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Recent Vegetation Cover Dynamics and Climatic Parameters Evolution Study in the Great Green Wall of Senegal

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Abstract

The drought recorded in 1970s and 1980s, particularly in the Sahara and Sahel region has greatly affected the population as well as the economies and the eco-systems of this area. In 2007, the African Union launched a Pan-African program, the Great Green Wall for the Sahara, the Sahel Initiative (GGWSSI) to reverse land degradation and desertification by planting a wall of trees stretching from Dakar to Djibouti. The objective is to improve food security, and support local people to adapt to climate change. This paper aims to evaluate the impacts of the reforestation program in Senegal, fifteen years after it was launched. This study uses a time series of satellite-derived vegetation cover and climatic parameters data to analyze the sustainability of these interventions. Change detection approaches were applied to identify and characterize the drives of the eventual changes. A comparative analysis of reforestation on climatic parameters was explored through the temporal analysis of the vegetation index over the periods 2000-2008 and 2009-2020. An increase in vegetation activity was noted 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. Soil moisture is the climatic parameter that has increased the most, with an increase of 25% to 54% of the 2000-2020 average, *i.e.* between 20 mm and 70 mm more. This study shows a significant improvement in the relationship between NDVI and climate parameters after the different reforestation actions of the GGW.

Keywords

Great Green Wall of Senegal, Vegetation Index, Precipitation, Soil Moisture

1. Introduction

The Sahel is the semi-arid transition region that lies between the arid Sahara Desert and wetter regions of equatorial Africa. It extends from the Atlantic Ocean in the West to the Indian Ocean in the East. The Sahel's latitudinal limits fluctuate with rainfall patterns. This region has experienced some of the most extreme climate events on earth in the 20th century, and data from 1900 shows clear long-term climate change with a tendency towards higher temperatures, lower precipitation and increased frequency of extreme event stressors such as floods and droughts [1]-[11]. The drought recorded particularly in the 1970s and 1980s has greatly affected the population as well as the economies and the ecosystems of this area. This drought observed in the Sahel during this period had no equivalent in the spatial dimension [2]. These dramatic events have severely impacted both populations and the Sahelian agro-pastoral landscapes, resulting in decreasing possibilities for the ecosystems to continue to provide many services, ensuring sustainability. Some of the striking illustrations of the drought are the displacement of the isohyets by about 200 km over the whole region and the dramatic shrinking of the area occupied by free waters in Lake Chad [12]. As we can note, the Sahel region is highly vulnerable to climate change because of its geographic location and the dependence of its population on rain-fed agriculture and transhumance systems.

Since the United Nations convention to combat desertification [13] and the improvement of the resilience of the human and natural systems to climate change, the concept to restore the continent's degraded landscapes and transform millions of lives in the Sahel has been developed by African Union Leaders [14] [15].

In 2007, the African Union launched a Pan-African program, the Great Green Wall for the Sahara, the Sahel Initiative (GGWSSI) to reverse land degradation and desertification in the region, improve food security, and support local people to adapt to climate change [16]. This ambitious project implemented across 22 African countries brings together African countries and international partners under the leadership of the African Union Commission and the Pan-African Agency of the Great Green Wall. Eleven countries in the Sahel-Sahara region-Djibouti, Eritrea, Ethiopia, Sudan, Chad, Niger, Nigeria, Mali, Burkina Faso, Mauritania, and Senegal adopted the GGWSSI to tackle the adverse social, economic and environmental impacts of desertification in the region. In recent years, northern Africa has seen the quality of arable land decline significantly due to climate change and poor land management. The bulk of the work on the ground was originally slated to be concentrated along a stretch of land from Djibouti, Djibouti, in the east to Dakar, Senegal, in the west an expanse 15 kilometers (9 miles) wide and 7775 kilometers (4831 miles) long (**Figure 1**). Initially, the project was conceived as a way to combat desertification in the Sahel region and hold back the expansion of the Sahara, by planting a wall of trees stretching across the entire Sahel. The modern green wall has since evolved into a program promoting water harvesting techniques, greenery protection and improving indigenous land use techniques, aimed at creating a mosaic of green and productive landscapes across North Africa [14] [15] [17].

The GGW project aims to restore 100 million hectares of degraded land by 2030, capturing 250 million tons of carbon dioxide and creating 10 million jobs in the process. The Great Green Wall is a flagship program that will contribute to the goal of the United Nations Conference on Sustainable Development, or RIO + 20, of "a land degradation neutral world".

As of March 2019, 15 percent of the wall was complete with significant gains made in Niger, Mauritania, Senegal and Ethiopia. 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 [18]. Ethiopia has had the most success with 5.5 billion seedlings planted, but Chad has only planted 1.1 million. Doubt was

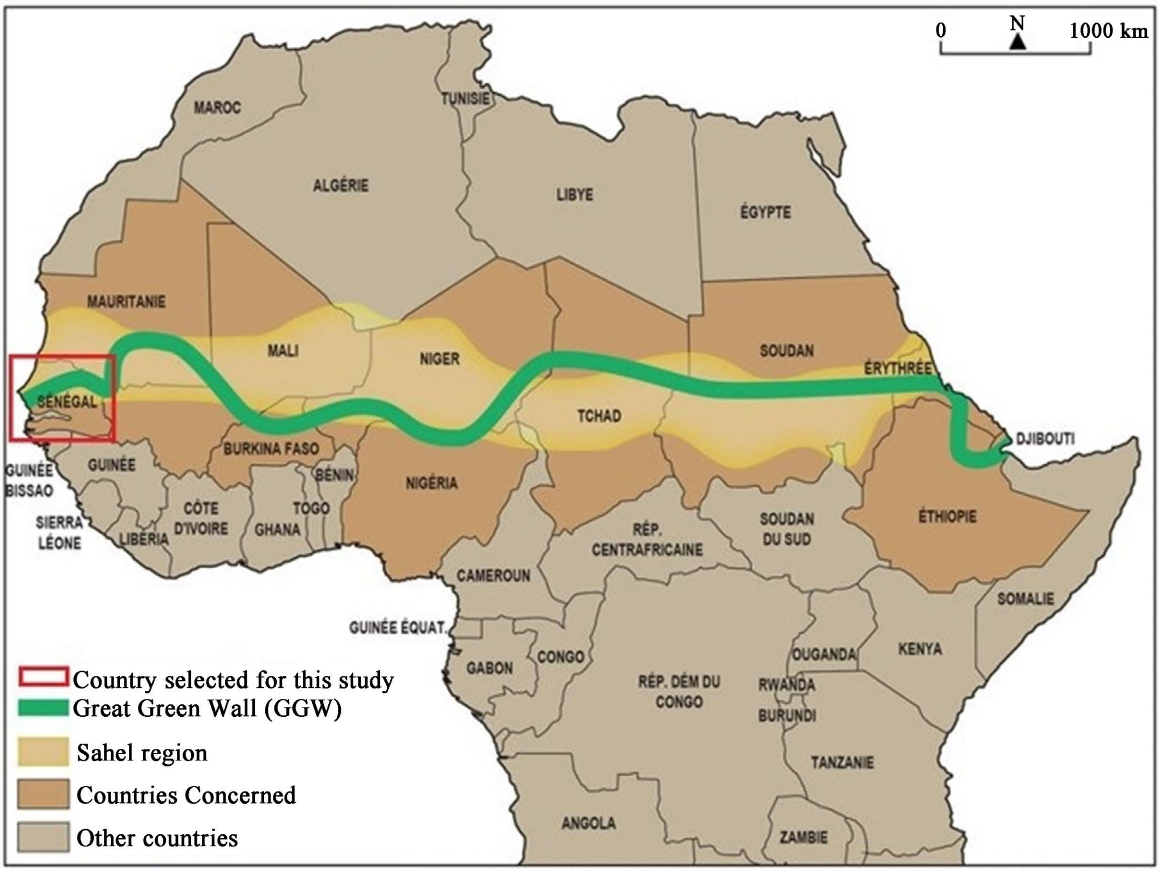

Figure 1. Location of the African Great Green Wall (Source: Agence de la Grande Muraille Verte; Crédit: http://geoconfluences.ens-lyon.fr, ENS de Lyon).

raised over the survival rate of the 18 million trees planted in Senegal. Examples of success include more than 50,000 acres of trees planted in Senegal. Many authors reported that progress was best in Senegal. Most of these are the acacia species Senegalia Senegal, which has economic value for the commodity it produces, gum arabic (gum arabic is primarily used as a food additive). A small portion of the trees is also fruit-bearing, which, when mature, will help combat the high levels of malnutrition in the country's rural areas. Even more dramatic is the project's potential social impact.

Fifteen years after the launch of the Pan-African program by the African Union, many studies have been conducted to evaluate the effectiveness of restoration and sustainability of the impacts of diverse interventions [16]. The study conducted by [16] focused on the project impact on biomass increase in the context of the GGW for the Sahara and Sahel Initiative Senegal. Time series satellite-derived precipitation estimates and Normalized Difference Vegetation Index data from 1981 to 2014 were utilized by [16] to characterize general precipitation and vegetation characteristics in the region and to compute long and short-term linear trends. This study noted that for some projects, slight positive changes after the intervention could be observed, indicating an increase in biomass. Other projects did not show any visible positive effect of the interventions. Our study utilizes a time series wider (1982-2020) than those of [16] and more climatic parameters to characterize the impacts of tree planting in Senegal. Furthermore, soil moisture which is an excellent indication of climatic change is performed.

In this study, some sites in Senegal were chosen as study areas as information was available through collaboration with the Fondation Cœur Vert. The objective of this study is to utilize a time series of satellite-derived vegetation cover and climatic parameters data to analyze general characteristics and trends.

The specific objectives of this paper are as follows:

1) Study the vegetation dynamic since the last 4 decades (1981-2020).

2) Analyze the impact of tree planting in Senegal based on climatic parameters from 2000 to 2020.

The structure of this paper could be summarized as follows:

The description of the study area, the data sources (vegetation index and climatic parameters) 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 [19]. 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 [20].

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 (**Figure 2**).

Figure 3 shows the Great African Green Wall (GGW) crossing northern Senegal.

