há) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| **Mingorine** | -14.944375° | 40.626329° | 7 | Abandoned Salt pan | 7 | 2 | 1 | 9 |
| **Total restorable** | | | 7 | | | | | |

### 4.10.1.7 Cabaceira Grande

At Cabaceira Grande, was identified 24.2 ha of potential area for restoration (Table 32). All this area was considered restorable and observations made in the field show that in these areas, the hydrological regime of the forest was not affected by any activity.

*Table 32: Potential areas for restoration at Cabaceira Grande*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| Cabaceira Grande -A | -14.990173° | 40.726359° | 12,7 | Logging | 4 | 3 | 1 | 7 |
| Cabaceira Grande -B | -14.984326° | 40.731681° | 5 | Logging | 4 | 2 | 1 | 6 |
| Cabaceira Grande -C | -14.982585° | 40.735539° | 4,5 | Logging | 4 | 2 | 1 | 6 |
| Cabaceira Grande -D | -14.981789° | 40.739144° | 2 | Logging | 4 | 2 | 1 | 6 |
| Total restorable | | | 24.2 | | | | | |

### 4.10.1.8 Lunga

At Lunga, 7.1 ha was identified as potential area for restoration (Table 33), this area was affected by severe logging. This area can be restored through direct planting combined with a hydrological restoration.

*Table 33: Potential areas for restoration at Lunga*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| Lunga | -15.199800° | 40.575300° | 7,1 | Logging | 13 | 2 | 1 | 15 |
| Total restorable | | | 7.1 | | | | | |

### 4.10.1.9. Mossuril Sede

At Mossoril Sede, an area of 14.5 ha was identified (Table 34). This area was not identified as a sampling point during the desktop study. As it was described in the methods, the field team collected qualitative data of areas of interest for restoration that were not identified as sampling points. This was one of such areas. Although structural data is not available for this site, the other requirements are present, thus it was selected as a restorable area. The area is an abandoned salt pan being colonized by mangroves. The intent is to improve the environmental conditions to facilitate mangrove colonization of the area.

*Table 34. Potential areas for restoration at Mossoril*

| Site | Center coordinates | | Area ha | Impact | Ecological Condition (MCI) | Degraded Area (ha) | Reversibility of the Impact | Final Score |
|---|---|---|---|---|---|---|---|---|
| | Y | X | | | | | | |
| **Mossoril sede** | -14.973005° | 40.669533° | 14.5 | Abandoned salt pan | Uknown | 3 | 1 | - |
| **Total restorable** | | | 14.5 | | | | | |

# 5 Conclusions and next steps

- Our assessment estimated that there are 2525.78 ha of mangroves in the study area in 2022 and a loss of 7.9% of the 2012 area was recorded, representing a total of 217.96 ha. Most losses were recorded at Mossuril (also popularly known as a major centre of salt production);
- This number is much lower than what it was estimated during the proposal phase and right above our proposed 150 ha to be restored. Not all lost area is restorable. For instance, salt pan areas are difficult to restore due to the ecological changes and due to the need for permits. Additionally, areas that are less than 1 ha may not be worthy restoring. Therefore, our recommendation is to focus on the restorable areas and ensure project success instead of investing in non-restorable areas where chances of success are limited;
- Seven species of mangroves were identified in the study area. Nantaca, Lunga and Lumbo all had 6 species, while Pangane had only one species. Saua Saua, Lunga and Mussengua had the highest stand density. However, the widest and tallest trees were found at Nantaca, Pangane, Fungo and Lunga. These figures were reflected in the Complexity index, which was much higher at Lumbo (high stand density and 6 species), Lunga (wide and tall trees, and 6 species) and Nantaca (wide and tall trees, and 6 species, despite the very low stand density);
- Crooked poles dominated at all sites, and were the only form at Saua Saua and Pangane. Crooked poles result from a combination of environmental parameters and selective logging. All sites at our study area are under human pressure, and this was visible by the number and density of stumps. Nantaca had the higher density of stumps (14 400 stumps.ha$^{-1}$), followed by Geba and Cabaceira grande (with 8400 and 8200 stumps.ha$^{-1}$). Sanhute, Lumbo and Mingorine had the lower densities of stumps. The highest density of die back was observed at Lumbo, Lunga, Sanhute and Geba. The dieback at Nantaca was probably underestimated as all sampling points fell out of a critical die back area. This area is under strong influence of a river system, and has a lot of sedimentation and associated die back.

