Article:

Marchant, Robert orcid.org/0000-0001-5013-4056, Makinde, E.O. and Salami, J.T. (2024) Assessing two decades of change across the Eco-Regions of West Africa using remote sensing technology. Scientific African. e02056. ISSN: 2468-2276

https://doi.org/10.1016/j.sciaf.2023.e02056

Scientific African 23 (2024) e02056

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Assessing two decades of change across the Eco-Regions of West Africa using remote sensing technology

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ARTICLE INFO

Editor: DR B Gyampoh

Keywords:
Green productivity
Geospatial
Land use land cover (LULC)
West Africa
MODIS
NDVI

ABSTRACT

The landscapes and Eco-Regions of West Africa have a unique biodiversity that reflects climatic regime and human interaction. Changes and trends in the Eco-Region land cover and its productivity was assessed using Aqua MODIS NDVI C6 satellite images on a geographical mapping grid at approximately 250m from between 2003 and 2021. Using cell statistics and geoprocessing tools within a GIS environment, the satellite images were processed and analysed. The processed and analyzed satellite images document changes across the region over 19 years. The results show that; Guinea Savanna Eco-Region records highest changes, with an increase in green productivity between 2007 and 2012 by 9.24 km^2; and decrease in green productivity in green productivity between 2007 and 2012 by 9.24km of 4.37 km^2 from 2012 to 2017 and by 9.30 km^2 from 2017 to 2021. The Grassland/Sudan Savanna fluctuated over the last 19 years with an overall reduction in green productivity by 3.43 km^2 while the Guinea Savanna increased by 1.0 km^2 over the same period. The Tropical Rainforest Eco-Region had the highest increase in productivity from 2003 to 2007 by 11.25 km^2 and less than a km^2 increase from 2007 to 2012. This study concluded that there was fluctuation in area coverages among the Eco-Regions across West Africa which varies seasonally and periodically. These Eco-Regions are vital for the development and economic suitability of West Africa, thus the need for continuous monitoring and study. Also, the fluctuation in area coverages detected in the study suggest that certain interventions by policy makers and stakeholders have brought about these changes, of which reforestation and land use policies are inclusive. Policymakers and government agencies are therefore apprised to maintain policies that support green productivity in the region.

Introduction

West Africa consists of a wide range of ecosystems, and bioclimatic regions from the rainforest to desert. There is a strong transition in land use land cover when moving from the north to the south. The northern area supports pastoralists while the southern area is predominantly an agroforestry economy [1]. The anthropogenic activities impact both ecosystems and feedbacks to the climate. [2] Observed that there is a relationship between forests and climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition; and that these complex and nonlinear forest-atmosphere

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https://doi.org/10.1016/j.sciaf.2023.e02056
Received 26 October 2022; Received in revised form 22 December 2023; Accepted 22 December 2023
Available online 28 December 2023

interactions can dampen or amplify anthropogenic climate change. Thus, charactering change of human environment interactions is of vital importance for the survival and sustainability of human livelihoods, understanding patterns and process of biodiversity in earth ecosystem, characterizing climate change and underpinning environmental modeling, design and monitoring of land use policies [3–5]. Extreme weather conditions; flooding, erosion, increases in temperature, droughts, public health disasters are all associated with Land Use and Land Cover [6]. Green productivity as a measure of economic productivity reference environmental protection and conservation as constraints; in terms of Land Use Land cover, green productivity correlates to the growth in land use land cover types that supports environmental conservation [7,8]. Land Use and Land Cover (LULC) mapping can provide valuable insight into the green productivity as well as the impacts of the adverse effects of climate change on the overall economic activities in a region [9]; and can lead the way to policy recommendations in adapting and mitigating adverse effects of climate change [3,5,6,10]. In West Africa, quantifying the impacts of adverse effects of climate change has become paramount given the threat posed to food security in the region [6].

Studies have shown that Remote Sensing and GIS dataset can be used to assess spatio-temporal changes in land cover [5,11,12]. Early satellite data used for mapping global Land Use and Land Cover include Advanced Very High-Resolution Radiometer (AVHRR) observations and data [13] followed by other earth observatory satellite data including NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat Missions [14]. Different Land Use and Land Cover mapping techniques and satellite data have been employed in evaluating, tracking, qualifying, and quantifying changes in land use and land covers, drivers of land use, and land cover dynamics [3]. Such techniques include the use of NDVI (Normalized Difference Vegetation Index) MODIS time series data, the use of TerraClass classification methodology, and the use of the MODIS land cover classification algorithm (MLCCA) [3,13]. The use of MODIS data and products is quite new with its application ranging from estimating NDVI (a surrogate for biomass density) to surface temperature, to evapotranspiration, to Leaf Area Index Analysis [15], to global and regional land cover products [10,13,16,17],. Like other earth observation satellites, MODIS data and products are subjected to some limitations including cloud cover and processing problems, however, MODIS has some comparative advantages over other satellite products like AVHRR such as improved spectral, spatial, geometric, and radiometric attributes with the quality of MODIS products improving with time [13,17].

