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Impact of anthropogenic and climatic factors on forest structure in and around the Muanda mangrove Marine Park in DR Congo

Impact des facteurs anthropiques et climatiques sur la structure de la forêt dans et autour du parc marin de la mangrove de Muanda en RD Congo

Teteli Soloum Clément[1,2], Kokou Kokouvi Bruno[1,3,4], Elangilangi Molo Jacques[1], Mukotanyi Mugisho Serge[1], Muhindo Mutumwa Anselme[1], Lobho Joel Lopa[1], Diop Alioune Badara[1], Ngoie Longwa Leontine[1], Lwanzo Daniel Virekero[1], Mbavumoja Tresor Selemani[1], Ahouandjinou Sèdjro David Igor Thierry Kévin[1], Pyame Onyo David[1], Balandi Julien Bwazani[1, 4], Atakpama Wouyo[3], Bernard Riera[1,6]

[1]Ecole Régionale Postuniversitaire d'Aménagement et de Gestion Intégré des Forêts et Territoires tropicaux, Université de Kinshasa, Commune de Lemba, - B.P. 15.373 - Kinshasa, République Démocratique du Congo
[2]*Research Unit in Tropical Mycology and Plants–Soil Fungi Interactions (MyTIPS), Faculty of Agronomy, University of Parakou, BP 125, Parakou, Benin, ur-mytips@leb-up.org / n.s.yorou@gmail.com*
[3]Laboratoire de Botanique et Écologie Végétale (LBEV), Département botanique, Faculté des sciences (FDS), Université de Lomé (UL), 01 B.P. 1515, Lomé 1, Togo
[4]African Centre of Excellence in Neglected and Underutilised Biodiversity (ACENUB), University of Mzuzu, P/BAG 201 LUWINGA, Mzuzu, Malawi
[5]Unité Biodiversité et Paysage, Gembloux Agro-Bio Tech, Université de Liège, 5030 Gembloux, Belgium
[6]Muséum National d'Histoire Naturelle, FRANCE

*Corresponding author: kokoubruno7@gmail.com

ORCDI des auteurs
Teteli Soloum Clément: https://orcid.org/0000-0002-571462-2144; Kokou Kokouvi Bruno: https://orcid.org/0009-0006-0852-1232
Elangilangi Molo Jacques: https://orcid.org/0009-0002-5391-3180 ; Mukotanyi Mugisho Serge: https://orcid.org/0000-0001-5902-9498 ; Lobho Joel Lopa: https://orcid.org/0009-0005-3306-8727 ; Diop Alioune Badara: https://orcid.org/0009-0009-1547-8350 ; Lwanzo Daniel Virekero: https://orcid.org/0009-0000-0319-0899 ; Mbavumoja Tresor Selemani: https://orcid.org/0009-0005-6930-6176 ; Muhindo Mutumwa Anselme: https://orcid.org/0009-0002-1607-5755 ; Ahouandjinou Sèdjro David Igor Thierry Kévin: https://orcid.org/0009-0000-5074-1526 ; Pyame Onyo David: https://orcid.org/0009-0005-4972-6499 ; Balandi Julien Bwazani: https://orcid.org/0000-0001-5717-7147 ; Atakpama Wouyo: https://orcid.org/0000-0001-7041-918X ; Bernard Riera: https://orcid.org/0000-0002-5320-9671

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Abstract

The study highlights the impact of global change on forest structure within and around the Muanda mangrove marine park in RD Congo, focusing on key forest structure parameters such as species composition, basal area, tree height, and Leaf Area Index (LAI). This study assessed forest structure parameters in and around the park and linked between forest structure to global change. Forest structure parameters, namely species composition, basal area, tree height and Leaf Area Index (LAI), were measured at 5 sites. Analyses showed significant variation in mean height between the different sites, in the order of 22m, 25m and 30m for the marine sites, and 7m and 10m for the terrestial sites. The mean basal area of trees varied from 52 m^2. ha-1 to 15 m2.ha-1. Two undisturbed mangrove sites have the highest basal area, the lesser disturbed sites have the average

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basal area and the degraded sites have the lowest basal area. The carbon stock capacity shows the same trend. The highest average LAI is 3.79. The lowest is 1.08. Within the same site, there is a certain homogeneity of LAI values for undisturbed sites, whereas the variability of these values is high for degraded sites. In other words, forest structure parameters vary from one area of the park to another for reasons related to human activities and climate change. The existence of a link between forest structure and global change is evident.

Keywords: Mangrove, Muanda marine park, Forest structure, anthropization, climate change

1. Introduction

Wetlands are ecosystems of strategic interest because of their ecological, economic, and sometimes cultural roles (De Groot et al., 2007). According to Finlayson and Davidson (2018), wetlands cover 9 to 10% of the earth's surface. In terms of ecological and functional diversity, wetlands are the most productive ecosystems on the planet (Drabo et al., 2016 and Nwamo et al., 2016) due to their multiple roles and high productivity (Mukabo Okito et al., 2017; Binet et al., 2017). In terms of biological biodiversity and natural productivity, they are second only to tropical forests (Pearce and Crivelli, 1994). They are currently 03 sites are designated as wetlands of international importance including the Muanda Mangrove Marine Park (Ramsar, 2022).

Unfortunately, these mangrove ecosystems are subject to numerous mutations due to the combined effects of anthropogenic activities and climate change (Diop et al., 2024). Muanda Mangrove ecosystems are considered highly fragile and vulnerable to human activities (Dahome-Di Ruggiero, 2017; Folega et al. 2017) and climate change (MEED and MAEP, 2019), yet they are among the most threatened in the world (Armah et al., 2008). The global surface area of mangroves fell from 18.8 million hectares in 1980 to 15.2 million hectares in 2005, a loss of 3.6 million hectares (FAO, 2007). The global population living in and dependent on coastal zones is estimated at around 450 million, or 55% of the world's population (Spalding et al., 2011). In addition to anthropogenic threats, mangroves are also sensitive to certain climatic parameters. These effects are not negligible: mangroves show maximum development densities when the temperature reaches 25°C (Hutchings and Saenger, 1987); reduced rainfall leads to reduced productivity, growth and survival of young seedlings; and could also lead to a change in species composition by favouring more salinity-tolerant species (Ellison, 2000 and 2004); and finally, flooding reduces mangrove productivity, photosynthesis and survival (Naidoo, 1983).