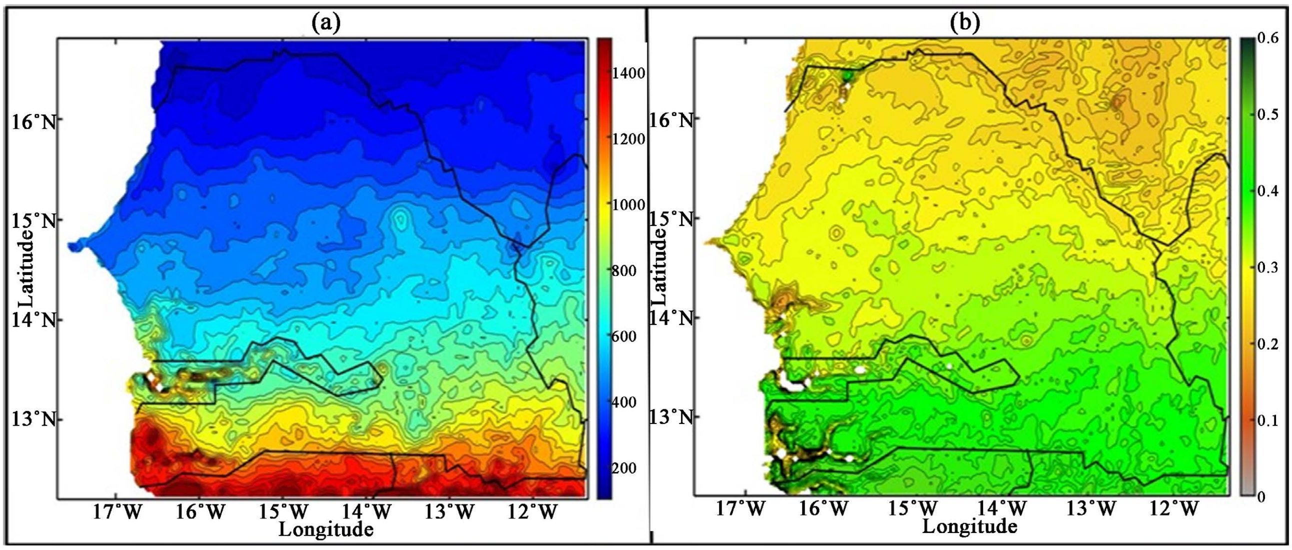

Figure 2. Spatial climatologies of annual (a) precipitation and (b) NDVI index in Senegal (1991-2020).

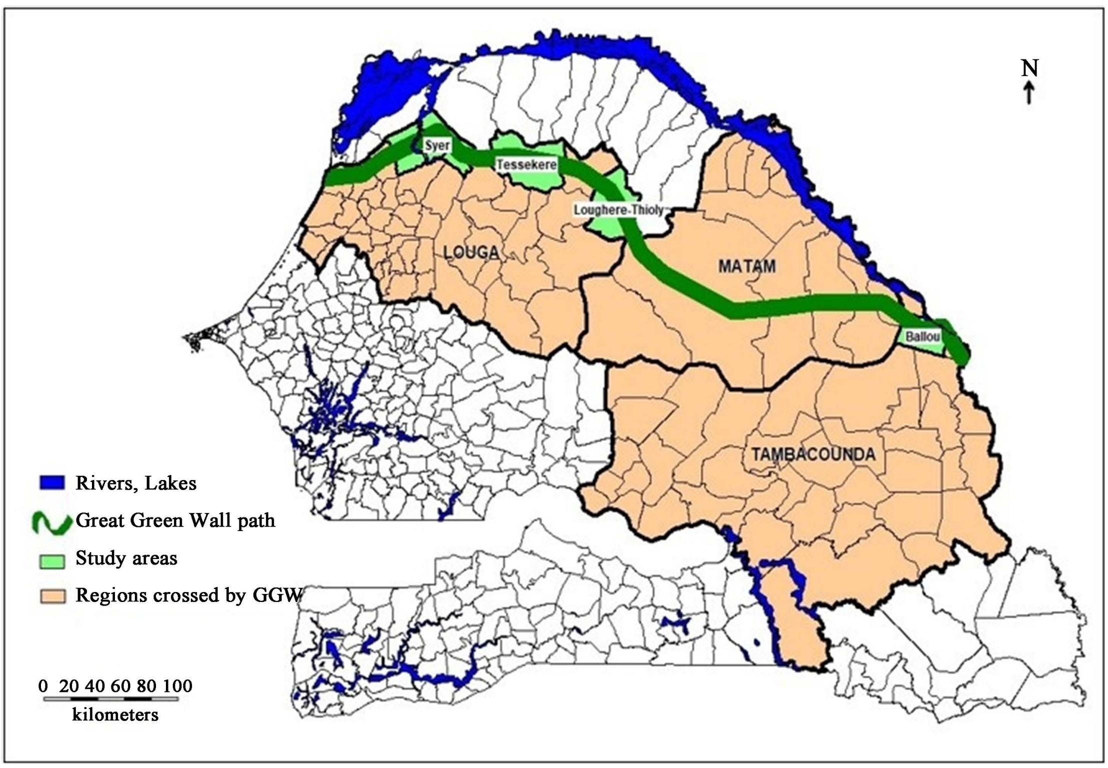

Figure 3. Location of study area and line of the GGW in Senegal.

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 817,500 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 surveys since 2006 (see **Table 1** and **Figure 3**).

2.2. Data Sources

Vegetation and climate dynamics are studied using Normalized Difference Vegetation Index (NDVI), Vegetation Health (VH), soil moisture, and Climate Hazards Group Infrared Precipitation with Stations (CHIRPSs) precipitation data.

NDVI and VH data were obtained from the National Oceanic and Atmospheric Administration Climate Data Record Program (NOAA-CDR, https://www.ncei.noaa.gov/data/avhrr-land-normalized-difference-vegetation-index/access/) and Center for Satellite Applications and Research [21] (NOAA-STAR, https://www.star.nesdis.noaa.gov/pub/corp/scsb/wguo/data/Blended_VH_4km/VH/) databases, respectively. The NDVI index is derived from Advanced Very High-Resolution Radiometer (AVHRR) data from NOAA satellites since 1981. The VH are available from 1982 to the present. These indices have a resolution of 4 km and are available at daily to weekly time steps.

CHIRPS precipitation data are a combination of station observations, cloud top temperature data and climatology data. These data were originally produced for climate trend analysis and seasonal drought monitoring [22] [23]. They have a spatial resolution of 5 km and cover the period from 1981 to the present. They are available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/.

Monthly soil moisture data are from the NOAA Climate Prediction Center (CPC) database and are available since 1948. These data are available on https://www.psl.noaa.gov/data/gridded/data.cpcsoil.htm. They represent a monthly average of soil water equivalent with a horizontal resolution of 0.5˚ × 0.5˚ over the entire globe. Soil moisture data are provided by a one-layer hydrological model [24]. The model uses observed precipitation and temperature data to derive soil moisture, evapotranspiration and runoff.

Table 1. Regions, departments and communes covered by GGW in Senegal and sites selected for this study (*) [19].

Administrative regions (inhabitants of region)	Departments	Municipalities	Length of GGB (km)	Inhabitants
Louga (1,091,268)	Louga. Linguere	Leona, NgueuneSarr, Sakal, Keur Momar Sarr, Syer*, Mboula, Tessekere* et Labgar	225	130,057
Matam (760,588)	Kanel.Ranerou	Loughéré-Thioly*, Oudalaye, Ourou Sidy, Dendory et Aoure	250	134,830
Tambacounda (904,032)	Bakel	Ballou*, Gabou et Bele	70	57,334
Total: 3 regions	5	16	545	322,221

2.3. Methodology

2.3.1. Vegetation and Rainfall Variability Analysis

This sub-section outlines the methods used to examine long-term trends and multi-year variations in vegetation and precipitation data. The Locally Estimated Scatterplot Smoothing (LOESS) regression method is used. It allows the adjustment of a window width equal to 100% (*i.e.* long-term trends) and 25% (*i.e.* short-term trends) of the number of values respectively [25].

The calculation of Standardized Precipitation Anomalies (SPIs) and Vegetation Anomalies Index (VAI) is used to remove the seasonal and climatic signal from the monthly and annual series respectively. In the case of SPI, it allows the user to highlight the different modes of variability and the different periods of parameter evolution, such as wetness, drought or vegetation stress. A negative SPI indicates drought, while a positive index denotes wet conditions [26]. **Table 2** shows different SPI values as defined by the World Meteorological Organization [27]. Subsequently, the SPI is used to detect extreme events in vegetation and precipitation.

The VAI is a measure of water stress in vegetation. This monthly quantitative index describes vegetation conditions. A positive value indicates satisfactory vegetation dynamics, while a negative value indicates vegetation stress.

2.3.2. Identifying Breaks in Vegetation and Climate Series

The Pettitt's test [28] is used to check for breaks in vegetation and climatic time-series. The probability associated with this test is interpreted in accordance with **Table 3** [29] to estimate the significance of the break.

The Bayesian Estimator of Abrupt Change, Seasonal Change and Trend

Table 2. SPI index as defined by the Worls Meteorological Organization (WMO) [27].

≥2.0	Extremelywet
1.5 - 1.99	Verywet
1 - 1.49	Moderatelywet
−0.99 - 0.99	Nearly normal
−1.0 - −1.49	Moderately dry
−1.5 - −1.99	Very dry
≤−2.0	Extremely dry

Table 3. Probability related to the Pettitt's test.

Relatedprobability	Class
<1%	Verysignificant break
1% - 5%	Significant break
5% - 20%	Minor break
>20%	Homogeneousseries (non-significant break)

(BEAST) algorithm [30] is also used to search for breaks in the climate and vegetation time series. BEAST decomposes a time series into a seasonal signal, a trend, an abrupt change and a noise signal. The variables that give the seasonal and trend components provide information on the probability, the confidence intervals and the number of abrupt changes that are estimated by the algorithm.

2.3.3. A Comparative Analysis of Vegetation and Climatic Changes before and after Reforestation in the GGW of Senegal

The aim is to compare the evolution of the different climatic parameters and the vegetation between 2000 and 2008, before the reforestation, and between 2009 and 2020, after the reforestation. First, the temporal evolution of the NDVI index between the two periods is compared using Student's and Mann-Whitney-Wilcoxon means tests [31] [32] [33] at 95% and 99% confidence levels. These tests are selected by applying the normality tests of Shapiro [34], Jarque-Bera [35], Kolmogorov-Smirnov and D'Agostino [36] [37] [38] (**Table 4**). The dynamic relationships between vegetation and climatic parameters are then assessed using temporal correlations at 95% and 99% confidence levels.

