VEGETATION AND LAND COVER CHANGE IN THE CONTEXT OF LAND DEGRADATION IN SUB-SAHARAN WEST AFRICA

Thesis submitted for the degree of

Doctor of Philosophy

at the University of Leicester

by

Yahaya Zayyana Ibrahim (MSc)

Department of Geography

University of Leicester

2017

Abstract

Vegetation and Land Cover Change in the Context of Land Degradation in sub-Saharan West Africa

Yahaya Zayyana Ibrahim (MSc)

Land degradation has been a serious environmental problem in dryland areas where moisture supply is limited. This thesis aims to assess vegetation and land cover change in the context of land degradation in the sub-Saharan West Africa, a hotspot of environmental change. The study combines various approaches which include statistical trend analysis of satellite derived Normalized Difference Vegetation Index (NDVI) residuals, indigenous knowledge of vegetation changes, and land use land cover change analysis to determine the spatial and temporal changes in vegetation and land cover in the context of land degradation over a 30-year period. Results have shown that, in spite of the ongoing scientific debate around the greening trend observed by satellite data in the past three decades, evidence of land degradation is very pronounced in the region, particularly when a soil moisture index is used in the residual trend analysis to correct for vegetation productivity instead of instantaneous rainfall. They also indicate a declining rate of diversity and density of indigenous wood vegetation species at the study sampling sites ($p < 0.05$), with nearly 80% of all the identified species found to have become either completely extinct or migrated to a region with sufficient moisture conditions. A continued decrease of closed forest and an increase in croplands were found, with agricultural land use being the major driving force of land cover change, and across the region nearly all the areas found under severe land degradation are croplands. This thesis has shown the importance and relevance of an interdisciplinary approach for land degradation studies. Future studies should go beyond the analysis of NDVI trends based on rainfall as the major driver of vegetation change. Instead, an integrated method should be used which will combine soil moisture, indigenous knowledge of vegetation and land cover and land use conditions as it would provide much more comprehensive data that can be used to support the vulnerable communities in sub-Saharan West Africa whose livelihoods rely on ecological resources.

Dedication

To my beloved late father, Alhaji Zayyana Ibrahim, who did not live long enough to witness his proud son's landmark achievement.

Acknowledgements

I am grateful to almighty God for making it possible to make this dream a reality. All praises be to Him, the creator of the universe and the Lord of majesty and bounty.

I would like to express my sincere appreciation to my supervisors Professor Heiko Balzter and Dr Jorg Kaduk who patiently provided the vision, encouragement and immense effort in making this study a reality. The time spent in carrying out this study has been very trying and challenging for my family and I. I therefore wish to thank my beloved wife Hafsat A. Yahaya for her patience, courage and endurance during this trying time. To my children (Khadija, Zayyan and Ummu-Salma), my absence at home has been challenging for you, I would like to thank you for your understanding, patience and endurance during the time I have been away. Equally, I would like to acknowledged the efforts of my thesis examiners in person of Juan Carlos Berrio and Robert Bryant, for a good observations and amendments that greatly improved the overall quality of the work.

To the data providers, I am grateful to C. Tucker, for providing NDVI3g data; Climate Research Unit (CRU)-East Anglia, National Oceanic Administration Agency (NOAA)-National Weather Service and Europena Space Agency-Climate Change Initiative (ESA-CCI) project for providing free access to the rainfall, soil moistute and land cover data respectively used in this study. Finally, the United State Geological Survey (USGS) for the use of GTOPO30 digital elevetion model data and DIVA-GIS for providing all the shapefiles used in this study.

I acknowledge the support and funding provided by the Umaru Musa Yar'adua University, Katsina (UMYUK) through their academic staff training and development programme, without which this research could have been impossible.

I appreciate the assistance of Dr. Martin Brandt, for guiding me through some of the challenging R scripts.

I wish to thank my field assistants: Nura M. Maiwada, Dr Lawal Abdularshid, Malam Gambo and Malam Maiwada, for their kind support throughout my field studies.

I appreciate the support of my friends and research colleagues at the centre for landscape and climate research (CLCR) and Geography department in general such as Usman Isyaku, Dr. Umar BB, Dr. Idris Jega, Dr. Murtala Chindo, Bashir Adamu, Sa'ad Ibrahim, Ajoke Onojeghuo, and many others I have not mentioned here. Words cannot be enough to express how grateful I am for all your kind support.

Table of Contents

List of figures

List of tables

List of acronyms and abbreviations

AVHRR	Advance Very High Resolution Radiometer
BS	Bare Surface
CAMS	Climate Anomaly Monitoring System
CCI	Climate Change Initiative
CF	Closed Forest
CL	Cropland
CPC	Climate Prediction Center
CRU	Climate Research Unit
DGVM	Dynamic Global Vegetation Model
EO	Earth Observation
ESA	European Space Agency
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organisation
FR	Full Resolution
GARI	Green Atmospherically Resistant Vegetation Index
GDOS	Global Dryland Observing System
GHCN	Global Historical Climatology Network
GHGs	Greenhouse Gases
GIMMS	Global Inventory Modelling and Mapping Studies
GLADA	Global Land Degradation Assessment
GL	Grassland
GLC	Global Land Cover
GRACE	Gravity Recovery and Climate Experiment
HANPP	Human Appropriation Net Primary Productivity
IK	Indigenous Knowledge
ITCZ	Inter-Tropical Convergence Zone
LPJ	Lund Postdam Jena
LULC	Land Use Land Cover
MA	Millennium Assessment
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectrometer

MVC	Maximum Value Composite
NDVI3g	Normalized Difference Vegetation Index 3rd generation
NIR	Near Infrared
NOAA	National Oceanic Atmospheric Administration
NPP	Net Primary Productivity
OLS	Ordinary Least Square
PAL	Pathfinder AVHRR Land
PAR	Photosynthetically Active Radiation
PMR	Precipitation Marginal Response
RCP	Representative Concentration Pathways
RESTREND	Residual Trend
RF	Radiative Forcing
RR	Reduced Resolution
RUE	Rain Use Efficiency
SDG	Sustainable Development Goal
SL	Shrubland
SPOT	Satellite Pour l'Observation de la Terra
SR	Simple Ratio
SST	Sea Surface Temperature
SV	Sparse Vegetation
TS	Time Series
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
UN-LCCS	United Nations Land Cover Classification System
VGT	Vegetation
WDRVI	Wide Dynamic Range Vegetation Index
WGS	World Geodetic System

Chapter 1：Introduction and thesis overview

1.1 Background, rationale and research questions

Land degradation is an obstacle to sustainable development due to its impact on the environment, food security, agroecosystem service provision and people's livelihoods (UNCCD, 2015). It is a combined local, regional and global problem that affects not only vulnerable dryland areas but all areas worldwide with varying degree of impacts. Land degradation, which is sometimes used synonymously with desertification in the dryland areas, is term that has long been associated with the reduction of ecosystem productivity in the dryland areas. These areas comprise 41% of the global land surface and cover 44% of the world's potential agricultural lands and are home to about one-third of the world's population, about 2 billion people (Raynolds, 2002, Mellenium Ecosystem Assessment, 2005, Verón et al., 2006). Special attention to land degradation in the dryland areas was first highlighted and reported by a French forester, Aubreville in 1949, when he was working in West Africa to describe the extent of vegetation clearance he found in the region, and the term captured international attention following the Sahelian drought of the 1970s. Globally, the concept of land degradation, its alleged causes, links among the causes as well as the potential impacts on the ecosystem and livelihoods of the affected communities remains unresolved among environmental scientists (Herrmann and Hutchinson, 2006).

Over the years, land degradation has received widespread debates at global level as documented in the literature (Middleton and Thomas, 1997). However, despite these debates, at least two major school of thoughts have emerged with respect to the process, severity and impacts of land degradation. The first school believes that land degradation is a serious global environmental threat posturing an adverse challenge to humans in terms of its negative impacts on biomass productivity and environmental quality (Dregne and Chou, 1992). This school of thought is mostly supported by ecologists, soil scientists and agronomists. The second school primarily believes that land degradation is not a severe issue as previously reported. According to this group, which comprise primarily economists believes if land degradation is a serious environmental challenge, why market forces have not taken care of it. Proponents argued that land managers such as farmers, have consigned interest in their lands and will not let it totally degraded to the level that will lead to negative return to their investments (Crosson et al., 1997).

Despite these disagreements, it is generally believed that a form of environmental degradation specific to dryland areas is taking place across global dryland areas with severe negative impacts mostly in vulnerable regions such as sub-Saharan Africa (Reynolds et al., 2007). According to the Millennium Assessment (MA) report, 2005, it has been estimated that between 10% and 20% of the global drylands or 10 to 20 million km^2 are affected by land degradation. In Africa, for instance, about 500 million ha of drylands are affected, which includes two-third of the continent's productive agricultural lands (Mellenium Ecosystem Assessment, 2005). Further estimates by the German Technical Development Cooperation (GTZ) show that between five and six million ha of land is permanently lost to agricultural practices annually through human-induced land degradation (German Technical and Development Cooperation GTZ, 2005). Furthermore, the extent of human-induced land degradation globally was reported by UNEP to include overgrazing (680 million ha); deforestation (580 million ha); agricultural mismanagement (550 million ha); fuelwood over consumption (137 million ha) and industries and urbanisation (19.5 million ha) respectively (Johnson et al., 2006). This clearly shows the extent of human influence as the main driver of the land degradation process.

Due to the persistent threat posed by land degradation globally, scientists are studying the nature and the consequences of the problem at different spatial and temporal scales. However, attention in the past was concentrated on studying the impact and likely socio-economic implications of the affected communities. In the early stages of land degradation research, literature on the subject was characterised as being too general, confusing and often contradictory due to the lack of data to support most of the arguments and the uncertainties surrounding the concept (some of these still persists) (Thomas and Middleton, 1994, Verón et al., 2006, Grainger, 2009). However, with the development of satellite technology into environmental studies, the approaches shifted to monitoring the extent as well as the major indicators of land degradation at different areas identified as hotspots. Scientists recognised the need for a multi-facet approach to study the problem by integrating heterogeneous and dynamic local biophysical parameters in assessing land degradation (Reed et al., 2013).

Global assessment of land degradation is not an easy process and it involves a wide sets of approaches. Today, researchers have developed and applied different methods of land degradation assessment ranging from field observation and measurements, satellite remote sensing, modelling, the use of spatial indicators and indigenous knowledge method and expert judgement among others (WMO, 2005). From there, a number of international, national and regional programmes were developed with the sole aim to monitor the degree and the extent of land degradation. Some of the programmes were designed particularly to identify and map out the extent of land degradation using spatial and temporal ecosystem conditions, so as to take appropriate measures to combat the problem. Notable programmes designed to identify and map out the extent and predict the future of desertification and land degradation include DIS4ME (Desertification indicator system for Mediterranean Europe), INDEX6 (Indicators and thresholds for desertification, soil quality and remediation), MEDALUS (Mediterranean desertification and land use), CAMELEO (Changes in arid Mediterranean ecosystem on the long-term and earth observation), ASMODE (Assessment of remote sensing techniques for monitoring the extent and progression of desertification in the Mediterranean area), DESURVEY (A surveillance system for assessing and monitoring of desertification), DESIRE (Desertification mitigation and remediation of land, a global approach for local solution) and LADA (Land degradation assessment in drylands) among others (Baartman et al., 2007).

In spite of these international and regional efforts on land degradation assessment, many of the programmes were criticised as being too general and concentrated heavily on Mediterranean Europe, where the poverty rate is very low compared to other dryland areas such as sub-Saharan West Africa. The programmes are mostly limited to identifying the quality of a particular indicator without necessarily assessing the links among the indicators, since one element alone cannot determine the extent of land degradation, but rather the condition of that particular element which can be affected by the conditions of other indicators (De Jong, 2011). For instance, to assess vegetation degradation, you need to examine the links among the functional ecosystem variables such as soil moisture, climate (in particular rainfall) and its relationship to vegetation productivity (Prince, 2002). However, with the advancement of remote sensing into environmental monitoring, scientists agreed that there are some physical environmental conditions that are manifestations of ecosystem improvement or degradation which can be observed by the remote sensing. These include the reduction or loss of biological productivity, the loss of vegetation cover, soil erosion, land cover change, a reduction in soil moisture and change in energy and water fluxes (Prince, 2002).

Despite this view by Prince, it is widely agreed that the most prominent physical manifestation of land degradation in the dryland regions are the reduction in total and biomass carbon, decrease in land productivity and change in vegetation cover (WMO, 2005). This is because the pattern and dimension of vegetation changes can be observed easily regardless of the causative agent of the changes. As a result, scientists uphold the idea of vegetation change to be the major physical manifestations of land degradation in the dryland regions and it is presently one of the leading indicators used for land degradation assessment (Verón et al., 2006, Reynolds et al., 2007). Therefore, land degradation and vegetation change are concurrent processes commonly linked to dryland areas. Nevertheless, the lack of uniform standard methodology remains the major bottleneck of the assessment and monitoring (Higginbottom and Symeonakis, 2014).

In sub-Saharan West Africa, recent studies based on the Normalized Difference Vegetation Index (NDVI) data trend indicates an increase in greening since the 1980s (Anyamba and Tucker, 2005, Fensholt et al., 2012). However, the study by Herrmann and Sop (2016) reported a decline and disappearance of woody vegetation species right before the major drought which occurred in the region, and along the same line, Herrmann and Tappan (2013) found a decrease in woody species and an increase in shrub densities between 1983 and 2010; an indication of the ecosystem adapting to the drier conditions with more tolerant xeric species. This implies NDVI signals alone cannot be relied on to infer on land degradation, and more than an analysis of the satellite greening pattern is required to carefully understand the composition of the greening index as well as its relationship with other spatial indicators such as species changes and land cover alteration among others. Even the greening trend in dryland areas was argued to have resulted from the enhanced level of CO_2 in the atmosphere, not necessarily due to improvement in ecosystem productivity (Lu et al., 2016).

Therefore, to assess the extent of land degradation in sub-Saharan West Africa in relation to the greening trend requires an understanding of the complex interaction between the processes of ecosystem functioning requiring the normal aggregation of multiple environmental parameters and the assessment of their states and relationships over time and space. Here indicators of ecosystem functioning related to vegetation, soil moisture, climate and long-term species changes are studied to ascertain their states, relationships and pattern of changes and inferred on the extent of ecosystem changes due land degradation in sub-Saharan West Africa using carefully designed multifaceted methodologies.

This study was designed and undertaken to further understand the complexity of land degradation and to develop an integrated assessment method in order to understand the extent of vegetation change in the context of the greening arguments. A multi-method approach is applied so that appropriate mitigation measures can be adopted to address land degradation in sub-Saharan West Africa. Therefore, in line with global threat forced by land degradation and the subsequent problems arising due to unreliability on NDVI and other satellite based assessment methods in monitoring and assessing land degradation, this research was conceived to examine the situation in sub-Saharan West Africa, so as to ascertain the extent of land degradation in the area. This constituted the research gap that this study addressed and has been achieved by applying and testing the suitability of the residual trend analysis method (RESTREND) and ascertained the spatial and temporal change of ecosystem productivity as related to land degradation. This has been achieved using new NOAA-AVHRR 8km NDVI3g data, rainfall data from Climate Research Unit (CRU) University of East Anglia and NOAA Climate Prediction Centre (CPC) soil moisture product. The RESTREND results were further supplemented by field observation and indigenous knowledge studies. These studies ascertained the extent of woody vegetation change along the Nigeria-Niger border region as well as the changes in land cover condition in the area.

1.2 Aims and Objectives

This research is conceived to achieve specific aims and associated objectives. As pointed out earlier, the overall target is to examine changes that took place on vegetation and land cover in the context of land degradation in sub-Saharan West Africa. This broader target was broken down into the following aims and objectives;

i. To examine the suitability and effectiveness of RESTREND method in land degradation assessment in the study area. This aim is specifically designed to test the applicability and suitability of RESTREND method in land degradation assessment. And equally to look at the possibility of improving the method by introducing soil moisture rather than historical application of rainfall data to run the model. Thus, this aim was achieved through the following objectives in *chapter 4* of the thesis;

a. To compute the RESTREND model based on NDVI-soil moisture.
b. To compute the RESTREND model based on NDVI-rainfall.
c. To compare the effectiveness of the two models in land degradation trend detection.
d. To evaluate the spatial and temporal pattern of land degradation in the study area.

ii. The second aim is to find out vegetation species changes due to land degradation in the drier Nigeria-Niger boarder region. This aim is generally designed for the need to address the discrepancies between satellite observed greening trend and changes of woody vegetation, which require the integration of multiple perspectives and scales. This is because many studies have documented that woody vegetation shifted from diverse species components towards fewer and more drought tolerant species in many sites across dryland regions. This aim has equally been achieved through the following specific objectives which are addressed in *chapter 5;*

a. To determine the changes taking place on woody species in the area.
b. To assess the driving forces behind the changes.
c. To test whether there is evidence of continuous land degradation or vegetation recovery in the area.

iii. The third aim is to find out land cover types that are mostly affected by land degradation when RESTREND method is employed in the area. This has been achieved through the following specific objectives in chapter 6;

a. To examine the trend of land cover change in the study area from 2000 to 2010.
b. To find out the land cover types mostly affected by land degradation in the degraded areas.

c. To evaluate the land cover trajectory in the degraded areas.

1.3 Thesis structure

The thesis comprises eight chapters arranged in three sections (Figure 1.1). It begins with Chapter 1 through 3, which together presents the general background and rationale of the study; literature review (Chapter 2) and the study area (Chapter 3). The literature review critically examines concepts and processes of land degradation, the environmental conditions in sub-Saharan West Africa in relation to land degradation, biophysical manifestations, and the application of NDVI in land degradation research as well as the common methods of land degradation assessments. Chapter 3 describes the geography of the study area especially the key environmental features such as climate, vegetation, population and land use.

Chapters 4 through 6, presents the analyses carried out in line with the research questions stated previously. Specifically, Chapter 4 presents the results of the RESTREND analyses and highlighted the spatial and temporal trends of NDVI residuals in the study area. Chapter 5 presents the results of the field work conducted along the Nigeria-Niger border region, and describes the changes taking place on woody vegetation species in the area. Finally, Chapter 6 examines land cover change and its trajectories in the sampling sites as well as the links between land cover types and areas under severe land degradation based on the five-year analysis of RESTREND carried out to match the land cover epoch.

Chapter 7 presents general discussions of the results presented in the previous chapters, linking all the key findings together and comparing them with previous studies. Finally, Chapter 8 provides a synopsis of the overall thesis highlighting the major conclusions, major achievements and contributions, the limitations of the study and finally identifies areas for further studies based on the findings of this thesis.

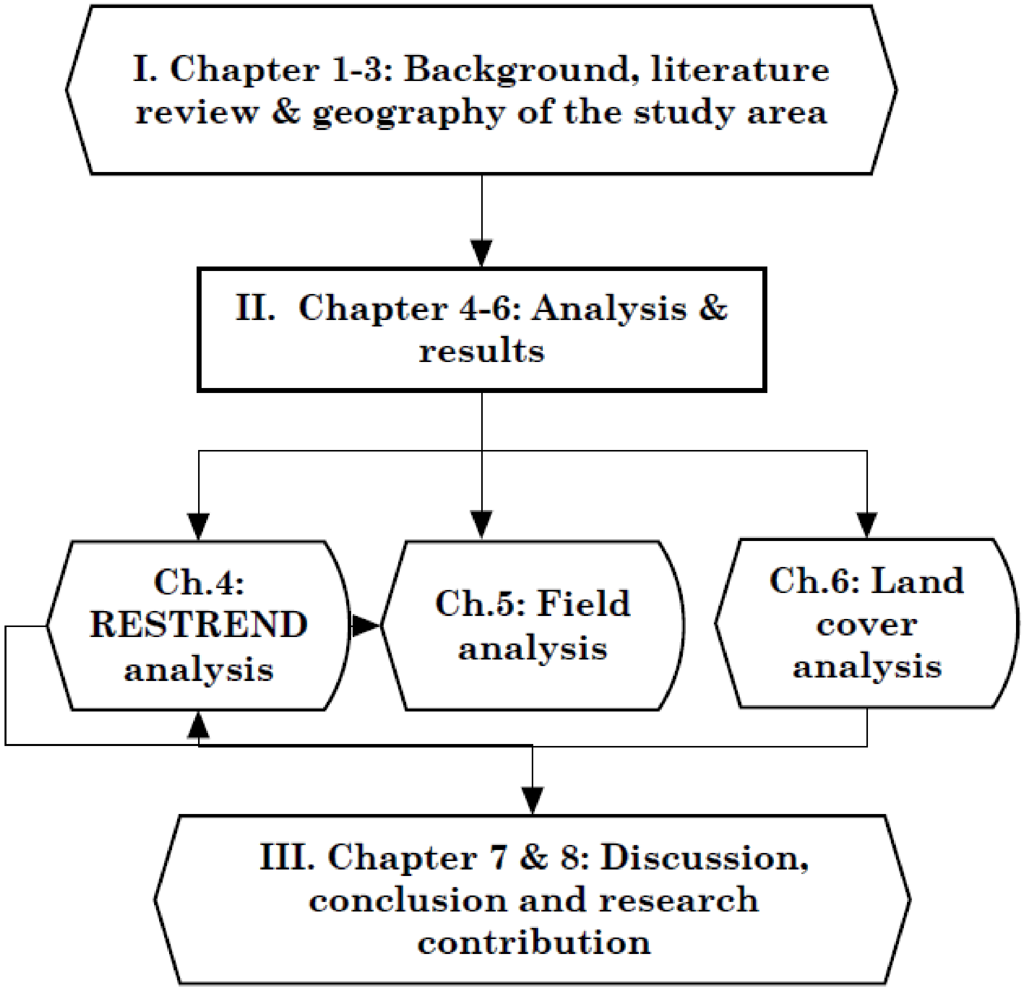


Figure 1.1. Structure and components of the thesis

2 Chapter 2: Literature review and concepts

This chapter begins by highlighting the concept and processes of desertification and land degradation. Although land degradation and desertification had been studied extensively over past decades, it still remains the subject of debates and controversy among environmental researchers. Here therefore first concepts and processes of desertification and land degradation are examined. The chapter also highlights the biophysical features and manifestations of land degradation. It also examines the development and role of satellite technology in land degradation assessment as well as human activities exacerbating the process in sub-Saharan West Africa. Finally, the general methodology used in this thesis and the strength and limitation of the data used are outlined.

2.1 Concepts and processes of desertification and land degradation

Desertification and land degradation has caused much argument among the general scientific communities and still continuing to do so to the day. The term was first introduced by French forester, Aubreville in 1949, when he was working in West Africa to describe the extent of vegetation clearance which he found in the region. It received international attention following the Sahelian drought of 1968-1973 (Hellden, 1991, Geist and Lambin, 2004). Later it became clear that desertification is not only confined to Africa, but is occurring across all the major global drylands (Middleton and Thomas, 1997). The term became a hot topic of discussion among the scientists and researchers at local, regional, national and international levels, and a number of studies were carried out on the topic (Hellden, 1991, Grainger et al., 2000, Raynolds, 2002, Prince et al., 2007). Some of the studies demonstrated not only the socio-ecological relevance of studying desertification (Nkoya et al., 2011), but the urgent need to intensify further research efforts because there are still major areas of uncertainty yet to be addressed (Burns, 1994, Verón et al., 2006). From the early time of discovery to the present, the concept of desertification lacks a specific and generally acceptable definition among researchers owing to the uncertainties surrounding the concept, making it difficult to accurately assess and measure its spatial extent (Verstraete, 1986, Raynolds, 2002).

The first attempt to define desertification dates back to the year of its discovery in 1949 by Aubreville - a French forester in his famous book which was written in French titled "Climats, Forest, et Desertification del' Afrique Tropicale", where he described desertification "*as a reduction of forest land in humid and sub-humid tropical zones into desert or semi desert type of vegetation as a result of a human activities, thereby making soil susceptible to erosion"* (Aubréville, 1949, Glantz and Orlovsky, 1983). Following this, a number of closely related definitions evolved in the literature; notable among them is the definition by UNEP 1984, which defined the concept as *"land degradation in the dryland regions as a result of human activities"* (Rasmussen et al., 2001). This concept clearly linked desertification solely to human activities, and neglected the natural environmental phenomena such as drought and climate change which might represent additional agents of desertification in the dryland regions.

The second attempt to describe desertification, which equally gained prominence in the literature, evolved around the definition by Dregne (1977), in which he defined desertification "*as depletion of ecological services in arid, semi-arid and dry sub humid areas as a result of careless human activity and drought"*. This view conceptualised desertification as an interaction between human activity and drought leading to ecological imbalance, and it emphasised that desertification is taking place not only in areas where there is a permanent loss of productivity but also in areas where the negative impacts will be minimal such as humid and sub-humid areas. Here the category of impacts were considered high or low depending on the nature and the type of environment, with high negative impacts mostly attributed to arid regions (Dregne, 1977).

The current definition of desertification, which is generally accepted in scientific literature, emanated from the United Nations Convention to Combat Desertification (UNCCD), a United Nations agency responsible for land degradation and desertification management. The UNCCD, together with its sister agencies, were formed in 1992 following the Rio Earth summit, also known as United Nations Conference on Environment and Development (UNCED). In in 1994, UNCCD defined desertification as "*land degradation in arid, semi-arid and dry sub humid areas resulting from various factors including climatic variations and human activities"* (UNCCD, 1994 art.1 [a]). In this definition, desertification is not only linked to human activities and drought, but also to all other forms of climatic variability that can accelerate the process in the dryland regions. It clearly shows how the concept has been understood differently by environmental researchers and the major difficulties in reaching an agreement on the causative agents of desertification in the dryland areas (Drake and Vafeidis, 2004, Wilson and Juntti, 2005).

Several issues emanated from the UNCCD concept of desertification. One of major significance is the introduction of "land degradation" into the definition, which makes it vague and less meaningful without properly elucidating what land degradation stands for in the context of the definition. For instance, the definition could have attempted to describe how desertification reveals itself for the purpose of evaluation, monitoring and control for prompt identification of the affected areas so as to design appropriate management options. Secondly, the concept failed to clearly specify the most common environmental manifestations of desertification leading to the widely different views among the scientists. Thirdly, the lack of clear benchmark data to compare the present condition with its past has led to varied conclusions depending on the methodology used in the assessment (Verón et al., 2006).

Following the issues raised from the UNCCD definition, the United Nations Environmental Programme (UNEP), went further to define "*land degradation as the decrease or loss of the productive capacity of land, arising from human activities or combination of processes including unsustainable agriculture, poor water and soil management, habitation or natural processes* *such as drought, floods and landslides among others".* Land degradation occurs in any environment. However when it occurs in the dryland areas, it is called 'desertification' (Geist and Lambin, 2004). In other words, land degradation and desertification are the same process, but the latter occurs in the dryland area. Therefore, in the context of this thesis, ***desertification*** and ***land degradation*** are used interchangeably to mean the same process in the study area although some scientists argued desertification is the extreme form of land degradation (Hellden, 1991). It is a process resulting from the adverse effect of human activities on the fragile ecosystem in the dryland areas as a result of the increasing pressure and imbalance between natural resources and population increase.

Another dimension of the concept of land degradation in the dryland areas that need to be discussed is its temporal dynamics-specifically whether desertification is a process that can result in different transformations between various ecosystem types or an episode/end-result of a process with a defined outcome, which again has divergent views among the scientific community. For instance, Glantz and Orlovsky (1983) argued that desertification as a process was largely seen as a step of gradual modification in ecological productivity in arid, semi-arid and sub-humid ecosystems. It can include variations such as a reduction in agricultural yield and animal productivity, a reduction in vegetation cover or change in a climatic cycle. On the contrary, as an episode/end-result, it is generally believed to change an environment to desert-like conditions. Scientists are finding it difficult to accept the second view as there are many other environmental problems that are not necessarily desertification features that add up to the emergence of desert-like conditions (Tiffen and Mortimore, 2002).

Generally speaking, the last two views signify the varied characteristics of a wider concept of desertification. Glantz and Orlovsky (1983) believed that from these two concepts, different statements about desertification emerged. Some of these statements include "the development of desert-like environment in areas once densely vegetated", "advancement of desert-like conditions", and "intensification of desert-like conditions", or less clear defines transformations such as "changes in soil and climate", and "land becoming less productive for agriculture"; have been included in the concepts and definitions of desertification (Glantz and Orlovsky, 1983).

Therefore, in this thesis I defined land degradation and desertification as a ***decrease, disappearance and or replacement of natural vegetation cover as a result of natural or anthropogenic factors***. And I also appreciate the diverse views of researchers on the topic and adopted the definition of desertification and land degradation by the UNCCD, which highlighted the importance of human activities and natural environmental changes in the process. Additionally, I accepted the major physical manifestations of land degradation as a decrease or loss of vegetation cover, a reduction of ecosystem productivity, natural land cover change through land use alteration and the disappearance and migration of indigenous woody plant species as pointed out by Prince (2002).

2.2 Land degradation and environmental condition in sub-Saharan West Africa

Drought, deforestation, climate change, land cover alteration and biodiversity loss are the major environmental problems that have been exasperating the problem of land degradation in sub-Saharan West Africa for several decades (Mellenium Ecosystem Assessment, 2005, Leadley, 2010). The impacts of these elements combined with high population pressure, poverty and the increasing number of displaced persons, create a detrimental environmental condition and threatens ecosystem services in the area (Stringer et al., 2009). They constitute a long-term environmental problem and exacerbate the challenges of meeting the livelihoods of locals, especially in rural sub-Saharan Africa, where many families still rely on subsistence farming for survival (UNCCD, 2007).

Over the years, many researchers had attempted to examine the link between land degradation and other environmental problems such as drought and climate change in sub-Saharan West Africa (Giannini et al., 2008). According to Grainger et al. (2000), a lack of clear understanding and demarcation between land degradation and climate change creates difficulties in discerning the synergy and complexity of environmental problems and making it difficult to harmonise and adopt UNCCD and United Nations Framework Convention on Climate Change (UNFCCC) approaches in addressing the issues. This coupled with a lack of clear picture of dryland syndromes as reported by Reynolds et al. (2007) and high population growth and poverty rates compared to other dryland areas, are deteriorating the condition and further triggering more environmental problems in the area.

The varied ecological conditions in sub-Saharan West Africa from the arid belt in the north, to the rainforest ecotone in the south down to the Atlantic coast, have made it possible to have different biophysical and socio-economic drivers of land degradation in the region (Mbow et al., 2015). Additionally, the different climatic regimes and mixed seasons which are related to large scale general atmospheric circulation exert pressure on the environment and influences the south-north migration of ITCZ (Nicholson, 2013). The extreme desertification along the Sahel belt and the deforestation of rainforest along the coastal areas of sub-Saharan West Africa are also believed to affect the West African monsoon circulation. As reported by Zheng and Eltahir (1997), desertification and deforestation were found to affect monsoon circulation, with large scale negative impacts attributed to deforestation further south, leading to the substantial decline of rainfall and exposing more lands to degradation.

Land degradation is also found to alter land cover and ecosystem functions. This can lead to changes and additional stress on local climatic conditions through positive feedbacks between the land and the atmosphere which consequently further weakens the monsoon circulation (Nicholson, 1998, Giannini et al., 2008, Lebel et al., 2009) and accelerates the land degradation processes, this is because vegetation plays a vital role in land-atmosphere interaction. Densely vegetated land is less exposed to desertification than bare surface and that is why vegetation degradation is considered as one of the major indictors of land degradation in sub-Saharan West Africa and many other dryland zones (Prince, 2002). Therefore, this thesis is concerned explicitly with vegetation degradation in the study area: this is because vegetation condition determines the rate and process of other environmental problems such as soil erosion, land-atmosphere interaction, sub-surface hydrology and micro-climatic conditions among others. The spatial and temporal changes of vegetation is therefore of utmost importance to land degradation studies and this thesis employs an interdisciplinary approach to examine the changes occurring in relation to land degradation in the study area.

2.3 Biophysical manifestation of land degradation in sub-Saharan West Africa

The sub-Saharan West Africa is one of the world's largest water limited ecosystems and is regarded as a highly susceptible region to climate change (Kaptué et al., 2015). The four decades of studies of the intermittent effects of drought in the area has been presided by a tale of land degradation, where human mismanagement of land and natural environmental changes combined to deteriorate the natural state of the environment (Mbow et al., 2015). Persistent arguments of the regional recovery emanated from the literature to dispute the land degradation debates from the 1980s using the re-greening arguments following the availability of time-series satellite data such as NDVI (Mbow et al., 2015), and to some extent the success story of community conservation within the region such as in Niger Republic (Reij et al., 2009). However, even among the anti-desertification and land degradation proponents, it is generally believed that the physical features of sub-Saharan West Africa manifests evidence of sustained land degradation through the gradual decline and disappearance of indigenous vegetation species, the conversion of grassland to agricultural land and the replacement of woody species by shrubs and grasses in spite of the re-greening trend recorded by the satellite data (Herrmann and Tappan, 2013, Sambou et al., 2016).

Despite the varied eco-regions in sub-Saharan West Africa, several biophysical characteristics are used or are portrayed as spatial indicators of land degradation depending on the peculiar nature of the affected location (UNEC, 2007). Furthermore, owing to the complexity of land degradation, the combination of physical, biological, social and economic conditions, otherwise known as socio-ecological systems as suggested by Reynolds et al. (2007), are carefully studied, with an emphasis on vegetation, soils, moisture and surface energy conditions among others, for the purpose of land degradation assessment and monitoring (Sommer et al., 2011). However, of all the symptoms and manifestations of land degradation, the scarcity and disappearance of vegetation which often provide fuelwood and fodder is the most well documented (Herrmann and Tappan, 2013). This is in addition to the dryness of water courses particularly, rivers and streams, the predominance of thorny weeds in previously pasture and shrubs rich areas among others (Stocking and Murnaghan, 2001). These manifestations have significant negative impacts on the people and the environment, and the various features and components of land degradation works in unison and advance from one stage to another as represented in the Figure 2.1.

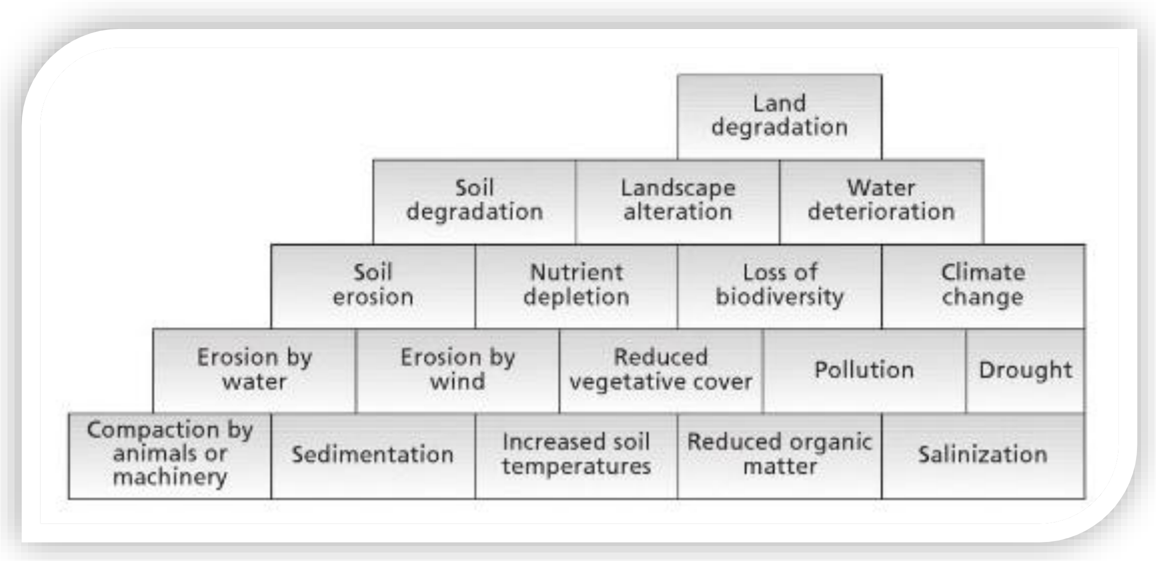


Figure 2.1. Linkages among land degradation process and manifestations (Stocking and Murnaghan, 2001)

The inherent characteristics of the land such as soil type and its condition, topography, vegetation and climate also affect the biophysical manifestation of land degradation (Costa and Soares, 2012). This is because the resilience across different ecosystems varies. Thus, an activity that is not degradation in the rainforest belt can be major land degradation in the Sahel belt. Hence for a proper identification of dominant features of land degradation, the relationship between the various components of landscape must be carefully recognised. For these reasons, spatial indicators are often used to represent changes in ecosystem processes and services, and to evaluate their possible impacts on livelihoods (Reed and Stringer, 2015).

The most common land degradation process in sub-Saharan West Africa, as portrayed by vegetation condition, include the conversion of grasslands and savanna to agricultural land. This has been a recurring problem in the vast part of the study area for many decades (UNEC, 2007). Additionally, the continued cutting down of tropical rainforests which is located down south along the coastal areas, has accelerated the loss of the traditional forests. According to the FAO (2010), between 2000 and 2005 Nigeria has lost 55.7% of its old growth forests. This is mostly due the large scale commercial logging; agricultural expansion and domestic biofuels need (mostly wood and charcoal). The rate of grasslands and savanna degradation is confounded by the increasing demands of forage due to the high increase of livestock density beyond the carrying capacity of the lands. For instance, in Nigeria between 1950 and 2006 the number of livestock increased from six million to 66 million. A similar trends prevails in other West African countries where livestock density has more than tripled, exceeding the carrying capacity of forage supply of the grasslands area (UNEC, 2007). Therefore, it can be concluded that vegetation change and its resulting impacts are the major physical manifestations of land degradation in sub-Saharan West Africa. However, the monitoring of these changes over time relied more on satellite data. That is why this study combines multiple approaches to study the problem.

2.4 Development and application of NDVI in land degradation assessment

Historically, the Normalized Difference Vegetation Index (NDVI) is a simple graphical indicator acquired using remote sensing that can be used to assess and analyse whether the object being observed contains live green vegetation or not. Started in the 1960s following the launch of Advance Very High Resolution Radiometer (AVHRR), instruments on board the National Oceanic and Atmospheric Administration (NOAA) platforms were used to study the relationships between climate and land ecosystems, earth surface monitoring, drought, fire, desertification and land degradation, carbon sequestration and a host of others (Myneni and Hall, 1995, Nemani et al., 2003, Anyamba and Tucker, 2005).

The AVHRR measures the reflectance (Figure 2.2) of the planet in red and near-infrared wave length bands as well as in the thermal infrared. The sensor has minimal spectral resolution, but tended to include bands in the red and near-infrared, which are useful to distinguish vegetation and cloud among other targets.

NDVI

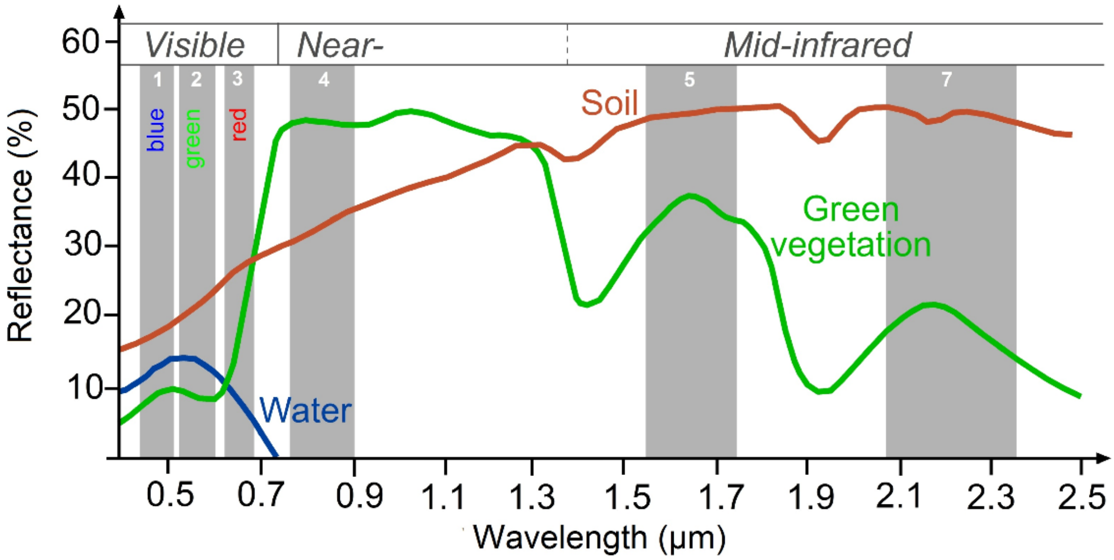


Figure 2.2. Reflectance of different surface types as a function of wavelength bands

Source:http://www.seos-project.eu/modules/classification/classification-c00-p05.html

The measured spectral reflectance data is usually compressed into vegetation indices. NDVI is one of such indices, which is a ratio of near-infrared to red vegetation reflectance (Myneni and Hall, 1995). NDVI is defined by equation 2.1;

$$NDVI = (NIR - RED) / (NIR + RED) \qquad [2.1]$$

Where NIR and RED are reflectance values in the near-infrared and red wavebands respectively as indicated in equation 2.1. Accordingly, the value of NDVI ranges from -1 to +1. The value > 0.7 indicates dense vegetation cover, while an NDVI value < 0 indicates cloud or water body (Tucker, 1979).

The earliest reported use of NDVI was in 1973, when a team of researchers in the Great Plains led by Rouse quantified the biophysical characteristics of the rangeland vegetation (Rouse Jr et al., 1974). Thereafter, Compton Tucker published a series of early scientific articles describing the use of NDVI and he was the first to use it to determine total dry matter accumulation (Tucker, 1979). Thus, NDVI was one of the most highly successful attempts to simplify and quickly identify vegetated areas and their conditions. It remains the most well-known and used index to distinguish live green plant canopies in multispectral remote sensing data (Anyamba and Tucker, 2005). NDVI can also be used to quantify the photosynthetic capacity of the vegetation canopy (Myneni and Hall, 1995).

The scientific basis of the NDVI assume that live green plants absorb solar radiation in the photosynthetically active radiation (PAR) spectral region, which serves as a source of energy in the photosynthesis process. Leaf cells have likewise evolved to re-emit solar radiation in the near-infrared spectral region since the photon energy at wavelength is longer than 700nm and is not large enough to synthesize organic molecules. Therefore, live green plants appear relatively dark in the PAR and relatively bright in the near-infrared region (Gates, 2012). Hence the measured solar radiation reflected by vegetation at red (0.6-0.7μm) and near-infrared (0.75-1.35 μm) channels were found to be the most useful in the remote sensing of vegetation (Myneni and Hall, 1995).

However, as mentioned earlier, NDVI is but one among over 150 spectral vegetation indices that were defined in the literature, and are generated from the numerical combination of different spectral bands, in most cases in the visible and near-infrared range of the electromagnetic spectrum (Bennett et al., 2012). Other closely related indices include the Enhanced Vegetation Index (EVI) (Huete et al., 1997); the Simple Ratio (SR) (Jordan, 1969); the Green Atmospherically Resistant Vegetation Index (GARI) (Gitelson et al., 1996) and the Wide Dynamic Range Vegetation Index (WDRVI) (Gitelson, 2004) among others. Most of these indices are species specific and in some cases not suitable when applied for several species with different canopy architecture and leaf structure. And they remain the simple and suitable method of mining information from remotely sensed data (Viña et al., 2011). This is due to the general belief that some algebraic combination of remotely sensed spectral bands can provide robust information such as vegetation structure, general condition of vegetation cover, photosynthetic capacity, and water content in the leaves among others (Jensen and Im, 2007).

