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Human-induced land degradation dominance in the Nigerian Guinea Savannah between 2003 – 2018

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ABSTRACT

Land degradation poses a persistent challenge to ecosystems and sustainable livelihoods in the Nigerian Guinea Savannah (NGS). While both human activity and climate variability have been implicated as degradation drivers, the lack of research fuels dispute over the causes and status of land degradation in the Savannah. Detailed evidence on the contributions of both rainfall and human activities can, however, help identify appropriate measures to address land degradation. MODIS vegetation "greenness" and TAMSAT rainfall data were employed to achieve the following objectives: (i) provide empirical insights on the pattern of savannah vegetation dynamics; (ii) control for rainfall effects in Savannah degradation; and (iii) characterize the extent, severity and geography of human-induced land degradation. The selected statistical techniques proved useful for highlighting the spatio-temporal dynamics of degradation in the NGS. Controlling for the effect of rainfall on vegetation greenness produces a Normalized Difference Vegetation Index (NDVI) residual that allows to us estimate the human impact on land degradation. Despite no indication of a worsening rainfall regime, inter-annual variation in vegetation greenness exhibits a consistently negative, declining trend. This continuous, negative, declining trend in the NDVI residual strongly suggests ongoing biomass loss in the NGS is the result of unsustainable human activity. Observed improvement is attributable to existing land management programmes (afforestation and the planting of drought tolerant species) initiated by states in the zone. In sum, approximately 38% of the NGS land area, including protected areas such as Kainji Lake National Park, are becoming more degraded, while 14% and 48% of the remaining area shows either improvement or no real change, respectively. These results serve as a baseline information resource for tracking future land use activities, land degradation and potential pathways for achieving more sustainable land management.

1. Introduction

Persistent loss of biomass is a pervasive form of land degradation (UNCCD, 2013, 2016), caused by constant interactions between social and natural processes over space and time. The restoration of degraded land is intended to enhance land resources and their ability to support life on land (Cowie et al., 2018; Orr et al., 2017). For this reason, global development actors have stressed the need to prevent land degradation and restore ecosystem performance (Scholes et al., 2018). From the RIO+20 summit to the recent development of the UN Sustainable Development Goals (SDGs), emphasis on tackling land degradation has increased, as this improves the likelihood of achieving many SDGs (UNCCD, 2016). Sustainable land-based initiatives are therefore encouraged to promote the global response to land degradation (Nkonya et al., 2016). Co-benefits include improved food security, improved resilience of the productive environment, including climate risk protection and biodiversity conservation (Scholes et al., 2018).

Several studies have implicated both human activity and rainfall (climate) variability as causes of global environmental change (IPCC, 2014; UNCCD, 2016; Cowie et al., 2018). Yet a clear distinction between

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these two drivers of land degradation is rarely made (Wright, 2017; Kundu et al., 2017). Moreover, the collective impact of human-induced drivers on savannah degradation is more complex and manageable than the impact of rainfall (Zhu et al., 2016). Although several studies on land degradation exist, only a few have addressed its broader causes. Bai et al. (2008) estimated that globally, more than 20% of all cultivated areas, 30% of forests and 10% of grasslands were degraded and raised concerns about the contested causes, coverage, and severity of land degradation. Nkonya et al. (2011) identified hotspots of land degradation at global scale by clustering countries into regions and proposed using the unique and prevailing local conditions, such as climatic variations or agro-ecological differences, as guides for understanding the complicated drivers of land degradation. Wessels (2009), in a cautionary note compared and suggested methods for assessing degradation and provided an improved approach for discriminating between human and non-human-induced degradation (e.g. declining rainfall). This differentiation is necessary to ascertain the contribution of distinct causes thereby enhancing a more decisive response to land degradation (Wessels, 2009; He et al., 2015; Wingate et al., 2019).

In Sub-Saharan Africa (SSA), land is associated with natural capital and wealth (Liniger et al., 2011). Since 60% of the people depend on land for their livelihood, owning degraded land is equivalent to being poor, particularly for millions whose economies depend on the ability to manage land-based resources (Barbier and Hochard, 2018; Pingali et al., 2014). While some studies in SSA have examined land degradation (Huber et al., 2011; Ibrahim et al., 2015) they do not identify the subnational patterns of degradation. Such studies substantiate the importance of subnational and agro-ecological considerations in operationalizing and setting national Land Degradation Neutrality (LDN) targets (Ifejika Speranza et al., 2019), which are crucial elements in implementing the LDN framework (Orr et al., 2017; Kust et al., 2017). However, the coarse and generalized nature of previous studies (Fensholt et al., 2009; Fensholt and Rasmussen, 2011; Ibrahim et al., 2015), overshadow subtle subnational and localized degradation, thereby fuelling historical controversies over the true status and trend of environmental degradation in West Africa (Gautier et al., 2016).

Apart from its huge population and oil resources, Nigeria is consistently topmost on the global degradation danger list (FAO, 2010; Hansen et al., 2013). Degraded land in Nigeria surpasses the landmass of Ghana (CILSS, 2016). However, Nigeria lacks a detailed analysis of the causes of land degradation, thus hindering targeted solutions, particularly across its agro-ecological zones. A large portion of Nigeria consists of the Guinea Savannah, often categorized as a heavily-degraded dryland ecosystem (Yirdaw et al., 2017), requiring urgent restoration (Macaulay, 2014). The Nigerian Guinea Savannah (NGS) is the largest and currently most threatened agro-ecological zone (CILSS, 2016), owing to its closeness to the extensively degraded Nigerian Sudano-Sahelian region, Hence its exposure to desertification effects is compounded by pressure from the encroaching Sahara desert (Macaulay, 2014). In the NGS, land use and socioeconomic activities are strongly seasonal and rural livelihoods are tied to the primary sector, in particular to farming and other pastoral activities. These activities have actively degraded the savannah, leading to the loss of biomass and ecosystem services, and further exacerbated impoverishment (CILSS, 2016).

Currently, there is no consistent accounting of the spatio-temporal, long-term trend of biomass loss caused by human activity and climate variability in Nigeria. This weakens critical efforts for ecosystem and environmental management as no recent studies have tried to dissociate climatic variables from human-induced impacts. The historical conflict between resource users (i.e nomadic cattle herders and farmers) is linked to the encroachment of the Guinea savannah into rainforest as a result of deforestation in Nigeria (Fasona et al., 2016; Agbelade and Fagbemigun, 2015) as well as, to the desertification of the savannah (Macaulay, 2014; Naibbi et al., 2014). However, most national studies on degradation and vegetation dynamics based on agro-ecological definitions, such as by Aweda and Adeyewa (2011) and Areola and Fasona (2018) are either too coarse or outdated. Osunmadewa et al. (2018) observed the long-term phenology of vegetation in the NGS, showing human and climate effects on vegetation, but downplayed finer vegetation dynamics due to the coarseness of their datasets i.e. 1 km resolution. Fashae et al. (2017) also grouped vegetation over Nigeria without contextualizing or discriminating climate induced and human-induced causes of vegetation degradation. In all, the omission and lack of detailed assessment of biomass degradation based on human-induced activities at a refined resolution were consistently missing.

