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A Preliminary Assessment of Land Restoration Progress in the Great Green Wall Initiative Region Using Satellite Remote Sensing Measurements

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Abstract: The Great Green Wall (GGW) initiative, which started in 2007 and is still in development as of 2024, aims to combat desertification and enhance sustainability over 8000 km across Africa's Sahel-Sahara region, encompassing 11 key countries and 7 countries associated with the initiative. Because of limited ground measurements for the GGW project, the progress and impacts of the GGW initiative have been a challenging problem to monitor and assess. This study aims to utilize satellite remote sensing data to analyze changes in the key factors related to the sustainability of the GGW region, including land cover type, vegetation index, precipitation rate, land surface temperature (LST), surface soil moisture, etc. Results from temporal analysis of these factors indicate that the deserts along the GGW are retreating and the regional mean of the Normalized Difference Vegetation Index (NDVI) has an increasing trend, although the precipitation has a slightly decreasing trend, over the past two decades. Further analysis shows spatial heterogeneity of vegetation, precipitation, and soil moisture changes. Desertification is still a challenging issue in some GGW countries. These results are helpful in understanding climate change in the GGW regions and the impacts of the Great Green Wall initiative.

Keywords: remote sensing; land cover; precipitation; vegetation indices; soil moisture; Great Green Wall

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1. Introduction

Land restoration in arid and semi-arid regions, such as the Sahel-Sahara, is essential for enhancing climate resilience, combating desertification, and supporting sustainable development. The Great Green Wall (GGW) initiative [1,2], launched in 2007 by the African Union, represents one of the world's most ambitious environmental restoration projects. Spanning 8000 km across 11 core countries—including Djibouti, Eritrea, Ethiopia, Sudan, Chad, Niger, Nigeria, Mali, Burkina Faso, Mauritania, and Senegal—and 7 associated countries—Cameroon, Ghana, Benin, Cape Verde, The Gambia, South Sudan, and Somalia [1]—the GGW seeks to restore degraded landscapes, mitigate desertification, and improve ecological and socio-economic conditions throughout the Sahel-Sahara region [1,2]. Despite its ambitious objectives, assessing the effectiveness of the GGW in achieving substantial land restoration remains challenging due to several factors [3–8]. First, the region's vast and ecologically diverse landscape complicates the monitoring of long-term changes. Second, ground-based surveys, often relied upon for tracking progress, face limitations in spatial and temporal coverage, especially in regions where security and political instability hinder data collection efforts [2,3]. This study addresses two key gaps in current monitoring approaches: (1) the need for consistent, large-scale monitoring that captures environmental changes across the entire GGW region and (2) the limited availability of high-resolution data necessary for understanding the nuanced impacts of GGW interventions over time.

Satellite remote sensing offers a promising solution to these challenges by providing consistent, broad-scale data on vegetation, land surface properties, and hydrological conditions. Remote sensing technology has been extensively used to monitor environmental indicators, such as vegetation, precipitation, and extreme events, in other regions [9–18]. For example, Qu et al. investigated agricultural drought over the Horn of Africa using MODIS and TRMM measurements [12], while Choi et al. used MODIS data to estimate evaporative fraction (EF) and study regional evapotranspiration (ET) patterns [14]. However, there has been limited research focused specifically on the GGW region [19–22], despite the critical need for such data to evaluate GGW's progress and potential impacts [23–26]. Fassinou et al. used remote sensing data and deep learning to map trees and their biomass across the Sahel region [19]. Ingrosso et al. used a high-resolution regional climate model to evaluate the climate impacts of the GGW scenarios [21]. However, there are monitoring gaps because of the lack of site monitoring of GGW intervention components, as revealed by Jalam et al. [22]. This study fills that gap by offering a satellite-based analysis of environmental changes in the GGW region, examining five key parameters: land cover, vegetation index, land surface temperature, precipitation, and soil moisture. To provide a comprehensive assessment of the GGW's progress, this study employs satellite-derived datasets, including land cover types and Normalized Difference Vegetation Index (NDVI) from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) for analyzing vegetation dynamics over the past two decades, as well as land surface temperature data from MODIS. While MODIS provides high temporal resolution, it has limitations in spatial resolution for thermal bands compared to other satellites such as Landsat. Precipitation data is sourced from the Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG), and soil moisture data from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) are analyzed to understand hydrological conditions. By leveraging these data sources, this study presents a detailed analysis of environmental parameters that reflect the GGW's potential impact over time. In summary, the objectives of this paper are to: (1) monitor vegetation changes and land surface temperature across the GGW region, (2) assess precipitation and soil moisture dynamics as indicators of hydrological conditions, and (3) determine how remote sensing technology can contribute to the comprehensive monitoring and evaluation of the GGW. Through this analysis, the study provides preliminary insights into the progress of the GGW initiative and supports data-driven strategies for future land restoration efforts in the Sahel-Sahara region.

2. Data and Methods

2.1. Study Area and Data

The Great Green Wall mostly spans the Sahel-Sahara region of Africa, consisting of 11 main participating countries (Burkina Faso, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Sudan, and Chad) and 7 other associated sub-Saharan countries (Cameroon, Ghana, Benin, Cape Verde, The Gambia, South Sudan, and Somalia) [1]. The focus area in which most work has been done stretches from the westernmost tip of Senegal all the way to the border between Djibouti and Ethiopia, as illustrated in Figure 1.

The Sahel-Sahara region is characterized by a sharp gradient in climatic conditions, ranging from hyper-arid deserts in the north, where annual rainfall is typically below 100 mm, to semi-arid and sub-humid zones in the south, where rainfall can reach up to 600 mm per year [27]. The region experiences a unimodal rainfall pattern, with the rainy season occurring between mid-June and October, peaking in August. Specific study areas were selected across multiple countries within the Great Green Wall region. These areas represent a range of land conditions, from bare, degraded lands to areas under agro-sylvo-pastoral use. The selection of these regions was guided by the need to capture the spatial variability of the region's environmental conditions and to assess the effectiveness of restoration interventions across different ecological zones. Country boundary coordinates for spatial analysis were obtained from the Global Administrative Areas (GADM) datasets, a collection of vector datasets including worldwide country boundaries [28]. The boundary data for GGW-related countries were used to generate spatial masks for each country and the whole GGW region.