MODIS data covering a period of ten years (2000 – 2010) have been used to evaluate the changing latitudinal gradients in vegetative phenology including the length of the growing season across the Sudano-Sahelian West African region [18]. MODIS fire products (MODI14A2, MYDI14A2, and MCD45A1) have also been used to assess and account for the variability in savanna fire regimes in West Africa with regards to land cover and savanna vegetation [19]. In the derivation of biophysical variables, MODIS vegetation

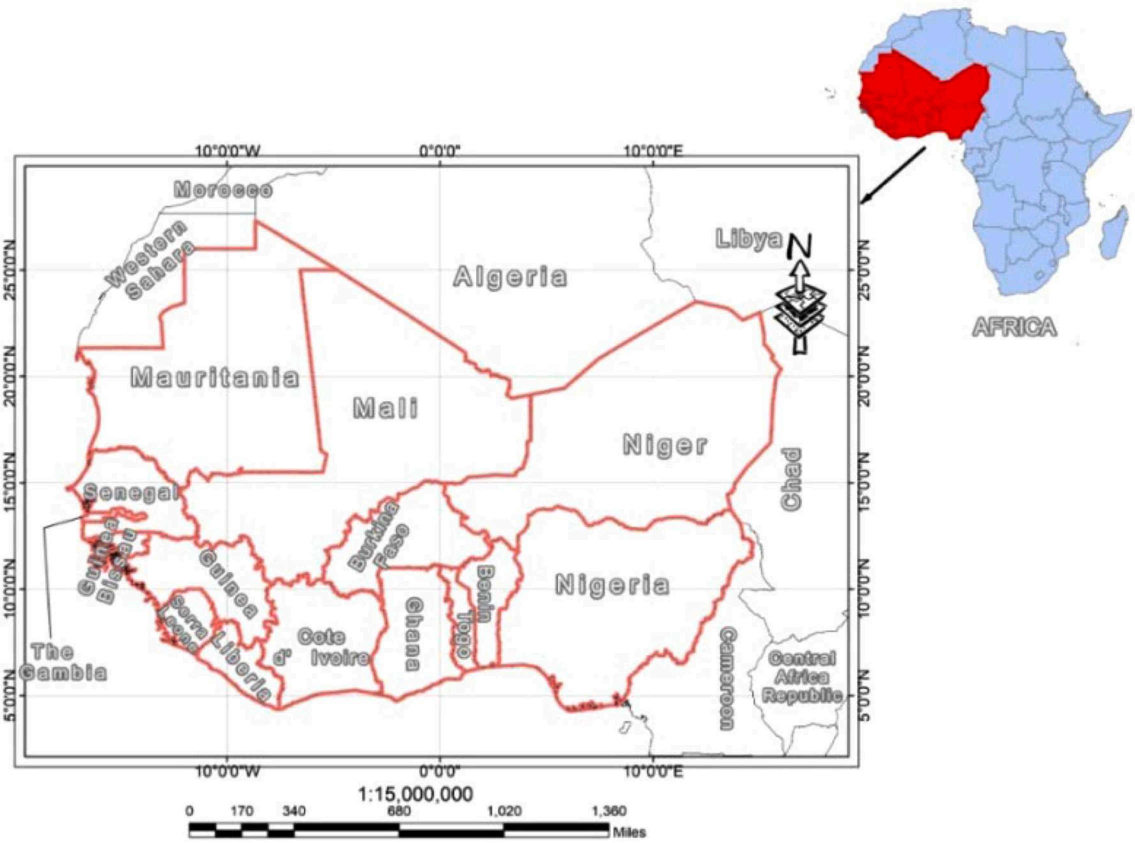

Fig. 1. Map of West Africa.

indices were used in West Africa with comparison to those from AVHRR satellite data [20]. MODIS are a good source of data for different processing techniques, analysis and products including phenological parameters estimates through double-logistic function fitted to MODIS NDVI trajectories.

In West Africa, most of its countries have only one rainy season which could last from one to about six months and this is related to the interface between two air masses one hot and humid, and the other cool and dry; West Africa has one rainy season lasting one to six months due to the interface between hot, humid and cool, dry air masses [21,22]. Thus, the amount of rainfall experienced directly reflects the number of vegetated areas the region will have. For example, the Sahel region has an average rainfall that ranges from 0 to 150mm per annum, has its vegetation cover very sparse or absent, except in oases, wadis, and depressions, where water is present at or just below the surface. The vegetation here is generally characterized by open herbaceous types (steppe and short grass savanna) often mixed with woody plants. However, areas like the Guinean region that experiences an average annual rainfall of about 1200 to 2200mm have forest canopies that are generally dense and closed, and forms woody understory [22]. Hence, there is a direct relationship between the ecological regions of West Africa and its climate pattern [23,24].

Ecological regions are known to be areas of relative homogeneity with respect to ecological systems that involves the interrelationships and integration of factors such as climate, soil, plants, animals, geology, geomorphology, vegetation cover, hydrology and their environment [22]. However, studies have shown that our climate is altering some of these known ecological systems globally and in West Africa [25–27]. It has been observed that variations in the sea surface temperatures of global oceans seem to play a major aspect in the Sahelian rainfall variability which is amplified by the presence of land cover [28]. At the local scale, the effect of temperatures and humidity on a bare soil compared to a vegetated cover is obvious, thus, climate driving the pattern of land use and land cover change, but to certain extent, is also driven by it [29]. Previous studies have not shown a two-decade data being used to assess the level of greenness of the West Africa region as it relates to climate. Therefore, this research study used MODIS to assess the land use and land cover dynamics in West Africa. This was with the view to assessing the changes that had taken place in the region over the last two decade and its influence on the amount of green productivity derived.

Material and methods

Study area

West Africa lies between latitudes 4°N and 28°N and longitudes 15°E and 16° covering approximate a quarter of Africa (Fig. 1)

Climate

Rainfall distribution is a major factor that has shaped the West Africa Region [30,31], with rainfall being essential to many activities such as agriculture and hydroelectric power generation. The region's rainfall regime is characterized by abundant precipitation at the Gulf of Guinea all year round and a decreasing pattern in the south north latitudinal gradient with Abidjan, in Côte d'Ivoire having a mean annual rainfall of about 1600mm whereas Ouagadougou, Burkina Faso records 700mm of rainfall within its five months rainy season; while and Agadez, in Niger records an annual rainfall of 165mm [22].

