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Estimation of the Carbon Sequestration Dynamics of Senegal's Great Green Wall Based on Land Cover over the Past Three Decades

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Abstract

The severe drought observed in the Sahel during 1970s, 1980s and 1990s has deeply affected the population as well as the economies and the eco-systems of this climatic area. The GGW Initiative spearheaded by Africa Union in 2007 proposed to combat the land degradation and desertification by planting a wall of trees stretching from Dakar to Djibouti. A reforestation was then conducted in the Senegal's GGW since 2006 as part as other areas in the Sahel. This paper aims to evaluate the carbon sequestration dynamics in the sites of the Senegal's GGW over the last three decades. The method consists firstly of analyzing the evolution of land cover and land use dynamics based on ESA-CCI LC satellite data. There is an improvement of the surface areas of tree and shrub savanna of 11.40% (Tessekere), 8.25% (Syer) and 2.70% (Loughere-Thioly). The regreening of the different localities and a positive dynamic observed is explained by the return to normal rainfall and to reforestation actions, agroforestry practices, better management of natural resources undertaken. However, some non-reforested sites showed an opposite trend despite of the normal rainfall. Secondly, the results on land mapping are used as a proxy for the assessment of carbon stocks. The dynamic observed in vegetation cover since the beginning of the reforestation made it possible to sequester 5.8 million tons of carbon representing respectively 2.31% of African GGW. This gain in stored carbon is equivalent to 21.2 million tons of CO_2 captured in the atmosphere. Through this study, it appears that carbon storage becomes significant 8 to 10 years after the start of reforestation. An urbanization without respect for the environmental factors could be a danger for the climate (case of Ballou).

Keywords

Great Green Wall of Senegal, Land Cover-Land Use (LCLU), Carbon Storage

1. Introduction

The Sahel region has experienced some of the most extreme climate events in the 20th century. The drought recorded particularly in the 1970s and 1980s has greatly affected the populations as well as the economies and the ecosystems of this region. The consequence was the displacement of the isohyets by about 200 km over the whole region ([1] [2] [3] [4] [5]). The Sahel became then highly vulnerable to climate change because of the dependence of its population on rainfed agriculture and transhumance systems. The land degradation due to this drought is characterized by a negative trend in land condition, typically involving the total or partial loss of vegetation cover, soil fertility, productivity and/or biodiversity, leading to a decline in ecosystem services ([6]-[17]).

In the Sahel, among the different initiatives to combat the land degradation and desertification and its impacts on ecosystems is the Great Green Wall Initiative, spearheaded by African Union in 2007 ([18]). This project aims to reverse land degradation and desertification in this emblematic region. The original objective has evolved from a focus on afforestation to an integrated ecosystem management approach that aims to develop a mosaic of different sustainable land use and agricultural productive systems ([19] [20]).

Fifteen years after the beginning of the reforestation in Senegal GGW, many studies were conducted to assess the impacts of these interventions on climatic parameters and vegetation dynamics. According to [17], there is an increase in vegetation activity through the NDVI at the interannual (+2% to +8%) and seasonal (+1.5% to 7% for the wet season and 1% to 4% for the dry season) scale and a positive and significant evolution is noted on the trace of the GGW. Also, the period 2009-2020 recorded an increase in rainfall of 2% to 8% of the average value 2000-2020 and 4% to 8% of the rainy season. The most remarkable result is about the soil moisture which has increased the most between 20 mm and 70 mm during 2000-2009. This change in Land use and, hence, vegetation cover directly impacts surface water, and energy budgets through plant transpiration, surface albedo, emissivity and roughness. They also affect primary production and, therefore, the carbon cycle.

A big issue in this project remains the carbon capture through the regreening of the Sahel region. Many programs have been developed at global scale since 1980s to understand land-atmosphere interactions and their effects on climate. The global monitoring of earth's vegetation cover had been identified as a major task of the International Geosphere-Biosphere program (IGBP), a program which ran from 1987 to 2015. The Global Carbon Project (GCP) was established in 2001 by a shared partnership between the International Geosphere-Biosphere Programme (IGBP) the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP) and Diversitas (https://www.globalcarbonproject.org/about/index.htm).

The GGW project aims to restore 100 million hectares of degraded land by 2030, capturing 250 million tons of carbon dioxide.

https://www.unccd.int/resources/publications/great-green-wall-implementation-status-way-ahead-2030).

In Senegal, over 18 million trees had been planted. In September 2020, it was reported that the Great Green Wall Senegal had only covered 4% of the planned area, with only 4 million hectares (9.8 million acres) planted [21]. Till now, the balance of the carbon stored derived from the reforestation is not assessed. This study aims to assess the carbon since the beginning of the reforestation and how it is sequestered.

However, the calculation of the stored carbon and the annual sequestration can be difficult to measure directly and requires specialist knowledge. It can be done more simply by using figures that have come from research and are provided in the Carbon MPI look-up tables for forestry and the Emissions Trading Scheme. The look up tables provide a value of tons of carbon dioxide per hectare. In this paper, we suggest to evaluate the carbon stock in the GGW Senegal area from 1992 to 2020. The assessment of carbon in the GGW results of the combination of carbon storage rate associated to a land cover/land-use class and the surface of area of this class. The first step aims at producing land cover and land-use maps. Then, the results on land mapping will be used as a proxy for the assessment of carbon stocks. The specific objectives of this paper are as follow:

1) analyzing the Land cover dynamic from 1992 to 2020.

2) assessing the carbon stocks due to reforestation.

The structure of this paper could be summarized as follows:

The description of the study area, the data sources (Land cover dataset ESA-CCI LC) and the methods are described in Section 2. The results and discussions are presented in Section 3.

2. Data and Methods

2.1. Study Area

Senegal is a country in West Africa located between 12˚8'N-16˚41'N and 11˚21'W-17˚32'W. It has a surface area of 196,722 km^2 and an estimated population of 17,215,433 in 2021 [22]. This Sudanese-Sahelian country has few rivers and regular rainfall deficits. It also has a rainy season (from June to October) and a dry season.

The rainy season peaks in August-September and varies with latitude. This rainy season corresponds to the monsoon period in the Sahel. Rainfall is lower in the north than in the south. The northern region of Senegal registers an average annual-rainfall of about 400 mm, whereas in the south it reaches 1000 mm. The

Senegalese growing vegetative season extends from July to November. In the north, this season starts generally in August and ends in October [17].

Figure 1 shows the Great African Green Wall (GGW) crossing northern Senegal. It is 15 km wide and about 545 km long. It represents 7% of the total length of the GGW. This line covers a surface of 817500 hectares. It passes through three regions: Louga, Matam and Tambacounda (Table 1). For this study, we selected at least one site in each region that has been subjected to various GGW reforestation

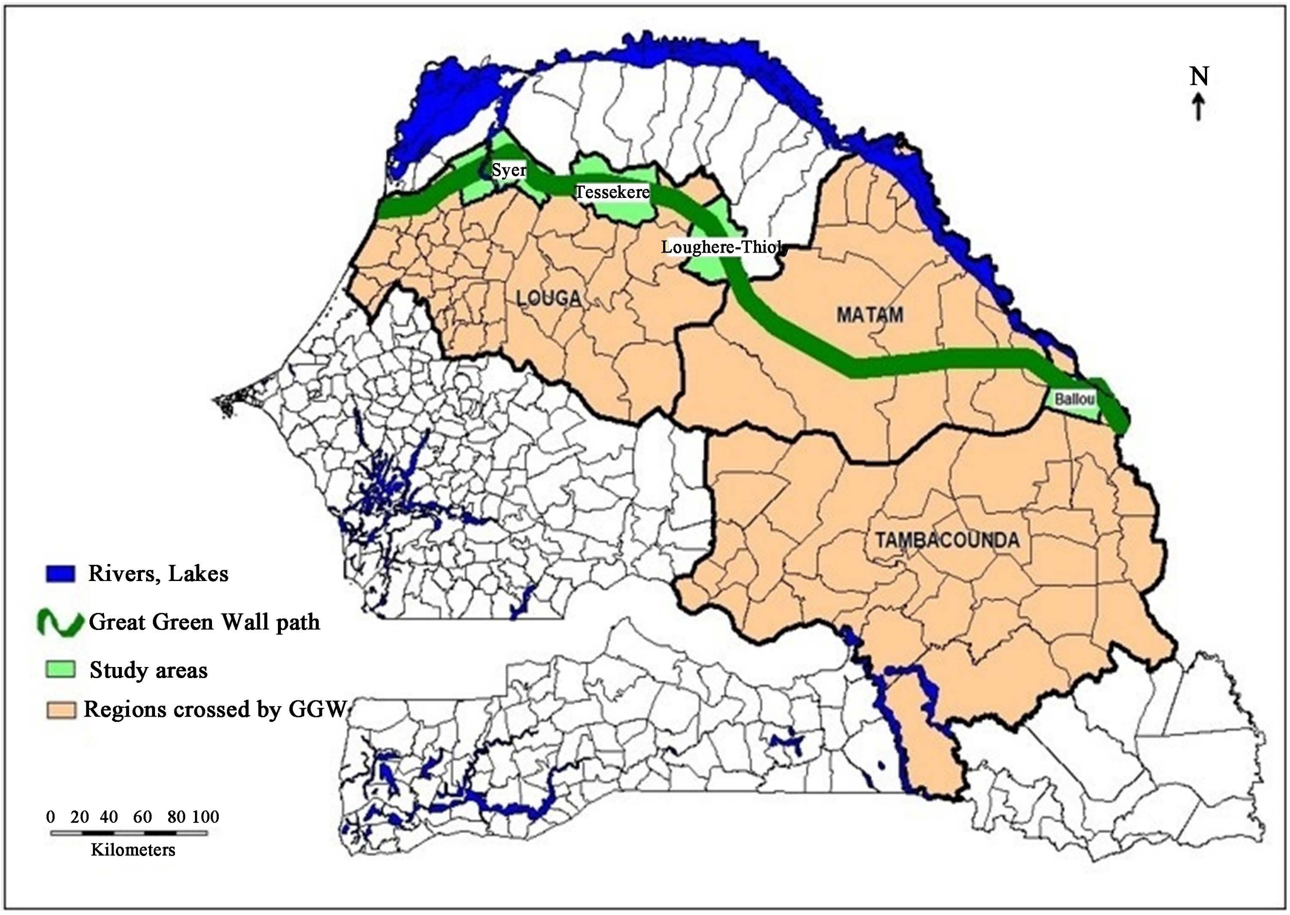

Figure 1. Location of study area and line of the GGW in Senegal (Source: [17]).