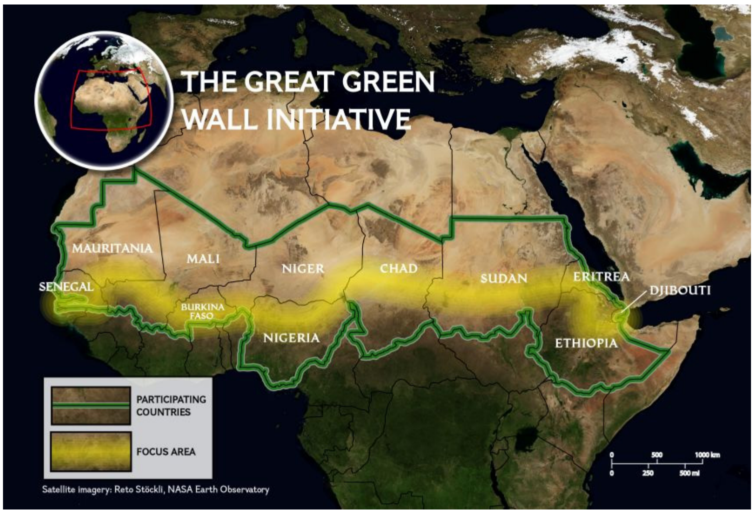

Figure 1. Map of the Sahel-Sahara region, highlighting the Great Green Wall focus area and an outlined mask of the 11 main participating countries (source: National Geographic [2]).

For monitoring the critical parameters indicative of the area's overall surface conditions, multiple satellite remote sensing data products from the years 2000–2024 were downloaded from NASA Earth Science Data [29], including MODIS land cover types, MODIS vegetation indices, MODIS land surface temperature data, and IMERG rainfall data products. Copernicus Climate Change Service (C3S) Soil Moisture data were used in this study [30]. The satellite remote sensing data products used in this study are summarized in Table 1, and a brief description of each follows:

- The Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Version 6.1 data product (MCD12Q1). The MCD12Q1 data product provides land cover types at 500 m spatial resolution with the International Geosphere-Biosphere Program (IGBP), University of Maryland (UMD), Leaf Area Index (LAI), BIOME-Biogeochemical Cycles (BGC), and Plant Functional Types (PFT) classification schemes. The IGBP Type I classification scheme is used in this study.
- Terra MODIS Land Surface Temperature/Emissivity monthly L3 data products (MOD11C3). MOD11C3 data products contain day- and night-time land surface temperatures at the spatial resolution of 0.05 degrees (around 5.6 km at the equator), as well as surface emissivity. Both day- and night-time land surface temperature data were used in this study.
- Terra MODIS Vegetation Indices Monthly L3 products (MOD13C2). The MOD13C2 products provide both NDVI and EVI on a monthly temporal resolution with a spatial resolution of 0.05 degrees, utilizing the best possible observations.
- IMERG monthly rainfall data products. The data are from NASA's Global Precipitation Measurement (GPM) mission, which provides near-global coverage of precipitation and is updated every half hour. The IMERG monthly data provides precipitation estimates at a 0.1 degree spatial resolution with near-global coverage [31,32].

The Copernicus Climate Change Service (C3S) soil moisture dataset provides estimates of surface soil moisture over the globe from the year 1978 to the present from a large set of sensors from a series of satellites [30]. The monthly surface soil moisture data at a spatial resolution of 0.25 degrees were used in this study. Precipitation and surface temperature have direct impacts on surface soil moisture, which is critical to vegetation health during growth seasons. Soil moisture is related to the exchange of water and heat between land surface and the atmosphere. Analysis of soil moisture is important to understand the land-atmosphere interactions and land cover dynamics.

Table 1. List of satellite remote sensing data products used in this study.

Data Products	Description	Spatial Resolution	Time Period of Data
Land Cover Type	The IGBP Type I classification from the MODIS Land Cover Type V6.1 data product (MCD12Q1)	500m	Yearly data from 2001 to 2023
Vegetation Index (NDVI)	NDVI from the Terra MODIS Vegetation Indices Monthly L3 V6.1 products (MOD13C2)	0.05 degrees	Monthly data from February 2000 to June 2024
Land Surface Temperature	Day- and night-time land surface temperature from the Terra MODIS Land Surface Temperature monthly L3 V6.1 data products (MOD11C3)	0.05 degrees	Monthly data from February 2000 to June 2024
Precipitation	Rainfall rate from NASA's Global Precipitation Measurement (GPM)	0.1 degrees	Monthly data from February 2000 to June 2024
Soil Moisture	Copernicus Climate Change Service (C3S) Soil Moisture data	0.25 degrees	Monthly data from February 2000 to June 2024

2.2. Methods for Data Processing and Analysis

2.2.1. Temporal Change Detection and Analysis

Land cover changes over the past two decades provide key information about the dynamics of the ecological conditions over the study area. Changes in barren and vegetated areas are analyzed to assess the changes in the desert areas along the GGW region. In the MODIS MCD12 land cover type data, barren areas are represented, with 16 in the IGBP type I classification schema. To quantify the desert changes, for the land cover type data LCP(x,y) with x in the longitude/horizontal direction and y in the latitude/vertical direction, the center of the desert location at each horizontal line (longitude) is defined as the mean of y coordinates (latitude) where the land cover type is a barren area (i.e., land cover type = 16), i.e.:

$$DC(\mathrm{x}) = \mathrm{mean}(\mathrm{y}|,\ \mathrm{x},\mathrm{y})\ \text{ is barren area) or}$$
$$DC(x_i) = \frac{\sum_{j=0}^{N_y} \alpha_{i,j} y_{i,j}}{\sum_{j=0}^{N_y} \alpha_{i,j}},\ \alpha_{i,j} = 1,\ \ if\ LCP(i,j) = 16;\ 0,\ \ LCP(i,j) \neq 16.$$

DC(x) for years from 2001 to 2023 is used to identify the movement of the deserts over the GGW region.

2.2.2. Time Series Analysis of Regional Mean

The regional mean values of NDVI, precipitation, LST, and soil moisture for the study area were calculated first using spatial masks generated with the boundary coordinates of the selected countries. The steps were as follows:

1. Data preprocessing and quality control. Each dataset was preprocessed to filter out invalid data according to quality flags and valid ranges, ensuring the data quality and reliability of the temporal analysis.
2. Data extraction and spatial weighting. For each month, the data values for NDVI, precipitation, LST, and soil moisture were extracted for the study area using spatial masks.
3. Then, for each variable, a weighted mean was calculated across the region using pixel areas as weights. For equal latitude and longitude grid, the areas of the grid pixels are different. To calculate regional mean, we used the following equation to calculate weighted mean for each variable representing the core GGW countries:

$$\overline{V} = \frac{\sum_i A_i V_i}{\sum_i A_i}$$

Here, A_i represents area of the pixel i and V_i represents variable value (NDVI, LST, etc.) at the pixel i.

Repeating the above steps for each variable, time series data of area-weighted mean values were generated for the 11 core countries, the 7 associated countries, and the entire study area (18 countries). In addition to regional averages, time series were generated for each individual country to capture the temporal trend of each country.