3. Results and Discussions

3.1. Vegetation Cover and Rainfall Analysis in the Senegalese GGW from 1982 to 2020

This section is devoted to the temporal analysis of the vegetation cover through the Normalized Difference Vegetation Index (NDVI) over the period 1982-2020. Afterwards, an analysis of precipitation indicators variability from 1981 to 2020 is followed.

3.1.1. Analysis of the Vegetation Cover Dynamic in the Senegalese Great Green Wall

1) Monthly Spatial climatology of vegetation index in Senegal

The Senegal normal climatology of the vegetation cover is represented in **Figure 2(b)** based on NDVI data computed over 1991-2020. This figure shows a zonal distribution of the vegetation cover with NDVI values decreasing from south to north (**Figure 4**).

In the south (12˚N and 13˚N), the NDVI values are between 0.4 and 0.5 and

Table 4. Selecting means comparison tests and computing correlation coefficients.

Verification of data normality	**Shapiro-Wilk test, Jaque-Bera test, Kolmogorov-Smirnov test and D'Agostino test**	
Normality and tests	Normal (parametric test)	Not Normal (non-parametric test)
Comparison of means	Student's test (95% and 99% confidence levels)	Mann Whitney-Wilcoxon test (95% and 99% confidence levels)
Correlation	Pearson correlation (95% and 99% confidence levels)	Kendall or Spearman correlation (95% and 99% confidence levels)

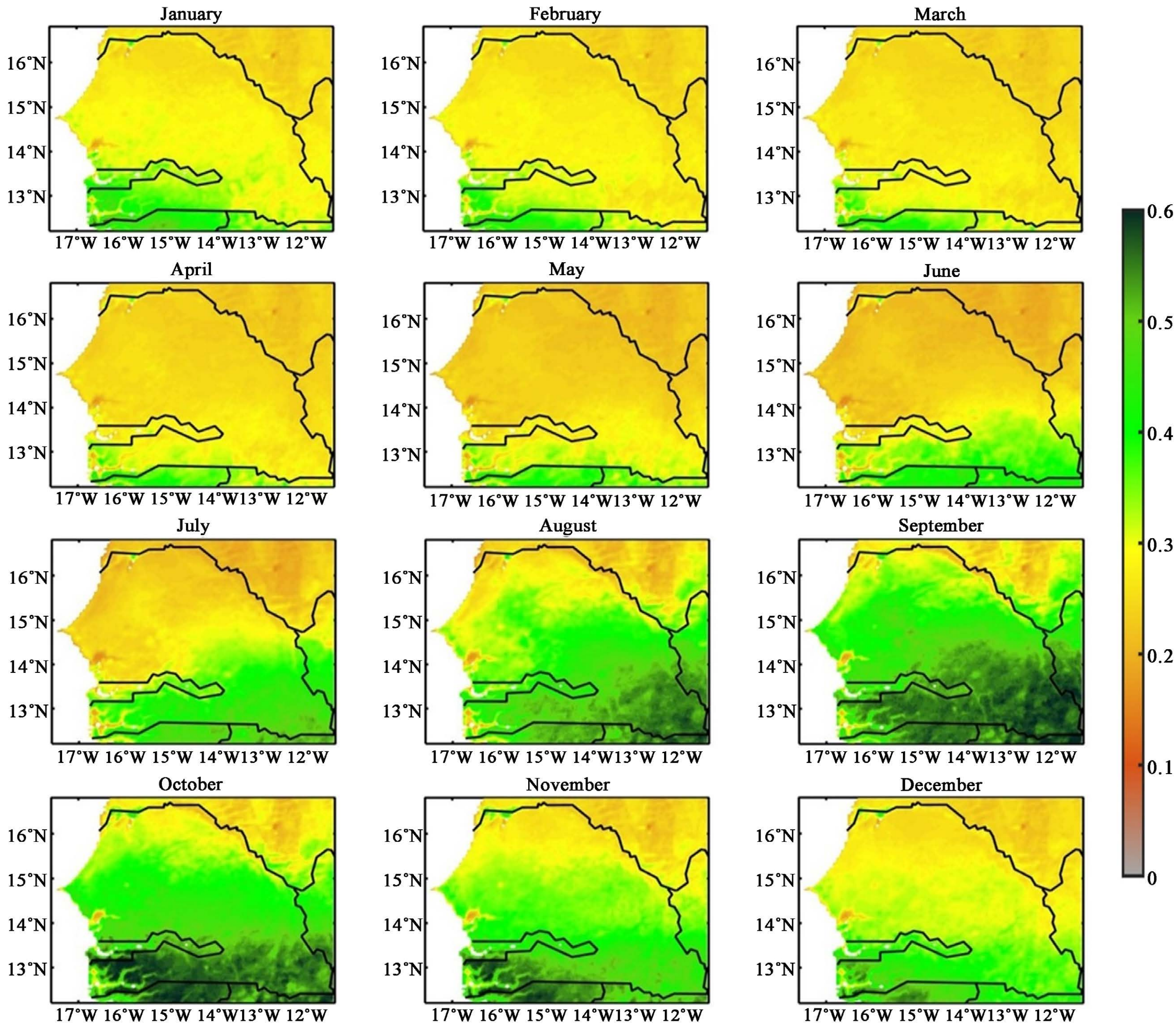

Figure 4. Monthly climatology of the vegetation index (NDVI) in Senegal over the period 1991-2020.

correspond generally to clear and dense forest.

The NDVI values between 0.3 and 0.4 represent savannah areas and are located on the latitude 13˚N - 15˚N.

The latitude between 15˚N - 17˚N is dominated by the steppe corresponding to NDVI values varying from 0.2 to 0.3.

The Senegalese growing vegetative season extends from July to November. In the north, this season starts generally in August and ends in October. The highest NDVI values are recorded in the south reaching 0.6 (Figure 4).

2) Temporal vegetation cover evolution in the Senegalese GGW (1982-2020)

The analysis of the temporal vegetation cover evolution is based on Vegetation Anomaly Index computed over 1982-2020 period (Figure 5). This figure highlights the variability of the vegetation cover evolution. An alternation of negative and positive behavior of the vegetation dynamic is observed in the different regions during the study period. However, the difference in the length of

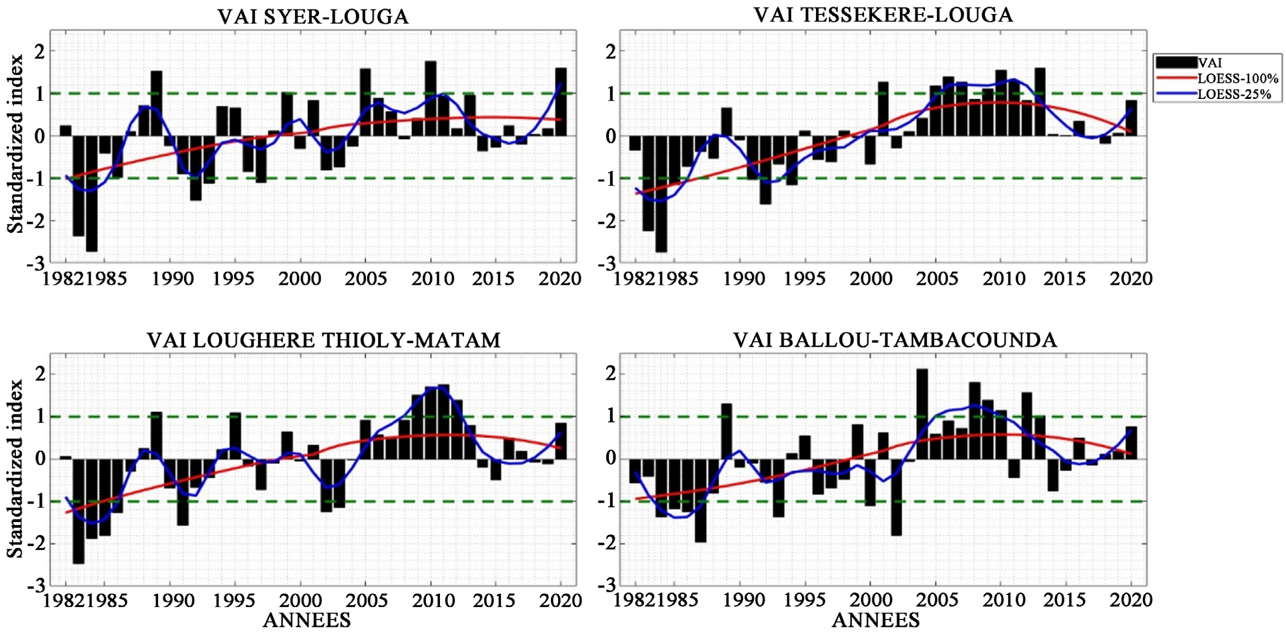

Figure 5. Evolution of vegetation index anomalies in Syer, Tessekere, LougehereThioly and Ballou GGW-Senegal from 1982 to 2020.

time and between the beginning and the end of each period vary from one region to another.

The shape of the long trend lines allows us to group the different sites on two (Tessekere and Loughere-Thioly) and three (Syer and Ballou) vegetation cover dynamics (**Figure 5**).

The long-term trend (LOESS-100%) on Syer (Louga) and Ballou (Tabacounda) reveals three periods corresponding to two abrupt changes in the vegetation cover dynamics. The first one corresponds to the stress of the vegetation cover (negative dynamic) from 1982 to 1997 on Syer site and at Ballou (1982-1999). The second one (positive anomaly) occurs at Syer (1998-2017/2018) and at Ballou (2000-2019). The third phase (negative dynamic) took place respectively during 2019-2020 (Syer) and 2020 (Ballou).

Two evolution regimes are observed on the long-term trend on Tessekere and Loughere-Thioly sites. There is a shift from negative (1982-1999) to positive (2000-2020) dynamics in 1999 on the two sites.