Temperatures in the West African lowlands are reported to be high all year round, having an annual mean of above 18°C while the Sahel has a maximum annual temperature of above 40°C. This region experiences scarcity of rainfall and its variability ranges from 10% to about 20% annually in the coastal areas to over 40% in the northern parts of the Sahel [26,32]. Drought is known to be a recurring phenomenon in semiarid area of West Africa, where the average rainfall patterns are skewed to dryness. Between the late 1960s and throughout the 1980s, it was reported that the Sahel zone of West Africa experienced droughts in an unprecedented spatial extent and duration [21]. These droughts occurred after the 1950s and early 1960s era that had experienced a period of plenty rainfall, which encouraged the government and farmers at that time to expand agriculture northward [25]. However, when the great Sahelian droughts occurred, it forced the government and farmers to abandon agriculture at the arid margin. The result of this decision was that a famine crisis was triggered that killed several thousands of people and their livestock. This famine crisis has been blamed for the widespread environmental degradation occurring in this region.

Data source: MODIS

The main source of Data is the Aqua eMODIS NDVI C6 from the U. S. Geological Survey (USGS) Earth Resources Observation Centre and Science (EROS) Centre. It is a satellite derived vegetation product from the Collection 6 Moderate Imaging Spectroradiometer (MODIS). This product known as 'eMODIS' is used for land monitoring applications on a near-real time bases. They are a composite of 10-day interval on a geographical mapping grid at approximately 250m spatial resolution to monitor vegetation conditions around the world. The band data available for Africa is the Normalized Differential Vegetation Index (NDVI) which is measure of the density of chlorophyll contained in vegetation cover computed as:

$$\mathrm{NDVI} = ((\mathrm{NIR} - \mathrm{RED}))/((\mathrm{NIR} + \mathrm{RED})) \quad (1)$$

The Red and near infrared (NIR) images are obtained and used to calculate an NDVI value for each pixel [33].

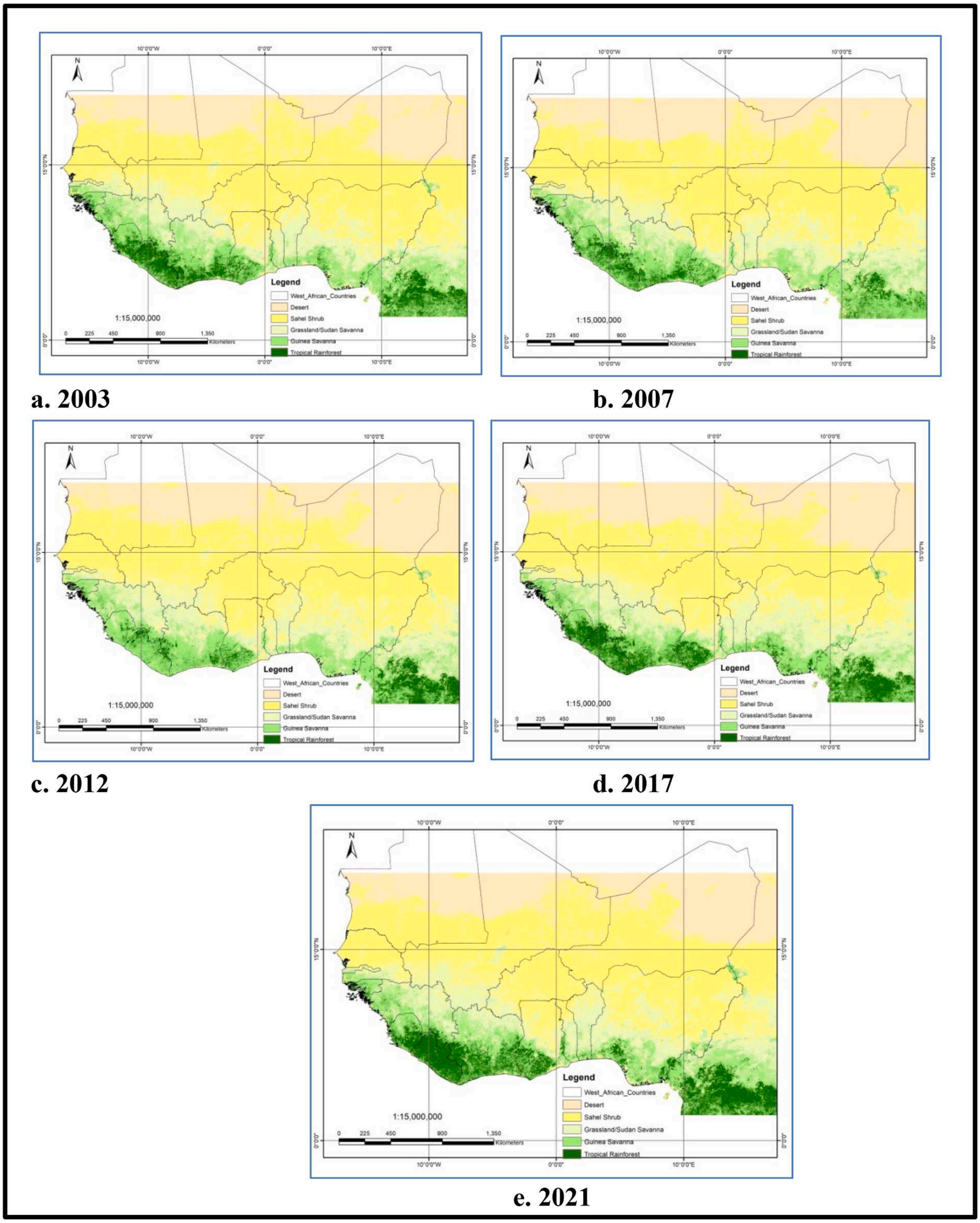

Fig. 2. Eco-regions during the dry seasons in the month of january.