In Africa, the total mangrove area is estimated at 3.2 million hectares (around 19% of global coverage). Over the past 25 years, the proportion of mangroves lost in West Africa has varied between 20% and 30%, while in East Africa the figure is 8% (Armah et al., 2008). This has led to a considerable reduction in the biodiversity of this ecosystem (Bekeli, 2007 ; Mugisho et al., 2022; Diop et al., 2024). This is the case of the mangrove marine park, which is subject to sometimes irreversible disturbance under the influence of anthropogenic pressures (poaching, deforestation and hydrocarbon pollution) and climate.

Faced with the challenges of conserving and sustainably managing natural resources, it is essential to monitor fragile ecosystems that are sensitive to climate change and human activity. With this in mind, a structure known as the African Network for Mangrove Conservation (RAM) was set up in Cameroon in May 2003 to safeguard mangroves. In the case of the mangrove marine park, few studies and data exist on its situation in relation to global change.

This study, carried out in and around the Muanda Mangrove Marine Park, focuses on the anthropogenic and climatic factors affecting the mangrove marine park. Its overall aim is to assess the influence of anthropogenic and natural factors on the forest structure of the Mangrove Marine Park and its surroundings. Specifically, it: (i) assess the forest structure parameters of the park and its surroundings; (ii) Establish the link between forest structure and global changes. It is understood that the forest structure parameters of the Mangrove Marine Park and its surroundings vary from one environment to another, and that global changes influence the forest structure of the Mangrove Marine Park.

2. Méthodes

2.1. Study environment

The Muanda Mangrove Marine Park was created by Ministerial Decree No°044/CM/ECN/92 of May 02, 1992 (IUCN/PAPACO, 2015). It is located on the northern bank of the mouth of the Congo River, near the localities of Banana and the territory of Muanda, in the province of Central Kongo. It covers an area of 768 km², 20% of which is located in the Atlantic

Ocean. The park is divided into two zones. The first (zone A), made up of islets and channels, is designed for complete protection, and contains most of the mangroves. The second zone (Zone B) is intended for partial protection. It is characterised by a bare wet savannah with ponds and a 2 km wide coastal strip along the Atlantic Ocean (ICCN, 2016; IUCN/PAPACO, 2010). The PMM is a Ramsar site and classified as a Wetland of International Importance (ZHII) that borders river (fresh) and marine (salt) waters. The permanent influence of the ocean confers particular ecological characteristics to the flora and fauna of the environment (ICCN, 2016).

The park's ecosystem is made up of savannah and gallery forest, with several species of mangrove and endemic plants. The main mangrove species are black mangrove or white mangrove, depending on the region: *Avicennia germinans* (L.) L., grey mangrove (*Laguncularia racemosa* (L.) C.F.Gaertn), *Conocarpus erectus* L., red mangrove (*Rhizophora harrisonii* Leechm., *Rhizophora racemosa* G. Mey), and *Rhizophora mangle* L., the golden fern (*Acrostichum aureum* L.), the candelabrum (*Pandanus candelabrum* P.Beauv.) and the raffia palm (*Raphia matombe*) (ICCN, 2016).

The Mangrove Marine Park boasts a remarkable fauna, with two of the world's seven species of egg-laying sea turtles (including the olive ridley turtle, which remains the most abundant, and the leatherback turtle) and the African manatee *Trichechus senegalensis* L. Mangroves are home to numerous species of freshwater and saltwater fish. According to Romañach *et al.* (2018), 80% of fish species consumed by humans are found in mangroves during at least one stage of their life. There's also the crustaceans and shellfish, *Varanus niloticus* (LINNAEUS, 1766). The last hippopotamuses (12 specimens currently listed) in Central Kongo reside in the Mangroves Marine Park. Buffalo, bushpig, *Cercopithecus* sp., *Cephalophe* sp., *Sitatunga*, are also present (PMM, 2015; ICCN, 2016).

According to Köppen's classification, the climate is humid tropical type, marked by alternating rainy and dry seasons (Maloueki et *al.*, 2013). Average temperature variations do not exceed 6°C over the course of the year. The average monthly temperature varies between 22° and 24°C. Average monthly relative humidity is in the range of 77% to 81%. In terms of rainfall, annual precipitation is around 772 mm. However, rainfall is highly variable from one year to the next. The rainy season extends from October to May, and the dry season from June to September. Soils in the study area vary from sandy, clayey-gritty to ferralitic and hydromorphic (MECNT, 2010).

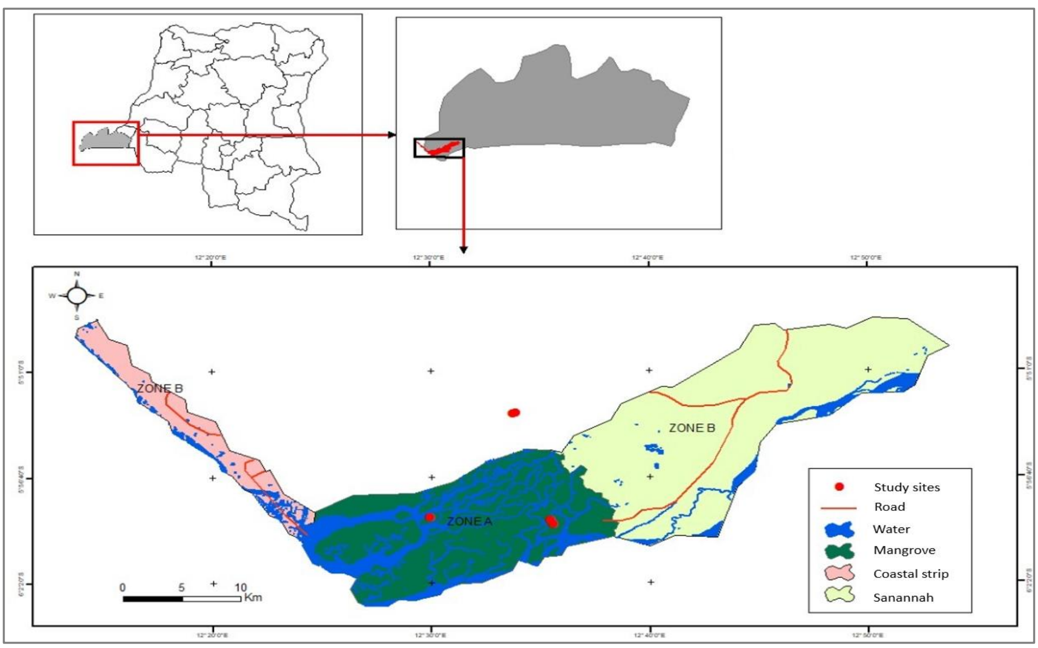

Figure 1. Study area map

2.2. Data collection

A total of 5 sampling sites were selected to measure certain structural parameters of the forest, including species composition, basal area, tree height and leaf area index. The first three sites were located in Zone A of the Mangrove Marine Park: (i) in a location well covered with *Rhizophora racemosa* (Mangrove 1), (ii) in a location moderately covered with *Rhizophora* *racemosa,* G.Mey., (Mangrove 2) and (iii) in a location where there had been deforestation of *Rhizophora racemosa* (Mangrove degraded). The last two sites were located the village of KIMBENZA on the outskirts of the Mangrove Marine Park: (iv) in a plantation of *Acacia mangium* Willd. and (v) in an orchard of mango, orange, safoutier, palm and coconut trees.