Globally, we can notice that the vegetation cover index presents a negative anomaly from 1982 to the end of the 1990 decade on all the Senegalese GGW sites.

3.1.2. Temporal Analysis of the Precipitation in the Senegalese Great Green Wall

According to [39], the major causes of land degradation stem from climatic conditions, including an arid environment and low irregular rainfall patterns. The aridity is becoming pronounced due to a reduction in the mean annual rainfall. The analysis of the climatic periods is based on the Standard Precipitation Index (SPI) usually carried out to quantify wetness/dryness of a given rainy season with respect to the climatology.

Figure 6 shows the evolution of the Standard Precipitation Index in Syer, Tessekere, Loughere-Thioly and Ballou localities. Two and three phases are observed through the non-parametric estimators have been performed. A first phase of a highlighting persistent drought period is observed from 1981 to 1997/1998 including a severe drought during 1981-1985 and 1990-1993 periods (SPI < −1.5) for the entire study zone. The second phase indicates a precipitation recovery of the wet conditions since 1998/1999. During this period, consecutive wet years are observed characterizing by a value of SPI greater than 1.5 (Syer and Tessekere: 2009-2011; Loughere-Thioly and Ballou: 2009-2012). In the last phase, a consistently decreasing of the precipitation is noted after the year 2018 (Syer and Tessekere: 2018-2020; Ballou: 2019-2020).

The interannual analysis based on LOESS-25% shows a short period of 3 wet years from 1987 to 1989 in Syer, Tessekere and Loughere-Thioly during the long dry period extending from 1981 to 1998. This observation is valid in 2015-2018 period in which a very short wet condition took place (1999-2020).

3.1.3. Breakpoints Analysis Derived from Vegetation and Climatic Parameters Time Series at Annual and Seasonal Scales in the Study Area

This section focuses on the detection of breakpoints relative to vegetation indices and climatic parameters (precipitation, soil moisture) time series. In statistic and signal processing, step detection is the process of finding abrupt changes in the mean level of a time series or signal. This method could help to establish and identify any probable causes. Parametric and non-parametric approaches are used

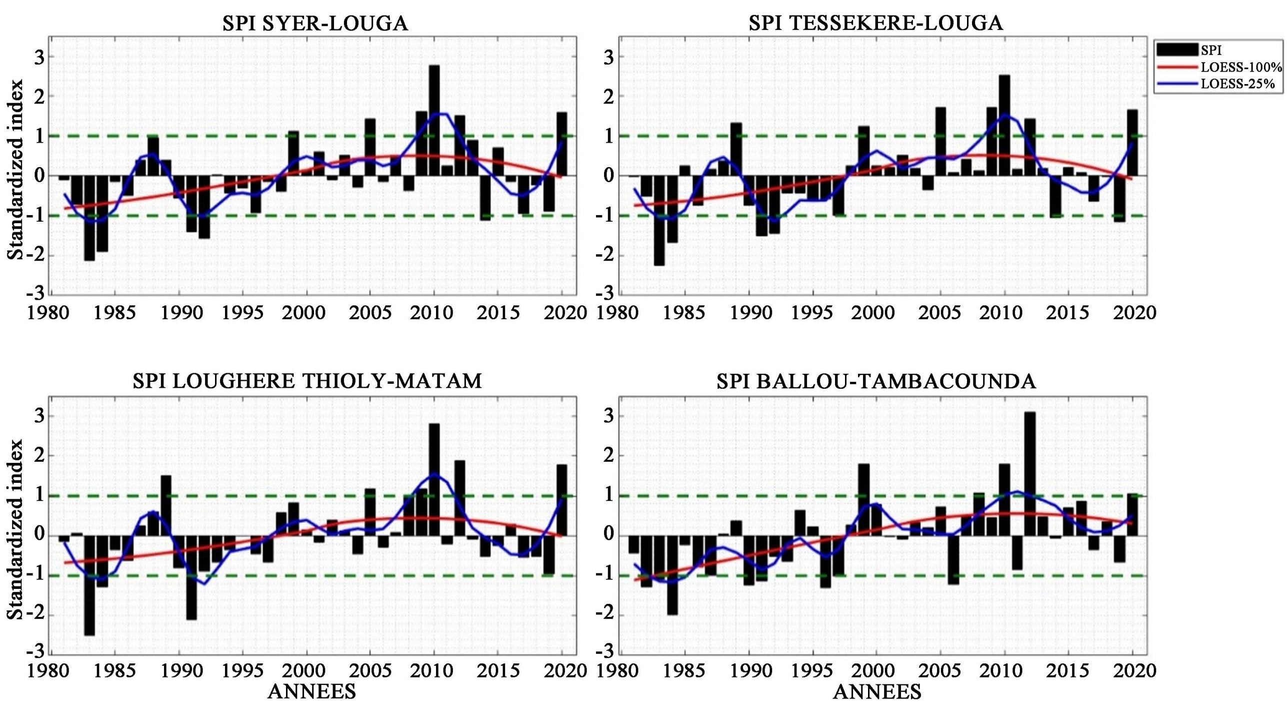

Figure 6. Evolution of precipitation anomalies in Syer, Tessekere, LoughereThioly and Ballou GGW-Senegal from 1981 to 2020.

to detect the breakpoints in vegetation indices and climatic parameters. The parametric approaches require features to follow specific statistical distributions, such as normal distribution and they are very sensitive to outliers. The non-parametric approaches do not require any prior assumption about the distribution characteristics of samples [40]. The detection of breakpoints is based on Pettitt's test (parametric approach) which is widely used in hydro-climatological studies for addressing abrupt change within the time series, allowing the detection of a single shift at unknown time t [41]. The second approach is based on Bayesian Estimator of Abrupt Change (non-parametric). This method is developed to identify gradual and abrupt change, allowing the detection of multiple breakpoints, while explicitly considering seasonal variations.

1) Breakpoints detection analysis based on Pettitt's test

Figure 7 and **Table 5**, **Table 6** give the main breakpoints of the mean NDVI, precipitations and soil moisture data during the 1981-2020 period. Regarding the results of **Table 5** and **Table 6**, the significant breakdates of annual precipitation detected are 1997 for Tessekere and Loughere-Thioly and 1998 for Ballou and Syer. The precipitation data relative to the wet seasons presents significant breakpoints. Those of the dry seasons are less significative.

Very significant breakpoints for annual NDVI are observed at Syer (2000), Loughere-Thioly (2004), Ballou (2002) and Tessekere in 2004. At seasonal level, the breakpoints relative to NDVI values are more significant in the dry seasons than in wet seasons. The Vegetation Health Index (VHI) time series present breakdates which occur before those detected in the NDVI data time series or at

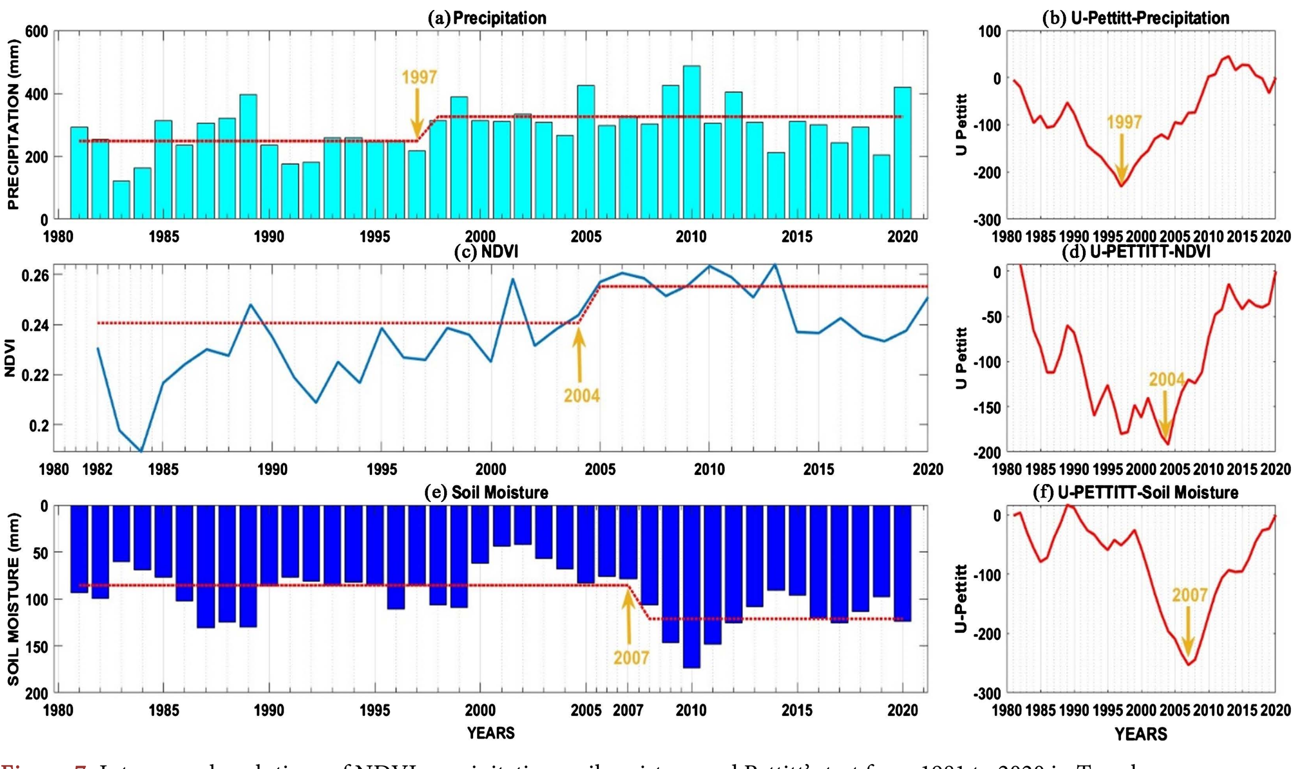

Figure 7. Interannual evolutions of NDVI, precipitation, soil moisture and Pettitt's test from 1981 to 2020 in Tessekere.

the same dates. The breakdates at Syer, Loughere-Thioly, Tessekere and Ballou are respectively detected in 1997, 2003, 2004 and 2002. The significant breakpoints during the wet seasons based on VHI values are detected in October 1997 at Syer, Tessekere and Loughere-Thioly and October 2002 at Ballou. Figure 7 showed that the breakdates performed with soil moisture data time series are identified for all of the study areas in 2007, excepted in Ballou where a non-significant break change took place in 2002.