The resulting time series for NDVI, precipitation, LST, and soil moisture were integrated for comparative analysis and statistical analysis to identify trends. NDVI, land surface temperature, precipitation rate, and surface soil moisture have seasonal cycles. For trend estimation, the seasonal cycles were removed based on the climatology of these variables to get anomaly time series. Anomalies for each variable were computed by subtracting the climatological monthly means over the baseline period 2001–2020 from the observed monthly mean values:

$$\Delta z_{k,m} = z_{k,m} - \overline{z_m}$$

$$\overline{z_m} = \frac{1}{20}\sum_{k=2001}^{2020} z_{k,m}$$

where k represents the year, m represents the month, and $\overline{z_m}$ is the climatological monthly mean of NDVI, LST, precipitation, or soil moisture for the month m.

The anomaly time series allowed us to identify deviations from average conditions, highlighting periods of unusual environmental change. For each variable, the slope of the regression line provided an estimate of the direction and magnitude of change over the study period. The p-value from the regression analysis was used to assess the statistical significance of the trends.

At the regional scale, the time series represented the mean values and anomalies of the environmental variables across the 11 core GGW countries. This aggregated analysis provided a holistic view of the overall trends and changes occurring within the GGW zone. The regional NDVI time series allowed us to track the average greenness across all the countries, giving a broad indication of how vegetation has responded to restoration efforts over the past two decades. The anomaly plots, combined with trend lines, helped to identify significant deviations from normal conditions, indicating periods of either environmental stress or recovery. To further refine the analysis and identify localized trends, the same time series methodology was applied to each GGW country individually. By generating and analyzing time series plots for each country, spatial variations in the environmental impacts of the GGW initiative can be detected. This country-level analysis was crucial for understanding how specific interventions, climate conditions, or management practices in different countries influenced the effectiveness of the restoration efforts.

2.2.3. Spatial Analysis of Trend

The spatial variations of each variable within the study area were investigated. The spatial analysis process was conducted as follows:

1. Trend Calculation for Each Pixel. Linear regression was applied to the anomaly time series at each pixel to compute the trend (slope) and its statistical significance (p-value). This step involved fitting a linear model to the time series data of each pixel, where the slope of the regression line indicates the rate of change over time. Only pixels with sufficient valid data points (more than 10 non-missing values) were included in the trend analysis to ensure robust results.
2. Spatial Mapping of Trends. The calculated trends for each pixel were mapped to visualize the spatial distribution of environmental changes. The generated maps provided a visual summary of the spatial variation in trends, enabling the identification of

spatial heterogeneity in the GGW region. The maps also allowed for the identification of spatial patterns in temperature, precipitation, and soil moisture trends, providing insights into the complex interactions between these variables and the overall effectiveness of the GGW initiative.

To understand the broader environmental impacts, the trends of NDVI, LST, precipitation, and soil moisture were compared across the GGW region. This combined analysis enabled a more comprehensive assessment of how changes in one variable might be related to changes in others (e.g., whether increases in vegetation cover were associated with changes in soil moisture or reductions in surface temperatures). By overlaying the trend maps for different variables, regions where multiple positive trends coincide are identified, indicating areas of significant environmental recovery, or where conflicting trends suggest complex challenges that need to be addressed.

In this study, the methodology, data processing, data analysis, and visualization were implemented with Matlab R2024a.

3. Results

3.1. Land Cover Changes in the Great Green Wall Sahel-Sahara Region

Figure 2 shows the MODIS land cover types in the years 2001 and 2023. Even though some changes can be identified visually, quantitative analysis provides insights into how desert areas and vegetated regions have been changing over the past two decades. Since most desert areas over the GGW region are located in the belt from 10° to 20° latitude, the quantitative analysis of land cover type changes was focused on the GGW belt from 10° to 20° latitude, i.e., the regions between the two dotted black lines in Figure 2.

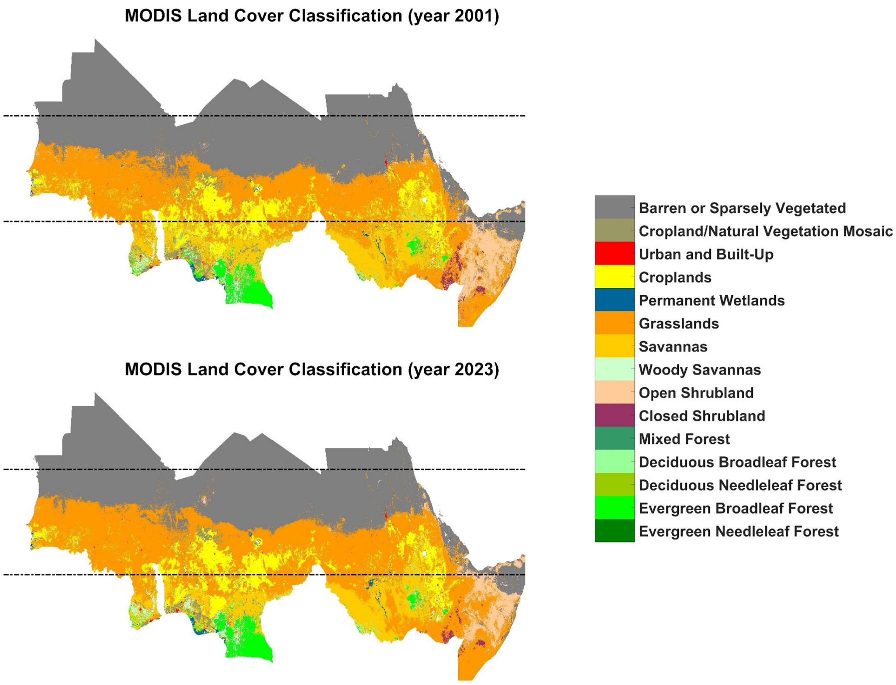

Figure 2. MODIS land cover type classification for the years 2001 and 2023. The two dotted black lines are used to indicate the regions along the GGW for statistical analysis of land cover type changes.

In Figure 3, the left figure indicates relative changes in desert areas, vegetated areas, and urban areas compared with the year 2001. The urban areas show a steadily increasing trend, indicating continuous urban development in the study area. Although there are fluctuations in the desert and vegetated areas, overall, the desert area is decreasing, while the vegetated area is increasing, especially during the past years since 2019. The right side in Figure 3 shows statistics of desert center changes from the year 2001 based on DC(x) calculated with locations of barren areas along the horizontal line (longitude direction) of the GGW region. From the year 2002 to 2023, the desert location moved northward in 79.24% of the regions along the longitude direction, while the other 20.76% of regions moved southward. The results indicate that the desert areas along GGW retreated during the past two decades.