Of all the vegetation indices, NDVI has been identified as the most suitable for land productivity assessments (Yengoh et al., 2015). Its potential had been rigorously and severally tested and its feasibility as a measure of ecosystem health and productivity has been acknowledged for about 30 years (Tucker et al., 1986) and has been found to show a strong correlation with Net Primary Productivity (NPP) (Prince and Goward, 1995, Higginbottom and Symeonakis, 2014). This is because the red and near-infrared bands are less sensitive to factors such as soil properties, atmospheric conditions, solar illumination and sensor viewing geometry which can affect spectral reflectance (Purkis and Klemas, 2011). The closely related index to NDVI for environmental monitoring is EVI which is a modification of NDVI developed for use with MODIS data to decouple the canopy background signal and reduce atmospheric effect (Jensen and Im, 2007). However, scientists have raised concerns over the use of EVI because the surface reflectance uncertainty of the blue band incorporated into the index is very high in the dense vegetated areas (Morton et al., 2014). Therefore, NDVI is the best index for land degradation assessment and has fewer problems than other indices and it is directly related to photosynthetic capacity (Myneni and Hall, 1995).

Over the years, a lot of research effort and resources have been invested in satellite sensors for the development of coarse-to-fine resolution NDVI datasets (Yengoh et al., 2015). One of the best known sensors is AVHRR on board the NOAA satellite which provides global NDVI datasets. Scheftic et al. (2014) reported that the development of these NDVI datasets by different research groups involves various schemes, procedures, and algorithms for corrections and processing.

Table 2.1. Commonly used NDVI datasets for environmental applications modified from (Higginbottom and Symeonakis, 2014)

Name	Sensor	Time Span	Time Step	Resolution
Pathfinder (PAL)	AVHRR	1981-2001	10-day	8 km
Global Vegetation Index (GVI)	AVHRR	1981-2009	7-day	4 km
Land Long-Term Data Record (LTDR)	AVHRR	1981-2013	Daily	5 km
FASIR	AVHRR	1982-1998	10-day	0.125^0
GIMMS	AVHRR	1981-2006	15-day	8 km
GIMMS3g	AVHRR	1981-2015	15-day	8 km
S 10	SPOT-vegetation	1998+	10-day	1 km
EM 10	ENVISAT-MERIS	2002-2012	10-day	1/1.2 km
SeaWiFS	SeaWiFS	1997-2010	Monthly	4 km
MOD (MYD) 13 A1/A2	Terra (Aqua)	2000+	16-day	500 m/1 km
MOD 13 (MYD) A3	√√	√√	Monthly	1 km
MOD 13 (MYD) C1/C2	√√	√√	16-day/monthly	5.6 km
MOD 13 (MYD) Q1	√√	√√	16-day	250 m
MEDOKADS	AVHRR	1989+	Daily	1 km

This provides the environmental change community with a range of datasets which can be used for different studies, depending on their desired objectives. Table 2.1 provides a summary of the commonly used NDVI datasets for environmental change studies.

The most widely and popular NDVI datasets used are GIMMS and GIMMS3g products due to their long-term time span (1980s to date), despite the availability of higher resolution datasets such as SPOT and MODIS. Fensholt and Proud (2012) reported that GIMMS is the most updated global time-series NDVI. On the other hand, the new version of NDVI3g consists of more than 33 years of data and is further re-adjusted and corrected for instrument calibration, variation in solar angle and view zenith angle, stratospheric aerosols from major volcanic eruptions, as well as other effects not directly related to vegetation changes (Pinzon and Tucker, 2014).

The potential of NDVI for land degradation assessment was first demonstrated by the famous work of Tucker et al. (1991) to determine the extent of the Saharan Desert. Thereafter, many scientists applied the data using different methods to assess desertification and land degradation, especially in the Sahel region of sub-Saharan West Africa. Many of these studies were carried out to assess land degradation and are reviewed in Chapter 4 of this thesis. Nevertheless, the interpretation of long term NDVI with respect to vegetation cover changes is not straightforward. In order to make better understanding and useful assessment of land degradation using NDVI, the synoptic overview provided by satellites need to be carefully related to real physical condition on the ground (Hermann and Sop, 2016). In this regards, the knowledge of local inhabitants on vegetation changes developed over time, has been used to support finding from ground survey and most remote sensing studies of land degradation (Hermann et al, 2014).

In spite of the availability, as well as its wide application by different environmental researchers, the use of NDVI to distinguish directly between degraded and non-degraded areas is still very challenging in both implementation and interpretation. Therefore, there is a need to carefully apply robust methodology that can enhance and possibly provide less ambiguous results when using NDVI in land degradation and other related vegetation change studies.

2.5 Methods of land degradation assessment and monitoring

The land degradation and desertification is a complex issue and, to date, scientists are yet to agree on the uniform method and approach for its assessment and monitoring. It is viewed as a contextual issue which depends on who, where, when and the purpose of the monitoring and assessment (Reed et al., 2013). Nevertheless, the need for an accurate, robust, repeatable and quantitative methodology to assess land degradation and desertification so as to have a more reliable feature of the process is becoming more demanding than ever before, this is due to its complexity and negative impacts on ecosystem services (Higginbottom and Symeonakis, 2014).

Over the years, the availability of earth observation (EO) data has provided the most viable option for land degradation assessment and monitoring at local, regional and global scale. Consequently, many scientists developed different methods and approaches. Some of the methods are criticised due to their inconsistencies, while others are relatively feasible but careful validation and standardisation are needed so that policy makers and planners can have confidence in the result for effective monitoring (Yengoh et al., 2015). However, the major difficulties in applying some of the methods are the lack of baseline and or long-term data records to validate the 30-year trends and paucity of sampling sites with spatial scale appropriate for validation of the results at country level. Due to these challenges, Verstraete et al. (2011) proposed the concept of the Global Dryland Observing System (GDOS) to serve as a source of long-term records which can be used to validate the accuracy and consistency of RS and other EO data used in land degradation studies. Thus, due to the strong correlation between water (rainfall, soil moisture) and vegetation in the dryland areas, it has been suggested that for any long-term appreciable degradation trend to be captured, the influence of moisture on the overall trend of vegetation must be removed (Higginbottom and Symeonakis, 2014).

Methodological issues over the years were raised regarding land degradation assessments. Here I briefly reviewed some of the methods developed over time to assess land degradation and desertification.

Rain Use Efficiency (RUE) Method

Rain Use Efficiency is the ratio of vegetation productivity to annual rainfall originally proposed by Le Houerou (1984) to assess ecosystem conditions. Theoretically, the method assumes proportionality between Net Primary Productivity as indicated by NDVI and rainfall. It was on the general premises that drylands would produce about 4kg of dry matter/ha/year per millimetre of rainfall, and it assumed that any subsequent reduction in the amount of RUE is an indication of land degradation (Le Houerou, 1984). Several studies of land degradation were carried out in arid and semi-arid regions using the RUE method.

Hein and De Ridder (2006) analysed the variability of RUE over the Sahel region and concluded that some evidence of anthropogenic land degradation manifested in the Sahel over the last two decades. They argued that the negative impact of grazing was under-reported in the previous studies. Furthermore, the vulnerability of the population of the Sahel to drought may be far beyond what was reported. Similar studies were carried out in the same region by Fensholt and Rasmussen (2011) and assessed decadal changes in the vegetation productivity using the RUE method. However, unlike the finding of Hein and De Ridder (2006), their study found an increase in rainfall and NDVI trend in the Sahel and Sudan savanna zone of sub-Saharan Africa from 1982-2007. This subsequently gave rise to the overall increase in RUE which undermines the earlier supposition of using the methods to separate the effect of rainfall and other factors, as the overall trend is predominantly influenced by rainfall. The study further suggested the use of residual trend (RESTREND) analysis as an alternative method of land degradation study which was found to show little anthropogenic changes after it was applied in the area. In a related development, Fensholt et al. (2013) used EO data and computed the RUE from 1982 to 2010. Their finding shows the predominance of a positive trend of RUE over the study period, and this further questioned the reliability of the method in land degradation studies.

The methodological weakness and assumptions of RUE raised many issues and questioned the reliability of the GLADA assessment carried out by Bai et al. (2008) which found a reduction of the trend of RUE across 24% of the global land areas. The question raised by Wessels (2009a) concerning the interpretation of this assessment suggested that the result of GLADA can be misleading because of the methodological flaws. Though further clarification by Dent et al. (2009) highlighted that RUE was used simply to separate NDVI trends caused by drought in the region where vegetation productivity directly depends on rainfall not to indicate land condition. Many other studies which were reviewed in Chapter 4 further pointed out the weakness of the RUE method, especially it's over reliance on NPP and the finding of some degradation scenarios occurring without any changes in NPP. This was found by Huenneke et al. (2002), where the replacement of grassland by desert scrub - an indication of land degradation took place in the Chihuahuan ecosystem without appreciable change in average NPP.

Furthermore, the assumption that RUE is constant across ecosystems was also disputed, as the trend of RUE was found to vary between different regions, making its applicability as an indicator of land degradation very controversial (Prince et al., 2007, Wessels, 2009a). These limitations weakened the usability of this method in land degradation and desertification assessments and gave rise to the emergence of new alternative robust methods.

Land use and Land cover change (LULC) method

The method of land use and land cover change has been used traditionally to assess conditions of ecosystems. Land use processes in particular are generally assumed to be a local environmental issues which normally trigger land cover change. Changes from the natural forests or woodlands to croplands, pastures, and/or urban areas have expanded in recent years, leading to the loss of the biodiversity with resulting impacts on ecosystem provisioning services (Foley et al., 2005). The extent of land cover change is site specific, depending on the human actions directed at manipulating the earth surface for their own benefits such as agriculture, urbanisation and grazing among others (Lambin and Geist, 2008). The change in LULC is regarded as very important in environmental change studies because it provides quantitative information on where, when, what and why land cover alterations takes place (Lambin, 1997).

The use of the LULC method to assess and monitor land degradation works on the assumption that land degradation involves the conversion of natural cover into another form of land use, which is either purely man-made or less stable, owing to the natural or anthropogenic factors. These changes are driven by two main causes: proximate (local) and underlying (global) and interacts with biophysical drivers such as drought and socio-economic factors to affect land productivity (Lambin et al., 2001). Several studies used resilience and vulnerability of land cover to assess land degradation. The study by Lambin and Geist (2008) argued that the dramatic environmental changes that led to the land cover alterations and climate change in sub-Saharan West Africa were largely due to conversion of natural cover into croplands and fuelwood logging, fuelled by the needs to satisfy food demands as a result of population increase.

Maitima et al. (2009) assessed the interlinkages between land cover change and land degradation. They found that expansion of croplands at the expense of natural vegetation is the major land use leading to land cover change in East Africa. The change led to a decline in soil fertility and soil moisture content, and in some cases soil erosion as the surface vegetation is cleared. Similarly, the study by Wessels et al. (2011) also found that communal land use on granite substrate has a strong impact on the woody cover below five metres, leading to an alteration of the ecological structure. Gang et al. (2014) documented that 49% of the global grassland is degraded from 2000 to 2010 due to climate change and man-made changes, with agriculture, urbanisation and overgrazing being the major drivers. Furthermore, Ramankutty and Foley (1999) reported the expansion of croplands to be the major driver of land cover change since the 1700s leading to land degradation. Equally, the study by Spiekermann et al. (2015) found a significant increase of croplands and the reduction of natural vegetation in Mali, though in some cases the direction of the changes were not always negative. They equally recorded a decline in natural species and the encroachment of degraded land.

Although this method can be used to assess and monitor land cover condition which can be further used to infer on land degradation status, the effects of local drivers of land use and land cover change, which varies according to many local factors such as technology, economic demands, and other social considerations, have made it difficult to apply the LULC method universally due to a lack of standardisation of the factors across different ecosystems. Furthermore, it was suggested that qualitative information should be integrated into the land cover change models, which may supplement the paucity of data that might be present in the quantitative land cover data (Lambin, 1997).

Modelling method

A model is a simplified representation of a concept, phenomena, relationship, structure or system in a real world. Models are meant to facilitate understanding and aid in decision making by simulating past and predicting future events on the basis of past observations. Following the arguments of the re-greening of the Sahel which spurred in the early 1980s based on the availability of NDVI data, many process-based ecosystem models were developed to assess the past ecosystem conditions and relate to the greening trends of the satellite data over the dryland regions (Seaquist, 2009). One common model which was used widely to assess the roles and impacts of different climatic and anthropogenic factors on the overall ecosystem condition in the dryland region is the Lund Postdam Jena Dynamic Global Vegetation Model (LPJ-DGVM) (Sitch et al., 2003).

Hickler et al. (2005) applied the LPJ-DGVM model and determined the extent of the greening trend in the Sahel which is controlled by rainfall. Their finding corroborated the earlier studies using the NDVI trend which shows that rainfall is the main driver of vegetation changes in the region and the vegetation trend oscillates relative to how favourable the season is and reflects the recent trend of greening as reported previously. Their findings disputed the continued land degradation due to the anthropogenic forces in the Sahel. The same model was also applied by Seaquist (2009) to separate the climatic and anthropogenic impacts on Sahelian vegetation dynamics from 1982-2002. The study works on the assumption that a small or negative agreement between observed and model vegetation dynamics would be related to the anthropogenic impacts on vegetation. They found a very good agreement between the model and the observed data, with little impact due to human activities, though they do not eliminate the likely negative effect of human activities on the vegetation dynamics due to changing land use patterns in the future.

Haberl et al. (2007) applied LPJ-DGVM to quantify and map out the aggregate human impact from land use on NPP on the terrestrial ecosystem. The study found that land use is the main factor transforming the terrestrial surface, resulting in the changes of biogeochemical cycles and diminishing the ability of an ecosystem to provide critical services to human beings. A further study by Zika and Erb (2009) also assessed the changes and loss of global NPP due to anthropogenic soil degradation in the drylands region using LPJ-DGVM. They found that an average of 2% of global NPP is lost annually due to land degradation, which is about 4% to 10% of the potential NPP in the drylands areas. This shows that land degradation is putting additional pressure on the marginal ecosystems in the dryland areas. The application of the model method to assess land degradation was equally used by Niedertscheider et al. (2012) to assess changes in land use in South Africa between 1961 and 2006. The study examined the relationship between land use and socio-economic changes by assessing the human appropriation of net primary productivity (HANPP); a parameter used to indicate the variation in an ecosystem due to man-made factors such as farming and land use conversion. The study found that land cover and the overall HANPP condition remained relatively the same throughout the study period.

Several other studies applied models to assess and monitor the condition of ecosystem health, which is used as an indicator of land degradation. However, the major limiting factor in applying the models method is a lack of uniform input data in running the models, making it difficult to apply the results universally. In addition, the localisation of land use and its effects on the ecosystem also affects the viability of ecosystem models in land degradation studies. Nevertheless, the need to understand and to quantify the general behaviour of terrestrial ecosystems being one of the major players in terrestrial biogeochemistry and biogeography makes the models still relevant in environmental change studies.

Indigenous knowledge and vegetation species change method

According to Blaikie et al. (1997) indigenous knowledge is the way people understand the world, interpret and apply meaning based on their own experience. It is about an understanding of subjective culturally-conditioned phenomena emerging from the complex and ongoing process involving selection, rejection, creation, development and transformation of information which are intimately linked to the physical and social environment, as well as the institutional context in which they are found. The application of indigenous knowledge and vegetation species changes, though subjective, is becoming increasingly relevant in environmental change studies due to the uncertainties of satellite data, and the lack of a long-term data archive of vegetation changes especially in Africa (Lykke et al., 2004). The knowledge of what was the condition of vegetation species and what is currently going on, and the likely factors responsible for the observed trends and changes, have been used extensively to minimise the ambiguity of satellite data and determine the status of vegetation species and its risk of extinction due to land degradation and other environmental changes in sub-Saharan Africa (Wezel, 2004).

Over the past decades, many studies applied indigenous knowledge and vegetation species change approach to assessed and monitored land degradation, and in some cases to validate satellite data trends in dryland areas affected by land degradation. The study by Bollig and Schulte (1999) examines the perception of herders on land degradation and environmental change in two African pastoral communities. They found that indigenous knowledge is fine-grained, though complex sometimes, but it is socially built and rooted in ideology. The pastoralist view on land degradation is not a complex relationship between landscape and the vegetation, but rather in the context of the availability of grasses to feed their herds. They believed that land degradation takes place when the landscape can no longer provide enough grasses to feed their grazing cattle. In a related development, Hellier et al. (1999) applied indigenous knowledge to assess the trend of biodiversity in the Chiapas region, Mexico. The study found that local people believed forest cover in the region has decreased substantially in recent decades and this has been accompanied by a reduction in useful indigenous species. The respondents argued that the changes resulted from the excessive utilisation and natural environmental changes, indicating the interplay of anthropogenic and natural factors on land degradation. However, their view was in disagreement with the overall satellite data record of the region.

Davis (2005) applied indigenous ecological knowledge to dispute expert opinion on desertification reversal in Southern Morocco. The study argued that experts' assessments of desertification were based on generalised, questionable evidences that are in disagreement with indigenous knowledge due to the economic and socio-political considerations. The communities perceived overgrazing and other related pastoralists' activities to be the driving force of desertification in the region. Furthermore, Lykke (2000) applied an ethnobotanical approach and interviewed 57 elderly villagers in Senegal. The study showed that local people observed change in their environment from forest to savanna (an indication of land degradation) during their life time and argued that the major causes of the named change are primarily the recurrence of local fires and declining rainfall. In another development, Nyong et al. (2007) highlighted the importance of indigenous knowledge into formal climate change mitigation and adaptation approaches.

In some cases, the indigenous ecological knowledge was used to validate remote sensing studies. Some of these studies were described in Chapter 5. Therefore, despite its subjectivity, indigenous people knowledge is a broad knowledge base of the behaviour of complex ecological systems of their own local environment. This knowledge is accumulated through a long series of observations transmitted from generation to generation.

Statistical trend analysis method

The application of the statistical trend analysis method to disentangle vegetation productivity from moisture (i.e. rainfall or soil moisture) trends has been developed. The most commonly used statistical trend method is Residual Trend Analysis (RESTREND) (Evans and Geerken, 2004). Details description, review and the feasibility of RESTREND in land degradation studies have been carried out in Chapter 4. The method centred on detecting a shift in the statistical relationship between moisture and NDVI which serve as a proxy of vegetation productivity. RESTREND is equally considered as the best method to detect vegetation condition because NDVI residuals did not correlate with rainfall and other moisture conditions and therefore can be monitored for trends in land condition (Wessels, 2009b).

Several studies of land degradation applied the RESTREND method to monitor vegetation condition in different regions (Wessels et al., 2004, Helldén and Tottrup, 2008, Ibrahim et al., 2015). It has been argued that the use of RESTREND, rather than a quotient approach, evades the limitations of the RUE method with regard to linearity and dependence, thus making it a more robust method of land degradation assessment (Wessels et al., 2007). This is because all trend analysis assessments are on the premise that sites with similar conditions when subjected to degradation will show reduced photosynthetic capacity, thus NDVI (Prince et al., 2009).

In addition to RESTREND, other statistical trend analysis methods used to study vegetation change and land degradation include the Precipitation Marginal Response (PMR) method used by Verón and Paruelo (2010), and the vegetation response ratio method (Ji and Peters, 2003) among others. Nevertheless, the emphasis of using rainfall as a sole driver of photosynthetic capacity and ignoring soil moisture in most of the statistical trend analysis methods constituted the major hitch. I tried and addressed this, as highlighted in Chapter 4, where soil moisture-NDVI RESTREND was found to be more robust than rainfall-NDVI RESTREND in showing negative trend of the NDVI residuals.

In conclusion, a variety of NDVI-based methods have been developed and applied in land degradation and other related vegetation change studies, but the validation of the results, and thus the suitability and reliability of these approaches in land degradation assessment, remain inadequate and require further improvement (Higginbottom and Symeonakis, 2014).

Chapter Summary

This chapter has reviewed and highlighted the concept and processes of land degradation and desertification, and its challenging nature which makes its study still very relevant. It also examines desertification definitions from the early time of discovery to present, as well as the controversies surrounding them. The link between land degradation and overall environmental conditions in sub-Saharan West Africa was also highlighted, basic biophysical manifestation used to monitor desertification and land degradation was also reviewed. Finally, the development of vegetation index-NDVI in particular was highlighted; various methods were used for land degradation assessment using NDVI, RUE etc. were equally reviewed.

From the foregoing review, it can be deduced that the land degradation problem, especially in sub-Saharan Africa, is still an ongoing issue in spite of the numerous research efforts over decades. This can be attributed partly to the methods and approaches adopted. Therefore, this thesis was designed to fill this research gap by applying an interdisciplinary approach to find out the condition of vegetation changes, and to ascertain whether the greening trend observed over years indicates a reversal of land degradation or otherwise using trend analysis, indigenous knowledge method and land use and land cover changes. Three specific aims were designed and addressed using specific objectives as presented in ***chapter 1*** respectively.

On the basis of foregoing, the following ***research questions*** were designed to guide the study based on the literature review, and these are;

i. How effective is the RESTREND method in land degradation assessment using NDVI-rainfall and NDVI-soil moisture models?
ii. Is there any significant historical change in woody vegetation cover to suggest continuity or a reversal of land degradation in the study area?
iii. What are the dominant land cover types that are mostly affected by land degradation in sub-Saharan West Africa?

Thus, Chapter 4 provides an answer to the question "*how effective is the RESTREND method in land degradation assessment using NDVI-rainfall and NDVI-soil moisture models?"* This question specifically addressed the methodological issues identified in the literature. Chapter 5, on the other hand, tested the suitability of the indigenous knowledge of the environment to ascertain the changes of woody vegetation condition, specifically it provides an answer to the question *"is there any significant historical change in woody vegetation cover to suggest continual or reversal of land degradation in the study area?*"This question was designed to evaluate the strength or weakness of land degradation studies based on satellite data alone. Finally, in Chapter 6, the question "*What are the dominant land cover types that are mostly affected by land degradation in sub-Saharan West Africa?"* was designed to fill the gap in the literature between land cover change and land degradation.

The most common land cover types found under areas of severe land degradation were examined.

3 Chapter 3: Geographical description of the study area

This chapter describes the geographical features of the study area – sub-Saharan West Africa, which is the most populous region in the African continent. The physical characteristics as well as the socio-economic features of unique relevance to the thesis such as the varied climatic, vegetation, land use and cultural regions are presented. Major environmental challenges affecting the region are also examined and some of the past and present works and efforts to tackle the devastating impacts of land degradation and desertification are also highlighted to further enhance the contextual basis for the current study.

3.1 Location and extent

The study area is sub-Saharan West Africa, and it covers an area of approximately 6,140,000 km^2, an area roughly about one-fifth of the African continent. Specifically, it is located between latitude 4^0N and 20^0N, and between longitude 17^0W and 15^0E (Figure 3.1). The area is situated between the arid and semi-arid regions of the Saharan desert in North Africa, and humid tropical savanna in the equatorial West Africa down to the Atlantic coast to the south. Hence it is marked by a south-north gradient in surface conditions with nearly zonal uniformity; from the coastal waters of the Gulf of Guinea, to the equatorial rainforests, the grasslands and the savanna of the Sahel. The eastern border is less precisely defined, running approximately from Mount Cameroun to Lake Chad. The vast majority of the land in the area is low-lying at <300m above mean sea level. Isolated mountains exist in several countries along the southern shore. The northern part of the region consists of semi-arid terrain and is known as the Sahel, a transitional boundary between the Sahara Desert and the Sudan savanna.

The region is an area of vegetation, climatic and environmental transitions and it has been intensively studied by environmental scientists. The sub-Saharan West African countries of Senegal, Mauritania, Mali, Niger and Burkina Faso and Guinea-Bissau, which have most of their parts in the Sahel, make up the dry region of West Africa. On the other hand, Nigeria, Benin, Ghana, Togo, Côte d'Ivoire, Liberia, Sierra Leone, Guinea and the

Gambia comprises Guinea which is the traditional name given to the area near the Gulf of Guinea, and makes up the humid part of West Africa.

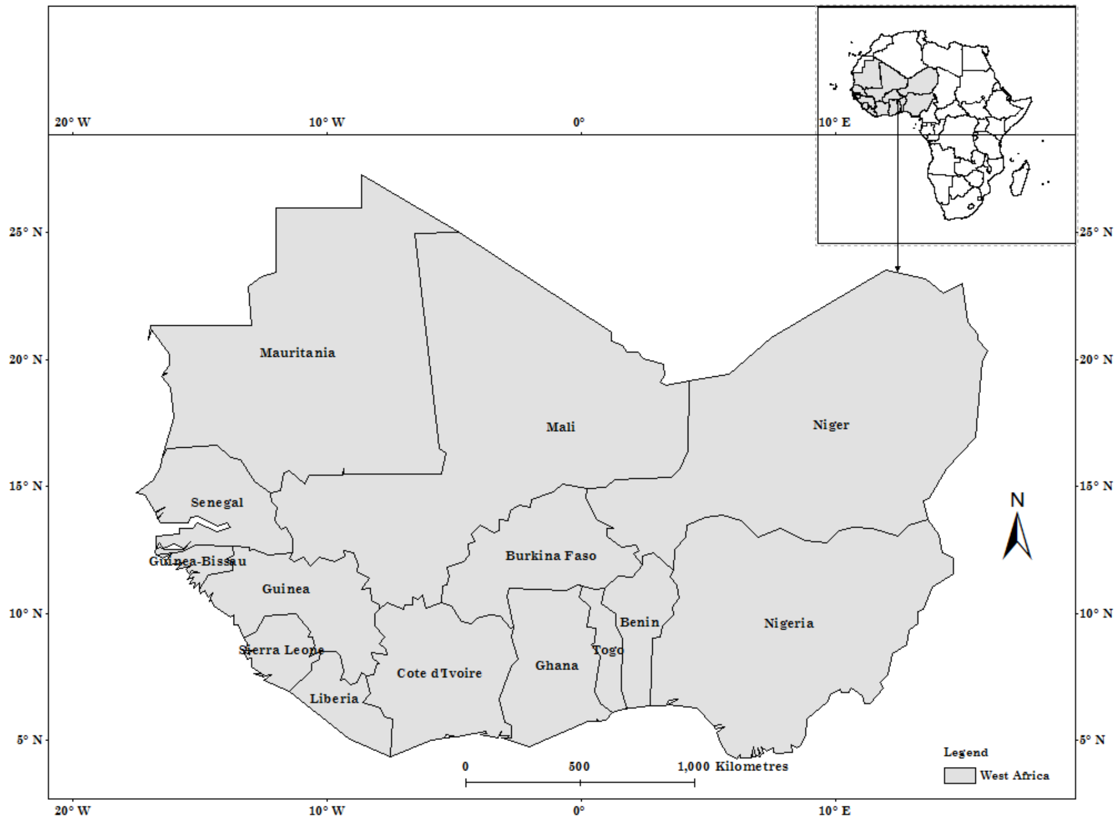


Figure 3.1. Location and extent of the study area

3.2 Climate

Climate is the major factor of the development of vegetation, soils, agriculture and general life styles in sub-Saharan West Africa (Nicholson, 1995). Regional climates are complex outcomes of local physical processes and the non-local response to major scale phenomena such as El Nino and other dominant modes of climate variability (IPCC, 2013). The climate of sub-Saharan West Africa is characterised by high temperatures throughout the year and varying rainfall regimes depending on the latitudinal location. The area is characterised by a seasonal scarcity of water; often the supply is erratic in time and space, and excessive heat throughout the year. The entire geography of the region is strongly linked to the nature of the climate, and its influence has been the major factor in the ecological development and stability of the area.

Rainfall is the vital element of climate in West Africa because it varies widely from place to place and from season to season, and it is the major limiting factor for agriculture which is the major economic activity in the region. Rainfall in the region is affected by monsoon circulation where notable upper air flow reversals are observed. The amount of rainfall received in the area varies with latitude as presented in Figure 3.2, and an alternate between the few months of rainfall in the northern part of West Africa to all year round rainfall with double maxima along the coastal areas near the Atlantic Ocean (Nicholson, 2013). In the Sahel part of the West Africa, there is a single rainy season, lasting between two to five months. In the Gulf of Guinea, there are two rainy seasons in most of the countries. In the Sahel part of West Africa, the distinction between the few months of rainfall and long dry seasons throughout the year is attributed to the swing in the large scale general atmospheric circulation patterns, which has a strong control and influence over the climate and weather in sub-Saharan West Africa (Nicholson, 1995, Nicholson, 2005, Lebel et al., 2009, Janicot et al., 2011).

According to Nicholson (1981), four distinct climate types are found in sub-Saharan West Africa based on the duration and amount of rainfall it receives, these are;

1. Sahelian climate - In this area, the rainy season is characterised as irregular, often lasting for a maximum of three months with rainfall never exceeding 500mm per annum.
2. Sudanian climate - The amount of rainfall received here does not exceed 800mm around its northern boundaries, such as northern Nigeria, and it reaches about 1000mm in the southern margin. It normally lasts for three to five months.
3. Humid tropical climate - This area is characterised by a bimodal rainfall pattern, with an average annual rainfall of 1500mm.
4. Equatorial climate: This type of climate is concentrated along the coastal areas in the Gulf of Guinea, with average annual rainfall of more than 2000mm.

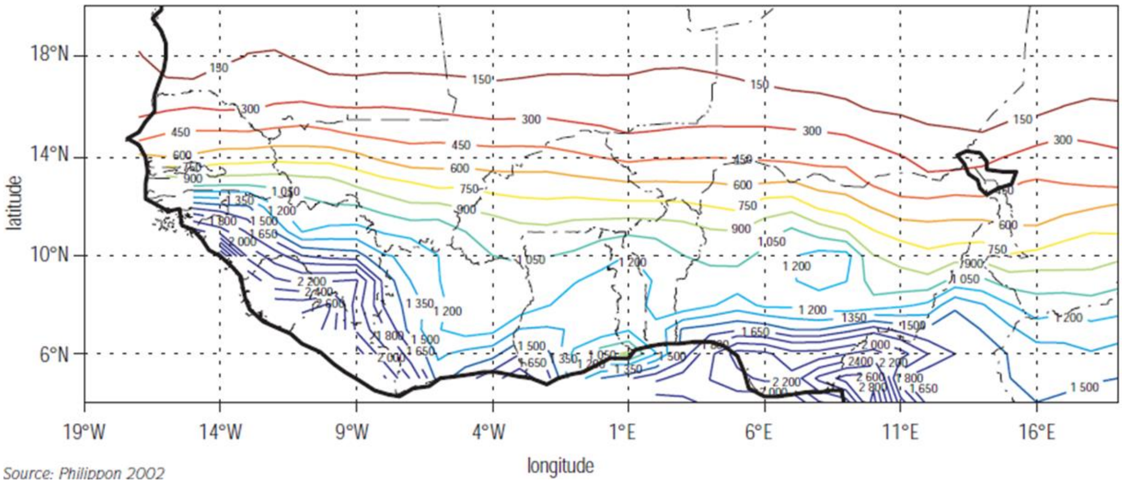


Figure 3.2. Average cumulative rainfall (mm) in West Africa 1968-1998 (UNEP, 2006)

Rainfall in the area is controlled by the interplay of the two dominant air masses i.e. the Harmattan which is a dry and cold, dusty air mass which originates from the Saharan desert; and the warm, moist monsoon, which originates from the Atlantic Ocean. These two air masses meets at a region called the Inter-Tropical Convergence Zone (ITCZ), at this point the moist warm air is forced to raise, giving rise to the cloud development and convective rainfall (Nicholson, 1995, Govaerts and Lattanzio, 2008). Therefore, rainfall is linked to ITCZ in the region and its seasonal migration determines the seasonal movement of the tropical rainfall in the area. Thus, ITCZ moves north and south, reaching its northern extreme around the Sahel during the high summer sun season (Figure 3.3), thereby bringing rainfall to the Sahel. The amount and duration of the rainy season increases from north to south (Nicholson, 2001).

The African Monsoon also plays a significant role in rainfall formations in the area (Janicot et al., 2011).One of the major components of the African Monsoon is the West African monsoon, which is influenced by inter annual to decadal variations, land processes and direct response to radiative forcing and dominates during the summer in the northern hemisphere (June-September). Key features of the West African monsoon are low level south-westerly flows from the Atlantic Ocean and the Inter-Tropical Convergence Zone (ITCZ) north of the equator. Monsoon rainfall over West Africa occurs during the June through September period (Figure 3.3, left). The West African Sahel is well known for the severe droughts that ravaged the region during the 1970s and 1980s. The vagaries nature of rainfall in sub-Saharan Africa have profound and often dire consequences on African society and economy (Nicholson, 1995). Finally, the onset of the summer monsoon over West Africa is linked to an abrupt latitudinal shift of the ITCZ from a quasi-stationary location at 5^0N in May-June to another quasi-stationary location at 10^0N in July-August (Sultan B and Janicot, 2003).

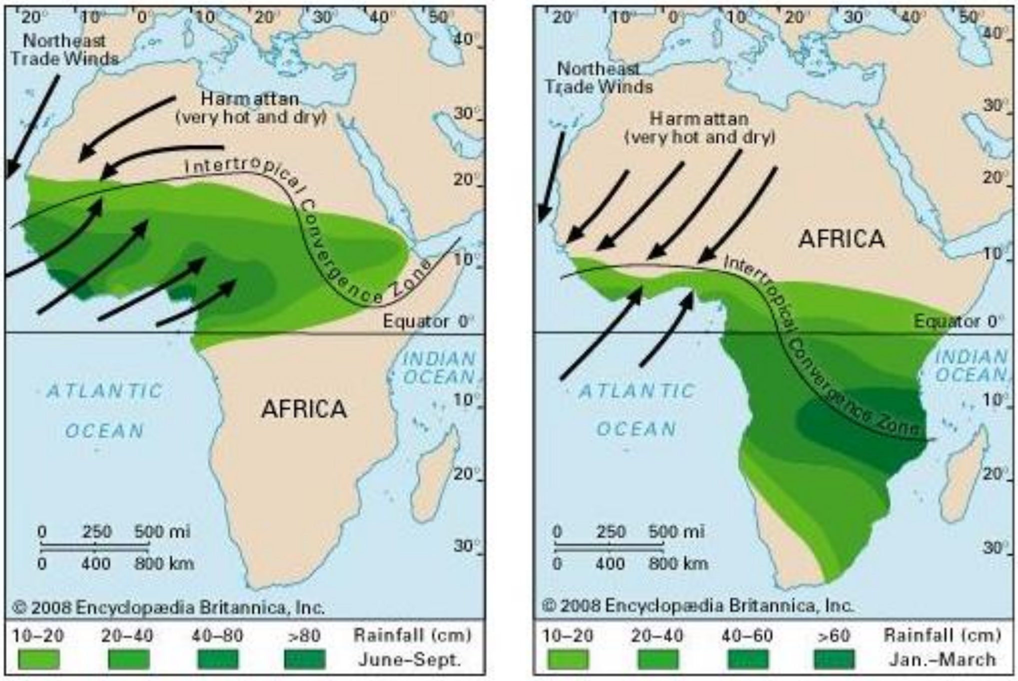


Figure 3.3. Seasonal migration of ITCZ over West Africa

Source: http://www.clivar.org/african-monsoon Access [20/01/2016]

Potential Evapotranspiration (PET) also varies between the northern and southern parts of the West African Sahel. It is about 2000mm per annum or higher in the north to about 1700mm per annum in the south. Rainfall in the region usually exceeded potential evapotranspiration by about one to two months of the year (Nicholson, 1995). The seasonal change in PET is also well pronounced due to the correlation between the areas of highest evapotranspiration, net radiation and temperature (Hayward and Oguntoyinbo, 1987).

Globally, the temperature trend has changed over the last several decades, due to the impact of climate change and other environmental changes (Figure 3.4), and sub-Saharan West African is not an exception. The temperature in the area is generally influenced by two air masses: the Harmattan, a dry and hot northeast wind blowing through the Sahara, and the Monsoon, a humid southwest wind blowing through the Atlantic Ocean. These two air masses are controlled by the seasonal movement of the ITCZ (Hayward and Oguntoyinbo, 1987).

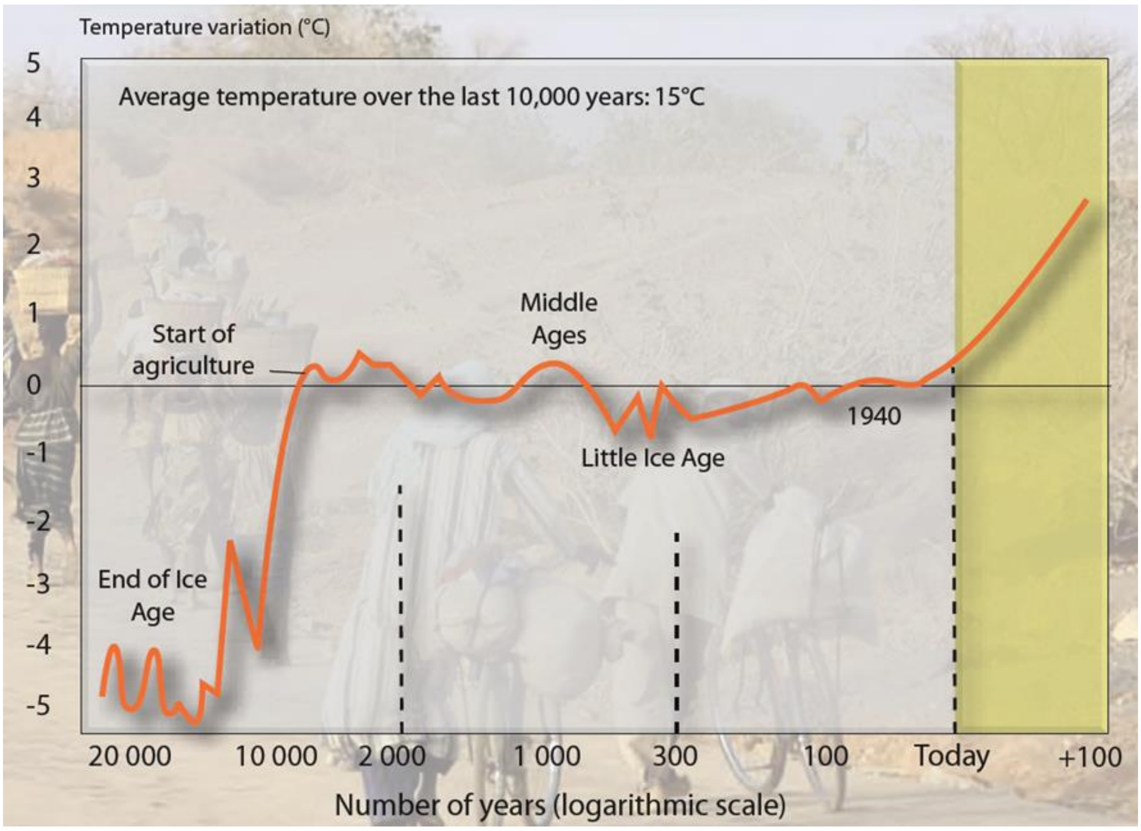


Figure 3.4. Temperature trends over the last 20,000 years (UNEP, 2006)

Temperature is generally high throughout the year in the area because of the high amount of solar radiation. Owing to the varied climatic zones within the region, the warmest months also vary from April to July, depending on the geographical location, and this is accompanied by the onset of the rainy season. During this hot period, the mean daily temperature ranges from 32^0C to 35^0C throughout the Sahel zone in the northern part of the region. In January, the temperature drops everywhere to an average of about 20^0C in the northern part and 22^0C in the southern part, giving rise to the cold winter season. Thus, the annual average of temperature throughout sub-Saharan West Africa ranges from 10^{0}C to 15^{0}C respectively (Nicholson, 2001). Diurnal and night temperatures also vary considerably. The mean daily maximum during the cold season in January is between 27^{0}C and 28^{0}C and ranges from 40^{0}C to 42^{0}C during the warmest months of the year around the Sahel boundary. These daily extremes are linked to the varied topography, cloud cover, surface moisture and vegetation across different biomes within the region. Temperature is considerably lower near the coastal areas, and the diurnal and annual ranges are also moderate (Nicholson, 1995).

Furthermore, temperature in sub-Saharan West Africa will be affected by the global surface temperature change as projected by IPCC in the fifth assessment report. To this end, temperature change for the end of 21st century is likely to exceed 1.5 C^0 relative to 1850 to 1900 for all the representative concentration pathways (RCP) scenarios except for RCP 2.6. This may lead to further warming of the surface beyond 2100 and create more adverse condition especially in the dryland regions (IPCC, 2013). This corroborated the stands of Bindoff et al, (2013) report which observed increase in global mean surface temperature from 1951 to 2010 to be very likely due to observed anthropogenic increase in GHGs concentration.

3.3 Vegetation and hydrology

The vegetation in sub-Saharan West Africa is determined by the aggregations of a multitude of processes and factors akin to climate and soil. It typically follows the longitudinal zonation of rainfall and north-south shift from savanna to the rainforest (Nicholson, 1995, Speth et al., 2010). Generally, the onset of rainy season in sub-Saharan Africa is a key factor triggering changes in the vegetation and surface properties that implies feedbacks to the local atmospheric heat and moisture cycle (IPCC, 2013). Equally, the vegetation structure also changes increasingly from the north to the south, characterised by big and taller trees with a better fraction of woody species and a greater amount of ground cover in the south. In the further north along the Sahara border, open grass vegetation predominates which is sometimes found mixed with scattered woody acacia species of small trees or shrubs. Grasses are generally perennial, not taller than 80cm, and the woody species are often thorny.

Three main savanna vegetation formations can be distinguished in the region based on their density and types of species present. The Sahel savanna is a location where vegetation is dominated by bare soil surface with few scattered trees and shrubs located along valleys and other favourable areas of soil and moisture which produce a mosaic pattern. Immediately after Sahel savanna to the south is Sudan savanna. Here the ground surface is covered by low grass cover, which is generally termed as grasslands, with a taller and more continuous cover. Next to Sudan savanna is Guinea savanna otherwise known as 'woodland savanna'. In this region, the trees become the dominant vegetation species and form the transition to the rainforest adjacent to the coastal areas (Schmidt et al., 2012).

In terms of hydrology, sub-Saharan West Africa is blessed with a number of rivers which provide economic and environmental security. The two prominent rivers are the River Senegal which flows through Mali, Mauritania and Senegal and the River Niger in Mali, Niger, Burkina Faso and Nigeria. They are the two most exogenous rivers in the region, and they originate from the highland of the humid region within the area, provide a perennial flow of water and often experience floods during a rainy season. The flooded areas are used for cultivation and pasture. Additionally, the largest inland natural lake, Lake Chad, is located in the area, though is significantly reduced in size due to climate change and land degradation (Nicholson, 1995).