It can be noted that the mean values of NDVI and climatic parameters

Table 5. Break dates and vegetation statistics (NDVI, VHI) of the Pettitt's test.

Pettitt's test Sites	NDVI				VHI			
	Break date	Averagebefo rebreakdate	Averageafte rbreakdate	Pettitt's statistics (U and P-value)	Break date	Averagebefo rebreakdate	Averageafte rbreakdate	Pettitt's tstatistics (U and P-value)
Annual data								
Syer	2000	0.224	0.248	U = 324 $Pv = 6.310^{-5}$	1997	42.47	53.66	U = 304 $Pv = 2.210^{-4}$
Tessékere	2004	0.240	0.255	U = 192 Pv = 0.05	2004	46.50	50.52	U = 112 Pv = 0.58
Loughéré-thioly	2004	0.237	0.257	U = 236 Pv = 0.008	2003	41.82	52.01	U = 202 Pv = 0.03
Ballou	2002	0.274	0.288	U = 256 Pv = 0.003	2002	45.81	51.15	U = 162 Pv = 0.15
Growing season								
Syer	08/2003	0.255	0.295	U = 1826 $Pv = 8.310^{-6}$	10/1997	41.67	54.88	U = 1576 $Pv = 1.910^{-4}$
Tessekere	10/2004	0.295	0.320	U = 870 Pv = 0.12	10/1997	44.91	54.68	U = 892 Pv = 0.10
Loughere-thioly	08/2004	0.290	0.321	U = 1150 Pv = 0.01	10/1997	41.86	54.57	U = 1272 Pv = 0.005
Ballou	08/2003	0.38	0.40	U = 760 Pv = 0.23	10/2002	45.82	59.07	U = 1690 $Pv = 4.910^{-5}$
Dry season								
Syer	07/1997	0.21	0.23	U = 14372 $Pv = 7.710^{-13}$	03/1998	42.79	53.38	U = 16216 $Pv = 3.110^{-16}$
Tessekere	07/1997	0.219	0.23	U = 9199 $Pv = 1.610^{-5}$	11/2004	46.14	48.96	U = 9494 Pv = 0.12
Loughere-thioly	07/2003	0.218	0.236	U = 10864 $Pv = 1.610^{-7}$	07/2003	40.98	50.59	U = 12222 $Pv = 2.110^{-9}$
Ballou	06/2003	0.23	0.251	U = 8172 $Pv = 1.910^{-4}$	06/2003	45.44	49.07	U = 5694 Pv = 0.02

Table 6. Break dates and statistics of precipitation and soil moisture of Pettitt's test.

Pettitt's test Sites	Precipitation				Soil moisture			
	Break date	Averagebeforebreakdate	Averageafterbreakdate	Pettitt's statistics (U and P-value)	Break date	Averagebeforebreakdate	Averageafterbreakdate	Pettitt's statistics (U and P-value)
Annual data ("precipitation(mm/year)" and "soil moisture (mm/month)")								
Syer	1998	228.53	294.12	U = 212 Pv = 0.03	2007	86.42	108.89	U = 195 Pv = 0.061
Tessekere	1997	248.15	325.65	U = 231 Pv = 0.01	2007	85.49	121.24	U = 253 Pv = 0.005
Loughere-thioly	1997	322.46	388.30	U = 195 Pv = 0.06	2007	88.39	117.32	U = 229 Pv = 0.016
Ballou	1998	481.89	580.90	U = 273 Pv = 0.002	2002	133.33	154.72	U = 142 Pv = 0.32
Wet season (mm/month)								
Syer	07/1997	66.41	87.50	U = 1179 Pv = 0.01	07/2005	102.41	136.13	U = 997 Pv = 0.065
Tessekere	08/1998	71.09	96.63	U = 1481 Pv = 0.001	07/2007	110.58	161.37	U = 1200 Pv = 0.014
Loughere-thioly	09/1997	93.58	114.36	U = 1017 Pv = 0.05	08/2004	115.35	152.10	U = 1049 Pv = 0.045
Ballou	07/1998	133.51	162.22	U = 1140 Pv = 0.02	07/2003	185.97	232.72	U = 1021 Pv = 0.055
Dry season (mm/month)								
Syer	10/1999	2.87	3.31	U = 3653 Pv = 0.36	06/2007	79.09	101.10	U = 5464 Pv = 0.043
Tessekere	05/2012	4.06	4.12	U = 1258 Pv = 1	06/2007	75.98	108.96	U = 8248 Pv = 3.210^{-4}
Loughere-thioly	10/1997	4.69	4.98	U = 174 Pv = 1	06/2007	78.07	104.69	U = 6772 Pv = 0.005
Ballou	03/2012	9.91	10.07	U = 940 Pv = 1	06/2003	113.39	132.65	U = 3794 Pv = 0.31

increase after the breakdates. The NDVI and the precipitation increase respectively from 5% to 10% and from 20% to 31%. The most significant rising value is recorded for the soil moisture with values between 26% to 37%.

2) Breakpoints detection analysis based on Bayesian Estimator of Abrupt Change, Seasonal Change and Trend (BEAST)

Figure 8 and Table 7 provide the breakdates, occurrence of probability breakpoints, the trend slopes of annual data of NDVI, precipitation and soil moisture during the 1991-2020 period. The trend decomposed by BEAST enables

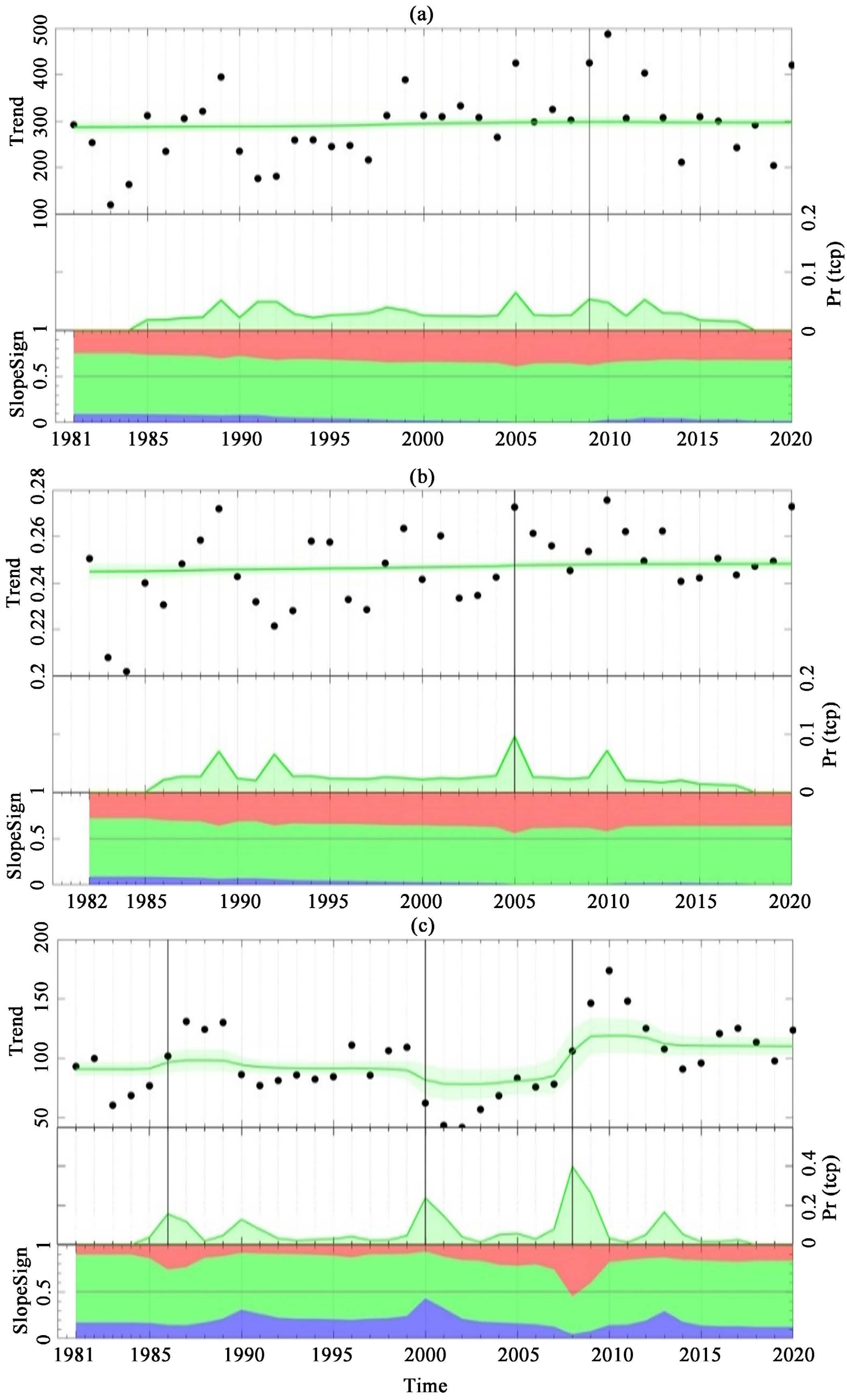

Figure 8. BEAST decomposition for annual (a) precipitation, (b) NDVI and (c) soil moisture from 1981 to 2020 inTessekere.

Table 7. Break dates, probability of occurrence of breaks, and slope of trends in annual precipitation, NDVI, and soil moisture data of Bayesian BEAST test.

