ENVIRONMENTAL CHANGE BASED ON EARTH OBSERVATION AND FIELD DATA – A LOCAL STUDY IN THE SAHEL ZONE OF MALI AND SENEGAL

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ABSTRACT

In the past 50 years the Sahel region has experienced significant environmental changes. Droughts, human expansion and a general decline in annual rainfall have led to theories of widespread and irreversible degradation. Recently, this paradigm has been largely replaced by a greening Sahel phenomenon, triggered by increasing rainfall, and observed in satellite based vegetation data. The purpose of this study is to assess local long term vegetation trends in the Sahel of Mali and Senegal by combining satellite datasets and field data. This thesis is designed to improve the knowledge base of the processes responsible for satellite derived trends and thus to shed more light on the degradation and re-greening debates of the Sahel zone.

A variety of earth observation products at different spatial and temporal resolutions were acquired and processed for two study areas around Bandiagara (Sahel of Mali) and Linguère (Sahel of Senegal). Intensive ground-truthing using interdisciplinary methods validates and explains vegetation changes observed in satellite data. High-resolution Corona (1965) and RapidEye (2011) imagery show woody vegetation and land cover change at tree level. Results reveal a significant reduction of natural vegetation, an increase of trees in cultivated areas and a general increase of cultivated land. Moreover, encroachment of degraded land and a moderate reduction in tree cover can be observed in both study areas.

Climate Research Unit (CRU) climate data show a significant and rapid increase in average annual temperature since the 1960s. Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Climatology Center (GPCC) rainfall data reveal that annual rainfall was 15% lower in Linguère (Sahel of Senegal) and 13% in Bandiagara (Sahel of Mali) for the period 1970–2010 compared to 1930–1970. However, both study areas have seen a significant increase in rainfall over the period 1982–2010 (34% in Linguère and 54% in Bandiagara), signifying a possible end of the prolonged dry period.

Coarse scale time series were studied from 1982–2010 using Normalized Difference Vegetation Index (NDVI) from Long Term Data Record (LTDR) as well as Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from Geoland Version 1 (GEOV1) (both 5 km pixel resolution) and GIMMS3g (8 km pixel resolution). The datasets agree that in both study areas significant greening trends can be observed over the studied time period but significant spatial discrepancies are observed at local scale. Annual rainfall increased since the 2000s, explaining more than 50% of the observed variations. The positive greenness trends can be confirmed by time series of ground measured biomass observations (since 1987), showing a strong increment in woody biomass since the 1980s. However, the higher resolution Moderate Resolution Imaging Spectroradiometer (MODIS) (250 m) and SPOT-Vegetation (VGT) (1 km) data identify a heterogeneous pattern of spatial variability and the presence of active land degradation at a local level, accounting for approximately 5–10% of each study areas.

Reasons for land degradation are both climatic and anthropogenic: (1) drought events, less rain and a higher temperature, and (2) an increased demand for cultivated areas and wood, especially in dry periods. However, beside the presence of degradation, greening areas prevail and cannot solely be explained by rainfall. Although reasons are often site-specific, several factors are true for both study areas: (1) agroforestry on farmer's fields, (2) strict protection laws, (3) large scale reforestation, and (4) a widespread dispersion of robust species, which are resilient to anthropogenic and climatic stress. In spite of the overall positive vegetation trends, a massive species impoverishment was disclosed by interviews with village elders and long term species monitoring. Apart from few dispersing species (*Balanites aegyptiaca, Acacia raddiana*), most other woody species have seen a decline and local extinction. Woody vegetation changes strongly depend on soil properties, which control human impact, drought resilience and vulnerability to erosion. Therefore, a heterogeneous pattern of environmental changes can be observed at a local level and neither the degradation nor the greening paradigm can be generalized.