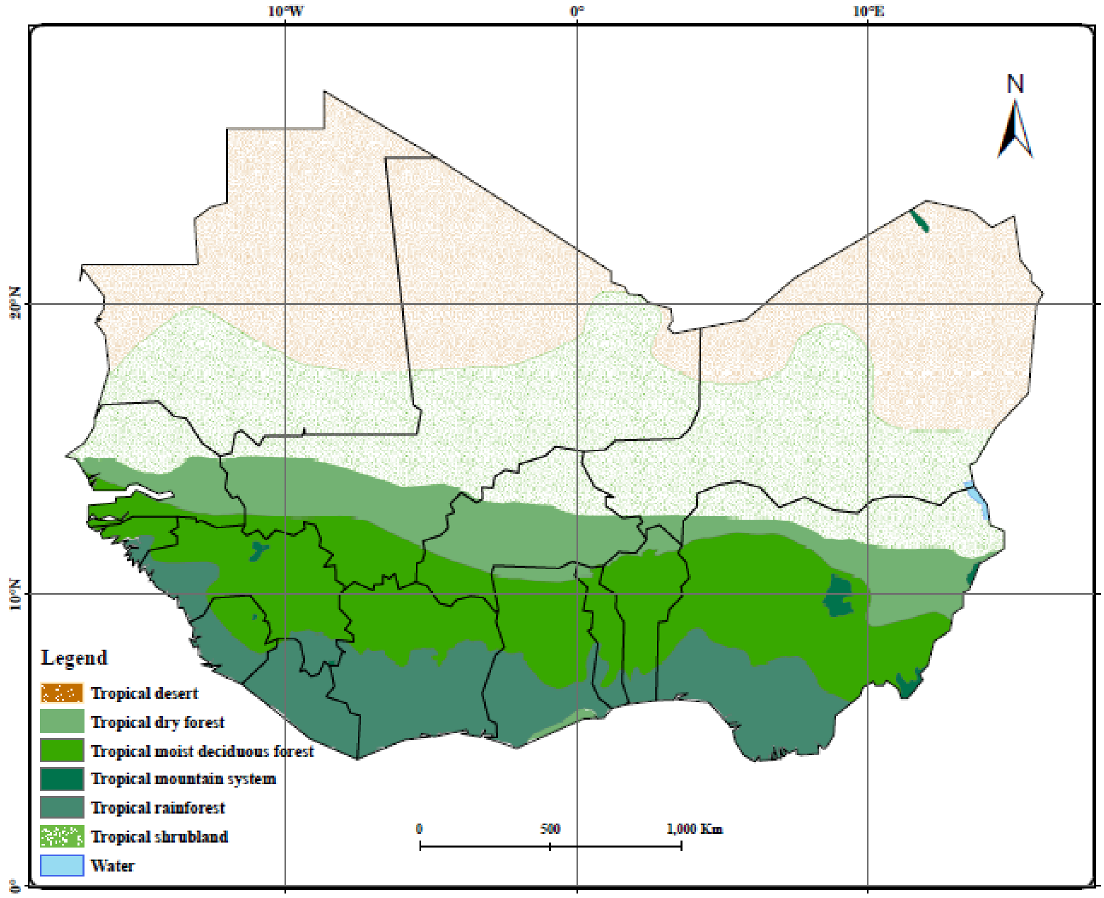


Figure 3.5. Ecotones of sub-Saharan West Africa. *Data source* (FAO, 2000)

The wide range of climatic regimes and ecosystems (Figure 3.5) such as forests, savanna, rivers, mountains, mangroves and coastal areas, makes the sub-Saharan West Africa unique and rich in biodiversity. The Sahelian zone has several wetlands along the Niger and Senegal rivers, Lake Chad and floodplains in Senegal and Niger which are very important for migratory birds. To the southern part of the region is the inner Niger delta, a vast floodplain (more than 30,000km^2) rich in natural resources. Situated in the middle of the Sahelian landscape is the Sudan and Guinea savanna, an area rich in natural resources and featuring varied ecosystems (lakes, forest, floodplains, flooded grasslands and savanna) which supports the livelihoods of millions of people. The Guinea forest, for example, contains half of the mammal species on the African continent, including the rare pygmy hippopotamus, the zebra duiker and the drill which is the most threatened primate (UNEP, 2006).

3.4 Topography, geology and soils

The sub-Saharan West Africa is generally characterised by a relatively flat terrain, lying usually between 200 to 500m above sea level, except in some isolated high points which exist in many states along the southern coastal areas (Speth et al., 2010). In the northern part of the region, stabilised sand dunes of less than 20m in height are found. However, a series of mountainous massifs are equally identified in the northern part such as Adraras of Iforas in Mali, which rose to 800m and Air Mountain in the Niger Republic, rising to 2300m (Le Houerou, 1980). Other areas of high lands are in the eastern part of Nigeria and the Guinea highlands among others as shown in Figure 3.6.

The sub-Saharan West African geological formation varies into different units across the region. In the western part near the Atlantic coast is the Guinea Rise, formed by the southern part of southern half of the West African craton, otherwise known as the Man Shield. The narrow Pan African belt of the Rokelides on its western boundary is associated with some marginal reactivation of the Archaen rocks. North of the craton from the

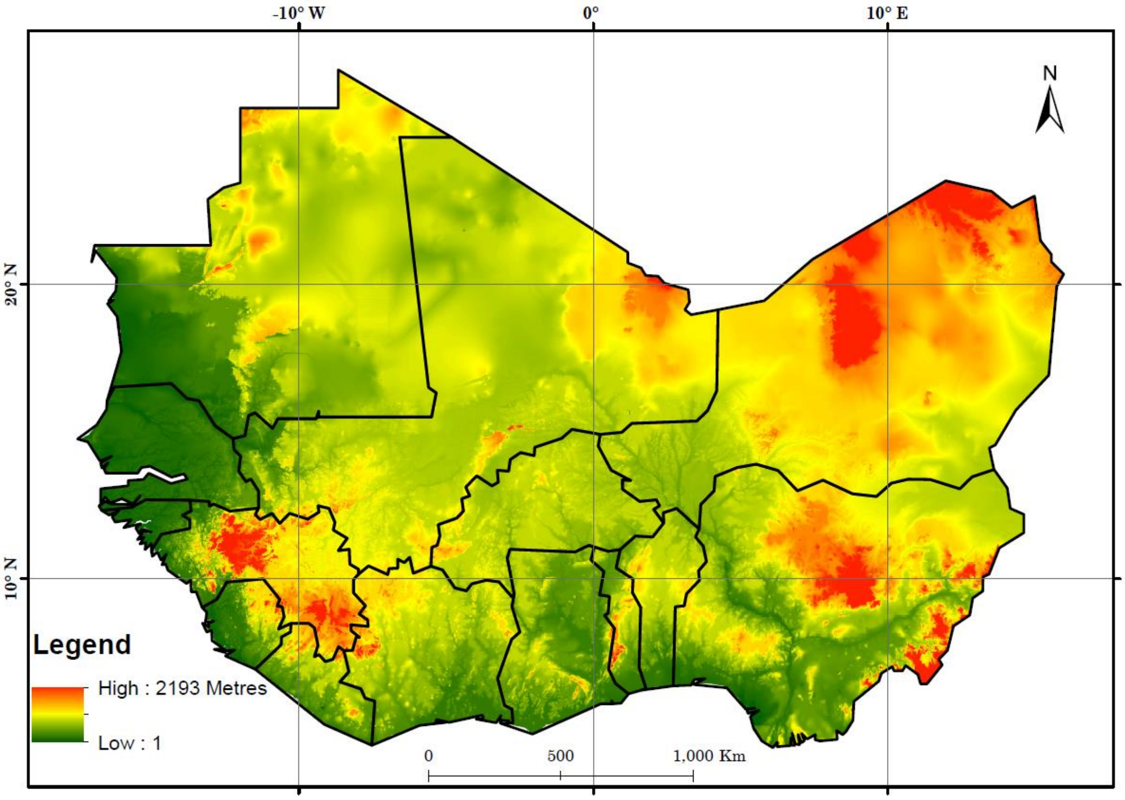


Figure 3.6. Elevation map of West Africa

Source: *Data available from the U.S. Geological Survey*

Infracambrian to lower Palaeozoic sediments of the great Taudeni Basin, obscured in the east by continental tertiary to quaternary deposits as shown in Figure 3.7. The Bove basin in the south-west is occupied by lower Palaeozoic sediments which interrupt the continuity of the Rokilide belt with the Mauritanide belt, and forms the eastern boundary of the much younger Senegal basin (Wright, 1985).

The eastern part of the craton is covered by Infracambrian to lower sediments of the Volta basin, separated by the intensely thrust-faulted rocks of the Togo belt from the mainly Pan African rocks of the Togo-Benin-Nigeria swell, also known as the Benin-Nigeria Shield. This is crossed by the narrow Cretaceous Bida basin and Benue Trough, which link up with the cretaceous to quaternary sediments of the Niger Delta.

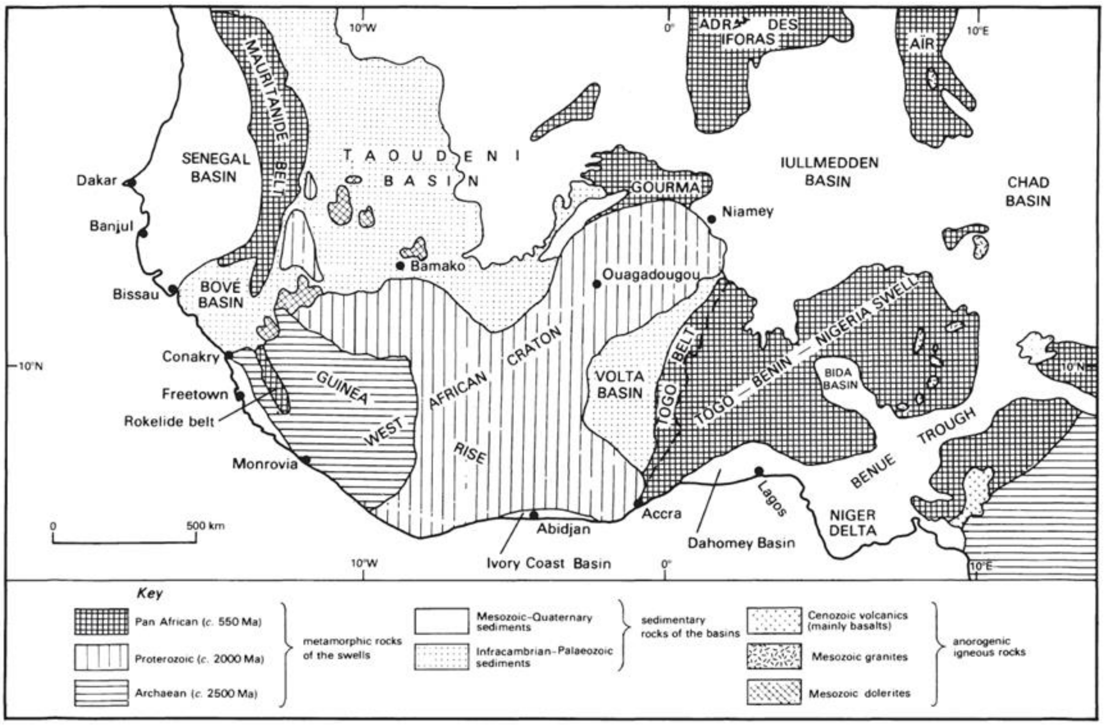


Figure 3.7. Main geologic unit of West Africa (Wright, 1985).

The Pan African rocks in the Adrar des Iforas and the Air, which form the northern boundary of the Mesozoic tertiary Iullmedden basin, are southern extensions of the basement block of the Hoggar, and the Pan African rocks of the Gourma on its western boundary. Further east is the Chad basin, mainly occupied by quaternary sediments. Along the southern coast of sub-Saharan West Africa are smaller, narrower basins dating back to the cretaceous in which sedimentation is still ongoing. Additionally, large dolerite sills of the Mesozoic age are found in the south-western Taoudeni basin, and there is an important Palaeozoic to Jurassic and tertiary province of granitic intrusions in Niger, Nigeria and Cameroun. Basaltic volcanism was widespread in the Cenozoic, mainly east of the craton (Wright, 1985).

Soils in sub-Saharan West Africa are products of recent geologic activities and climate. Thus, the variation between periods of extreme aridity and humid conditions strongly influence the process of soils formation in the region. Generally, according to Nicholson (1995), three main categories of soils can be distinguished in the area, these are;

a) ***Sandy Aeolian soils***: This is a deep and sometimes uniform soil over a large expanse of the northern part of sub-Saharan Africa up to the Saharan boundary. These soils are remnants of arid periods and cover about 50% of the area. They are yellowish-red in colour and slightly acidic, luvic arenosols according to the FAO classification as shown in Figure 3.8. In some cases, where depressions occur, vertisols are found (Le Houerou, 1980). However, they are generally limited to areas where mean annual rainfall is about 500mm.

b) ***Iron-rich (loamy) soils:*** These soils are marked mostly by bare expanses of hard, rocky and impervious sandstone or laterite crusts which form due to the decomposition of the underlying rocks. They usually have a loamy texture, are quite erogenous and are prone to intense erosion. The organic matter content of these soils is generally low, with a high content of potassium and traces of other elements.

c) Fluvial or Lacustrine soils: These soils are produced from sediments of former lakes or streams or along the inland Niger Delta region. They often have a sandy surface and clay layers at the bottom, hence they have poor drainage. In most of the areas these recently formed types of soil have high fertility.

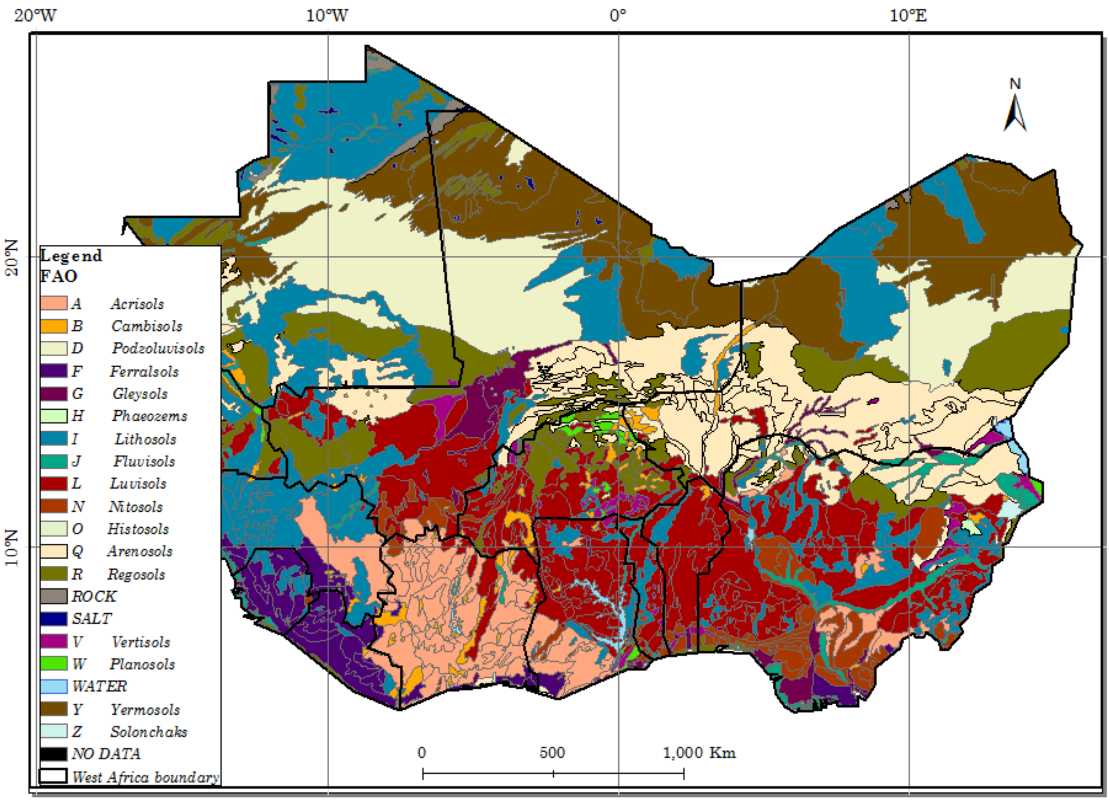


Figure 3.8. FAO Soil map of West Africa. *Data source* (FAO, 1981)

3.5 Population and Land use

The sub-Saharan West Africa is a densely populated region with highly diverse inhabitants. The population of West African countries as of 2011 is estimated to be around 300 million, with an average population density of 49.2 persons/km^2. The region is characterised by high population growth rate which increased from 70 million in 1950 to about 318 million in 2010, and it is projected to be around 650 million by 2050 (United Nations, 2015).

Land uses in sub-Saharan West Africa are numerous and generate goods and services to the populace. However, agricultural activities are the dominant activities depending on the location in the region. The area is recognised as one of the fastest regions of land cover conversion to agriculture in the past 20 years (Nkonya et al., 2013). In the more extreme northern part around the Sahel border, nomadic and transhumant pastoralism is the dominant land use activity. In addition, some form of cereal cultivation is carried out by the transhumant farmers, with millet being the dominant crop produced (Le Houerou, 1980). In the Sudan savanna zone, the competition between rangelands and cropland is very common, leading to the clearance of more virgin rangelands to provide additional space for farming in order to support the food demand of the ever growing population in the area. Finally, down southward, around the Guinea savanna and rainforest areas, agriculture is still the dominant activity, though in some cases lumbering is practised which adds pressure to the forest in the region.

3.6 Environmental challenges

Environmental problems and challenges associated with sub-Saharan West Africa are manifold; specifically the northern part of the region which became an epicentre of scientific investigation following the devastating drought of the 1970s, which led to the death of hundreds of cattle and the displacement of millions of people (Nicholson, 1995, Le Houerou, 1980). The region suffers from deforestation along the coast; soil erosion, desertification and wetland degradation among others (Mabogunje, 1995).

Land degradation and desertification are the major causes of biodiversity loss in sub-Saharan West Africa (Darkoh, 1998, Symeonakis and Drake, 2004, Vogt et al., 2011, Owusu, 2012) . Three major factors contribute to these problems: a relatively dense and growing population with strong dependence on natural resources; relatively easy access to resources; and recurrent droughts (Darkoh, 1998). These factors affect grasslands, steppe and savanna and woodlands. Dust storms, forest fires, locust outbreaks and population displacement are all linked to the phenomenon of desertification, and have strong, negative consequences for people, in particular, through the loss of livelihoods and economic opportunities (Higginbottom and Symeonakis, 2014).

Land degradation affects biological diversity directly and indirectly. It may affect the survival of species and alter processes that support their life, or it may trigger socio-economic phenomena that impact on living species and their ecosystem. Land degradation processes, such as water and wind erosion, directly affect biodiversity. Along major river basins, siltation processes accumulate debris and materials that engulf natural vegetation, such as

Acacia nilotica riparian forest. Soil erosion contributes to moving the seed capital of the ground, uprooting grassy as well as woody species, and in accumulated areas it smothers valuable species. This commonly occurs in the sand dune areas of countries such as Mauritania, Mali, Niger, northern Nigeria and Senegal.

The coping strategies adopted by the people to deal with environmental change in the region are also indirectly causing land degradation. The migration of people south towards to the sub-humid and humid tropical areas has resulted in the depletion of natural resources; loss of primary forests and woodlands, repeated logging of the secondary vegetation, and the depletion of a number of species (Nicholson, 1995). Additionally, the influx of refugees from war-stricken areas such as Nigeria, Niger, Mali etc., also triggers severe land degradation in host regions. The degradation and fragmentation of the natural landscape caused by agricultural expansion affects the survival and regeneration of the ecosystem in the area.

Finally, the impact of climate change and occasional drought exert additional pressure to the marginal ecosystems of the area. The impact of El-Nino especially in the northern part of sub-Saharan West Africa also adds to the environmental problems in the region, thereby forcing people to abandon their lands and move to favourable areas. This sometimes led to agricultural intensification in the new settled areas, thereby creating more damage to the environment through vegetation clearance and rapid urbanisation. Therefore, despite the development and progress witnessed in sub-Saharan West Africa, environmental knowledge and conscious is still scanty among the rural dwellers and land degradation and desertification still remains a major environmental challenge in the region.

According to IPCC (2013), drivers of climate and environmental change in sub-Saharan are both natural and anthropogenic, which all geared towards altering the earth's energy budget. And it was discovered that radiative forcing (RF) is the most common among the drivers. Positive RF is closely related to land degradation in the area because it leads to surface warming mostly due to the increase in GHGs and CO_2 concentration in the atmosphere. This may further aggravate land degradation and overall changes in the all components of climate system in the region because all the Representative Concentration Pathways (RCP) shows higher CO_2 concentration in 2100 relative to present time due to further additional CO_2 into the atmosphere during the 21st century.

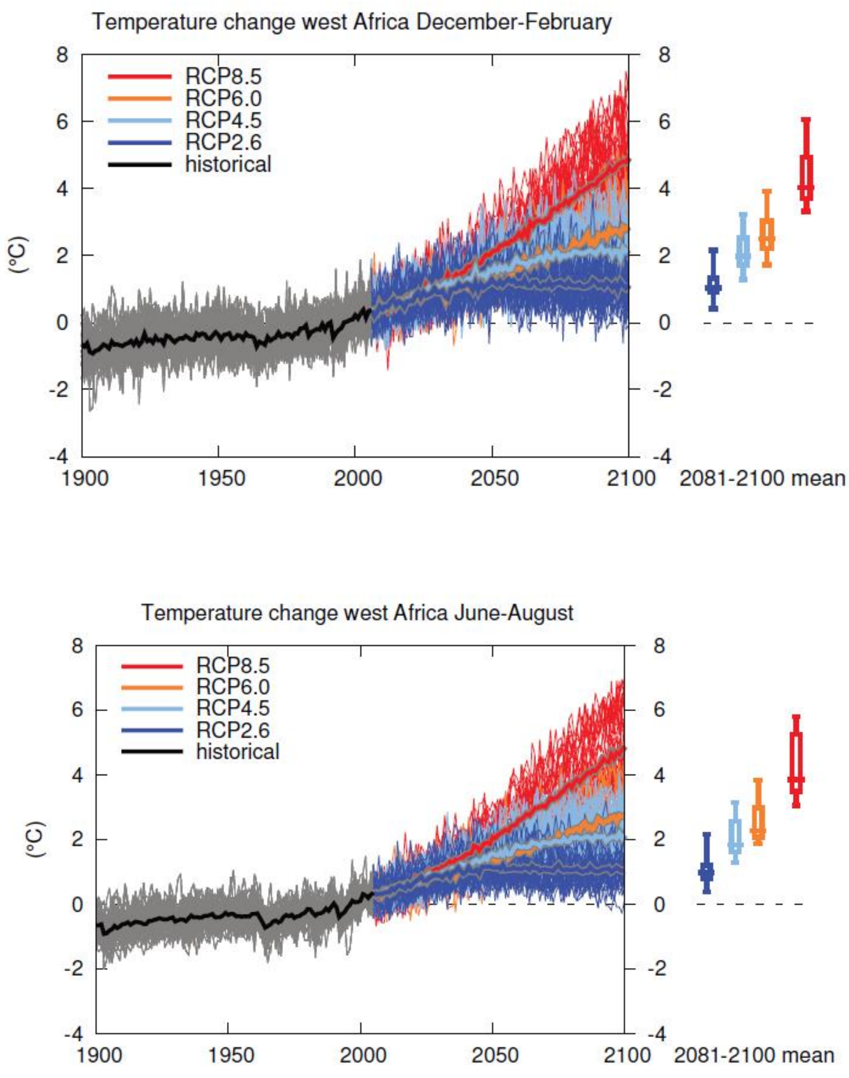


Figure 3.9. Temperature change relative to 1986-2005 averaged over land grid point in West Africa (IPCC, 2013)

Future projection of climate and other environmental changes in sub-Saharan Africa is generally dominated by monsoonal system that brings rainfall during one season only (Polcher et al, 2011). And the climate in the region is very likely continue to warm during the 21st century. Furthermore, sub-Saharan regions closed to the Sahel which is already dry, will likely to remain very dry according to CMIP5 model. However, there is low confidence about drying and wetting of the region, with medium confidence in projection of a small delay in the rainy season (IPCC, 2013).

4 Chapter 4: Land degradation assessment using trend analysis in sub-Saharan West Africa

Parts of the work presented in this chapter have been published as:

Ibrahim, Y., Balzter, H., Kaduk, J. & Tucker, C. 2015. Land Degradation Assessment Using Residual Trend Analysis of GIMMS NDVI3g, Soil Moisture and Rainfall in Sub-Saharan West Africa from 1982 to 2012. *Remote Sensing,* 7, 5471-5494.

4.1 Introduction and rationale

In Chapter 2, the concept, biophysical manifestation and various methods of land degradation monitoring and assessment were highlighted. In this chapter, I applied the Residual Trend Analysis (RESTREND) method to assess land degradation in sub-Saharan West Africa, and to compare the suitability between soil moisture and precipitation in land degradation assessments using the RESTREND model.

The livelihoods and wildlife in the sub-Saharan West African environment depend largely on the moisture regime, which is the main limiting factor to ecosystem productivity (Hulme, 2001). Historically, wetter climates prevailed in the Sub-Saharan region between 1930 and 1965, which was followed by extreme widespread droughts from 1968 to 1973, 1982-1985 and in the 1990s leading to large scale food shortages and famine (Hellden, 1991, Hulme, 2001). Speculations about the major causes of these droughts are still unresolved (Olsson et al., 2005) and to date there are two major multifaceted explanatory frameworks. On the one hand, it has been argued that rainfall variability in the region is influenced by large scale sea surface temperature (SST) patterns which is evidenced by overall changes in anomaly trends (Giannini, 2003, Caminade and Terray, 2010). On the other hand, some studies have claimed that rainfall variability in the area can be traced to the overall changes in land cover and land-atmosphere interactions in the region (Nicholson, 2000, Myoung et al., 2012).

The overall impacts of the drought led to widespread land degradation in the sub-Saharan West Africa, especially in the Sahel. However, the debate on the relative importance of climate and human actions as controlling factors of land degradation, and in particular vegetation degradation in the region, started in the 1930s (Tucker and Nicholson, 1999). Today, land degradation, synonymously referred to as ‘desertification’ in this thesis, is identified as one of the pressing environmental problems in the sub-Saharan West Africa (Mellenium Ecosystem Assessment, 2005, UNEC, 2007). It implies a persistent reduction of land productivity. This reduction expresses itself in a declining provision of the land’s biological products, including forage, food, fibre, timber, etc.

Research on land degradation in the sub-Saharan West Africa from 1980 onwards has followed a new line of reasoning, enabled by the availability of increasingly long-term satellite time-series data (Nicholson, 1998). The accessibility of NDVI data from the National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer (NOAA-AVHRR) has enabled intensive research in the Sahel environment. Many recent studies have questioned the continued land degradation in the area. Some studies have described a greening of the Sahel (Eklundh and Olsson, 2003, Anyamba and Tucker, 2005, Helldén and Tottrup, 2008, Fensholt et al., 2012, Eastman et al., 2013) and an increase in NDVI; others have found mixed greening and browning – a decrease in NDVI – in satellite data records of the region (Brandt et al., 2014b, Huber et al., 2011). Finally, some studies have argued that vegetation impoverishment takes place in the Sahel and other areas of sub-Saharan Africa through species migration and local extinctions in spite of the overall greening trend, which is evidence for continuing land degradation (Brandt et al., 2014a, Herrmann and Tappan, 2013).

However, recent studies have suggested that the overall increase in greening across different dryland regions is largely due to the increase in CO_2 in the atmosphere and its resultant effects on the plant water savings (Lu et al., 2016). This suggestion was reaffirmed by Donohue et al. (2013) where they applied gas exchange theory and predicted a 14% increase in atmospheric CO_2 between 1982-2010. This according, to them, led to a five to

10% increase in green foliage cover in the warm arid environment. This suggested that in addition to major environmental factors such as rainfall, CO_2 is also an important component of land surface processes and plays an active role in the greening or browning trend in the arid environment. Thus, in some areas, an increase in greening was recorded without the corresponding increase in rainfall. While in some others, rainfall has increased with no increase in vegetation activity (Fensholt et al., 2012).

Drivers of vegetation photosynthetic capacity in the sub-Saharan West Africa are manifold, but it is generally believed that rainfall is the main factor, and strong relationships with NDVI in the area have been found (Olsson et al., 2005, Herrmann et al., 2005, Sendzimir et al., 2011). The best correlation between NDVI and rainfall ascends to multi-month moisture totals and NDVI lagging rainfall. Rainfall is not directly available to plants but is partitioned into runoff, groundwater recharge, soil moisture and evapotranspiration. This suggests that soil moisture, an index of the portion of the rainfall that becomes directly available to plants, would be a better indicator of the greening or increased photosynthetic capacity than immediate rainfall in the area (Nicholson et al., 1990). Many studies in the sub-Saharan Africa have neglected the influence of soil moisture and focus only on rainfall when examining Sahelian vegetation greenness trends. Until recently, a lack of long-term soil moisture data for the region has limited progress in this field. Today, gridded long-term satellite and model based soil moisture data products are available, providing new opportunities to further explore the vegetation dynamics in the area.

The link between soil moisture and vegetation dynamics impacts on the structure and function of arid and semi-arid ecosystems. It has been argued that the development of dryland vegetation depends largely on the availability of soil water resources and irregular patterns of vegetation distribution, a recurrent attribute of dryland environment which is usually associated with heterogeneous patterns of root zones soil moisture (Mueller et al., 2014). The feedback between vegetation and soil moisture vary not only across various ecosystems, but also within and between different vegetation life forms and canopy structures. This led to the formation of two different stable states of vegetation: one with moister sub-canopy soils that are capable of supporting woody seedlings and plant growth and another on dry inter-canopy soils that are too desiccated for woody vegetation growth and survival. As a result of non-linear changes caused by the dynamics of vegetation-soil moisture feedbacks, changes in climate forcing and the disturbance regime can lead to rapid degradation from sparsely vegetated to bare soil conditions. The abrupt nature of this change has been often associated to the rapid rate of desertification, taking place in most of the drylands around the globe (Nicholson, 2000).

Greening or increased photosynthetic capacity is generally seen as an indicator of vegetation improvement and browning or decreased photosynthetic capacity is an indicator of reduced vegetation density which, if continued over time, results in land degradation. These observables have widely been used to study land degradation and to disentangle human impacts and climate influence on the greening-browning trends (Hoscilo et al., 2014). From the traditional use of rain use efficiency (Hein and De Ridder, 2006, Fensholt and Rasmussen, 2011, Fensholt et al., 2013) to the process-based modelling approach (Seaquist, 2009) and to the more recent statistical and residual trend analyses (Wessels et al., 2004, Evans and Geerken, 2004, Wessels et al., 2007, Helldén and Tottrup, 2008, de Jong et al., 2011, Huber et al., 2011, Fensholt et al., 2012), the majority of studies have assumed that correcting for climate components of greening-browning allows an examination of the status of an ecosystem, which can then be used to infer whether an area is degraded or not.

The use of Rain Use Efficiency (RUE), a ratio between above-ground Net Primary Productivity, ANPP, and annual rainfall) to study land degradation has been questioned by some authors (Wessels et al., 2007, Prince et al., 2007). This is due to the over-dependence of RUE on ANPP, the lack of accurate information on ANPP for very low rainfall and the discovery that some land degradation scenarios do not cause changes in ANPP. For instance, the study by Huenneke et al. (2002) found a replacement of grassland by desert scrub, an indication of land degradation, with little or no reduction in average ANPP. Although the use of statistical trend analysis in detecting land degradation has its own limitations (Forkel et al., 2013, Wessels et al., 2012), residual trend analysis (RESTREND) (Evans and Geerken, 2004) is today one of the most reliable trend analysis techniques for disentangling the effects of climate from human-accelerated land degradation and its results were found to be more effective than that of the RUE method.

In the RESTREND method, analysing the residuals from the NDVI-soil moisture or NDVI-rainfall regression model over time reveals the proportion of NDVI change that is not due to climatic variability. A significant increase of the residual NDVI over time is considered as an indication of an increase in vegetation photosynthetic capacity, while a gradual decrease is suggesting a decrease in vegetation photosynthetic capacity. Areas with a long-term decline in vegetation vigour are assumed to be subject to land degradation. The main limitation of most of the previous studies on land degradation using the RESTREND method is that they largely constrained themselves to the analysis of rainfall as the sole driver of vegetation productivity with little or no consideration of soil moisture, even though soil moisture is the ecological water resource that plants can access.

In this chapter, I applied the RESTREND method to assess land degradation in the sub-Saharan West Africa using the new GIMMS NDVI3g, rainfall and soil moisture data products. The specific aim and objectives of this chapter were presented in chapter 1. The chapter compares the spatial and temporal distribution of degraded areas and their links to rainfall and soil moisture changes from 1982 to 2012. The chapter will provide answers to the research question;

How effective is the RESTREND method in land degradation assessment using NDVI-rainfall and NDVI-soil moisture models?

4.2 Materials and methods

4.3.1 Datasets

NDVI data

Normalized Difference Vegetation Index (NDVI) is the most commonly used remote sensing dataset for vegetation and land degradation monitoring. In this study, NDVI is used to represent the photosynthetic capacity of vegetation after Myneni and Hall (1995) and it is widely used as a surrogate for various vegetation characteristics (Anyamba and Tucker, 2005, Kogan, 2005). It is a sensitive indicator of the interannual variability of rainfall. This study uses the Global Inventory Modelling and Mapping Studies (GIMMS) NDVI 3rd generation (NDVI3g) dataset for the African continent (Pinzon and Tucker, 2014). The data is a new long-term time series of NDVI which was derived from NOAA-AVHRR instruments (sensor 7, 9, 11, 14, 16, 17, 18 and 19). The data is an improved version of the previous GIMMS NDVI and is processed using an adaptive Empirical Mode Decomposition (EMD) (Pinzon et al., 2005). The EMD is used to find and remove artefacts from the NDVI time-series including solar zenith angle, trends associated with orbital drift, discrepancies in the AVHRR data among sensors due to their differences, and other factors that introduce non-linear and non-stationary effects to the dataset. In contrast to the previous version, the new dataset covers the period of July 1981 to December 2012 with a bi-weekly temporal and 8km spatial resolution (Pinzon and Tucker, 2014). The effect of sensor change that affected the quality of the AVHRR sensor is significantly reduced in the new GIMMS NDVI3g.

The GIMMS NDVI product has been tested and compared with other products such as Spot-4 VGT and MODIS NDVI by other studies and it was found to be consistent with these products. The study by Fensholt et al. (2006) showed that GIMMS NDVI explained more of the variance of Spot-4 VGT NDVI compared to PAL; therefore it is considered the more accurate long-term AVHHR data product. Similarly, the work of Fensholt et al. (2009) and Schucknecht et al. (2013) reported the consistency and strong correlation between the average annual value of GIMMS NDVI and MODIS NDVI, this relationship was found to be very strong in the semi-arid West African zone.

The data was processed for January 1982 to December 2012 in order to analyse only years with complete data coverage. The NDVI3g dataset comes with the different quality flags, and only flag 1, which is a good value, was used for this study in order to restrict the analysis to the most reliable NDVI values (Tucker et al., 2005, Xu et al., 2013). The bi-monthly data was converted to monthly aggregates using the Maximum Value Composite (MVC) method (Holben, 1986) in order to further minimise the effects of cloud contamination. They were projected to the WGS 1984 coordinate system. Finally, the data corresponding to the spatial extent of the study area, i.e. 17^0 W - 15^0 E and 4^0 N - 20^0 N, was extracted.

Rainfall data

The sub-Saharan West Africa has a sparse and irregular rain gauge network (Dinku et al., 2007). In this study, the newly available Climate Research Unit (CRU) of the University of East Anglia time series (TS) version 3.21 products, released in July 2013 and covering the period 1901 to 2012 were used. The CRU TS v3.21 data is a monthly gridded rainfall estimate based on monthly observational data, which is calculated from daily or sub-daily data by National Meteorological Services and other external agencies.

The data consists of total monthly rainfall in millimetres calculated on a 0.5^0 grid and are based on an archive of monthly averages of daily maximum and minimum temperatures and rainfall provided by over 4,000 weather stations distributed across the world (Jones and Harris, 2013). The CRU v3.21 is an updated version of the CRU v3.20, and extended to 2012 record. All the errors incurred in the old version were corrected (Jones and Harris, 2013). The rainfall data covers the entire period for which NDVI is available. The data was resampled to an 8km grid using a nearest-neighbour algorithm.

Soil moisture data

Soil moisture estimates were generated by NOAA's National Centre for Environmental Prediction (NCEP), Climate Prediction Centre (CPC), with global spatial coverage at 0.5^0 resolution from 1948 to present. The data is calculated on a daily time step based on the water balance in the soil by a layered hydrological model using observed rainfall and temperature (Van den Dool et al., 2003) and converted into a monthly product (V2). The rainfall data used in the model is based on an interpolation of rain gauge observations at over 15,000 stations worldwide and collected from version 2 data sets of the Global Historical Climatology Network (GHCN) and Climate Anomaly Monitoring System (CAMS) using an optimum interpolation algorithm. The monthly temperatures used in the model were coined from the station observations.

The CPC soil moisture product was modelled based on a single column depth at 1.6m because, for a land surface process, the moisture in the upper 1-2m is the soil moisture pool that can evaporate back to the atmosphere. It has a maximum water holding capacity of 760mm, a common porosity of 0.47 respectively (Fan and van den Dool, 2004). The data was tested and validated with *in situ* soil moisture as well as other global products. In spite of its simplicity, the product matches the seasonal and interannual variability of *in situ* soil moisture fairly well. The results of its comparison have shown that it agrees well with most of the observed and other modelled products including the Gravity Recovery and Climate Experiment (GRACE) soil moisture product. Its column depth of 1.6m is suitable for vegetation growth, as soil moisture content within the upper 60cm is the key factor that restricts seed germination and seedling growth and affects vegetation growth and density (Li et al., 2013). Dirmeyer et al. (2004) found the CPC soil moisture product to be suitable for a warmer climate that is marked by contrasting wet and dry seasons; hence it is suited well for the sub-Saharan West African environment.

The data corresponding to the temporal and spatial extent of NDVI and rainfall was extracted, resampled and projected to the NDVI and the rainfall format.

4.3.2 Methods of analysis

In this section, I describe in detail the analysis and the statistical techniques applied to evaluate the nature and the strength of the linear relationship between NDVI and rainfall, or respectively soil moisture, in order to examine the spatio-temporal patterns of the residual NDVI trends over the 31 years of the study period (January 1982 to December 2012) which was used to infer on land degradation trends.

Regression analysis

First, pixel-wise Ordinary Least Square (OLS) regression models of NDVI against rainfall, respectively soil moisture, were computed using mean annual data. The OLS minimises the sum of the squared residuals and it is widely used in environmental studies (Foody, 2004). The method measures the linear relationship between a dependent (y) and independent variables (x), and it is represented by the equation 4.1:

$$y = \alpha + \beta x + \varepsilon \quad [4.1]$$

Where;

y = Dependent variable and in this case the NDVI

x = Independent variable i.e. rainfall and or soil moisture

α = intercept which represents the value of y when x is (or is near 0) (measured in units of the y variable).

β= slope of the relationship between the x and y variables, and it measured the rate of change of y per unit change of x, while ε is the error term.

Residual trend analysis method (RESTREND)

The RESTREND analysis method examines the trend of the residual differences between the observed NDVI and the predicted NDVI from the linear regression model with either rainfall or soil moisture as the explanatory variable. The method assumes that water is the most limiting factor to vegetation productivity in most of the dryland ecosystems and there is a strong correlation between vegetation productivity and climatic variables in dryland areas (Evans and Geerken, 2004, Huber et al., 2011). Ecosystem productivity in drylands reaches its climax in years with a very high amount of rainfall; hence it is possible to understand the effect of human-induced activities on the general vegetation condition if the impacts of rainfall and other climatic factors such as soil moisture, have been accounted for. The method follows three steps.

1. Firstly, a regression model between the observed NDVI and rainfall or soil moisture is calculated for each pixel.
2. Secondly, the residual difference between the observed NDVI and the predicted NDVI from the linear model is calculated. This is called *RESTREND residuals*.
3. Finally, another linear regression of the RESTREND residuals against time is carried out. Trends in these residuals are interpreted as changes in vegetation productivity that are independent of rainfall or soil moisture and are used as an indicator of land degradation. In this regards, areas with negative trends of residuals are considered degraded while areas with positive trends are not degraded.

Mann- Kendal non-parametric trend analysis

This non-parametric statistical method was applied to examine the consistency of RESTREND in the study area. It was first described by Mann in 1945 and has been widely used in environmental time-series data analysis (de Jong et al., 2011). Kendall's coefficient τ measures the extent to which a trend is monotonically increasing or decreasing. It ranges from -1 to +1, where -1 indicates a trend that is consistently decreasing and never increases and +1 indicating the opposite. A value of zero indicates no trend.

All the mapping and statistical analyses were implemented in R version 3.0.1, an open source statistical software http://www.r-project.org/ using different library packages. Some of the R scripts used to run the RESTREND model are presented as Appendix 1.

4.3 Results

4.3.1 Comparison between the rate of NDVI change due to changing rainfall and soil moisture

Linear regression models of NDVI against soil moisture and/or rainfall were analysed. The per-pixel slope (Figures 4.1 and 4.2) and the intercept (Figures 4.3 and 4.4) were compared to examine the spatial patterns of the rate of change and the minimum value of NDVI and how they relate to changes in rainfall and soil moisture from 1982 to 2012. In the semi-arid Sahel zone, a strongly positive increase of NDVI due to soil moisture is observed, which is less pronounced in the humid coastal areas where soil moisture is generally not in short supply (Figure 4.1). NDVI increases in response to higher rainfall in the areas with positive slopes (Figure 4.2).

The intercept (Figure 4.3) represents the NDVI predicted by the regression when the soil moisture is zero. It shows that some scattered areas seem to be independent of soil moisture variability or do not experience low soil moisture conditions. This is likely due to the presence of water bodies like lakes and rivers or indicates continuous, sufficient precipitation as reflected by the increase of the NDVI values towards the Atlantic coast. However, as a general pattern, NDVI approaches zero when rainfall is zero (Figure 4.4). From 15^0N latitude northwards this pattern prevails, except in very small portions where the moisture from the nearby water sources such as Lake Chad in northern Nigeria, supplied and compensate for low rainfall due to natural through flow. Also in both the two figures, high values of NDVI are concentrated along the coastal areas in the southern and western parts of the study area; this is due to the availability of water in the soil throughout the year around these areas.