Parameters Sites	Precipitation			NDVI			Soil moisture		
	Year	Probability	Slope	Year	Probability	Slope	Year	Probability	Slope
	2009	0.15	0.73	2014	0.41	−0.006	2010	0.20	0.40
	1992	0.12	0.41	2001	0.29	0.004	2002	0.17	0.12
SYER	2012	0.11	−0.20	2005	0.20	0.001	1991	0.05	−0.001
	1999	0.09	1.20	1989	0.13	0.001			
				1992	0.07	0.0006			
	1992	0.13	0.38	2005	0.16	0.0004	2008	0.67	18.88
	2012	0.12	−0.47	1989	0.13	0.0001	2000	0.42	−7.43
TESSEKERE	1998	0.11	2.04	2010	0.12	9.3910^{-5}	1986	0.29	4.07
				1992	0.11	7.6610^{-5}	2013	0.25	−4.53
				1998	0.07	0.0001	1990	0.24	−3.03
	2010	0.17	0.27	2005	0.21	0.002	2009	0.53	12.38
	1991	0.16	0.12	2014	0.18	−0.001	2000	0.44	−11.76
LOUGHERE THIOLY	1998	0.08	0.65	1987	0.17	0.002	1986	0.38	9.08
	2005	0.07	0.43	1994	0.11	0.0007	1990	0.34	−7.04
							2013	0.30	−5.95
	1999	0.31	9.87	2004	0.47	0.004	2002	0.19	0.24
	2010	0.14	1.33	1989	0.26	0.001	1997	0.18	0.05
BALLOU	2006	0.12	1.06	2014	0.14	−0.0006	1985	0.05	0.09
	1994	0.09	2.71	2008	0.10	3.8610^{-5}			
				1994	0.07	0.0001			

identifying several distinct breakdates. Precipitation time series data exhibits positive trends in the periods 1991/1992, 1998/1999, 2005/2006, 2008/2009 and 2010. A negative trend is recorded in 2012 at Syer and Tessekere. Significant change points in annual mean values of NDVI with positive slopes were detected by BEAST in 1987 (Loughere-Thioly), 1989 (Syer, Tessekere, Ballou), 2001, 2004/2005, 2008 and 2010 (Syer). The break change points associated to negative slope is observed in 2014 in Syer, Loughere-Thioly and Ballou localities. In contrary, only breakpoints with positive slopes are detected in Tessekere.

The soil moisture time series are characterized by many breakpoints associated with high slope values. These breakpoints are detected during the years 1985/1986, 2002, 2008 (Tessekere), 2009 (Loughere-Thioly), 2010 (Syer). In contrast, the breakdates associated with negative slopes are detected in 1990/1991, 2000 and 2013 (Tessekere, Loughere-Thioly). The soil moisture time series of Ballou are characterized by breakpoints associated to positive slopes.

It was observed that changepoints are abrupt variations in time series data and may represent transition between different states. In this study, obtained these results based on the detection of breakdates in time series are in accordance with the standardized anomalies analyses associated with NDVI and precipitation dataset in the study area.

The significant breakdates detected by BEAST and Pettitt's test are similar to those found when analyzing the temporal values of NDVI and climatic standardized anomalies. These result agrees with the analysis of Sahelian SPI in the basis of data from 600 stations monitored by AGRHYMET Regional Centre which mentions two distinct periods [12]: the first period from 1950-1969 was characterized by a persistence of wet years and the second period from 1970 to 1993, by a persistence of over twenty dry years. So, the 1970s marked a change in climate in the Sahel. This study based on AGRHYMET stations shows three wet years recorded in the Sahel 1994-1999-2003.

The results of the NDVI variability, precipitation and the change point detection studies spanning over four decades revealed a negative dynamic of the vegetation cover (land cover degradation) due to the severe drought that occurred between 1982 and the end of 1990s. This period was characterized by many severe episode droughts recorded in 1970s, 1980s and 1990s in all the Sahelian regions [1]-[11]. Land degradation typically stems from both human-related and natural factors. Overfarming, overgrazing, rainfall deficit, and extreme weather are the most common causes of the reduction of the forests, savannah, and cultivated areas during the years 1980s, and 2000s. The rainfall deficit recorded in the study region was 11 to 20% during 1990-2020. In the Sahel, this rainfall deficit represents 15 to 25% comparing to the mean rainfall recorded from 1900 to 2015 and 25 to 50% during the wet period lasting from 1950 to 1967 [10]. During the years classified as drought years, there was a decrease of vegetative activities between 4% - 8.5%. A study conducted by [5] based on rainfall gauges over 1950-2006 period revealed that the period 1970-1990 was characterized by a continuous rainfall deficit of 50% compared to the previous 1950-1969 wet period at 15˚N. They also noted a greater rainfall interannual variability during 1970-1990 and a contrast between western Sahel which remained dry and the eastern Sahel returning to wetter conditions.

According to [42], the spontaneous vegetation has undergone a strong regression in the Ferlo (Tessekere) region. [43] noted that the protected areas remained stable but there was a regression of the wooded and tree savannah areas. In the Ferlo region, the wooded and tree savannahs have respectively lost 306,305 and 160,576 ha for the benefits of shrub and wooded savannahs. [43] and [44] noted that the main causes of land degradation (extension of steppe areas) are due to the low irregular rainfall patterns, human activities, increase of the cattle and the human population [6] [7] [8] [9] [10] [45] [46].

One can observed a progressive dynamic of vegetation cover from 2000 to 2020. This progressive dynamic is observed one or two years after the recovery of the precipitation. The wet condition started in 1997/1998. The regreenness of the vegetation increased from 1.5 to 3%. With the recovery of the precipitation (from 3 to 7% relative to the mean 1991-2020) after the 1980s and 1980s dry years, there was a regrowth of the vegetation cover.

This positive vegetation dynamic lies on the impacts of different projects implemented. In Senegal, several projects (e.g. reforestation, forage, and community gardens) have been implemented in the context of the GGWSSI by the Great Green Wall agency under the responsibility of the ministry of Environment, which concentrates funds for rehabilitation of soils and reforestation in a zone of Senegal (Programme d'Appui au Développement Agricole et à l'Entreprenariat Rural (PADAER) in 2011; [43] [47] [48] [49] and good management of local natural resources [10] [50] [51] [52]. According to [48] [49], 4,000 ha of bare soil have been restored in the Tessekere area. The decrease of the bare soil areas is due to the implementation of the agro-pastoral land development Germano-Senegalese project since 1986 funded by GTZ. This could explain the breakpoints associated with positive slopes detected at Tessekere and Loughere-Thioly respectively in 1989 and 1987. The extension of the cultivated areas in Tessekere was related to the GGW tree plantation project which started in 2005.

Within the GGWSSI, different kinds of projects have been implemented. Over the period 2005-2019, Senegal accounted for 4% of the restored land.

3.2. Comparative Analysis of the Impact of Reforestation over Climatic Parameters from 2000 to 2020 in the GGW Senegal

1) Analysis of normality tests vegetation (NDVI, VHI) and climatic parameters (precipitation, soil moisture) time series data

Tables 8-11 present the results of the tests applied to NDVI, VHI, precipitation and soil moisture data on annual and monthly scales over the period 1981-2020 (case of Syer). The NDVI, VHI, precipitation and soil moisture of annual time series data follow a normal distribution. But the same data set (except VHI) do not follow a normal distribution at monthly scale.

A comparison with student test (parametric test) is performed to assess the mean of annual NDVI and climatic parameters data and monthly VHI data. The comparison Mann Whitney-Wilcoxon (non-parametric test) is carried out in order to compare the NDVI, precipitation and soil moisture monthly mean values.

2) Interannual evolution of vegetation cover and climatic parameters during the period 2000-2020

Table 12 and Table 13 represent respectively the mean annual statistics and those of mean wet seasonal (July-August-September) values of vegetation (NDVI, VHI) and climatic parameters (Precipitation, soil moisture) over the periods 2000-2020, 2000-2008 and 2009-2020 in the GGW Senegal study areas.

The NDVI shows an increase of 2% to 8% when comparing the periods 2000-2008 and 2009-2020. The NDVI recorded an increase of 1.5% to 7% during

Table 8. Results of normality tests of annual and monthly NDVI series of Syer locality.

Data (NDVI)	Test name	Test statistics	P-value	Normality decision (1: normal, 0: not normal)
Annual (number of years: 39)	Kolmogorov-Smirnov	0.58	0.88	1
	Shapiro-Wilk	0.96	0.18	1
	Jarque-Bera	1.77	0.41	1
	Dagostino & Pearson	2.59	0.27	1
Monthly (number of months 468)	Kolmogorov-Smirnov	1.90	0.001	0
	Shapiro-Wilk	0.96	3.40×10^{-10}	0
	Jarque-Bera	63.48	1.64×10^{-14}	0
	Dagostino & Pearson	49.74	1.59×10^{-11}	0

Table 9. Results of normality tests of annual and monthly VHI series of Syer locality.

Data (VHI)	Test name	Test statistics	P-value	Normality decision (1: normal, 0: not normal)
Annual (number of years: 39)	Kolmogorov-Smirnov	0.86	0.46	1
	Shapiro-Wilk	0.95	0.056	1
	Jarque-Bera	3.065	0.22	1
	Dagostino & Pearson	3.43	0.18	1
Monthly (number of months 468)	Kolmogorov-Smirnov	1.04	0.23	1
	Shapiro-Wilk	0.99	0.19	1
	Jarque-Bera	1.71	0.42	1
	Dagostino & Pearson	1.65	0.44	1

Table 10. Results of normality tests of annual and monthly precipitation series of Syer locality.

Data (precipitation)	Test name	Test statistics	P-value	Normality decision (1: normal, 0: not normal)
Annual (number of years: 40)	Kolmogorov-Smirnov	0.73	0.65	1
	Shapiro-Wilk	0.98	0.76	1
	Jarque-Bera	0.78	0.67	1
	Dagostino & Pearson	1.56	0.46	1
Monthly (number of months 480)	Kolmogorov-Smirnov	6.74	0	0
	Shapiro-Wilk	0.63	0	0
	Jarque-Bera	721.24	0	0
	Dagostino & Pearson	209.32	0	0

Table 11. Results of normality tests of annual and monthly soil moisture series of Syer locality.

Data (soil moisture)	Test name	Test statistics	P-value	Normality decision (1: normal, 0: not normal)
Annual (number of years: 40)	Kolmogorov-Smirnov	0.47	0.98	1
	Shapiro-Wilk	0.98	0.86	1
	Jarque-Bera	0.32	0.85	1
	Dagostino & Pearson	0.61	0.74	1
Monthly (number of months 480)	Kolmogorov-Smirnov	2.47	9.98×10^{-6}	0
	Shapiro-Wilk	0.91	3.33×10^{-16}	0
	Jarque-Bera	101.95	0	0
	Dagostino & Pearson	72.14	2.22×10^{-16}	0

Table 12. Annual mean statistics of the evolution of vegetation activity and climatic parameters of the localities of the GGW-Senegal from 2000-2020 (Student's t-test of comparison of means at the significance levels $\alpha = 0.05$(*) and $\alpha = 0.01$(**)).