ZUSAMMENFASSUNG

Die Sahel Region erfuhr in den vergangenen 50 Jahren signifikante Umweltveränderungen. Dürren, extensive Ausbreitung des Menschen und ein allgemeiner Rückgang des jährlichen Niederschlags führten zu Theorien flächenhafter und irreversibler Degradierung. Neuerdings wird dieses Paradigma weitgehend von einem "greening Sahel" Phänomen abgelöst. Dieses Phänomen beruht auf zunehmenden Niederschlägen und positiven Vegetationstrends, welche in grobauflösenden Satellitenaufnahmen erkennbar sind. Ziel der vorliegenden Dissertation ist es, Langzeittrends der Vegetation in zwei Untersuchungsregionen in der Sahelzone Malis und Senegals auf lokaler Ebene zu untersuchen. Hierbei soll anhand von zahlreichen satelliten– und bodengestützten Datenquellen mehr Licht auf die Paradigmen der Desertifikation und des "greening Sahel" geworfen werden.

Hierzu wurden eine Vielzahl satellitengestützter Datensätze mit unterschiedlichen räumlichen und zeitlichen Auflösungen aufbereitet. In Satellitenaufnahmen erkannte Vegetationsveränderungen wurden durch intensive und interdisziplinäre Feldarbeit validiert und interpretiert. Hochauflösende Corona (1965) und RapidEye (2011) Aufnahmen zeigen Veränderungen in der Gehölz- und Oberflächenbedeckung auf Baumebene. Die Ergebnisse zeigen eine signifikante Abnahme von natürlicher Vegetation, eine Zunahme von Bäumen auf Feldern und eine generelle Ausbreitung von kultiviertem Land. Außerdem kann eine Zunahme degradierter Flächen und eine mäßige Abnahme der Baumbedeckung in beiden Untersuchungsregionen beobachtet werden.

Climate Research Unit (CRU) Klimadaten beweisen einen rapiden Anstieg der durchschnittlichen Jahrestemperatur seit den Mitte des 20. Jahrhunderts. Tropical Rainfall Measuring Mission (TRMM) und Global Precipitation Climatology Center (GPCC) Niederschlagsdaten zeigen für die Periode 1970 bis 2010 einen um 15% (Linguère, Senegal) bzw. 13% (Bandiagara, Mali) niedrigeren Jahresniederschlag, verglichen mit dem Zeitraum 1930 bis 1970. Jedoch weisen beide Untersuchungsregionen über die Periode 1982 bis 2010 einen erheblichen Anstieg von 34% (Linguère, Senegal) bzw. 54% (Bandiagara, Mali) des jährlichen Niederschlages auf, was auf mögliches Ende der Trockenphase hindeuten könnte.

Grobauflösende Zeitreihen, basierend auf Normalized Difference Vegetation Index (NDVI) aus Long Term Data Record (LTDR) Daten sowie Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) aus Geoland Version 1 (GEOV1) (beide 5 km Pixelauflösung) und GIMMS3g (8 km Pixelauflösung) Datensätzen, wurden über den Zeitraum 1982–2010 analysiert. Die Datensätze zeigen übereinstimmend signifikant positive Vegetationstrends für beide Untersuchungsregionen. Hierbei werden über 50% der Variabilität durch zunehmenden Niederschlag erklärt. Die positiven "greenness" Trends werden durch eine Zeitreihe manuell aufgenommener Biomasse bestätigt (seit 1987), welche eine signifikante Zunahme der Gehölzbiomasse seit Ende der 1980-er zeigt. Allerdings kann anhand höher auflösender Moderate Resolution Imaging Spectroradiometer (MODIS) (250 m) und SPOT Vegetation (VGT) (1 km) Aufnahmen gezeigt werden, dass auf lokaler Ebene ein heterogenes Muster räumlicher Variabilität vorhanden ist und aktive Landdegradierung etwa 5–10% des jeweiligen Arbeitsgebietes ausmacht.