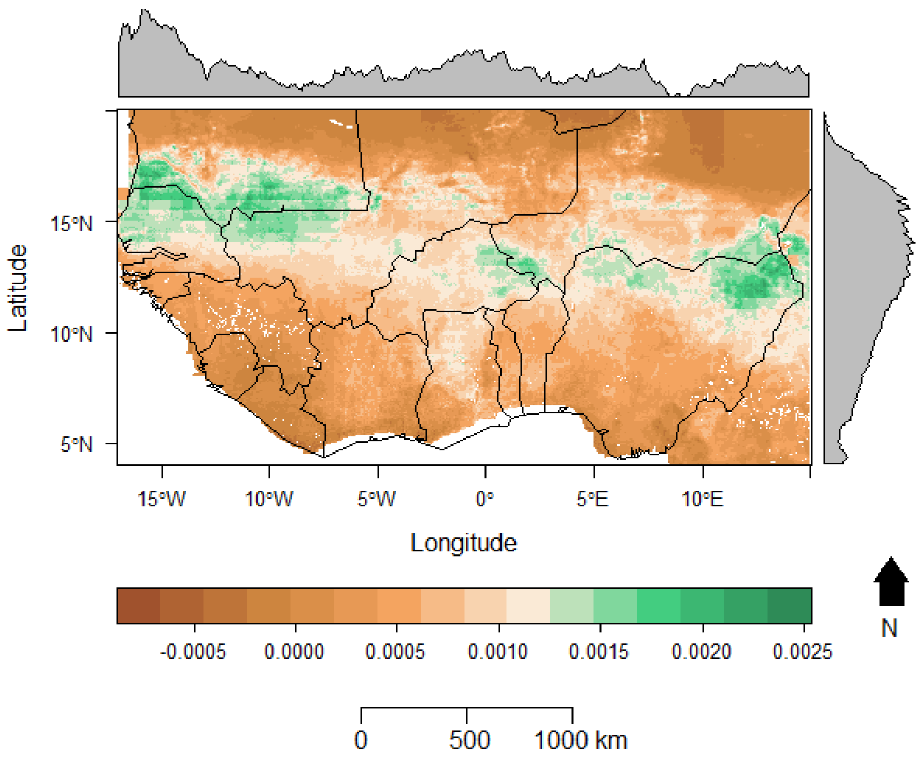


Figure 4.1. Spatial pattern of slope of the linear regression of NDVI against soil moisture

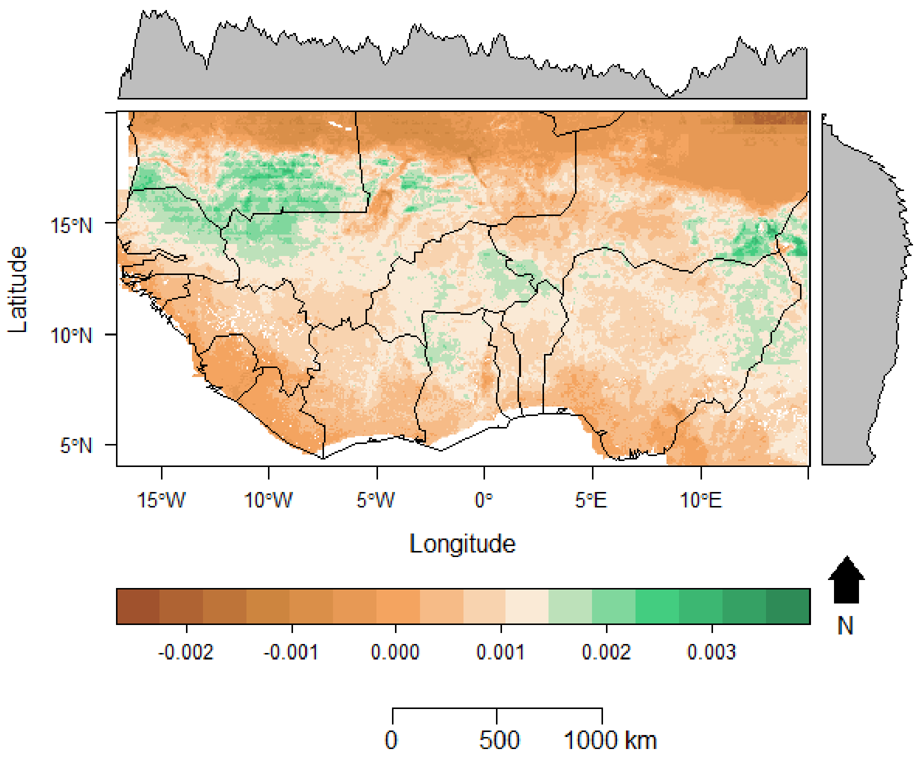


Figure 4.2. Spatial pattern of slope of the linear regression of NDVI against rainfall

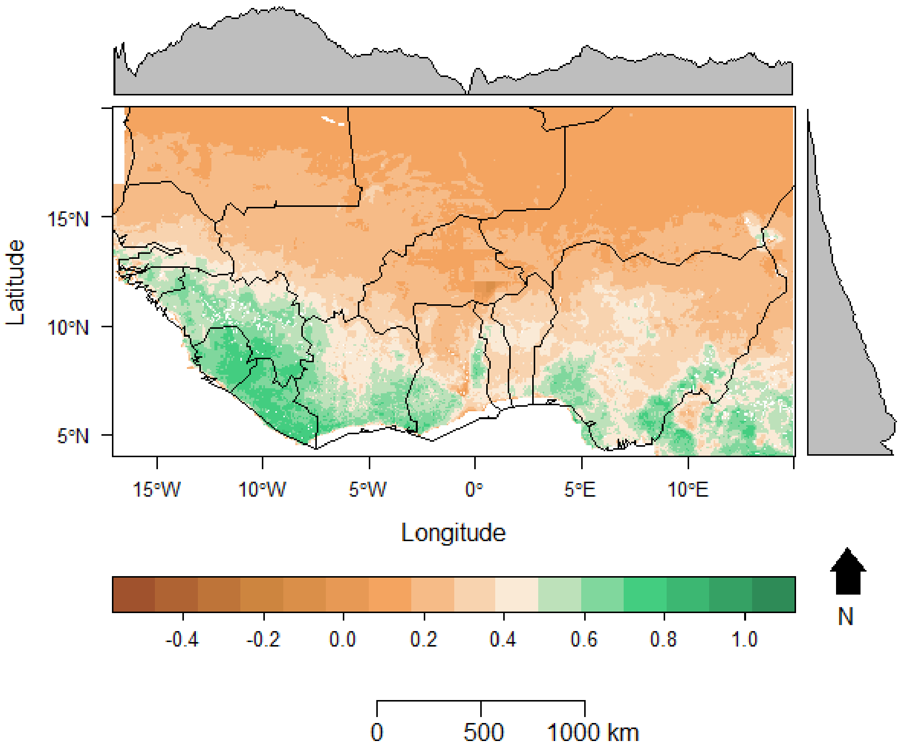


Figure 4.3. Intercept of NDVI in sub-Saharan West Africa when soil moisture is zero

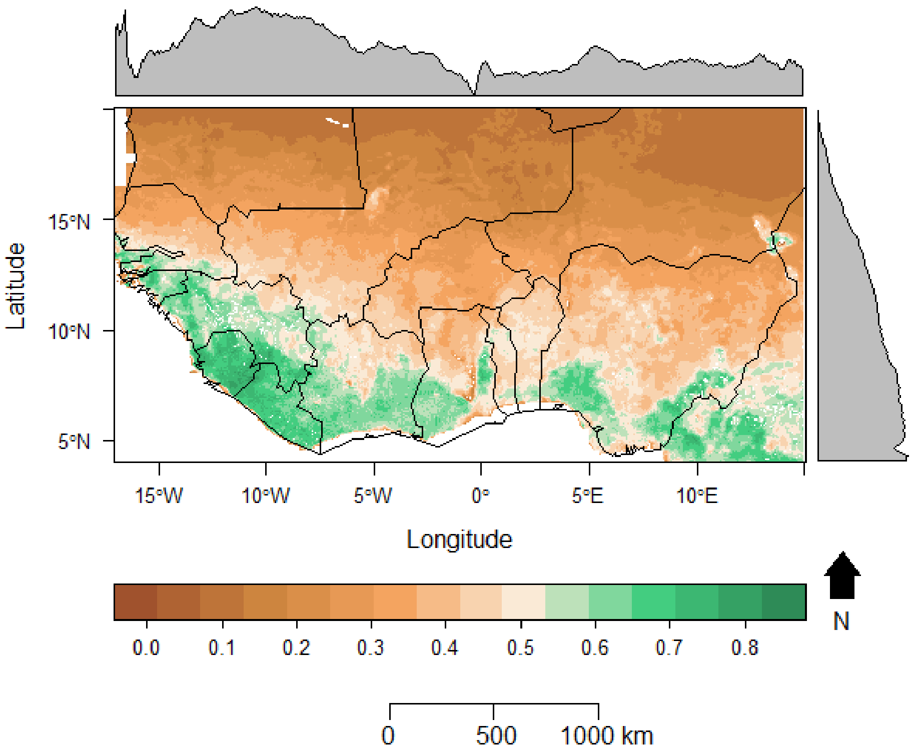


Figure 4.4. Intercept of NDVI in sub-Saharan West Africa when rainfall is zero

4.3.2 Spatial pattern of the residual trends of soil moisture and rainfall

An analysis of the residual NDVI that is not explained by rainfall (or soil moisture) and its trend over time provides additional information on the land degradation process. This trend was analysed spatially to identify regions with significant negative or positive trends of the NDVI residuals. Such areas show vegetation photosynthetic changes that are caused by factors other than moisture variability. The RESTREND method assumes that areas which show a significant negative trend are degraded, while those with a positive trend are improved or at least not degraded. Figures 4.5 and 4.6 respectively show the RESTREND results based on soil moisture and rainfall.

The figures show areas with positive and negative trends of vegetation productivity that have been adjusted for either soil moisture or rainfall. In Figure 4.5, the RESTREND residuals based on soil moisture show both areas with positive and negative trends. Further analysis was carried out to identify only areas with significant negative trend. Figure 4.7 clearly shows areas with significant negative trends based on soil moisture RESTREND and which are considered as degraded. In contrast (the rainfall-based RESTREND residuals in Figure 4.6) the trend does not clearly show desertified areas fairly well when compared to soil moisture RESTREND. A closer examination of areas with significant negative trends at 95%, a significant level based on rainfall as shown in Figure 4.8, is also found to be fairly negative compared to areas with significant negative trend based on soil moisture Figure 4.7.

Almost all parts of the study area show a mixture of degraded and non-degraded patches, raising doubts about the consistency of the results. However, areas with significant negative trends i.e. degraded areas can be

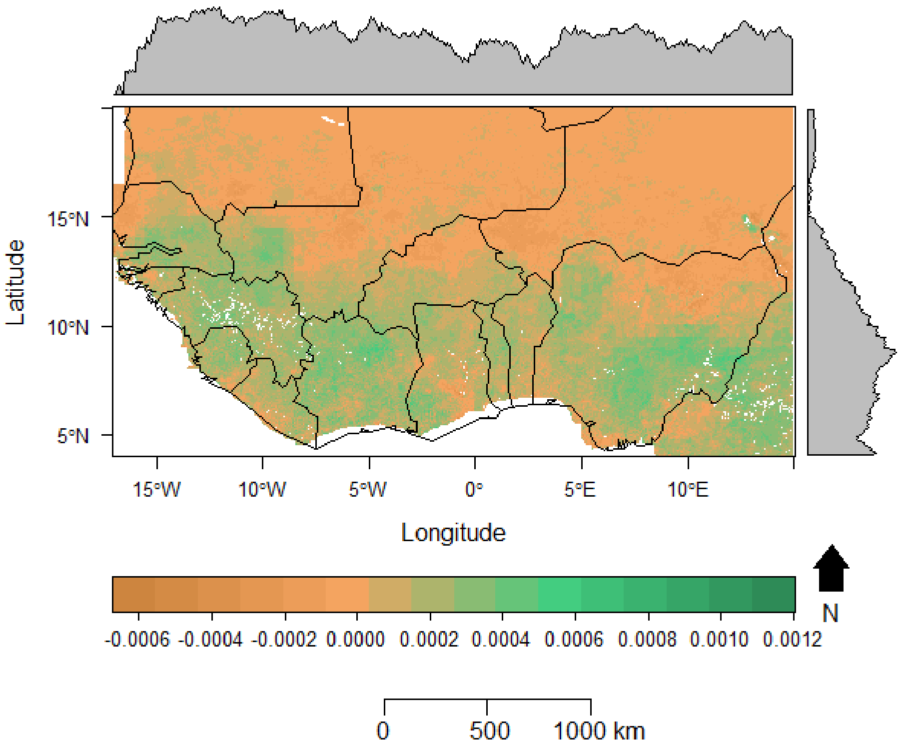


Figure 4.5. Spatial distribution of slopes of the residuals of regressions of NDVI against time from the RESTREND analysis using soil moisture

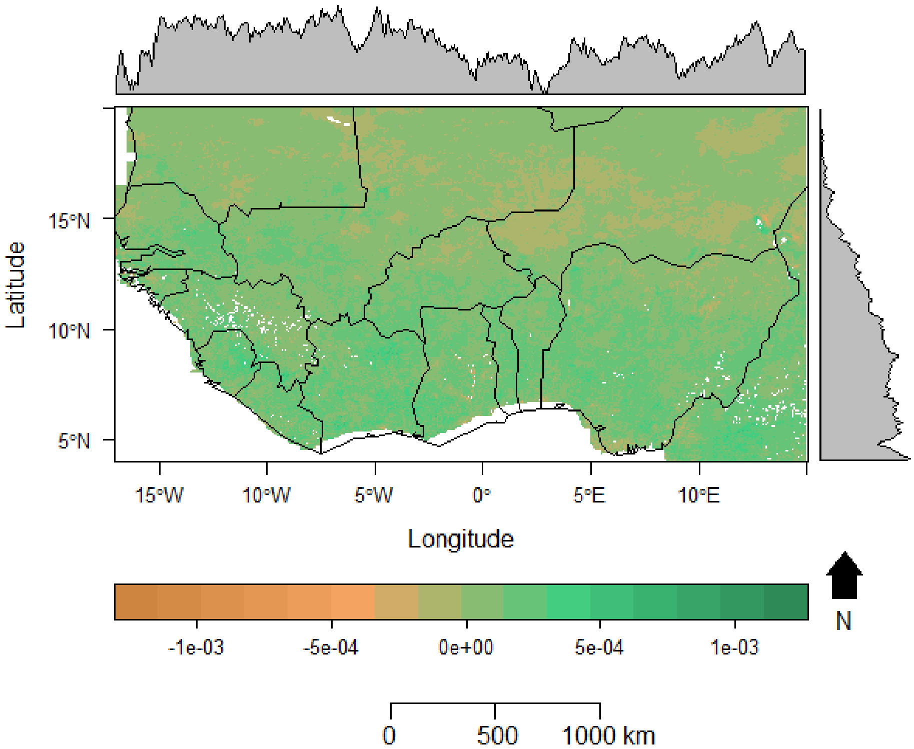


Figure 4.6. Spatial distribution of slopes of the residuals of regressions of NDVI against time from the RESTREND analysis using rainfall

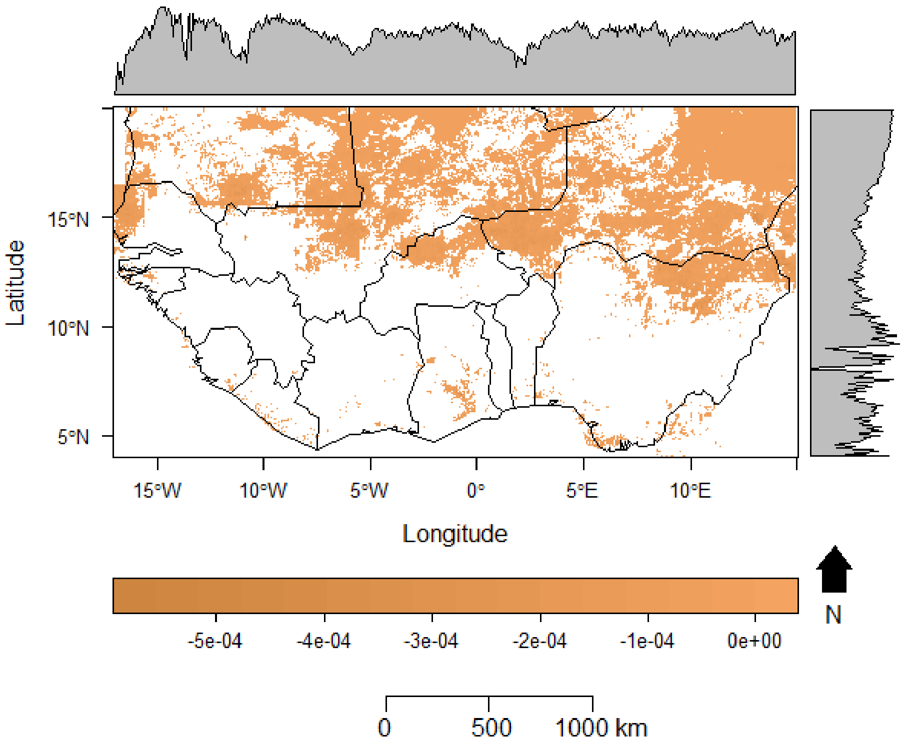


Figure 4.7. Areas with significant negative RESTREND (95% confidence) based on soil moisture

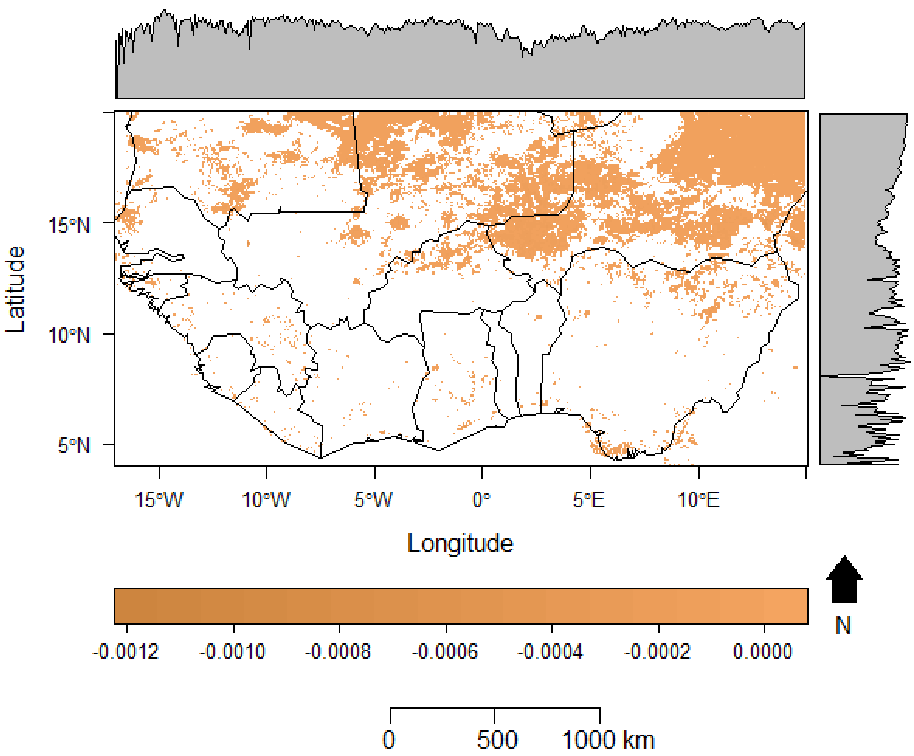


Figure 4.8. Areas with significant negative RESTREND (95% confidence) based on rainfall

***White colour indicates areas with non-significant changes**

seen more clearly in Figure 4.7 north of the 12^0 N of latitude, especially in northern Nigeria, Niger, Mali and northern Burkina Faso. Also in Figure 4.8, rainfall-controlled RESTREND shows degradation in the same region, but is less pronounced compared to Figure 4.7. The two maps in Figures 4.7 and 4.8 show that soil moisture adjusted RESTREND provides a much more robust and consistent identification of areas that show a land degradation trend than rainfall does as shown in the figures. Land degradation is not only confined to the more arid north. It also occurs within humid tropical regions, especially in Ghana, some parts of Côte d'Ivoire and other south-western countries in the area.

An examination of the distribution of positive and negative trends of the NDVI residuals from the two models shows that the soil moisture adjusted NDVI RESTREND has more of a negative trend than the NDVI RESTREND that is adjusted for rainfall variability, as shown in Figure 4.9. In Figure 4.9, the distribution of soil moisture adjusted NDVI residuals shows a predominantly negative trend. The rainfall adjusted NDVI residuals, on the other hand, show an overwhelmingly positive trend (Figure 4.10). This indicates a stronger influence of soil moisture on NDVI than rainfall partly due to exogenic soil water resulting from the run off from the surrounding higher areas which fosters vegetation growth. Equally, the effect of rainfall-soil moisture lead and lag relationship can as well play a major role, as it takes some few months of rainfall before soil moisture can become fully available for vegetation in sub-Saharan Africa and many other dryland areas.

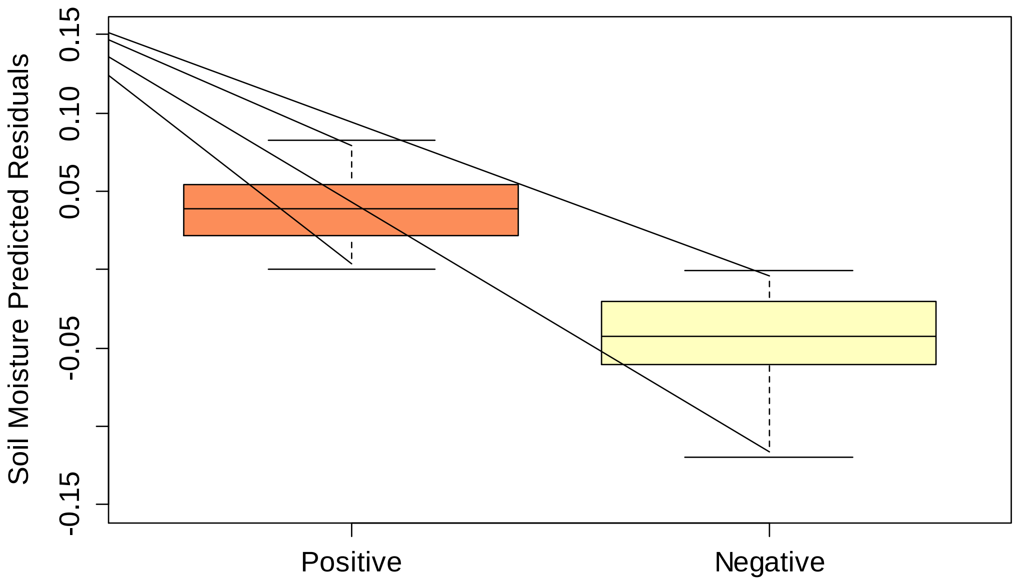


Figure 4.9. Trends of NDVI residuals that have been adjusted for soil moisture

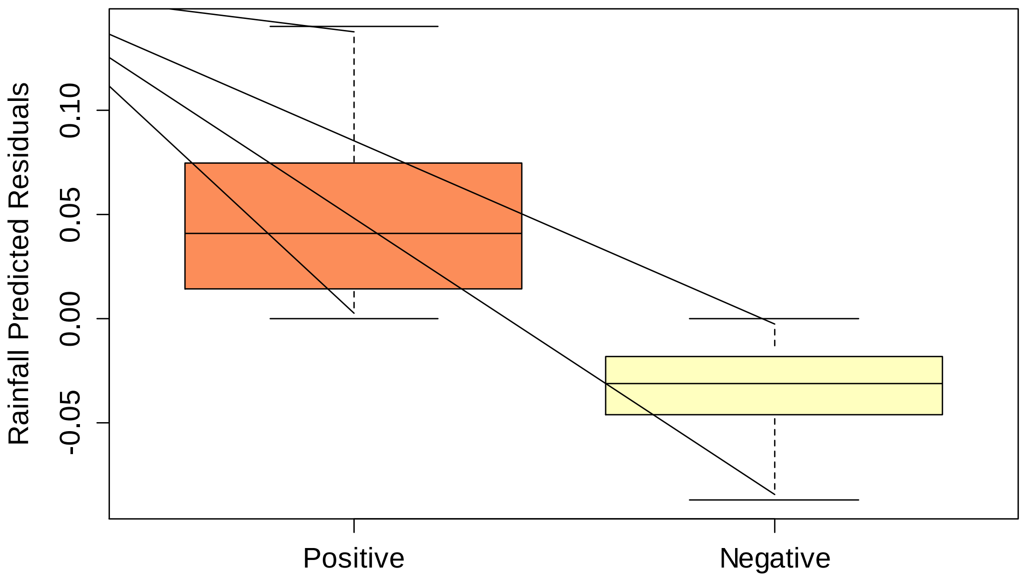


Figure 4.10. Trends of NDVI residuals that have been adjusted for rainfall

4.3.3 Temporal variation of annual NDVI residuals from RESTREND from 1982-2012, adjusted for soil moisture and rainfall

The RESTREND maps in Figures 4.5 and 4.6 show areas that are likely to be subjected to land degradation (negative trend of residuals) or not (positive residuals). The temporal trend of the mean annual residuals averaged over the study region is presented in Figures 4.11 and 4.12 for soil moisture-NDVI RESTREND and rainfall-NDVI RESTREND respectively.

In the figures, the years 1984, 1988, and 1994 show the strongest negative residuals over the study period. In those years the vegetation in the study region was less green than in an average year. In the soil moisture adjusted RESTREND analysis, the temporal trend of the residuals in Figure 4.11 shows a much clearer negative extent than rainfall in Figure 4.12. From 1996 onwards, a reversal of the land degradation trend is observed in most of the years, with positive residuals dominating the time-series, except in the years 2000, 2009, 2010 and 2012, where negative residuals dominate. The most extreme negative residuals are found following extreme drought periods in the area which caused the serious loss of vegetation greenness in the early 1980s.

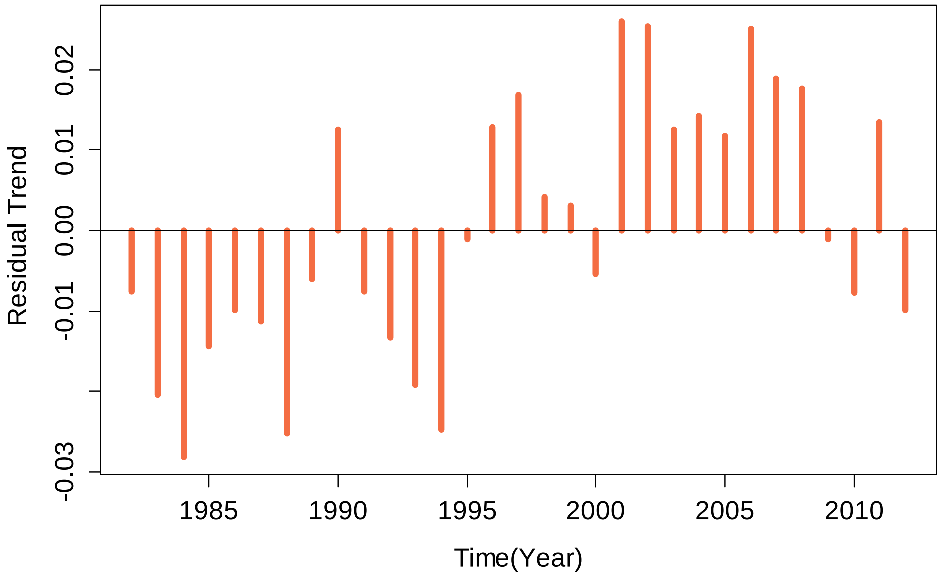


Figure 4.11. Temporal trend of annual NDVI residuals from the RESTREND from 1982-2012 averaged over all pixels in the study area adjusted for soil moisture

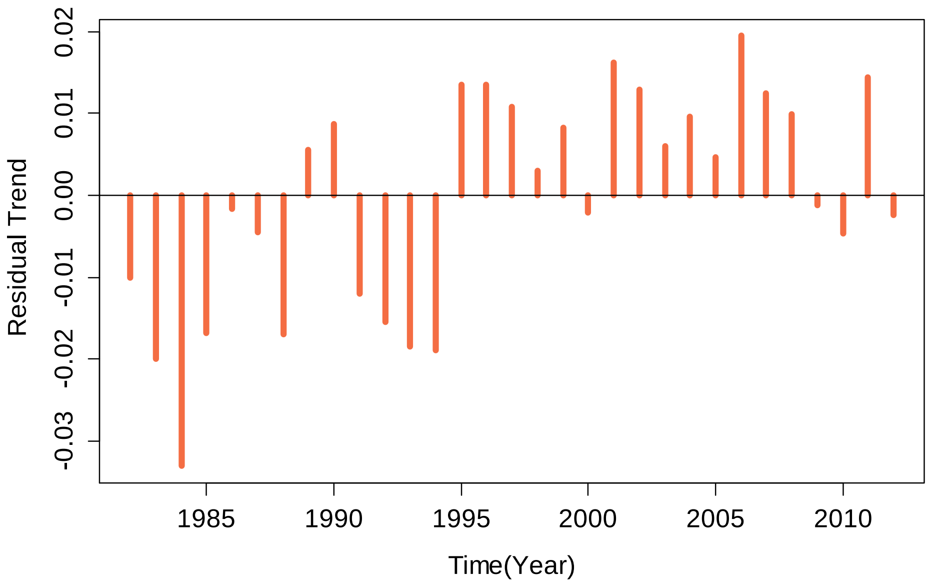


Figure 4.12. Temporal trend of annual NDVI residuals from the RESTREND from 1982-2012 averaged over all pixels in the study area adjusted for rainfall

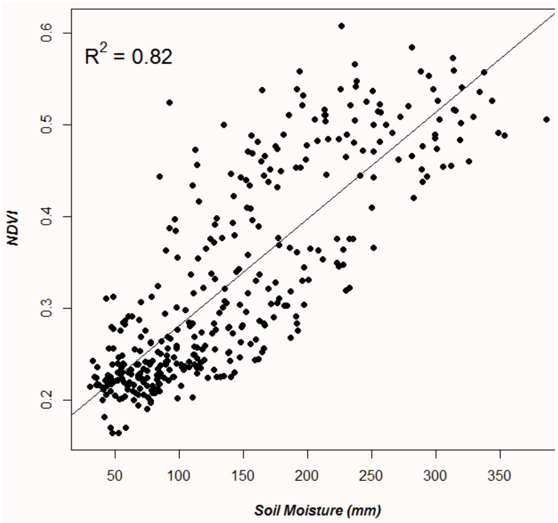
For the rainfall adjusted NDVI residuals from the RESTREND shown in Figure 4.12, the temporal trend is similar to that of soil moisture, but with less pronounced negative values, as is also indicated spatially in Figures 4.5-4.8. If only rainfall is used as the explanatory variable in RESTREND, the results re-affirm the greening trend of the Sahel. However extreme drought in the 1980s is clearly visible in the results for the rainfall adjusted RESTREND.

The Mann-Kendall coefficient τ was calculated to test whether the residual trend is monotonic or not from 1982-2012 (Table 4.1). The Kendall coefficient was applied to annual data (τ) and rainy seasonal data (τ_s). Table 4.1 shows that the overall and seasonal trends of the RESTREND in the study area are weakly positive but highly significant ($p<0.005$) for all of the RESTREND models. This means that the trend of the adjusted NDVI residuals for both soil moisture and rainfall are increasing slightly but significantly in the area.

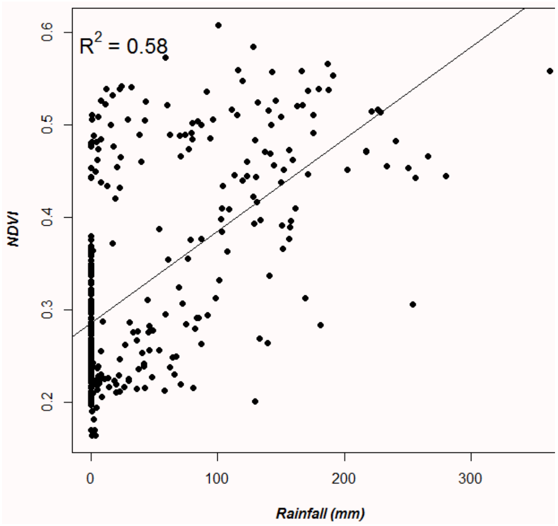
Table 4.1. Mann-Kendall's trend analysis coefficients: Annual τ and seasonal τ_s. * indicates p<1%.

RESTREND	τ	τ_s	p	
			(τ)	(τ_s)
Rainfall-NDVI (all years)	0.107	0.217	0.0021*	<0.0001*
Soil moisture-NDVI (all years)	0.128	0.281	<0.0001*	<0.0001*

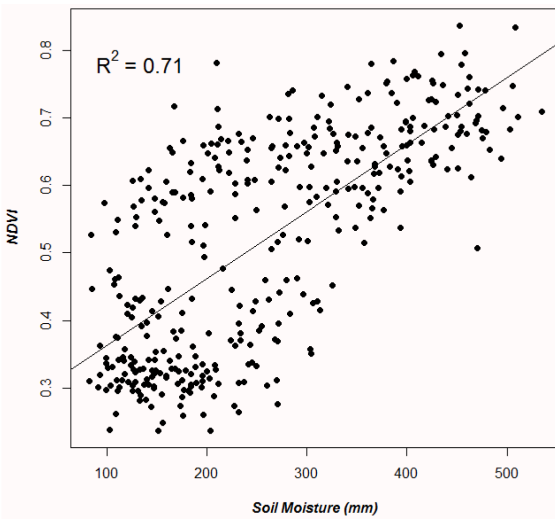
To examine the strength of the co-variation between soil moisture [rainfall] with NDVI, a detailed analysis of several sampling sites was carried out. Pearson's correlation coefficient (r) was used to examine the pixel-wise relationship between NDVI and soil moisture; and NDVI and rainfall (1982-2012) in six selected sampling sites (Figure 4.13): Nigeria (13.15N,7.15E); Ghana (10.00N,0.00E); Senegal (15.00N,15.00W); Burkina Faso (14.00N,2.00E); Mali (18.00N,5.00W) and Niger (15.00N,5.00E). These areas were selected systematically to represents all the major ecotones of the study area where sign of land degradation is observed from the RESTREND model. The results corroborate that soil moisture has a stronger relationship with NDVI than rainfall across the entire sampling sites except for the location in Mali, where soil moisture-NDVI and rainfall-NDVI correlation coefficients were $R^2 = 0.18$ and $R^2 = 0.40$, respectively. For all the remaining sampling sites, soil moisture was more highly correlated to NDVI than rainfall and NDVI.



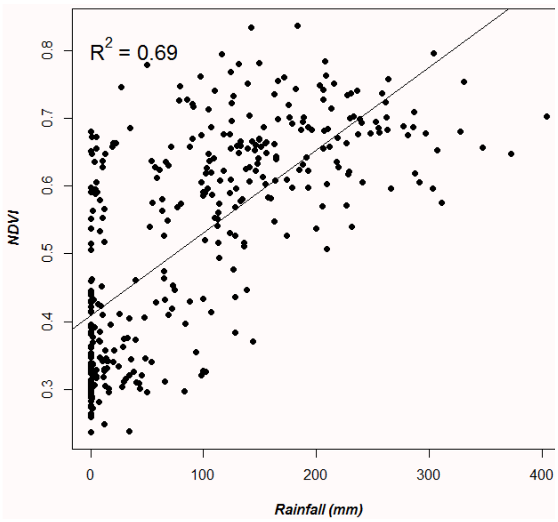
Nigeria (13.15N, 7.15E)



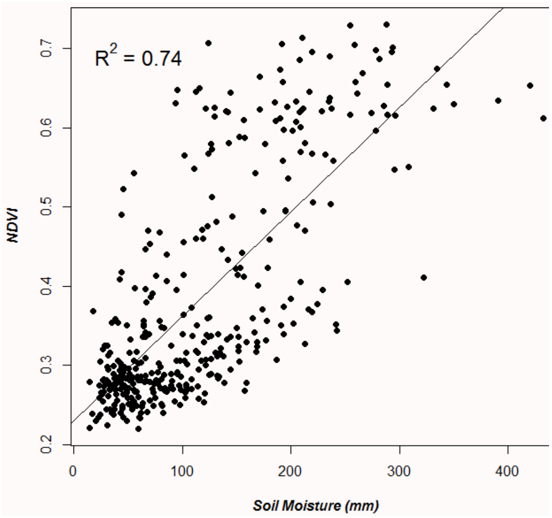
Nigeria (13.15N, 7.15E)



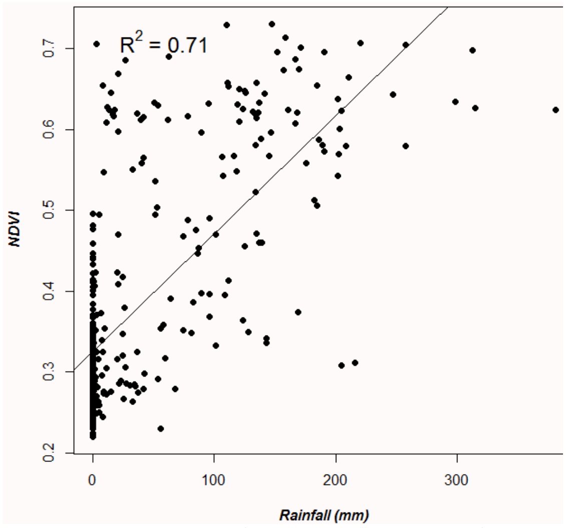
Ghana (10.00N, 0.00E)



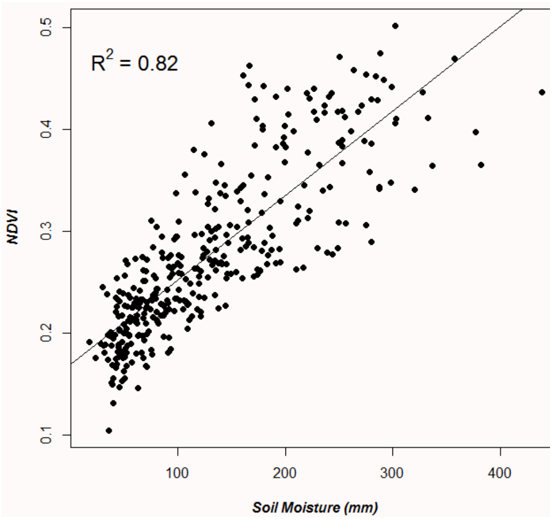
Ghana (10.00N, 0.00E)



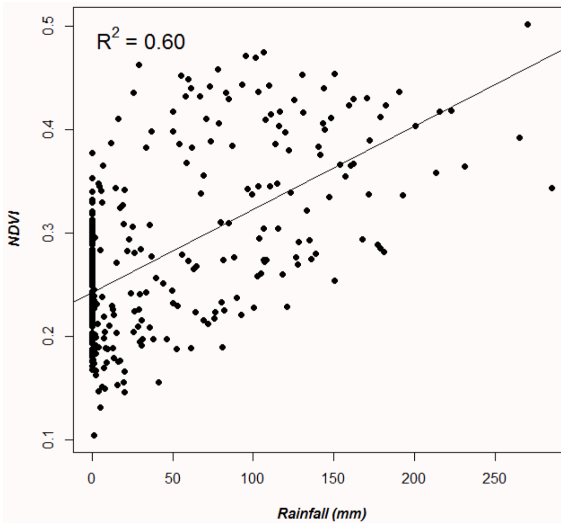
Senegal (15.00N, 15.00W)



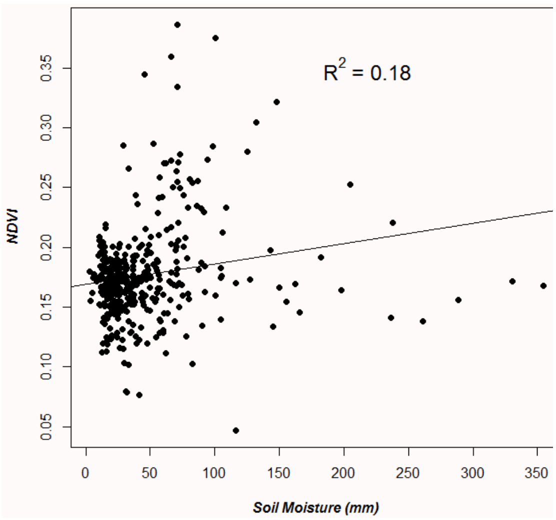
Senegal (15.00N, 15.00W)



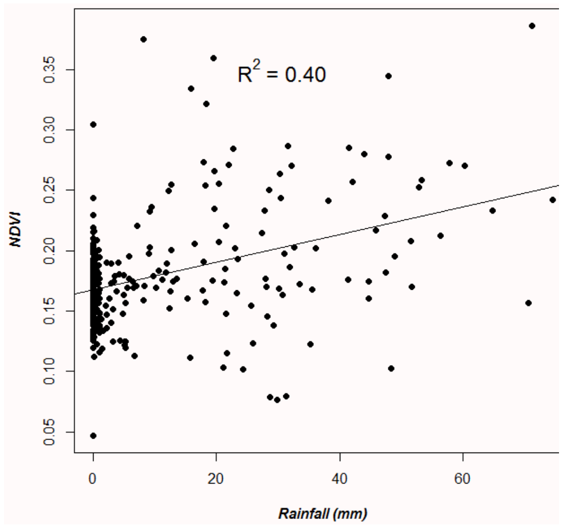
Burkina Faso (14.00N, 2.00E)



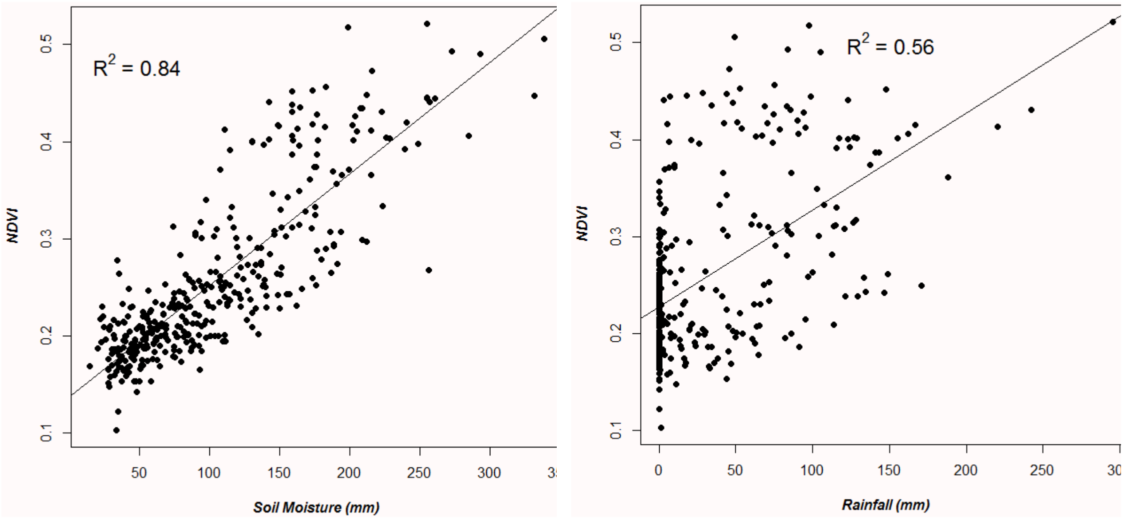
Burkina Faso (14.00N, 2.00E)



Mali (18.00N, 5.00W)



Mali (18.00N, 5.00W)



Niger (15.00N, 5.00E) Niger (15.00N, 5.00E)

Figure 4.13. Comparison between the correlation coefficients of NDVI and soil moisture; and NDVI and rainfall across the six sampling sites in the study area

4.4 Discussion

The slopes and intercepts of the regression lines of NDVI against soil moisture and rainfall from 1982 to 2012 in Figure 4.1 and 4.2 show that a large proportion of vegetated areas in the sub-Saharan West Africa responded faster to rainfall than to soil moisture. However, the Sahel portion of Senegal, Mali, Burkina Faso, Niger, Northern Nigeria and Northern Ghana, show a strong response of NDVI to soil moisture, in accordance with the findings of Huber et al. (2011). The intercepts in Figures 4.3 and 4.4 show areas with near zero NDVI (bare soil) for a theoretical zero-soil moisture [rainfall] limit across the area. These areas are mostly in Nigeria, Ghana, Senegal, Mali, Burkina Faso and Niger, indicating that NDVI in these areas is strongly dependent on rainfall and soil moisture. With soil moisture near zero, NDVI was found to be very low, and in particular even lower than the NDVI response to rainfall approaching zero. Although many studies have used the RESTREND method to identify areas with negative or positive trends of vegetation indices (Wessels et al., 2004, Evans and Geerken, 2004, Wessels et al., 2007, Omuto, 2011), most do not analyse the spatial patterns of the slopes and intercepts of the models. The current study shows that the information contained in these spatial maps provides important information about spatial patterns of land degradation and greening trends.

The spatial distribution of the areas identified as degraded by the RESTREND method is presented in Figures 4.5-4.8. It indicates that RESTREND based on soil moisture reveals degraded areas more consistently than rainfall. Degraded areas can be found in Nigeria, Ghana, Niger, Mali, Burkina Faso, Senegal and other areas. These areas fall under the very high to moderate land degradation vulnerability regions reported by Reich et al. (2004). In this context, the results presented here suggest that land degradation is not only confined to extreme climatic regions but occurs in humid tropical regions under certain circumstances. This pattern of land degradation based on the RESTREND method can be attributed to overgrazing, fuelwood extraction, and cropping intensity in these areas as reported by Geist and Lambin (2004). This was re-affirmed by Sendzimir et al. (2011) who reported a decline in on-farm tree density in Nigeria compared to Niger, even though Nigeria has a more favourable climate than Niger. Equally, evidence of land degradation in Senegal was provided by Herrmann and Tappan (2013) who found vegetation impoverishment despite greening in the area.