- **Tree height**

The woodcutter's cross was used to measure the height of trees. The technique requires the use of two sticks of equal length. They are held perpendicular to each other by the operator next to his eye. The operator moves along, staring at the tree, until he can see the top and bottom of the tree. The height of the tree is the distance between the operator and the observed tree.

- **Basal area**

The chain relascope was used to measure the basal area of trees. The relascope system allows rapid estimates based on a statistical method. In practice, the notch is held at a fixed distance from the eye. The chain is kept taut to maintain a constant angle. After a complete survey, all trees with an apparent diameter is greater than the notch are counted and assigned a value of 1, while the tangent tree is given a value of 0.5. The total value obtained is multiplied by the scale used to obtain the basal area per hectare. This system has 4 notches, representing the basic factors 0.5; 1; 2 and 4. For each plot, the appropriate scale is selected on the basis of tree size in order to avoid under- or overestimation of basal area. On this basis, scale 4 was chosen for site 1 and site 2 as these were large diameter trees, while scale 2 was chosen for sites 3, 4 and 5 as these were medium diameter trees.

- **Leaf area index**

The light LAI meter was used to calculate the Leaf Area Index (LAI). This is the ratio of the total upper leaf surface to the soil surface on which vegetation is growing. It is a good indicator of plant growth, biomass and stand density (Weiss, 1998). On 03/08/2022, direct LAI measurements were taken between 10:30' and 10:43' at the Mangrove 1 site (with 75 measurements) from geographical coordinates 5.98366°S and 12.59142° E; between 11:30' and 11:45' at the Mangrove 2 site (with 272 measurements) from geographical coordinates 5.98712°S and 12.5332° E; between 12:20' and 12:50' at the Mangrove degraded site (with 61 measurements). On 04/08/2022, measurements were taken between 12:00 and 12:30 at the *Acacia mangium* plantation (with 140 measurements) from coordinates 5.88804°S and 12.56493° E and between 12:51 and 13:17 on an orchard (with 60 measurements) from coordinates 5.88883°S and 12.56266° E. These operations were carried out under dry, cloudy and sunny conditions. The mechanism consisted of measuring the light transmittance value at every meter along a defined transect using an LAI meter. The brightness of the sun's rays, which influences the light transmittance value, was indicated during the measurements using codes B, L, C. Code B (Bright) represents the presence of the sun and no clouds; code BL (Bright Luminous): the presence of the sun and clouds at the same time; code L (Bright): no clear shadow; code LC (Bright Overcast) and code C (Overcast): cloudy.

2.3. Data processing and analysis

Recorded data were entered into a Microsoft Excel Spreadsheet, version 2019. These data were used for statistical analysis and graphing in R and Excel (Kokou et *al*., 2023). Variability in forest structure was determined by reproducing measured parameters for every site and then comparing them. Parameters considered were: the mean height (m), the basal area (m²/ha), the carbone stock (tonnes/ha) and the LAI.

To estimate the aboveground carbon stock, basal area and tree height were used to calculate biomass, which was then converted to carbon stock. The following formula was used to estimate the epigeous carbon stock: Carbon stock = (stand volume (m^3/ha))/4 where stand volume = basal area (m^2/ha) x height (m) (m^3/ha).

Measured light transmittance values were corrected by multiplying them by the solar radiation brightness coefficient to obtain the actual value (Cournac et al., 2002). Leaf indices were then calculated using the following formula: LAI= -1/k (b1 lnR + b2 lnR^2) +offset with Offset =1/k (b1 lnRo + b2 lnRo^2) with ln (Ro) = a0 + a1 ln (IB) + a2 ln (IB) ^2.
Where K = 0.88 and IB = 455 (Cournac *et al.* 2002).
After calculating the LAI, a descriptive statistic was performed for each site, and then a comparison of the descriptive statistical parameters was made according to the measurement sites. One-way ANOVA (at 5% threshold) was used to determine whether LAI was significantly different between locations. Shapiro-Wilk test was used to check the normality of data, and Levene test to check equality of variance. The Turkey test was used to structure the LAI averages by site.

3. Results

The average height of the vegetation in the different types of sites is shown in the figure 2: Mangrove 1, Mangrove 2, Degraded Mangrove, Acacia Plantation and Orchard. Mangroves have the tallest trees, with an average height of 30 m for Mangrove 1 and 25 m for Mangrove 2. Degraded mangroves show a decrease in tree height, with an average of 22 m. Anthropized sites, such as the Acacia plantation and the Orchard, show significantly lower heights of 10 m and 7 m respectively. This may indicate that the intensification of human activities and the degradation of local ecosystems is leading to a decrease in trees' means height. The average basal area (m^2/ha) for the different sites is shown in Figure 2. Mangrove 1 has the largest basal area of all the sites with 52 m^2/ha. Among the mangrove sites, the two that are not degraded and have *Rhizophora* species have significantly higher basal area values than the other sites. The two dryland sites, have moderate basal area values, indicating a distinct vegetation structure. The degraded mangrove site has the lowest basal area, only 9 m^2/ha. This demonstrates the effect of ecosystem degradation on forest structure and density of. The carbon stock at each site is shown in the same figure. The Mangrove 1 and Mangrove 2 sites have the highest carbon storag capacity with values of 390 tonnes/ha and 156 tonnes/ha respectively. With values of 50, 38, and 26 tonnes/ha, respectively, the degraded mangrove, the orchard, and the Acacia mangium plantation show significantly lower carbon stocks. This striking disparity highlights how vegetation type and land degradation affect the ability of plants to store carbon.