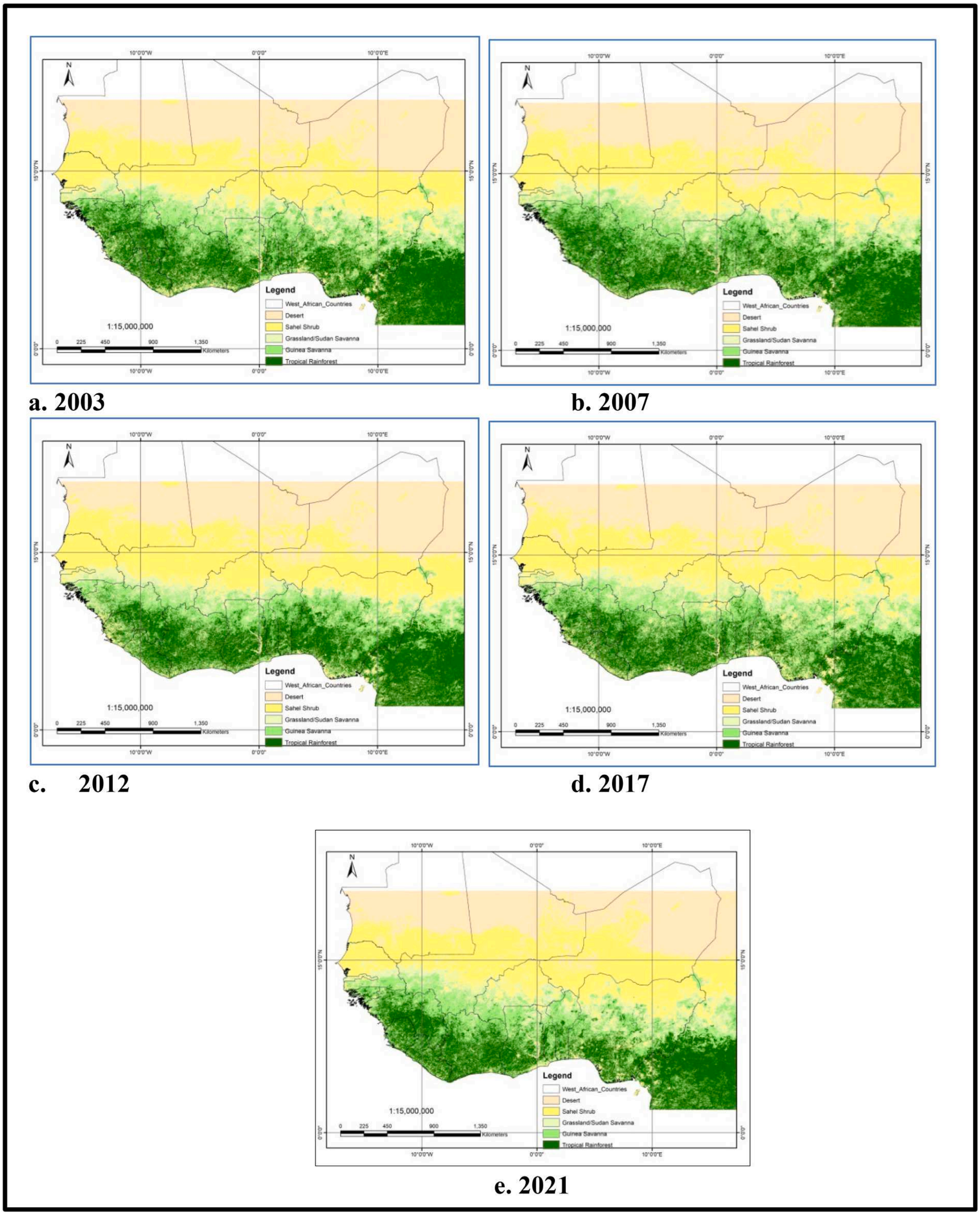

Fig. 3. Eco-regions during the wet seasons in the month of june.

Image processing and analysis

Available derived satellite images products of eMODIS (250m) with a five-year interval for 2003, 2007, 2012, 2017, and 2021 were acquired for West Africa and downloaded from the USGS website. Three images for the month of June (the peak of the rainy season) and three images for the month of January (the peak of the dry season) were acquired for each year. The images were preprocessed by rectifying to Universal Transverse Mercator (UTM) WSG84 Datum, Zone 32 coordinate system; with assumptions on the absence of snow and regions of active aerosols sources, the product used was deemed corrected for atmospheric effects within the study area [34], reconstructed the 10-day data by linear interpolation based on the Day of the Year (DOY) band and Julian calendar; and filter to remove 'no data' pixels, reduce noise and improve the quality of data. The maximum NDVI (MaxNDVI) was extracted using the Cell Statistics Tool in ArcGIS 10.3 and a new image called the Maximum NDVI image (for each month) was produced. Using Google Earth Imagery for accuracy assessment, Table SM4 to Table SM13 show the accuracy assessment for the image processing for each year, with a minimum of 86% relative accuracy [35].