The long-term mean temporal variation of the RESTREND residuals in Figures 4.11 and 4.12 respectively shows that land degradation in the region is often triggered by climatic droughts, but this trend can reverse in rainy years. This is because drought and land degradation in the sub-Saharan West Africa are inseparably coupled (Stringer et al., 2009). Using the data from all years (1982-2012), the pattern of extreme land degradation follows the trend of rainfall, with the 1980s experiencing considerable negative trends. From around 1995 onwards, the mean annual trend changes to positive until around 2010 when it reversed to negative again. This trend is consistent with the findings of Anyamba and Tucker (2005), Herrmann et al. (2005) and Huber et al. (2011) who observed that above-average greening in the Sahel occurred from the 1990s to 2007. It also reinforces earlier findings of Nicholson et al. (1990) who found a large increase in rainfall over the last few decades in the region.

However, Figures 4.11 and 4.12 also indicate a possible oscillating pattern of approximately 5-years periodicity for the residual NDVI trend after adjusting for soil moisture [rainfall]. Such a pattern could be driven by the autocorrelation in climate data of the African monsoon. Even after adjusting the NDVI for soil moisture [rainfall] such a pattern is visible. This could be due to the lag effect of rainfall effects on NDVI and soil moisture in the area or reflect a longer term climate oscillation. For example, Huber et al. (2011) found a strong linear relationship between NDVI and rainfall 3-months earlier in the Sahel.

The Mann-Kendall non-parametric test was used to test whether the temporal trend of the residual NDVI averaged over the study region was monotonic or not (Table 4.1). The result shows that the trend of land degradation is increasing slightly over time as the drier conditions alternate with the wetter conditions. Although land degradation involves a total decline or loss of productivity (Verón et al., 2006), the temporal trend of the RESTREND in the area shows that the seasonal trend is also statistically significant and more consistent than the overall annual trend.

Finally, the correlation analysis of the selected sampling sites within the study area (Figure 4.13) shows that NDVI has a stronger relationship with soil moisture than with rainfall. When taking this more plausible ecological relationship into account, the soil moisture adjusted NDVI residuals show a more pronounced negative trend than is observable if only rainfall is used. The significance of this result is that studies that only focus on rainfall could potentially underestimate rates of land degradation in the study area. Soil moisture data provides a more robust way of studying land degradation.

The findings in this chapter show that land degradation is evident when the soil moisture-NDVI RESTREND model is used as shown by the trend of the residuals from the analysis of the data carried out instead of the rainfall-NDVI model. This indicates a stronger relationship between soil moisture and NDVI than rainfall and NDVI in the study region. Although I was unable to incorporate socio-economic drivers of land degradation in the analysis, I compared my results with the findings of previous studies carried out in the region, which integrated their results with ecological and socio-economic drivers of vegetation changes and land degradation. This is because land degradation and vegetation changes are generally influenced by anthropogenic drivers such as land use conversion, irrigation and nitrogen deposition among others. It has been reported that about 20% of the variability in the global NDVI trend is attributed to human land use practices and this invariably affects the long-term trend of NDVI (Mueller et al., 2014). Several studies attributed the decline of ecosystem productivity to the availability of soil moisture within the root zone. And it has been argued that even within the wetter region, the level of moisture availability may differ due to differences in ecological and socio-economic factors, notably precipitation, variation in river water level, elevation and land form types. These factors determine the availability and variations of soil moisture content available to vegetation in different seasons (Li et al., 2013).

Many locations within sub-Saharan Africa in both dry and humid zones show stronger links between NDVI and soil moisture than NDVI and rainfall. The study by Jamali. S (2011) has also found a stronger relationship between *in situ* soil moisture and MODIS NDVI and EVI in six study sites than with *in situ* rainfall. Equally, the relationship between soil moisture and EVI is stronger than soil moisture-NDVI within the upper 1m soil layer. This finding was justified by the study of Seneviratne et al. (2010), where soil moisture was reported to be the major limiting factor to vegetation transpiration and photosynthesis in several regions rather than rainfall, and this consequently influences the water, energy and biogeochemical cycles. Therefore, future studies of land degradation using statistical trend analysis should go one step further and integrate soil moisture and other ecological and socio-economic drivers of land degradation into their analysis approach.

4.5 Conclusions

In view of the persistent threat and nature of land degradation, developing alternative methods to examine its nature and trend using available long-term time series data will no doubt provide a leeway in solving multiple environmental problems affecting sub-Saharan West African. This chapter has shown that the RESTREND analysis of NDVI and soil moisture data can provide indicators of land degradation and vegetation recovery in sub-Saharan West Africa more reliably than if only rainfall data is used. The results of correlation analysis between NDVI and soil moisture show a higher value of R^2 for all the sampling sites within the study area than NDVI and rainfall except in Mali, where R^2 is 0.18 and 0.40 for NDVI-soil moisture and NDVI-rainfall correlation respectively. Also the Mann-Kendall seasonal trend was higher for soil moisture RESTREND ($\tau_s = 0.28$) than rainfall RESTREND ($\tau_s = 0.21$) which are both monotonically significant at $p < 0.005$. Although land degradation is a complex phenomenon, the areas identified as being subject to a land degradation process are consistent with previously published findings by other authors.

Therefore, I argue that in order to draw conclusions on dryland degradation, soil moisture data should be used to adjust the NDVI time-series, not only rainfall. Soil moisture conditions are an aggregated expression of the hydrological regime in the area, incorporating the full water balance of rainfall, evapotranspiration, surface runoff and groundwater supply. Soil moisture contains the water that is directly available to plants. Finally, this trend should be carefully interpreted since the trend might show opposing conditions to reality. Therefore, field work across different selected locations within the area is indispensable before strong inference can be drawn on the results of RESTREND.

5 Chapter 5: Woody vegetation changes attribution to land degradation in sub-Saharan West Africa: A case of Katsina-Nigeria and Maradi-Niger border region

Some parts of the work presented in this chapter is published as:

Brandt M, Pierre H, Rasmussen K, Mbow C, Kergoat L, Tagesson T, ***Ibrahim Y.Z,*** Abdoulaye W, Tucker C.J, Fensholt R 2016. Assessing woody vegetation trends in Sahelian drylands using MODIS based seasonal metrics. *Remote Sensing of Environment,* 183, 215-225

Also under review for publication as:

Ibrahim, Y., Balzter, H., & Kaduk, J. 2016. Woody species change attribution to land degradation in the Nigeria-Niger border region. *Regional Environmental Change,* id: REEC-D-16-00067.

5.1 Introduction and rationale

In Chapter 4, remote sensing data and statistical trend analysis were used to assess land degradation in sub-Saharan West Africa. The method was explained previously in works on the premise that a resulting trend of vegetation productivity independent of climatic control (in this case moisture) can be inferred and reflects land degradation or improvement depending on the trend being positive or negative. However, the major weakness of the method is its inability to precisely tell what the exact ecosystem is and vegetation condition is on the ground. Therefore, this chapter was designed to connect the land degradation trend observed in Chapter 4 with the actual condition of indigenous woody vegetation species in seven border villages along Nigeria and Niger Republic region. In this case, the chapter served as validation for remote sensing data analyses carried out in chapter 4 and 6 respectively.

Environmental change and land use patterns of human activities in sub-Saharan West Africa have produced perilous environmental conditions over the past decades. After several decades of drought, many studies have suggested a (re)greening of the Sahel based on large scale climatological and remote sensing observations. However, these suggestions were drawn following little or no field validation (Rasmussen et al., 2001, Anyamba and Tucker, 2005, Sop and Oldeland, 2011, Dardel et al., 2014). The last three decades have been characterised by a controversial discussion of the hypothesised greening of the West African Sahel and the possible reversal of desertification and land degradation in the region (Higginbottom and Symeonakis, 2014).

Some authors have argued that the (re)greening of the Sahel is a recovery process of vegetation from a long period of degradation thought to be associated with an increase in rainfall (Eklundh and Olsson, 2003, Nicholson, 2005). Others acknowledge the rainfall increase but suggest that changes in land use and land management practices are the major driving force, with other important factors such as cultural issues, ownership of trees on farmlands, forestry laws and economic opportunities contributing to the greening (Reij et al., 2009). Generally, in West and Central Africa, annual precipitation increases towards the equator and temperature decreases towards the coasts. These biogeographical conditions make it possible to distinguish three main ecological zones which are differentiated by their vegetation species types and density: the Sahel, Sudan and Guinea biome zones (Gonzalez et al., 2012).

Recent studies of sub-Saharan West Africa have shown a decrease in tree density and changes in species diversity in the last half of the 20th century in spite of the greening trend (Seaquist et al., 2006, Herrmann and Tappan, 2013, Herrmann and Sop, 2016). These changes are directly attributable to land degradation (caused by climate change and human activities) due to the increase in aridity, an increase in human population and changes in the natural vegetation species composition (Gonzalez, 2001). The decrease of vegetation cover intensifies through the weakening of positive feedbacks between precipitation and vegetation amidst reduced evapotranspiration (Zeng et al., 1999, Los et al., 2006) and increased surface albedo which may further enhance the dryness of the region (Charney et al., 1975, Kucharski and Zeng, 2013).

Changes in woody vegetation in West Africa have been under investigation since the 1970s following the drought of the 1970s and 1980s which occurred following the decades of below average rainfall (Nicholson, 2000, Wezel and Lykke, 2006). This led to a decrease and disappearance of some natural woody species in the area. However, if the tree species native to mesic Guinea and Sudan savanna disappear but appear in the Sahel savanna, the reason of change in this case is human activity and not climate (Herrmann and Tappan, 2013).The natural distribution of trees has long been altered by human activity. Deforestation and degradation of woody species through fuelwood collection and overgrazing are among the major causes of land degradation in dryland areas (Sop and Oldeland, 2011). Changes in land use, grazing pressure and soil fertility can trigger changes in vegetation composition with a strong decline in species diversity (Hiernaux et al., 2009b). A number of studies documented the decline of woody species density in different locations across the ecological zones in sub-Saharan West Africa. Tree decline was observed in Senegal (Tappan et al., 2004, Vincke et al., 2010) and an expansion of xeric trees and a decrease of mesic species was reported in Burkina Faso and Niger (Wezel and Lykke, 2006). Tree species disappearance due to agriculture and livestock overgrazing was observed in Mauritania (Niang et al., 2008), to name a few such studies.

Over the last three decades, the sub-Saharan West African environment has been subjected to a series of environmental disruptions as a result of land degradation (Brink and Eva, 2009). These disruptions are manifested in changes of the natural vegetation cover, where agricultural expansion and other human activities are degrading natural vegetation cover. For instance, a study by Hiernaux et al. (2009a) found a decrease in tree cover due to fuelwood cutting, land cultivation and overgrazing. A 57% increase of agricultural land was recorded throughout the West African Sahel from 1975 to 2000 at the detriment of natural vegetation which decreased by 21%. It is estimated that about five million hectares of natural forest and non-forest vegetation are lost annually in the region (Brink and Eva, 2009).

In recent years, vegetation cover change in sub-Saharan West Africa has been assessed using satellite data (Gonzalez et al., 2012, Brandt et al., 2014b, Ibrahim et al., 2015, Spiekermann et al., 2015). However, studies assessing changes in woody cover based on satellite data alone have limitations primarily due to the lack of reliable maps showing woody vegetation cover changes in Africa (FAO, 2010) and over-dependence on the Normalized Difference Vegetation Index (NDVI) to represent woody vegetation (Herrmann and Tappan, 2013). It is an index of the fraction of photosynthetically active radiation absorbed by plants which is relative to green leaf area (Myneni and Hall, 1995). A regular NDVI observation at the global scale began with AVHRR in 1982 and represents the longest continuous satellite record of the land surface; however, it cannot easily distinguish trees from other vegetation.

In many parts of sub-Saharan West Africa, the green leaf area of the herbaceous layer is made up of annual grasses and shrubs, which significantly surpass the green leaf area of woody vegetation. The resulting high value of NDVI is often interpreted as ecological improvement (Gonzalez et al., 2012). As a result, any small increase in rainfall will lead to a short-term increase in NDVI as witnessed in the 1980s and 1990s, showing a temporary increase of vegetation cover (Olsson et al., 2005). Many scientists have interpreted this increase of NDVI as re-greening (Myneni and Hall, 1995, Prince et al., 2007). However, field observation and local environmental knowledge can reveal trends of vegetation cover as a function of changes in woody and herbaceous species composition and density much more reliably than NDVI. This is because many trees often endure years of stress before their death (Allen et al., 2010).

Structured surveys of local communities and botanical fieldwork surveys have been used to study land degradation by assessing the current and past condition of natural vegetation and information of species distribution (Lykke, 1998, Gonzalez, 2001, Wezel, 2004, Sop and Oldeland, 2011). Other researchers have combined remote sensing and fieldwork to study woody vegetation changes and land cover conversion (Gonzalez et al., 2012, Herrmann and Tappan, 2013, Dardel et al., 2014, Brandt et al., 2014b, Spiekermann et al., 2015). The use of local knowledge to study land degradation has gained prominence in the last decade and is becoming increasingly important due to the uncertainties in the interpretation of satellite data and the absence of long-term data records of vegetation changes in Africa (Lykke et al., 2004). Recently, field observations have been used to reduce the ambiguity of satellite data. This approach enables data acquisition of presence/absence and cover of each plant species, which can be used to determine which species might be at risk of disappearance and guide local resource planning and management (Wezel, 2004).

Local environmental knowledge of people, especially in rural Africa, is central to ecosystem monitoring, and is the major source of historical data of species distribution, especially the endangered ones (Lykke et al., 2004). Despite the robustness of this method, few studies exist to date that correlate the greening and browning trend detected using remotely sensed data to actual woody vegetation cover along the Nigeria-Niger border; a region that falls between northern Sudan and the southern Sahel savanna. As an ecotone, this region will respond more clearly to environmental stresses, and changes in tree and shrub distributions will be more apparent here than in the inner regions of the biomes. Trees and shrubs are important functional components of dryland ecosystems and contribute to maintaining suitable conditions for agriculture, rangeland and human livelihoods. They provide ecological goods and services to rural populations (FAO, 2010).

In this chapter, I assess the changes of indigenous woody vegetation species distributions in seven study villages that cut across Nigeria and Niger Republic border region. The chapter intends primarily to examine the historical and current changes taking place on woody vegetation species as highlighted in the aim and objectives presented in chapter 1. The chapter provides answer to the following research question:

Is there any significant historical change in woody vegetation cover to suggest continual or reversal of land degradation in the study area?

5.2 Materials and methods

5.2.1 Study area

The study area extends along the border between Nigeria and the Niger Republic, roughly located between latitudes 12^{0} 40’^{1}N and 13^{0} 20’N, and longitudes 7^{0} 00’^{1}E and long 9^{0} 00’E. The border region is characterised by extensive dryland plains used for subsistence agriculture. The area is the heartland of Hausa land - a vast and populous area of economic activity straddling northern Nigeria and southern Niger. The border region is located half-way between the Sahel and the Northern Sudan savanna lands; this axis is the heart of the region as it has significant agricultural potential. However, the area exhibits a high spatial variability of natural resources and ecosystems. The seemingly monotonous landscape is comprised of a mosaic of features and ecosystems.

The physiography is characterised by large parallel fossil dune ridges dominated by herbaceous vegetation, inter-dune areas with predominantly Solonetz soils with typical Sahelian *Acacia* savanna, and wetlands on vertisols in the lowest-lying areas. The flora in this Sahelian environment is comprised of nearly 400 species and each major soil unit is supporting specialised plants that do not grow on the other units, with light sandy soils (Arenosols) having the highest number of specialised species (Nicholson, 1995).

The climate of the region is subtropical and is characterised by a very hot, dry and short rainy season of three to five months (June to September). The dry season lasts for between seven and nine months (October to May). The potential evapotranspiration is two to four metres per annum: rainfall hardly ever exceeds 600mm per year, and in most cases is as low as 300mm per year over most of the region. The rainfall pattern follow the Sudano-Sahelian savanna configuration, with wetter conditions around the Sudan savanna border and drier conditions towards the north, and its distribution is often erratic (Nicholson, 1995).

Land degradation symptoms are numerous and include wind erosion on dune crests, sheet erosion in the inter-dunes, sedimentation and siltation of wetlands and watercourses. More importantly, the impact of land degradation entails reduced productivity of rangeland and agricultural fields, which often force local communities to convert new, often more marginal land to agriculture to sustain their livelihoods. The degradation of pasture areas coupled with climate change generally leads to the reduction and disappearance of important plant species.

For the purpose of this study, seven local communities were selected in the Nigeria-Niger border region: Birnin-Kuka, Bumbum, Dankama, Magama, Sawani and Yakubawa, in Katsina State, Nigeria, and Madarounfa in Maradi, Niger Republic (figure 5.1). These villages were selected using systematic sampling techniques because the falls along the transect of boarder between Nigeria and Niger republic. This locational factor gave an opportunity to the researcher to examine the nature and changes of vegetation across these two countries within varying degree of vegetation resource management.

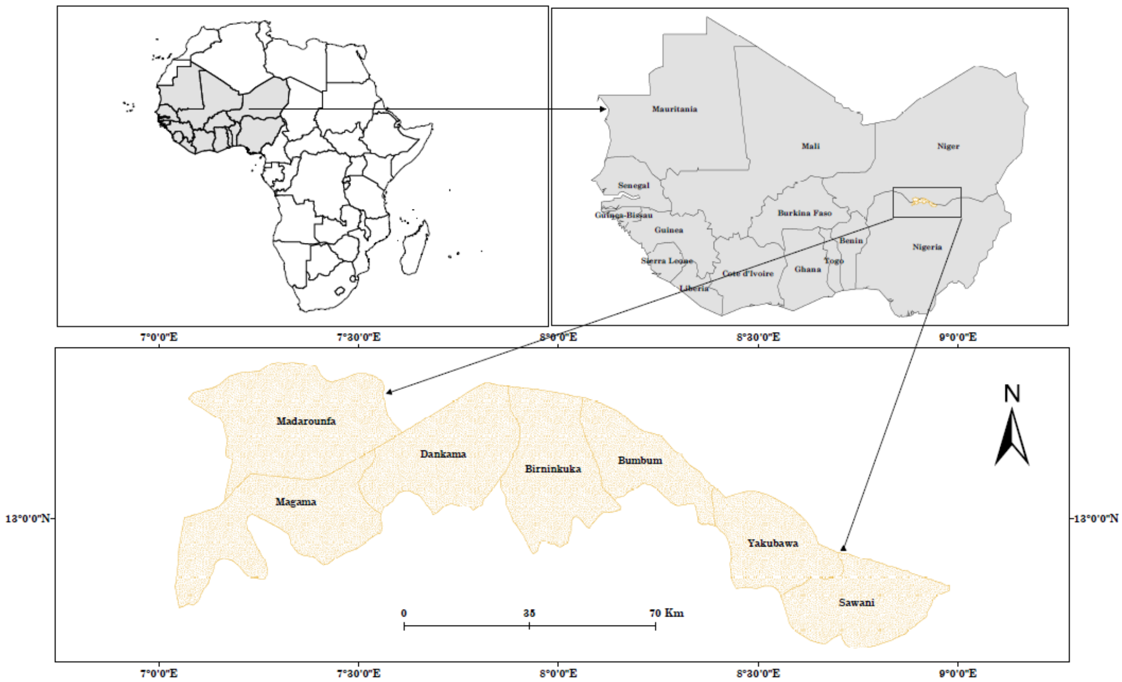


Figure 5.1. Study area and location of the selected villages

5.2.2 Botanical inventory of woody vegetation species

An inventory of trees and shrubs was carried out in the area around the seven selected villages in order to determine the status of woody vegetation species and compare it with the vegetation species condition over the past 30 years using field observations and indigenous knowledge of the local environment. This method has been used widely to validate remote sensing data, especially land cover maps. In each village, a comprehensive list of woody species present was created with the help of field assistants. The fieldwork was conducted form April-July 2014 by Y. Ibrahim. This period was chosen because it coincided with the end of the dry season and the early onset of rainfall in the area.

Table 5.1 provides a complete list of the recorded woody species which comprises indigenous trees and exotic/new species found in the area. The species were identified at site by their local names with the help of field assistants and were later translated into scientific names using the Blench and Dendo (2007) guide to plant and tree names. A total of 42 vegetation

Table 5.1. List of vegetation species identified in the study area

Species Names	Local Name	Family	Vegetation Zone
Acacia ataxacantha	Duhu	Mimosaceae	Sudan
Acacia nilotica	Bagaruwa	Mimosaceae	Sahel
Acacia polyacantha	Karki	Fabaceae	Sudan
Acacia sieberiana	Farar kaya	Mimosaceae	Sudan
Acacia senegal/seyal	Dakwara	Mimosaceae	Sahel
Acacia tortilis	Kandili	Fabaceae	Sahel
Adansonia digitata	Kuka	Bombacaceae	Sudan
Albizia chevalieri	Katsari	Mimosaceae	Sahel
Anogeissus schimperi	Marke	Combretaceae	Sudan
Annona senegalensis	Gwandar daji	Annonaceae	Guinea
Azadirachta indica	Dalbejiya	Maliaceae	Sahel-Sudan
Balanites aegyptiaca	Aduwa	Balanitaceae	Sahel
Bauhinia rufescens	Jiga	Bombacaceae	Guinea
Borassus aethiopum	Giginya	Arecaceae	Sudan
Ceiba pentandra	Rimi	Malvaceae	Guinea
Commiphora africana	Dashi	Burseraceae	Sahel
Daniella oliveri	Ma'aje	Caesalpiniaceae	Guinea
Eucalyptus camaldulensis	Turare	Myrtaceae	Sudan
Faidherbia albida	Gawo	Mimosaceae	Sudan
Ficus glumosa	Kawuri	Moraceae	Guinea
Ficus platyphylla	Gamji	Moraceae	Guinea
Ficus polita	Durumi	Moraceae	Guinea
Ficus thonningii	Chediya	Moraceae	Guinea
Hyphaene thebaica	Kaba	Arecaceae	Sahel
Khaya senegalensis	Madaci	Maliaceae	Guinea

Lannea acida	Faru	Anacardiaceae	Guinea
Mangifera indica	Mangwaro	Anacardiaceae	Sudan
Mitragyna inermis	Amazo	Rubiaceae	Sudan
Moringa oleifera	Zogale	Moringaceae	Sudan
Parkia biglobosa	Dorawa	Mimosaceae	Sudan
Phoenix dactylifera	Dabino	Arecaceae	Sahel
Piliostigma reticulatum	Kalgo	Caesalpiniaceae	Sudan
Prosopis Africana	Kirya	Mimosaceae	Guinea
Sclerocarya birrea	Lundu-Lundu	Anacardiaceae	Sudan
Tamarindus indica	Tsamiya	Caesalpiniaceae	Sudan
Terminalia avicennioides	Baushe	Combretaceae	Sudan
Terminalia Catappa	Me gado-gado	Combretaceae	Sudan
Vitellaria parodoxa	Kadanya	Sapotaceae	Sudan
Vitex doniana	Dinya	Verbenaceae	Sudan
Ximenia Americana	Tsada	Olacaceae	Guinea
Zizyphus mauritiana	Magarya	Rhamnaceae	Sahel
Ziziphus spina christi	Kurna	Rhamnaceae	Sahel

Source: Field survey 2014.

species were recorded. Some of the species identified that are not described by Blench and Dendo (2007) were validated with the assistance of vegetation experts in the area.

5.2.3 Focus group discussions

Due to the absence of historic data on the woody vegetation species of the area, historic information relied on local indigenous knowledge. Local knowledge has been widely used to provide supplementary information on woody vegetation species changes and to find out the species that were extinct or endangered (Wazel and Lykke, 2006). Although the method may introduce bias and uncertainties, as in some cases the respondents may not recall vividly the real conditions of indigenous woody vegetation species in the past but still remains the only alternative method to acquire historical data especially in data limited regions. Focus groups with selected participants were convened to identify the types of woody species that existed in the past 30 years, compare them to the present species and examine possible reasons that led to those changes.

In each of the seven villages, a group of 10 elders were selected using purposive sampling. This consisted of six males and four females; it also included farmers and Fulani cattle herders proportionally to their population fractions of 60:40 ratio in all the study villages. All participants were older than 50 years; this is in order to acquire information on vegetation species for the past 30 years. All the discussions were held in the local language of the area (Hausa) and later translated into English. In each village, the villagers were asked to list all known woody plant species past and present in the area and classify them according to the agreed categories. Respondents were equally asked to explain the factors responsible for the changes taking place on the vegetation species in their area. Details of the check list used and ethical approval form are attached as appendix 2.

During the discussion, a categorisation was agreed and applied to all the tree species. The following are the categories which were agreed with the respondents and adopted in all the seven villages;

Category 1: Any species which is judged to be increasing.

Category 2: Any species which have decreased.

Category 3: Any species that have disappeared.

Category 4: Any species which are non-native/new arrival but present in the area (exotic).

5.2.4 Data analysis

The collected data was categorised according to the villages, and all the vegetation species observed in addition to the ones listed by the respondents in each study village were ordered according to the four agreed categories. Tables were used to present each village's species and their categories. Pie charts were used to present all the species recorded according to their categories. The χ^2 test was used to test for the significance of the differences in the species presence data among the seven villages.

5.3 Results

5.3.1 Vegetation characteristics of the study area

The Nigeria-Niger border region is a semi-arid environment, and land use is characterised by non-intensive agricultural activities such as cereal cultivation and grazing. The climate is characterised by a high inter annual rainfall variability and hence its vegetation structure, species composition, and biodiversity mode of adaptation differ from that of other ecological regions. The landscapes consist of useful indigenous plant species scattered on the crop fields and form the components of the farmlands in the area. This system of farming, where crops and trees are integrated together on the same piece of farmland, is known as 'agroforestry parkland system' and it has been successfully described by Merem (2005).

Most of the trees and shrubs in the area have fine leaves, and the sparse grasses have a thorny and short structure. The average height of the trees recorded in the area is 6.61m; 2.79m for shrubs and 1.19m for grasses (Mohammed, 2004). There is also considerable variation in tree density over small distances in most parts of the study area. Merem (2005) suggested that the differences arise from 1) the varying attitudes of individual farmers to trees on their farms; 2) the density and composition of economically valuable trees in the primary woodlands and 3) the length of time the area has been farmed. In Bumbum village, 5-10 trees per hectare were recorded. In Sawani, 10-15 trees per hectare were recorded in the surrounding farmlands, but most of the trees are exotic species dominated by Neem species (*Azadirachata indica*).

Although the farm parkland system has assisted in preserving indigenous species in the area, and has been described as a good example of a traditional biodiversity management system (Aturamu and Daramola, 2005), the future sustainability of the practice is under serious environmental threat from land degradation. This is accelerated by the changes in agricultural practices due to the high increase in the demand for cultivatable lands resulting from population increase. While the fallow period has generally been shortened, exploitation of scarce vegetation resources has increased due to the high demand for fuelwood, which is the major source of energy for the rural population in the area.

5.3.2 Trends of NDVI, soil moisture and precipitation in the study villages

The study villages being ecologically and climatically uniform, shows almost uniform annual trends and seasonal cycles of NDVI, soil moisture and precipitation. In all the villages, the trend of NDVI is increasing especially from the year 2010 upwards as shown in Appendix 5 (Figures A5.1-A5.7; this reaffirmed the greening of the sub-Saharan Africa which was documented based on the satellite data records. For the seasonal cycle, the month of September recorded the peak of NDVI and the lowest value is in the month of April in all the study villages, and these two variations corresponded to the periods of peak of rainy and dry seasons in the area.

For the precipitation, the overall trends are also similar in the areas except that there is evidence of local variation in some of the years as indicated in Appendix 5 figures. However, the overall trend of the mean annual precipitation is fluctuating proportional to the drought episodes. The mean seasonal cycle of precipitation also follows the trend of two distinctive seasons in the area i.e. dry and wet seasons. Wet season begins with onset of precipitation which normally starts from the month of April, reaching its highest peak in August and ends in October. From November to March, the whole region is under dry condition, with zero amount of precipitation.

Mean annual soil moisture across the whole seven study villages also show similar pattern of seasonal trends as presented in Appendix 5 figures, with high values on years with good precipitation and low values during the periods of low precipitation or dry spell, corresponding to the drought periods in the area. However, the seasonal cycle follows the same pattern of NDVI, with peak value in the month of September and the lowest value in the months of April and May, indicating lag relationship with precipitation.

The overall trends of NDVI, soil moisture and precipitation in the whole study villages' shows increased in annual mean NDVI, soil moisture and precipitation. However, the seasonal cycle of NDVI and soil moisture shows lag correlation of at least one month with precipitation. This is similar to the finding of most of the previous studies in the area. It also highlighted the weakness of NDVI time series analysis to study land degradation, as the overall trend shows improvement towards greening from 1982 to 2012 in all the sampling sites in the area. What is left to be seen is whether these increases reciprocate the trends and condition of indigenous woody vegetation in the area, been the major indicator of ecological stability and land degradation condition.

5.3.3 Local perception on woody species change

For all the surveyed villages, a total of 42 indigenous and exotic woody plant species from 21 families were identified and categorised together with respondents according to the agreed ranking order. These categorisations were based on the consensus among the participants in the focus group on the status of the species among all the villages. Table 5.2 provides the status of each tree species and the categories that are now described in more detail:

Category 1: Increasing species

Village to village analyses of the species presence data reveals that an average of 6.5% of all the indigenous species were perceived to have increased by the respondents in the last 30 years across all the villages. For instance, in Magama and Sawani only 2.4% of the species have increased, representing only one species increased per village (*Acacia nilotica* and *Faidherbia albida*). In Birnin-Kuka and Bumbum, 4.8% of the species increased. The focus groups identified *Faidherbia albida*, *Annona senegalensis* and *Adonsania digitata* as the species to have increased, with *F. albida* common in the villages. In Yakubawa about 7.1% of all the identified species have increased and in Dankama 9.5% of species have increased. Finally, in Madarounfa, which is the most northward village in the region, about 14.3% of the species were perceived to have increased over the last 30 years. Figure 5.2 shows the categories of each species identified in the villages. The high percentage of increased species recorded in Madarounfa, despite being located in Niger Republic, (which is climatically less favourable than Nigeria) is attributed to good management of available species by the farmers and the strict implementation of relevant forest protection laws. For example, the forestry division of the village has a nursery farm where indigenous vegetation species are grown (Appendix 2).

Category 2: Decreased species

A substantial numbers of indigenous species were reported to have decreased in the last 30 years. The focus groups attributed the decline of these species to both natural and human activities (land degradation) taking place in the areas. In Dankama village for instance, 36% of the inventoried species were reported to have decreased. Respondents perceived a 43% decrease of species in Birnin-kuka, Bum-bum, Magama and Sawani villages respectively. In Yakubawa, 50% of species have decreased and in Madarounfa 60% of all the species have decreased. The dominant species which have decreased most commonly among all the villages include *Acacia tortilis, Ficus glumosa, Balanite aegyptiaca* among others as presented in Figure 5.2. The informants perceived poor tree planting programmes, deforestation and overgrazing as the major factors causing the decrease in tree species presence. For example, heaps of fuelwood were observed in Bumbum in the backyard of houses for sale and family use.

Category 3: Disappeared or extinct species

Across all the villages, *Albizia chevalieri*, *Acacia Senegal, Ficus thonningii* and *Khaya senegalensis* are among the tree species reported to have locally disappeared. With the exception of Madarounfa (19%) and Yakubawa (36%), nearly 50% of all the identified species were perceived to have disappeared. In Birnin-kuka and Bum-bum, about 45% of all the species have become locally extinct. A similar condition occurs in Dankama, Magama and Sawani, where about 48% of all tree species in the areas are perceived to have become extinct. The respondents highlighted those environmental and man-made factors such as a dropping water table, increasing temperature, erratic rainfall patterns, land clearance for agricultural expansion, the use of plants for fuelwood and animal feeds as being among the major causes for the disappearance.

Category 4: New arrival or exotic species

One common feature across all the study villages as observed during the fieldwork is the presence of new stable vegetation species that are exotic and brought to the areas through agroforestry programmes. These species are fast-growing and are fully domesticated because of their abilities to thrive in dryland environments. *Azadirachta indica*, *Eucalyptus camaldulensis* and *Terminalia catappa* were 100% present in all the study villages. *A. indica* in particular, is the most densely vegetated woody species in the area and throughout most of dryland areas in the tropical and subtropical regions with annual precipitation as low as 150-250mm per annum. This species is very resistant to weed competition and is widely used to rehabilitate degraded ecosystems in dryland areas. *E. camaldulensis* on the other hand is a larger perennial woody tree, evergreen and has greater access to water at greater depth than other deciduous vegetation species.

While these exotic species provide physical protection to the soil and serve as wind breaks, most of the respondents argued that their long-term environmental effect on the soil chemical condition and to their farmland's future productivity is worrying. According to the informants, *A. indica* competes with the crops on their farmlands, thereby affecting the yield per unit of farmland. *E. camaldulensis* was reported to have harmful effects on germination and seedling growth of most crops in the area.

Table 5.2. Status of woody species in the study villages

Species Names	Birnin-Kuka	Bumbum	Dankama	Madarounfa	Magama	Sawani	Yakubawa
Acacia ataxacantha	2	3	2	2	2	3	2
Acacia nilotica	2	2	1	1	1	2	2
Acacia polyacantha	2	2	2	2	3	2	2
Acacia sieberiana	3	2	3	2	2	3	2
Acacia senegal/seyal	3	3	3	2	3	3	3
Acacia tortilis	2	2	2	2	2	3	2
Adansonia digitata	1	2	2	1	2	2	1
Albizia chevalieri	3	3	3	3	3	3	1
Anogeissus schimperi	3	3	3	2	2	3	2
Annona senegalensis	3	1	1	2	3	2	2
Azadirachta indica	4	4	4	4	4	4	4
Balanites aegyptiaca	2	2	2	2	2	2	2
Bauhinia rufescens	2	2	2	2	2	2	2
Borassus aethiopum	2	2	2	3	2	2	2
Ceiba pentandra	3	3	3	1	3	3	3
Commiphora africana	2	2	1	1	2	2	2
Daniella oliveri	2	3	3	2	3	2	3
Eucalyptus camaldulensis	4	4	4	4	4	4	4
Faidherbia albida	1	1	2	1	2	1	1
Ficus glumosa	2	2	2	2	3	2	2
Ficus platyphylla	3	3	3	2	3	2	3
Ficus polita	3	3	3	2	3	3	3

Table 5.2 (continued)

Species Names	Birnin-Kuka	Bumbum	Dankama	Madarounfa	Magama	Sawani	Yakubawa
Ficus thonningii	3	3	3	3	3	3	3
Hyphaene thebaica	3	2	2	2	3	3	2
Khaya senegalensis	3	3	3	3	3	3	3
Lannea acida	3	3	1	2	2	2	2
Mangifera indica	2	2	2	2	2	3	2
Mitragyna inermis	2	2	2	2	2	2	2
Moringa oleifera	2	2	3	3	2	2	3
Parkia biglobosa	3	2	3	1	2	2	2
Phoenix dactylifera	3	3	3	2	3	3	3
Piliostigma reticulatum	2	2	2	2	2	2	2
Prosopis Africana	2	2	3	2	3	2	2
Sclerocarya birrea	3	2	2	2	3	3	2
Tamarindus indica	2	3	3	3	3	3	3
Terminalia avicennioides	3	3	3	2	3	3	3
Terminalia Catappa	4	4	4	4	4	4	4
Vitellaria parodoxa	3	3	3	3	3	3	3
Vitex doniana	3	3	3	3	3	2	3
Ximenia Americana	3	3	3	2	3	3	3
Zizyphus mauritiana	2	3	2	2	2	3	3
Ziziphus spina christi	2	3	3	2	2	3	2
No of Increasing	2	2	4	6	1	1	3
No of Decreasing	17	18	14	24	17	18	20

Table 5.2 (continued)

Species Names	Birnin-Kuka	Bumbum	Dankama	Madarounfa	Magama	Sawani	Yakubawa
No of Disappeared	19	18	20	8	20	19	16
No of New Arrival	3	3	4	3	3	3	3

Key. 1: Increased 2: Decreased 3: Disappeared 4: New arrival/Exotic

Pearson Chi-Square = 65.84, df = 27, p-value = Insignificant

Likelihood Ratio Chi-Square = 3.01, df = 27, p-value = Insignificant

Significance level $\alpha = 0.05$

Overall, the perceptions of the respondents match across all villages except in some local cases such as in Madarounfa. Because of close similarities of opinions by the respondents from the various villages, Pearson's χ^2 test shows no significance differences in the status of tree species change between villages ($p>0.05$, table 5.2). This indicates that the trends of vegetation changes in the area and the category of changes taking place are following the same pattern, indicating a loss of ecological stability and highlighting the continuing land degradation in the border region.

5.3.4 Perception of the major driving force of species change

Over 80% of respondents listed a decline in the amount of soil moisture, as a result of the long-term changes in precipitation patterns leading to frequent droughts, as the major cause of vegetation change. Many of the respondents claimed that in the past 30 years, the water table in the region was about 10m below the surface. However, at present the water table is often 30m below the surface.

Generally, respondents believed poverty is another major driving force of vegetation degradation in the study area. They argued that a high poverty rate has contributed to the cutting down of many trees, especially during the dry season to supplement the family income. That is why heaps of fuelwood for sale have become the common feature along the major roads in the area, particularly on the Nigerian side of the border.

The relative importance of other major physical and man-made driving forces of vegetation change varied among the respondents in different villages. In Madarounfa for instance, respondents believed aging, north-south geographical migration of tree species and expansion of agricultural land as the major causes of tree species changes. This is in addition to tree lopping for animal feed during the dry season. However, in the remaining villages in Nigeria, the major driving factors of vegetation changes are local deforestation, the expansion of agricultural land due to increasing population, overgrazing, fuelwood extraction and poor tree planting and management programmes among others. Finally, bush burning by the local farmers during the dry season for land preparations for the next farming season also accounts for a loss in vegetation by killing the young indigenous species, especially those found on the farmlands.

5.3.4 Vegetation condition in the context of land degradation in the area

Around 80% of all the indigenous woody species in the study area were reported by the informants to have either decreased or disappeared in the last 30 years. This is contrary to many studies documented on the greening or improvement of sub-Saharan West Africa based on satellite derived vegetation indices where increases in NDVI were used to dispute land degradation in the region. This suggests that determining the extent of land degradation should not rely exclusively on satellite data, and leads us to conclude that vegetation degradation is a general problem that is still ongoing in rural sub-Saharan West Africa.

In one of the study villages (Bum-bum), farmers ascertained that in the past 30 years, *Ficus polita* and *Ficus thonningii* were among the dominants species in the area. However, at present neither of these tree species is found in this village because they have all wilted and died. They attributed the extinction of these species to the decline in the plant-available soil moisture as a result of occasional droughts, which have led to a decrease in the amount of precipitation in recent years and the dropping of the water table in the area. *Azadirachata indica*, an exotic species, is now the dominant woody vegetation in all the villages visited.

Throughout the study area, the common feature of tree species is that indigenous highly water-dependent trees such as *Acacia sieberiana, Acacia senegal/seyal, Albizia chevalieri, Ficus platyphylla, Ficus polita, Hyphaene thebaica, Khaya senegalensis, Phoenix dactylifera, Tamarindus indica, Terminalia avicennioides, Vitellaria parodoxa, Vitex doniana, Ximenia Americana* and *Zizyphus mauritiana* have either completely disappeared or decreased. These species were dominant in the area 30 years ago.

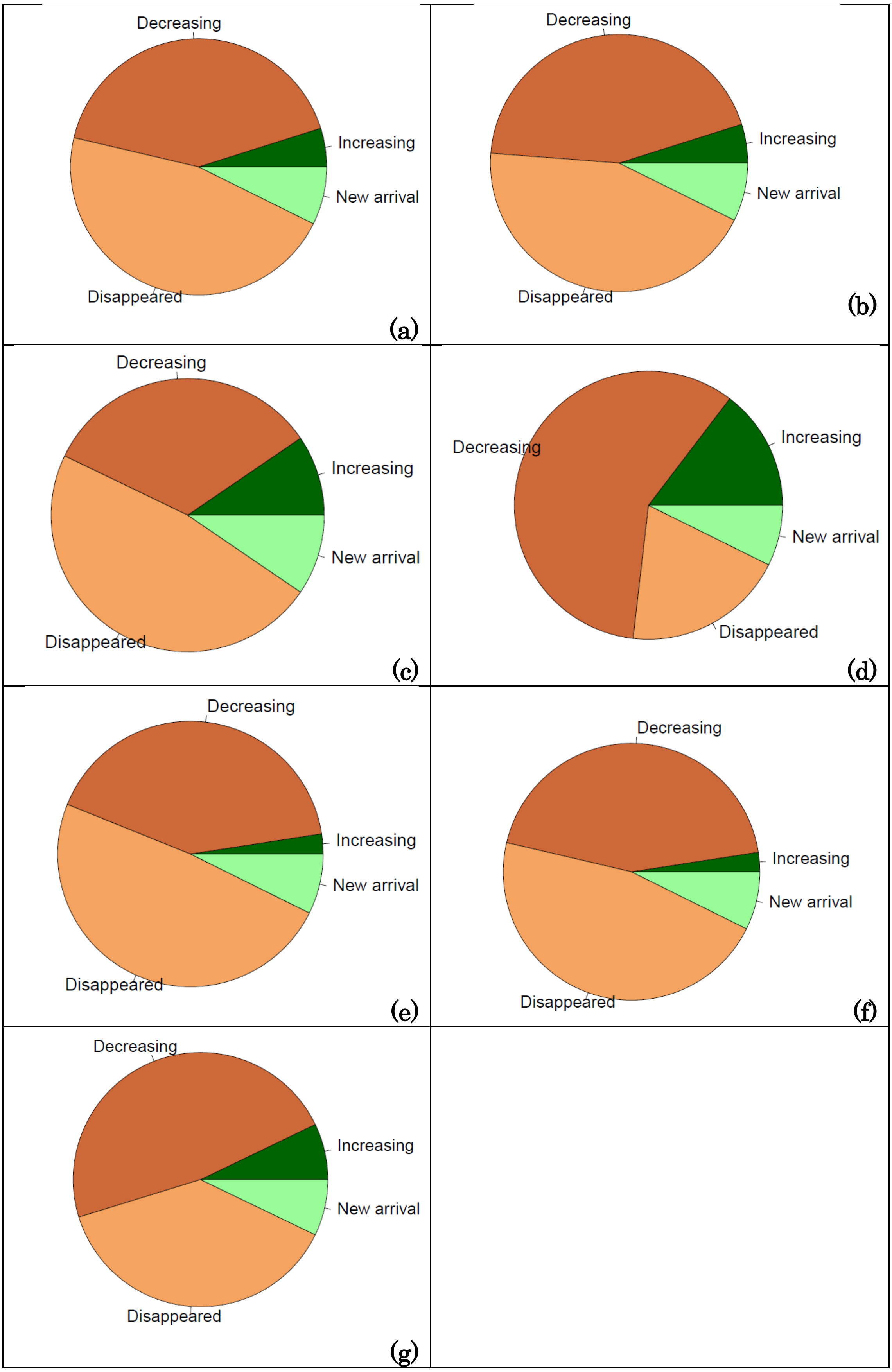


Figure 5.2. Distribution of vegetation species according to the categorisation order (a)Birnin-kuka (b) Bumbum (c) Dankama (d) Madarounfa (e) Magama (f) Sawani (g) Yakubawa

The respondents ascertained that some of these species have migrated to the more humid Sudan savanna zone where moisture conditions are more conducive for their growth.

The results presented here suggests that land degradation is still a pressing problem in the study area, as evidenced from the field observations and local indigenous knowledge which highlighted the decrease and disappearance of certain tree species. The presence and dominance of drought resistance, and other exotic tree species brought into the area through various afforestation programmes, shows that an ecological vegetation succession is taking place. This is one of the common features of land degradation in dryland environments where native plant species have migrated, died or been displaced by the new exotic species.

5.4 Discussion

The composition of indigenous woody plant species and their geographical presence in the study area is similar to the species found in other parts of the African drylands with similar environmental conditions. As reported by Gonzalez (2001), most of these species are found on farmlands under farm parkland systems, which have helped in preserving them in the area, and it is one of the local measures of ecological management in the region as reported by Aturamu and Daramola (2005).

