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Comparative and Prospective Evaluation of the Carbon Potential of the Mangrove of the Sine-Saloum Delta (Senegal) from 2016 to 2021

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Abstract

With the rupture of the Sangomar spit and climate change, ecosystem functions such as carbon absorption and storage by the Saloum Delta Biosphere Reserve are threatened. Initiatives are carried out as a response to the degradation of the mangrove ecosystem, such as the PRECEMA project. To measure its impact, an assessment of the carbon potential of the mangrove was conducted in 2016 on permanent plots. The present study is part of the monitoring of carbon potential. It aims to contribute to the updating of information on the evaluation of carbon storage potential. The method "afforestation and reforestation of degraded mangrove habitats on a large scale CDM or AR-AM0014 version 04.0" was applied. The mangrove vegetation assessed is dominated by *Rhizophora racemosa* with 69.9% of the total. With a relatively bushy habit (height = 1.91 m), the height distribution shows a right skewness (Skewness = 2.17; Kurtosis = 4.07) with a tail containing more observations than a normal distribution. The distribution is observed for diameters is skewed with Skewness = 1.5 but Kurtosis = 2.3. Thus the stand is young with an average diameter of 3.90 cm and 79.6% of the trees have a diameter < 5 cm. The annual increase in carbon potential of the mangrove has decreased by 80% in 5 years (2016 assessment - 2021 assessment). For a 15-year period, the total carbon stock projected by the model increases globally from 201.396 $TeqCO_2$ in 2011 to 277,318 $TeqCO_2$ in 2026. The projections showed an overall annual stock decrease of 14,164 $TeqCO_2$ (94%). For 2021, the total projected stock (270.289 $TeqCO_2$) is slightly higher than the assessed stock (251.059 $TeqCO_2$), a difference of 7%. Also, the projected annual carbon stock for 2021 (2844 $TeqCO_2$) is higher than the assessed stock (1353 $TeqCO_2$), a gap of 52%.

Keywords

Carbon Sequestration, Mangrove Forest, Sangomar

1. Introduction

Carbon owes its importance to the fact that it alone forms more compounds than all the chemical elements combined through these bonds [1]. Carbon exists in an inorganic or organic form and in solid, liquid and gaseous states. Its transfer from one reservoir to another, is done by a set of numerous and complex biogeochemical processes, leading to a global cycle [2]. Human activities emit about 10 GtC/year through fossil fuel combustion, industries, transportation and deforestation. On the other hand, forest ecosystems, with their capacity to absorb and store carbon, play an important role in the context of climate change [3]. Indeed, for the same area of forest, mangrove biomass has the capacity to store three times more carbon than other types of forests [4]. It accounts for 3% of the carbon sequestered by tropical forests [5]. An amount of 1023 MgC/ha is stored in mangroves, *i.e.* 90% in the soil and 10% - 40% in aerial and root biomass [6]. Covering 4% of mangroves in Africa, the mangroves of Senegal are the most northerly in Africa with 200,000 ha [7]. The mangrove of the Saloum Delta represents 13.4% or an area of 58,300 ha [7]. However, it underwent a very strong degradation between 1970 and 1980 [8]. Its rate of regression is greater than its rate of appearance [9]. With the return of the rains in the 1990s, vegetation in the Saloum estuary regenerated [10]. It is therefore necessary to update the information by assessing the existing carbon potential. In 2016, the resulting carbon potential was evaluated by the PRECEMA project. The study contributes to the monitoring of the carbon potential of the Saloum Delta mangrove. Specifically: to evaluate the amount of carbon stored in the above-ground and root biomass in the soil and to analyze the evolution of carbon potential between 2016 and 2021. Two hypotheses are made in this study. The first asserts that the amount of carbon stored in aboveground and root biomass and in the soil increased between 2016 and 2021. The second argues that the increase in carbon potential is due to reforestation and conservation of the Delta mangrove or to other natural and anthropogenic phenomena.

2. Materials and Methods

2.1. Presentation of the Study Area

The present study was conducted in the communes of Toubacouta, Bassoul, Dionewar, Palmarin Facao, Djilor, Diossong and Djirnda in the Saloum Delta Biosphere Reserve (**Figure 1**).

The climate is Sudan-Sahelian [11] and rainfall varies between 400 and 800 mm. A nine-month dry season alternates with a three-month rainy season [12]. The soils are tropical ferruginous, hydromorphic, halomorph (saline and tannic