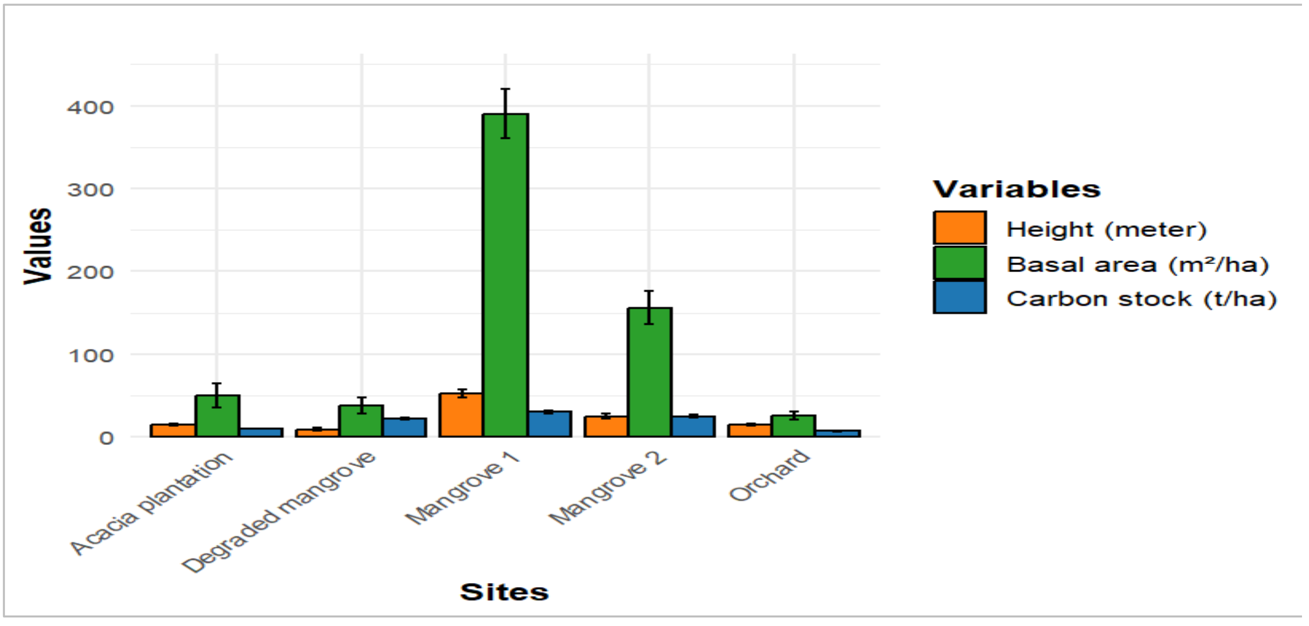

Figure 2: Comparison of Heights, Basal Areas, and Carbon Stocks by Site with Standard Deviation

Table 1 presents statistical LAI parameters for different sites. The average LAI is highest in Mangrove 1 (3.79) and 3.45 (m2/m2) in Mangrove 2. At the orchard site, the *Acacia mangium* plantation, and the degraded Mangrove site, the lowest averages LAI were found to be 1.45, 2.93, and 1.08, respectively. With coefficients of variation of 75.17% and 78.7% respectively, there was a significant degree of variability in LAI at the *Acacia* plantation and degraded mangrove sites. The Mangrove 1 and Mangrove 2 sites, on the other hand, showed minimal variability in LAI, with coefficients of variation of 29.55% and 25.8%, respectively.

Table 1. Statistical indicators for each site

Sites	**Mangrove 1**	**Mangrove 2**	**Degraded mangrove**	***Acacia mangium* plantation**	**Orchard**
Minimum	0,65	1,25	0,26	0,08	0,56
Maximum	5,13	4,92	4,85	3,66	5,18
Average	3,79	3,45	1,45	1,08	2,93
Standard deviation	1,12	0,89	1,09	0,85	1,25
Coefficient of variation (%)	29,55	25,8	75,17	78,7	42,66

Analysis of variance (ANOVA 1) shows that there is a significant difference in mean LAI between sites at the 5% threshold, as Pr (>F) <0.05. Measurements of the LAI (in m2/m2) taken along a transect at the Mangrove 1 site are displayed in Figure 5. In space, LAI varies greatly, from 0.65 m2/m2 to 5.13 m2/m2. The low variability of the LAI is indicated by the low variance of the curve, which leads to the conclusion that the leaf cover at this location is homogeneous. Observations indicate that this location has a good amount of dense leaf cover (figure 3). There aren't many big gaps, as seen by the low presence of low LAI windows. There is less disturbance in this park.

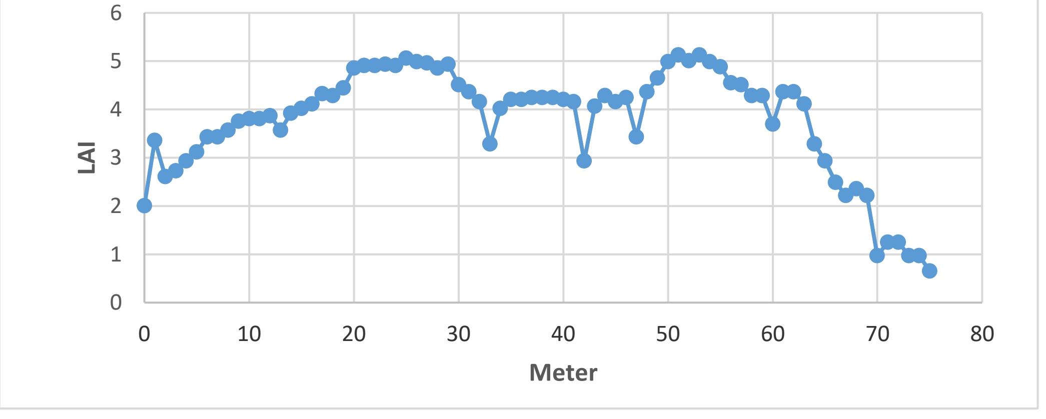

Figure 3: LAI variation per meter at Mangrove 1 site

The Mangrove 2 site's transect is used in Figure 4 to display the LAI data (in m2/m2). Along the transect, the spatial variability of LAI is somewhat considerable, ranging from 1.25 m2/m2 to 4.92 m2/m2. At this site, there is less leaf-cover homogeneity, as evidenced by the slightly more varied LAI curve than at Mangrove 1. There are a few gaps visible by the somewhat large windows of tiny LAI values. As a result, compared to the Mangrove 1 site, there is less vegetation cover. There has been some disturbance at this place.