This study aims to fill these gaps by assessing recent human-induced biomass loss in the NGS at a refined scale of medium resolution between the years 2003 and 2018. The study objectives therefore are to: 1) provide empirical insights into the current vegetation status and trends, including anomalies in the pattern of savannah vegetation dynamics based on the analysis of finer medium resolution satellite data; 2) control for climate change, in particular change in rainfall, which is generally considered strongly correlated with vegetation, thereby separating rainfall changes from other factors affecting increasing degradation of the savannah; 3) characterize the extent, severity and the geography in terms of the distribution of human-induced degradation across the NGS and identify degradation hotspots. The output from this research provides a baseline for future studies in the separation, identification, and characterization of non-climate related causes of land degradation in the NGS.

2. Materials and methods

2.1. Study area

Our study area, the Nigerian Guinea Savannah (NGS), lies between 6.50°N and 9.62°N, 2.77°E and 13.20°E, and is bordered by the rainforest in the South and the Sudan Savannah in the North (Fig. 1). In Nigeria, sub-national administrative units are called states and the states in this zone are regarded as the "middle belt" of the country. The middle belt is the largest agro-ecological zone in the country, covering about 49% of the country's land mass and 25 of its 36 states. The belt is divided into two regions, the Northern and Southern Guinea Savannah, based on differences in vegetation composition (Wakawa et al., 2016; Fasona et al., 2011). In the southern region, the vegetation is characterized by a mix of trees and tall grasses, with shorter grasses and fewer trees in the Northern part. The NGS is a crucial habitat for threatened fauna, such as chimpanzee (*Pan troglodytes*), and flora, such as the African rosewood (*Pterocarpus erinaceus*). A distinct montane vegetation characterizes the central and eastern regions within the NGS (Iloeje, 2001). The belt further encompasses parts of the two major rivers, the Niger and the Benue, and their confluence.

Several national hydropower stations, such as the Kainji and Shiroro stations are located in the zone. Several protected areas such as the Foge Islands and Kainji Lake National Park, most of which are Ramsar Convention wetland sites, are also located in the zone (Ayanlade and Proske, 2016). This fertile region is a major food basket of the country, with primarily rainfed production. The zone likewise provides grazing resources for livestock, of which a large share derives from transhumance systems (i.e. seasonal nomadism). The inhabitants consist of diverse ethnic and religious groups. Several major towns and urban centres are located in the NGS, including Abuja, the capital of Nigeria. With population growth and heavy dependence on natural resources, maintaining land quality is increasingly challenging and conflicts over access to, and control of, the land often occur (Fasona et al., 2016).

2.2. Rationale and indictors for land degradation

Concerns about the assessment, monitoring and management of land degradation have risen dramatically in recent years (Orr et al., 2017; Kust et al., 2017), and have informed an agreement on the relevant

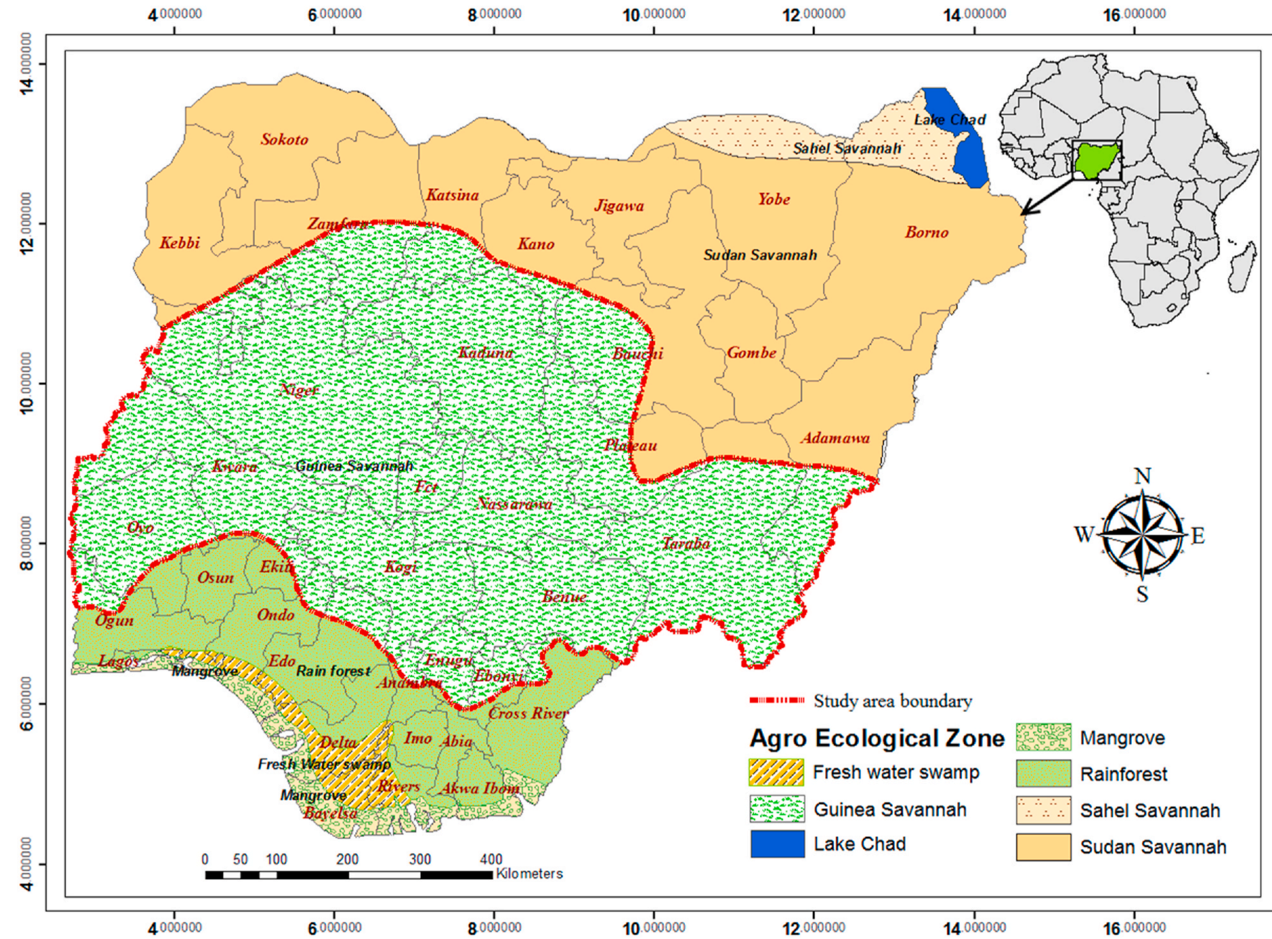

Fig. 1. Overview of the agro-ecological zones of Nigeria, with the boundary of the Nigerian Guinea Savannah indicated (adapted from Iloeje, 2001).