- Potential restoration areas were found at all sites totaling 92.53 ha. However, highlight can be made to the following sites:
    i. Nantaca, where mangroves were cut and river influence is much lower. Nantaca had the highest density of stumps, which indicates the need for sensitization and restoration actions at this site;
    ii. Geba which had a large number of stumps and salt pans and had a good potential for restoration;
    iii. Sanhute and Mussengua has a number of apparently abandoned salt pans, which would benefit from hydrological restoration.
    iv. Cabaceira Grande presented the second largest estimated area with potential to be restored.
- Nineteen species of fauna were found at the study sites, the main groups being mollusks and crabs. *Paraleptuca chlorophthalmus, Tubuca annulipes, Tubuca urvillei and Cranuca inversa* were the dominant species in most of the sites. Lichens diversity (five species) was also low, which indicates the poor conservation of the mangrove I the study area.
- Our study suggests that Lumbo, Cabaceira Grande and Lunga are potentially good sites for the establishment of community restoration and protection areas, considering:
    i. The balanced regeneration potential;
    ii. The good regeneration potential, particularly for Lunga;
    iii. The high number of species and high complexity index of both sites;
    iv. Human presence and use of mangrove resources, which creates opportunity for mangrove restoration, community engagement and raising awareness.
    v. Large degraded area for restoration especially at Cabaceira Grande;
    vi. Cabaceira Grande, Lumbo and Mingorine are located within the same bay, and there is probably some degree of ecological connectivity between them. Additionally, Cabaceira Grande has a huge area with great potential for restoration, which is a good starting point for a REDD+ project and makes also a good candidate for biodiversity offsets. Cabaceira also had relatively less salt pans, suggesting that human influence might be limited in that aspect.

Limitations and recommendations

- This study was conducted during the wet season and rain peak in 2023 which led to difficulties regarding access routes. Some areas identified as potential for restoration through change detection were not sampled due to time and logistical constraints. Such areas are presented in Table 35 and account for 55.69 ha.

*Table 35. Assessment of possible restoration areas that were not visited during the field sapling.*

| District | Site | Center Coordinates | | Area (ha) | Main Impacts | Restorability of the Impact |
|---|---|---|---|---|---|---|
| | | Lat. | Long. | | | |
| **Memba** | Geba | -14.350884° | 40.625964° | 2,88 | Unknown | Unknown |
| | | -14.354256° | 40.626056° | 9,1 | Unknown | Unknown |
| | Nantaca | -14.237909° | 40.555077° | 0,5 | Unknown | Unknown |
| | | -14.238683° | 40.556257° | 1,66 | Unknown | Unknown |
| | | -14.239907° | 40.558843° | 2,37 | Unknown | Unknown |
| **Mossuril** | Lunga | -15.211922° | 40.472256° | 4,78 | Unknown | Unknown |
| | | -15.211922° | 40.472256° | 8 | Unknown | Unknown |
| | | -15.200987° | 40.480952° | 7,4 | Unknown | Unknown |
| **Mz Island** | Lumbo | -15.113533° | 40.579843° | 19 | Unknown | Unknown |
| **Total** | | | | 55.69 | | |

- Therefore, it is recommended these sites to be visited before or during the initial stages of the restoration activities as a way to identify the causes of mangrove degradation and assessing their restoration potential. If these areas are determined as restorable, then the restorable 92.53 ha identified so far, can reach 148,22 ha, which is close to the initially proposed restoration area. Fieldwork should be carried out as soon as possible during the dry season to assess these sites.