Die Gründe für Landdegradierung sind klimatischer und menschlicher Ursache: (1) Dürren, weniger Niederschlag und höhere Temperaturen und (2), ein wachsender anthropogener Bedarf an kultivierten Flächen und Gehölz. Jedoch überwiegen positive Trends gegenüber degradierten Flächen und die Gründe für diese Entwicklung sind nur teilweise durch Niederschlag zu erklären. Auch wenn viele

Gründe standortbezogen sind, gelten einige Faktoren für beide Regionen: (1) Agroforstwirtschaft auf Feldern, (2) strikte Gesetze zum Schutz der Bäume, (3) großflächige Aufforstungsmaßnahmen und (4) weitflächige Ausbreitung von robusten Arten, welche an anthropogenen und klimatischen Stress angepasst sind. Trotz der allgemein sehr positiven Vegetationstrends zeigen Interviews mit Dorfältesten und Langzeitbeobachtungen eine massive Abnahme einheimischer Arten. Abgesehen von einigen sich ausbreitenden Arten (*Balanites aegyptiaca, Acacia raddiana*), ist bei fast allen anderen Gehölzarten ein starker Rückgang und lokales Aussterben zu beobachten. Veränderungen in der Baumschicht hängen sehr stark von Bodeneigenschaften ab, welche den menschlichen Einfluss, die Widerstandsfähigkeit gegenüber Dürren, sowie die Verwundbarkeit gegenüber Bodenerosion steuern. Auf lokaler Ebene kann ein sehr heterogenes Muster an Umweltveränderungen beobachtet werden, welches weder die Generalisierung des Degradierungs- noch des "greening" Paradigmas erlaubt.

RÉSUMÉ

Depuis 50 ans, la région du Sahel connaît d'importants changements environnementaux qui ont conduit à des théories de dégradations irréversibles de l'environnement à grande échelle : sècheresses, expansion des populations humaines et baisse générale des précipitations annuelles. Mais plus récemment, ce modèle a été remis en question par un phénomène de verdissement du Sahel, qui se fonde sur l'augmentation des précipitations et des tendances positives de la végétation reconnaissables sur des données satellites. L'objectif de cette thèse est alors d'explorer au niveau local les différentes tendances liées aux transformations environnementales dans deux zones d'étude situées dans la région Sahel du Mali et du Sénégal. En combinant des données issues aussi bien de satellites que d'un travail de terrain, nous espérons donner un nouveau regard sur les modèles de désertification et de verdissement du Sahel.

Diverses données satellitaires avec différentes résolutions spatiales et temporelles ont ainsi été traitées pour deux zones autour de Bandiagara (Sahel du Mali) et Linguère (Sahel du Sénégal). Les changements dans la végétation observés grâce aux données satellites ont ensuite été validés à travers le recours à des méthodes intenses et interdisciplinaires de vérification au sol. Les images de haute résolution de Corona (1965) et RapidEye (2011) montrent les transformations du couvert arboré et terrestre et leur analyse révèle une baisse significative de la végétation naturelle, une augmentation des arbres dans les champs et une augmentation générale de surfaces cultivées. De même, nous pouvons observer une extension des surfaces dégradées

et une réduction modérée du couvert arboré dans les deux régions étudiées.

Les données climatiques du Climate Research Unit (CRU) témoignent d'une hausse rapide de la température annuelle moyenne depuis les années 1960. Les données pluviométriques du Tropical Rainfall Measuring Mission (TRMM) et du Global Precipitation Climatology Centre (GPCC) montrent que, sur la période de 1970 à 2010, les précipitations annuelles ont baissé de 15% pour Linguère (Sénégal) et de 13% pour Bandiagara (Mali) par rapport à la période de 1930 à 1970. Cependant, si l'on considère la période de 1982 à 2010, les deux zones étudiées ont connu une augmentation significative des précipitations (34% à Linguère et 54% à Bandiagara), ce qui pourrait signifier une fin possible à cette longue période de sécheresse.