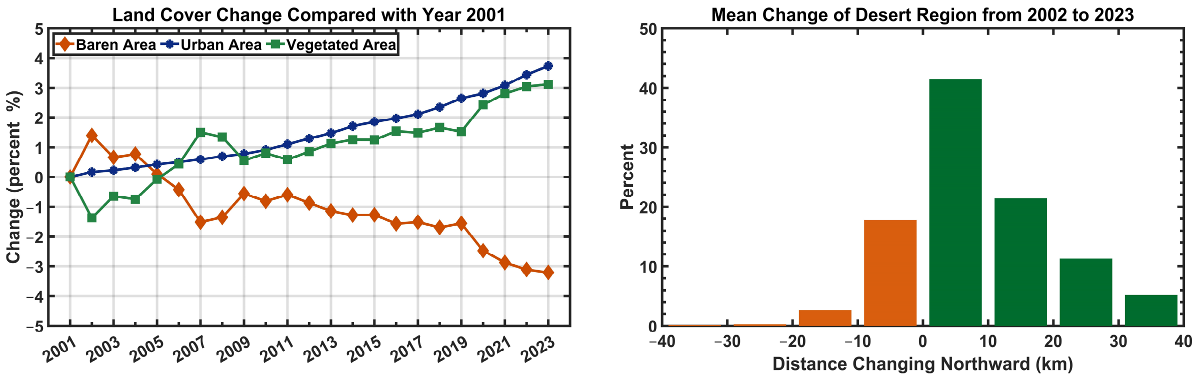

Figure 3. Land cover type changes from 2001 along the GGW region (between the two dotted lines in Figure 2, i.e., the belt between 10° and 20° latitude). The left figure shows the percent of barren areas, urban areas, and vegetated areas changes compared with the year 2001. The right figure shows statistics of mean desert location (latitude) changes from the year 2001 along the longitude direction.

3.2. Great Green Wall Sahel-Sahara Region Temporal-Spatial Trend Analysis

Figure 4 below shows the temporal trends of NDVI, precipitation, day-time land surface temperature, and surface soil moisture across the entire Great Green Wall region. In general, the NDVI, LST, and precipitation results are statistically significant in the 95% confidence interval, all having a p-value less than 0.05; however, the soil moisture results do not. As shown in the NDVI time series in Figure 4, there is a positive trend of 0.00060 per year (p-value = 0.000). The NDVI increase suggests that vegetation health has been improving over the past two decades, especially during recent years after 2019, potentially indicating that the GGW initiatives are contributing positively to land restoration efforts in previously degraded areas. The spatial trend map in Figure 5 below displays the NDVI trend across the whole GGW region, with green areas indicating regions where vegetation is increasing (positive ΔNDVI/year) and yellow to red areas showing regions where vegetation is declining (negative ΔNDVI/year). Notably, the Sahel region, including northern Nigeria, shows some positive trends in vegetation growth, likely reflecting the impact of restoration efforts such as the Great Green Wall, while other regions, particularly in Central and Southern Africa, exhibit declining NDVI trends, suggesting vegetation stress or land use changes.

The overall day-time LST presents a slightly decreasing trend with a rate of −0.02052 per year (p-value = 0.004) in the GGW region. This decrease in land surface temperature within the 95% confidence interval might reflect some localized cooling effects, possibly due to increased vegetation cover or other microclimatic factors. However, the mean night-time LST shows a different temporal pattern, with a steadily increasing trend of 0.05618 K/year. Additionally, the spatial trend map in Figure 6 below shows the trend of day- and night-time land surface temperature (LST). Areas shaded in blue indicate a cooling trend, while areas in yellow to red represent a warming trend. Notably, all the GGW regions are experiencing a warming trend of night-time LST. For day-time LST, much of the Sahel and parts of eastern Africa are experiencing a cooling trend, possibly associated with increased vegetation, while scattered regions in West and Southern Africa show a slight warming trend, which could be linked to land degradation or reduced vegetation cover.

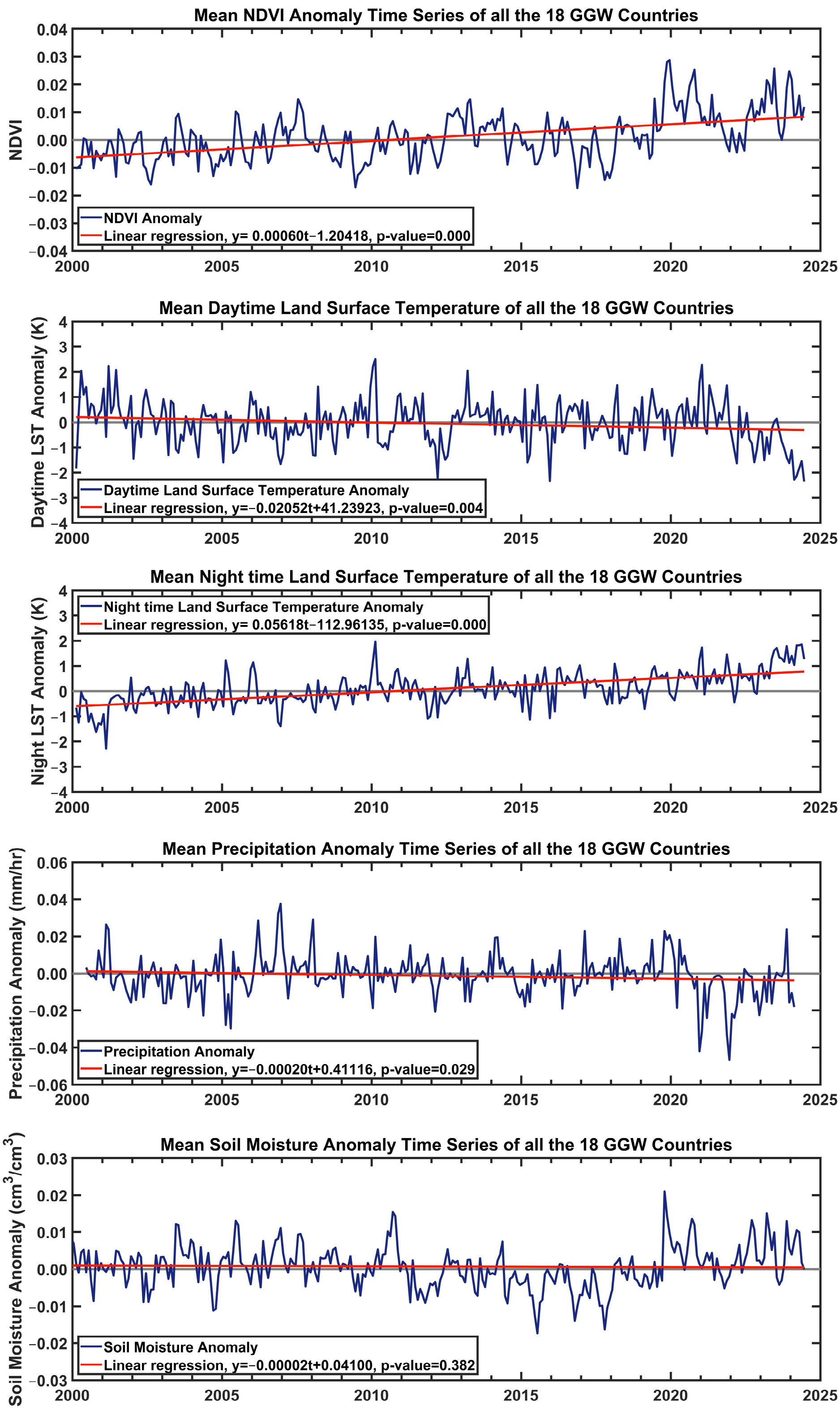

Figure 4. Anomaly time series of NDVI, precipitation, day-time land surface temperature, and surface soil moisture for all the 18 GGW countries. Anomalies were calculated by removing monthly climatology of 20 years from the base period from 2001 to 2020.