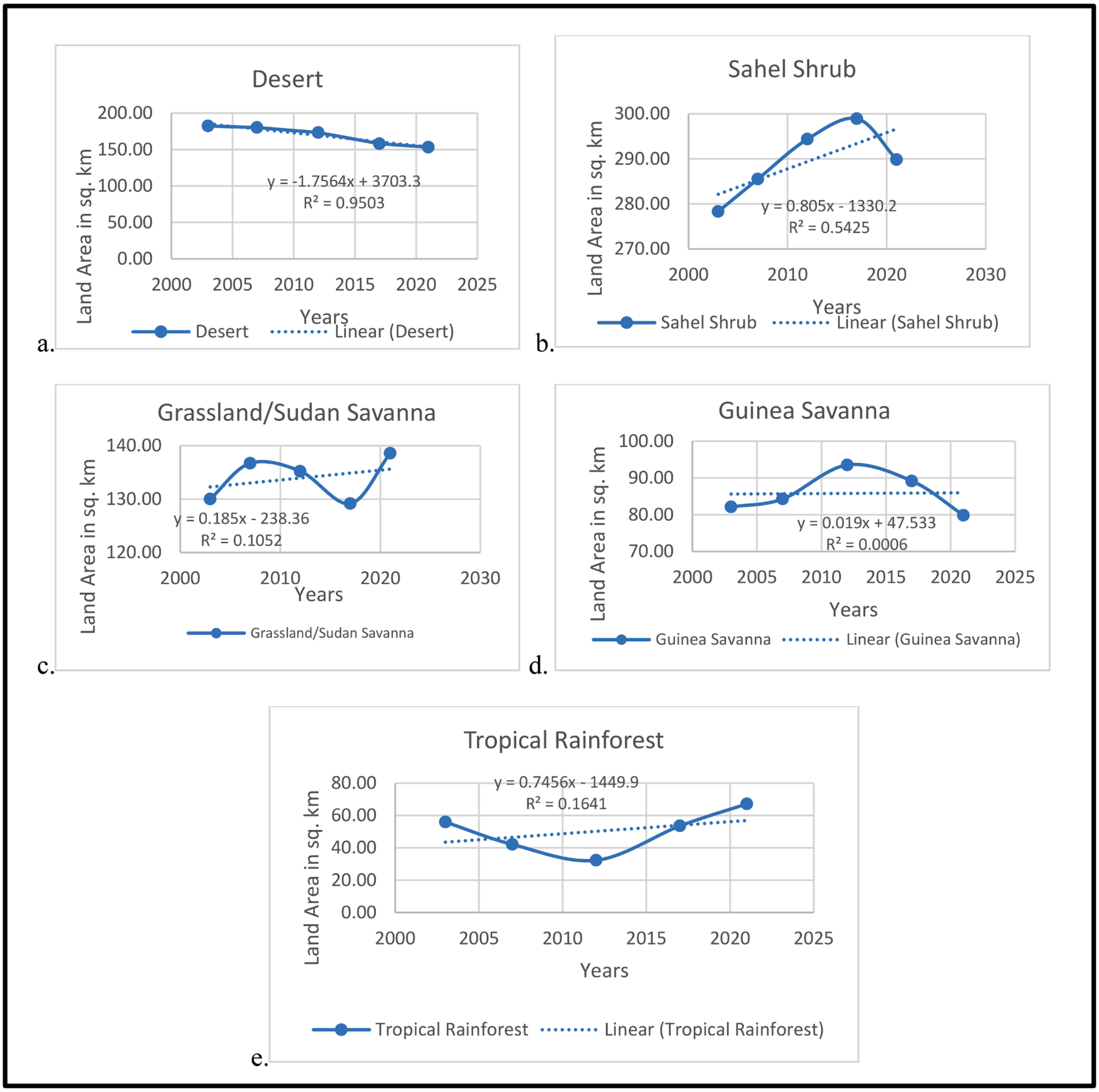

Fig. 4. Changes And Trend Line Analysis Of Eco-Regions (a) desert (b) Sahel Shrub (c) grassland/Sudan Savanna (d) Guinea Savanna (e) Tropical rainforest during the dry season from 2003 to 2021.

Eco-regions

It is clear that the West Africa region's climate determines the vegetation type; to identify the vegetation types on the eMODIS images maximum likelihood classification technique was applied, as suggested by [36,37]. The vegetation classes of West Africa were divided into five distinct regions: Desert, Sahel Shrubs, 14 Grassland/Sudan Savanna, Guinea Savanna, and Tropical Rainforest. The reclassification performed was based on the NDVI surface spectral reflectance characteristics (NDVISR) of the region; which is known to useful and reliable for multi-zones data [38]. This process reclassifies the entire images spectral characteristics into five different categories. Subsequently, the areas covered by each vegetation type were computed for in the attribute table using the cell size and the pixel count.

Change detection and green productivity

The time series images for June and January were partitioned and analysed for changes in the greenness of the Eco-Regions to determine the changes between the vegetation regions in West Africa between 2003 and 2021; change detection was performed and a residual image that represent the changes produced. This was performed by subtracting the maximum NDVI image of 2021 from the