The seasonal trends of NDVI, soil moisture and precipitation examined in the study villages shows overall positive increase which supported the most common scientific supposition in West Africa that was based on the analysis of satellite data as reported by different scientists. For instance, the study by Dardel et al. (2014), Rasmussen et al. (2001), Olsson et al. (2005), Anyamba and Tucker (2005), and Eklundh and Olsson (2003), reported an increased in NDVI, all of which indicate a possible reversal of land degradation in the region. Equally, Nicholson (2005) recounted increase in precipitation in sub-Saharan West Africa, marked as recovery from the dry spells of 1968-1997. This triggered the increase in photosynthetic activities in the region, with many scientists attributing to be the possible factor in increasing vegetation cover (Olsson et al., 2005). The same trend is witnessed for soil moisture, where it consistently increased in the overall pattern similar to that of the NDVI.

A number of studies used the increased NDVI trend in Sub-Saharan West Africa, which was generally termed as "(re)-greening" of the area, to dispute land degradation and desertification generally believed to be the major ecological problem affecting most part of the region prior to the advancement of NDVI data (Hutchinson et al., 2005). Based on the satellite data record, it was also claimed that desert advancement southward of the Sahel was not enlarging (Tucker and Nicholson, 1999). However, these trends do not reflect the actual condition of woody vegetation species in different parts of West Africa where satellite data shows a positive increase in all the study villages.

The results of the indigenous survey of botanical knowledge of vegetation changes across the study area show that the process of woody vegetation degradation is continuing and that a large proportion of trees were either extinct or reduced in abundance: nearly 80% of all the species reported by the respondents fall into these categories. This is contrary to satellite data shown in appendix 5. This finding is consistent across the seven villages and is similar to most previous studies in different parts of sub-Saharan West Africa where woody plant species were found to be declining in terms of density and diversity, especially in the Sahel savanna; see for example (Gonzalez, 2001, Tappan et al., 2004, Wezel and Lykke, 2006, Seaquist et al., 2006, Niang et al., 2008, Vincke et al., 2010, Gonzalez et al., 2012, Herrmann and Tappan, 2013). However, a distinctive feature of vegetation species increase was observed in Madarounfa, where about 14% of the species increased. This accounted for the highest proportion of species that increased across all the villages. The case of Madarounfa is attributed to government policies such as the establishment of nurseries of indigenous trees and the implementation of relevant forest laws in the area.

The results of the analysis of major driving forces of vegetation changes in the area show that a recurrence of drought has been triggering the decline of available soil moisture. This is the main factor of vegetation degradation in all the seven villages that were examined here. This finding is consistent with Sop and Oldeland (2011), and Hiernaux et al. (2009b), whose studies highlighted the influence of moisture content on the degradation of tree species density. The decrease in soil moisture content for woody species is accelerated by the dominance of herbaceous plant cover, which grows and competes for the available moisture with woody plant species in the region. A similar case was documented by Picard et al. (2005) in dryland savanna of Mali, where herbaceous plants, a large fraction of the plant community, compete for the available soil moisture with woody plants. This leads to the north-south migration of the vegetation species to the more favourable Sudan savanna climate zone. Similar plant species migration processes were reported in Niger and Burkina Faso by Wezel and Lykke (2006).

The importance of socio-economic activities and land use changes such as agricultural expansion, deforestation, tree lopping for animal feed, overgrazing, weak afforestation programmes and poverty alleviation actions, among others, play a major role in the woody species decline in the area. Similar conditions were reported in Mauritania, where woody plants decrease in density due to agricultural expansion and livestock grazing (Niang et al., 2008). Equally, Khan et al. (2013) found that human cultural habits and land use affect the vegetation condition which is also corroborated by Hiernaux et al. (2009b), whose study found that land use change and grazing pressure triggered a decrease in vegetation species. In many parts of Nigeria where woody vegetation species are present, locals take advantage of the poor implementation of forest laws and poverty to cut trees for fuelwood and for sale to earn income, particularly during the dry season. This is similar to the findings of Salami (1998) who reported the same situation in south-western Nigeria, where poor natural regeneration of trees due to the high demand of fuelwood was documented.

Available evidence from the literature based on the analyses of satellite data in the last three decades suggested that a re-greening has taken place in sub-Saharan West Africa (Nicholson, 1998, Helldén and Tottrup, 2008, Olsson and Mryka, 2008, Eastman et al., 2013). This trend is viewed as the likely reversal of desertification and land degradation in the region, which was caused by the droughts of the 1970s and 1980s (Herrmann et al., 2005). However, in the study presented here nearly 80% of all the indigenous plant species observed or reported by the respondents of the seven villages in the border region are either decreasing or disappearing from the region, despite the increase of the greening trend as seen in Figure 5.2. This changing pattern shows that woody vegetation degradation is still ongoing in the study area. This continued degradation of vegetation is similar to the trend that had been reported for different parts of sub-Saharan West Africa (see, for example, (Lykke et al., 2004, Wezel and Lykke, 2006, Sop and Oldeland, 2011). Therefore, based on the views and perceptions of local people living along Nigeria-Niger border, vegetation species are not recuperating or re-greening in the area. However, there might be local processes seemingly indicating a re-greening which might not necessarily be an improvement in ecological conditions, or at best a marginal improvement under specialised conditions. Reij et al. (2009) have observed human-driven re-greening processes in Niger Republic and reported similar phenomena. At the same time, the massive disappearance of indigenous species brought about by the worsening land degradation condition in sub-Saharan Africa has led to a new argument of a de-greening process rather than re-greening process in the area (UNCCD, 2010).

Although it is possible that both re-greening and de-greening may be simultaneously taking place in an area (Reij et al., 2009), this depends on the size and spatial scale under consideration. But in the case of the Nigeria-Niger border region, the level of decreased and disappeared indigenous species observed and reported by the respondents, indicates that de-greening is the dominant process taking place and that vegetation degradation is still a serious environmental problem despite the greening trend observed from the analyses of satellite data. This finding reaffirms the claim made by Tappan et al. (2004), Wazel & Lykke (2006), and Hiernaux et al. (2009b), where the decline and widespread disappearance of woody species was documented.

An understanding gained from this detailed analysis of historical changes of vegetation species offers the benefit of carrying out better land degradation management planning, reducing future degradation of land and in mitigating impacts on humanity, environment and the economy of the areas under study.

5.5 Conclusions

The analysis carried out in this chapter has shown that tree species degradation is still an ongoing problem in the Nigeria-Niger border region contrary to the 30-year greening trend observed from remote sensing studies. The findings from the seven rural areas have highlighted the importance of local ecological knowledge because the respondents were able to explain the ecological condition of the woody species as well as the major driving forces of the vegetation changes in the area. They were able to point to the decline in soil moisture content as a result of long-term drought to be the major cause of vegetation decline and disappearance in the region. This study also underlined the importance and relevance of indigenous knowledge for the long-term study of vegetation and environmental change.

The status of most of the tree species reported in the area is similar to the findings of several of the previous studies carried out in different parts of sub-Saharan West Africa using conventional survey methods. This is a very valuable approach for ecological studies, especially in a situation where comprehensive field surveys cannot be conducted. Therefore, local knowledge should be integrated in ecological resource management, especially at the local level, where locals relied on woody trees for food, income and fuelwood, so that species at risk of extinction can be preserved and, where possible, regenerated for conservation and sustainable use of the woody plant species in the region. Chapter 4 and Chapter 5 of this thesis have shown that integrating remote sensing and indigenous knowledge approaches for land degradation assessment is a valuable tool for better ecological studies.

6 Chapter 6: Assessment of dominant land cover types affected by land degradation in sub-Saharan West Africa

6.1 Introduction and rationale

In Chapter 4 of this thesis, I applied the Residual Trend Analysis method (RESTREND) and examined the nature of land degradation in the study area. In this chapter, I assessed the dominant land cover types that are mostly affected by land degradation.

Land degradation and desertification issues are among the milestone pillars of the international environmental sustainable and development agendas. Specifically, goal number 15 of the recently adopted United Nations Sustainable Development Goals (SDGs) targets combating desertification and reversing land degradation (UNCCD, 2015). Not only because it affects the livelihoods and well-being of entire societies in the affected areas, but also due to the devastating effects on ecosystems' stability, functions and services, loss of biodiversity (as shown in Figure 6.1) and an endless list of other ill-related severances (Mellenium Ecosystem Assessment, 2005).

Environmental problems in the dryland areas are aggravated when land degradation, mostly a human-induced process, is combined with natural climatic fluctuations (Karlson and Ostwald, 2016). The end results include, among others, a temporary or permanent decline in the structure, density, species composition and or productivity of vegetation cover (Grainger, 1996). This result in land cover change which is triggered by land use alterations and may vary significantly from one place to another depending on the prevailing conditions and the extent of man's acquisition of natural environment/resources to satisfy his immediate needs, is often to the detriment of land cover (Foley et al., 2005, van Dijk and Bose, 2016).

Information about the condition of land cover is of vital importance for many environmental applications (See et al., 2014). Over the years, interest on the possible connection between land degradation and land cover change vis-a-vis predominant land uses leading to the change emerged in global environmental literature, with the realisation that land surface processes influence climate and other environmental changes (Bontemps et al., 2012, Nicholson, 2013). In the mid-1970s, it was recognised that land cover changes modifies surface albedo, and thus surface-atmosphere energy exchanges which have a direct impact on regional climate (Charney et al., 1975, Eltahir and Bras, 1996, Los et al., 2006). Land cover change alters the partitioning of precipitation into soil water, evapotranspiration and run off (Foley et al., 2005). It also affects the biotic diversity worldwide, accelerates soil degradation, and weakens the ability of the biological system to support human needs (Hansen et al., 2013). Land cover change also determines the vulnerability of places and people to climatic, economic and socio-political trepidations (Kasperson and Archer, 2005).

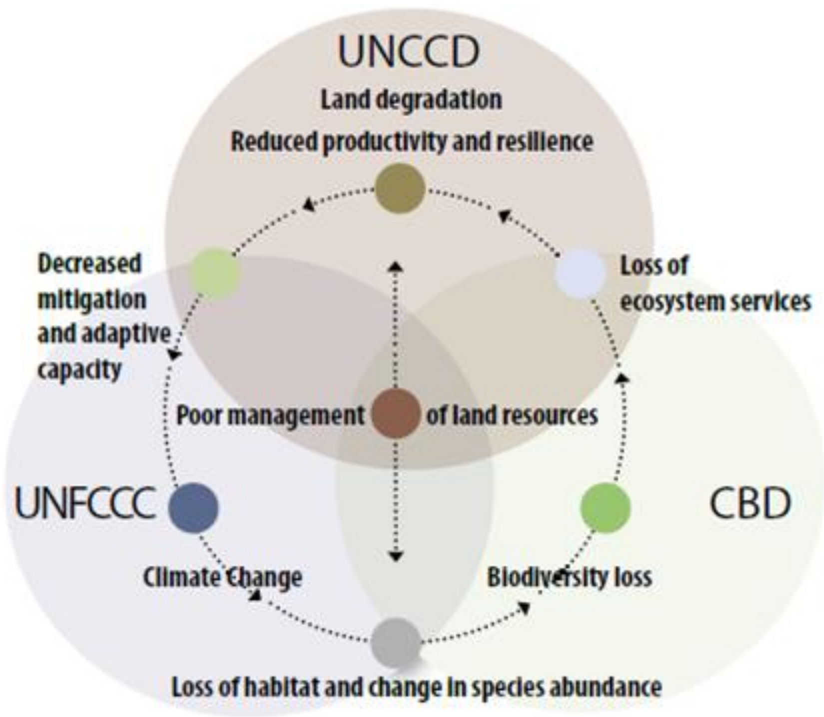


Figure 6.1. Interlinkages between Land and Climate in the context of UN conventions (UNCCD, 2015)

It has been argued that contemporary land cover change is generated principally by human actions directed at manipulating the surface of the earth for their personal benefits, such as agriculture, urbanisation, grazing, etc. (Lambin and Geist, 2008). This leads to the degradation of vegetation cover, which is also a cause and consequence of climate change (UNCCD, 2015). As shown in Figure 6.1, land degradation and climate change form feedback circles where intensive production increases emission and at the same time, the loss of vegetation and soil considerably reduces carbon sequestration. The end-result is more carbon in the atmosphere feeding a vicious cycle of land degradation, biodiversity loss and climate change (UNCCD, 2015). Further arguments by Lee et al. (2015) highlighted the role of vegetation cover in the overall feedback mechanism of the recent vegetation changes. They suggested that positive effects of vegetation cover through agricultural activities on regional rainfall could lead to positive feedback between vegetation and climate, especially in water limited ecosystems such as sub-Saharan Africa.

Generally, concerns about the resilience and vulnerability of land cover to land degradation is gaining prominence. Several arguments and suppositions were proposed over the years to be the major causes of land use and cover change (Lambin et al., 2001). In West Africa for example, dramatic changes in the climate and land cover witnessed over the past 60 years was argued to be principally due to the clearance of natural vegetation for cropping and fuelwood which is driven by the population growth and the need for food security (Lambin and Geist, 2008, Liu et al., 2003). In East Africa, the displacement of natural vegetation is expanding rapidly due to the change in land uses which is dominated by the expansion of farmlands, grazing areas and human settlements leading to the loss of biodiversity and land cover alteration (Maitima et al., 2009). At a local scale, the significance of fire incidence was also found to be an important factor of land cover change (Wessels et al., 2011).

Globally, it was documented that about 49% of the grassland ecosystem suffered degradation from 2000 to 2010 as result of climate change and human activities. And 33% of this degradation is as a result of overgrazing, agriculture and urbanisation (Gang et al., 2014). Equally, global expansion of croplands since 1850 had converted about six million km^2 of forest/woodlands and 4.7 million km^2 of savanna/grassland/steppe vegetation. Within these categories, respectively, 1.5 and 0.6 million km^2 of cropland have been abandoned (Ramankutty and Foley, 1999). Additionally, modern agriculture has been successful in increasing food production; it has also caused extensive environmental damage leading to a net loss of approximately 7 to 11 million km² of forest in the past 300 years, as shown in Figure 6.2 (Foley et al., 2005). This demonstrates that agriculture and other closely related land uses are the major causes of land cover change leading to land degradation in many parts of the world. Though in some cases steady restoration of grassland degradation was recorded due to a government effort in limiting the effect of human-induced land cover change (Cai et al., 2015).

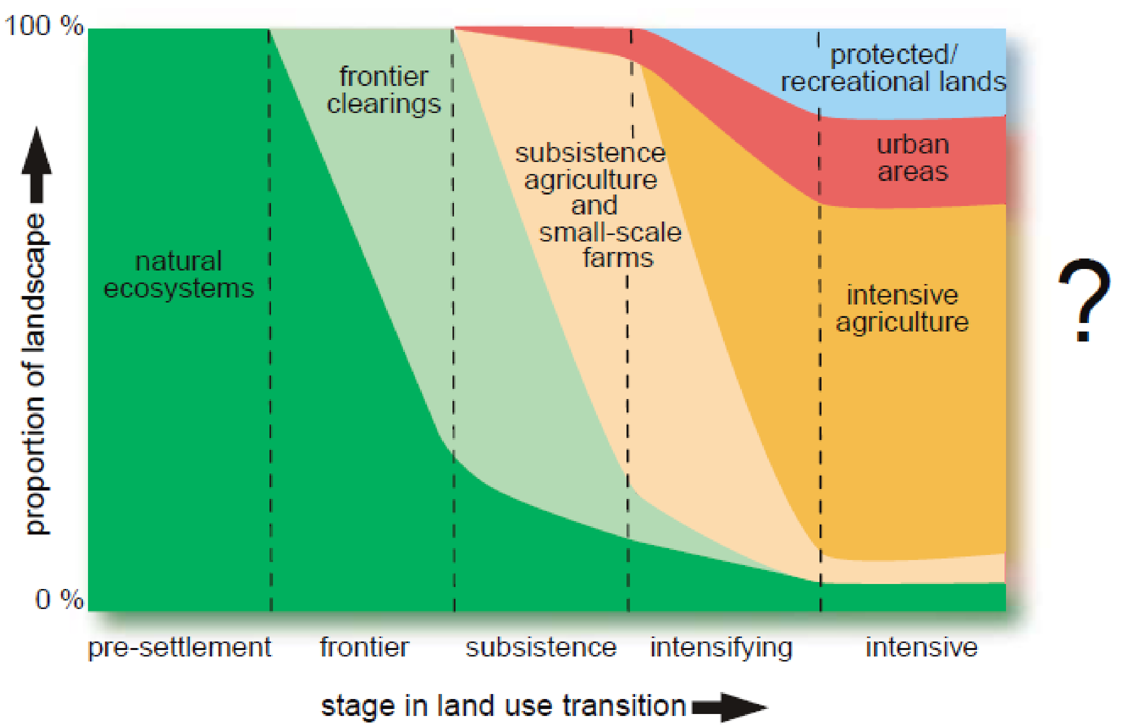


Figure 6.2. Stages of land cover change due to the land use transitions (Foley et al., 2005).

Due to the immense multitude of functions and services that land provides to humanity, it is important to study and monitor the state of land cover, especially in the extremely degraded areas in sub-Saharan Africa where 70% of the population depends on ecosystem services for their survival. In this chapter, I examine the dominant land cover types affected by land degradation in sub-Saharan West Africa from 2000 to 2010. The chapter intends primarily to present the result of the analysis of land cover as it relates to land degradation when RESTREND method was used to assess land degradation as highlighted in chapter 1 under specific aim and objectives. Thus, it provides answer to the research question *"What are the dominant land cover types that are mostly affected by land degradation in sub-Saharan West Africa?"*

6.2 Materials and Methods

6.2.1 Data sets

To address the research question raised in this chapter, I used climate change initiative land cover data CCI-LC (http://www.esa-landcover-cci.org/). The data is a product of CCI-LC projects which provide global land cover maps at 300m spatial resolution. Sponsored by the European Space Agency (ESA), it aims at providing multiyear maps for three 5-year epochs centred on the years 2000 (1998-2002); 2005 (2003-2007) and 2010 (2008-2012). I opted to use this land cover data because at present it is the only data archive produced in a repeatable way. It was designed to be globally consistent and regionally-tuned. Today, it is one of the most dynamic products in the form of a time series span from 2000 to 2014.

The product classification was developed by Universite Catholique de Louvain UCL-Geomatics. And it was built on the Globcover unsupervised classification chain, which combined the spectral and temporal richness of the medium resolution imaging spectrometer full resolution (MERIS FR) time series. In addition, MERIS reduced resolution (RR) was also used to supplement for the lack of MERIS FR data in some places and observations acquired by SPOT-VGT were also used to extend the temporal coverage of the project for the years 1998-2002 (Hollmann et al., 2013). The classification module of the CCI-LC processing chain first transformed the 7-day MERIS FR and RR multispectral $5*5^0$ tiles produced by the pre-processing module into meaningful land cover maps. Based on the entire 2003-2012 MERIS FR and RR archive, a 10-year global land cover map was generated and served as a baseline to derive the 2000, 2005 and 2010 maps using back and updating techniques based on SPOT-VGT time series. Table 6.1 provides detailed information of the data and sources.

Table 6.1. CCI-LC product description

CCI land cover map	Reference period	Spatial coverage and resolution	Data source
LC map 2010	2008-2012	Global/300m	MERIS 10-year LC map as baseline SPOT-VGT time series for updating
LC map 2005	2003-2007	Global/300m	MERIS 10-year LC map as baseline SPOT-VGT time series for back and updating
LC map 2000	1998-2002	Global/300m	MERIS 10-year LC map as baseline SPOT-VGT time series for backdating

The data were tested and validated using both ground and satellite reference data sources. In addition, expert opinions were also used to supplement the ground truth. The validation was enhanced following the experience gained from the GLC 2000 and Globcover maps project respectively. The accuracy of the data was evaluated using three complementary approaches: confidence building procedure, the statistical accuracy assessment and comparison with other global land cover products as well as temporal consistency assessment between the CCI land cover products themselves (ESA, 2014). The data typology was defined based on the UN land cover classification system (UN-LCCS), and it was compatible with the GLC 2000 and Globcover 2005 and 2009 products respectively.

6.2.2 Data analysis

In this section, I describe the procedure followed to achieve the stated research objectives from the data pre-processing to the detail analyses which was carried out.

Data pre-processing

The original CCI-LC came with 23 land cover classes which were reclassified into eight new land cover classes by aggregating the land cover categories which shared relevant, and to some extent common characteristics in order to have a limited number of land cover classes within the study area and to minimise data processing time. The original and new land cover classes developed are presented in Table 6.2.

Table 6.2. List of the original ESA-CCI- LC classification and the new classes derived from the aggregation of different land covers

ESA-CCI- Land cover classification	Land cover classification used in this study
Cropland, rainfed Crop land, irrigated or post-flooding Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	Crop lands
Grassland Herbaceous cover Sparse herbaceous cover (<15%)	Grasslands
Shrubland Shrubland deciduous Sparse shrub (<15%) Shrub or herbaceous cover, flooded, fresh/saline/brackish water Mosaic herbaceous cover (>50%) / tree and shrub (<50%) Mosaic tree and shrub (>50%) / herbaceous cover (<50%) Sparse vegetation (tree, shrub, herbaceous cover) (<15%) Tree or shrub cover	Shrub land

Mosaic tree and shrub (>50%) / herbaceous cover (<50%) Sparse vegetation (tree, shrub, herbaceous cover) (<15%) Tree covers, broadleaved, deciduous, open (15-40%)	Sparse vegetation
Tree cover, mixed leaf type (broadleaved and needle leaved) Tree cover, flooded, fresh or brackish water Tree cover, flooded, saline water	Closed Forest
Urban areas	Built up
Bare areas Consolidated bare areas Unconsolidated bare areas	Bare surface
Water bodies	Water bodies

After the reclassification, new land cover maps for the year 2000, 2005 and 2010 were produced and presented as Figure 6.3. All the analyses were carried out using Arc GIS.

Change detection

A change detection analysis was carried out to examine the trend of land cover change in the study area from 2000 to 2010. The extents of each land cover category were calculated and the percentages of each at any given year were computed. The percentage difference between the two or more successive periods was used to examine the trend of land cover change within the study period.

Land cover trend and trajectory in the most degraded areas

In this section, I applied the same RESTREND method, as presented in Chapter 4, but in this case based on 5-years epoch backdating each land cover date. Based on the RESTREND maps, I selected five sampling points across the study area that fall under severe land degradation condition for both soil moisture and rainfall RESTREND models. Table 6.3 shows the name and the location of the sampling points.

Table 6.3. Name and location of degraded sampling points

Location Name	Latitude	Longitude
Nigeria	12°49'44.4"N	9°17'9.6"E
Burkina Faso	13°33'18"N	1°36'46.8"W
Senegal	14°57'28.8"N	16°0'10.8"W
Ghana	8°1'8.4"N	0°24'46.8"W
Mali	16°11'9.6"N	0°39'39.6"E

The land cover types of each of the five sampling locations were examined for the years 2000, 2005 and 2010 respectively in order to find out the land cover type mostly affected by land degradation in these areas. Also the land cover trajectories at each location were evaluated to assess the pattern of changes over the study period. Finally, the land degradation trends for the year 2000(1996-2000), 2005(2001-2005) and 2010(2006-2010) were extracted from the RESTREND maps in order to have an insight into how land cover types responds to the resultant land degradation trend changes. These RESTREND maps are presented as appendix 3 respectively. The analysis was carried out using R statistical software.

6.3 Results

6.3.1 Land cover trend and change analysis

The land cover maps of sub-Saharan West Africa presented in Figure 6.3, show that bare surface makes up the largest percentage of landscape in the area, with about 41% for each of the years 2000, 2005 and 2010. Cropland makes up the next largest land cover and it occurs in most parts of the area, especially south of Sahel boundary down to Atlantic coast. The size of the croplands has increased from the year 2000 to 2010, indicating a continuous demand of agricultural land due to an increase in the population in the area.

Closed forest and sparse vegetation continue declining in the study area as shows in Table 6.4.

However, the extents of the changes were found to be infinitesimal due to the short-time span of the study coverage as a result of the paucity of long-term consistent land cover data. Also northward bare surface increased, indicating more land had been abandoned as it had become unproductive due to land degradation in the area. This is because the area falls within the Sahel and Saharan deserts, which are the heart of desertification in the region.

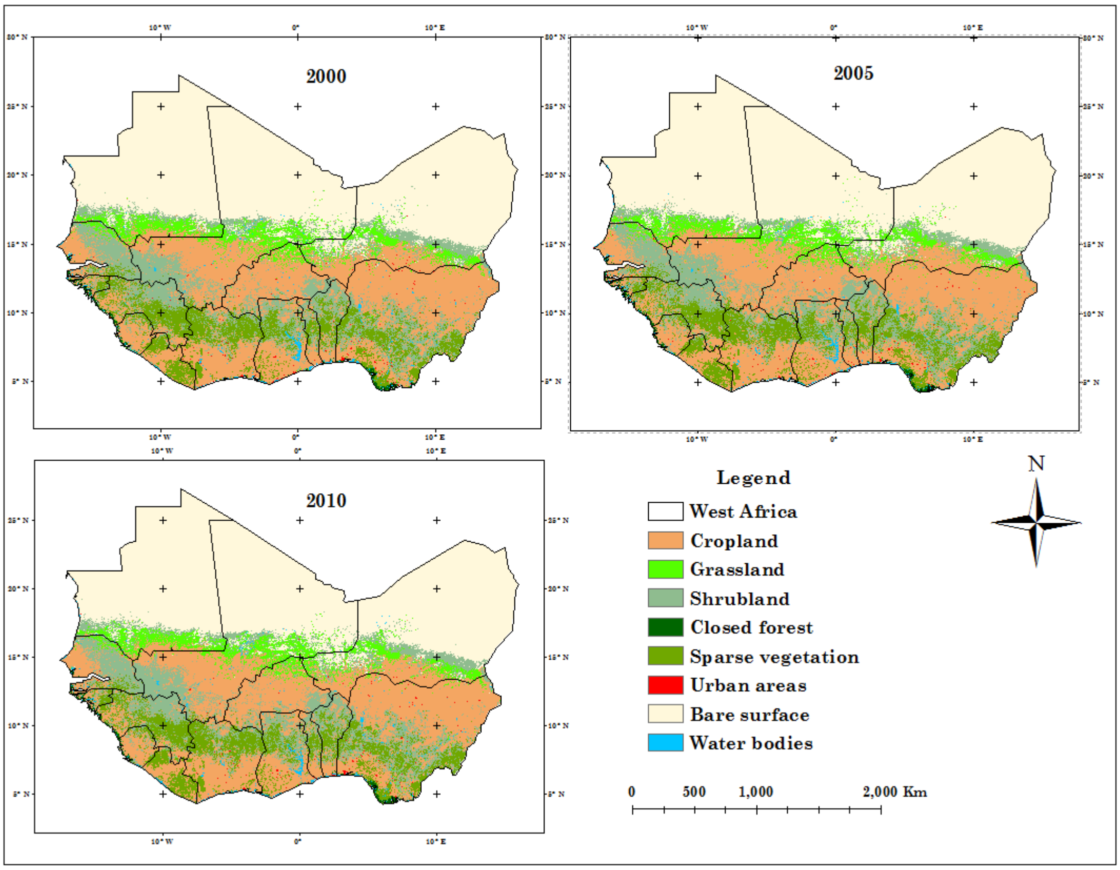


Figure 6.3. Land cover maps of West Africa at three time periods

@ *ESA-CCI*

6.3.2 Land cover change trajectories

Land cover change trajectories in the five study sampling locations for the years 2000, 2005 and 2010 show that land cover types at these locations remained the same from 2000 to 2010. In Nigeria, Burkina Faso and Senegal, the land cover type is cropland and the overall trajectory is also cropland

(Table 6.5). For Ghana, the land cover type trajectory is sparse vegetation throughout the study period. Finally, in Mali, which is located northward in the study area, the land cover type was found to be bare surface.

Table 6.4. Land cover changes in Sub-Saharan West Africa 2000-2010

Land covers	2000 Area (km²)	2000 %	2005 Area (km²)	2005 %	2010 Area (km²)	2010 %	Change (%) 2000-2005	Change (%) 2005-2010	Change (%) 2000-2010
Cropland	1662497	28	1665309	28	1665603	28	**+0.05**	**+0.005**	**+0.05**
Grassland	306929	05	306932	05	306932	05	+0.00005	**-0.0000015**	+0.00005
Shrubland	904889	15	910580	15	911147	15	**+0.0960**	**+0.0096**	**+0.12**
Closed forest	24155	0.41	24142	0.41	24142	0.41	**-0.00022**	0.000	**-0.00022**
Sparse veg.	527164	09	518670	09	517810	09	**-0.14**	**-0.015**	**-0.16**
Urban areas	11356	0.19	11356	0.19	11356	0.19	0.00	0.00	0.00
Bare surface	2448946	41	2448947	41	2448947	41	**+0.000011**	0.00	**+0.000011**
Water bodies	37999	0.64	37999	0.64	37999	0.64	0.00	0.00	0.00

Table 6.5. Land cover change trajectory in the selected degraded points

Location	Land cover type			Trajectory
	2000	2005	2010	
Nigeria	CL	CL	CL	CL
Burkina Faso	CL	CL	CL	CL
Senegal	CL	CL	CL	CL
Ghana	SV	SV	SV	SV
Mali	BS	BS	BS	BS

Key: CL- Cropland; SV- Sparse vegetation; BS- Bare surface

In the first three sampling points, the 2000-2010 land cover change trajectory shows stable primary and/or secondary agricultural activities. As indicated in Table 6.5, these areas were found to be stable at the expense of natural vegetation in the area (CL-CL-CL). It suggests that these changes were extensively induced by organised human activities. For the sampling point in Ghana, which is located mostly is forest and semi-deciduous woodland, the sampling point is under stable sparse vegetation (SV-SV-SV). Finally, the land cover type of the sampling location in Mali is under stable bare surface (BS-BS-BS), and is therefore more vulnerable to land degradation and desertification.

6.3.3 Land cover types mostly affected by land degradation

Based on the land cover change trajectories carried out at the five sampling sites, it can be deduced that the dominant land cover type affected by land degradation and desertification in the study area is cropland. This is followed by sparse vegetation and bare surfaces. This result is not surprising considering the fact that most of the croplands were converted from their original primary land cover to cultivation, replacing the natural vegetation cover with crops either raised as mixed farming or planted and maintained as monoculture. In the case of Ghana, where sparse vegetation was found to be the land cover type most affected, the area is under rainforest and hence it supposed to be under closed vegetation. However, due to land degradation in the area arising from the land use changes, the resulting consequences are a decrease in the number and percentage of vegetation species which altered the original thick vegetation to sparse vegetation structure in the area.

Finally, bare surface which was technically degraded and desertified is the dominant land cover affected by land degradation in Senegal and many other parts of northern West Africa. This area is located mostly in the Sahel and fringes of the Saharan desert.

6.3.4 Land cover change corresponding to land degradation trend

To examine the trend of land cover for the years 2000, 2005 and 2010 which corresponded to the land degradation trend maps presented in Chapter 4, I used Figures 6.4, 6.5 and 6.6 respectively. The trend of land degradation for each land cover category was extracted using polygons of each category. The land cover types were abbreviated as follows; CF-closed forest; SV-sparse vegetation; CL-crop land; GL-grass land; SL-shrub land; and BS-bare surface.

Based on the boxplots (Figures 6.4-6.6) presented, it is evident that land degradation is more pronounced in the year 2010. Also the land degradation trend based on soil moisture is more pronounced compared to rainfall predicted land degradation as shown earlier in Chapter 4. The land cover categories mostly affected by these degradation trends were grasslands, shrub lands and bare surfaces. This indicates the continuation of land degradation in the area.

It should be noted however; the RESTREND for each year was arrived at based on the land degradation trend of the previous 5 years. Thus, for the year 2000, I used the trend of 1996-2000 for 2005, it was based on 2001 to 2005 and finally for the year 2010, which was based on 2006 to 2010 residual trend maps respectively. The RESTREND maps of the corresponding periods were presented as Appendix 3.

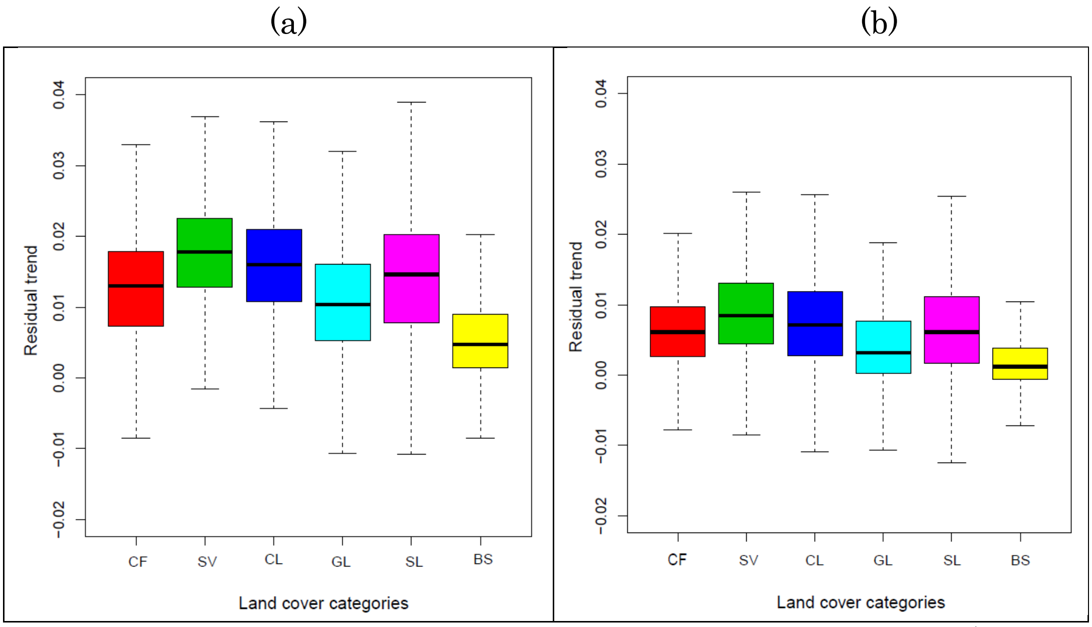


Figure 6.4. Land cover categories and RESTREND for the year 2000(1996-2000) based on (a) rainfall and (b) soil moisture.

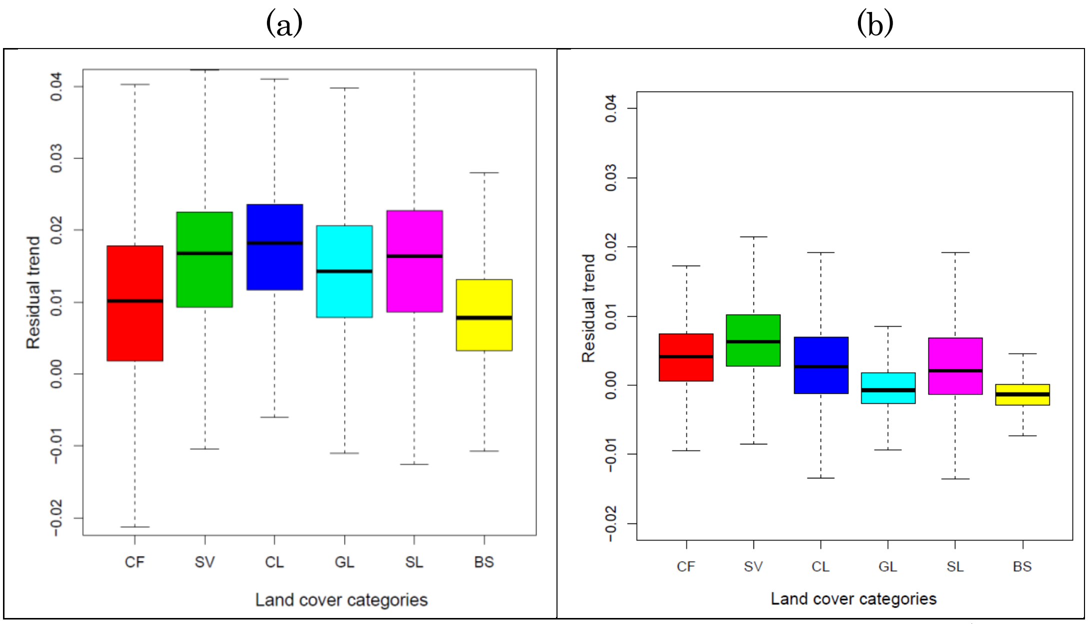


Figure 6.5. Land cover categories and RESTREND for the year 2005(2001-2005) based on (a) rainfall and (b) soil moisture.

(a) (b)

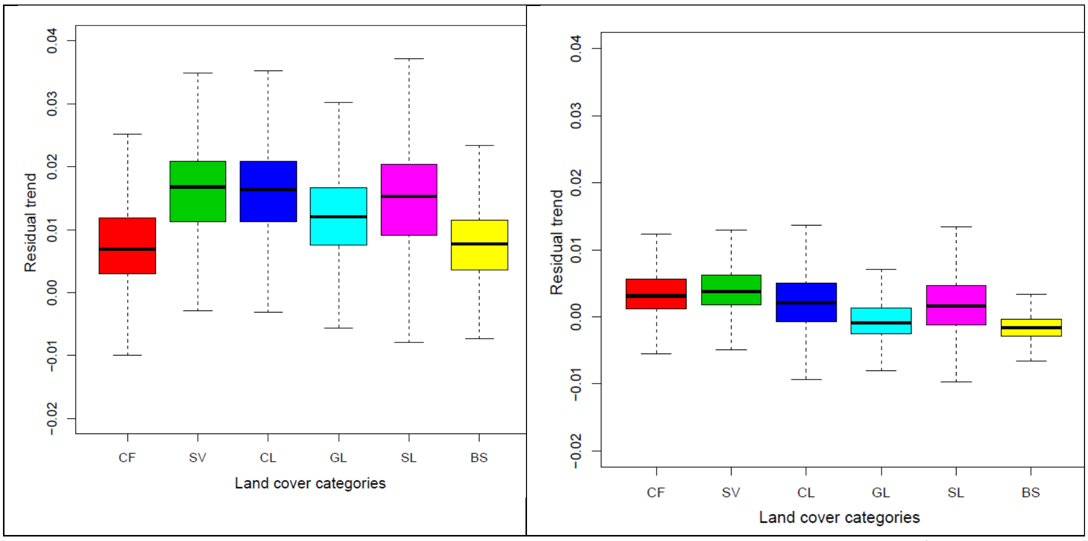


Figure 6.6. Land cover change and RESTREND for the year 2010(2006-2010) based on (a) rainfall and (b) soil moisture.

6.4 Discussion

The work presented in this chapter provides an empirical assessment and a possible link between land degradation and land cover change dynamics in sub-Saharan West Africa. The results show that land cover change trajectories involve a series of complex processes, some of which are cyclical and reversible, while others are linear and permanent. These diverse trajectories are consistent with a highly dynamic landscape dominated by forms of small holder land uses that reflect heterogeneous livelihood strategies. Usually, in rural sub-Saharan Africa, the landscape is dominated by a peasant farming system. Forest cover loss is attributed to shifting cultivation. The result shows that expansion of cropland is one of the direct causes of the decline of closed forest and sparse vegetation in the area.

The recent forest degradation relates mostly to the peasant agricultural system and can be associated to an increasing firewood demand from an expanding population in urban areas outside the cities and villages. A similar scenario was documented in southern Chile by Marín et al. (2011) and corresponds to the evidence of one of the landscape transformation causes in the Czech Republic put forward by Boori and Vozenilek (2014). And in some cases the decline of economic trees was observed due to agricultural intensification (Serra et al., 2008). Far north of the West African Sahel around Sahel-Saharan boundary, bare surface land has increased. This can be attributed to the expansion of degraded lands mainly due to the agricultural abandonment as land become unproductive for agriculture and grazing, forcing farmers to migrate southward. A similar situation has been highlighted over Saharan Africa and many other drylands areas over the globe for several decades (Symeonakis et al., 2004, Henao and Baanante, 2006, Shalaby and Tateishi, 2007).

With regards to the changes that took place on land cover from 2000 to 2010, some of the changes are directly linked to land degradation. This includes the decrease of closed forest and sparse vegetation and an increase of cropland and bare surface. These changes are either man-made through improper land uses or due to natural climatic fluctuations. This finding is similar to the work of Symeonakis et al. (2004), where the combination of forest fire, grazing and forest clearance were found to be the main causes of land cover change, leading to land degradation.

However, the land cover trajectories presented in the five sampling points does not portray much change. This can be attributed partly to the temporal extent of the study (15-years) and the spatial resolution of the data. It has been argued that for any reasonable land cover trajectory to be observed, the data should at least go beyond two decades (Symeonakis et al., 2004, Boori and Vozenilek, 2014). Nevertheless, about 60% of all the sampling points fall under CL-CL-CL land cover trajectories. These are areas mostly used by small holder and large scale farmers for crop production. Cereal crops such as maize, Guinea corn and millet are the dominant crops produced in the area. These areas fall under Nigeria, Burkina Faso and Senegal. The next trajectory is SV-SV-SV and it was found in Ghana from 2000 to 2010, and finally the BS-BS-BS trajectory was found in the most arid zone located in Mali. However, some of the studies which examined land cover change trajectories have documented land cover alterations over three consecutive periods. For instance, the study by Boori and Vozenilek (2014), found alteration in land cover trajectories from 1991 to 2013.

The analysis of land cover type mostly affected by land degradation in the study area shows that all the land cover types are affected. However, the dominant land covers affected based on the five sampling points are cropland, sparse vegetation and bare surface. These areas were found under an extreme negative residual trend, and the areas are located both in humid south and arid northern parts of the study area. This indicates the impact of human activities in land degradation, and agricultural activity in particular, which was found to be the major driving force of land cover degradation in the area. That is why most of the degraded areas were found under cropland. A similar scenario played out in different parts of the globe where grassland and other dominant land covers were transformed to agricultural fields due to the increased demands for food as a result of the increase in population and other human needs (Cai et al., 2015, Gang et al., 2014, Shalaby and Tateishi, 2007). Equally, the intensification of agriculture was found to be the major factor of land cover degradation in Dakar, Senegal (Bobée et al., 2012). Although Ghana falls under a humid climate, increasing pressure to satisfy energy demands and other provisioning ecosystem services have contributed to land degradation in the area. A similar condition was documented by Wessels et al. (2011), where about 50% of woody cover was degraded in the Lowveld savanna of South Africa due to human activities. Finally, the land degradation on the bare surfaces, especially in Senegal and other parts of northern sub-Saharan West Africa, can be linked to human activities. Some of these areas were previously under intensive farming and grazing. However, due to the consequences of climate change and poor human management, many of them are now abandoned. This corresponds to a similar situation in dryland areas of northern China where it was found to be under the risk of desertification due to land cover degradation (Huang and Siegert, 2006).

The trend of land cover change in relation to land degradation shows that degraded land covers are closely linked to soil moisture RESTREND than rainfall RESTREND model as presented in Figures 6.4, 6.5 and 6.6 respectively. Temporally, the year 2010 was found to portray land cover degradation more than any other corresponding time over the study period. Additionally, the vulnerability of each land cover category to degradation increases with time, and closed forest change negatively in 2010, indicating decline of natural cover. This finding corresponds to the finding of Brink and Eva (2009), who recorded the decline of natural vegetation cover over 25 years in Africa. However, on the overall croplands, grasslands and shrub lands were found to show high degradation potential. This is possibly due to the fact that most of the agricultural and grazing lands in sub-Saharan West Africa were either previously grassland or shrubland; with grassland being the most converted land cover type. This argument is supported by the findings of Gang et al. (2014) and Foley et al. (2005), who highlighted the vulnerability of grassland to land degradation.