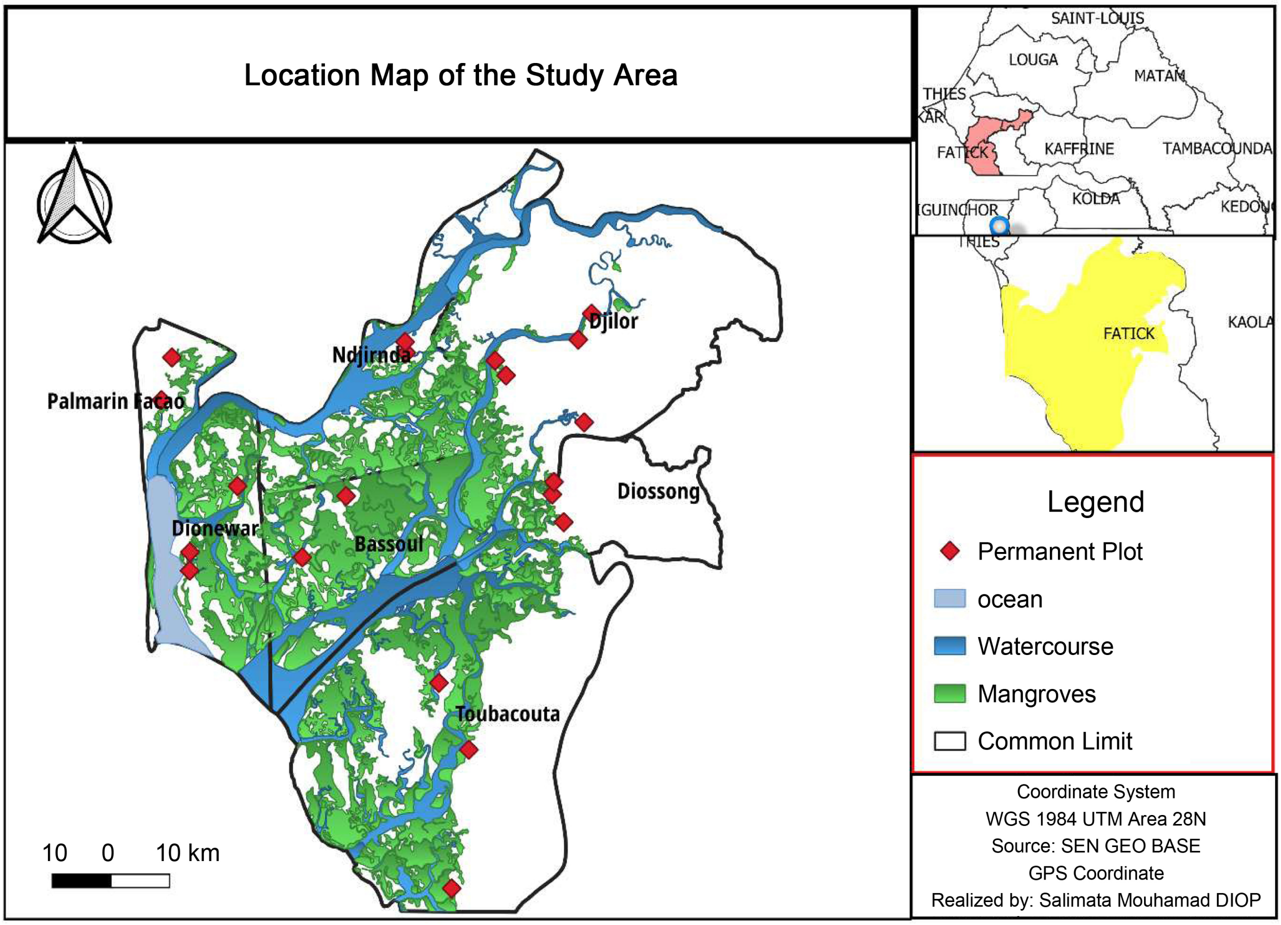

Figure 1. Location map of the study area.

soil) and mangrove mudflat soils. The relief is flat with dunes and accumulations of oysters and arches of less than 0.5 m in altitude [13]. The hydrographic network is formed by the sea arms, the Saloum, the Diomboss and the Bandiala. It is interconnected tidal connected to the Atlantic Ocean by a mouth [14]. The lack of freshwater inflow, the high evaporation of water colonizing the land and the inertia of the basin are at the origin of the reverse functioning of the estuary [15] [16]. The inertia of the basin causes delays in filling (7 h) and emptying (5 h 25) [16]. The vegetation is composed of gallery forests, open forests, wooded savannahs. The frequent species are *Borassus flabellifer* L., *Cordyla pinnata* Lepr. Ex A. Rich, *Combretum glutinosum* Perr. Ex DC, *Ziziphus abyssinica* Hochst, *Faidherbia albida* Del, *Pterocarpus erinaceus* Poir, *Detarium senegalense* J. F. Gmel, *Parinari macrophylla* Sabine, *Tamarindus indica* L., *Balanites aegyptiacus* L. Delile, *Khaya senegalensis* Desv. A. Juss, *Ceiba pentandra* L., *Adansonia digitata* L., *Acacia seyal* Del, *Acacia ataxacantha* DC. *Cocos nucifera* L. plantations are encountered in the islands [14] [17]. In the mangrove zone, six species are encountered: *Rhizophora racemosa*, *Rhizophora mangle*, *Rhizophora harrisonnii*, *Avicennia africana*, *Laguncularia racemosa* and *Conocarpus erectus*. The terrestrial fauna includes green monkeys, warthogs, spotted hyenas, bushbucks, jackals, greater cane rat, Nile monitors, *Python sebae* etc. The sedentary avifauna includes green pigeons, turtledoves, guinea fowl, and francolin. The migratory avifauna is represented by the pink flamingo, Gambia goose, sacred ibis, ducks… The fish fauna includes fish, mollusks, shrimps, crabs. As a result of this diversity, six leased areas are being built. The density is 115 inhabitants/km^2 in 2019 [12].

2.2. Methods

The study is part of the monitoring of the carbon potential assessed in 2016 by the RECEMA project. Its purpose is to assess the evolution of the said potential from 2016 to 2021 and to compare the results obtained with those of the proposed modeling. Therefore, the same method was applied on the same permanent plots. It is the CDM afforestation and reforestation Large-scale methodology: AR-AM0014 "afforestation and reforestation of degraded mangrove habitats", version 4.0. This modelling of storage covers 6000 ha including 300 ha of reforestation and 5700 ha of management. The selected carbon sinks are aboveground biomass (trunk, branches, and leaves), belowground biomass (roots), dead wood and soil.