Sites	Parameters	PERIODS			Difference (2009-2020) from (2000-2008)	Evolution in % (2009-2020) and (2000-2008)
		2000-2020	2000-2008	2009-2020		
TESSEKERE (LOUGA)	NDVI	0.252	0.24	0.26	0.02	7.94%
	VHI	49.04	47.90	49.89	1.98	4.06%
	Precipitation	323.27	319.836	325.846	6.01	1.86%
	Soil moisture	99.38	68.57	122.5	53.93**	54.27%
SYER (LOUGA)	NDVI	0.247	0.247	0.25	0.003	1.21%
	VHI	53.31	53.03	53.52	0.49	0.92%
	Precipitation	291.85	282.2	299.08	16.88	5.78%
	Soil moisture	98.74	84.49	109.43	24.94**	25.26%
LOUGHERE-THIOLY (MATAM)	NDVI	0.253	0.247	0.257	0.01	3.95%
	VHI	49.62	46.64	51.86	5.22	10.52%
	Precipitation	385.82	377.77	391.85	14.08	3.65%
	Soil moisture	97.23	68.71	118.62	49.91**	51.33%
BALLOU (TAMBACOUNDA)	NDVI	0.285602	0.285604	0.285601	-3×10^{-6}	0.00%
	VHI	49.19	48.53	49.68	1.15	2.34%
	Precipitation	576.49	561.15	588	26.85	4.66%
	Soil moisture	150.24	151.75	149.1	−2.65	−1.76%

the wet season (JAS). The vegetative activities upgraded respectively 3.33 percent, 0.83 percent and 4.12 percent in Tessekere, Syer and Loughere-Thioly during the dry season. There is an increase of the Vegetation Health Index

Table 13. Mean statistics in wet season "JAS" of the evolution of vegetation activity and climatic parameters of the localities of the GGW-Senegal from 2000-2020 (Mann Whitney-Wilcoxonn comparison test at the significance levels $\alpha = 0.05(*)$ and $\alpha = 0.01(**)$).

Sites	Parameters	PERIODS "Wetseason JAS"			Difference (2009-2020) from (2000-2008)	Evolution in % (2009-2020) and (2000-2008)
		2000-2020	2000-2008	2009-2020		
TESSEKERE (LOUGA)	NDVI	0.287	0.287	0.29	0.003	1.05%
	VHI	51.00	51.37	50.72	−0.66	−1.28%
	Precipitation	285.73	279.178	290.65	11.472	4.01%
	Soil moisture	132.45	94.77	160.71	65.94**	49.78%
SYER (LOUGA)	NDVI	0.264	0.266	0.27	0.004	1.52%
	VHI	54.27	54.15	54.36	0.21	0.39%
	Precipitation	261.78	250.5	270.25	19.75	7.54%
	Soil moisture	109.06	93.99	120.36	26.37*	24.18%
LOUGHERE-THIOLY (MATAM)	NDVI	0.282	0.27	0.29	0.02	7.09%
	VHI	50.09	47.91	51.71	3.8	7.59%
	Precipitation	339.86	329	348.01	19.01	5.59%
	Soil moisture	142.7	102.93	172.53	69.6**	48.77%
BALLOU (TAMBACOUNDA)	NDVI	0.369	0.374	0.366	−0.008	−2.17%
	VHI	51.93	52.67	51.37	−1.3	−2.50%
	Precipitation	480	454.68	499	44.32	9.23%
	Soil moisture	221.52	229.2	215.77	−13.43	−6.06%

Table 14. Interannual correlations between NDVI and precipitation, soil moisture of GGW-Senegal localities for the periods 2000-2020, 2000-2008 and 2009-2020 (at the significance levels $\alpha = 0.05(*)$ and $\alpha = 0.01(**)$).

Sites GWW-Senegal	Vegetation index	Climatic parameters	Periods		
			2000-2020	2000-2008	2009-2020
TESSEKERE (LOUGA)	NDVI	Precipitation	0.62**	0.54	0.72**
		Soil moisture	0.47*	0.35	0.69*
SYER (LOUGA)	NDVI	Precipitation	0.56**	0.29	0.75**
		Soil moisture	0.41	−0.07	0.78**
LOUGHERE-THIOLY (MATAM)	NDVI	Precipitation	0.56**	0.28	0.71*
		Soil moisture	0.75**	0.76*	0.85**
BALLOU (TAMBACOUNDA)	NDVI	Precipitation	0.38	0.06	0.72**
		Soil moisture	0.50*	0.55	0.46

(VHI) throughout the study areas from 2009 to 2020. This gain varies from +0.5 to +5.5 which means an evolution of 0.92 percent (Syer), 10.52 percent (Loughere-Thioly). Overall, this reflects an improvement of vegetation indices from the period 2009-2020 (after reforestation).

The annual precipitation values in 2000-2020 are higher than of climatological data computer over 1991-2020 on the GGW Senegal localities (see Table 12). An annual precipitation means values comparison between 2000-2008 and 2009-2020 indicates an increase of annual rainfall after 2009. These excesses mean annual rainfall represent 2 to 5 percent of the 2000-2020 rainfall mean value. This is an indicator of excellent wet seasons during JAS.

The interannual mean of soil moisture evolution is positive between the periods 2000-2008 and 2009-2020 in Syer, Tessekere and Loughere-Thioly localities. According to Table 12, the soil moisture increased by 25 to 55 percent which represents a depth of water in the ground of +24 to 54 mm. Moreover, there is an increase of soil moisture both in the dry and rainy seasons.

There is an increase of soil moisture from 24 to 50% in comparison of the period 2000-2020. This is equivalent to water in the ground of respectively 26.37 mm, 65.95 mm and 69.6 mm in Syer, Tessekere and Loughere-Thioly (Table 12 and Table 13). The same observation can be noted during the dry season with a soil moisture of 17.49 mm (Syer), 49.93 mm (Tessekere) and 52.49 mm (Loughere-Thioly). In contrast, a decrease of soil moisture is recorded from the periods 2000-2008 to 2009-2020 in Ballou. This loss of water infiltration represents −1.76% at annual scale and −6.06% during the wet season (JAS).

3) Recent intra-seasonal variability of the vegetation index and the climatic parameters during the period 2000-2020

Figure 9 represents the seasonal variability of NDVI and VHI over Tessekere, Syer, Loughere-Thioly and Ballou localities for the periods 2000-2008 and 2009-2020. The graphic representing the NDVI seasonal evolution is unimodal with a pic observed in September. The peaks of the period 2009-2020 are higher than those of 2000-2008. In contrast, the seasonal evolution of the NDVI during the two periods is almost identical in Ballou where the reforestation is weak. In the other hand, the Vegetation Health Index representing in Figure 9 shows a bimodal distribution. The main one takes place in September and the minor in February.

Figure 10 represents the seasonal precipitations and soil moisture patterns for the two analyzed periods. The cycles associated to these patterns are unimodal. The peaks of precipitation are observed in August for the 2000-2008 period while they occurred in September for 2009-2020. Moreover, the monthly precipitation means recorded during the wet seasons (JAS) in 2009-2020 are greater than those of 2000-2008.

The monthly values of the seasonal soil moisture patterns over the period 2009-2020 are greater than those of 2000-2008 in Syer, Tessekere and Loughere-Thioly localities. Moreover, it is recorded a gain of 50 to 100 mm in September-October in these areas. When comparing the soil moisture of the periods 2000-2008 to 2009-2020, it is observed a difference of around 150 mm/month from August to November for Syer, Tessekere and Loughere-Thioly (Figure 10). In contrast, there is a low decrease of soil humidity over 2009-2020 in Ballou.

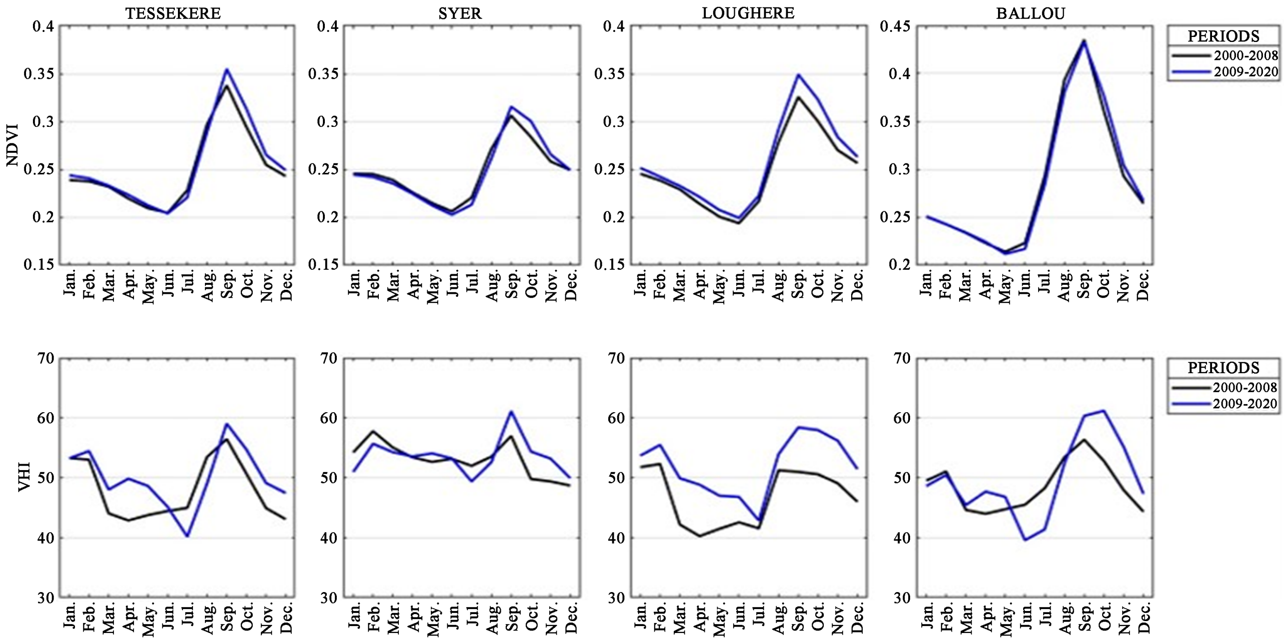

Figure 9. Seasonal cycle of NDVI and VHI of Tessekere, Syer (Louga), Loughere-Thioly (Matam), Ballou (Tambacounda) GGW-Senegal for the periods 2000-2008 and 2009-2020.