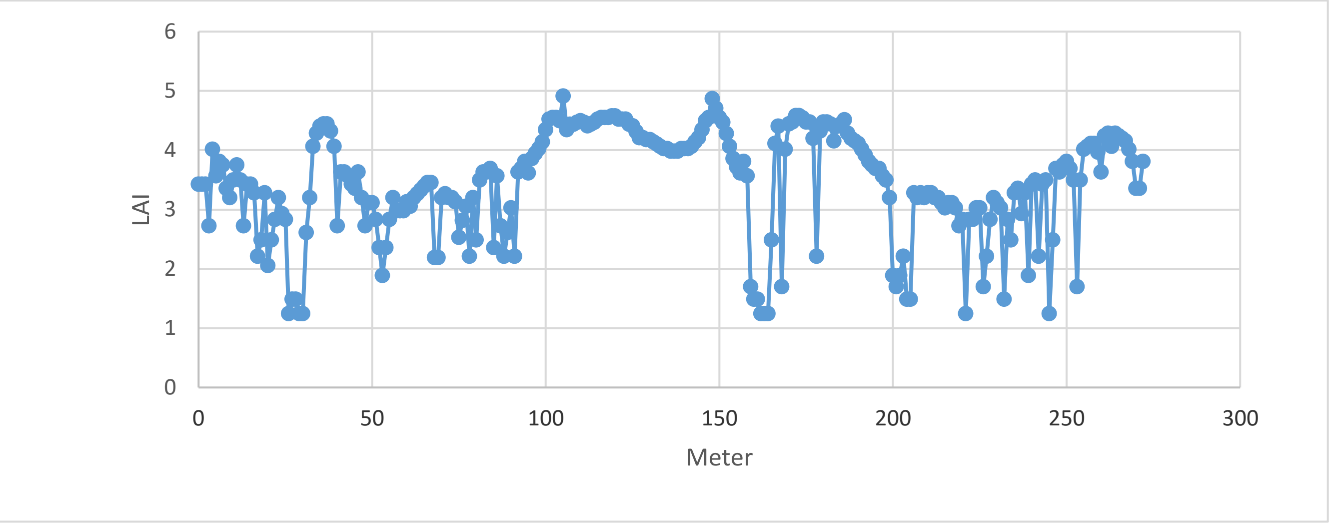

Figure 4: LAI variation per meter at Mangrove 2 site

The variance in LAI readings (measured in m2/m2) along the degraded mangrove site transect is displayed in Figure 5. The wide variation in LAI suggests a heterogeneous forest cover. The LAI value ranges from 0.26 m2/m2 at the minimum to 4.85 m2/m2 at the greatest. This site appears to have little forest cover, as seen by the broad windows of small LAI values and the few peaks of significant values.

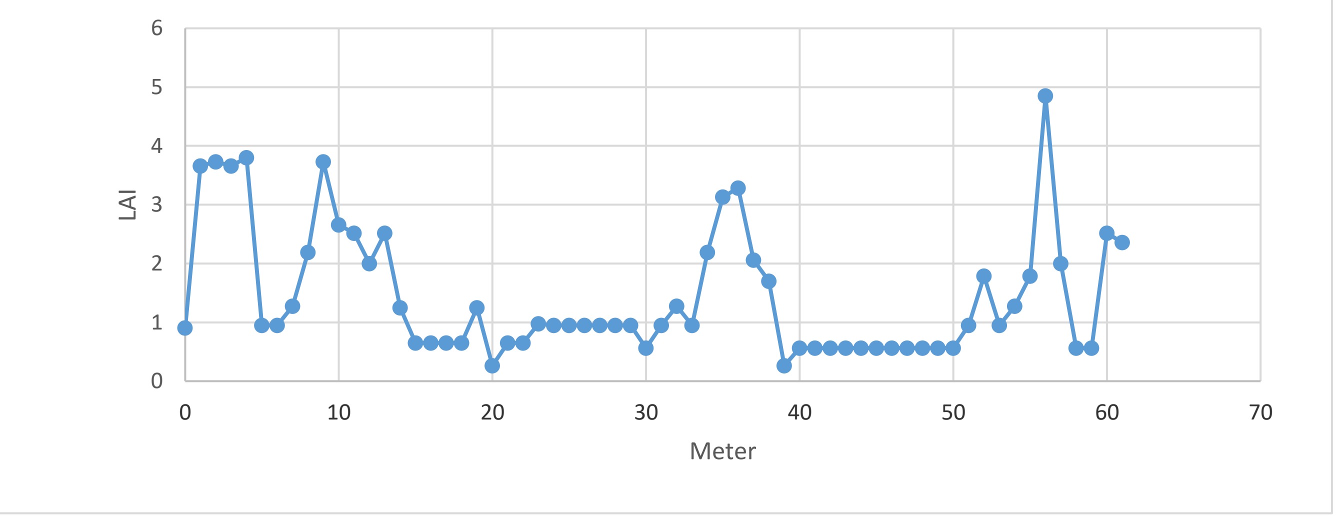

Figure 5: Variation in LAI per meter at the degraded mangrove site

The LAI measurements (m^2) from *Acacia mangium* dry land plantation at Kimbenza hamlet are shown in figure 6. The heterogeneity of the land cover is reflected in the LAI curve, which varies greatly over the entire measurement distance. The range of LAI is from 0.65 m2/m2 to 5.13 m2/m2. 3.66 m2/m2 is the maximum LAI value, with a minimum of 0.08 m2/m2. There are significant areas without leaf cover, as evidenced by the presence of large windows with low LAI values. The plantation therefore has a low tree density. There is a disturbance at this site.