2.2.1. Sampling Methods

Stratified sampling was based on the division of the area into homogeneous units according to land use. These homogenous units are subdivided into more homogeneous sub-areas in terms of ecological facies. For a given sub-area, a cluster of four (4) circular plots is installed twenty meters (20 m) from the cluster center along the cardinal directions. The cluster arrangement allows for the heterogeneity of the site to be taken into account. The network of permanent plots is designed to cover the entire area, ensuring the most homogeneous spatial distribution possible.

2.2.2. Distribution of Permanent Plots Done in 2016

The high mangrove (HM) and the low mangrove (BM) are the identified strata. Based on accessibility (HM = 38,953 ha; BM = 29,823 ha), the number of plots to be surveyed is defined for each stratum (**Table 1**).

The network of permanent plots consists of 22 clusters of 88 plots located in the PRECEMA project area. The cluster is installed around a central point found by GPS. With the SUUNTO compass, the centers of the four circular plots are marked along the cardinal directions at 20 m from the cluster center. Each plot has a radius of 10 m (**Figure 2**).

Table 1. Distribution of inventoried plots by mangrove type.

Strata	Number of clusters	Number of plots
High mangrove	9	36
Low mangrove	13	52
Total	**22**	**88**

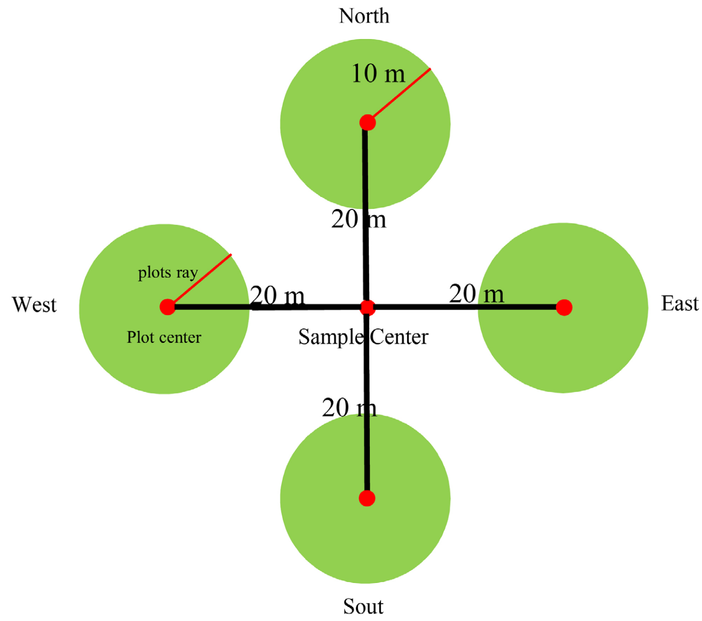

Figure 2. Permanent plot cluster.

2.2.3. Sampling

The inventory protocol developed in 2016 was adopted. On an inventory form, the dendrometric and station characteristics are filled in, including the date, time of departure and arrival, the plot number, the attached village and the status of the vegetation. In addition to the scientific name of the species, the dendrometric characteristics are recorded: the diameter at the base at 5 cm (D0) and the diameter at 1.3 m from the ground (DHP) taken with a forestry compass, the height taken with a SUUNTO dendrometer, the cross-sectional diameter of the crown with a tape measure and the number of *Rhizophora* per foot counted.

2.3. Data processing

Cover is estimated by calculating the average crown area from the cross-sectional diameter of the "large crown" and "small crown":

$$S = [\pi(L\_mean/2)]^2.$$

S = crown area, Lmean = cross crown diameter and $\pi = 3.14$.

The crown of the trees in a cluster is reported on the area of the cluster (1256 m^2).

The carbon stored by the mangrove is the sum of carbon stored by tree biomass (above and below ground), dead wood, and carbon stored in the soil [18] through the following equation:

$$\Delta CO_2 = \Delta CO_{2\ Tree} + \Delta CO_{2\ Dead\ Wood} + \Delta CO_{2\ Soil}$$

2.3.1. The Amount of Carbon Stored by Tree Biomass ($\Delta CO_{2\ TREE}$)

The amount of carbon in the tree biomass is obtained following a dozen calculations previously made with the Excel spreadsheet. The database developed included:

- Average diameter by species (*Rhizophora* or *Avicennia*), by plot and by stratum,
- Above-ground biomass by species and by stratum,
- The average number of stems per species, per plot and per stratum,
- The number of contacts per species, per plot and per stratum,
- The density by species and stratum ($density_{j\ HM/BM}$),
- The ratio (R_j) of below-ground to above-ground biomass per hectare by species and stratum,
- Tree biomass/ha and by stratum ($b_{TREES\ HM/BM}$),
- The biomass of trees present in year t ($B_{.tree,t}$) in grams of dry matter (gdm),
- The amount of carbon stored by the biomass trees ($CO_{2\ trees,t}$) in year t (teq-CO_2),
- The amount of CO_2 stored by the trees ($\Delta CO_{2\ tree,t}$).