indictors for land degradation studies. Therefore, the performance of three indictors; 1) land cover (metric: Land Cover Change (LCC), 2) land productivity (metric: net primary productivity), and 3) carbon stocks above and below ground (metric: soil organic carbon) are prescribed as the determinant parameters for identifying degraded land and gauging neutrality (UNCCD, 2015). The Normalized Difference Vegetation Index (NDVI) is widely used as a global proxy for land productivity (Orr et al., 2017; Kust et al., 2017). Beside vegetation status and condition, NDVI is a key indicator of vegetation health condition. Therefore, adopting NDVI for discriminating human-induced from non-human-induced degradation is particularly relevant for NGS. Moreover, NDVI is more and more frequently being used to examine land degradation (Wessels et al., 2012; Kundu et al., 2017; Wingate et al., 2019).

2.3. Datasets and processing

2.3.1. NDVI data

Considering the large geographic extent and the difficulties in obtaining adequate primary data at the subnational level, we decided to assess land degradation using medium resolution (250m) satellite data. We opted for the pre-processed Moderate-resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) 10-day time series product, with a spatial resolution of 250m. MODIS' 250m spatial resolution compensates for the limitations of previous large-scale studies of the study area, such as Ibrahim et al. (2015), who used bi-weekly 8 km resolution Global Inventory Modeling and Mapping (GIMMS) NDVI (NDVI3g) datasets to assess land degradation. For our study, the Swets et al. (1999) corrected MODIS NDVI 10-day time series product was downloaded for the years 2003–2018 from the USGS Famine Early Warning System (FEWS) project (https://earlywarning.usgs.gov/fews). The dataset has proven to be a suitable proxy for detecting land degradation and vegetation greening, particularly in semi-arid to arid environments and is reportedly consistent over time (Fensholt et al., 2009; Wenxia et al., 2014). Furthermore, the 250m MODIS data resolution is able to capture human activity such as deforestation (Yengoh et al., 2015; Eckert et al., 2015) and has been extensively used in the assessment of land degradation in Africa (Zoungrana et al., 2018). In order to correct for the influence of clouds, atmosphere and solar elevation angles, the Maximum Value Composite (MVC) method for calculating the highest NDVI value was applied to the 10-day mean NDVI time series. We generated two outputs from the MVC data: (1) the monthly maximum NDVI, out of which we then calculated (2) the NDVI yearly sum (see Supplementary File, Fig. S1)

2.3.2. Rainfall data

We used TAMSAT (Tropical Applications of Meteorology using SATellite and ground-based observations) gridded rainfall data. The data has a spatial resolution of 4 km, which is suitable for assessing the spatial pattern and potential changes in rainfall, as well as its potential influence on NDVI (Maidment et al., 2017). In this study, we use the TAMSAT data to disentangle climate- and human-induced changes in NDVI. Since the TAMSAT rainfall product was specifically developed to provide meteorological data for all of Africa, we opted for the yearly sum rainfall product (Tarnavsky et al., 2014). The calibrated (i.e. over space and time) time series data of TAMSAT makes linking to the similarly calibrated MODIS NDVI product possible (Tarnavsky et al., 2014; Maidment et al., 2017). TAMSAT data can be downloaded at (http://www.met.reading.ac.uk/~tamsat/data/).

2.4. Methodology

The specific objectives of the study were addressed by means of the workflow represented in Fig. 2. The methodological steps are described in the following sections. Illustrations of the intermediate inputs and outputs can be found in the supplementary file, Figs. S2–S6.

2.4.1. Vegetation status and trends

To spatially link rainfall with the NDVI data, the TAMSAT dataset was resampled to match the 250m resolution in the NDVI dataset by applying nearest neighbour resampling. Although TAMSAT has a very coarse resolution of 4 km, which may be critical when linking to the 250m MODIS data, it is the most readily available and most reliable data for Nigeria because of its consistency with ground-based observations (Maidment et al., 2017; Tarnavsky et al., 2014). We then projected all data to the Minna/UTM zone 31N coordinate system. For each of the sixteen years, we calculated the mean of the yearly sum of the (monthly 10-day) maximum NDVI. Furthermore, to generate monthly NDVI profiles for each observed year we calculated the mean 10-day maximum NDVIs. Both outputs were generated for each pixel in our study area. NDVI is defined as a measurement of the status and presence of photosynthetically active vegetation, and ranges from −1 to +1, with negative NDVI values indicating low greenness and low presence of photosynthetically active vegetation and positive values indicating high greenness and presence of photosynthetically active vegetation. Changing NDVI over time, thus corresponds to a change in the presence of photosynthetically active vegetation and may suggest vegetation loss or gain. The standardized NDVI anomaly (Z) is defined as deviation from the long-term mean vegetation dynamics. It is particularly useful for identifying outliers of periodic NDVI events and may indicate non-periodic changes in the analyzed vegetation dynamics (Nanzad et al., 2019). To examine the magnitude of NDVI anomalies in our time series (2003–2018), two types of standardized NDVI anomalies were calculated, a monthly (Zm) and a yearly (Zy) NDVI anomaly (see Supplementary File, Tables S1 and S2). The standardized NDVI anomaly Z is calculated by subtracting observed NDVI from mean of the period, i.e. monthly and yearly, respectively, and dividing it by the monthly and yearly standard deviation of the period, respectively (Aweda and Adeyewa, 2011).