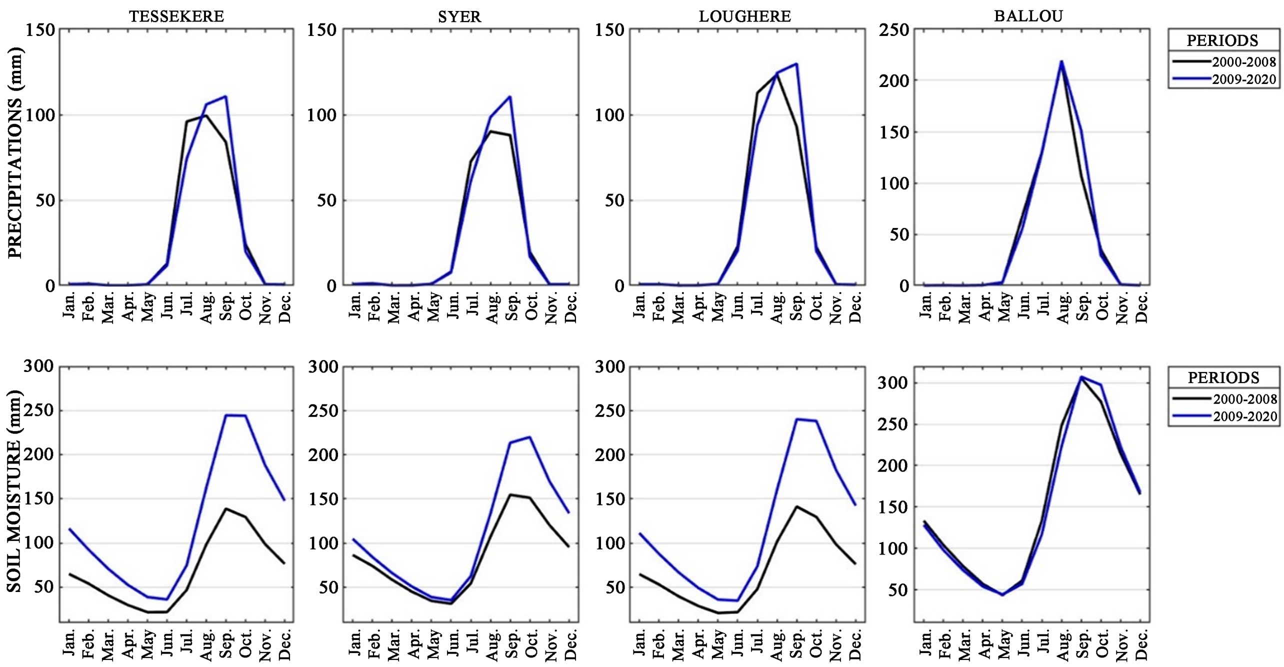

Figure 10. Seasonal cycle of precipitation and soil moisture of Tessekere, Syer (Louga), Loughere-Thioly (Matam), Ballou (Tambacounda) GGW-Senegal for the periods 2000-2008 and 2009-2020.

4) Relationship between vegetation and climatic parameters in the study area.

This part evaluates the temporal variability impacts of the climatic parameters (precipitation and soil moisture) and vegetation indices. So, correlation coefficients are computed to highlight the link between climatic parameters and vegetation cover patterns in the study areas (see **Table 14**). This assessment covers two periods: 2000-2008 and 2009-2020. The previous results in this study showed that the vegetation dynamic closely follows the seasonality of rainfall. Some authors have mentioned narrow results eight years after the starting of the reforestation [16]. **Table 14** indicates clearly that the correlation between NDVI and climatic parameters (soil moisture and precipitation) were weak over the period 2000-2008 (except in Loughere-Thioly; r = 0.76). In contrast, during the period 2009-2020 (after the reforestation), the correlation coefficient between NDVI and precipitation varies from 0.71 to 0.75.

The results of the comparative analysis of recent dynamics over the wet period 2000-2020 of vegetation cover and climatic conditions, within the reforested sites of the GGW-Senegal, show an increase in vegetation activity, precipitation and soil moisture from 2000-2008 to 2009-2020.

Indeed, this study shows the impact of reforestation (started from 2005 in some localities of the GGW-Senegal), on the increase of the NDVI index from 4% to 8% and from 4% to 10% for the VHI at interannual and seasonal scales. This result corroborates those of [53] which states that the rate of contribution of human activities to the increase in vegetation, in the desert/grassland transition zone over the period 1982-2015, was 97.7% and climatic factors (Temperature and Precipitation) contributed 47.5%. For [9] [10], the regreening of the Sahel is also to be attributed to the local populations who plant and maintain these trees.

Moreover, the reforestation activities carried out would have improved the humidity rate and local rainfall amounts on the different sites studied (2% to 8% of the annual total and 4% to 8% of the JAS rainy season). Thus, the increase in vegetation indices (NDVI and VHI) leads to an increase in evapotranspiration and favors the transport of humidity into the middle layers of the atmosphere [54] [55] [56].

These results are in agreement with the work of [57]-[63] who showed, using regional model simulations, that reforestation in an area impacts rainfall both locally and in distant regions. For [62] this precipitation increase is around 2 to 4 mm/day in the reforested area. In the simulation by [59], replacing the vegetation cover by forest, tall grass, and short grass savanna, the rainfall gain varies between 1.9 to 2 mm/day (Western Sahel [18˚W - 10˚ W and 10˚N - 20˚N]). And, the simulation by [58] over Senegal shows an increase of 1 to 3 mm/day over northern Senegal.

The results of the correlations between the periods 2000-2008 and 2009-2020, show the improvement of the link between vegetation and precipitation. These results are in line with those of [61] and [53]. The study conducted by [61] showed that during the 1980s, the correlation between NDVI and precipitation was higher than 0.6 in Senegal, Guinea and southern Mali. He subsequently observed a decrease in this value during the 1990s and 2000s. For [53], the correlation coefficient between NDVI and rainfall in the desert/grassland transition zone varied from −0.55 to 0.83 with a correlation coefficient of 0.24 over the study period 1982-2015. Areas in which NDVI was positively correlated with precipitation represented 86.7% of the total area of the desert/grassland transition zone.

The results of the positive dynamics of soil moisture and vegetation cover confirm the contribution of reforestation to water infiltration on the GGW-Senegal sites. Soil moisture has shown a strong evolution from 22% to 50% of the average for the period 2000-2020. This attests to the capacity of these soils to store more water [64] [65] [66] [67].

Thus, the results of [65] explain that a tree-covered soil favors the infiltration of water into the soil more than other land use. For [64], a forest-covered soil allows almost all the annual rainfall to be infiltrated as opposed to 2% of runoff. In western Burkina, [66] shows a very high capacity for water infiltration under and between trees.

The relationship between NDVI and soil moisture, from 2000-2008 to 2009-2020, showed a remarkable and significant increase in the interannual scale (reforested sites). Reforestation has contributed to water availability in the surface layers and root zone (necessary for plant growth). The study carried out by [68] (in south-west Nigeria) revealed strong relationships between tree volume and the soil moisture indices (correlation coefficients vary between 0.75 and 0.91). This study suggests that tree volume can be predicted based on soil moisture content. And, any negative anomaly in soil moisture content could lead to regression of vegetation.

The decrease in the relationship between NDVI and soil moisture in the locality of Ballou (Tambacounda) from 2000-2008 to 2009-2020 is explained by the lack of reforestation operations in this locality.

In the Ferlo region (Senegal), [69] had shown that the variation in soil moisture was more correlated and significant than precipitation variation on vegetation using the Leaf Area Index (LAI) over the period 2000-2010. In other words, soil moisture appears to be a better indicator to detect anomalies impacting LAI. Thus, for [70], the greenness of vegetation in semi-arid regions is strongly related to soil moisture.

4. Conclusions

This study, which aims to assess the dynamics of vegetation cover within the Great Green Wall of Senegal between 1982 and 2020, analyzed the evolution of vegetation cover using AVHRR-NDVI satellite data (from the NOAA-CDR and NOAA-STAR databases) and also the variability of precipitation (CHIRPS data) over the same period. It reveals a degradation of the cover between the early 1980s and the end of the 1990s. Then, a regreening of the different localities is observed with the return of a rainfall higher than 1991-2020 normal.

In fact, the reforestation that began in 2005 and the various reforestation campaigns have made it possible to restore more than 27,000 hectares of degraded land and to put more than 13,000 hectares in the GGW-Senegalese localities studied under protection.

Finally, the comparative analysis of reforestation on climatic parameters was first explored through the temporal analysis of the NDVI vegetation index over the periods 2000-2008 and 2009-2020. And, there is noted an increase in vegetation activity through the NDVI at the interannual (+2% to +8%) and seasonal (+1.5% to 7% for the JAS season and 1% to 4% for the dry season) scale. And a positive and significant evolution is noted in the trace of the GGW-Senegal. Also, the period 2009-2020 records an increase in rainfall of 2% to 8% of the average value 2000-2020 and 4% to 8% of the JAS rainy season. Soil moisture (CPC-NOAA database) is the climatic parameter that has increased the most, with an increase of 25% to 54% of the 2000-2020 average, *i.e.* between 20 mm and 70 mm more.

Moreover, the relationship between the evolution of vegetation activity and climate parameters was compared between the periods 2000-2008 and 2009-2020. It shows a significant improvement in the relationship between NDVI and climate parameters after the different reforestation actions of the GGW.

This study will help the decision-maker community with some of the advances of the Great Green Wall in Senegal and the impact of reforestation on the climate. It will also serve as a reference for the progress of this initiative in other countries in the region. Taking into account the preliminary results presented in this study, it would be desirable to encourage the various countries and partners of the Great African Green Wall initiative to intensify reforestation.

To improve this work, a complementary study of the dynamics of land use within the Great Green Wall initiative sites is underway.

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Conflicts of Interest

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

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