Table 1. Climatics characteristics (from [17]) and soil characteristics ([23]) of the sites selected for our study.

Municipalities (Administrative regions)	Precipitations (mm) 2000-2020	Soilmoisture (mm) 2000-2020	Soils types	Main land cover classes	Municipality area (Km^2)
Syer (Louga)	291.85	98.7	Brown Red soils; Ferruginous Tropical soils	TreeSavanna; Steppe/Grassland	2000
Tessékéré (Louga)	323.27	99.4	Ferruginous Tropical soils	TreeSavanna	2100
Loughéré-Thioly (Matam)	385.82	97.2	Lithosols soils	Shrub Steppe; Tree Savanna	1800
Ballou (Tambacounda)	576.49	150.2	Hydromorphic soils; sub-arid brown soils	RainfedCrops, Shrub Steppe	1210

surveys since 2006 (See Tables 1-3 and Figure 1).

The main soil types encountered in Senegal are, in order of importance: non-leached and leached tropical ferruginous soils (34.40%), lithosols (21.38%), hydromorphic soils (10.93%), regosols (8.16%), less developed soils (7.74%), red-brown soils (6.15%), ferrallitic soils (5.78%), halomorphic soils (2.90%), vertisols (1.65%), sub-arid brown soils (0.64%) and crude mineral soils (0.27%)

Table 2. Status of GGW implementation in Senegal from 2008 to 2015 (Source: APGMV https://www.grandemurailleverte.org/).

Years	Plants products	Area reforested (Ha)	Firebreaks (Km)	Exclosure (Ha)
2008	2,500,000	5000	240	
2009	2,200,000	3000	2100	
2010	2,700,000	3700	2200	
2011	1,650,000	4000	2560	13,000
2012	1,950,000	3900	1200	
2013	2,025,000	5000	1500	
2014	1,380,624	4000	1500	
2015	1,733,800	4700	1500	
Total	**16,139,424**	**33,300**	**12,800**	**13,000**

Table 3. GGW reforestation campaign and results in Senegal by the Green Heart Foundation from 2006 to 2019 (Source: Green Heart Foundation, https://fondationcoeurvert.org).

Years	Sites	Plants products	Area reforested (Ha)
2006	WidouThiengoly (Tessekere)	31,540	250
2007	Loumbol Samba Abdoul (Ouadalaye)	25,000	252
2008	Tessekere	75,000	594
2009	LougherеThioly	192,500	1200
2010	Syer	162,500	1040
2011	Mbar Toubab (Syer)	110,000	443
2012	Mbar Toubab (Syer)	40,000	250
2013	Mbar Toubab (Syer)	110,000	443
2014	BellyGawdy Cherif (Syer)	27,975	225
2015	Bélèl Aya (Syer)	50,000	250
2016	Tagar (LougherеThioly)	36,000	180
2017	Mbanar	57,000	220
2018	Kalom	76,250	305
2019	N'Gadou Thiel	88,000	176
Total		**1,081,765**	**5828**

[23]. On the other hand, the main soil types crossed by GGW Senegalese, from west to east, are dry sandy soils, ferruginous soils, red-brown soils, lithosols and sub-arid brown soils.

2.2. Data Sources

The land cover dataset is from the European Space Agency Climate Change Initiative Land Cover (ESA-CCI LC) and Copernicus Climate Change. This dataset provides global maps describing the land surface into 22 classes, which were defined using the United Nations (UN) Food and Agriculture Organization (FAO) Land Cover Classification System ([24] [25] [26] [27]). This database has a spatial resolution of 300 meters and available from 1992 to the present, with one year delay (1992-2020). The ESA-CCI LC is a combined product of global surface reflectance from different satellites missions (ENVISAT, MERIS, SPOT 4, SPOT 5, Proba-V, NOAA-15 (AVHRR)). They are available on http://maps.elie.ucl.ac.be/CCI/viewer/download.php and https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover/.

Details of the in-depth validation of the land use maps are available in the product quality assessment report (https://datastore.copernicus-climate.eu/documents/satellite-land-cover/D5.2.3_PQAR_ICDR_LC_v2.1.x_PRODUCTS_v1.1.pdf; [28]).

Thanks to long-term data consistency, annual updates and a high level of thematic detail based on global observational data, the ESA-CCI LC map series served as an input for various applications such as the impact of land cover change (LCC) on climate ([29]), long-term historical reconstructions for LC climate modeling and biodiversity accounting ([30] [31] [32] [33]), as well as forest [34] [35] [36]) and desertification monitoring in scientific research ([37] [38]), carbon and climate change models ([36] [39]), policy-making and in the business sector ([40] [41] [42] [43]).

As part of the 2018 reporting to the UNCCD (United Nations Convention to Combat Desertification) and assessment of these indicators (Land Cover Trends; Land Productivity Trends; Organic Carbon Stock Trends), LC ESA-CCI land cover data has been advised and provided to member countries as default level 1 data ([40]).

2.3. Methodology

2.3.1. Cartography and Dynamics of Land Cover

Land cover dynamics is defined as the spatiotemporal evolution of land cover classes, either towards a stage of degradation, or improvement, or towards a more or less stable state of equilibrium ([44] [45]). These dynamics enable us to synthesize the changes in land use classes that have occurred in the same landscape over different periods ([46]).

In this study, the method of comparing differences in land cover class between (diachronic analysis) different periods (1992 to 2020 or 2000 to 2020) is carried out to analyze the dynamics of land cover change. The first step is to map the vegetation cover based on land cover data (Land Cover ESA-CCI LC) for a given locality over a given period. Then, using image histogram analysis, the area of each class will be calculated. Image histograms visually synthesize the distribution of a continuous numerical variable by measuring the frequency with which certain values appear in the image.

For each map produced, the statistics for the different land-use classes are presented in relative surface area. This is the ratio of the area occupied by a given land-use class to the total area of the locality. The dynamics of land use are the result of the difference between periods (map 2020 and map 1992, for example).

Finally, rates of change (Tc) in land cover and average annual evolution (Te) between two dates were calculated for each land cover class.

$$Tc(\%) = \left(\frac{A2 - A1}{A1}\right) * 100 \quad (1)$$

$A1$ and $A2$ are the initial and final area of the land cover class, respectively.

The average annual rate of evolution for each land cover class was calculated using the formula below:

$$Te(\%) = \left(\frac{100}{t2 - t1}\right) * \ln \frac{A2}{A1} \quad (2)$$

Te: annual evolution rate for class "i"; $A1$: area of class "i" at time $t1$; $A2$: area of class "i" at time $t2$.

2.3.2. Estimation of Carbon Stocks in the Vegetation Cover of the GGW in Senegal

Organic carbon, a major determinant of soil properties and an essential component of carbon and greenhouse gas cycles, is highly sensitive to land use and management: forest, savanna, crop, grassland ([21] [47] [48]). Thus, the estimation and variation of carbon stocks, within the sites of the Great Green Wall of Senegal, uses as proxies land cover (vegetation mapping, [39] [40] [48] [49] [50] [51]), average carbon stock values from bibliographic data from the region ([52]-[57]) and equation (3) below (**Table 4**).

$$Carbon\ sequestration_{LCi} = Area_{LCi} * Stock_{LCi} \quad (3)$$

where:

- $Carbon\ sequestration_{LCi}$: is the carbon sequestration associated with land cover class "i" in ton Carbon (t.C);
- $Area_{LCi}$: is the surface area of class "i" expressed in hectares (ha);
- $Stock_{LCi}$: is the carbon storage rate of class "i", expressed in t.C/ha.

These studies provide average carbon stock values per unit area. These carbon storage estimates are based on allometric methods ([56] [58] [59] [60] [61]) and infrared spectrometric analysis of soil samples taken from a site ([52] [62] [63] [64]). Allometric equations make it possible to estimate the amount of carbon stored in an area, from its total biomass using measurable information such as Tree Height, Trunk Diameter, Trunk Circumference, Wood Density. And to measure the carbon stock in a soil sample over a given depth, you need to know

Table 4. Average soil carbon stock values from bibliographic data for the region (Senegal).

Land cover types	Carbon stocks (t C./ha)	Sources
TreeSavanna	32.42 ± 5.4 t.C/ha	[54]
ShrubSavanna	19.44 ± 2.7 t.C/ha	
Shrub steppe	8.29 ± 1.0 t.C/ha	
Open forest/Woodland	40.45 ± 5.0 t.C/ha	
Shrub steppe and Grassland (Northern sandy pastoral region)	14.73 t.C/ha	[52]
Shrubby savannas, often relatively dense (Ferruginous pastoral region)	15.23 t.C/ha	
Tree savannas and wooded savannas (Oriental transition region)	29.37 t.C/ha	
Herbaceous steppes (Ferlo)	2.0 t.C/ha	[68]
Annualcrops (groundnuts + millet)	8.9 t.C/ha	[55] [56]
Tree plantation (Balanites aegyptiaca, Acacia raddiana)	1.73 tC/ha	[58]
Shrubs, grasslands and sparsely vegetated areas	19.18 ± 2.3 tC/ha	[53]
Cropland	17.18 ± 2.2 tC/ha	
Wetlands	59.14 ± 5.0 tC/ha	

the soil's carbon content (in g C·kg^{-1} soil), its density and the proportion of gravel (>2 mm) in it (in kg·dm^{-3}).

Then, to better appreciate soil carbon stock dynamics, we calculated average stocks and standardized carbon stock anomalies over the period 2000-2020. The Buishand (Buishand's U statistic, [65]) and Bayesian BEAST (Bayesian Estimator of Abrupt Change, Seasonal Change and Trend, [66]) statistical tests were used to detect breaks in carbon sequestration time series over the period 2000-2020. The Buishand's test detects a single break, and this break is highly significant when the probability associated with the test is less than 1% (P-value < 1%, [67]). The BEAST test, on the other hand, detects several breaks in the trends, with the probabilities and slopes associated with their occurrence.