The above link between land cover and land degradation indicates how the increasing nature of human activity significantly increases pressure on the ecosystems in the study area. This led to the conversion of forest and other resilient land cover types into agricultural lands as shown in the land cover change trends. These trends and trajectories should be taken into consideration when devising any strategy for land degradation control and any subsequent future environmental planning for sustainable management of the area to be successful. However, although the size of the study area and the spatial and temporal resolutions of the land cover data used for this study may not be an absolutely true representation of the actual land cover condition of the area, it provides us with a generalised idea of the possible process of land cover change taking place in the area and the likely trajectories pattern. Overall, the land cover degradation reflects the conflicting relationship between the physical and human systems in the study area.

6.5 Conclusions

This chapter has demonstrated how results of the RESTREND model can be used in combination of land cover, to identify areas of signinificant change and the nature of land degradation in these areas in sub-Saharan West Africa. The results presented shows a continued decline in closed forest and sparse vegetation and an increase in cropland; an indication of land degradation. This pattern of land cover change is accelerated by the increasing human population which are estimated to be growing at the rate of 2-3% in Africa by the year 2100. This increase in population is expected to upsurge the the size of cropland for food security, which will exert more pressure on the ecosystem. Overall, the land cover change trajectories in the five sampling sites shows that the major changes in the land cover have been caused by human activities and to some extent natural climatic variations, especially along the marginal areas where the size of bare surface has increased.

However, the links between RESTREND and land cover changes at regional scale was found to be insignificant, this can be attributed partly to the low resolution and reclassification system applied on the land cover. Nevertheless, the approach has the potentials to improve in identification of the vulnerable land use at mercy of land degradation.

Therefore, there is a need to carryout a comprehensive land cover assessment at local level to ascertain the major local driving forces and biophysical drivers of land cover degradation in the study area. The land use land cover change process should be included in the sustainable development agenda, so that the impact of land degradtion and desertification can be minimised for the general improvement of the livelihoods of the rural dwellers of sub-Saharan West Africa, who rely more on their lands as a means of survival.

7 Chapter 7: General discussion

7.1 Introduction

The analyses and results presented in Chapters 4, 5 and 6, show how a multi-method approach can be used to study land degradation, here, in sub-Saharan West Africa. Contrary to the general view of the ongoing greening of the region based on EO data, the evidence from this multi-method approach, the RESTREND analysis based on soil moisture index and, local field work backed by indigenous local knowledge, shows areas judged to be degraded and with declining abundance of woody vegetation species. Agricultural land use was found to be the major force driving land cover change based on the analysis carried out. In this chapter, I discuss the key findings of this research and its relationship with previous research carried out in the region and other dryland areas. A general discussion of the results from the preceding chapters is presented here, linking all the results together.

7.2 General overview and discussion

There is no doubt that sub-Saharan West Africa suffered a series of environmental perturbations accelerated by the recurrence of drought since 1960s (Nicholson, 1981). Many hypotheses were proposed as the causes of these droughts (Olsson et al., 2005). The overall impacts of the droughts, coupled with over-dependence on the ecological resources for livelihood by the vulnerable population in sub-Saharan West Africa, has led to widespread land degradation, especially along the climatically susceptible areas such as Sahel zones (Geist and Lambin, 2004). However, the problem of land degradation became a global topic following the Sahelian drought of the 1970s, and the United Nations agreed that land degradation is not only confined to sub-Saharan Africa, but occurs across all global dryland areas.

From 1980s onward, the debate on land degradation took another dimension following the availability of satellite data, and the difficulties to separate the effects of land degradation from other environmental problems such as climate change and drought. In Chapter 4 of this thesis, an attempt was made to assess land degradation using a relatively less ambiguous method (RESTREND) from 1982 to 2012. A key finding from the chapter was that the RESTREND method applied showed that, contrary to the widespread greening argument in sub-Saharan West Africa since 1980s (Fensholt et al., 2012, Eastman et al., 2013), evidence of land degradation can be seen both temporally and spatially across the region. This is even more glaring when soil moisture is used in the model to remove climate influences from the NDVI data set than instantaneous rainfall (Ibrahim et al., 2015). The degraded areas can be seen in Nigeria, Ghana, Niger, Mali, Burkina Faso, Senegal and other parts of the region. These are areas which, according to Reich et al. (2004), fall under very high to moderate land degradation vulnerability. This result is supported by the findings of Herrmann and Tappan (2013), where evidence of vegetation impoverishment was recorded in Senegal despite greening on the long-term trend of NDVI recorded by the satellite data.

The long-term temporal variation of the RESTREND residuals presented indicates a possible oscillation of land degradation relative to the climatic fluctuations. The trend shows that land degradation in the region is triggered by drought, with a likely possible reversal in rainy years, thus, re-affirming the difficulties of separating the effects of drought and land degradation (Stringer et al., 2009). Nevertheless, the patterns of human use of ecological resources play a significant role in the reversal, but not necessarily the climatic condition as reported by Sendzimir et al. (2011).

Having established spatial and temporal trends of land degradation based on the RESTREND method, the next step is to understand the actual condition of woody vegetation species which will help to further buttress the land degradation trend or greening arguments. In Chapter 5, a study was carried out to examine the condition of indigenous vegetation species along the Nigeria-Niger border region using field observation and an indigenous local knowledge. It also built on the results of similar studies carried out across other parts of the region and assessed the land degradation in relation to woody species changes. The results in Chapter 5 show that the process of land degradation by the gradual decrease and extinction of indigenous woody vegetation species is ongoing across the sampling sites studied. This finding is consistent with other relevant studies carried out within the region, where woody species decline was recorded (Wezel and Lykke, 2006, Gonzalez et al., 2012, Herrmann and Tappan, 2013, Herrmann and Sop, 2016).

An analysis of the major driving forces of vegetation change carried out in the area shows that combinations of natural and anthropogenic factors played a significant role. As reported by the respondents, the decline of the available soil moisture due to the recurrence of drought and the short rainy season is the major reason for vegetation degradation. This is coupled with other socio-economic factors such as land use changes, deforestation, tree lopping for animal feeds and fuelwood, and overgrazing among others. Thus, elsewhere in sub-Saharan West Africa, similar scenarios were documented where change in soil moisture content was found to be responsible for the decrease in woody species (Hiernaux et al., 2009b, Sop and Oldeland, 2011, A. Diouf, 2012). Furthermore, agricultural expansion as a result of increased demand for food plays a significant role in vegetation degradation across all the study sites.

The importance of land use and land cover change in the overall environmental process and land degradation in particular, cannot be overestimated. Therefore, in Chapter 6 an attempt was made to examine the possible link between land cover change and land degradation in sub-Saharan West Africa. This was achieved using CCI time series land cover data from 2000 to 2010. As highlighted earlier, agricultural expansion and overgrazing were found to be the major drivers of land cover alteration leading to the decline in vegetation species and triggered land degradation in the study area. The analysis of land cover further shows that forest cover loss is attributed to shifting cultivation. Some of the land cover changes that took place which are directly linked to land degradation are a decrease in closed forest and sparse vegetation; an increase in croplands and bare surfaces from 2000 to 2010. These changes were either driven by anthropogenic or natural forces. Similar land cover alteration was documented by Symeonakis et al. (2004).

Furthermore, the trend of land cover trajectories across the five sampling points selected under severe land degradation, shows that croplands were found to be the dominant land cover types. This is followed by bare surface and sparse vegetation. In all the selected areas, the land cover type remained unchanged from 2000 to 2010. This insignificant change in land cover trajectories can be attributed to the duration of land cover data records (2000-2010), which is infinitesimal to show detailed changes of land cover at regional scale. Also in Chapter 6, an attempt was made to find the possible link between land cover change and land degradation. This was achieved by computing RESTREND based on 5-year data for each land cover type as described extensively in the chapter. The finding shows that land becomes more degraded when anthropogenic land uses such as agriculture intensify and expand at the expense of natural cover such as forest. And the trend is portrayed by the land cover from the analysis carried out. This was similar to previous results reported by Brink and Eva (2009), and further highlighted the vulnerability and high degradation potentials of the grasslands and shrubland to land degradation in sub-Saharan West Africa, because most of the newly converted lands for agriculture or grazing were either previously grassland or shrubland. Grassland is the most vulnerable as highlighted by Foley et al. (2005) and Gang et al. (2014) where grassland was found to be the most sensitive land cover type to land degradation.

The above findings from the results presented in the analyses chapters have shown that land degradation studies require an application of multiple approaches in order to obtain relatively less ambiguous outcomes. It also highlighted the inadequacy of over reliance on satellite data alone to capture the true ecosystem status; even with application of robust methodology such as RESTREND which was found to be more efficient based on soil moisture-NDVI than rainfall-NDVI. The result from the RESTREND was only able to highlight areas presumed to be degraded. However, a further application of indigenous knowledge and other field studies conducted across the region, reported a decline in the abundance of woody species - an indication of land degradation. Equally the trend of land cover has shown that land use and land cover changes point toward land degradation because the size of forest and grasslands is shrinking at the detriment of croplands and other man-made uses.

Therefore, this work has highlighted and addressed the discrepancies arrived over time between the greening trend, woody species change and land use-land cover change. It has shown the robustness of the multiple approaches in desertification and land degradation research as applied in this study and its appropriateness for other dryland regions affected by land degradation. It further highlighted that land degradation involves three critical aspects: processes, land use issues and real causes. Therefore, any approach or method to tackle land degradation must takes cognizance of the intertwined relationship among these aspects. Hence the need to adopt the multi-method approach as applied in this study.

8 Chapter 8: Conclusion, research contributions, limitations and area of further research

This thesis has assessed land degradation in sub-Saharan West Africa using multi-approach methods of statistical trend analysis, indigenous knowledge and land use and land cover change. The work has also undertaken added knowledge and new dimensions to land degradation studies, and has highlighted how the RESTREND method can be improved with soil moisture for the overall improvement of land degradation assessment which can be applied in other dryland regions in the future.

8.1 Conclusion

The major conclusions of this thesis can be highlighted according to the results presented in the previous chapters as follows;

In ***Chapter 4***, the results of the assessment of land degradation using the RESTREND method was reported. The major highlights and key conclusions drawn in the chapter are;

- In spite of the greening trend recorded by satellite data in sub-Saharan West Africa, the evidence of land degradation and desertification is present in the area.
- RESTREND analysis of NDVI and soil moisture data is a better indicator of land degradation and vegetation recovery than if only rainfall data is used.
- A strong correlation was found between NDVI and soil moisture than NDVI and rainfall in most of the sampling sites, and Mann-Kendall seasonal trend analysis is monotonically significant for both soil moisture and rainfall RESTREND.

In ***Chapter 5***, the condition of indigenous woody vegetation species in relation to land degradation was examined. The following conclusions were made:

- Land degradation is evident through the gradual decline and extinction of indigenous woody vegetation species which is ongoing across different regions in sub-Saharan West Africa in spite of the greening trend recorded by 30-year satellite data.

- Indigenous local knowledge of the environment is a vital tool for ecological resource monitoring, especially in data scarce regions such as the study area. Locals were able to understand and describe the major process and effects of land degradation in their environment.
- The policies and programs of vegetation monitoring put in place determine the rate of species changes. Areas with sound conservation and management practices tend to have a more stable ecosystem than other places where people uses resources without care.

In ***Chapter 6***, a new analysis of land cover change and its link to land degradation based on RESTREND analysis of five-year data to match each land cover epoch was carried out. The following conclusions were reached at the end of the analysis:

- There is continuous decline of closed forest and sparse vegetation, and an increase in cropland-an indication of land degradation in the study area.
- There is no significant change in land cover trajectories from 2000 to 2010, which is partly attributed to the data resolution and the time frame of the data.
- Most of the areas found under severe land degradation based on RESTREND model, were under croplands, this in combination with an increase in croplands highlighted by the role of human land uses practices, especially agriculture in land degradation processes in sub-Saharan West Africa. This pattern of land use change has been attributed to the high demands of food to satisfy the increasing population, which is estimated to grow at the rate of 2-3% by 2100.

8.2 Research contributions

There is no doubt that research on desertification and land degradation has been going on in sub-Saharan West Africa since time immemorial. However, the uniqueness and the original contributions of this study can be summed up as follows:

This research has improved the performance and applicability of the RESTREND method in land degradation assessment by introducing soil moisture data into the model as against the traditional use of rainfall data to correct for vegetation productivity (NDVI). Soil moisture was found to be the better indicator of actual ecological condition than instantaneous rainfall, since vegetation species depend largely on soil water. Equally, as reported in Ibrahim et al. (2015), areas presumed to be degraded were more clearly identified when soil moisture-NDVI was used rather than rainfall-NDVI residual trend analysis both spatially and temporally.

Although over the years, satellite RS data has shown an increase in photosynthetic activity in sub-Saharan West Africa since 1980s, this study applied indigenous local knowledge and field observation and reported a decrease and extinction of woody vegetation species, as well as the emergence of new exotic ones in many villages across Nigeria-Niger border. These changes are indicators of ecological stress and disputes that the greening trend recorded by RS does not necessarily mean ecosystem stability because the signal might be that of grasses or agricultural fields. This research therefore documented evidence of land degradation despite greening and corroborated other relevant field studies based land degradation assessments carried out across sub-Saharan West Africa.

Finally, the approach of the multiple methods concept adopted in this research, minimises the ambiguity involved in land degradation and desertification studies than the single method approach. This is because a combination of process and drivers are involved in environmental change. Thus, this study has contributed in opening up new integrated dimensions to land degradation studies so that appropriate interpretations and inferences can be made.

8.3 Limitations of the study

There are a number of limitations in the data and methods used in this research. To begin with, the use of coarse resolution NDVI, soil moisture and rainfall datasets is one of the major impediments of this study. However, the data was used because, at the moment, the only archive which contains NDVI data and extends beyond 30-years is 8km AVHRR NDVI data. Similarly, the soil moisture and rainfall datasets used in this study are satellite estimates and in some cases model estimates. This is due to a lack of long-term observed data covering the study area. As described earlier in the thesis, for any appreciable environmental change to be observed, the data used in the analysis should extend beyond 15 years, hence the use of this available datasets despite its limitations.

Equally, the generalisation of the study to cover the entire sub-Saharan West Africa from the arid north down to Atlantic coast despite their varied environmental conditions may not provide succinct feature of land degradation. The study could have been conducted at local scale level rather than regional; however, the paucity of long-term data as mentioned earlier leaves the research with no option. Nevertheless, at the moment, new high resolution data products are becoming available, but their time coverage limited their application for long-time environmental studies.

The RESTREND method used in this study, does not exclusively indicate whether the area is degraded or not, but it provides hints and signs of the likely land degradation features based on the predominance of positive or negative trends of the NDVI residuals. That is why further investigations are required to determine what the trends meant on the ground as carried out along the Nigeria-Niger border region in this study. Therefore, in spite of the robustness of the RESTREND method, careful analysis should be carried out before strong inference can be made.

Ideally, field work aspects of this research should have been carried out to cover as many areas as possible within sub-Saharan West Africa. However, it is limited to Nigeria-Niger border villages. Additionally, the used of indigenous knowledge to obtain historical data of vegetation conditions has been widely criticised. However, in a situation where it is impossible to get historical data, it has been proven to be the best alternative option. Nevertheless, the study relied on the findings of previous studies carried out within the region where both field observations and field measurements were used. And the results do not show much disagreement.

Finally, the land cover data used, and the generalisation of land cover classes adopted, made it difficult to observe sizeable change in the overall long-term land cover change trajectories in the selected sampling sites that fall under severe land degradation based on the RESTREND method used. It could have been better if the land cover resolution was higher so that localised changes can be seen vividly compared to the slight changes recorded from 2000 to 2010. This may under or overestimate the land cover classes, which may have a significant effect on the actual change taking place. Despite these limitations, the overall trends shown by land cover change and trajectories, tilted toward signs favourable to assume the continued land degradation than greening.

8.4 Area of further research

This research furthers the understanding of the complexity of land degradation in sub-Saharan West Africa by highlighting the importance of different approaches and dimensions of the problem. As a researcher with an interest in dryland environments, my future studies will focus on local studies with high resolution data and possibly observation data, so that specific driving forces and process of land degradation can be carefully monitored.

Although the RESTREND method has been proven to be an effective method, there is a need to improve the model by integrating local drivers of land degradation, so that major local processes leading to the problem and other environmental changes can be monitored. This may involve monitoring of both short-term and long-term processes, which may affect the ecological processes, and thus land degradation.

In sub-Saharan West Africa, LUCC is a very important factor that has a strong influence on the overall environmental processes. Therefore, there is a need to consider a comprehensive assessment of local drivers of LUCC using high resolution data, this will provide avenues for future improvement of the understanding of the major connections between LUCC and land degradation.

9 Bibliography

A. Diouf, N. B., A. M. Lykke, P. Couteron, V. Deblauwe, A. Mahamane, M. Saadou and J. Bogaert 2012. Relationships between fire history, edaphic factors and woody vegetation structure and composition in semi-arid savanna landscape (Niger, West Africa). *Applied Vegetation Science*.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D. & Hogg, E. T. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management,* 259, 660-684.

Anyamba, A. & Tucker, C. J. 2005. Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. *Journal of Arid Environments,* 63, 596-614.

Aturamu, O. & Daramola, A. 2005. Agroforestry policy options for Nigeria: A simulation study. *Journal of Food, Agriculture & Environment,* 3, 120-124.

Aubréville, A. 1949. Climats, forêts et désertification de l'Afrique tropicale.

Baartman, J. E., van Lynden, G. W., Reed, M., Ritsema, C. & Hessel, R. 2007. Desertification and land degradation: origins, processes and solutions. *DESIRE Report,* 4.

Bai, Z., Dent, D., Olsson, L. & Schaepman, M. 2008. Global assessment of land degradation and improvement 1: identification by remote sensing. *Report 2008/01, FAO/ISRIC-Rome/Wageningen*.

Bennett, R., Welham, K., Hill, R. A. & Ford, A. L. 2012. The application of vegetation indices for the prospection of archaeological features in grass - dominated environments. *Archaeological Prospection,* 19, 209-218.

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013. Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Blaikie, P., Brown, K., Stocking, M., Tang, L., Dixon, P. & Sillitoe, P. 1997. Knowledge in action: Local knowledge as a development resource and barriers to its incorporation in natural resource research and development. *Agricultural systems,* 55, 217-237.

Blench, R. & Dendo, M. 2007. Hausa names for plants and trees. *Draft prepared for comment only) 2nd edn. Cambridge, United Kingdom,* 8.

Bobée, C., Ottlé, C., Maignan, F., de Noblet-Ducoudré, N., Maugis, P., Lézine, A. M. & Ndiaye, M. 2012. Analysis of vegetation seasonality in

Sahelian environments using MODIS LAI, in association with land cover and rainfall. *Journal of Arid Environments,* 84, 38-50.

Bollig, M. & Schulte, A. 1999. Environmental change and pastoral perceptions: degradation and indigenous knowledge in two African pastoral communities. *Human ecology,* 27, 493-514.

Bontemps, S., Herold, M., Kooistra, L., van Groenestijn, A., Hartley, A., Arino, O., Moreau, I. & Defourny, P. 2012. Revisiting land cover observation to address the needs of the climate modeling community. *Biogeosciences,* 9, 2145-2157.

Boori, M. S. & Vozenilek, V. 2014. Assessing land cover change trajectories in Olomouc, Czech Republic. *Int J Environ Ecol Geol Min Eng,* 8, 540-546.

Brandt, M., Romankiewicz, C., Spiekermann, R. & Samimi, C. 2014a. Environmental change in time series – An interdisciplinary study in the Sahel of Mali and Senegal. *Journal of Arid Environments,* 105, 52-63.

Brandt, M., Verger, A., Diouf, A., Baret, F. & Samimi, C. 2014b. Local Vegetation Trends in the Sahel of Mali and Senegal Using Long Time Series FAPAR Satellite Products and Field Measurement (1982–2010). *Remote Sensing,* 6, 2408-2434.

Brink, A. B. & Eva, H. D. 2009. Monitoring 25 years of land cover change dynamics in Africa: A sample based remote sensing approach. *Applied Geography,* 29, 501-512.

Burns, W. C. 1994. International Convention to Combat Desertification: Drawing a Line in the Sand, The. *Mich. J. Int'l L.,* 16, 831.

Cai, H., Yang, X. & Xu, X. 2015. Human-induced grassland degradation/restoration in the central Tibetan Plateau: The effects of ecological protection and restoration projects. *Ecological Engineering,* 83, 112-119.

Caminade, C. & Terray, L. 2010. Twentieth century Sahel rainfall variability as simulated by the ARPEGE AGCM, and future changes. *Climate Dynamics,* 35, 75-94.

Charney, J., Stone, P. H. & Quirk, W. J. 1975. Drought in the Sahara: A Biogeophysical Feedback Mechanism. *Science,* 187, 434-435.

Costa, A. C. & Soares, A. 2012. Local spatiotemporal dynamics of a simple aridity index in a region susceptible to desertification. *Journal of Arid Environments,* 87, 8-18.

Crosson, P., Lal, R., Blum, W., Valentin, C. & Stewart, B. 1997. The on-farm economic costs of erosion. *Methods for assessment of soil degradation.*, 495-511.

Dardel, C., Kergoat, L., Hiernaux, P., Mougin, E., Grippa, M. & Tucker, C. J. 2014. Re-greening Sahel: 30years of remote sensing data and field observations (Mali, Niger). *Remote Sensing of Environment,* 140, 350-364.

Darkoh, M. B. K. 1998. The nature, causes and consequences of desertification in the drylands of Africa. *Land Degradation & Development,* 9, 1-20.

Davis, D. K. 2005. Indigenous knowledge and the desertification debate: problematising expert knowledge in North Africa. *Geoforum,* 36, 509-524.
de Jong, R., de Bruin, S., de Wit, A., Schaepman, M. E. & Dent, D. L. 2011. Analysis of monotonic greening and browning trends from global NDVI time-series. *Remote Sensing of Environment,* 115, 692-702.
De Jong, R., De Bruin, S., Schaepman, M.E. & Dent, D 2011. Quantitative mapping of global Land Degradation Using Earth Observation. *International Journal of Remote Sensing,* 32, 6823-6853.
Dent, D., Bai, Z., Schaepman, M. & Olsson, L. 2009. Letter to the editor. *Soil Use and Management,* 25, 93-97.
Dinku, T., Ceccato, P., Grover - Kopec, E., Lemma, M., Connor, S. & Ropelewski, C. 2007. Validation of satellite rainfall products over East Africa's complex topography. *International Journal of Remote Sensing,* 28, 1503-1526.
Dirmeyer, P. A., Guo, Z. & Gao, X. 2004. Comparison, validation, and transferability of eight multiyear global soil wetness products. *Journal of Hydrometeorology,* 5, 1011-1033.
Donohue, R. J., Roderick, M. L., McVicar, T. R. & Farquhar, G. D. 2013. Impact of CO2fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters,* 40, 3031-3035.
Drake, N. & Vafeidis, A. 2004. A review of European Union funded research into the monitoring and mapping of Mediterranean desertification. *Advances in Environmental Monitoring and Modelling,* 1, 1-51.
Dregne, H. E. 1977. Desertification of arid lands. *Economic Geography,* 53, 322-331.
Dregne, H. E. & Chou, N.-T. 1992. Global desertification dimensions and costs. *Degradation and restoration of arid lands*, 73-92.
Eastman, J., Sangermano, F., Machado, E., Rogan, J. & Anyamba, A. 2013. Global Trends in Seasonality of Normalized Difference Vegetation Index (NDVI), 1982–2011. *Remote Sensing,* 5, 4799-4818.
Eklundh, L. & Olsson, L. 2003. Vegetation index trends for the African Sahel 1982–1999. *Geophysical Research Letters,* 30.
Eltahir, E. A. & Bras, R. L. 1996. Precipitation recycling. *Reviews of geophysics,* 34, 367-378.
Evans, J. & Geerken, R. 2004. Discrimination between climate and human-induced dryland degradation. *Journal of Arid Environments,* 57, 535-554.
Fan, Y. & van den Dool, H. 2004. Climate Prediction Center global monthly soil moisture data set at 0.5 resolution for 1948 to present. *Journal of Geophysical Research: Atmospheres,* 109.
FAO 1981. *FAO-UNESCO soil map of the world, 1: 5,000,000*, UNESCO.
FAO 2000. The global ecofloristic zones mapped by United Nations Food and Agricultural Organization. *In:* Fao (ed.). Rome, Italy.
FAO 2010. Global forest resource assessment. *In:* Fao (ed.). Rome, Italy.
Fensholt, R., Langanke, T., Rasmussen, K., Reenberg, A., Prince, S. D., Tucker, C., Scholes, R. J., Le, Q. B., Bondeau, A., Eastman, R., Epstein,

H., Gaughan, A. E., Hellden, U., Mbow, C., Olsson, L., Paruelo, J., Schweitzer, C., Seaquist, J. & Wessels, K. 2012. Greenness in semi-arid areas across the globe 1981–2007 — an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment,* 121, 144-158.

Fensholt, R., Nielsen, T. T. & Stisen, S. 2006. Evaluation of AVHRR PAL and GIMMS 10 - day composite NDVI time series products using SPOT - 4 vegetation data for the African continent. *International Journal of Remote Sensing,* 27, 2719-2733.

Fensholt, R. & Proud, S. R. 2012. Evaluation of earth observation based global long term vegetation trends—Comparing GIMMS and MODIS global NDVI time series. *Remote sensing of Environment,* 119, 131-147.

Fensholt, R. & Rasmussen, K. 2011. Analysis of trends in the Sahelian 'rain-use efficiency' using GIMMS NDVI, RFE and GPCP rainfall data. *Remote Sensing of Environment,* 115, 438-451.

Fensholt, R., Rasmussen, K., Kaspersen, P., Huber, S., Horion, S. & Swinnen, E. 2013. Assessing Land Degradation/Recovery in the African Sahel from Long-Term Earth Observation Based Primary Productivity and Precipitation Relationships. *Remote Sensing,* 5, 664-686.

Fensholt, R., Rasmussen, K., Nielsen, T. T. & Mbow, C. 2009. Evaluation of earth observation based long term vegetation trends — Intercomparing NDVI time series trend analysis consistency of Sahel from AVHRR GIMMS, Terra MODIS and SPOT VGT data. *Remote Sensing of Environment,* 113, 1886-1898.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. & Snyder, P. K. 2005. Global Consequences of Land Use. *Science,* 309.

Foody, G. M. 2004. Spatial nonstationary and scale dependency in the relationship between species richness and environmental determinants for the sub-Saharan endemic avifauna. *Global Ecology and Biogeography,* 13, 315-320.

Forkel, M., Carvalhais, N., Verbesselt, J., Mahecha, M., Neigh, C. & Reichstein, M. 2013. Trend Change Detection in NDVI Time Series: Effects of Inter-Annual Variability and Methodology. *Remote Sensing,* 5, 2113-2144.

Gang, C., Zhou, W., Chen, Y., Wang, Z., Sun, Z., Li, J., Qi, J. & Odeh, I. 2014. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. *Environmental Earth Sciences,* 72, 4273-4282.

Gates, D. M. 2012. *Biophysical ecology*, Courier Corporation.

Geist, H. J. & Lambin, E. F. 2004. Dynamic Causal Patterns of Desertification. *BioScience,* 54, 14.

German Technical and Development Cooperation GTZ 2005. Fact sheets desertification: Africa convention project to combat desertification.

Giannini, A., Biasutti, M. & Verstraete, M. M. 2008. A climate model-based review of drought in the Sahel: Desertification, the re-greening and climate change. *Global and Planetary Change,* 64, 119-128.

Giannini, A. S., R. and Chang, P 2003. Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales. *Science,* 302, 1027-1030.

Gitelson, A. A. 2004. Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation. *Journal of plant physiology,* 161, 165-173.

Gitelson, A. A., Kaufman, Y. J. & Merzlyak, M. N. 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. *Remote Sensing of Environment,* 58, 289-298.

Glantz, M. H. & Orlovsky, N. 1983. Desertification: A review of the concept. *Desertification Control Bulletin,* 9, 15-22.

Gonzalez, P. 2001. Desertification and a shift of forest species in the West Africa Sahel. *Climate Research,* 17, 217-228.

Gonzalez, P., Tucker, C. J. & Sy, H. 2012. Tree density and species decline in the African Sahel attributable to climate. *Journal of Arid Environments,* 78, 55-64.

Govaerts, Y. & Lattanzio, A. 2008. Estimation of surface albedo increase during the eighties Sahel drought from Meteosat observations. *Global and Planetary Change,* 64, 139-145.

Grainger, A. 1996. Integrating the socio-economic and physical dimensions of degraded tropical lands in global climate change mitigation assessments. *Forest Ecosystems, Forest Management and the Global Carbon Cycle.* Springer.

Grainger, A. 2009. The role of science in implementing international environmental agreements: The case of desertification. *Land Degradation & Development,* 20, 410-430.

Grainger, A., Mark Stafford Smith, Victor R Squires & Glenn, E. P. 2000. Desertification and Climate Change: The case for greater convergence. *Mitigation and adaptation strategies for global change,* 5, 361-377.

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W. & Fischer-Kowalski, M. 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences,* 104, 12942-12947.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O. & Townshend, J. R. 2013. High-resolution global maps of 21st-century forest cover change. *Science,* 342, 850-3.

Hayward, D. & Oguntoyinbo, J. S. 1987. *Climatology of West Africa*, Rowman & Littlefield.

Hein, L. & De Ridder, N. 2006. Desertification in the Sahel: a reinterpretation. *Global Change Biology,* 12, 751-758.

Hellden, U. 1991. Desertification: Time for an Assessment? *Ambio,* 20, 372-383.

Helldén, U. & Tottrup, C. 2008. Regional desertification: A global synthesis. *Global and Planetary Change,* 64, 169-176.
Hellier, A., Newton, A. C. & Gaona, S. O. 1999. Use of indigenous knowledge for rapidly assessing trends in biodiversity: a case study from Chiapas, Mexico. *Biodiversity & Conservation,* 8, 869-889.
Henao, J. & Baanante, C. 2006. *Agricultural production and soil nutrient mining in Africa: implications for resource conservation and policy development*, IFDC-An International Center for Soil Fertility and Agricultural Development.
Herrmann, S. M., Anyamba, A. & Tucker, C. J. 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change,* 15, 394-404.
Herrmann, S. M. & Hutchinson, C. F. 2006. The Scientific basis: links between land degradation, drought and desertification. *Governing Global desertification: Linking Environmental Degradation, Poverty and Participation. Ashgate Publishing, Hamphsire, England*, 11-27.
Herrmann, S. M. & Sop, T. K. 2016. The Map Is not the Territory: How Satellite Remote Sensing and Ground Evidence Have Re-shaped the Image of Sahelian Desertification. *The End of Desertification?* : Springer.
Herrmann, S. M., Sall, I. & Sy, O. 2014. People and pixels in the Sahel: A study linking coarse-resolution remote sensing observations to land users' perceptions of their changing environment in Senegal. *Ecol. Soc,* 19, 29.
Herrmann, S. M. & Tappan, G. G. 2013. Vegetation impoverishment despite greening: A case study from central Senegal. *Journal of Arid Environments,* 90, 55-66.
Hickler, T., Eklundh, L., Seaquist, J. W., Smith, B., Ardö, J., Olsson, L., Sykes, M. T. & Sjöström, M. 2005. Precipitation controls Sahel greening trend. *Geophysical Research Letters,* 32.
Hiernaux, P., Ayantunde, A., Kalilou, A., Mougin, E., Gérard, B., Baup, F., Grippa, M. & Djaby, B. 2009a. Trends in productivity of crops, fallow and rangelands in Southwest Niger: Impact of land use, management and variable rainfall. *Journal of Hydrology,* 375, 65-77.
Hiernaux, P., Diarra, L., Trichon, V., Mougin, E., Soumaguel, N. & Baup, F. 2009b. Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). *Journal of Hydrology,* 375, 103-113.
Higginbottom, T. & Symeonakis, E. 2014. Assessing Land Degradation and Desertification Using Vegetation Index Data: Current Frameworks and Future Directions. *Remote Sensing,* 6, 9552-9575.
Holben, B. N. 1986. Characteristics of maximum-value composite images from temporal AVHRR data. *International journal of remote sensing,* 7, 1417-1434.
Hollmann, R., Merchant, C., Saunders, R., Downy, C., Buchwitz, M., Cazenave, A., Chuvieco, E., Defourny, P., De Leeuw, G. & Forsberg, R. 2013. The ESA climate change initiative: Satellite data records for

essential climate variables. *Bulletin of the American Meteorological Society,* 94, 1541-1552.

Hoscilo, A., Balzter, H., Bartholomé, E., Boschetti, M., Brivio, P. A., Brink, A., Clerici, M. & Pekel, J. F. 2014. A conceptual model for assessing rainfall and vegetation trends in sub-Saharan Africa from satellite data. *International Journal of Climatology*, n/a-n/a.

Huang, S. & Siegert, F. 2006. Land cover classification optimized to detect areas at risk of desertification in North China based on SPOT VEGETATION imagery. *Journal of Arid Environments,* 67, 308-327.

Huber, S., Fensholt, R. & Rasmussen, K. 2011. Water availability as the driver of vegetation dynamics in the African Sahel from 1982 to 2007. *Global and Planetary Change,* 76, 186-195.

Huenneke, L. F., Anderson, J. P., Remmenga, M. & Schlesinger, W. H. 2002. Desertification alters patterns of aboveground net primary production in Chihuahuan ecosystems. *Global Change Biology,* 8, 247-264.

Huete, A., Liu, H., Batchily, K. v. & Van Leeuwen, W. 1997. A comparison of vegetation indices over a global set of TM images for EOS-MODIS. *Remote sensing of environment,* 59, 440-451.

Hulme, M. 2001. Climatic perspectives on Sahelian desiccation: 1973–1998. *Global Environmental Change,* 11, 19-29.

Ibrahim, Y., Balzter, H., Kaduk, J. & Tucker, C. 2015. Land Degradation Assessment Using Residual Trend Analysis of GIMMS NDVI3g, Soil Moisture and Rainfall in Sub-Saharan West Africa from 1982 to 2012. *Remote Sensing,* 7, 5471-5494.

IPCC, 2013. Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jamali. S, S. J. W., Ardo. J and Eklundh. L 2011. Investigating Temporal Relationships Between Rainfall, Soil Moisture and MODIS-derived NDVI and EVI for Six Sites in Africa. *34th International Symposium on Remote Sensing of Environment.*

Janicot, S., Caniaux, G., Chauvin, F., de Coëtlogon, G., Fontaine, B., Hall, N., Kiladis, G., Lafore, J. P., Lavaysse, C., Lavender, S. L., Leroux, S., Marteau, R., Mounier, F., Philippon, N., Roehrig, R., Sultan, B. & Taylor, C. M. 2011. Intraseasonal variability of the West African monsoon. *Atmospheric Science Letters,* 12, 58-66.

Jensen, J. R. & Im, J. 2007. Remote sensing change detection in urban environments. *Geo-Spatial Technologies in Urban Environments.* Springer.

Ji, L. & Peters, A. J. 2003. Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. *Remote Sensing of Environment,* 87, 85-98.

Johnson, P. M., Mayrand, K. & Paquin, M. 2006. The United Nations Convention to combat desertification in global sustainable development governance. *Governing Global Desertification: Linking Environmental Degradation, Poverty and Participation, Aldershot: Ashgate*, 1-10.

Jones, P. & Harris, I. 2013. University of East Anglia Climatic Research Unit, CRU TS3. 21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901—Dec. 2012). *NCAS British Atmospheric Data Centre*.

Jordan, C. F. 1969. Derivation of leaf-area index from quality of light on the forest floor. *Ecology*, 663-666.

Kaptué, A. T., Prihodko, L. & Hanan, N. P. 2015. On regreening and degradation in Sahelian watersheds. *Proceedings of the National Academy of Sciences,* 112, 12133-12138.

Karlson, M. & Ostwald, M. 2016. Remote sensing of vegetation in the Sudano-Sahelian zone: A literature review from 1975 to 2014. *Journal of Arid Environments,* 124, 257-269.

Kasperson, R. E. & Archer, E. R. 2005. Vulnerable Peoples and Places. *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group,* 1, 143.

Khan, S. M., Page, S., Ahmad, H. & Harper, D. 2013. Identifying plant species and communities across environmental gradients in the Western Himalayas: Method development and conservation use. *Ecological Informatics,* 14, 99-103.

Kogan, F. N. 2005. *NOAA/AVHRR satellite data based indices for monitoring agricultural droughts*, New York: Oxford University Press.

Kucharski, F. & Zeng, N. 2013. Positive and negative feedbacks in the vegetation impact on the Sahel Drought/Mecanismos de realimentación positivos y negativos en el impacto de la vegetación en la sequía del Sahel. *Física de la Tierra,* 25, 89.

Lambin, E. F. 1997. Modelling and monitoring land-cover change processes in tropical regions. *Progress in physical geography,* 21, 375-393.

Lambin, E. F. & Geist, H. J. 2008. *Land-use and land-cover change: local processes and global impacts*, Springer Science & Business Media.

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., Coomes, O. T., Dirzo, R., Fischer, G. & Folke, C. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global environmental change,* 11, 261-269.

Le Houerou, H. N. 1980. The rangelands of the Sahel. *Journal of Range Management*, 41-46.

Le Houerou, H. N. 1984. Rain use efficiency: a unifying concept in arid-land ecology. *Journal of Arid Environments,* 7, 213-247.

Leadley, P. 2010. *Biodiversity scenarios: projections of 21st century change in biodiversity, and associated ecosystem services: a technical report for the global biodiversity outlook 3*, UNEP/Earthprint.

Lebel, T., Cappelaere, B., Galle, S., Hanan, N., Kergoat, L., Levis, S., Vieux, B., Descroix, L., Gosset, M., Mougin, E., Peugeot, C. & Seguis, L. 2009. AMMA-CATCH studies in the Sahelian region of West-Africa: An overview. *Journal of Hydrology,* 375, 3-13.

Lee, E., He, Y., Zhou, M. & Liang, J. 2015. Potential feedback of recent vegetation changes on summer rainfall in the Sahel. *Physical Geography,* 36, 449-470.

Li, H., Shen, W., Zou, C., Jiang, J., Fu, L. & She, G. 2013. Spatio-temporal variability of soil moisture and its effect on vegetation in a desertified aeolian riparian ecotone on the Tibetan Plateau, China. *Journal of Hydrology,* 479, 215-225.

Liu, J., Daily, G. C., Ehrlich, P. R. & Luck, G. W. 2003. Effects of household dynamics on resource consumption and biodiversity. *Nature,* 421, 530-533.

Los, S. O., Weedon, G. P., North, P. R. J., Kaduk, J. D., Taylor, C. M. & Cox, P. M. 2006. An observation-based estimate of the strength of rainfall-vegetation interactions in the Sahel. *Geophysical Research Letters,* 33.

Lu, X., Wang, L. & McCabe, M. F. 2016. Elevated CO2 as a driver of global dryland greening. *Sci Rep,* 6, 20716.

Lykke, A. 2000. Local perceptions of vegetation change and priorities for conservation of woody-savanna vegetation in Senegal. *Journal of Environmental Management,* 59, 107-120.

Lykke, A., Kristensen, M. & Ganaba, S. 2004. Valuation of local use and dynamics of 56 woody species in the Sahel. *Biodiversity & Conservation,* 13, 1961-1990.

Lykke, A. M. 1998. Assessment of species composition and change in savanna vegetation by means of woody plants' size class distributions and local information. *Biodiversity and Conservation,* 7, 1261-1275.

Mabogunje, A. L. 1995. The environmental challenges in sub-Saharan Africa. *Environment: Science and Policy for Sustainable Development,* 37, 4-10.

Maitima, J. M., Mugatha, S. M., Reid, R. S., Gachimbi, L. N., Majule, A., Lyaruu, H., Pomery, D., Mathai, S. & Mugisha, S. 2009. The linkages between land use change, land degradation and biodiversity across East Africa. *African Journal of Environmental Science and Technology,* 3.

Marín, S. L., Nahuelhual, L., Echeverría, C. & Grant, W. E. 2011. Projecting landscape changes in southern Chile: simulation of human and natural processes driving land transformation. *Ecological modelling,* 222, 2841-2855.

Mbow, C., Brandt, M., Ouedraogo, I., de Leeuw, J. & Marshall, M. 2015. What Four Decades of Earth Observation Tell Us about Land Degradation in the Sahel? *Remote Sensing,* 7, 4048-4067.

Mellenium Ecosystem Assessment 2005. Ecosystem and Human well being: Desertification synthesis. *In:* Assessment, M. E. (ed.).

Merem, E. The Agroforestry systems of West Africa: the case of Nigeria. AFTA 2005 Conference Proceedings, 2005.

Middleton, N. & Thomas, D. 1997. *World atlas of desertification*, Arnold, Hodder Headline, PLC.

Mohammed, S. 2004. *Adaptive Management of Genetic Diversity of Pearl Millet Cultivar under indigenous cultivation at small holders' level in semi – Arid Northern Nigeria.* PhD, Bayero University, Kano.

Morton, D. C., Nagol, J., Carabajal, C. C., Rosette, J., Palace, M., Cook, B. D., Vermote, E. F., Harding, D. J. & North, P. R. 2014. Amazon forests maintain consistent canopy structure and greenness during the dry season. *Nature,* 506, 221-224.

Mueller, T., Dressler, G., Tucker, C., Pinzon, J., Leimgruber, P., Dubayah, R., Hurtt, G., Böhning-Gaese, K. & Fagan, W. 2014. Human Land-Use Practices Lead to Global Long-Term Increases in Photosynthetic Capacity. *Remote Sensing,* 6, 5717-5731.

Myneni, R. B. & Hall, F. G. 1995. The interpretation of spectral vegetation indexes. *Geoscience and Remote Sensing, IEEE Transactions on,* 33, 481-486.

Myoung, B., Choi, Y.-S., Choi, S.-J. & Park, S. K. 2012. Impact of vegetation on land-atmosphere coupling strength and its implication for desertification mitigation over East Asia. *Journal of Geophysical Research,* 117.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B. & Running, S. W. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *science,* 300, 1560-1563.

Niang, A., Ozer, A. & Ozer, P. 2008. Fifty years of landscape evolution in Southwestern Mauritania by means of aerial photos. *Journal of Arid Environments,* 72, 97-107.

Nicholson, E. S. 1981. Rainfall and Atmospheric circulation during drought periods and wetter years in West Africa. *American Meteorological Society.*

Nicholson, S. 2000. Land surface processes and Sahel climate. *REVIEWS OF GEOPHYSICS-RICHMOND VIRGINIA THEN WASHINGTON-,* 38, 117-140.

Nicholson, S. E. 1995. Sahel, West Africa. *Encyclopedia of Environmental Biology,* 3.

Nicholson, S. E. 2001. Climatic and environmental change in Africa during the last two centuries. *Climate Research,* 17, 123-144.

Nicholson, S. E. 2005. On the question of the "recovery" of the rains in the West African Sahel. *Journal of Arid Environments,* 63, 615-641.

Nicholson, S. E. 2013. The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability. *ISRN Meteorology,* 2013, 1-32.

Nicholson, S. E., Davenport, M. L. & Malo, A. R. 1990. A comparison of the vegetation response to rainfall in the Sahel and East Africa, using normalized difference vegetation index from NOAA AVHRR. *Climatic change,* 17, 209-241.

Nicholson, S. E., Tucker, C.J & Ba, M.B 1998. Desertification, Drought and surface vegetation: An example from West African Sahel. *Bulletin of the American Meteorological Society,* 79.

Niedertscheider, M., Gingrich, S. & Erb, K.-H. 2012. Changes in land use in South Africa between 1961 and 2006: an integrated socio-ecological analysis based on the human appropriation of net primary production framework. *Regional Environmental Change,* 12, 715-727.

Nkonya, E., Koo, J., Kato, E. & Guo, Z. 2013. Trends and patterns of land use change and international aid in sub-Saharan Africa. WIDER Working Paper.