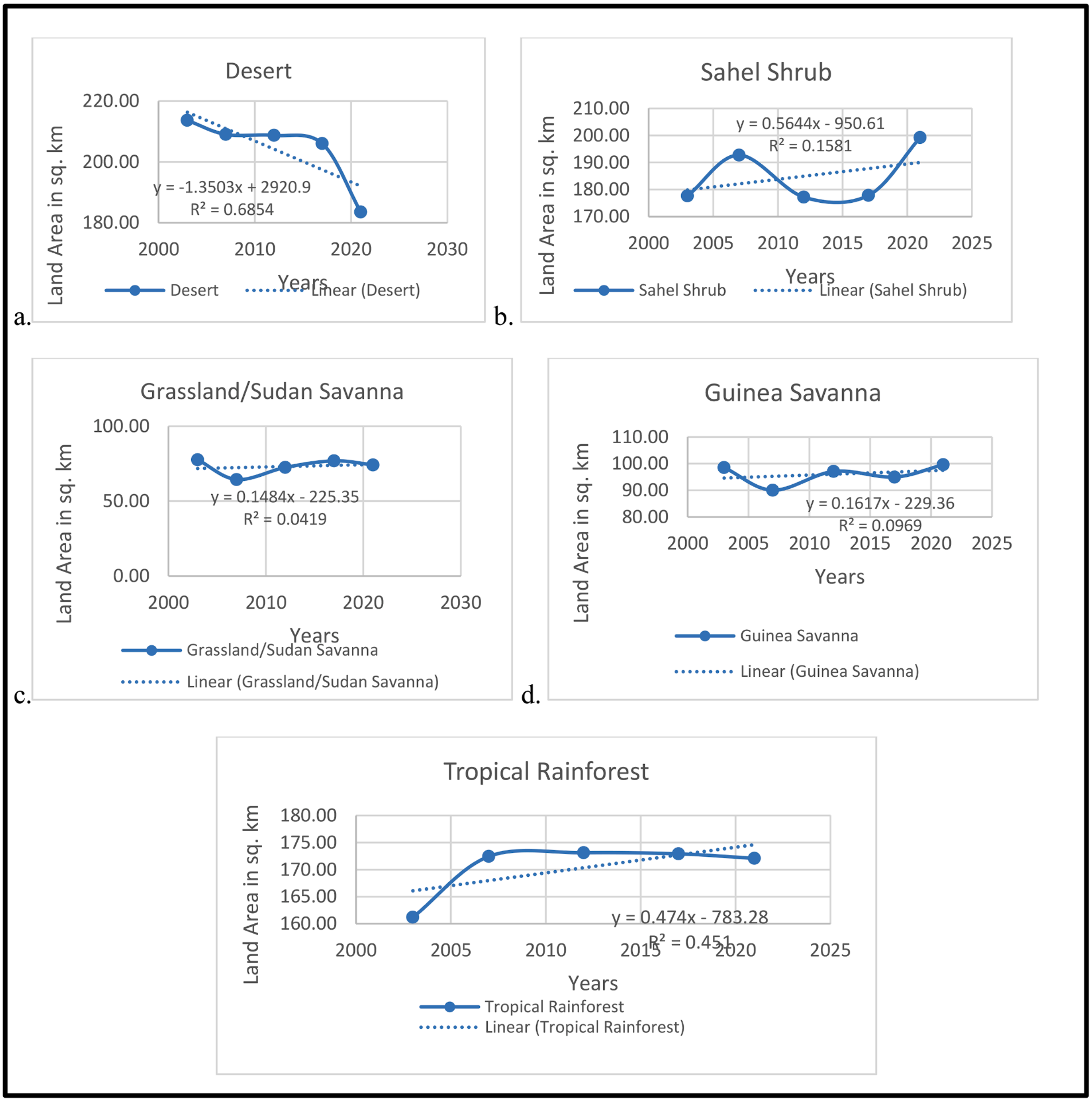

Fig. 5. Changes and trend line analysis of eco-regions (a) desert (b) Sahel Shrub (c) grassland/Sudan Savanna (d) Guinea Savanna (e) tropical rainforest during the wet season from 2003 to 2021.

maximum NDVI image of 2003. Mathematically, the difference image is:

$$\mathrm{Id}(x, y) = \mathrm{I1}(x, y) - \mathrm{I2}(x, y) \quad (2)$$

Where I1 and I2 are images from time t1 and t2 and (x, y) are coordinates and Id is the difference image. Pixels with no change in radiance are distributed around the mean [39] while pixels with change are distributed in the tails of the distribution curve [40].

Results/analysis

Maximum NDVI

The computed Maximum NDVI for 2003, 2007, 2012, 2017, and 2021 during the dry season (January) and Wet season (June) respectively (Figure SM1 and SM2). These images are the maximum NDVI extracted from the MODIS data in both Dry and Wet Seasons of West Africa, and they all have different spectral variations.

Eco-regions

On table Figs. 2 and 3, the various Eco-Regions can be observed from year to year and season to season.

Figs. 2 and 3 both depict the patterns and distribution of the identified Eco-Regions within West Africa during the dry and wet seasons respectively at a map scale of 1:15,000,000. At a glance the variations in the patterns are identical within each season, however, there seems to be a spread in the Sahel shrub eco-region towards the Northern part of West Africa during the dry season compared to the wet season. In the same vein, the Tropical rainforest increased in coverage area in the wet season than in the dry season.

Linear trend analysis of the eco-regions

From Table SM1, indicates the area covered by each Eco-Regions, the maximum and mean NDVI values and pixel counts. It can be observed (Fig. 4) that the Eco-Region of Desert had its land area reduced from about 182.30km in year 2003 to about152.21km in year 2021 during the dry season. However, this is different for the other Eco-Regions which fluctuate over the 19-year period.

Table SM2 presents the tabular analysis of the area coverage by each Eco-Region during the wet season across the years, along with the maximum and mean NDVI values and pixel counts. From the table, it can be seen that the Desert Eco-Region also reduces in area coverage from 213.68km in 2003 to 183.55km in 2021 similar to that of the dry season; while the Guinea Savanna on the 48 one hand, remain fairly stable, the other Eco-Regions fluctuated. Fig. 5 shows the variation and trend line analysis in the area coverage of each class of Eco-Region during the wet season.