The annual estimate of carbon sequestration gain or loss after reforestation is given by the following Equation (4):

$$CSG_{site} = \sum_{t}^{2020} \left(CSeqAftRef_t - mean\ CseqBefRef \right) \quad (4)$$

where:

- CSG_{site} is the estimating the carbon sequestration gain per site (in t.C);
- $CSeqAftRef_t$: is the annual carbon sequestration after reforestation (in t.C);
- *mean CseqBefRef*: is the average carbon sequestration before reforestation (in t.C).

2.3.3. Calculating the Uncertainties Associated with Results

For the various carbon sequestration results, we have computed the uncertainties in accordance with IPCC guidelines [48]. To carry out these calculations, it is normally necessary to know the uncertainty weights for all the parameters involved in determining soil organic carbon stocks (the different land cover classes). The known information that needs to be combined for the calculations are therefore the uncertainties of the land cover classes and the average stocks associated with each land cover class, where available. The IPCC method for combining uncertainties quantities by multiplication uses Equation (5), and for addition or subtraction Equation (6).

$$I_{totale} = \sqrt{I_1^2 + I_2^2 + \cdots + I_n^2} \quad (5)$$

- I_{totale}: Uncertainty in the product of carbon stock quantities;
- I_i: Uncertainties associated with each carbon stock.

$$I_{totale} = \frac{\sqrt{(x_1 * I_1)^2 + (x_2 * I_2)^2 + \cdots + (x_n * I_n)^2}}{|x_1 + x_2 + \cdots + x_n|} \quad (6)$$

- I_{totale}: Uncertainty in the sum of carbon stock quantities;
- x_i et I_i: Uncertain carbon stock quantities and the uncertainties associated with them, respectively.

3. Results and Discussions

This section is devoted to land use through land cover (LC) data over the period 1992-2020. Afterwards, an analysis of the estimate and the variability of the carbon stock from 1992 to 2020 is presented.

3.1. Analysis of the Land Cover Dynamic in the Senegalese Great Green Wall from 1992 to 2020

The land use database derived from LC ESA-CCI allowed the establishment of the land cover maps of Syer, Tessekere, Loughere-Thioly and Ballou from 1992 to 2020.

1) Syer (Louga)

The analysis of land use between 1992 and 2020 shows 14 land cover classes in Syer area (**Figure 2**; **Table 5** and **Table 6**). **Figure 2**, **Figure 3** and **Table 5** illustrate the extend of changes in land use during this period. There is an increase in the area of tree and shrub savannas (+8.5%), rainfed crops (0.95%), irrigated crops (+0.68%), mosaic crops (1.55%), tree cover flooded saline (+0.38%). **Table 5** shows that there is a decrease in area of steppe/grassland (−9.8%),

2) Tessekere (Louga)

Figure 4 represents the spatiotemporal distribution of the nine land cover classes over Tessekere site from 1992 to 2020. The main land cover classes are tree savanna and steppe. The rates of evolution and change in area are recorded in **Table 6**.

There is a decline area for steppe/grassland, rainfed crops, mosaic agriculture, natural mosaic vegetation, shrub steppe and bare soils during 1992-2020 varying from 38.7% to 95.74% (**Table 6**). On the other hand, there is a spatial extension

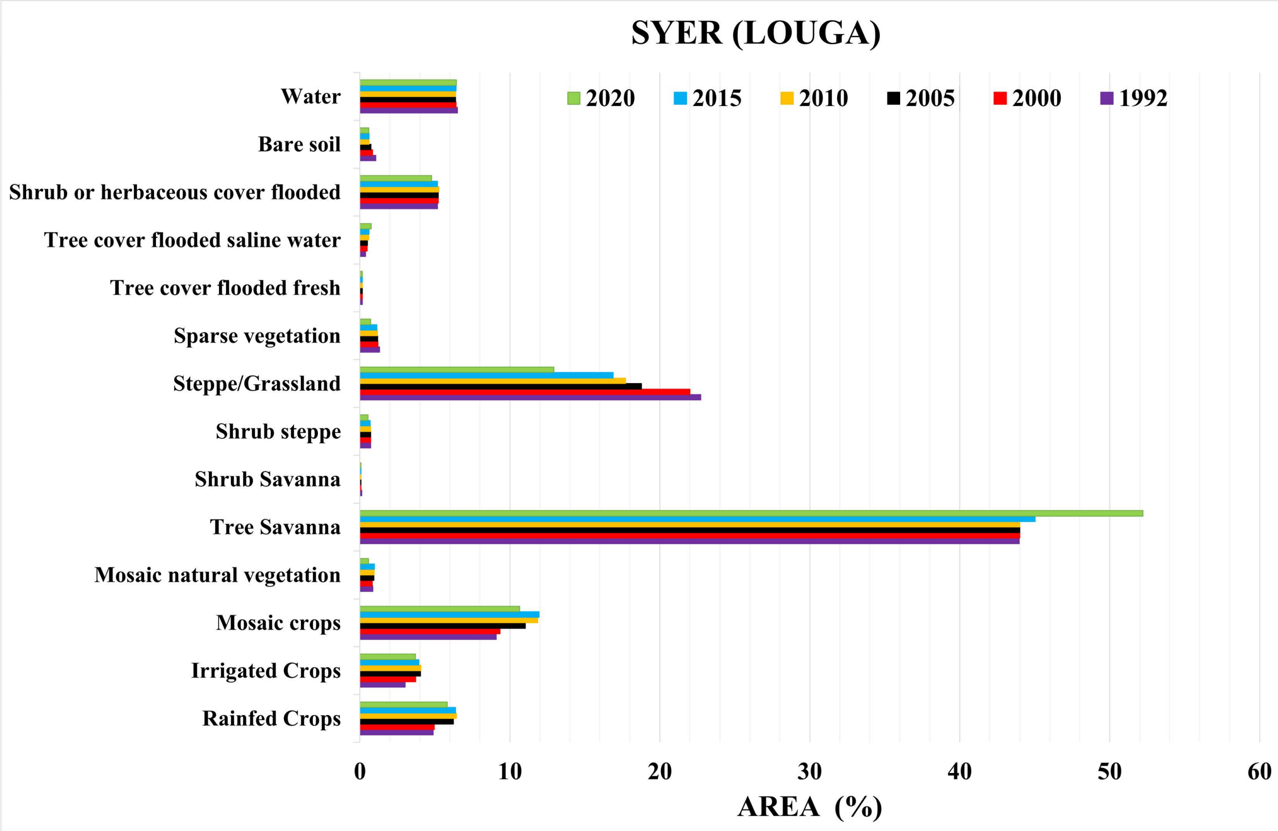

Figure 2. Evolution of land cover classes in Syer (Louga) from 1992 to 2020.

Table 5. Statistics of land cover classes in Syer (Louga) from 1992 to 2020.

Syer (Area 2000 Km^2) Land Cover Classes	Area (%)						Difference 2020-1992 (%)	Difference 2020-2000 (%)
	1992	2000	2008	2010	2015	2020		
Rainfed Crops	4.88	4.96	6.21	6.44	6.37	5.83	0.95	0.86
Irrigated Crops	3.02	3.72	4.05	4.06	3.93	3.7	0.68	−0.01
Mosaic crops	9.1	9.34	11.10	11.85	11.95	10.65	1.55	1.31
Mosaic natural vegetation	0.86	0.83	0.93	0.95	0.97	0.58	−0.28	−0.25
Tree Savanna	43.97	44	44.00	44	45.02	52.22	8.25	8.22
Shrub Savanna	0.12	0.08	0.08	0.08	0.08	0.08	−0.04	0
Shrub steppe	0.72	0.72	0.72	0.72	0.68	0.54	−0.17	−0.17
Steppe/Grassland	22.73	22.01	18.75	17.71	16.89	12.93	−9.8	−9.08
Sparse vegetation	1.32	1.21	1.18	1.16	1.13	0.72	−0.6	−0.48
Tree cover flooded fresh	0.16	0.16	0.16	0.16	0.16	0.16	0	0
Tree cover flooded saline water	0.38	0.48	0.61	0.6	0.62	0.76	0.38	0.27
Shrub or herbaceous cover flooded	5.18	5.23	5.26	5.26	5.18	4.78	−0.4	−0.44
Bare soil	1.06	0.85	0.73	0.62	0.61	0.6	−0.46	−0.26
Water	6.5	6.41	6.24	6.38	6.42	6.44	−0.06	0.03

Table 6. Rates of evolution and change in area at Syer, Tessekere (Louga), Loughere-Thioly (Matam), Ballou (Tambacounda).

Land Cover Classes	SYER 1992-2020		TESSEKERE 1992-2020		LOUGHERE 1992-2020		BALLOU 1992-2020	
	Rate of Evolution (Te) (%)	Rate of Change (Tc) (%)	Rate of Evolution (Te) (%)	Rate of Change (Tc) (%)	Rate of Evolution (Te) (%)	Rate of Change (Tc) (%)	Rate of Evolution (Te) (%)	Rate of Change (Tc) (%)
Rainfed Crops	0.63	19.37	−1.75	−38.76	−0.28	−7.49	0	0
Irrigated Crops	0.72	22.49					−0.02	−0.68
Mosaic crops	0.56	17.07	−1.23	−29.17	0.96	30.73	0	0
Mosaic natural vegetation	−1.41	−32.58	−1.18	−28.06	0.65	19.84	0	0
Tree Savanna	0.61	18.77	0.48	14.53	0.1	2.71		
Shrub Savanna	−1.59	−36	0	0			1.21	40.5
Shrub steppe	−0.99	−24.16	−0.94	−23.08	−0.01	−0.29	0	0
Steppe/Grassland	−2.01	−43.11	−2.45	−49.62	−1.39	−32.32	0	0
Sparse vegetation	−2.15	−45.26	0	0	0.19	5.56		
Tree cover flooded fresh	0	0						
Tree cover flooded saline water	2.5	101.28						
Shrub or herbaceous cover flooded	−0.29	−7.72					0	0
Bare soil	−2.03	−43.38	−11.28	−95.74				
Water	−0.03	−0.89					0	0
Woodland/ Open forest							−0.57	−14.73
Urban area							2.9	125

of savanna tree and savanna shrub of respectively 78.43% to 89.82% from 1992 to 2020.