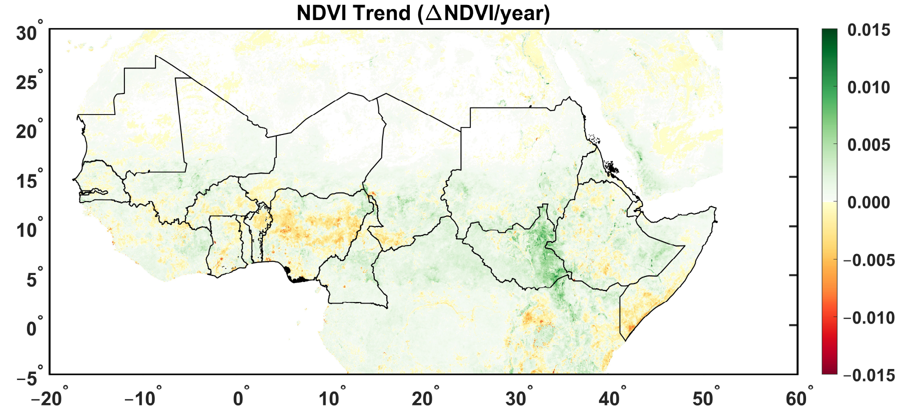

Figure 5. Map of NDVI trend (ΔNDVI/year) over the Great Green Wall region. The boundaries of the GGW countries are outlined with a black line. Green color indicates regions that are greening from 2000 to the present, while yellow to red colors indicate regions where vegetation is stressed or there are land use changes.

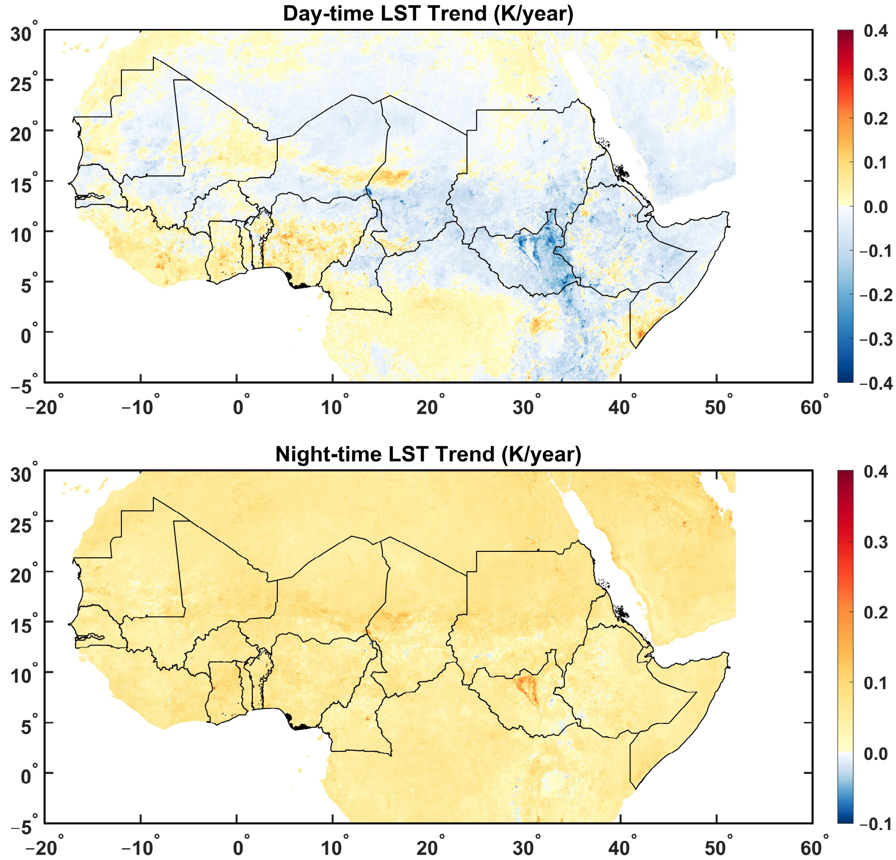

Figure 6. Map of the day- and night-time LST trend in the GGW region. Areas shaded in blue indicate a cooling trend from 2000 to the present, while areas shaded in yellow to red colors indicate a warming trend from 2000 to the present. Most GGW regions are experiencing relatively homogeneous warming at night-time, while the day-time LST are heterogeneous, spatially.

In contrast, the precipitation anomaly time series in Figure 4 shows a significant decreasing trend at a rate of -0.00028 mm/hr per year (p-value = 0.002). This decline in precipitation within the 95% confidence interval suggests a reduction in rainfall and increasing drought events, which could pose challenges to the GGW's long-term sustainability. Reduced rainfall may limit the success of vegetation restoration efforts, as water availability is crucial for plant growth and survival.

Finally, the soil moisture anomaly in Figure 4 shows a slightly decreasing trend, which is consistent with the precipitation trend; however, the soil moisture trend is not statistically significant (p-value = 0.382). Although the trend is not significant within the 95% confidence interval, the fluctuations in soil moisture highlight the variability in water availability, which is critical for vegetation growth in the GGW region.

3.3. Temporal-Spatial Analysis of Individual Countries

Figures 5 and 6 demonstrate the spatial heterogeneity of NDVI and LST trends. Table 2 shows the temporal trends of the 11 primary GGW countries. Most of these countries show a slight trend in vegetation greening, except Nigeria. The warming trends of night-time land surface temperature are statistically significant for all these countries. For day-time land surface temperature, although all these countries have cooling trends, some of the trends are not statistically significant. For precipitation, only the trends of Nigeria and Ethiopia are positive and statistically significant; the other countries either have a decreasing trend or a statistically insignificant trend. For surface soil moisture, only three countries, Burkina Faso, Mauritania, and Senegal, have statistically decreasing trends. We selected two countries, Nigeria and Ethiopia, for more detailed analysis.

Table 2. Trends of the 11 primary GGW countries. Trend values marked with * indicate that the trends are statistically insignificant (p-value > 0.05).