2.4.2. RESTREND

We apply the Residual Trend Analysis (RESTREND) method (Wessels et al., 2007, 2012) to control for and remove rainfall effects from the NDVI time series data. RESTREND builds on the strong positive relationship between NDVI and rainfall in arid/semi-arid regions (He et al., 2014; Ibrahim et al., 2015) and performs better than other techniques such as Rain Use Efficiency (RUE) (Kundu et al., 2017). RESTREND makes it possible to distinguish the human causes of degradation from rainfall-driven change in NDVI by using the pixel-specific differences between NDVI residuals and observed rainfall (Ibrahim et al., 2015; Wingate et al., 2019) and thus permits investigation of the trend in, and spatial assessment of, human-induced land degradation (Kundu et al., 2017; Wingate et al., 2019). Before applying RESTREND to the data, a Pearson product-moment linear correlation between MODIS and TAMSAT pixels for the entire observed timespan (2003–2018) was performed. An illustration of the resulting coefficients of spatial correlation (R) can be found in the supplementary file, Fig. S2. The linear trend of the inter-annual pixels provides further insights on the relationship between rainfall and vegetation dynamics. Consequently, the resulting outputs (Fig. 2.), from the Pearson product-moment linear correlation were used to correct the (uncorrected) yearly NDVI trend for the influence of rainfall (Ibrahim et al., 2015). The resulting rainfall corrected yearly NDVI trend can then be interpreted as follows: 1) if no trend exists, we can assume there is no human-induced degradation or

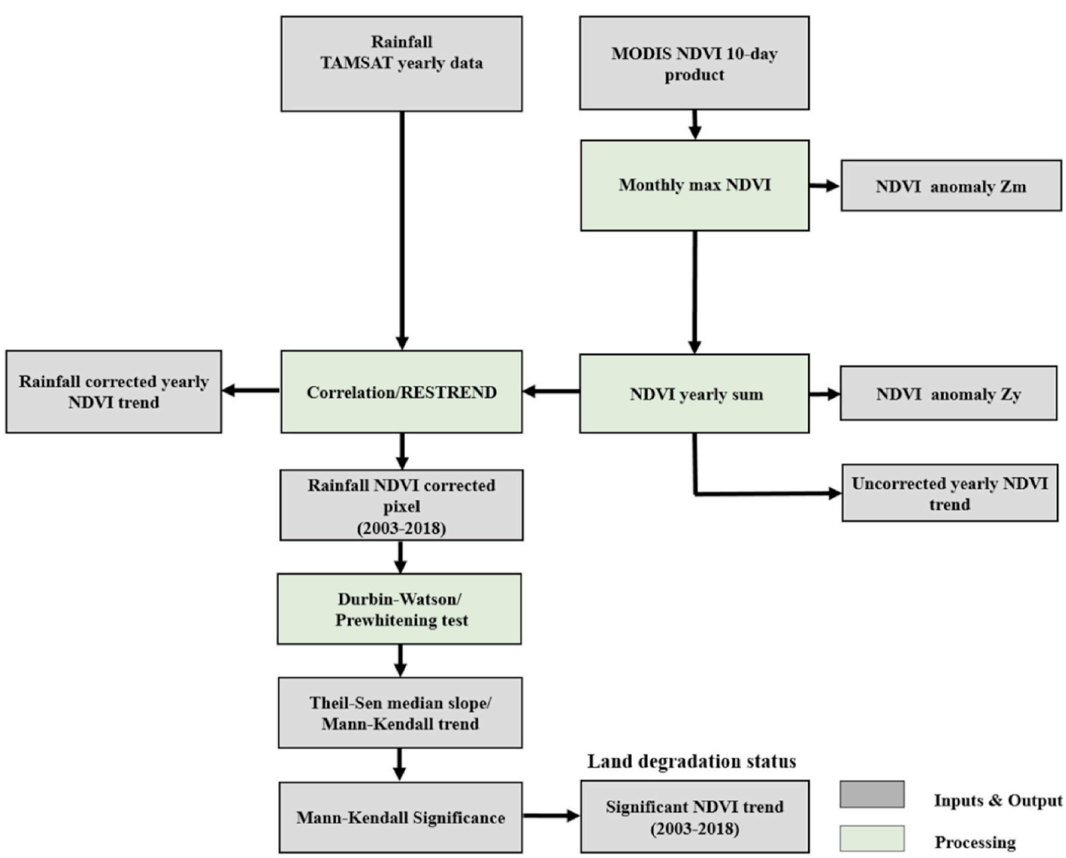

Fig. 2. Overview of the study workflow.

regeneration (i.e. improvement) happening. 2) A decreasing trend in the corrected yearly NDVI trend suggests degradation caused by human activities, while 3) an increasing trend indicates improvement in vegetation conditions due to non-climatic factors such as conservation and restoration efforts (Evans and Geerken, 2004; Wessels et al., 2007). Additionally, we verify whether there is a potential lag between rainfall and our NDVI data by applying a Durbin-Watson test and a trend preserving pre-whitening technique (Razavi and Vogel, 2018; Osunmadewa et al., 2018). For further details see the supplementary file (Fig. S3).

2.4.3. Theil-Sen slope and Mann-Kendall test

In order to derive the magnitude of the persistence of rise and fall in pixels of the yearly NDVI time series, we apply a median Theil-Sen (TS) slope estimator, a robust non-parametric statistical approach that is insensitive to small outliers and missing values (Burrell et al., 2017; Taxak et al., 2014). The TS slope is derived by calculating all pairwise combinations of rainfall corrected yearly NDVI values for the 2003–2018 time series and then deriving the median values (see supplementary file, Fig. S4). Afterwards, a Mann-Kendal (MK) trend test (Ibrahim et al., 2015) was performed to measure the direction of trend (i.e. degradation or improvement). A Kendall τ coefficient, which determines the consistent upward or downward trend, was applied. The test is based on the following equation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1} \operatorname{sign}(x_j - x_k)$$

$$\operatorname{sign}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 \text{if } x_j - x_k = 0 -1 & \\ & \text{if } x_j - x_k < 0 \end{cases}$$

x_j *and* x_k are the sequential data values and n is the length of the dataset. Positive values of S indicate an upward trend and the opposite a downward trend (i.e. -1 indicates a trend consistently decreasing, never increasing, while $+1$ indicates the opposite). A value of 0 indicates no trend or relative stability (Fensholt et al., 2009; Ibrahim et al., 2015). An illustration of the resulting monotonic trends can be found in the supplementary file, Fig. S5. Through a standardized Z scores and the corresponding probability (P) of MK, the significance of the trends of human-induced land degradation were identified at the $p < 0.05$ and $p < 0.01$ confidence intervals, respectively (Burrell et al., 2017). These results were used to derive and summarize the status of the study area and state-specific land degradation in the NGS.