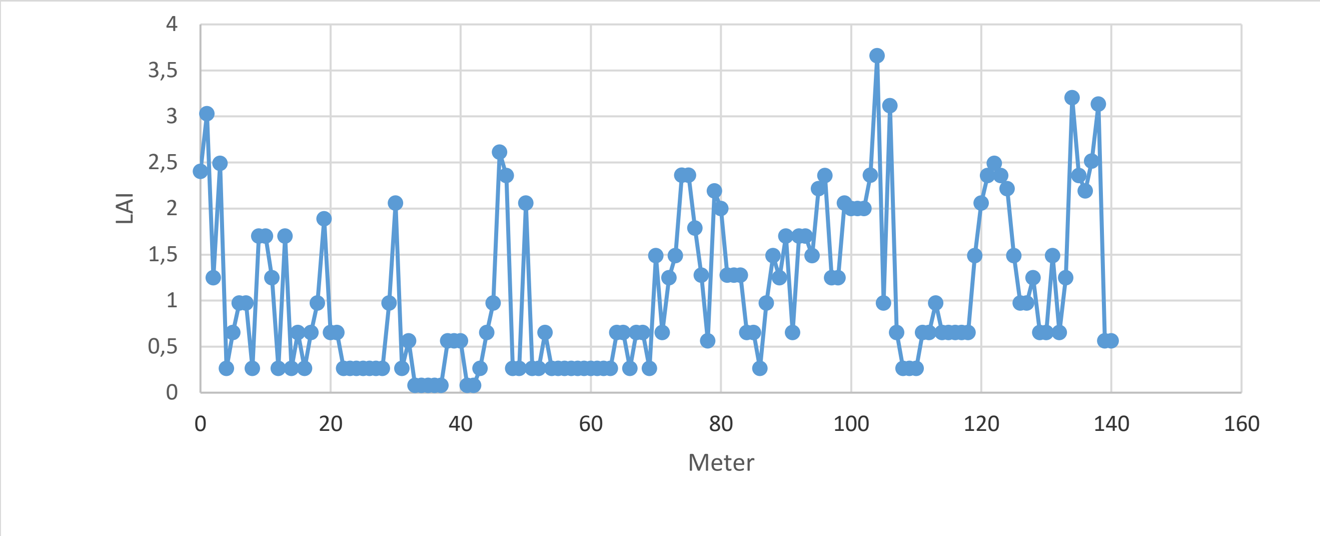

Figure 6: Variation in LAI per meter in the *Acacia mangium* plantation

In the orchard near Kimbenza village, figure 7 displays the variation in LAI per meter. It is evident from this figure that leaf cover is relatively uniform, as the LAI is constant in some locations over the measuring distance. The minimum and maximum LAI values are between 0.08 m2/m2 and 3.66 m2/m2, the lowest and maximum LAI values are found. The difference between foliar and non-foliar cover is relatively small.

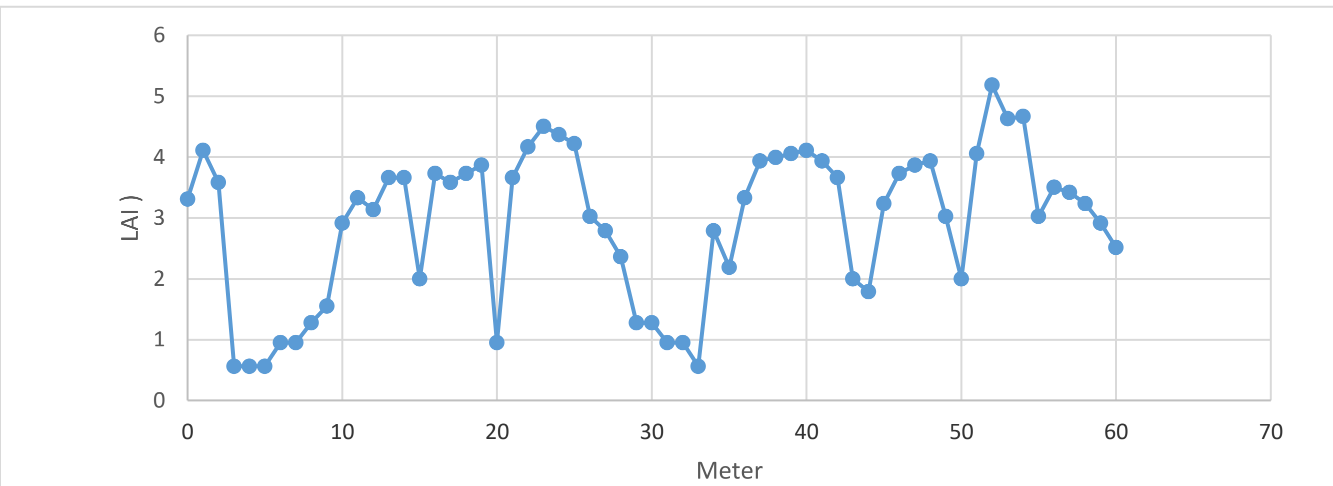

Figure 7: LAI variation per meter at orchard level

The distribution curves of the LAI values for each site are displayed in Figure 8. The graph shows how the mangrove 1 and mangrove 2 sites are, with comparable leaf cover. Conversely, the mangrove degraded site and *Acacia mangium* plantation are nearby and represent disturbed forests.

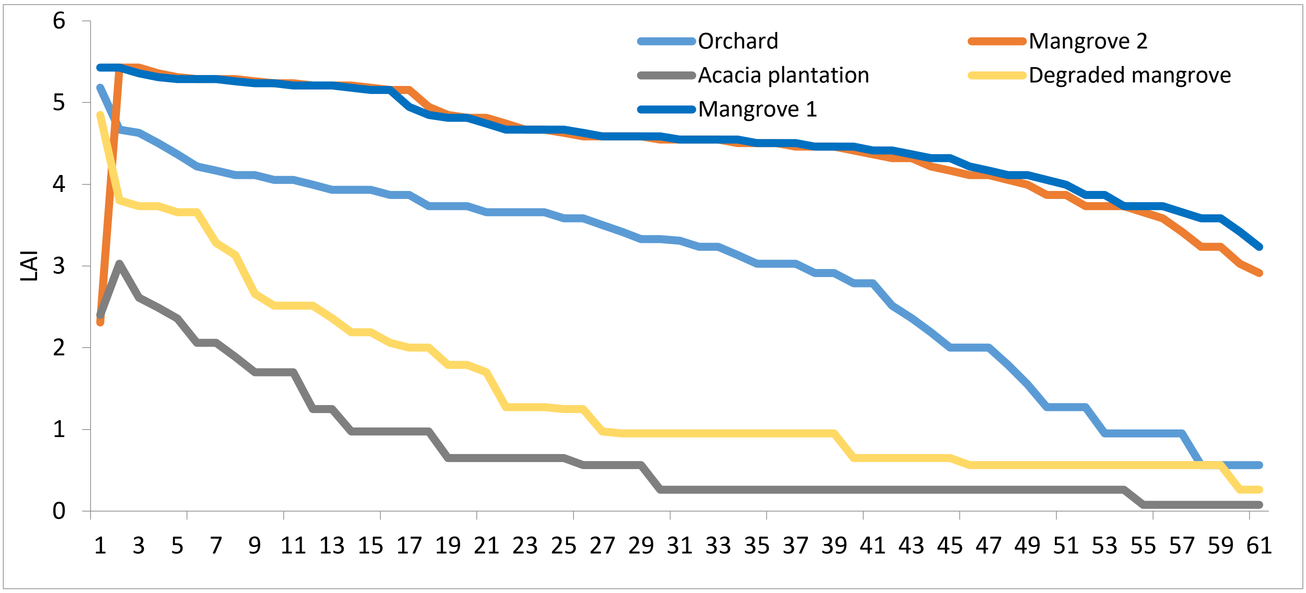

Figure 8: Distribution curve of LAI values ordered by decreasing value for the different sites.