Country	NDVI	LST_Day	LST_Night	Precipitation	Soil Moisture
Burkina Faso	0.00046	* −0.00645	0.05922	* −0.00001	−0.00022
Djibouti	* 0.00015	−0.03345	0.05243	* 0.00034	* −0.00009
Eritrea	0.00085	−0.03106	0.05450	* −0.00074	* 0.00001
Ethiopia	0.00108	−0.04572	0.04197	0.00086	* 0.00006
Mali	0.00052	* −0.00348	0.05774	−0.00005	* −0.00005
Mauritania	0.00018	* −0.00724	0.04986	* −0.00005	−0.00006
Niger	0.00029	* −0.01864	0.06259	−0.00014	* −0.00002
Nigeria	−0.00028	* 0.01494	0.05709	0.00019	* −0.00003
Senegal	0.00057	* −0.00746	0.04867	−0.00014	−0.00020
Sudan	0.00064	−0.03005	0.06303	−0.00133	* −0.00001
Chad	0.00055	−0.02797	0.05717	−0.00067	* −0.00001

3.3.1. Nigeria

As shown in Figure 7, which highlights the overall trend of Nigeria and the trend map, the anomaly trend exhibits a downward slope in the linear regression line, suggesting a statistically significant (p-value of 0.014) declining trend in vegetation greenness anomalies over time (−0.00028/year). This points to a gradual decrease in vegetation health or density relative to the historical baseline. The map of NDVI trends across Nigeria provides insight into the localized changes in vegetation:

- Northern Nigeria: The northern regions, which fall within the Sahel zone and are targeted by the Great Green Wall (GGW) initiative, show areas of greening, as indicated by the greenish hues on the map. This positive spatial trend in NDVI suggests that GGW efforts, such as tree planting and sustainable land management, are having a positive impact on vegetation in these areas, countering desertification and promoting restoration.
- Central and Southern Nigeria: In contrast, the central and southern parts of Nigeria exhibit more areas with negative NDVI trends (depicted in yellow to reddish hues). This indicates a decline in vegetation health or cover in these regions. Such declines could be due to deforestation, agricultural expansion, urbanization, or other environmental pressures that lead to vegetation loss.

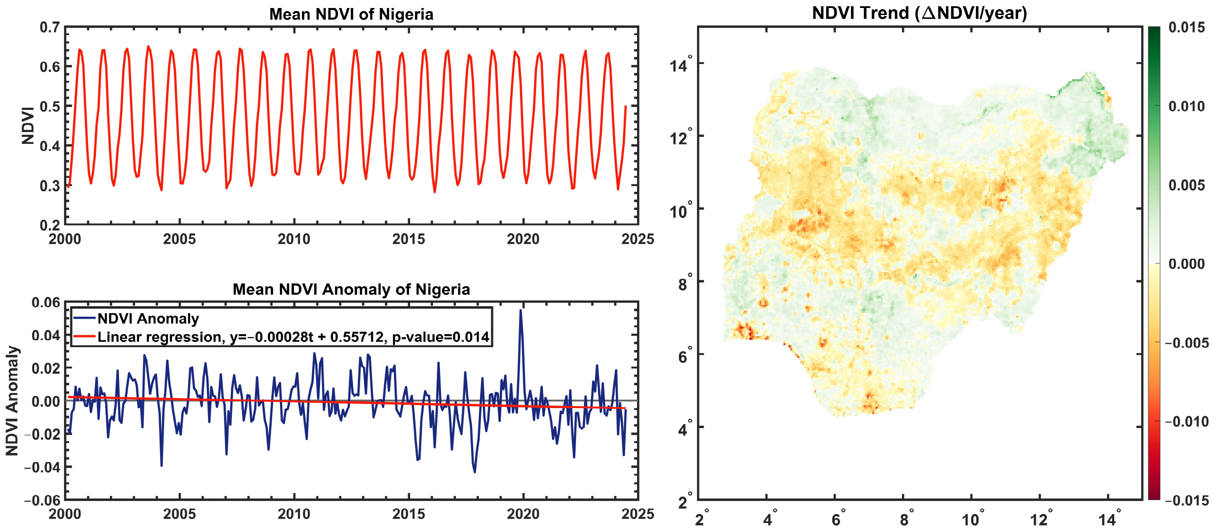

Figure 7. NDVI time series and trend map in Nigeria. The green color indicates where NDVI has an increasing trend, while the yellow to red color indicates where NDVI has a decreasing trend. Although the overall NDVI of Nigeria has a decreasing trend (lower left panel), most of the northern Nigeria region is greening.

Combining the temporal and spatial trends, it can be observed that while the overall vegetation anomalies in Nigeria are on a decline, especially in the central and southern regions, the northern regions show a positive trend in vegetation growth. The downward slope in the NDVI anomalies at the national level suggests that the gains in northern vegetation health are not sufficient to offset the declines elsewhere. The positive spatial trend in northern Nigeria aligns with the efforts of the Great Green Wall initiative, which is actively working to restore degraded lands in the Sahel region. This localized improvement shows consistency with the targeted restoration efforts. However, the overall declining trend in NDVI anomalies at the national scale underscores the need for more widespread and comprehensive interventions to address vegetation loss in other parts of Nigeria.

As a result of this increase in vegetation due to the Great Green Wall initiative in Northern Nigeria, a similar positive indicative trend can be seen from the analysis of the spatial and temporal data of the day-time LST in Nigeria. From Figure 8, the LST anomaly time series shows a subtle upward trend in day-time temperatures, as evidenced by the positive slope (0.01505) in the linear regression line. Although the trend is not statistically significant (p-value of 0.061), it does suggest a slight increase in day-time LST anomalies across Nigeria in the most recent two decades. Actually, during the past recent years, the LST is decreasing. The spatial map of day-time LST anomalies provides insight into the localized changes in surface temperature across Nigeria:

- Northern Nigeria: Contrary to the general upward trend, the northern regions of Nigeria, which are the primary focus areas of the Great Green Wall (GGW) initiative, exhibit decreasing LST anomalies. This is represented by cooler anomalies (bluish hues) on the map. The GGW's efforts, including reforestation and sustainable land management, appear to be mitigating the warming trends in this region by increasing vegetation cover, which helps lower surface temperatures through increased evapotranspiration and reduced heat absorption.
- Central and Southern Nigeria: Conversely, the central and southern regions of Nigeria show increasing LST anomalies, as indicated by the warmer hues on the map. These regions are experiencing higher-than-average day-time LST, likely due to factors such as deforestation, agricultural expansion, and urbanization. The loss of vegetation in these areas reduces the land's ability to cool itself, leading to higher surface temperatures.