De plus, des séries temporelles à petite échelle sur la période de 1982 à 2010 ont étés analysées en utilisant les données Normalized Difference Vegetation Index (NDVI) du Long Term Data Recod (LTDR) ainsi que Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) du Geoland Version 1 (GEOV1) (tous deux à la résolution : 5 km) et GIMMS3g (résolution : 8km). L'ensemble des données s'accordent sur le fait que, sur les deux zones d'étude, d'importantes tendances au verdissement peuvent être observées sur la période de l'étude mais qu'il existe de considérables divergences spatiales au niveau local. Les précipitations annuelles ont augmentées depuis les années 2000, ce qui explique plus de 50% des variations observées. La tendance positive de la végétation peut être confirmée par des séries temporelles de mesure au sol de la biomasse (depuis 1987), qui montrent une significative augmentation de la biomasse ligneuse depuis la fin des années 1980. Néanmoins, à un niveau local, nous démontrons également que les données à haute résolution du Moderate Resolution Imaging Spectroradiometer (MODIS) (250 m) et du SPOT-Vegetation (VGT) (1 km) dessinent un motif hétérogène de variabilité spatiale et la présence de dégradation active des sols à hauteur approximative de 5 à 10% pour chaque zone d'étude.

Les causes de cette dégradation des sols sont aussi bien climatiques que liées à l'homme : (1) sécheresses, peu de précipitation et températures élevées et (2) un besoin croissant en surfaces cultivées et boisées, particulièrement durant les périodes sèches. Toutefois, les tendances au verdissement prédominent sur les dégradations et ne peuvent uniquement être expliquées par les précipitations. Même si la plupart des causes sont spécifiques à un lieu donné, certains facteurs sont valables pour les deux régions : (1) de l'agroforesterie dans les champs, (2) des lois strictes pour la protection des arbres, (3) une reforestation à grand échelle et (4) une dispersion étendue d'espèces robustes qui sont adaptées au stress climatique et anthropique. Malgré une tendance positive dans l'ensemble de la végétation, des entretiens avec des anciens des villages et une surveillance des espèces sur le long terme montrent une réduction massive des espèces natives. En dehors de quelques espèces en expansion (*Balanites aegyptiaca, Acacia raddiana*), on observe que les autres espèces ligneuses connaissent presque toutes une forte décroissance voire une disparition. De plus, les transformations du couvert arboré dépendent fortement des propriétés du sol, elles-mêmes influencées par les hommes en ce qui concerne la résistance aux sècheresses et la vulnérabilité à l'érosion des sols. Finalement, au niveau local nous pouvons donc observer un motif extrêmement hétérogène de transformations environnementales ne permettant pas de généraliser les modèles de dégradation ni ceux du verdissement.

PREFACE

This dissertation is part of the BMBF [1] founded project *micle* [2]. *Micle* aims to find linkages between migration, climate and environment. The project started in September 2010 and ended in April 2014.

"To date there is little scientifically validated knowledge about the relation between climate change, environmental changes and migration. It also remains unclear whether or not Europe will have to reckon with an increasing number of migrants as a result of climate change. The members of the micle research project are investigating the social-ecological conditions under which population movements take place. The relevance of environmental and climate change for migration decisions is studied, based on the neighbouring Sahelian countries Mali and Senegal.

The project aims at a better understanding of the complex interactions between ecological, social, demographic, economic and political factors. The practical objective is to identify possible courses of action for political decision makers and societal stakeholders. This joint project runs for three years until August 2013 and is coordinated by the ISOE - Institute for Social-Ecological Research. Associated partners are the Department of Geography at the University of Bayreuth and the Department of Geography and Regional Research at the University of Vienna." [3]

The present dissertation contributes to the natural scientific part of the project by providing data and analyses dealing with environmental change in the study areas in the Sahel of Mali and Senegal.