3) Loughere-Thioly (Matam)

Seven land cover classes were identified in Loughere-Thioly according to the 1992 land cover map (Figure 5 and Table 6). The spatial extension of these classes from 1992 to 2020 shows that there is an increase of the area corresponding to mosaic agriculture of 1.85%, natural mosaic vegetation (+1.91%), tree savanna (0.76%). The rate of steppe/grassland area declines from 13.30% to 9.0%. The other classes remained stable.

4) Ballou (Tambacounda)

The Ballou land cover data processing provided 11 classes (Figure 6). The main land use classes are rainfed crops (47.33%) and shrub steppe (33.66%). There is a reduction in the surface area of woodland/open forest of 14.73% (Table 6). In the other hand we can observe an increase in the surface area associated to urban and shrub savanna classes of respectively 125% and 40.5%. The other classes areas remained stable from 1992 to 2020. So, we can notice a great

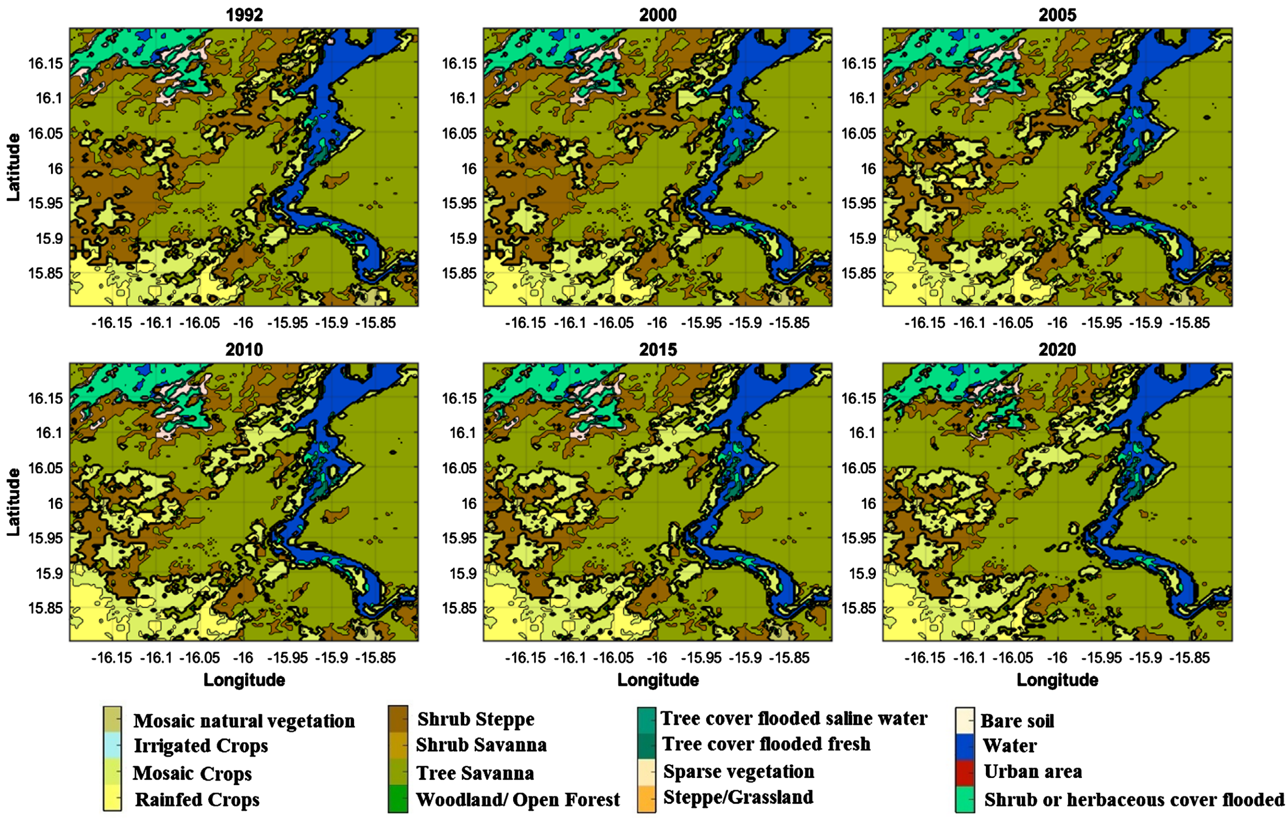

Figure 3. Evolution of land cover mapfrom 1992 to 2020 in Syer (Louga).

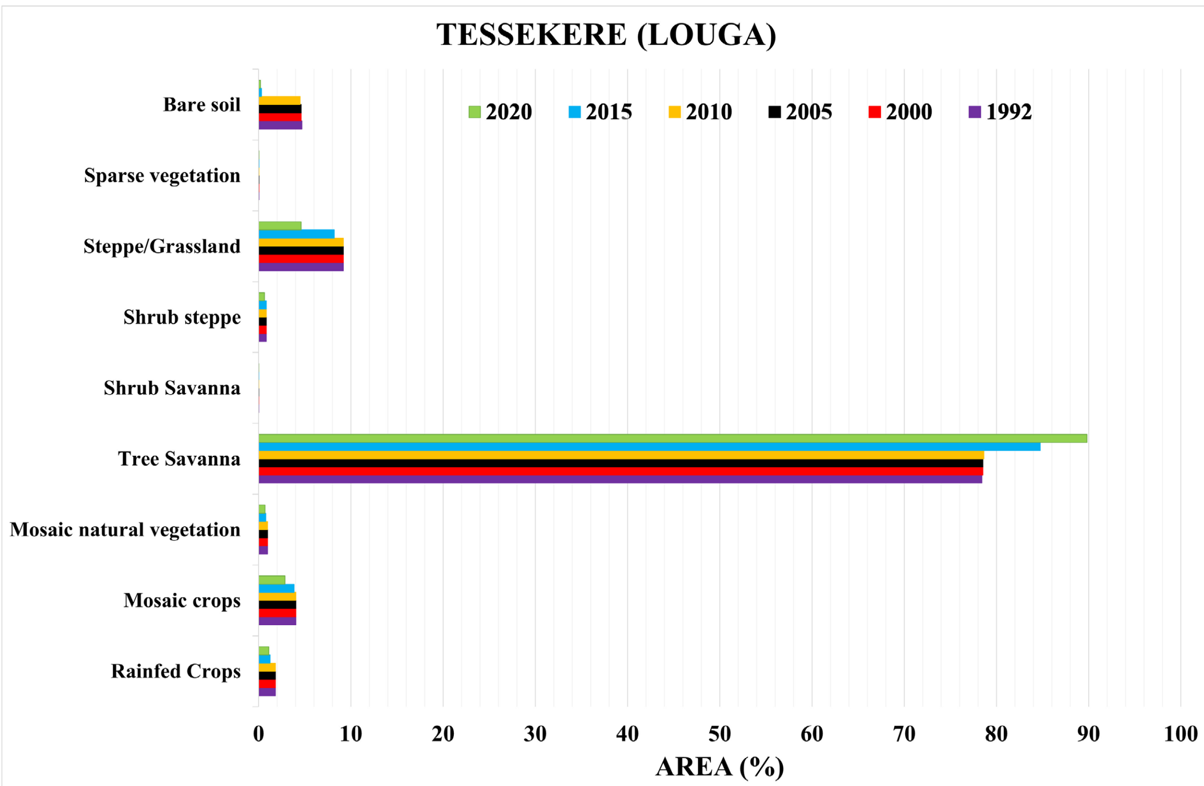

Figure 4. Evolution of land cover classes in Tessekere (Louga) from 1992 to 2020.

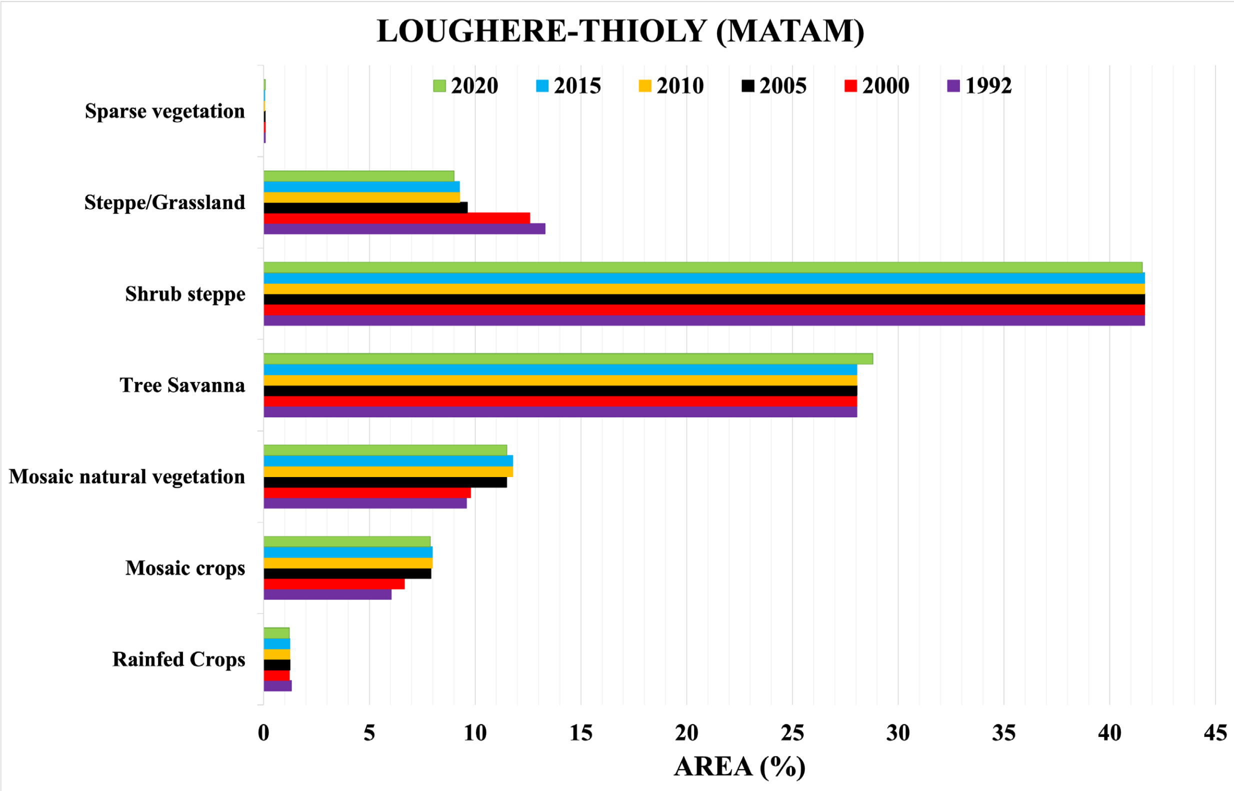

Figure 5. Evolution of land cover classes in Loughere-Thioly (Matam) from 1992 to 2020.