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Mangrove 2     Mangrove coupée          Mangrove1 Plantation d'acacia
       "c"                 "a"                "c"                 "a"
    Verger
       "b"
```

The Turkey test confirms the same results, showing that the LAI averages of the Mangrove 1 and Mangrove 2 sites are closed, and the averages of the Mangrove degraded site and the *Acacia mangium* plantation site are close. The orchard site is isolated and has intermediate cover.

4. Discussion

4.1. Factors influencing variability in forest structure in and around the Mangrove Marine Park

The mean height of *Rhizophora racemosa* observed in the Mangrove Marine Park is similar to that obtained by Ajonina *et al*. (2014) as part of an assessment of mangroves in the DRC. The maen height observed in *Rhizophora racemosa* mangroves are not similar to those obtained by Ajonina *et al.* (2014) and Simard (2019) in Gabon, which were 41 m and 62.8 m respectively. The factors underlying the difference in forest structure are natural and anthropogenic. For the first two marine sites (Mangrove 1 and Mangrove 2), the hight average heights and basal area observed are related to the natural factors of mangrove growth, which are optimal: the presence of brackish water, temperature, physical properties, chemical composition, salinity and acidity of the soil and water. The position of the mangroves also seems to play a role in relation to the winds, which can limit the height.

The low values of height and basal area values observed in this study, compared with those obtained in Gabon, can be explained by the abundant rainfall that characterizes the Gabonese estuary: up to 3,000 mm (Ondo, 2006), whereas the average annual rainfall in Muanda is only about 772 mm (M'Fu, 1995). Global warming in the present era is likely to have already reduced this rainfall figure. The same applies to the results of Andriamalala *et al.* (2010), who report a basal area of 58.5 m2/ha for a Madagascan forests (in the Alaotra Mangoro region) where annual rainfall varies between 1800 and 2000 mm. However, the 52m²/ha observed at the Mangrove Marine Park during this study is well above the maximum value observed in most mangroves in Cameroon. Monteil (2015) indicates around 9 m²/ha, while Biosci (2015) reports about 1.12 m^2/ha in the Bamusso site (Southwest Cameroon). However, according to Nfotabong (2011), some rare sites can be distinguished themselves with a basal area of 42.01 m2/ha. The author points out that this particularity can be explained by the fact that the degree of structural degradation of mangroves decreases when they are adjacent to dense forests on dry land. This is the case, for example, of the mangrove forests at the mouth of the Nyong River and those around the village of Mpalla (Kribi), and in Gabon, where the mangrove forests are adjacent to the mainland forest.

The large differences in basal area observed in the two non-degraded Mangrove sites, Mangrove 1 (52m²/ha) and Mangrove 2 (25m²/ha), could be attributable to natural factors such as natural regeneration after windthrow. Indeed, the report on a mangrove restoration project in Oronjia, Madagascar, reveals regeneration that has increased the total basal area per hectare (stems> 5 cm) from 16.1 m² in 2012 to 24.28 m² in 2019 (Project ref 109549-Association Tsimoka, 2020). This situation corroborates that observed by Tazo (2021), according to whom in Cameroon, the best dendrometric parameters were recorded in the case of natural regeneration of the Tiko mangrove, compared with the Mbiako plantation. Mangrove2's low basal area value (25m²/ha) is thus thought to be the result of a natural dynamic process that creates an opening in the canopy by the fall of a large tree, causing the death of young plants, followed by the natural regeneration of mangroves at this site. While Mangrove1 (52m²/ha) would easily continue to grow, sheltered from any such disturbance.

In the case of *Acacia mangium* plantations on dry land, the low height and basal area can be explained by both anthropogenic factors (bush fires, plantation spacing) and climatic factors (temperature, rainfall, soil, etc.). In this environment, plants are faced with the problem of water stress due to drought, which adversely affects their growth. High temperatures, especially in the dry season, facilitate bush fires. These observations have been confirmed by several studies. According to Dasgupta *et al.* (2017), abiotic factors such as light, slope, physical structure of substrates and chemical composition are decisive for the emergence, growth, distribution and survival of mangrove species. Amores *et al.* (2013), Chen and Ye (2014) and Vovides *et al.* (2018) have shown that site salinity is a key factor influencing the survival, establishment, growth and productivity of mangrove species. According to Ranaivoson Nampoina (2016), temperature and precipitation are factors that favour plant development in general.

The low average height and basal area values observed in the orchard are linked to plant physiological factors. The plants present on this site, such as orange trees, are species that generally have limited growth in height and diameter. Windfalls are also factors that create gaps in the forest, i.e. large trees in terms of their cycle and by falling cause damage to others. At the degraded mangrove site, the low height and basal area observed is purely anthropogenic and linked to the uncontrolled cutting of mangroves by the local population. Trees of great height and diameter have generally been cut down, which explains the low average height.

Mangroves are known for their high carbon storage capacity. The two non-degraded mangrove sites (Mangrove 1 and Mangrove 2) have the highest carbon storage capacity. This high capacity is due in part to the low anthropogenic pressure observed and in part to the good ecological conditions favoring tree growth. However, on the Mangrove degraded site, the carbon stock is low due to the influence of anthropogenic disturbances. Deforestation has led to a significant loss of carbon stock. On this site, we estimate a loss of around 70% of carbon stock, corresponding to a lost quantity of around 235 tonnes/ha of carbon. Similarly, the low-carbon stock in the *Acacia mangium* plantation is linked to anthropogenic impact, notably bush fires, and also to the fact that the plantation is young. Man is therefore an important factor in the degradation of mangrove marine park ecosystems. These results corroborate those of Fousseni *et al*. (2017), Teteli *et al.* (2023), who indicate that in

Togo and Benin, anthropogenic pressures are the major causes of these modifications, which lead to degradation and consequently have a negative impact on the ecosystem services provided by forest like mangroves, as well as their productivity. Further, Kokou *et al.* (2023), also demonstrated in their study on the dynamics of carbon stock in the classified forest of Amou-Mono in Togo, and they found that anthropization is one of the factors that influences the capacity of trees to sequester carbon.

The mangrove marine park ecosystem is under threat, weakened mainly by human activity, with three main threats: deforestation, poaching and water pollution by hydrocarbons. Areas of the park close to built-up areas are more exposed to anthropization. According to Din and Blasco (2003), mangrove degradation is a direct consequence of urbanization. Roads increase traffic flows, accentuating the phenomenon of sedentarization on the periphery of the mangrove marine park. The same results were found by Sene (2012) who studied the impact of the Nouakchott-Nouadhibou Road on the Banc d'Arguin National Park. In addition, Ajonina *et al.* (2014) showed that undisturbed mangroves store more carbon than logged forests. The significant difference between the carbon stocks of undisturbed ecosystems and those of moderately exploited systems indicates that it is possible for mangroves to release relatively high carbon stocks after degradation, and that it is important for mangroves to remain in totally undisturbed states to maximize storage Ajonina *et al.* (2014).