2.3.2. The Amount of Carbon Stored by Dead Wood ($\Delta CO_{2\ DEAD\ WOOD,t}$)

This amount results from the change in the amount of carbon stored by dead wood at t in $TeqCO_2$ in high and low mangroves ($\Delta CO_{2\ DEAD\ WOOD,t,\ HM/BM}$) which is the amount of carbon stored by dead wood at year t in $TeqCO_2$ ($CO_{2\ DEAD\ WOOD,t,HM/BM}$) following the equation:

$$\Delta CO_{2\ DEADWOOD,t} = \Sigma CO_{2\ DEADWOOD,t}$$

To estimate the amount of carbon stored by dead wood at a year t, the conservative default equation in section 6.2 of AR-TOOL12 is used [10]:

$$CO_{2\ DEADWOOD,t,\ HM/BM} = CO_{2\ TREES,HM/BM,t} \times DF$$

$CO_{2\ DEADWOOD,t,HM/BM}$ = Amount of carbon stored by deadwood in year t in $TeqCO_2$;

$CO_{2\ TREE,t}$ = Amount of carbon stored by tree biomass in year t in TCO_2/year);

DF = conservative ratio of carbon stored in dead wood to carbon stored in tree biomass in percent DF = 1%.

2.3.3. The Amount of Carbon Stored by the Soil ($\Delta CO_{2\ soil,t}$)

The amount of carbon stored by the soil in year t in $TeqCO_2$ is:

$$\Delta CO_{2\ SOL,t} = \Sigma 44/12 \times \text{Proj area} \times dSOCt \times 1\ yr$$

$Surface_{Proj}$ = Reforestation surface = 300 ha and management surface = 6000 ha;

dSOCt = Ratio of soil carbon stock change in one year in $TeqCO_2$/ha;

dSOCt = 0.5 tC for $t_0 < t < t_{20}$ and dSOCt = 0 tC for $t > t_{20}$.

The evolution of mangrove carbon sequestration was monitored by comparing the results of the assessment to those of the modeling projection made in 2016.

3. Results and Discussion

3.1. Results

3.1.1. Permanent Plots in 2021

In 2021, the study was conducted in 20 clusters or 80 plots from the 22 clusters and 88 plots installed in 2016 (**Table 2**). The geographical coordinates of 2 clusters have not been found and the 3rd cluster, that of Dionewar, is bare.

Figure 3 is an illustration of the Dionewar bare cluster with 4 bare plots.

3.1.2. Structuring of Mangrove Stands

1) Specific diversity

The 3 main species encountered are *Rhizophora racemosa*, *Rhizophora mangle* and *Avicennia africana* (syn: *Avicennia germinans*). **Table 3** shows a dominance of *R. racemosa* with 69.9% of total contacts and 76.5% of individuals on the high mangrove. It also remains dominant in the low mangrove with 61.8% of contacts.

2) Vertical structure

The subjects were classified according to height with 1.3 m amplitude. **Figure 4** represents the distribution of mangrove individuals according to height classes. The vertical structure shows a predominance of individuals of height class between 1 and 2.3 m. This mangrove has a bushy habit with an average height of 1.91 m. The height distribution (in L) shows a right skewness (Skewness = 2.17) with a tail containing more observations than a normal distribution (Kurtosis = 4.07). The height peaks at 6.5 m.

3) Horizontal structure

Individuals were classified according to diameter with a range of 2 cm. **Figure 5** represents the distribution of the inventoried individuals in diameter class. The lower classes (1 and 2) have almost all the individuals of the mangrove. The classes (7 and 8) of diameter between 13 and 17 cm have few individuals. Indeed,

Table 2. Number of permanent plots surveyed in 2021.

Strata	Number of clusters		Number of plots	
	2016	2021	2016	2021
High mangrove	9	7	36	28
Low mangrove	13	13	52	52
Total	**22**	**20**	**88**	**80**

Table 3. Average frequency of species inventoried by type of mangrove.

Species	High mangrove		Low mangrove		Total	
	Number of contacts	%	Number of contacts	%	Number of contacts	%
Avicennia africana	106	13.6	245	8.6	351	9.6
Avicennia sp	8	1.0	29	1.0	37	1.0
Rhizophora mangle	63	8.1	591	20.6	654	17.9
Rhizophora racemosa	598	76.5	1950	61.8	2548	69.9
Rhizophora sp	7	0.9	50	1.7	57	1.6
Total	782		2865		3647	

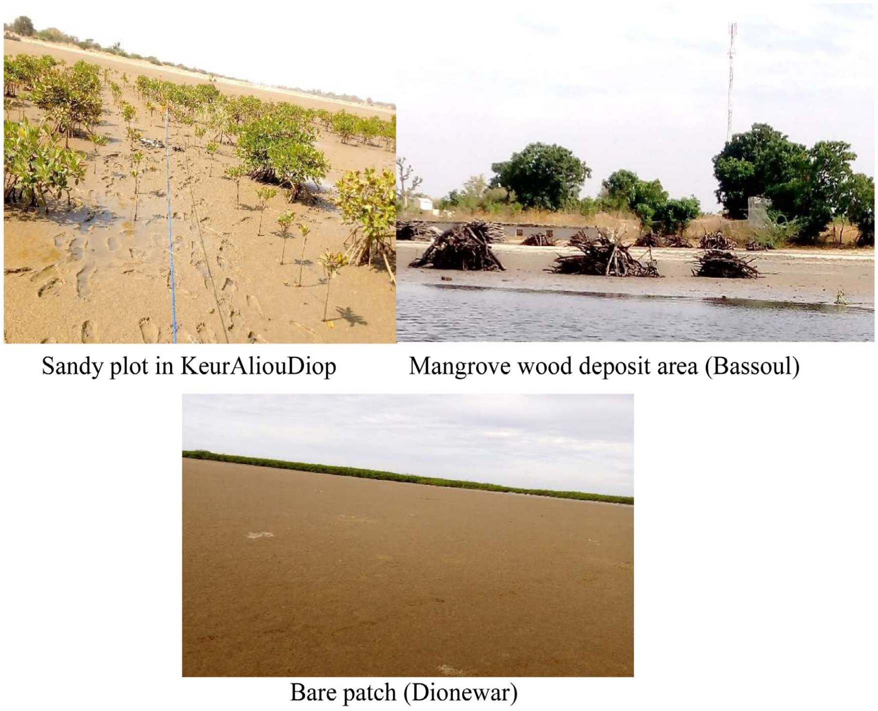

Figure 3. Surveyed plots and wood disposal area.