Analysis of the green productivity of the eco-regions using change detection

Dry season

Figure SM3 and Table SM3 considered the change detection in the area coverage of all the Eco-Regions during the dry seasons and wet seasons, in between the years, and across the years. It was observed that there was a decline in this Eco-Region over the past 19 years for the Desert Eco-Region. The highest change (reduction) in area occurred between 2012 and 2017 (See Figure SM3 and Table SM3) which was 15.32 sq. km, however, the total net change in area over the entire period (2003–2021) was 29 sq. km in the dry season with reference to the Desert Eco-Region.

However, an increase in green productivity was observed in the Sahel shrub Eco-Region with the highest change detection occurring between 2017 and 2021of about 8.86 sq. km and a net change (also an increase) of 11 sq. km across the 19-year period (Figure SM3 and Table SM3). Also, the Grassland/Sudan savanna Eco-Region had the highest change (increase) between 2017 and 2021 of about 9.41 sq. km and a net change of 8.55.sq. km increase overall, across the entire period (Figure SM3 and Table SM3).

Also, it was observed that the Guinea savanna Eco-Region had the highest change, which is an increase in green productivity between 2007 and 2012 by 9.24 sq. km; however, there was equally a decrease in green productivity of 4.37 sq. km from 2012 to 2017 and another decrease from 2017 to 2021 by 9.30sq. km. Thus, there was a reduction (net change) in the green productivity of the Guinea savanna Eco-Region over the past 19 year of about 2.26 sq. km in the dry season (Figure SM3 and Table SM3).

Tropical Rainforest seems to have an increase in green productivity with its peak being between 2012 and 2017 of about 21.22sq. km and a net change of 11.23 sq. km within the 19-year period under study (Figure SM 3 and Table SM 3).

Wet season

Generally, across the Eco-Regions of West Africa, there seems to be an increase in green productivity during the wet season due as a result of precipitation (Figure SM3 and Table SM3). This is clearly seen in the land area covered by the vegetation class type called Desert where it was observed that the highest change detection (a reduction) occurred between 2017 and 2021 by 22.49sq. km and a net change of about 30 sq. km had occurred over the 19-year period. It is clear that the Desert Eco-Region had reduced greatly (Figure SM3 and Table SM3) over the last 5 years. The Sahel Shrub reduced in land mass by 15.50sq. km from 2007 to 2012, however, it increased by 21.37 sq. km from 2017 to 2021; and has a net change (increase) of 21.55sq. km over the 19-year period (Table SM3).

In addition, it can be reported that the Grassland/Sudan Savanna fluctuated over the last 19 years, thus the green productivity reduced by 3.43 sq. km (Table SM3) while the Guinea Savanna increased by 1.07 sq. km over the same period (Figure SM11). The Tropical Rainforest Eco-Region had the highest increase in productivity from 2003 to 2007 by 11.25 sq. km and less than a sq. km increase from 2007 to 2012. There was, however, a further reduction in the greenness of the tropical forest from 2012 to 2021 (Figure SM3).

Discussion

This study used the time series eMODIS NDVI C6 satellite data of West Africa covering 19 years (2003- 2021) for the month of June (peak of the rainy season) and January (peak of the dry season. This study identified five ecological regions in West Africa from the eMODIS images which are consistent with the report of [41]. It was observed that areas with high luxuriant greenness were areas that had higher amount of rainfall. Rainfall is a major climate variable that affects the vegetation of an area and this is also noted by [42], who stated that the variation of NDVI is a reflection of the greenness of an area mainly depends on Climate factors such as precipitation. However, from the land use land cover and change detection analysis, certain variations were observed within each Eco-Region. It was observed that the MaxNDVI values remained constant over the years within a particular season while the land area covered by each Eco-Region changed. For example, the Desert Eco-Region had a consistent MaxNDVI values for 19 years, but the area covered by Desert reduced in size from about 182.30sq km in 2003 to about 153.21sq km by 2021during the dry season and also from about 213.68sq km in 2003 to about 183.55sq km in 2021 during the wet season. Thus, there was a decline in the Desert Eco-Region over the last 19 years. These declines are attributed to some intervention to combat the adverse effect of climate change.

Similarly, other Eco-Regions had experienced some form of increase in the level of greenness (re-greening) from 2003. Although, some fluctuations were observed, however, there were obvious increases in the land area covered by vegetation in 2021 than in 2003. This can be seen in the Tropical Rainforest Eco-Region where the green productivity increased from 161 sq.km in 2003 to 172 sq. km in 2007 and remain relatively so. It was observed that the Sahel Shrub and the Grassland/Sudan Savanna Eco-Regions had experience some form of re-greening especially during the wet season. This finding agrees with previous studies on the re-greening observed in West Africa [43,44,45]. Also, the fluctuation in the increase and decrease of the level of greenness observed in this study agrees with [46] who reported that West Africa had experience simultaneous losses and gains in the major LULC categories.

Although, there were varying values of net loss and gain across this study which indicates the increase or decreases in the re-greening of the west African region, [47,48], stated that net change (net loss or gain) alone is not sufficient to understand the total LULC dynamics and patterns in a landscape. They argued that as total changes are masked by the estimates of net change because gross gains of a given LULC category at certain locations in a given time may be compensated by gross losses of the same LULC category at different locations on the same landscape at the same time. Thus, when there is a zero net change, this does not indicate the absence of changes in the land cover [49].