3. Results

3.1. Vegetation status and rainfall effects

Fig. 3a shows the spatially aggregated yearly sum of NDVI for the study area over the complete time series (orange line). This line still contains the influence of rainfall. The NDVI trendline (dotted black line) shows a decline in vegetation greenness ranging from 0.763 to 0.734. Fig. 3b illustrates the standardized yearly anomalies in the NDVI time series. This data also contains the effect of rainfall. Nevertheless, we can still observe a clear decline in greenness (see Supplementary File, Table S2). From 2003 to 2009, a strong positive anomaly can be observed, while from 2010 onwards, with the exception of 2011 and 2012, strong negative anomalies are detected. In 2008, 2011 and 2014, no or little deviations from the trend line were observed. Fig. 3c depicts rainfall corrected yearly NDVI variations after controlling for the effect of rainfall. The NDVI also shows a declining trend in vegetation greenness and lower values in scale (i.e. ranging from 0.340 to 0.305). Aside from clearly visible fluctuations, the highest recorded corrected NDVI values were observed for 2003, while the lowest was observed in 2017. The R^2 of 82.7% suggests the observed decline in vegetation greenness is consistent, with or without correcting for the influence of rainfall. Interestingly, inter-annual variation in mean annual rainfall (Fig. 3d) indicates little variation with a slight but clear increase towards the end of the study period. The trendline increases slightly, but not significantly, suggesting very mild improvement in the NGS rainfall regime during the study period. Thus, the strongly decreasing trend in the annual, rainfall corrected NDVI (Fig. 3c) suggests human activity is the main cause of the observed decline in greenness and biomass loss in the NGS.

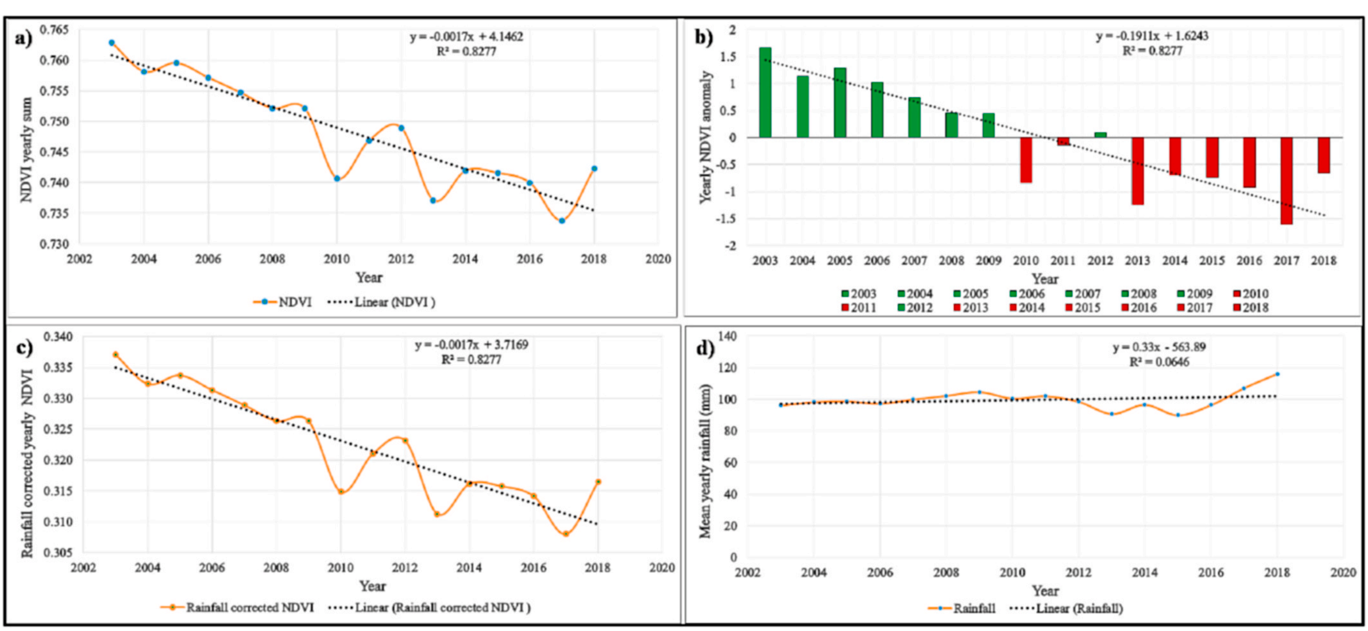

Fig. 3. (a) Spatially-aggregated yearly sums of NDVI (orange) and its linear trend (black) in the NGS for the entire time series including the influence of rainfall; (b) yearly NDVI anomaly (Zy) from 2003 to 2018; (c) spatially-aggregated, rainfall corrected yearly sums of NDVI for the entire time series; (d) inter-annual variations of the mean yearly rainfall (orange) and its linear trend (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Mann-Kendall significance

In Fig. 4, the relative significance of the NDVI trend for the analyzed time series (2003–2018) is geographically illustrated. As thresholds for the two degradation and improvement categories, we use $P < 0.05$ and $P < 0.01$ significance levels. The illustration mirrors the pattern of the TS median slope map (see Supplementary File, Fig. S4). The additional significance categories emphasize the widespread land degradation in the NGS.

The areas ranging from the northwest to the central and northeast of the NGS, encompassing the states of Kebbi, Niger, parts of northern Kwara, FCT (mainly around Abuja, see area illustrated in Fig. 4b), and parts of the states Nasarawa, Plateau, Taraba and Adamawa have been particularly affected. Improvement can be found primarily in the north, i.e. in the states of Zamfara, Katsina, northwest Kaduna (Fig. 4c). Besides the northcentral states of Plateau and Bauchi, the southern states of Oyo, Kogi and Nassarawa also show dispersed patches of improvement. Land degradation is particularly apparent both around and within protected areas, as can be seen in and around the Zugurma sector (e.g. Fig. 4a). Table 1 provides an overview of the relative percent shares and absolute areas for each of the illustrated NDVI trend categories.

Fig. 5 presents a simplified overview of the statistics for the general NDVI trend categories (grouped by land degradation status) for all states in the NGS (for the complementary table, see Supplementary File, Table S4). Note that blue land areas lie outside the NGS and were not part of this analysis. Most of the states for which the majority of the total land cover is within the NGS experienced degradation on 16%–62% of their land. The four states with the largest shares of degraded land in the NGS are Niger (62.9%), FCT (44.7%), Nassarawa (40.1%) and Kwara (36.8%). The four states with the greatest share of improvement are Kogi (18.4%), Kaduna (17.3%), Enugu (16.8%), and Oyo (15.4%). In addition, Kogi (57.4%), Enugu (56.5%), Benue (55.2%), and Kaduna (52.2%), and Oyo (51.3%) are states with comparatively large stable areas.