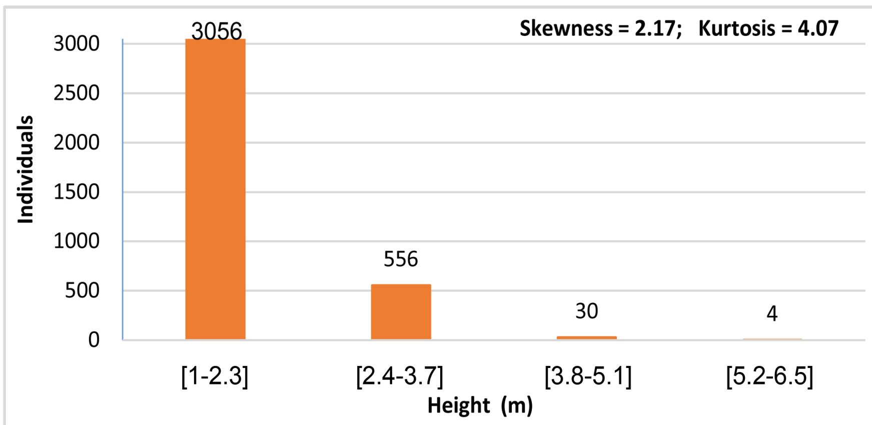

Figure 4. Number of individuals per height class.

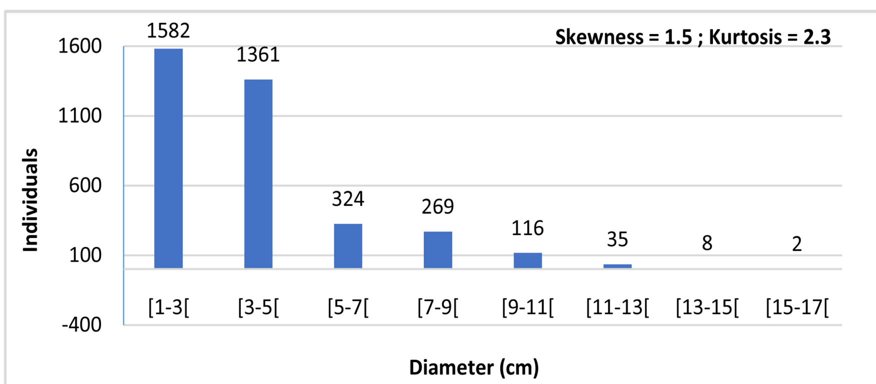

Figure 5. Number of individuals per diameter.

the appearance of the figure reveals a young mangrove. The distribution is L-shaped or inverted J-shaped with an average diameter of 3.90 cm (right asymmetry) and 79.6% of subjects have a diameter less than 5 cm.

Figure 6 presents the coverage rates by locality. The highest rates are noted in the localities of Bambougar Malick, Keur Mbar, Mansarinko and Sadioga. Their recovery is above 50% (from 58.34% to 72.18%). On the other hand, the lowest rates are in Diogane, Falia, Niodior and Péthie with recoveries of less than 20% (from 06.03% to 14.52%). The average for all samples is 36.50% and the coefficient of variation (55.63%) attests to a heterogeneous vegetation cover. Note that each village name in this Figure 6 represents the plots inventoried.

- **Coverage according to mangrove strata**

Recovery was calculated for the high mangrove and low mangrove (Figure 7). The high mangrove has a higher average coverage (CV = 43.38%) than the low mangrove (CV = 61.64%) which has a more heterogeneous coverage.

3.1.3. Amount of Carbon Stored in 2011, 2016, 2021 and 2026

The evolution of the carbon potential is followed on the one hand over five (05) years on the basis of evaluations carried out in 2016 and 2021 and on the other hand over fifteen (15) years on the basis of projections according to modeling

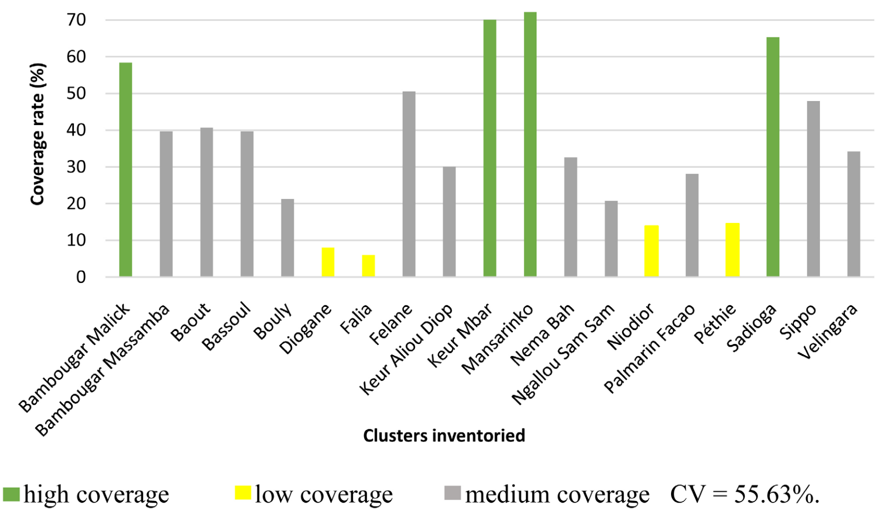

Figure 6. Coverage rate by location.