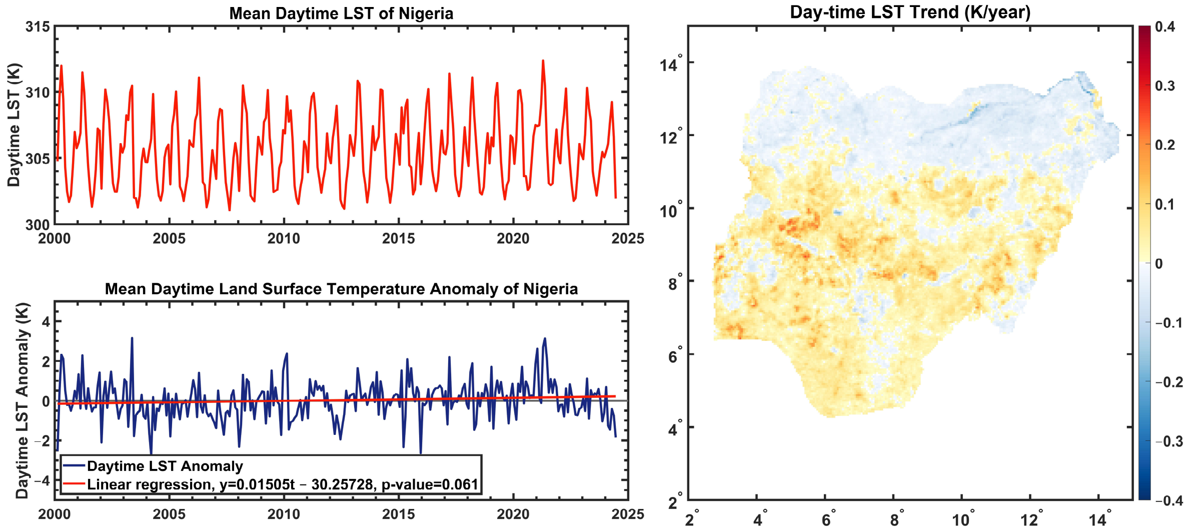

Figure 8. Overall time series of day-time LST and trend map of Nigeria. The blue color indicates where LST has a decreasing trend, while the yellow to red color indicates where LST has an increasing trend. Although the overall day-time LST of Nigeria has an increasing trend (lower left panel), most of the northern Nigeria region is cooling slightly.

While the overall trend in day-time LST anomalies shows a slight increase, this is not uniform across the country. Northern Nigeria, which is benefiting from the GGW's reforestation and land management efforts, is experiencing a cooling trend, which is helping to counteract the broader warming trend. On the other hand, Central and Southern Nigeria are facing increasing temperatures, driven by environmental degradation and urban expansion.

3.3.2. Ethiopia

As shown in Figure 9 below, which isolates the temporal trend of NDVI and map of the trend in Ethiopia, the anomaly trend exhibits an upward slope in the linear regression line, suggesting a statistically significant (p-value of 0.02905) positive trend in vegetation greenness anomalies over time (+0.00074/year). This indicates a gradual improvement in vegetation health or density relative to the historical baseline. The spatial trends of NDVI across Ethiopia provide insight into localized vegetation changes:

- Northern and Eastern Ethiopia: The northern and eastern regions, which are targeted by land restoration efforts and are vulnerable to desertification, exhibit areas of greening, as represented by the green hues on the map. This positive spatial trend suggests that restoration initiatives, such as reforestation and sustainable land management, are improving vegetation conditions, likely contributing to the ongoing greening in these areas.
- Central and Southern Ethiopia: In contrast, the central and southern parts of Ethiopia show areas of negative NDVI trends (yellow to orange hues), indicating a decline in vegetation health or cover. Factors such as agricultural expansion, overgrazing, or land degradation could be contributing to this decline, impacting the vegetation dynamics in these regions.

This is further corroborated in Figure 10, which focuses on the temporal and spatial trends of precipitation in Ethiopia, the anomaly trend exhibits a positive slope in the linear regression line, suggesting a statistically significant (p-value of 0.017) increase in precipitation anomalies over time (+0.00045/year). This indicates a gradual rise in precipitation levels relative to the historical baseline, potentially contributing to changes in vegetation health and water availability in Ethiopia. The spatial map of precipitation trends across Ethiopia further elaborates the localized variability in precipitation:

- Northern and Eastern Ethiopia: These regions show pronounced positive trends in precipitation, as indicated by the green hues on the map. The increase in precipitation in these areas is a promising sign, especially for regions that are prone to arid conditions and land degradation. This rise in rainfall aligns with the areas showing positive NDVI trends, suggesting that increased rainfall may be contributing to vegetation recovery and restoration efforts, possibly linked to ongoing initiatives like the Great Green Wall.
- Western Ethiopia: The western parts of Ethiopia display more neutral to slightly negative trends in precipitation (depicted in yellowish hues). These areas may not be experiencing significant changes in rainfall, and the slight declines could be contributing to localized environmental challenges such as reduced agricultural productivity or water stress.

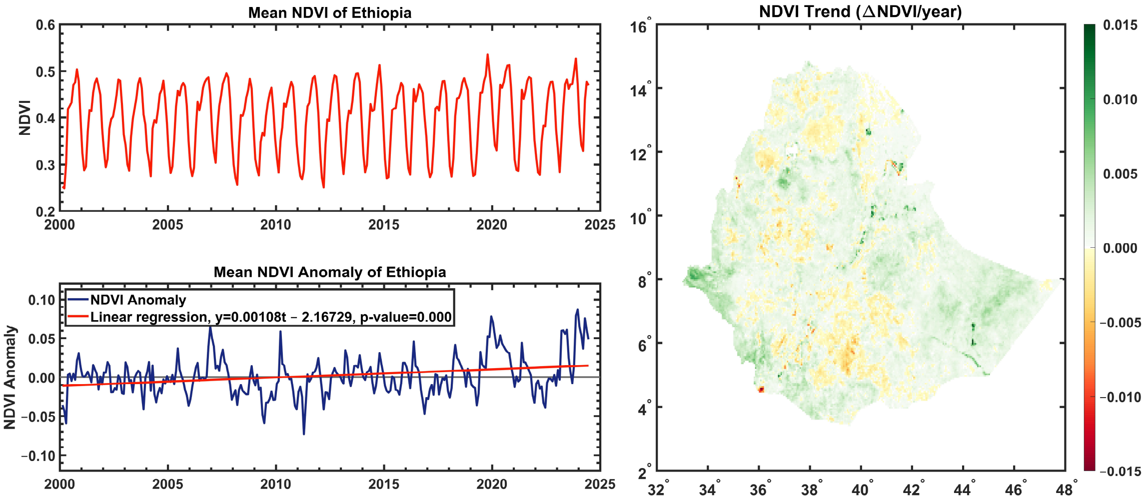

Figure 9. NDVI time series and trend map in Ethiopia. The green color indicates where NDVI has an increasing trend, while the yellow to red color indicates where NDVI has a decreasing trend. Although the overall NDVI of Ethiopia has an increasing trend (lower left panel), some regions have decreasing trends.