Table 1
Statistical Overview of the principal NDVI trend categories in the NGS (percent shares and absolute areas).

Mann Kendal significance	Area (%)	Area (Km^2)
Degradation (significant decrease, $p < 0.01$)	0.37	1620.77
Degradation (significant decrease, $p < 0.05$)	37.59	164,661.82
Stable (no significant change)	48.25	211,357.62
Improvement (significant increase, $p < 0.05$)	13.77	60,319.06
Improvement (significant increase, $p < 0.01$)	0.02	87.61
Total	100.00	438,046.88

4. Discussion

4.1. Vegetation dynamics

Both the uncorrected, as well as the rainfall corrected, average annual NDVI time series indicate a continuous, declining NDVI trend across the entire NGS. The yearly NDVI anomaly (Zy) also illustrates a declining trend with positive anomalies in the first half of our time series (2003–2009). As of 2010, they become negative and continue to decline up to 2018. The slightly positive anomaly detected in 2012 may be the

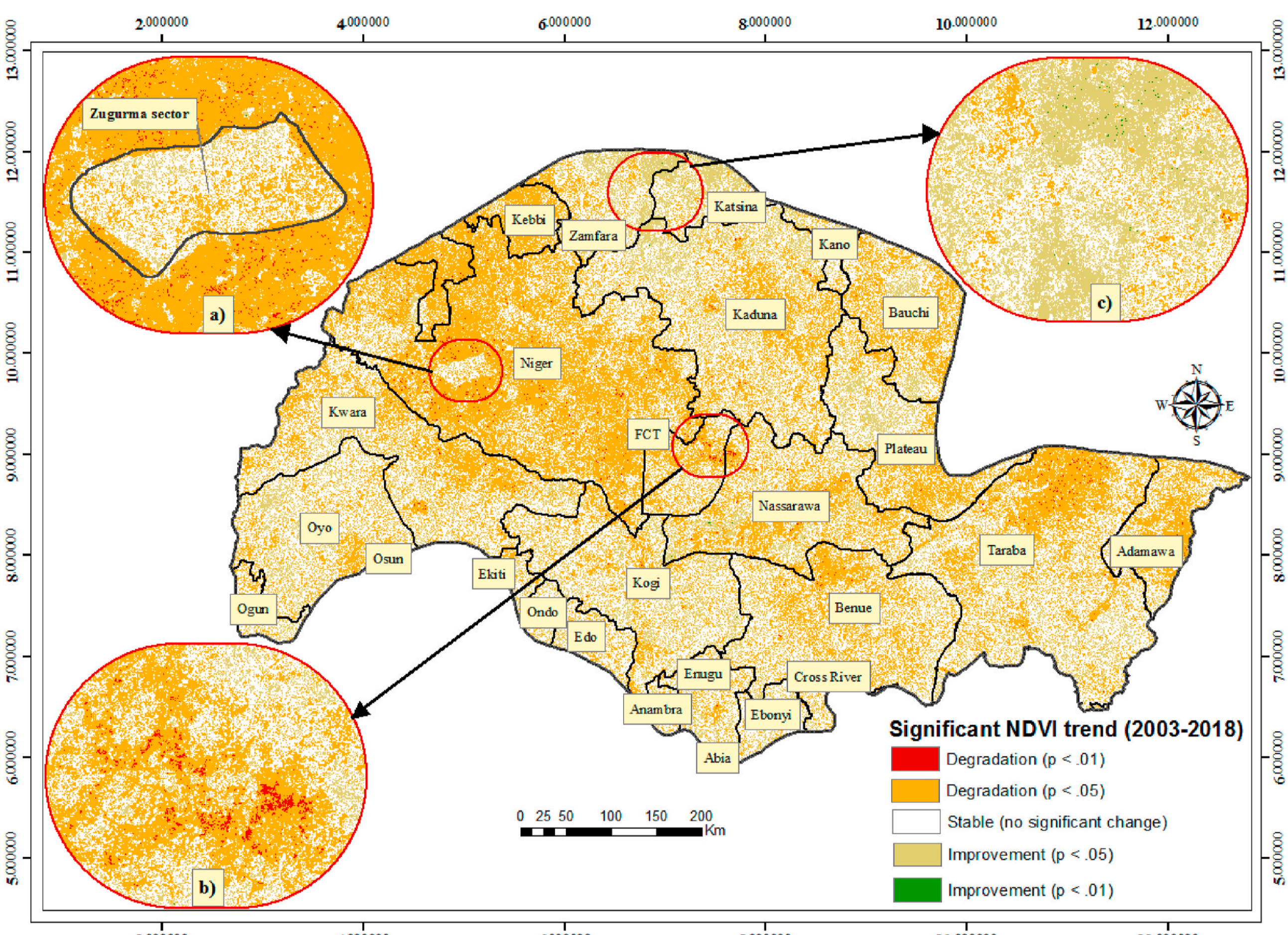

Fig. 4. Significant NDVI trend (2003–2018) indicating changes in vegetation cover induced by human activity. Zoom images of (a) a protected area, (b) a hotspot of significant ($p < 0.01$) degradation, and (c) an area of significant improvement.