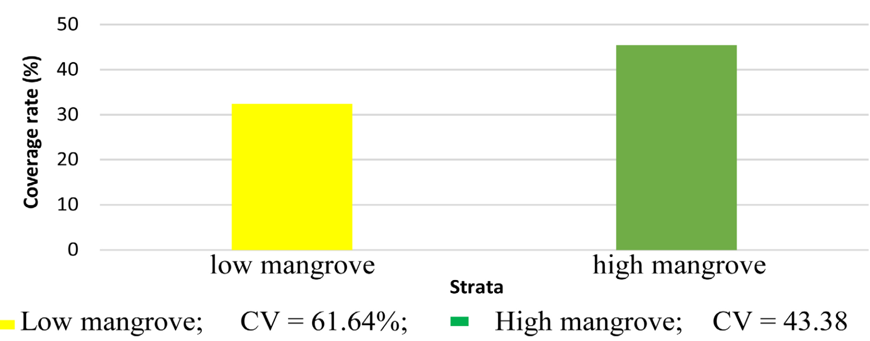

Figure 7. Coverage rate by stratum.

from 2011 to 2026.

1) Total carbon stock assessment in 2016 and 2021

The first evaluation was made in 2016 by the PRECEMA project and 5 years later, the second evaluation was made through this study of 2021. Thus the total carbon stock increased by 1353 $TeqCO_2$ (**Figure 8**) which corresponds to an average annual stock of 270.6 $TeqCO_2$. The carbon stock value (projected) is related to the period for 100% of the cases.

2) Average annual change in potential from 2016 to 2021 according to the assessment

The average annual change in carbon potential in 2016 is much higher than that of 2021 (**Figure 9**). In five (05) years, the mangrove has lost 20% of its potential.

3) Total carbon stock projection from 2011 to 2026 based on modeling

Overall, the projected carbon potential is increasing from 2011 (201,396 $TeqCO_2$) to 2026 (277,318 $TeqCO_2$) (**Figure 10**). For 2021, the model predicts a stock (270,289 $TeqCO_2$) slightly higher than the stock actually assessed (251,059 $TeqCO_2$), a gap of 7%. The value of carbon production (projected) is related to the period for 84% of the cases.

4) Average annual change in potential from 2011 to 2026 as projected

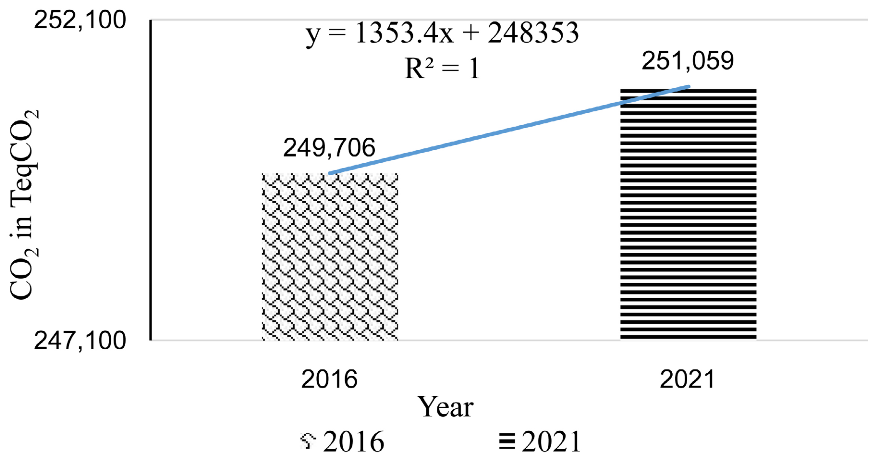

Figure 8. Total carbon storage in 2016 and 2021.

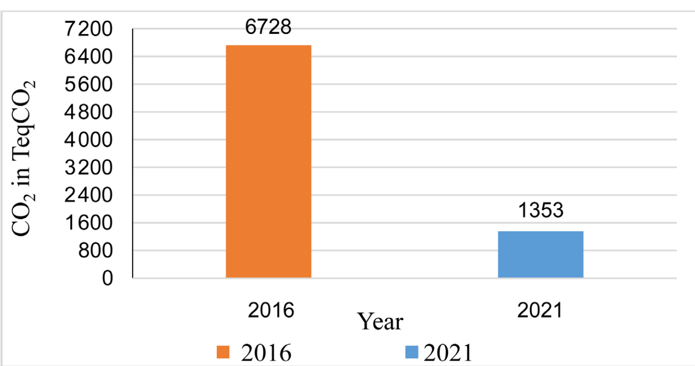

Figure 9. Average annual change in carbon potential in 2016 and 2021.

From 14,990 TeqCO_2 in 2011, the potential decreases to 826 TeqCO_2 in 2026, a decrease of 14,164 TeqCO_2 (**Figure 11**). Moreover, the quantity obtained with the projection for 2021 (2844 TeqCO_2) is higher than the one actually evaluated (1353 TeqCO_2) for the same year; that is to say a difference of 52%. The value of the projection is related to the period for 75% of the cases.