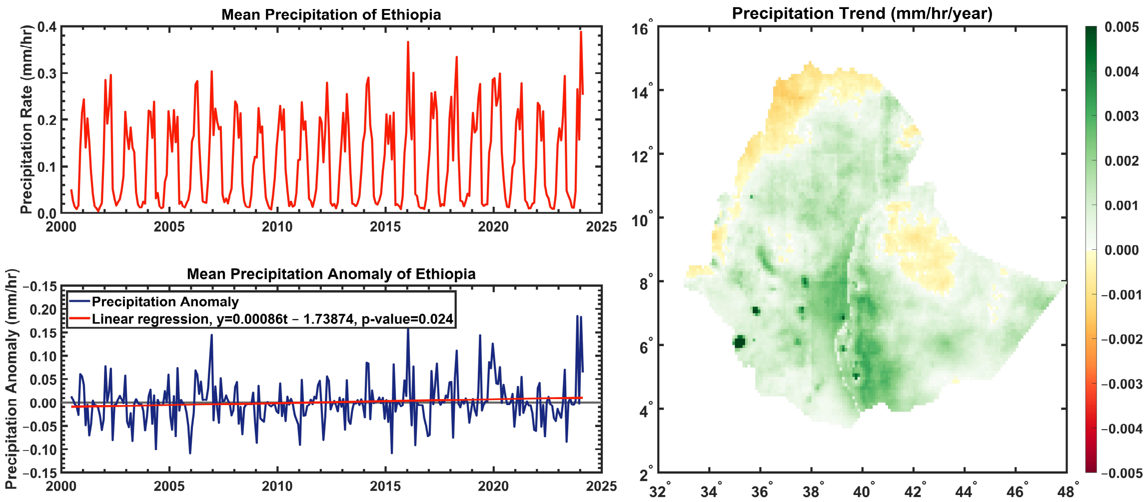

Figure 10. Precipitation time series and trend map in Ethiopia. The green color indicates where precipitation has an increasing trend, while the yellow to red color indicates where precipitation has a decreasing trend. Although the overall precipitation of Ethiopia has a slightly increasing trend (lower left panel), some regions, especially Northern Ethiopia, have a decreasing trend.

In summary, combining both the temporal and spatial analysis, it is evident that Ethiopia is experiencing an overall increase in precipitation anomalies, particularly in the northern and eastern regions. This trend correlates with improvements in vegetation, as observed in the corresponding NDVI data. However, some regions in the west are not benefiting as much from these precipitation increases, indicating a need for tailored water management strategies to ensure balanced resource distribution across the country.

4. Discussion

The assessment of the Great Green Wall (GGW) initiative using satellite remote sensing provides a novel, multi-dimensional approach to tracking environmental changes in the Sahel-Sahara region, focusing on vegetation, land surface temperature, precipitation, and soil moisture. Unlike previous studies that often lack temporal continuity or sufficient spatial coverage, our approach integrates multiple satellite datasets—MODIS NDVI, IMERG precipitation, and C3S soil moisture—to deliver a consistent and comprehensive view of ecosystem dynamics. This combination allows us to monitor vegetation health, moisture conditions, and climate patterns across this vast region, generating data that can directly inform strategies for reducing desertification. The insights gained from positive NDVI trends, for instance, underscore areas of vegetation recovery, which are crucial for reducing soil erosion, enhancing moisture retention, and fostering biodiversity. These indicators offer a valuable feedback mechanism for policymakers, helping guide and refine GGW's restoration objectives based on observed environmental responses.

However, there are notable limitations and challenges associated with this approach. Chief among them is the lack of ground-based observations for validation, particularly for soil moisture and precipitation data, which constrains the robustness of our conclusions. Ground-truth data are essential for calibrating and validating satellite-derived products, yet the Sahel-Sahara region suffers from a scarcity of in situ observations due to logistical and economic constraints. This deficiency limits our ability to confirm soil moisture and precipitation estimates, impacting the accuracy of drought assessments and vegetation monitoring, which are critical to evaluating reforestation success. In addition, remote sensing data gaps, often due to cloud cover or sensor malfunctions, can introduce biases—especially in assessments of vegetation growth during key periods such as the rainy season. Moreover, harmonizing datasets with different spatial and temporal resolutions, such as 5 km MODIS NDVI, 10 km IMERG precipitation, and 25 km C3S soil moisture, may introduce errors, particularly in ecologically heterogeneous areas. Although alternative vegetation indices, such as the Normalized Difference Water Index (NDWI) or Phenology-Adjusted Drought Index (PADI), could offer added insights, their implementation fell outside the scope of this study. Spatial analysis limitations also pose interpretive challenges, as regional-scale trends may obscure significant local variations in restoration impacts. Positive trends in NDVI across broad regions could mask areas experiencing localized degradation, which might lead to overly optimistic conclusions about the GGW's success. Our pixel-level regression analysis maps offer valuable spatial insights, but these trends are sensitive to data noise, especially in arid zones where vegetation cover is sparse. Another aspect meriting consideration is seasonality; while annual averages were used here, seasonal variations provide critical information on natural vegetation cycles and their responses to extreme events, such as droughts or atypical rainfall. By segmenting NDVI and other indices seasonally, future studies could capture vegetation patterns more accurately, thereby refining the analysis of GGW's impacts.

To address these limitations, future research could benefit significantly from expanded ground-based observations in collaboration with local agencies, enabling a robust ecological monitoring network within the GGW region. Incorporating maps of actively restored areas could also help validate observed remote sensing trends and enhance the interpretation of restoration efforts. A seasonal analytical approach would also allow for a more nuanced tracking of vegetation cycles, yielding clearer insights into the success and resilience of restoration initiatives.

5. Conclusions

The Sahel-Sahara region continues to face significant environmental challenges due to the compounded effects of climate change, land degradation, and anthropogenic pressures. The Great Green Wall (GGW) initiative was launched with the objective of addressing these issues through large-scale land restoration and sustainable management practices. This study analyzed satellite-derived data to assess vegetation trends using the Normalized Difference Vegetation Index (NDVI), along with day-time land surface temperature (LST) changes and precipitation variability across the region. Our findings reveal an overall positive trend in vegetation health in the Sahel-Sahara region, with evidence of retreating desert areas and expanding vegetated zones, especially since 2019. These changes suggest some alignment with the goals of the GGW initiative, although it is challenging to directly attribute the observed vegetation growth solely to GGW efforts without supportive ground-based validation. The observed vegetation increase may be influenced by a combination of factors, including climatic variations and GGW-related interventions. Precipitation patterns showed variability, with regions experiencing both positive and negative trends, which in turn impact vegetation and LST dynamics. Although urban areas continue to expand, reflecting development pressures, the positive NDVI trends highlight improvements in vegetation health, particularly in areas where GGW activities are focused. However, the lack of ground-truth data remains a limitation, as it restricts the capacity to distinctly separate the impacts of GGW activities from broader climatic changes. In summary, this study underscores the complex interaction between climate, vegetation dynamics, and land restoration efforts in the GGW region. While significant land cover changes are apparent, further research with integrated ground-based and remote sensing approaches is essential to conclusively evaluate GGW's contribution to these trends. Continued and adaptive management strategies will be crucial for achieving the GGW's long-term goals of enhancing climate resilience and ecological stability in the Sahel-Sahara region.

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