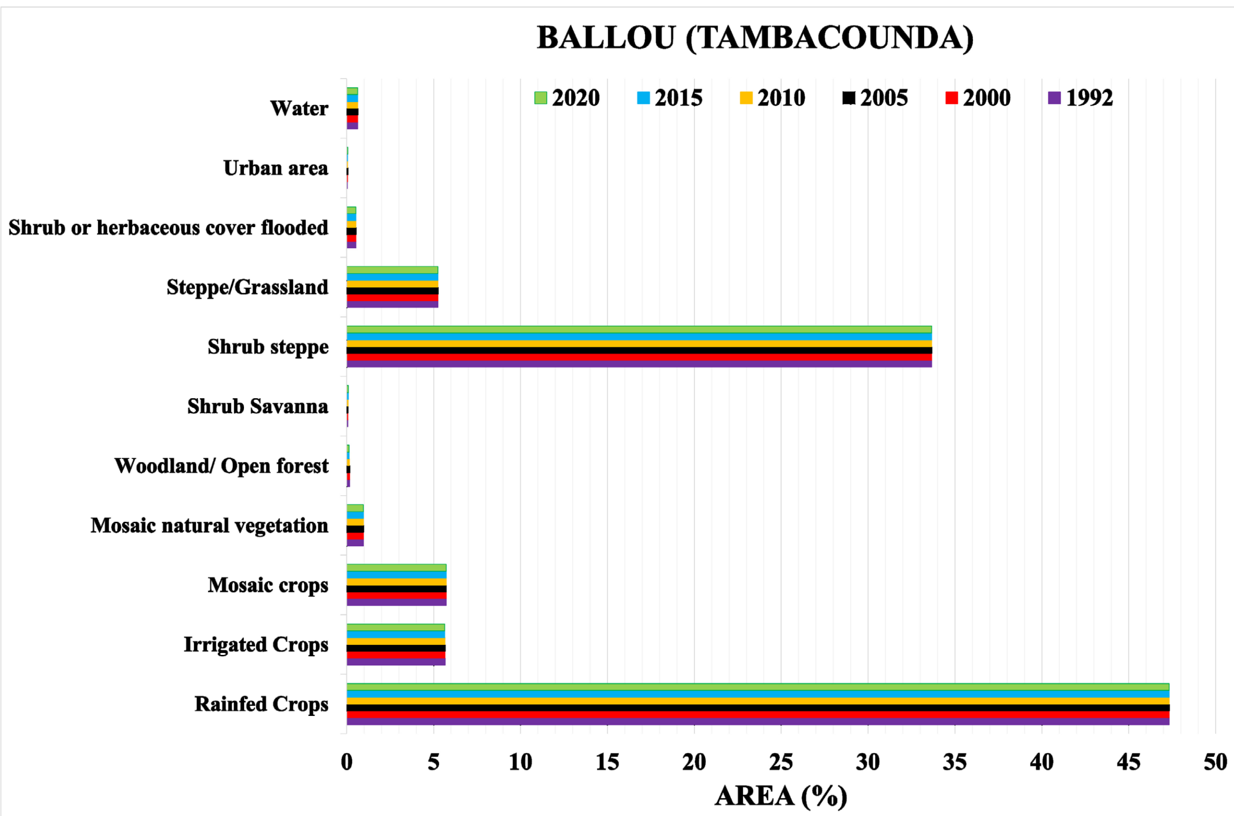

Figure 6. Evolution of land cover classes in Ballou (Tambacounda) from 1992 to 2020.

spatial extension and development of urban areas in Ballou.

The temporal evolution of the land-use maps from 1992-2000 show globally a degradation of the vegetation cover. There is a reduction in the surface area of tree savanna, rainfed and mosaic crops, woodland/open forest and water classes. This situation results from the drought recorded particularly in the 1970s, 1980s and 1990s in the Sahel region ([4] [5] [17] [69] [70] [71] [72] [73]). The overexploitation of land combined with irregulat rainfall have caused the reduction of agricultural, tree savanna and forest areas during dryness episodes. The rainfall deficit on the study areas recorded varies from 11% to 20% and the lost of vegetative activities through the vegetation index is between 4% and 8.5% [17]. These results are in agreement with the works of ([6] [9] [11] [15] [74]) in the Ferlo region (north of Senegal).

A study based on 40 years satellite data carried out by the CILSS (Comité Inter-états de Lutte contre la Sécheresse dans le Sahel "CILSS" [9]) during 1975 and 2013 has shown that 26% of the land in Senegal are overexploited, included the agricultural areas causing savanna and open forest fragmentation. According to [15]), the spontaneous vegetation has been highly degraded (−13.4%) during 1974-2013 in the Ferlo region (Tessekere). [12] and [75] have shown that the losses in surface of protected areas are low for the steppe and high for the wooded and tree savanna. The land cover degradadtion results from the human activities and the lack of precipitations ([5] [70] [71] [72] [76]).

A regreening of the different localities and a positive dynamic are observed with the return of a rainfall values higher than the those recorded in 1992-2000. Gains in surface of tree savanna and cultivation areas instead of bare soils are observed. There is an improvement of the surface areas of tree and shrub savanna of 11.40% (Tessekere), 8.25% (Syer) and 2.70% (Loughere-Thioly). In spite of the gradual improvement of the rainfall in Ballou after the year 2000, the vegetation cover was continuously in degradation. 37 km^2 of deciduous forest areas was lost after the year 2000s in benefit to shrub savanna and urbanization area.

With regrad to the non-uniform distribution of vegetation cover in the Sahel, particularly in our study area, the return of rainfall could not be the only factor in the vegetation regreening ([77]).

Agroforestry practices, reforestation, good management of natural resources should be taken into account in the success of the positive vegetation dynamic ([6] [9] [12] [18] [72] [74] [77] [78] [79]. According to [11] [12], the conversion with improvement of vegetation cover has affected 4000 ha in the Tessekere area. The regressing of bare soil surface areas was also due to the implementation of the Senegalese-German GTZ project since 1986. The progressing of cultivation areas was favorited by the planting of trees in the Ferlo region since 2007 (Senegalese Great Green Wall). With the collaboration of the local population, the GGW project has managed to plant 13,000 ha (case of Koyli Alpha Park), 52 plots of forest plantations and agroforestry (18,599 ha), about ten multi-purpose village gardens at Syer, Tessekere, Labgar, Loughere-Thioly and Sakal ([80]) and more than 27000 ha of land restored ([81]).

3.2. Analysis of the Evolution of Carbon Storage in the Senegalese Great Green Wall from 1992 to 2020

1) Analysis of estimated carbon storage on Senegalese GMV sites

The results of the evolution of land use carried out in the first part of this work were used as tools for quantifying and evaluating the dynamics of carbon stocks on our different study sites.

The method uses the different types of land cover and land use over each site and their average carbon stock values. In this way, we are able to estimate the total quantity of carbon and the average stock of plant cover from 1992 to 2020 (Figure 7), and carry out a comparative analysis of the evolution of carbon between these periods.

Figure 7 corresponds to the estimate of average carbon stocks in the different study sites. The carbon values per hectare show two dynamics. Indeed, carbon sequestration increases in the soils of Syer, Tessekere, Loughere-Thioly from 1992 to 2020. On the other hand, Ballou recorded a drop in carbon stock over the same period. Note that the average carbon stock values recorded in our study