5) Average annual change in potential from 2011 to 2021 for the 19 clusters

The results from the 22 clusters were reported to 19 clusters as for the 2021 assessment. The average annual carbon change in the 15-year time interval is steadily decreasing (−2781.8). Also the potential obtained with the projection according to the modeling for 2021 remains always higher than the potential actually evaluated (**Figure 12**). The value of the carbon potential is related to the period for 76% of the cases.

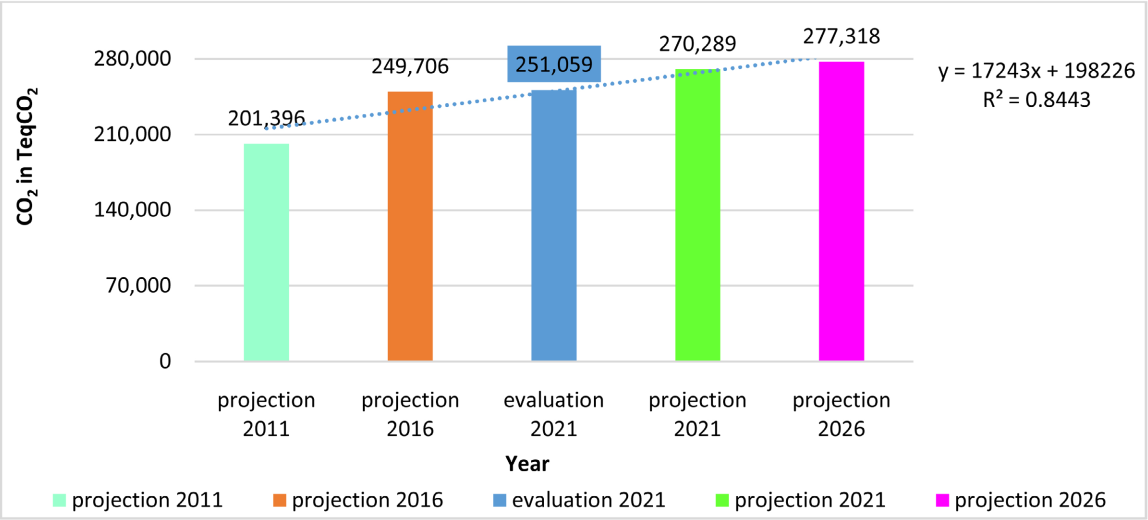

Figure 10. Total carbon stock projection from 2011 to 2026.

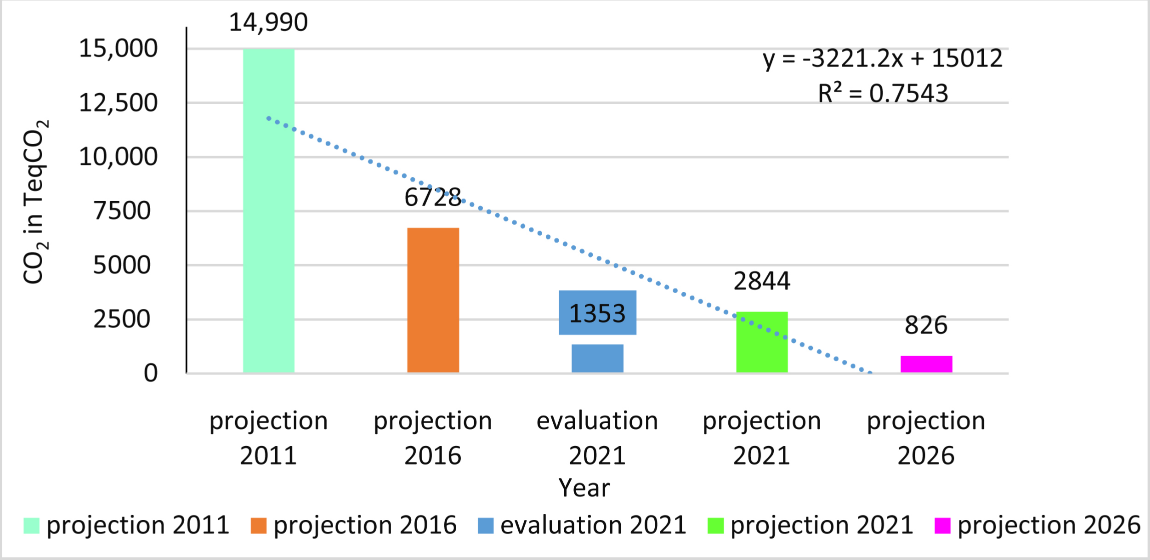

Figure 11. Average annual change in carbon potential from 2011 to 2026.

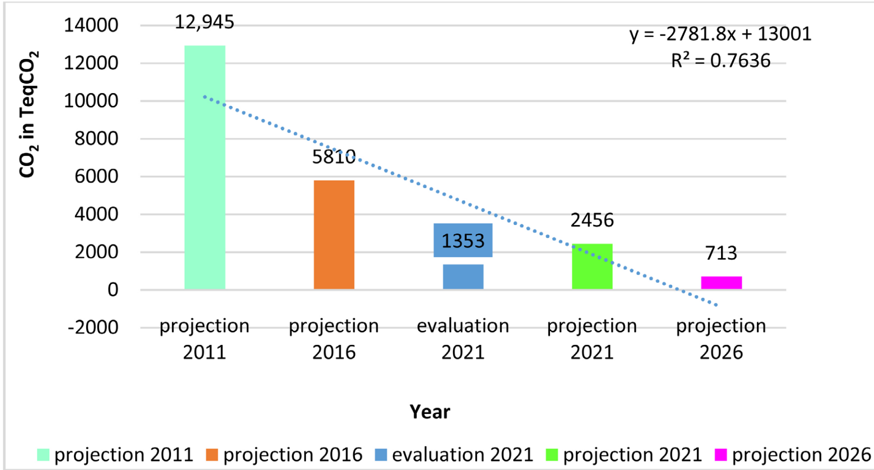

Figure 12. Annual change in carbon potential from 2011 to 2026 reported on 19 clusters.