Variability in leaf area index is influenced by both anthropogenic and natural factors. The two undisturbed mangrove sites (Mangrove 1 and Mangrove 2) have a large leaf area, reflecting the plant's great capacity to capture $CO2$ (carbon storage). At the degraded Mangrove site, there is little leaf area due to the absence of trees caused by deforestation. In the Acacia mangium plantation, the low average LAI value is primarily due to the high plantation spacing and the structure of the A. mangium leaves, as well as anthropogenic and climatic factors. Climatic factors include drought, and anthropogenic activities include bush fires. The wide variation in LAI in degraded mangroves and Acacia mangium plantations bears witness to their heterogeneous leaf cover. According to Nziengui *et al.* (2007) and Simmen *et al.* (2021) undisturbed forests with high tree density are characterized by higher mean LAI values, whereas disturbed forests have low mean LAI values. The low variability of LAI in mangrove 1, mangrove 2 shows the homogeneity of leaf cover. LAI is a good indicator for assessing forest leaf cover. LAI also has an impact on tree growth through light interception. Light availability under canopies is the main factor limiting tree recruitment and growth in forests (Cournac *et al.,* 2001).

4.2. Link between forest structure and global change

The variability of forest structure in and around the Mangrove Marine Park is linked to anthropogenic and climatic factors. These different factors are influenced by global change. Thus, through these factors, global change indirectly influences the forest structure of the Mangrove Marine Park. Generally speaking, in this study, the anthropogenic factors influencing the forest structure of the mangrove marine park are deforestation and bush fires. Indeed, deforestation reduces the carbon storage capacity of the MMP, thus increasing greenhouse gas emissions. According to Donato *et al.* (2011), degradation of mangrove ecosystems potentially contributes 0.02 - 0.12 Pg of carbon emissions per year, equivalent to 10% of total emissions due to deforestation worldwide. The same authors add that mangroves play an essential role in mitigating climate change, as they are capable of absorbing and storing 3 to 5 times more carbon than other mountain forests, mainly in the soil. As far as bush fires are concerned, the rise in temperature and the extension of the dry season under the influence of climate change are important factors that facilitate bush fires. According to Adjonou *et al.* (2009), climate change has a direct impact on bush fires, the intensity of which leads to the degradation of forest ecosystems. In a study carried out in the Sahelian and Sudanian part of Senegal, Sow (2013) concludes that bush fires are influenced by biomass moisture content and relative air humidity, which in turn are conditioned by climate.

The climatic factors influencing forest structure in this study are precipitation, salinity, temperature, wind, etc. These factors are directly influenced by climate (Kokou et *al*., 2024, Teteli *et al.*, 2022). Indeed, for Lenssen *et al.* (2019), climate change leads to an increase in temperature. Many climate changes act on the temperature change, the precipitation change, the continental and the terrestrial water salinity, wind regimes that cause windthrow (UNFCC, 2011). According to Sultan *et al.* (2001) and Kokou et *al*. (2024) climate variability impacts vegetation through temperature, a factor that favours plant development in general. Climate change has strong repercussions and exacerbates existing pressures on coastal ecosystems. According to IPCC (2007) the rise in relative sea level and seawater temperature, with a possible increase in precipitation frequency, salinity regime and community composition due to changes in salinity and a change in primary production are highly influential elements. Changes in physical parameters linked to climate change, such as the atmospheric concentration of carbon dioxide (CO2), are likely to alter photosynthetic rates (Ball *et al.,* 1997), but there is likely to be little or no change in canopy production, although species responses differ (Alongi, 2002, 2008). In terms of storm intensity and frequency, defoliation is one of the major impacts (Cahoon 2003). In terms of precipitation, increased precipitation can increase diversity and improve growth and cover through the colonization of new areas that were previously devoid of vegetation, whereas reduced precipitation will lead to the opposite (Smith and Duke, 1987).

5. Conclusion

This study has shown the influence of anthropogenic and climatic factors on forest structure in and around the Mangrove Marine Park. It should be noted that the forest structure parameters vary from one area of the park to another, for reasons linked to human activities and climate change. The first hypothesis of this study is therefore confirmed. The most anthropized areas have the lowest values of forest structure parameters, as in the case of deforested mangrove swamps. Less disturbed areas, on the other hand, have high values for forest structure parameters such as carbon sequestration. The reduction in carbon sequestration resulting from the disappearance or disturbance of mangroves accentuates the effect of greenhouse gases and thus climate change. There is therefore an important link between forest structure and global change. It will be important for mangrove marine park managers to take appropriate measures to mitigate the effects of global change, which is a major threat to the park's sustainability.

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Authors' contributions

Contributor's role	**Authors' names**
Conceptualisation	Bernard Riera, Teteli Soloum Clément, Kokou Kokouvi Bruno, Elangilangi Molo Jacques, Mukotanyi Serge, Lobho Joel Lopa, Diop Alioune Badara, Ngoie Longwa Leontine, Lwanzo Daniel Virekero, Mbavumoja Tresor Selemani, Muhindo Mutumwa Anselme, Ahouandjinou Sèdjro David Igor Thierry Kévin, Pyame Onyo David
Data management	AGIFT

Formal analysis	Teteli Soloum Clément, Kokou Kokouvi Bruno, Elangilangi Molo Jacques, Mukotanyi Serge
Acquisition du financement	ERAIFT
Survey and investigation	Kokou Kokouvi Bruno, Teteli Soloum Clément, Elangilangi Molo Jacques, Mukotanyi Serge, Lobho Joel Lopa, Diop Alioune Badara, Ngoie Longwa Leontine, Lwanzo Daniel Virekero, Mbavumoja Tresor Selemani, Muhindo Mutumwa Anselme, Ahouandjinou Sèdjro David Igor Thierry Kévin, Pyame Onyo David
Methodology	Bernard Riera, Kokou Kokouvi Bruno, Teteli Soloum Clément, Elangilangi Molo Jacques, Mukotanyi Serge, Lobho Joel Lopa, Diop Alioune Badara
Project management	ERAIFT
Ressources	ERAIFT
Software	Kokou Kokouvi Bruno, Teteli Soloum Clément, Elangilangi Molo Jacques, Mukotanyi Serge
Supervision	Bernard Riera , Balandi Julien Bwazani
Validation	Bernard Riera, Balandi Julien Bwazani
Visualisation	Atakpama Wouyo, Bernard Riera
Writing – Preparation	Teteli Soloum Clément, Kokou Kokouvi Bruno, Elangilangi Molo Jacques, Mukotanyi Serge
Writing – Revision	Kokou Kokouvi Bruno, Teteli Soloum Clément, Elangilangi Molo Jacques, Mukotanyi Serge

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