Nkoya, E., Gerber, N., Baumgartner, P., Von Braun, J., De Pinto, A., Graw, V., Kato, E., Kloos, J. & Walter, T. 2011. Economics of Desertification, Land Degradation and Drought: Toward an integrated global assessment. *In:* Technology, E. P. A. (ed.).

Nyong, A., Adesina, F. & Elasha, B. O. 2007. The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation strategies for global Change,* 12, 787-797.

Olsson, L., Eklundh, L. & Ardö, J. 2005. A recent greening of the Sahel—trends, patterns and potential causes. *Journal of Arid Environments,* 63, 556-566.

Olsson, L. & Mryka, H. 2008. Greening of the Sahel. *Encyclopedia of Earth. Eds. CJ Cleveland. Washington, DC: Environmental Information Coalition, National Council for Science and the Environment.[First published in the Encyclopedia of Earth January 30, 2008. http://www. eoearth. org/article/Greening_of_the_Sahel.(Last Accessed on February 17, 2010).*

Omuto, C. T. 2011. A new approach for using time-series remote-sensing images to detect changes in vegetation cover and composition in drylands: a case study of eastern Kenya. *International Journal of Remote Sensing,* 32, 6025-6045.

Owusu, A. B. 2012. Farmers coping with the threat of desertification: A case study of the upper East region, Ghana. *Wudpecker journal of Agricultural Research,* 18, 317-330.

Picard, N., Guéguen, K., Abdoulaye, H. A., Diarisso, D., Karembé, M., Birnbaum, P. & Nasi, R. 2005. Tree formations in relation with soil and grasses in a dry savanna in Mali, West Africa. *African Journal of Ecology,* 43, 201-207.

Pinzon, J., Brown, M. E. & Tucker, C. J. 2005. *EMD correction of orbital drift artifacts in satellite data stream*, World Scientific Publishing Co Pte Ltd.: Singapore.

Pinzon, J. & Tucker, C. 2014. A Non-Stationary 1981–2012 AVHRR NDVI3g Time Series. *Remote Sensing,* 6, 6929-6960.

Prince, S. 2002. Spatial and temporal scales for detection of desertification. *Global desertification: Do humans cause deserts*, 23-40.

Prince, S., Becker-Reshef, I. & Rishmawi, K. 2009. Detection and mapping of long-term land degradation using local net production scaling: Application to Zimbabwe. *Remote Sensing of Environment,* 113, 1046-1057.

Prince, S. D. & Goward, S. N. 1995. Global primary production: a remote sensing approach. *Journal of biogeography*, 815-835.

Prince, S. D., Wessels, K. J., Tucker, C. J. & Nicholson, S. E. 2007. Desertification in the Sahel: a reinterpretation of a reinterpretation. *Global Change Biology,* 13, 1308-1313.

Purkis, S. J. & Klemas, V. V. 2011. *Remote sensing and global environmental change*, John Wiley & Sons.
Ramankutty, N. & Foley, J. A. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global biogeochemical cycles,* 13, 997-1027.
Rasmussen, K., Fog, B. & Madsen, J. E. 2001. Desertification in reverse? Observations from northern Burkina Faso. *Global Environmental Change,* 11, 271-282.
Raynolds, J. F. S.-S., D.M 2002. *Global Desesrtification: Do humans cause Desert?*, Dahlem University Press.
Reed, M. S., Fazey, I., Stringer, L. C., Raymond, C. M., Akhtar-Schuster, M., Begni, G., Bigas, H., Brehm, S., Briggs, J., Bryce, R., Buckmaster, S., Chanda, R., Davies, J., Diez, E., Essahli, W., Evely, A., Geeson, N., Hartmann, I., Holden, J., Hubacek, K., Ioris, A. A. R., Kruger, B., Laureano, P., Phillipson, J., Prell, C., Quinn, C. H., Reeves, A. D., Seely, M., Thomas, R., van der Werff Ten Bosch, M. J., Vergunst, P. & Wagner, L. 2013. Knowledge Management for Land Degradation Monitoring and Assessment: An Analysis of Contemporary Thinking. *Land Degradation & Development.*
Reed, M. S. & Stringer, L. C. 2015. Climate change and desertification: Anticipating, assessing & adapting to future change in drylands.
Reich, P., Numbem, S., Almaraz, R. & Eswaran, H. 2004. Land resource stresses and desertification in Africa. *Agro-Science,* 2.
Reij, C., Tappan. G & Smale. M 2009. Agroenvironmental transformation in the Sahel: anothe kind of "Green Revolution". *IFPRI discussion paper, Washington, D.C. : International Policy Research Institute.*
Reynolds, J. F., Smith, D. M., Lambin, E. F., Turner, B. L., 2nd, Mortimore, M., Batterbury, S. P., Downing, T. E., Dowlatabadi, H., Fernandez, R. J., Herrick, J. E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F. T., Ayarza, M. & Walker, B. 2007. Global desertification: building a science for dryland development. *Science,* 316, 847-51.
Rouse Jr, J. W., Haas, R., Schell, J. & Deering, D. 1974. Monitoring vegetation systems in the Great Plains with ERTS. *NASA special publication,* 351, 309.
Salami, A. T. 1998. Vegetation modification and man-induced environmental chnage in rural Southwestern Nigeria. *Agriculture, ecosystem & environment,* 70, 159-167.
Sambou, A., Theilade, I., Fensholt, R. & Ræbild, A. 2016. Decline of woody vegetation in a saline landscape in the Groundnut Basin, Senegal. *Regional Environmental Change.*
Scheftic, W., Zeng, X., Broxton, P. & Brunke, M. 2014. Intercomparison of seven NDVI products over the United States and Mexico. *Remote Sensing,* 6, 1057-1084.
Schmidt, M., Janßen, T., Dressler, S., Hahn, K., Hien, M., Konaté, S., Lykke, A. M., Mahamane, A., Sambou, B. & Sinsin, B. 2012. The West African Vegetation Database. *Vegetation databases for the 21st century.– Biodiversity & Ecology,* 4, 105-110.

Schucknecht, A., Stefan, E., Irmgard, N. & Jorg, M. 2013. Assessing vegetation variability and trends in north-eastern Brazil using AVHRR and MODIS NDVI time series. *European Journal of Remote Sensing*, 40-59.

Seaquist, J. W., Hickler. T, Eklundh. L, Ardo. J and Heumann. B. w 2009. Disentangling the effects of climate and people on Sahel vegetation dynamics. *Biogeosciences,* 6, 9.

Seaquist, J. W., Olsson, L., Ardö, J. & Eklundh, L. 2006. Broad - scale increase in NPP quantified for the African Sahel, 1982–1999. *International Journal of Remote Sensing,* 27, 5115-5122.

See, L., Schepaschenko, D., Lesiv, M., McCallum, I., Fritz, S., Comber, A., Perger, C., Schill, C., Zhao, Y., Maus, V., Siraj, M. A., Albrecht, F., Cipriani, A., Vakolyuk, M. y., Garcia, A., Rabia, A. H., Singha, K., Marcarini, A. A., Kattenborn, T., Hazarika, R., Schepaschenko, M., van der Velde, M., Kraxner, F. & Obersteiner, M. 2014. Building a hybrid land cover map with crowdsourcing and geographically weighted regression. *ISPRS Journal of Photogrammetry and Remote Sensing*.

Sendzimir, J., Reij, C. P. & Magnuszewski, P. 2011. Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger. *Ecology and Society,* 16.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B. & Teuling, A. J. 2010. Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews,* 99, 125-161.

Serra, P., Pons, X. & Saurí, D. 2008. Land-cover and land-use change in a Mediterranean landscape: A spatial analysis of driving forces integrating biophysical and human factors. *Applied Geography,* 28, 189-209.

Shalaby, A. & Tateishi, R. 2007. Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. *Applied Geography,* 27, 28-41.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J., Levis, S., Lucht, W. & Sykes, M. T. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology,* 9, 161-185.

Sommer, S., Zucca, C., Grainger, A., Cherlet, M., Zougmore, R., Sokona, Y., Hill, J., Della Peruta, R., Roehrig, J. & Wang, G. 2011. Application of indicator systems for monitoring and assessment of desertification from national to global scales. *Land Degradation & Development,* 22, 184-197.

Sop, T. K. & Oldeland, J. 2011. Local Perceptions of Woody Vegetation Dynamics in the Context of a 'Greening Sahel': A Case Study from Burkina Faso. *Land Degradation & Development,* 24, 511-527.

Speth, P., Christoph, M. & Diekkrüger, B. 2010. *Impacts of global change on the hydrological cycle in West and Northwest Africa*, Springer Science & Business Media.

Spiekermann, R., Brandt, M. & Samimi, C. 2015. Woody vegetation and land cover changes in the Sahel of Mali (1967–2011). *International Journal of Applied Earth Observation and Geoinformation,* 34, 113-121.
Stocking, M. & Murnaghan, N. 2001. *Handbook for the field assessment of land degradation*, Earthscan.
Stringer, L. C., Dyer, J. C., Reed, M. S., Dougill, A. J., Twyman, C. & Mkwambisi, D. 2009. Adaptations to climate change, drought and desertification: local insights to enhance policy in southern Africa. *Environmental Science & Policy,* 12, 748-765.
Sultan B & Janicot, S. 2003. The West African Monsoon Dynamics. Part II: The "Preonset" and "Onset" of the Summer Monsoon. *Climate,* 16, 3407-3427.
Symeonakis, E. & Drake, N. 2004. Monitoring desertification and land degradation over sub-Saharan Africa. *International Journal of Remote Sensing,* 25, 573-592.
Symeonakis, E., Koukoulas, S., Calvo-Cases, A., Arnau-Rosalen, E. & Makris, I. A landuse change and land degradation study in Spain and Greece using remote sensing and GIS. Proceedings of XXth ISPRS Congress, Istanbul, Turkey, http://www. isprs. org/istanbul2004/comm7/papers/110. pdf,(15 January, 2006), 2004.
Tappan, G. G., Sall, M., Wood, E. C. & Cushing, M. 2004. Ecoregions and land cover trends in Senegal. *Journal of Arid Environments,* 59, 427-462.
Thomas, D. S. & Middleton, N. J. 1994. *Desertification: exploding the myth*, John Wiley & Sons Ltd.
Tiffen, M. & Mortimore, M. Questioning desertification in dryland sub–Saharan Africa. Natural Resources Forum, 2002. Wiley Online Library, 218-233.
Tucker, C., Dregne, H. E. & Newcomb, W. W. 1991. Expansion and contraction of the Sahara Desert. *Science,* 253, 299-301.
Tucker, C., Justice, C. & Prince, S. 1986. Monitoring the grasslands of the Sahel 1984-1985. *International Journal of Remote Sensing,* 7, 1571-1581.
Tucker, C., Pinzon, J., Brown, M., Slayback, D., Pak, E., Mahoney, R., Vermote, E. & El Saleous, N. 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *International Journal of Remote Sensing,* 26, 4485-4498.
Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote sensing of Environment,* 8, 127-150.
Tucker, C. J. & Nicholson, S. E. 1999. Variations in the size of the Sahara Desert from 1980 to 1997. *Ambio*, 587-591.
UNCCD, U. N. C. t. C. D. 2015. Land Matters for Climate Reducing the Gap and Approaching the Target. Available from: http://www.unccd.int/Lists/SiteDocumentLibrary/Publications/2015Nov_Land_matters_For_Climate_ENG.pdf 2015].
UNEC, U. N. E. C. 2007. Africa Review report on Drought and Desertification. Regional Implementation Meeting ed.
UNEP 2006. Africa Environment Outlook 2: Our Environment, Our Wealth. *In:* (Dewa), D. O. E. W. a. A. (ed.). Nairobi, Kenya: Earthprint.

United Nations, D. o. E. a. S. A., Population Division, UNDESA 2015. Word Population Prospects: The 2015 Revision, Key findings and Advance tables. *In:* Department of Economic and Social Affairs, P. D. (ed.). New York: United Nations.
Van den Dool, H., Huang, J. & Fan, Y. 2003. Performance and analysis of the constructed analogue method applied to US soil moisture over 1981–2001. *Journal of Geophysical Research: Atmospheres,* 108.
van Dijk, H. & Bose, P. 2016. Dryland Landscapes: Forest Management, Gender and Social Diversity in Asia and Africa. *Dryland Forests.* Springer.
Verón, S. R. & Paruelo, J. M. 2010. Desertification alters the response of vegetation to changes in precipitation. *Journal of Applied Ecology,* 47, 1233-1241.
Verón, S. R., Paruelo, J. M. & Oesterheld, M. 2006. Assessing desertification. *Journal of Arid Environments,* 66, 751-763.
Verstraete, M. M. 1986. Defining desertification: a review. *Climatic Change,* 9, 5-18.
Verstraete, M. M., Hutchinson, C. F., Grainger, A., Stafford Smith, M., Scholes, R. J., Reynolds, J. F., Barbosa, P., Léon, A. & Mbow, C. 2011. Towards a global drylands observing system: Observational requirements and institutional solutions. *Land Degradation & Development,* 22, 198-213.
Viña, A., Gitelson, A. A., Nguy-Robertson, A. L. & Peng, Y. 2011. Comparison of different vegetation indices for the remote assessment of green leaf area index of crops. *Remote Sensing of Environment,* 115, 3468-3478.
Vincke, C., Diedhiou, I. & Grouzis, M. 2010. Long term dynamics and structure of woody vegetation in the Ferlo (Senegal). *Journal of arid environments,* 74, 268-276.
Vogt, J. V., Safriel, U., Von Maltitz, G., Sokona, Y., Zougmore, R., Bastin, G. & Hill, J. 2011. Monitoring and assessment of land degradation and desertification: Towards new conceptual and integrated approaches. *Land Degradation & Development,* 22, 150-165.
Wessels, K. 2009a. Letter to the editor: Comments on 'Proxy global assessment of land degradation'by Bai et al.(2008).
Wessels, K. J. 2009b. Letter to the Editor. *Soil Use and Management,* 25, 91-92.
Wessels, K. J., Mathieu, R., Erasmus, B. F. N., Asner, G. P., Smit, I. P. J., van Aardt, J. A. N., Main, R., Fisher, J., Marais, W., Kennedy-Bowdoin, T., Knapp, D. E., Emerson, R. & Jacobson, J. 2011. Impact of communal land use and conservation on woody vegetation structure in the Lowveld savannas of South Africa. *Forest Ecology and Management,* 261, 19-29.
Wessels, K. J., Prince, S. D., Frost, P. E. & van Zyl, D. 2004. Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series. *Remote Sensing of Environment,* 91, 47-67.
Wessels, K. J., Prince, S. D., Malherbe, J., Small, J., Frost, P. E. & VanZyl, D. 2007. Can human-induced land degradation be distinguished from the

effects of rainfall variability? A case study in South Africa. *Journal of Arid Environments,* 68, 271-297.
Wessels, K. J., van den Bergh, F. & Scholes, R. J. 2012. Limits to detectability of land degradation by trend analysis of vegetation index data. *Remote Sensing of Environment,* 125, 10-22.
Wezel, A. 2004. Local knowledge of vegetation changes in Sahelian Africa-implications for local resource management. *The Sahel (eds. Lykke AM, Due MK, Kristensen M. & Nielsen I.)*, 37-52.
Wezel, A. & Lykke, A. M. 2006. Woody vegetation change in Sahelian West Africa: evidence from local knowledge. *Environment, Development and Sustainability,* 8, 553-567.
Wilson, G. A. & Juntti, M. 2005. *Unravelling desertification: policies and actor networks in Southern Europe*, Wageningen Academic Pub.
WMO, W. M. O. 2005. Climate and Land Degradation.
Wright, J. B. 1985. *Geology and mineral resources of West Africa,* Netherland, Springer.
Xu, L., Myneni, R., Chapin Iii, F., Callaghan, T., Pinzon, J., Tucker, C., Zhu, Z., Bi, J., Ciais, P. & Tømmervik, H. 2013. Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change,* 3, 581-586.
Yengoh, G. T., Dent, D., Olsson, L., Tengberg, A. E. & Tucker III, C. J. 2015. *Use of the Normalized Difference Vegetation Index (NDVI) to Assess Land Degradation at Multiple Scales: Current Status, Future Trends, and Practical Considerations*, Springer.
Zeng, N., Neelin, J. D., Lau, K.-M. & Tucker, C. J. 1999. Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. *Science,* 286, 1537-1540.
Zheng, X. & Eltahir, E. A. 1997. The response to deforestation and desertification in a model of West African monsoons. *Geophysical Research Letters,* 24, 155-158.
Zika, M. & Erb, K.-H. 2009. The global loss of net primary production resulting from human-induced soil degradation in drylands. *Ecological Economics,* 69, 310-318.

Appendices

Appendix 1: R-codes for RESTREND

```
RESTREND USING NDVI AND SOIL
MOISTURE/RAINFALL################################################
#################
#packages required
library(ncdf)
library(raster)
library(rgdal)
library(maptools)
library(GISTools)
library(mapdata)
library(lattice)
library(rasterVis)
library(maps)
library(latticeExtra)
#Load data sets as a raster bricks(NB the variables must have
the same spatial
# and temporal resolutions.
cru = brick("cru.nc", varname="variable")# loading rainfall data
cpc = brick("cpc.nc", varname="variable") # loading soil
moisture data
NDVI = brick("nNDVI.nc", varname="variable")# loading NDVI data
# add projection to the data sets
projection(NDVI) <- "+proj=longlat +ellps=WGS84 +datum=WGS84
+towgs84=0,0,0" # same projection applies to all data
#Create a stack with NDVI and cpc
s <- stack(NDVI, cpc)
# Exclude NA from the cpc brick and mask it with a stack layer.
s2=calc(cpc, fun=mean)
s3=mask(s, s2)
# create a function to calculate the slope of the regression
model
fun=function(x) { if (is.na(x[1])){ NA } else { lm(x[1:372] ~
x[373:744])$coefficients[2] }} # 1:372 monthly data for 31 years
slope <- calc(s3, fun)
# Plot the slope of the relationship using levelplot
levelplot(slope, margin=T, main="Slope of NDVI- Soil Moisture
Regression",panel = panel.levelplot.raster,
par.settings=list(regions=list(col=(topo.colors(100)))))
latticeExtra::layer(sp.lines(mapaSHP,fill=NA,col=1,add=T))
#Map scale and Legend
map.scale(x=-6,y=-8, ratio=FALSE, relwidth=0.2)
north.arrow(x=20, y=-3, len=0.5, lab="N", fill=TRUE,
col="black")
# then the intercept
fun=function(x) { if (is.na(x[1])){ NA } else { lm(x[1:372] ~
x[373:744])$coefficients[1] }}
intercept <- calc(s3, fun)
#levelplot(intercept, margin=F, main=" Intercept of Soil
Moisture-Rainfall Regression")
levelplot(restrend, margin=T, main="Intercept of NDVI- Soil
Moisture Regression",panel = panel.levelplot.raster,
          par.settings=list(regions=list(col=topo.colors(100))))
```

```
# Then r.squared for the relationship
fun=function(x) { if (is.na(x[1])){ NA } else { m <- lm(x[1:372]
~ x[373:744]);summary(m)$r.squared }}
r.squared <- calc(s3, fun)

# calculate soil moisture predicted NDVI
pred.NDVI <- slope*cpc + intercept

# Then calculate the RESIDUALS
Residuals <- NDVI - pred.NDVI

#Then calculate the trend from the residuals;
st<- cellStats(Residuals, stat='mean')

#calculate time series for the residuals
Resid.ts = ts(st, start=1982, end=c(2012,12), frequency=12)
plot(Resid.ts, main="", col="red")

# Regress residual on time
time <- 1:nlayers(Residuals)
fun=function(x) { if (is.na(x[1])){ NA } else { m = lm(x ~
time); summary(m)$coefficients[2] }}

# calculate the residual trend
restrend=calc(Residuals, fun)

plot(restrend)
# To add boundaries of the countries.
data(wrld_simpl)
plot(wrld_simpl, add=TRUE, lwd=1.8)

rf <- writeRaster(r, filename="test.tif", format="GTiff",
overwrite=TRUE)

#now we need to see which trends are significant. Thus we first
extract the p-value:
fun=function(x) { if (is.na(x[1])){ NA } else { m = lm(x ~
time); summary(m)$coefficients[8] }}
p <- calc(restrend, fun=fun)
plot(p, main="p-Value")

#then mask all values >0.05 to get a confidence level of 95%:
 m = c(0, 0.05, 1, 0.05, 1, 0)
rclmat = matrix(m, ncol=3, byrow=TRUE)
p.mask = reclassify(restrend, rclmat)
fun=function(x) { x[x>0] <- NA; return(x)}
p.mask.NA = calc(p.mask, fun)

#and finaly mask all insignificant values in the trend map, so
we only get restrend change significant at the 95% level:
trend.sig = mask(restrend, p.mask.NA)
plot(trend.sig, main="significant NDVI change")
```

Appendix 2: Research questionnaire used for vegetation species changes along Nigeria-Niger boarder region

Introduction: I am a postgraduate student of University of Leicester, UK undertaking a fieldwork to ascertain the conditions (past and present) of indigenous tree species in your locality. I would be grateful if you could spare some minutes out of your busy schedule and answer my questions. All information provided will be handle with absolute confidentiality and its intended for research purpose only.

1. Name of locality:
2. Name of available vegetation species present in your area
3. How can you describe the nature of indigenous vegetation species in your area presently and in the past 30 years?
4. What is the nature of changes that happened to vegetation species in your area?
5. What are the major factors behind the observed changes?
6. Is there any links between vegetation changes and land degradation in your locality?

Thank you so much

Yahaya Zayyana Ibrahim

Appendix 3: Field work images

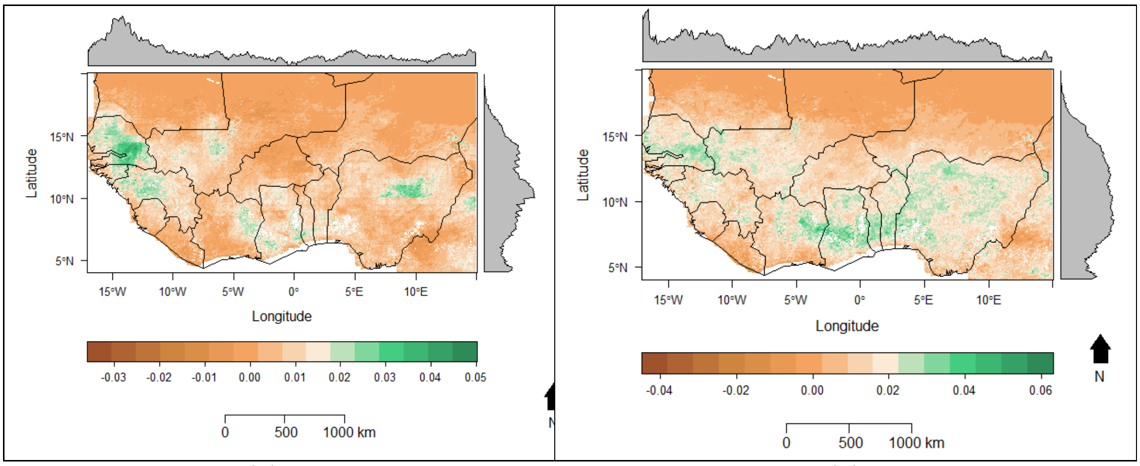
Figure A3.1. Nursery farm of indigenous trees in Madarounfa, Niger Republic

Figure A3.2. Watering of indigenous trees during dry season in Madarounfa, Niger Republic

Figure A3.3. Field work in Madarounfa, Niger Republic

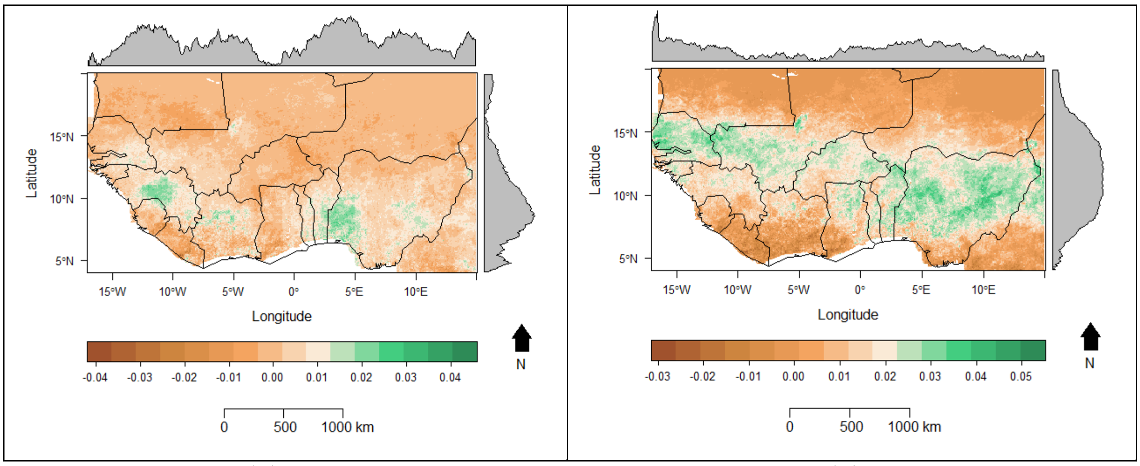
Appendix 4: RESTREND maps used for land cover analysis

Figure A4.1. RESTREND map for the year 2000(1996-2000) based on (a) soil moisture and (b) rainfall



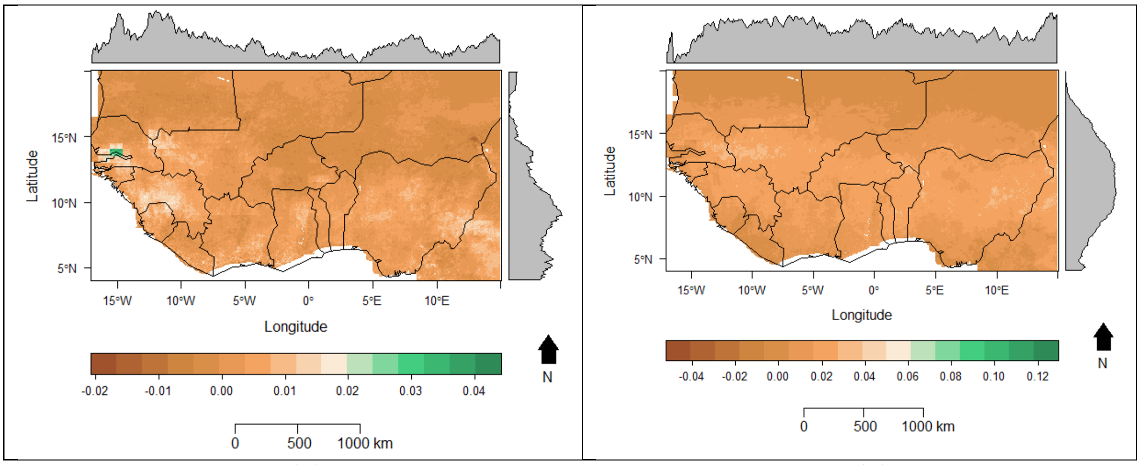
(a) (b)

Figure A4.2. RESTREND map for the year 2005(2001-2005) based on (a) soil moisture and (b) rainfall



(a) (b)

Figure A4.3. RESTREND map for the year 2010(2006-2010) based on (a) soil moisture and (b) rainfall



(a) (b)

Appendix 5: Images of NDVI, Precipitation and Soil moisture for the seven selected villages along Nigeria-Niger boarder region

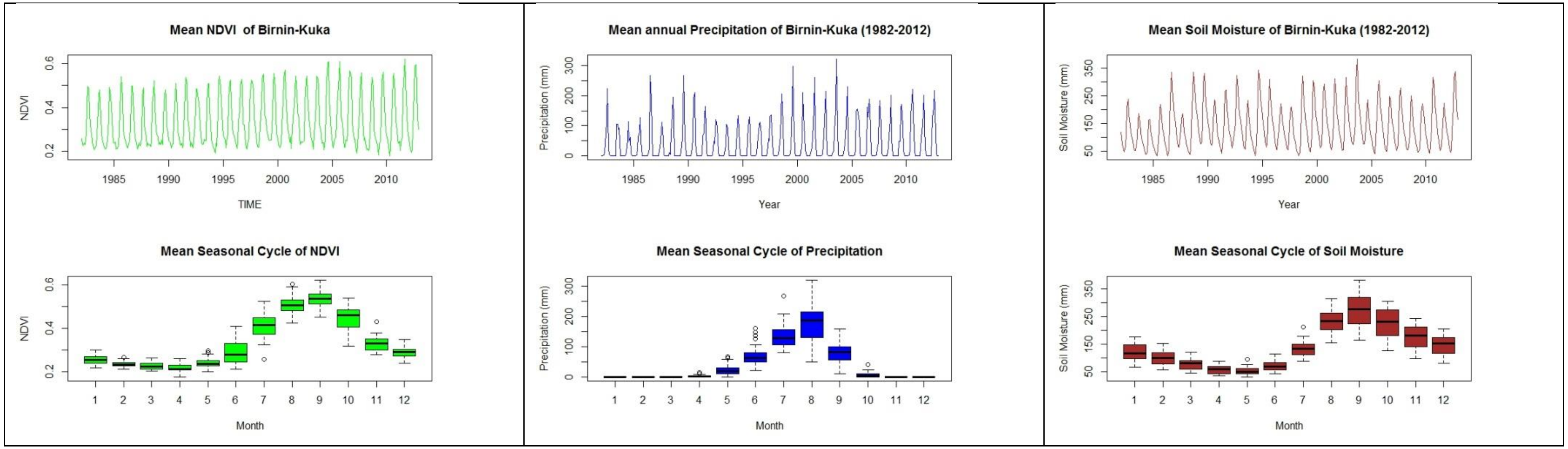


Figure A5.1: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Birnin-Kuka.

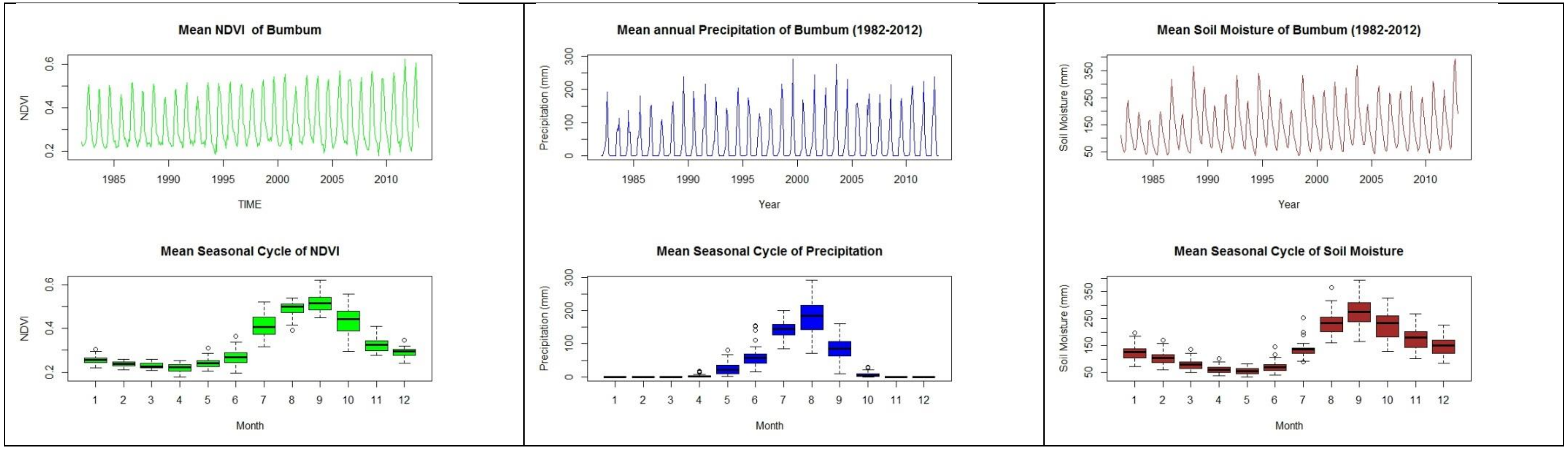


Figure A5.2: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Bumbum.

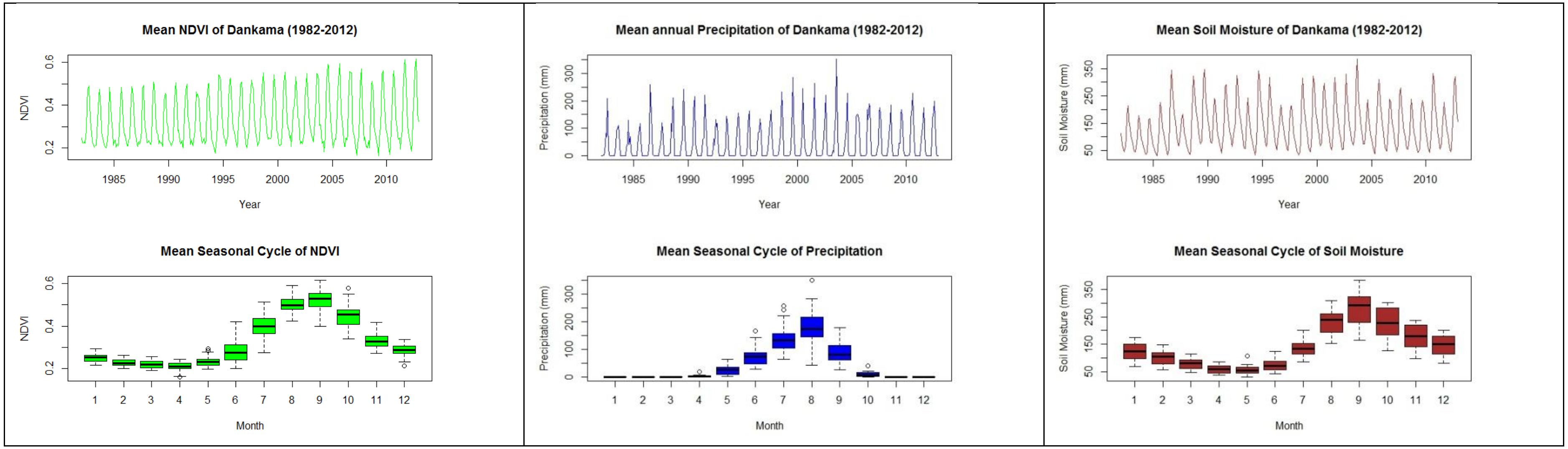


Figure A5.3: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Dankama.

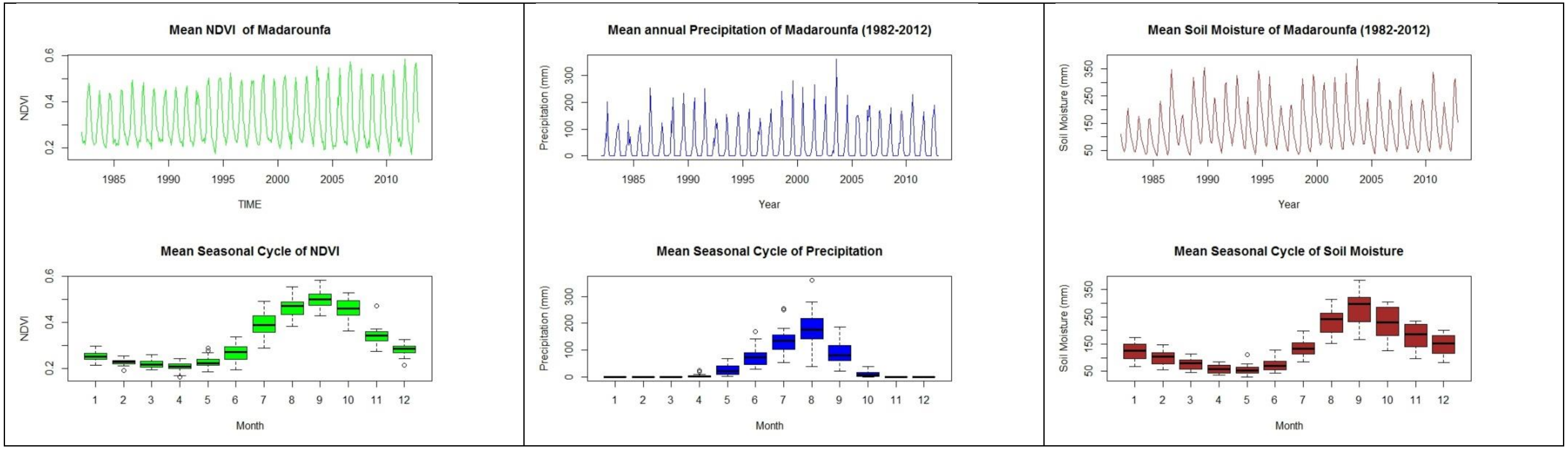


Figure A5.4: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Madarounfa.

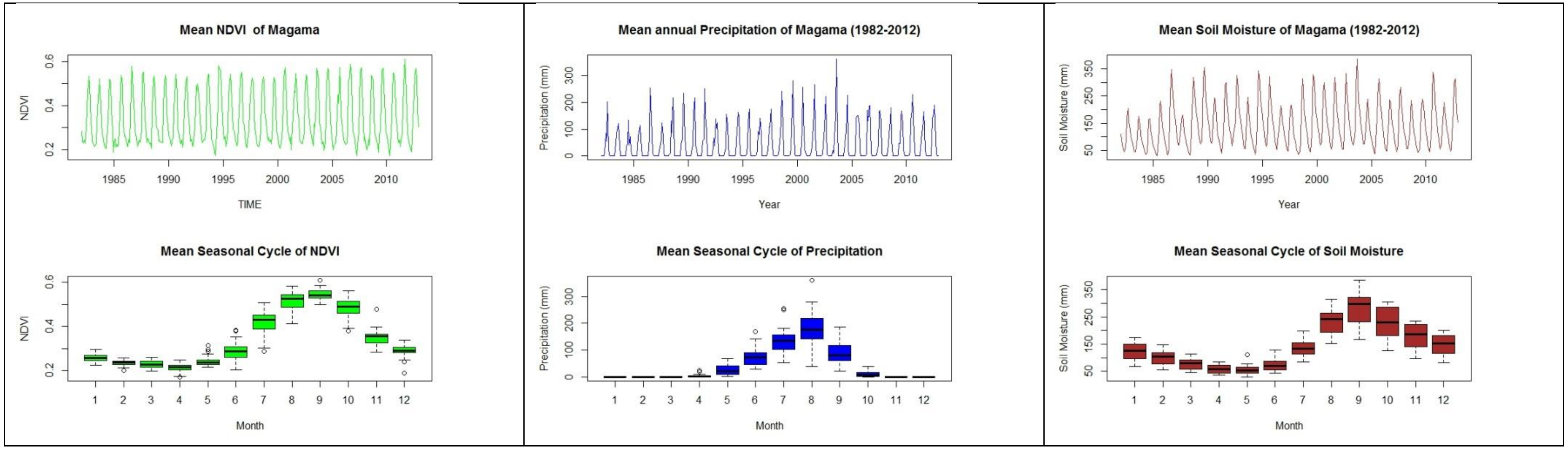


Figure A5.5: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Magama.

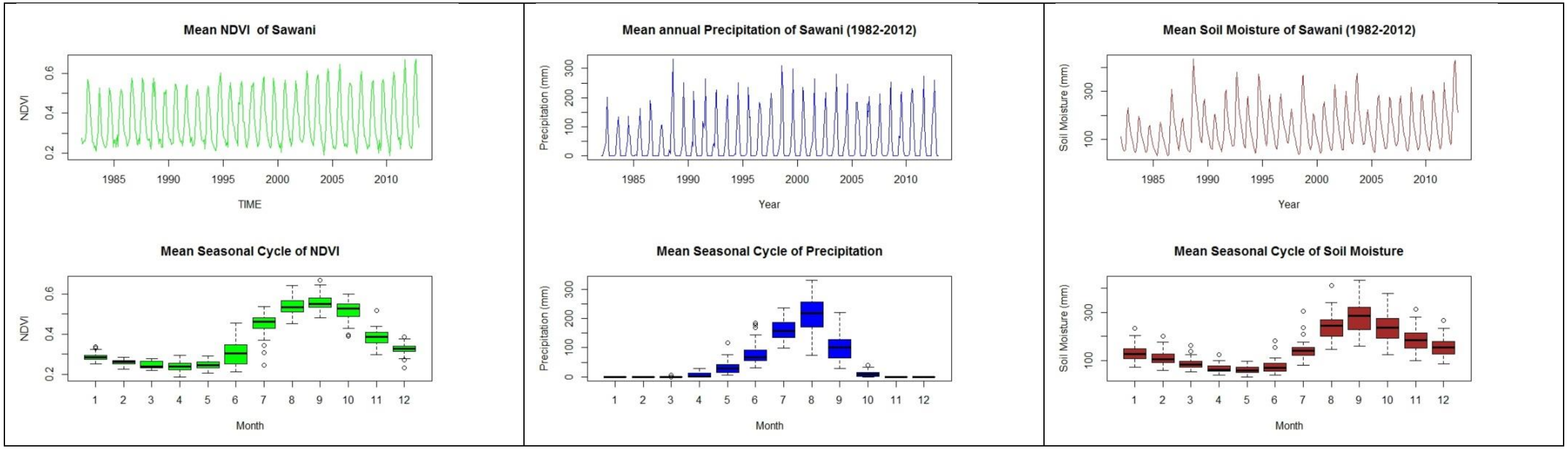


Figure A5.6: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Sawani.

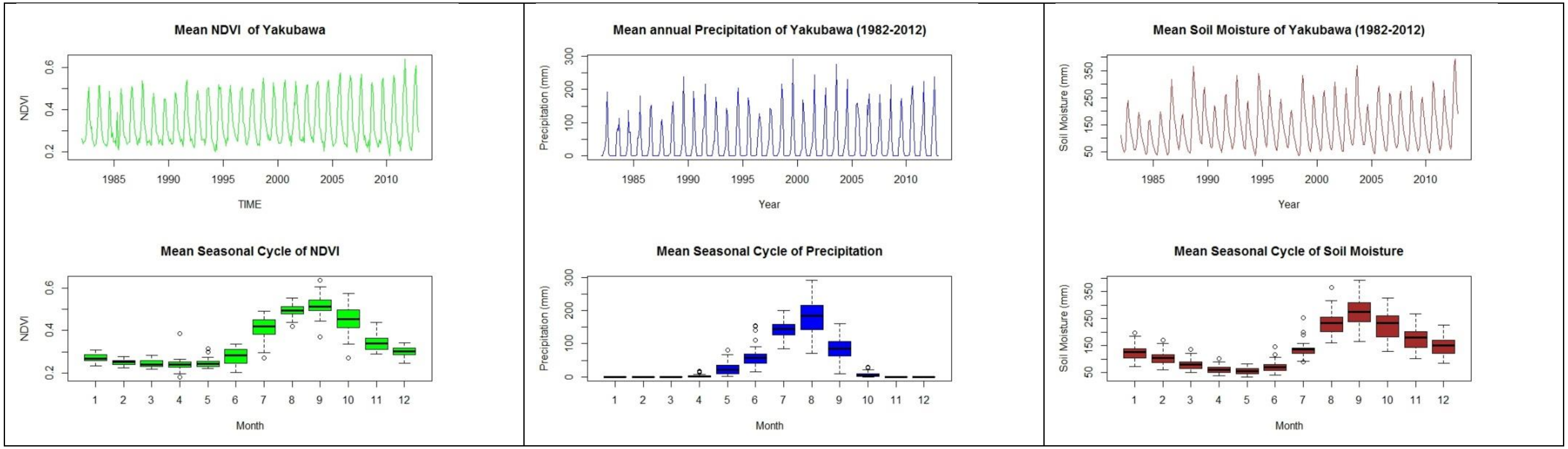


Figure 5.7: Long-term mean trends and seasonal cycles of NDVI, precipitation and soil moisture in Yakubaw