3.2. Discussion

3.2.1. Changes in Mangrove Stand Structure from 2016 to 2021

In terms of specific diversity, 3 main species were inventoried: *Rhizophora racemosa*, *Rhizophora mangle* and *Avicennia africana*. In 2021, *Rhizophora racemosa* is dominant in all strata. In contrast, in 2016, *Avicennia africana* was dominant in the lower mangrove [10]. It occupied 27% of total contacts in the first assessment [10] and 9.6% in the second. Results reveal that *A. africana* is in the minority in 12/19 clusters inventoried. This species seems to be a victim of the effects of climate change and logging, while the dominance of *R. racemosa* would be related to its share in reforestation. Indeed, PRECEMA's goal was to restore 50 ha of *Avicennia* reforestation (300,000 seedlings) and 250 ha of *Rhizophora* (1,250,000 propagules) [10]. During the survey, *R. racemosa* was found in 17/19 bunches and was dominant in 12 bunches with percentages varying from 57% for Bouly to 100% for Diogane. It is absent in the clusters of Baout and Bambougar Massamba and weak in Sadioga. For the vertical structure, the highest heights noted during the inventory in 2021 reach 5.5 m for *A. africana* and 6 m for *R. racemosa*. It is 5.8 m for *A. africana* and 7.8 m for *R. racemosa* [10]. The horizontal structure reveals high numbers in the smaller diameter classes in 2021. Indeed, for all clusters and all species combined, diameter classes between 4 cm and 9 cm are dominant [10]. This may indicate that woody individuals with stems larger than 05 cm in diameter are preferred for harvesting. The average recovery of mangrove stands is 36.50% with a coefficient of variation (CV) of 55.63% in 2021. It was 40.58% with a CV of 50.54% in 2016 [10]. This decrease in the cover rate reflects the level of degradation observed in the low mangrove, hence the relatively sparse state of the stand.

3.2.2. Disparity between the 2016 and 2021 Clusters

The data showed a disappearance of vegetation in some clusters testifying to the degradation of the mangrove. In addition, the loss of data for certain clusters calls into question the backup of project data. And the pattern of distribution of young individuals relates to the choice of reforestation and preservation sites. Indeed, if the reforestation site is very close to the houses, the plants are trampled by the cattle but also by the fishermen looking for space to maintain their fishing nets.

3.2.3. Evolution of the Carbon Stock

The total carbon stock increases overall during a 15-year period (2011-2026). In contrast, the annual change in potential shows a decline since 2012 [10]. Between 2011 and 2026 (projection), it goes from 14,990 $TeqCO_2$ to 826 $TeqCO_2$. For 2021, the total carbon stock assessed is still lower than the model projection. The small annual increase in stored carbon is thought to be due to the loss of reforested plants and limited monitoring of conservation areas. These include the adverse effects of climate change (drought, salinity, silting, erosion of Sangomar), anthropogenic actions, local governance and the lack of coordination between actors. The Sangomar rupture caused abrupt erosion of the mangrove with increased salinity, marine hydrodynamic forces, and sandy sedimentation [10] [19]. Indeed, the sites of Falia, Bambougar Massamba, Bassoul and Diogane have one of the four plots located in the sandy and bare tans. Despite reforestation, the mangrove has declined significantly in Djirnda and Bassoul with salinity, silting and erosion [14]. Sonwa [20] estimated carbon stocks of 243 t/ha in cocoa farms in southern Cameroon. However, some areas are well protected (Bouly, Keur Mbar, Diogane, Pethie, Keur Aliou Diop and Niodior) with restoration actions and natural regeneration of Rhizophora noted in the island of Sippo, in Ngallou Sam, Keur Mbar, Falia, Nema Bah, Niodior and in Avicennia in Mansarinko. Despite the threats, Faye [14] reveals the good condition of mangroves in landlocked and island areas.

4. Conclusion

This work is part of the monitoring of the carbon potential of the mangrove of the seven communes evaluated in 2016 by the PRECEMA project. For a 15-year period (2011 to 2026), the projected carbon stock gradually increases. But conversely, annual gains are steadily declining. The projected 2021 stock results are slightly higher than those estimated for both the total stock and the annual gain. This annual decline in the projected stock is caused by natural factors, most often related to climate change, anthropogenic factors and the failures of stakeholders. However, the results of the projection remain theoretically in line with the reality on the ground. However, to reach the potential of the model in a future assessment, measures will have to be taken to limit the stresses on the mangrove. Despite the threats to the Saloum Delta mangrove, it remains an important carbon sink for climate change mitigation. These results are an alert for the reinforcement of conservation and restoration actions but also an orientation for the elaboration of new action plans to mitigate the impacts of the Sangomar spit rupture. Thus it would be important to conduct this study in other mangrove areas.

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Author Contributions

SMD worked on the protocol, inventory, data processing, and writing of the article. MT, ON, and CS led the work from protocol writing, data collection and processing, and writing. SN supervised the work.

Conflicts of Interest

The authors declare that they have no conflicts of interest in their article.

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