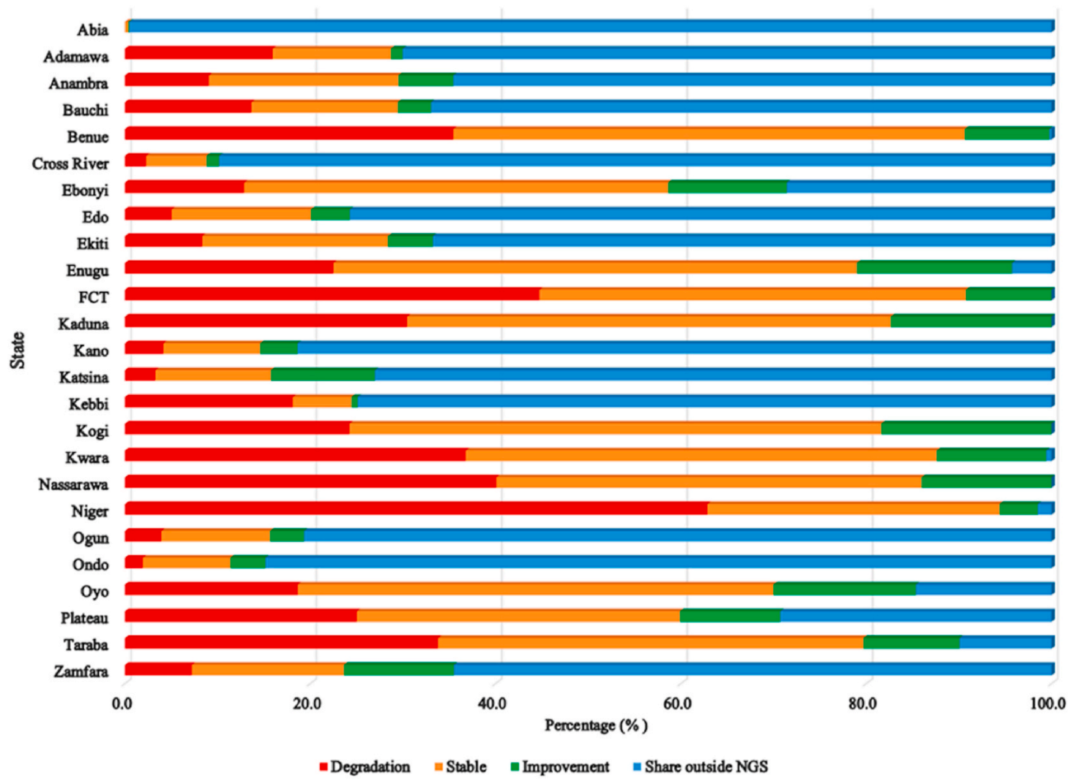

Fig. 5. Percentage shares of land status by states in the NGS. Note: The relative status of land shares outside the NGS (blue) were not analyzed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

result of an extreme rainfall period that occurred in the same year (Nnaji et al., 2016). This might have led to increased vegetation growth in the following growing season. The extreme rainfall led to catastrophic flooding that affected most states in the NGS and other West African countries (Agada and Nirupama, 2015).

Aweda and Adeyewa (2011) performed a similar study but for a different, earlier period (1982–2000). Moreover, they used NDVI data from a different satellite sensor. Thus, it is hard to compare or link their results with ours. The year-to-year NDVI anomaly variation in their study is rather high. Nevertheless, in their study they observed a generally increasing trend in the annual NDVI anomaly for the NGS, starting with negative anomalies in 1982 and 1983, becoming positive up to 1999, and abruptly turning negative again in 2000. NDVI data for the years 2001 and 2002 are not readily available.

While the cause of the declining NDVI trends and anomalies in previous studies was attributed to the effect of droughts that occurred in West Africa in the 1980s (Epule et al., 2014; Gautier et al., 2016), the decline observed in our study can be attributed almost entirely to human activity (Osunmadewa et al., 2018). This confirms previous global forest loss assessments in which Nigeria was considered one of the countries experiencing the highest forest loss rates globally since 2000 (FAO, 2010). These findings underline the relative importance of savannah restoration, as there is obvious evidence of biomass loss (Vogt et al., 2011; Macaulay, 2014; CILSS, 2016), even after excluding the impact of change in rainfall.

4.2. Rainfall effects and offset from the degradation of Savannah

We found that the inter-annual trend in mean yearly rainfall was relatively uniform, with slightly increasing rainfall amounts in recent years (Fig. 3d). The increase towards the end of the study period supports the observations of the varying increase in rainfall amounts over parts of the NGS and Nigeria as a whole (Odjugo, 2010; Areola and Fasona, 2018), and further suggests that the long period of low rainfall in the 1970s and 1980s over West Africa is not currently affecting the NGS (Gautier et al., 2016). The results further suggest that the NGS is not under the period of declining rainfall, and that any increase in land degradation generally cannot be explained by change in rainfall (Nicholson et al., 2018). Also, the general pattern of the long-term mean monthly NDVI anomaly (Fig. S3), remains consistent – the bimodal nature of vegetation greenness and photosynthetic activity with respect to rainfall is maintained (Osunmadewa et al., 2018). Thus, the overall positive response of savannah vegetation to rainfall has not changed (Areola and Fasona, 2018; Nnaji et al., 2016).

Surprisingly, there is little difference in the variation of the correlation coefficients inside and outside national and state protected areas (see Supplementary File, Fig. S3). Vegetation loss due to extensive human activity has occurred both outside and inside protected areas (Naibbi et al., 2014; Fasona et al., 2016). As observed also in a study by Aweda and Adeyewa (2011), the range of the correlation coefficients suggests vegetation greenness in the NGS is sensitive to rainfall. Besides rainfall, which is the principal limiting factor for vegetation greenness, other variables also affect the NDVI anomaly and/or degradation, i.e. temperature (Igbawua et al., 2016) and soil moisture (Ibrahim et al., 2015). The RESTREND technique (Fig. 3c) results in a rainfall corrected NDVI which estimates the human component of land degradation. The declining trend in the rainfall corrected NDVI (Fig. 3c) suggests that large-scale land degradation in the NGS is due to unsustainable human activities and not to rainfall dynamics (Kundu et al., 2017).

4.3. Human-induced land degradation

The TS slope identifies surfaces with a persistent rise or fall in the annual, rainfall corrected NDVI (see Supplementary File, Fig. S4), thus highlighting the large differences between areas experiencing rapid loss in savannah vegetation compared to their surroundings. Negative slopes implying high vegetation loss (i.e. leading to rapid land degradation) relative to their surroundings are pervasive across the middle of the

NGS, from its north-western to its eastern border. These areas have negative trend values twice as high as neighbouring pixels and have experienced twice as much degradation as surrounding areas with positive slopes indicating a relatively stable or improving status of land quality. In the NGS, approximately 1621 km^2 i. e. 0.37% ($P < 0.01$) and 164,662 km^2 i. e. 37.59% ($P < 0.05$) experienced significant degradation, while about 88 km^2 i. e. 0.02% ($P < 0.01$) and 60,319 km^2 i. e. 13.77% ($P < 0.05$) respectively, experienced improvement in land quality. For about 211,358 km^2 (48% of the NGS), no significant change was observed (Table 1). Therefore, 38% of the total area is degraded and 14% has improved at the $P < 0.05$ significance level. The shares of severe change ($P < 0.01$) are comparatively small.