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## Ficha de colheita de Dados

Data:___/___/____ Distrito____________Quadrícula Nr______Quadrado [Nr____; Letra_____]
Local/Site________________________ coordenadas: Y_________________X________________
Espécie dominante_______________________ Colectores ______________________________

| Composição do solo | Classe de Inundação | Fenologia | % Cobertura | Tipo de Solo | Tipo de floresta |
|---|---|---|---|---|---|
| ☐ Areia | ☐ Toda Maré baixa | ☐ Dormente | ☐ 0 - 20 | ☐ Mole | ☐ Bacia |
| ☐ Argila | ☐ Toda Maré alta | ☐ Flor | ☐ 21 - 40 | ☐ Intermediário | ☐ Mangal Anão |
| ☐ Turfa | ☐ Maré viva alta | ☐ Fruto | ☐ 41 - 60 | ☐ Firme | ☐ Sobrelavado |
| ☐ Areia/argila | ☐ Maré viva extrema | ☐ Propágulo | ☐ 61 - 80 | | ☐ Ribeirinho |
| ☐ Turfa/argila | ☐ 2x por ano | | ☐ 81 - 100 | | ☐ Franja |
| ☐ Turfa/areia | | | | | |

Observações ______________________________________________________________________
__________________________________________________________________________________
__________________________________________________________________________________

| | Árvores adultas | | | | | Regeneração | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tamanho do Quadrado _____x_____ | | | | | Tamanho do quadrado _____x_____ | | | |
| | | | | | | | Classe de Regeneração | | |
| | Espécie | DBH (cm) | Altura (m) | Condição da árvore | Qualidade do caule | Espécie | I | II | III |
| 1 | | | | | | | | | |
| 2 | | | | | | | | | |
| 3 | | | | | | | | | |
| 4 | | | | | | | | | |
| 5 | | | | | | | | | |
| 6 | | | | | | | | | |
| 7 | | | | | | | | | |
| 8 | | | | | | | | | |
| 9 | | | | | | | | | |
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|---|---|---|---|---|---|---|---|---|---|

## Appendix 2: Lichen data collection Sheet

Date:___/___/____ District_____________Transect ID_____ Plot nr ____Plot Letter________
Local___________________________ Coordinates: Y__________________X_________________
Forest type _______________ Colector(s) __________________Coverage % ________________
Lichen Species

| | | | |
|---|---|---|---|
| ☐ *Dirinaria picta* | ☐ *Parmotrema perlatum* | | Other |
| ☐ *Dirinaria aegiliata* | ☐ *Ramalina farinacea* | | |
| ☐ *Graphis scripta* | ☐ *Roccella montagnei* | | |
| ☐ *Lecanora sp* | ☐ *Teloschistes sp* | | |
| ☐ *Opegrapha sp* | ☐ *Usnea sp* | | |

Observations______________________________________________________________________
__________________________________________________________________________________

| | **Adult trees** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Plot size _____x_____** | | | | | | | |
| | **Mangrove Specie** | **DBH (cm)** | **Height (m)** | **Tree condition** | **Stem quality** | **Lichens specie** | **Nr of grids where the specie appears in the grid** | **Grid size: P (6x6) G (10x16)** |
| 1 | | | | | | | | |
| 2 | | | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | |
| 6 | | | | | | | | |
| 7 | | | | | | | | |
| 8 | | | | | | | | |
| 9 | | | | | | | | |
| 10 | | | | | | | | |
| 11 | | | | | | | | |
| 12 | | | | | | | | |
| 13 | | | | | | | | |
| 14 | | | | | | | | |
| 15 | | | | | | | | |
| 16 | | | | | | | | |
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| 19 | | | | | | | | |
| 20 | | | | | | | | |
| 21 | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|
| 22 | | | | | | | | |
| 23 | | | | | | | | |

## Appendix 3: Fauna Data collection Sheet

Date:___/___/202__ District___________Transect ID_____ Plot nr ______Plot Letter________
Local/Site_________________________ Coordinates: Y__________________X________________
Colector(s) _______________________________

Observations______________________________________________________________________
__________________________________________________________________________________
__________________________________________________________________________________

| **Plot size _____x_____** |
|---|

| Nr | **Species** | **Nr of individuals** |
|---|---|---|
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |
| 11 | | |
| 12 | | |
| 13 | | |
| 14 | | |
| 15 | | |

| | |
|---|---|
| Nr of Holes | |