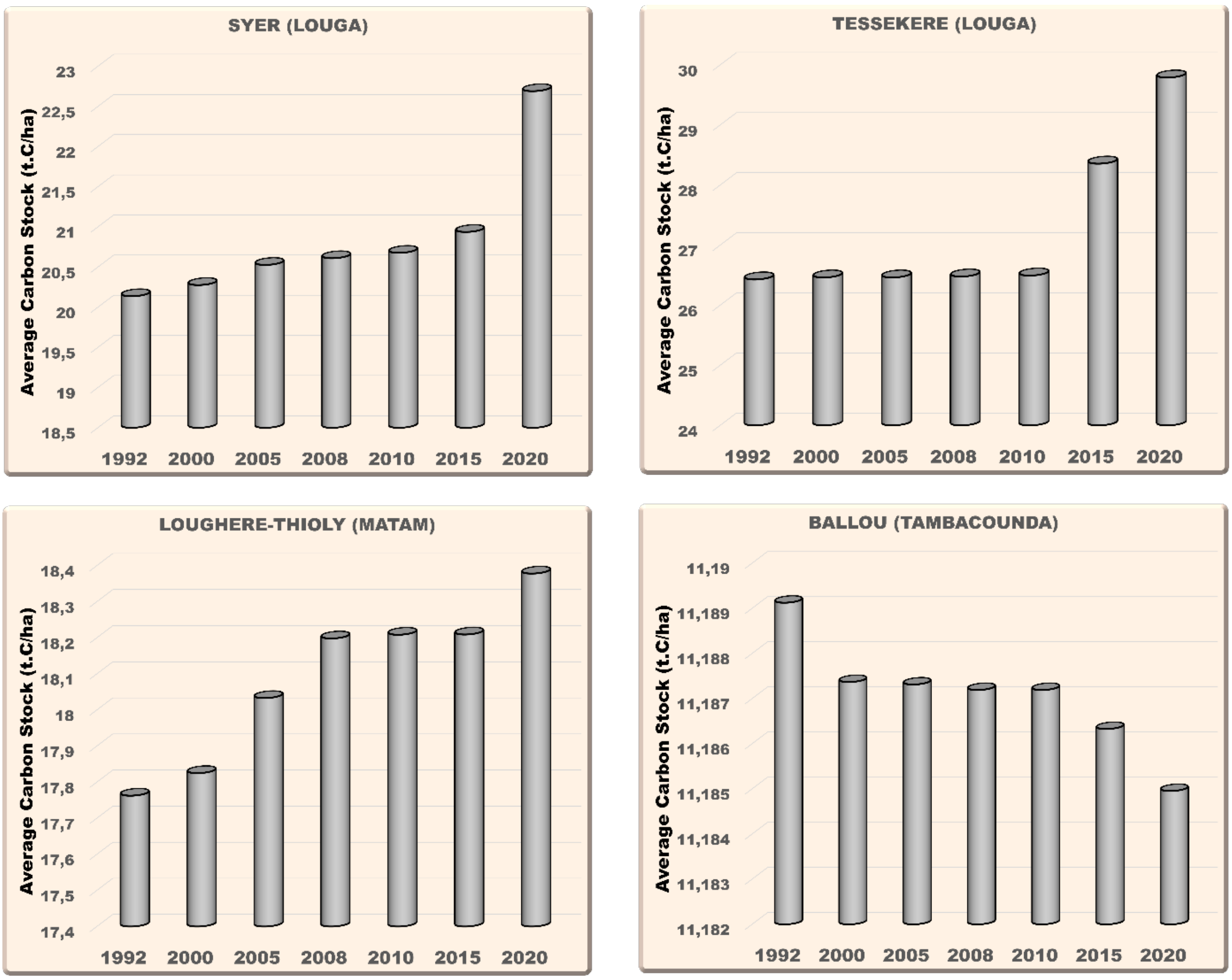

Figure 7. Evolution of average carbon stocks in Syer, Tessekere, Loughere-Thioly and Ballou soils from 1992 to 2020.

sites vary between 11.18 ± 0.001 t.C/ha and 27.33 ± 1.34 t.C/ha. With the highest value observed in the locality of Tessekere (29.80 t.C/ha in 2020) and the lowest in Ballou (11.185 t.C/ha in 2020). For the different localities, the average annual values of organic carbon stocks from 1992 to 2020 range from 4,177,726 ± 12,539 t.C (Syer); 5,740,287 ± 23,306 t.C (Tessekere); 3,257,418 ± 7087 t.C (Loughere-Thioly) and 1,353,630 ± 2779 t.C (Ballou). The relative uncertainties of the study sites are in the range 0.2% to 0.4% of the different annual storages.

The results obtained on the quantities of average carbon stocks sequestered in the GGW zones of Senegal present large differences from one site to another in terms of carbon storage potential. This disparity is linked both to climatic conditions ([56] [82] [83]) but it is reinforced by the areas of trees in the different plant covers. Tree savannas, for example, represent on average 81.4% in Tessekere, 45% in Syer and 28% in Loughere-Thioly of the land use of these localities.

These averages of carbon storage are of the same order of magnitude as those reported by [52] [61] [84] [85] [86] [87].

In 1992, the quantities of sequestered carbon were estimated at 4,027,459 ± 12,360 t.C (Syer), 5,550,062 ± 22,785 t.C (Tessekere), 3,197,238 ± 7173 t.C (Loughere-Thioly) and 1,353,884 ± 2778 t.C (Ballou). The main land use classes in these localities' contribution vary from 35% to 96% of carbon storage. Tree savanna allows to sequester 2,850,821 ± 17,305 t.C (Syer); 5,339,604 ± 23683 t.C (Tessekere) and 1,636,259 ± 13,110 t.C (Loughere-Thioly) (**Table 7**).

In 2010, the annual carbon sequestration increased from 0.3% to 2.7% compared to that of 1992 on the Syer, Tessekere and Loughere-Thioly sites. On the other hand, sequestration is down by −0.02% in Ballou site (**Table 8**) due to the high urbanization.

In 2020, the total carbon storage in the soils of Syer, Tessekere and Loughere-Thioly is estimated between 3.5% and 12.7% compared to 1992. Compared to 2010, carbon sequestration increased from 1% to 12.4% (9.74% in Syer; 12.44% in Tessekere and 0.93% in Loughere-Thioly). In Ballou soils, the storage loss is −0.04% and −0.02% compared respectively to 1992 and 2010.

Table 7. Total quantities of carbon sequestered by the main land cover-land uses (LCLU) in the soils of Syer, Tessekere, Loughere-Thioly and Ballou from 1992 to 2020.

Sites	Main land cover classes	1992 (t.C/year)	2000 (t.C/year)	2010 (t.C/year)	2020 (t.C/year)
Syer (Louga)	TreeSavanna	2,850,821 ± 17,305	2,852,697 ± 17,310	2,852,697 ± 17,310	3,385,839 ± 18,859
	Steppe/Grassland	90,934 ± 768	88,040 ± 755	70,853 ± 678	51,736 ± 579
Tessékéré (Louga)	TreeSavanna	5,339,604 ± 23,683	5,346,412 ± 23,698	5,353,220 ± 23,713	6,115,422 ± 25,345
Loughéré-Thioly (Matam)	Shrub Steppe	1,104,182 ± 7259	1,104,182 ± 7259	1,104,182 ± 7259	1,100,999 ± 7249
	Tree Savanna	1,636,259 ± 13,110	1,636,259 ± 13,110	1,636,259 ± 13,110	1,680,537 ± 13,286
Ballou (Tambacounda)	RainfedCrops	509,699 ± 3834	509,699 ± 3834	509,699 ± 3834	509,699 ± 3834
	Shrub Steppe	599,886 ± 5351	599,886 ± 5351	599,886 ± 5351	599,886 ± 5351

The improvement in the areas of land use classes of tree savannas, shrub savannas and crop areas to the detriment of bare soils, steppes and grassland generated a gain of 510,756 ± 26,490 t.C. in Syer, 705,834 ± 47,560 t.C in Tessekere and 110,784 ± 14,357 t.C. in Loughere-Thioly between 1992 and 2020. The spatial extension of the urban zone and shrub savanna classes at the expense of woodland/open deciduous forest, generated a loss in carbon stock in Ballou site of −505 ± 5557 t.C.

2) Analysis of carbon storage dynamics from 2000-2020

Figure 8 which represents the evolution of standardized carbon sequestration anomalies in the soil from 2000 to 2020 exhibits two dynamics.

The localities of Syer, Tessekere and Loughere-Thioly present a period with a negative anomaly followed by a second phase of positive anomaly. The positive periods began in 2007, 2013 and 2014 respectively for Loughere-Thioly, Tessekere and Syer. The positive sequestration anomalies became significant (greater than 1) in 2017 (Tessekere), 2018 (Syer) and 2019 (Loughere-Thioly). On the other hand, the dynamic in the locality of Ballou is reversed. This evolution of carbon storage is decreasing. Indeed, a negative anomaly is observed since 2010 in this site. The significance of soil carbon storage in reforested sites occurs 8 to 10 years after the start of the various tree plantations of the Senegalese GGW.

Table 8. Total quantities of carbon sequestered in Syer, Tessekere, Loughere-Thioly and Ballou soils from 1992 to 2020.

Sites	1992 (t.C/year)	2000 (t.C/year)	2010 (t.C/year)	2020 (t.C/year)
Syer (Louga)	4,027,459 ± 12,360	4,055,389 ± 12,289	4,135,511 ± 12,053	4,538,215 ± 14,130
Tessékéré (Louga)	5,550,062 ± 22,785	5,556,871 ± 22800	5,563,679 ± 22,816	6,255,896 ± 24,776
Loughéré-Thioly (Matam)	3,197,238 ± 7173	3,208,478 ± 7148	3,277,503 ± 7005	3,308,022 ± 7184
Ballou (Tambacounda)	1,353,884 ± 2779	1,353,671 ± 2778	1,353,650 ± 2778	1,353,379 ± 2779

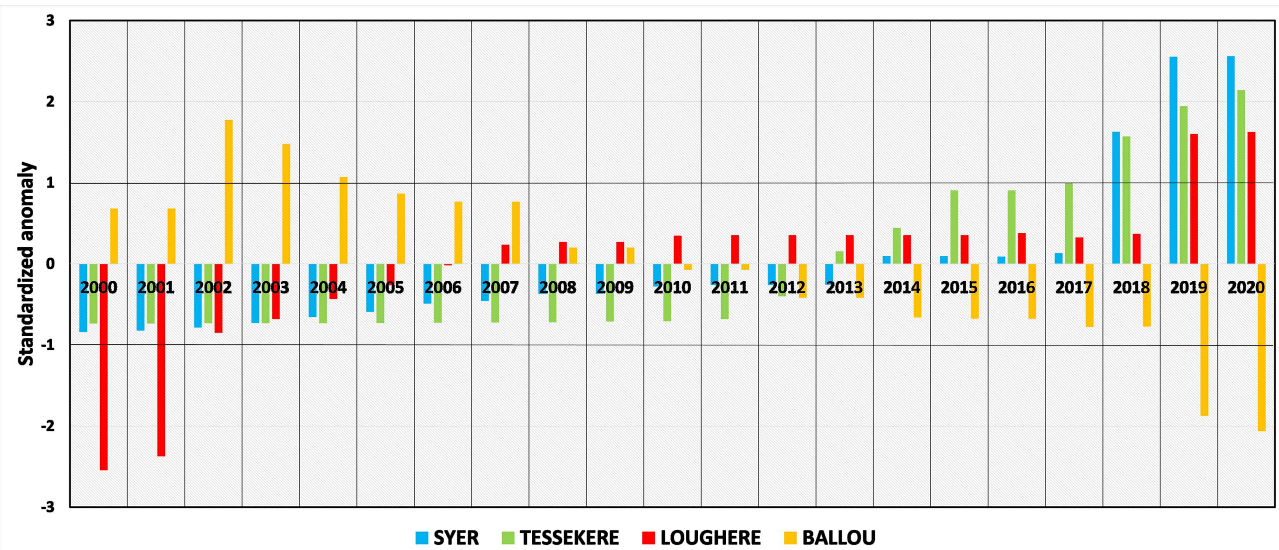

Figure 8. Evolution of carbon stock anomalies in Syer, Tessekere, Loughere Thioly and Ballou GGW-Senegal from 2000 to 2020.