Findings from this study indicated that across West Africa, changes had occurred in the LULC of the region thereby affecting the green productivity of the region. It is clearly observed that the Desert Eco-Region had reduced even in the dry season by about 29 sq. km from 2003 to 2021 while the Sahel Savanna, the Grassland/Sudan Savanna and the Tropical Rainforest had increased within the same period. Although, there was a reduction in the Guinea Savanna, there was generally a rise in the greenness of the region across all the dry seasons. Studies into tropical rainforest regions on the African continent have shown that the tropical rainforest areas are on the increase even during the dry season [50,51,52]; this has been attributed to the effect of climate change in form of weaken seasonality (57), the uncertain response of African tropical rainforest to climate extremes like temperature anomalies (564), declining rates of deforestation and increasing afforestation measures [53,50]. This corroborate the findings in Fig. 4. Also, it can be clearly seen that there is a sharp decline of the Desert Eco-Region in the wet season and at the same time, an increase in green productivity for all the other Eco-Region classes. This could be attributed to some friendly practices and interventions such as afforestation and irrigation which have assisted in militating against the adverse effects of desertification and climate change. World Bank, United Nations and other organizations had embarked on some form of interventions in conjunction with the Economic Community of West Africa States (ECOWAS), Permanent Interstate Committee for Drought Control in the Sahel (CILSS) and others to conduct research and proffer solutions to desertification in the region [54–56].

It was reported [57] that following the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, the international community acknowledged that Desertification, Land Degradation and Drought (DLDD) were major constraints to the economic and social development of the West Africa region and thus adopted the United Nations Convention to Combat Desertification in countries severely affected by drought and/or desertification, especially in Africa (CCD). And afterwards, the Sub-regional Action Programmes/Desertification Control (SRAP/DC) was established in which sixteen (16) countries in West Africa and Chad (in Central Africa), decided in September 1994 to cooperate in developing and implementing a sub-regional action programme to combat desertification and manage shared resources. That West Africa" (SRAP/WA) under the aegis of ECOWAS and programme was titled "SRAP –CILSS (SRAP–West Africa Report, 2013). The second generation of SRAP/WA (SRAP2) was developed for the adoption of UNCCD's ten-year strategy (2008–2018). It addresses the two-fold concern of the 17 ECOWAS and CILSS countries to improve the implementation of the CCD in the sub-region [57,58]. Other interventions included: World Bank's Sahel and West Africa Program in Support of the Great Green Wall (SAWAP) Initiative (2012–2019) and "BRICKS" (Building Resilience through Innovation, Communication and Knowledge Management) project, where the focus was on expanding Sustainable Land and Water Management in Targeted Landscapes and Climate Vulnerable Areas. This was supported by grants from the Global Environmental Facility (GEF) Trust Fund, Special Climate Change Fund (SCCF), and West Africa Terra Africa which covered agriculture, food security, disaster risk management, rural development, and watershed management. The program was aimed at building on a series of World

Bank investments which was reported to amount to $1.8 billion in co-financing in countries [59]. "BRICKS", a regional learning and Monitoring and Evaluation (M&E) structure to support the SAWAP. It was reported that the outcome of SAWAP projects have surpassed their initial cumulative targets establishing 1.6 million hectares (ha) of SLWM practices across the twelve countries (an area larger than Lebanon), with success stories particularly in Ethiopia, Niger, Nigeria, and Sudan. At the macro level, the SAWAP program has demonstrated success in some difficult country contexts. While two of its outcomes were largely surpassed, two outcomes (Normalized Difference Vegetative Index and carbon accumulation rates in biomass and soil) faced methodological problems [59].

In 2010, African Development Bank (AfDB) reported some of its interventions which included the Rural Water Supply and Sanitation Initiative (RWSSI) which took off in 2003 with operations in 20 Countries, with the overall objective of extending safe water and basic sanitation coverage to 80 percent of the rural population by 2015, at an estimated cost of UA 9.22 billion or USD13.9 billion [60]. Other interventions established in partnership with other governments in Europe and America were: The Multi-Donor Water Partnership Program (MDWPP), The Multi-Donor Water Partnership Program (MDWPP), The African Water Facility (AWF), Integrated Water Resources Management (IWRM) policy. In addition, the Intervention Framework for the Development of Climate Smart Agriculture under the West Africa Regional Agricultural Policy (ECOWAP/CAADP) implementation Process, Climate Change Adaptation in Africa Programme, Climate Change Adaptation in Africa Programme, Africa Union's Agenda 2063 and the Africa Water Vision for 2025 were some of the other interventions among others [61,9].

Therefore, it can be clearly stated that all these interventions had positive impacts on the green productivity of the West Africa Region. This is because there were obvious changes on the landscape of West Africa which are very visible from satellite images. These images clearly identify these changes and patterns over several decades. It can be categorically stated that the increase in the greenness or the NDVI of the landscape of the West Africa region and the strides [62] achieved in mitigating desertification has been yielding positive results. It is our recommendation [45] therefore, that these interventions at regional and country levels are intensified. Intensifying these interventions will strongly mitigate the adverse effect of global climate change today.

Conclusion

This study assessed the greenness of the West Africa region using MODIS satellite imageries from 2003 to 2021 and observed fluctuations across the five major ecological regions. This study reported that there is a direct relationship between the type of Eco-Regions and its green productivity in both wet and dry seasons. In line with the African Union's Agenda 2063, the goal of inclusiveness and sustainable development cannot be achieved without significant understanding of the continent's Eco-Regions. The overall green productivity across the Eco-Regions increased over the years due to certain practices that were introduced and these practices led to some observed changes in the region. Therefore, a need to ensure continuity of the practices beyond geopolitical encumbrances. This study concludes that there was an increase in the amount of greenness in the desert regions of West Africa within the period under study. The paper had a limitation regarding the number of years covered, it is therefore recommended that more number years should be added in future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The Authors are appreciating the Commonwealth Scholarship Commission for the Postdoctoral Fellowship given to begin this research in the UK in 2018.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2023.e02056.

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