The supplementary file, Fig. S4, and the result in Fig. 4., show areas in the NGS suffering from degradation due to high human pressure on the savannah, which invariably reduces the savannahs' potential to provide ecosystem services because of the poor management of savannah vegetation (Macaulay, 2014; Zhang et al., 2016). Such human pressures usually have immediate or direct impacts that can trigger noticeable degradation in that they place huge demands on the savannah and its resources (Osborne et al., 2018). Among such pressures are agricultural expansion, urbanization, and wood fuel extraction, including deforestation and overgrazing, documented accelerators of land degradation in Nigeria (CILSS, 2016; Igbawua et al., 2016). According to our result, the pervasive degradation in the NGS is mainly caused by unsustainable agricultural activities (CILSS, 2016), fuelled by huge food and land demand from the continuously increasing population. These pressures drive the loss of biomass and ecosystem services, leading to impoverishment (Macaulay, 2014; Igbawua et al., 2016). Our results thus provide additional, direct evidence of ongoing and extensive land degradation in Niger state, Nigeria with little to no improvement in land quality in other parts of the state. This indicates the urgent need to address human-induced land degradation across the NGS, especially in states such as Niger state, which is currently experiencing degradation on more than half its territory.

Degradation caused by human activity is also particularly severe in and around protected areas (see Fig. 4a and Supplementary File, Figs. S4 and S5). This is particularly concerning because people are technically not permitted to enter protected areas. However, these protection rules are apparently inadequately enforced (Abdulaziz et al., 2015). The Zugurma sector of the Kainji Lake National Park, for example, is clearly affected by land degradation (Figs. 4a and 6a), suggesting encroachment pressures and threats to protected areas from local resource users (Ducrotoy et al., 2018; Nchor and Ogogo, 2012). Enforcing protected area status is thus required to tackle these negative human impacts. Thus, there is a need for field level studies to identify in detail which land use practices and human activities drive land degradation (Kundu et al., 2017), particularly along agro-ecological context of Nigeria (Ifejika Speranza et al., 2019).

The noticeable improvements in some of the states, mostly those bordering the Sudan Savannah, can be traced to land management programmes such as afforestation and reforestation with local species, including the adoption of drought tolerant shrub species, which have been promoted both across Nigeria (Wingate et al., 2019) and by the governments of these states. Despite the negative trend in parts of the Zurgurma Sector noted above, there are still stable areas in most protected areas. The NGS is thus very relevant for the federal government's nature conservation initiative, as the largest and oldest national parks are found in this zone ((Abdulaziz et al., 2015; Usman and Adefalu, 2010).

Although, several data sources exist that can help answer questions about national or state-level land degradation, the MODIS data from Famine Early Warning System (FEWS) has proven useful for characterizing land degradation, especially when coupled with other relevant datasets (Funk et al., 2019). The 250 × 250m spatial resolution used in our analysis makes a case for a critical assessment of land degradation using TAMSAT and MODIS data, as the coarse nature of both might raise concern especially for local level assessment. Thus, theoretically, employing finer resolution satellite data such as Landsat or Sentinel-2 data may lead to a better identification of land degradation and improvements in some areas. However, one has to keep in mind that Sentinel-2 data of Nigeria is only available from 2015 on, and frequent cloud cover, particularly during the rainy seasons, may lead to substantial data gaps in a long-term time series. In addition, we hold that assessing land degradation with the NDVI greenness trend does not adequately distinguish between different vegetation types and plant species (Dardel et al., 2014), which leaves the current analysis open to future refinements. Moreover, our study period does not adequately reflect much of historical events such as the drought of the 1970s and 1980s but rather the period after severe drought has receded (Nicholson et al., 2018). Thus, our results can be improved through ground truthing, additional land use/land cover information, or even by including novel multivariate statistical indices (see e.g. Coluzzi et al., 2019). Such refinements, however, for financial and logistical reasons, remain beyond the scope of the current study.

5. Conclusions

Our study provides evidence of ongoing land degradation in Nigerian Guinea Savannah by assessing degradation and improvement trends based on satellite imagery captured between 2003 and 2018. We have disentangled human and rainfall-induced effects on NDVI, the proxy we have employed to analyze changes in the photosynthetic activity of savannah vegetation.

We find that the annual mean NDVI and annual NDVI anomalies observed in the NGS between 2003 and 2018 show a clear declining trend. Overall, a total of 38% of the NGS land area has experienced degradation, while 14% has experienced improvement and the remaining 48% appears to be stable. In addition, we have determined that land degradation is occurring both outside and inside protected areas. Human activity appears to be the driving force threatening vegetation conditions in and around these protected areas. More generally, after correcting for the potential influence of rainfall

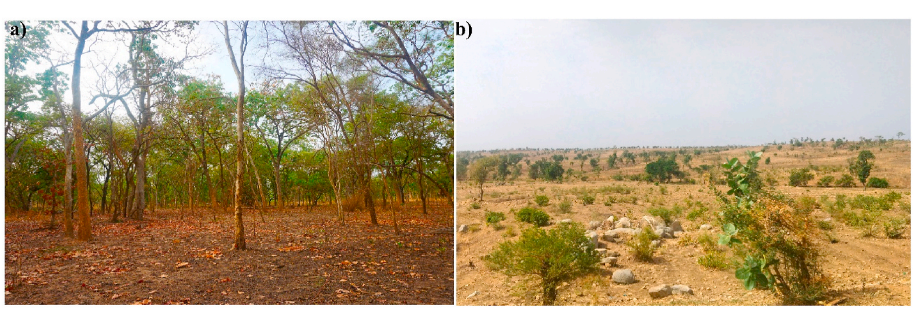

Fig. 6. (a) A degraded, thinned patch (front) of typical savannah vegetation (background) in Zugurma sector; (b) a mix of degraded land with few bushes and trees interspersed in Borgu, Niger state. (Source: Own field work, 2019).

variability, we find that unsustainable human activities are presumably the main force behind large-scale degradation in the NGS.

This study further reveals the need for future investigation into the local mix of unsustainable human activities and related drivers of savannah land degradation. Understanding the extent, severity, and hotspots of land degradation in the zone ultimately requires improved knowledge of the spatial mix of land degradation drivers. More importantly, these local mixes can further guide response actions for improving land quality in the NGS, particularly in the protected areas where the need to maintain the status of natural vegetation is threatened by increasing human impacts. This knowledge is particularly important for protecting natural vegetation and addressing ongoing land degradation in protected zones. Finally, our results suggest that MODIS NDVI is suitable for evaluating land degradation in a heavily-degraded dryland ecosystem.

CRediT authorship contribution statement

Ademola A. Adenle: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Sandra Eckert:** Supervision, Data curation, Writing - review & editing, Validation. **Oluwatola I. Adedeji:** Formal analysis, Software. **David Ellison:** Conceptualization, Writing - review & editing. **Chinwe Ifejika Speranza:** Conceptualization, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2020.100360.

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