For Ballou, the loss of capacity to store carbon in the soil is observed and became significant since 2019.

The results of the break tests applied to the carbon sequestration data are presented in the Table 9 and Figure 9. The Buishand test, which shows the main break in the time series, reveals very significant breaks in the different localities. These breaks occurred in 2012 (Tessekere) 2013 (Syer), i.e., 3 to 4 years after the beginning of reforestation on these sites, and in 2006 at Loughere-Thioly. The

Table 9. Break dates, carbon storage statistics of the Buishand's test, and probability of occurrence of breaks, and slope of trends of Bayesian BEAST test.

Tests	Buishand's test				Bayesian BEAST test		
Sites	Break date	Average before break date (t.C/ha)	Average after break date (t.C/ha)	Buishand's statistics (U and P-value)	Break date	Probability	Slope
Syer	2013	20.51	20.60	U = 1.25 Pv = 2.2×10^{-16}	2017	0.994	0.39
					2008	0.012	0.04
Tessékéré	2012	26.50	28.62	U = 1.58 Pv = 2×10^{-16}	2012	0.936	0.44
					2016	0.162	0.28
					2007	0.004	3×10^{-04}
Loughéré-thioly	2006	18.02	18.23	U = 1.28 Pv = 5×10^{-05}	2006	0.502	0.03
					2017	0.275	0.01
Ballou	2009	11.19	11.18	U = 1.68 Pv = 2.1×10^{-16}	2004	0.513	-2.1×10^{-04}
					2016	0.028	-1.5×10^{-04}

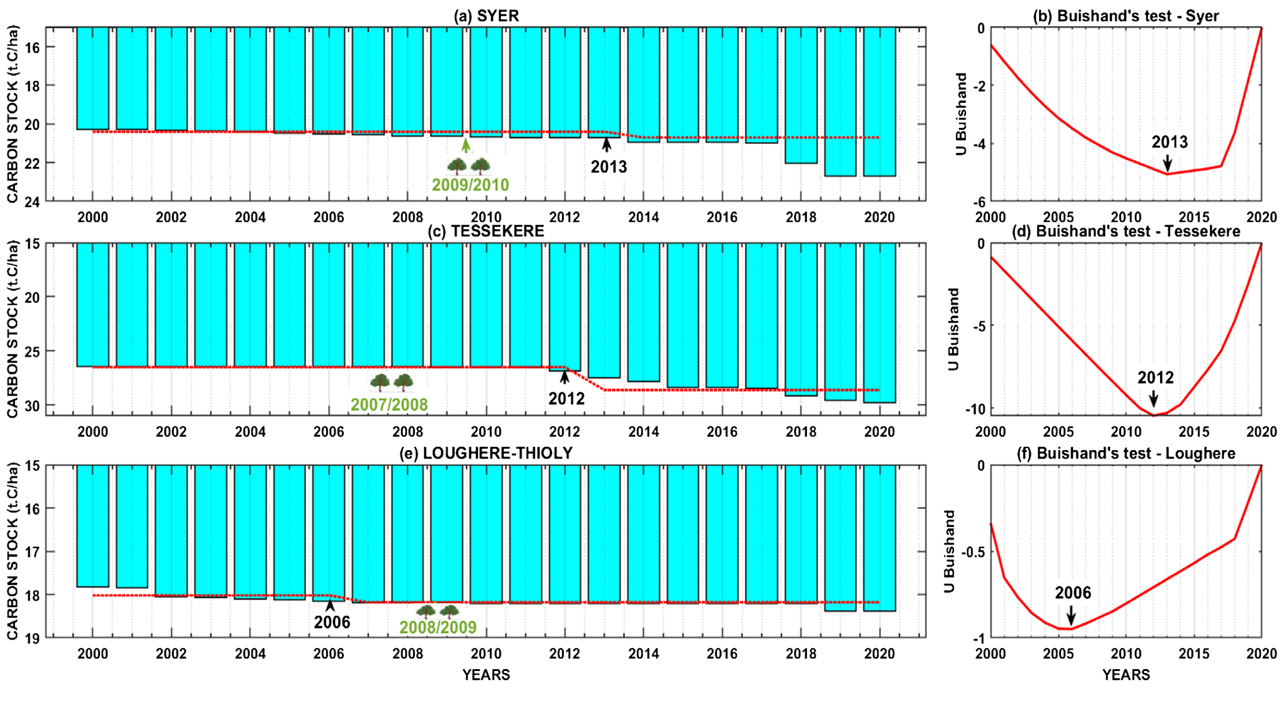

Figure 9. Annual evolutions of carbonstorage and Buishand's test from 2000 to 2020 in Syer, Tessekere and Loughere-Thioly.

results of the BEAST test, which detect several breaks, show a change break in the trend in 2006, 2007, 2008 respectively in Loughere-Thioly, Tessekere and Syer. These years correspond to the beginning of tree planting on these sites. Then other breaks are located in the trends of the carbon storage series in 2016 (Tessekere) and 2017 (Syer and Loughere-Thioly). This second break corresponds to the year when carbon sequestration became significant in these localities. This result is in agreement with the representation of the standardized anomalies. The Bayesian test confirms the break change in 2012 at Tessekere. In the non-reforested locality (case of Ballou), the breaks are observed in 2004, 2009 and 2016. That of 2009 corresponds to the beginning of loss of open forest area.

One can note also that the average carbon stocks (t.C/ha) are still increasing and the slopes of the trends remain positive after the breaks in the reforested localities. On the other hand, in the locality not yet reforested, the average carbon stock is decreasing and the slopes are negative.

3) Quantity of carbon sequestered on GGW sites since reforestation.

One of the objectives of the Great Green Wall initiative is to sequester 250 million tons of carbon in the soil by 2030. Thus, this part of the work is dedicated to the assessment of the quantity of carbon stored on each site after the reforestation campaigns of the GGW initiative in Senegal.

In the commune of Syer, the quantity sequestered after 2010 is estimated at 1,679,931 ± 127,085 t.C. which represents an annual gain of 119,406 ± 9550 t.C/year. In Tessekere the carbon stock for the period 2009-2020 represents 3,729,318 ± 283,822 t.C and corresponds to 248,848 ± 17,420 t.C/year. In Loughere-Thioly after the various reforestation campaigns (started in 2009), the sequestration of organic carbon amounts to 362,902 ± 29,032 t.C, or 30,495 ± 1525 t.C/year. For all of the reforested sites in our study, the gain in carbon sequestration amounts to 5,772,151 ± 439,939 t.C or 398,749 ± 27,910 t.C/year.

On the other hand, on the non-reforested site of Ballou, the loss is estimated at −3055 ± 153 t.C, or -204 ± 10 t.C/year (see **Figure 10**).

The results of the organic carbon storage estimation in GGW Senegalese soils show an upward dynamic in carbon sequestration for the reforested sites of Syer, Tessekere (Louga), Loughere-Thioly (Matam) and a loss capacity to store carbon on non-reforested sites (case of Ballou in Tambacounda region) over the period 1992-2020. Other works ([17] [50]) had shown a positive dynamic of reforested sites based on vegetation indices (NDVI and VHI). The results of these studies reinforce ours on the positive dynamics of carbon sequestration observed in the different reforested soils of the GGW. Carbon storage and emission could be considered as good integrators of the state of plant cover health and anthropogenic pressures [88].

In the Senegal Sudanian zone, land cover and land use have a strong impact on the storage of organic carbon [84]. This study shows that the conversion of forests to peanut fields causes a transformation of soil texture and a loss of organic carbon. Indeed, the carbon storage of dominant crop soils, in this case

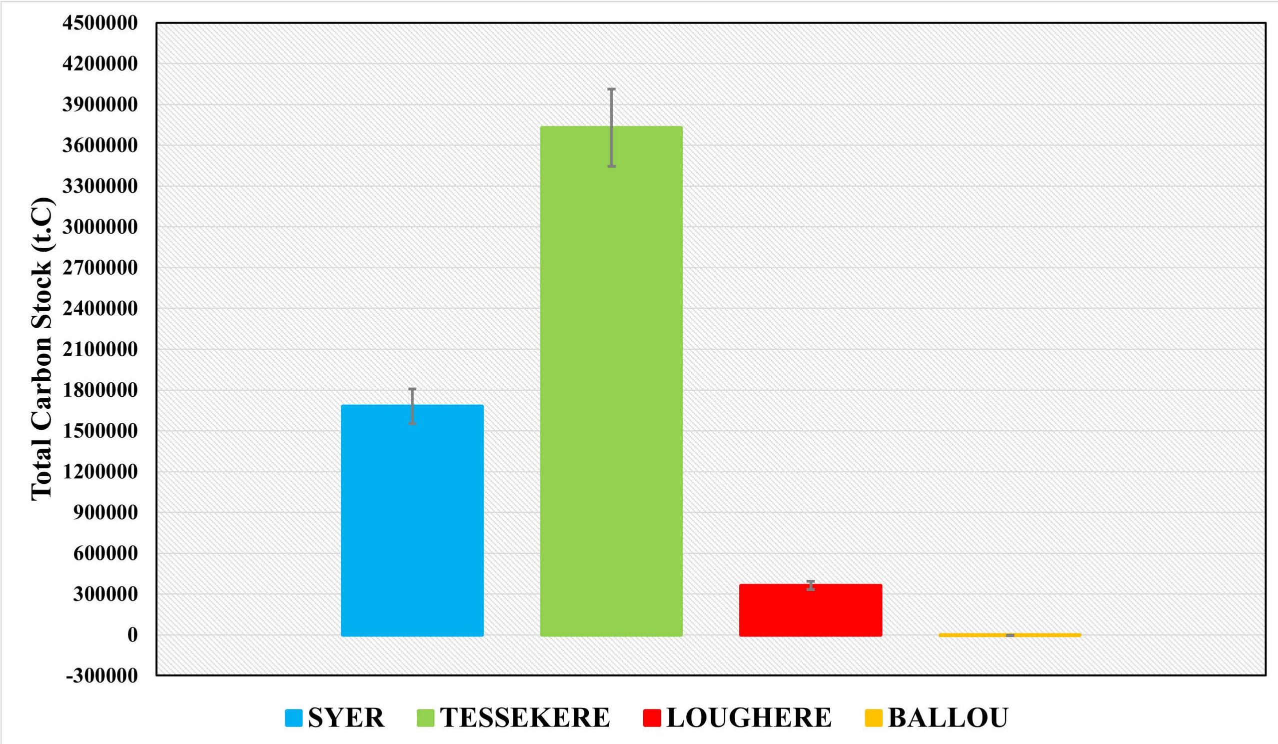

Figure 10. Gains and losses of sequestered carbon at Syer, Tessekere, Loughere-tioly and Ballou after reforestation.

peanut fields, is 27% to 35% lower than in semi-natural savanna soils. Organic carbon stock total is lower for sandy soils than in sandy clay soils. Furthermore, the study of [52] which was carried out on carbon stock measurements of 15 sites ranging from the North (Dagana department) At the South-East (Tambacounda region) in Senegal made a comparison between soil carbon stocks under the canopy and outside the canopy of trees. The study reveals that under the crown the carbon stock is estimated to 22.1 t.C/ha compared to 17.6 t.C/ha of outside the crown.

In the sub-region particularly in the agroforestry park of Saria in Burkina Faso, it is shown that the first layers of the soil contained 91% of the total carbon stock and these quantities varied between 8.74 ± 6.05 t.C/ha and 26.59 ± 7.94 t.C/ha ([85]). In the semi-arid landscape of Dano (Burkina Faso), the average stock is estimated at 24 t.C/ha. This study mentioned that the gallery forest soils stored more carbon (30.2 ± 15.6 t.C/ha) than those of savanna (22.1 ± 6.1 t.C/ha), forests (22 ± 8.2 t.C/ha), tree savanna (21.4 ± 7.4 t.C /ha), and cultivated land (14.9 ± 5.7 t.C/ha) ([86]). For these authors, these dry zone forest management systems play an important ecological role by contributing significantly to the fight against climate change through the strong potential for carbon sequestration. Trees and shrubs used in agroforestry systems increase carbon storage thanks to the addition of aerial and root biomass ([56] [85] [87] [89]). In Mali, the quantity of carbon sequestered varies depending on the agroforestry system and the maintenance techniques of these systems [89]. The rate of sequestered carbon differs from one system to another. It is estimated at 26 t.C/ha in the

Fallow system followed by the Savanna orchard system of 19 t.C/ha and 8 t.C/ha for the Plantation system.

The dynamics of the average carbon stock of the different reforested sites is increasing. In municipalities not yet reforested, the temporal evolution of organic carbon storage is decreasing. This is the case of areas in full urbanization (Ballou).

In Senegal, the estimation of the temporal evolution of carbon storage in soils is often based on modeling approaches ([55] [56] [84] [90]). The Century and RothC models were the most frequently used to predict soil carbon dynamics under different agronomic and soil scenarios ([56] [90]). [90] applied the Century model to Senegalese agrosystems. The different modes of agricultural land use lead to a reduction in soil organic carbon stocks between 2002 and 2050. Continuous crop rotation (groundnut-millet) without external carbon input leads to the greatest reduction in carbon stocks (−1.4 to −3.9 t.C/ha). On the other hand, agroforestry based on Faidherbia albida plantations generates the greatest increase in soil organic carbon stocks of +11 t.C/ha between 2002 and 2050 or 0.23 t.C/ha/year. The application of the RothC model in the same region shows that crop rotation (groundnut-millet) leads to the most significant reduction in organic carbon stocks from −1.8 to −5.1 t.C/ha ([55] [56]). Organic carbon stocks (from layer 0 - 25 cm) went from 8.1 t.C/ha in 2009 to 3.3 t.C/ha in 2050, a loss of 4.8 t.C/ha. By integrating an agroforestry scenario based on Faidherbia Albida, the increase in carbon stock is estimated at +12 t.C/ha between 2009 and 2050, i.e., an annual gain of 0.29 t.C/ha/year. In northern Senegal, [91] quantified carbon stock dynamics with the GEMS model. In 2000, the average carbon stock, taking into account land use (cultivated plots, fallow plots, forest areas, savannas and reforestation), was estimated at 28 t.C/ha in the 0 - 40 cm layer. According to [91], carbon stocks derived from bare soils vary between 5 t.C/ha and 15 t.C/ha for soils on irrigated cropping systems [91].

In the semi-arid region of Dano in Burkina Faso, the results of the HadGEM2-ES and MPI-ESM-MR models by 2070 showed that climate change could affect the carbon storage potential of woody species in different land use and land cover (LULC). These models estimate the reduction in carbon storage capacity of 90% for the HadGEM2-ES model and 89.4% for the MPI-ESM-MR model ([86]).

The results of the temporal evolution of carbon sequestration from these different simulations corroborate the dynamics observed on our study sites. On the other hand, a difference is noted between the carbon stock values obtained by the models and that derived from land use and land Cover maps. This difference could be explained by the input parameters used in the models (choice of planted species, soil texture, crop rotation, plantation ages) and the land cover data only taken into account in our study. Indeed, taking into account the species of reforested trees and the age of the plantations could improve the estimate of carbon storage ([86] [92]). The study carried out by [92] in Sudan, showed that aboveground biomass in Acacia-Senegal plantations (*Senegalia* Senegal*)* is more important in 45-year-old plantations than in plantations of 16-year-old trees. Then, the average stock of sequestered carbon is 11.9 t.C/ha for 35-year-old plantations and 1.2 t.C/ha for 16-year-old plantations.

This study, which was carried out in certain localities of the GGW in Senegal shows the impact of reforestation (started in 2006 on certain sites) on the capacity of trees to capture atmospheric carbon dioxide and bury it in the soil. The results of our study estimated the average total sequestration has 4,177,726 ± 12,539 t.C to Syer; 5,740,287 ± 23,306 t.C in Tessekere; 3,257,418 ± 7087 t.C in Loughere-Thioly and 1,353,630 ± 2779 t.C for Ballou. After reforestation, the storage of carbon in the soil and the reduction of CO_2 in the atmosphere of these different sites increased by +3.5% at Loughere-Thioly and by +12.7% at Syer and Tessekere.

These results are consistent with the work of [93] [94] [95]. This work shows that vegetation restoration is an effective tool for increasing plant biomass and organic carbon content. And, Soil organic carbon content is significantly higher in natural vegetation restoration than in managed vegetation and plowed land.

In Senegal, the implementation and inventories of forest areas as part of the PROGEDE 1 and 2 projects (Sustainable and Participatory Management of Traditional and Alternative Energy Project; [54] [96]) in seven regions of Senegal since 1998, have made it possible to quantify 15.37 million tons of sequestered carbon and 56.41 million tons of CO_2. The highest values of stored carbon were recorded in the forests of eastern and southern Senegal. The carbon quantities of the Koar, Guimara and Kandiator sites were 3,488,107 t.C respectively; 2,444,917 t.C and 2,422,389 t.C.

In China, the implementation of Grain to Green Program (GTGP) and eco-environmental emigration in the rocky Karstic desert region (Southwest China) have made it possible to sequester carbon and produce oxygen. Between 2000 and 2010, [97] showed the impact of ecological rehabilitation initiatives started in 1999 in this region on soil carbon storage and oxygen production. It notes a significant annual increase of 20.94% in carbon sequestration and oxygen production. The total increase in carbon and oxygen production in different counties in this region was estimated to be 7.66 million tons and 3.51 million tons respectively in Baise and Huanjiang.

4. Conclusions

This study, which aims to evaluate the carbon sequestration dynamics in the sites of the Great Green Wall (GGW) of Senegal over the last three decades, made it possible to initially analyze the evolution of land cover and land use based on ESA-CCI LC satellite data. It reveals a degradation of the vegetation cover between 1992 and 2000. This situation is a consequence of the droughts during 1970s, 1980s and 1990s periods. Unfavorable climatic conditions associated with overexploitation of land led to reductions in agricultural areas, tree savannas and forests. During the decades 2000-2020, a greening of different localities was observed. The gains in surface area of tree savannas and crop areas instead of steppes, grassland and bare soils vary between +2.7% to +11.4%. This greening of different localities and the improvement in the areas of tree and shrub savannas are due to above-normal rainfall on the one hand and to reforestation actions, agroforestry practices, better management of natural resources undertaken on the other hand. However, some non-reforested sites showed an opposite trend despite good rainfall.

Then, the carbon sequestration of the different localities of GGW Senegalese is computed according to the maps derived from the land cover. Estimated results for average total carbon sequestration range from 1.3 million t.C to 5.7 million t.C. Improvement of vegetation cover, mainly areas of tree and shrub savannas, by planting more than 18 million trees, restoring 15% of land, 9% of the GGW tree planting objective of Senegal and the setting aside of 13,000 ha, made it possible to sequester 2.31% of the African GGW objective. This gain in stored carbon amounts to 5.8 million tons of carbon which represents 21.2 million tons of CO_2 captured in the atmosphere. It appears from this study that carbon storage becomes significant 8 to 10 years after the start of reforestation. This study shows a loss of capacity to store carbon on non-reforested sites (case of Ballou). These results show the importance of implementing intelligent and sustainable land use management practices, intensifying reforestation in order to increase the carbon sequestration potential of these localities and combating the harmful effects of climatic changes.

Finally, the present results could be improved by integrating in future work the species of trees planted and the age of the consolidated plantations and serve as a reference level to evaluate the objectives of land restoration, carbon sequestration of the African GGW.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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