1. Bundesministerium für Bildung und Forschung
2. for more information see http://www.micle-project.net
3. cited from http://www.micle-project.net 2013.08.14

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ACRONYMS

AVHRR	Advanced Very High Resolution Radiometer
CSE	Centre de Suivi Ecologique
CRU	Climate Research Unit
DEM	Digital Elevation Model
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GAC	Global Area Coverage
GEOV1	Geoland Version 1
GPCC	Global Precipitation Climatology Center
GIMMS	Global Inventory Modeling and Mapping Studies
3g	third Generation
IER	Institute d'Economie Rurale
LAC	Local Area Coverage
LTDR	Long Term Data Record
MODIS	Moderate Resolution Imaging Spectroradiometer
MAUP	Modifiable Areal Unit Problem
MVC	Maximum Value Composite
NA	Not Available
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
RMA	Reduced Major Axis
SPOT	Satellite Pour l'Observation de la Terre
VGT	Vegetation

STL	Seasonal Trend decomposition based on Loess
UNEP	United Nations Environment Programme
TRMM	Tropical Rainfall Measurement Mission

Part I

CONCEPTUAL DESIGN

1 MOTIVATION AND RESEARCH QUESTIONS

Human activities and climatic variability have caused major environmental changes in semi-arid drylands in the past 50 years. Remote sensing has been an increasingly valuable tool for assessing and quantifying changes in vegetation cover, especially in areas with scarce ground data. As a hot-spot of environmental change, the Sahel region has been subject to a host of remote sensing applications, using a variety of datasets at various spatial and temporal scales. However, due to a lack of linkages to local field studies, only little is known about how realistic coarse earth observation products reflect the local heterogeneous processes in the Sahel. Moreover, the underlying causes of observed vegetation changes are often unknown at a local scale. The purpose of this study is to assess local long-term vegetation trends in the Sahel area of Mali and Senegal by combining satellite datasets and ground based data. This thesis is designed to improve the understanding of the processes responsible for satellite derived trends and thus to shed more light on the degradation and re-greening debate of the Sahel zone.

The first part (I) of this thesis introduces the topic by giving an overview of incisive research conducted in the past 30 years regarding environmental changes in the Sahel. A brief summary of recent state-of-the-art remote sensing studies provides an outline of knowledge gaps, which lays the path for the objectives and research aims as described in this chapter. They are followed by a brief description of the study areas and the applied datasets and methods. The second part (II) includes five peer-reviewed publications building the core of the present thesis. The formating of the corresponding journal is maintained. The final third part (III) summarizes the results in a synthesis and gives an outlook relating to future research needs. An Appendix lists all thesis-related publications and presentations.

1.1 INTRODUCTION

The West African Sahel has often been acclaimed as a hot-spot of environmental change with millions of climate-refugees, water scarcity, famines and land degradation documented and predicted by the United Nations Environment Programme (UNEP), various reports and scientific assessments (e.g. UNEP, 2012; Kandji et al., 2006; WBGU, 1996). These statements are the result of severe Sahel-droughts occurring in the 1970s and 1980s, followed by a dry period which lasted until the end of the 1990s (e.g. Ali & Lebel, 2009; Zeng, 2003; L'Hote et al., 2002). In combination with regional conflicts and political instability, international attention has been attracted to the Sahel region since several decades (Herrmann & Hutchinson, 2005; Hutchinson, 1996).

According to the UNEP and global degradation assessments, the interacting processes of population growth, deforestation, increased cropping, intensive grazing, reduced rainfall and unstable policies have transformed approximately 30% of the West African Sahel into barren land (e.g. Kandji et al., 2006; Oldeman et al., 1990). Large areas have been acclaimed as irreversibly degraded with a continuing reduction of people's livelihood (e.g. Hammer, 2005; Dregne, 1985). However, scientists did not find evidence of large-scaled degradation (e.g. Niemeijer & Mazzucato, 2002; Prince et al., 1998) and the theories of irreversible degradation and an encroaching Sahara desert were correctly identified and explained as natural fluctuations with the potential of a full recovery (Nicholson & Grist, 2001; Tucker & Nicholson, 1999). This led to a questioning of the existence of widespread land degradation (Tiffen & Mortimore, 2002; Warren, 2002) and a changing context in the scientific debate, highlighting manifold and interdisciplinary approaches for the assessment and management of degradation in drylands (Reynolds et al., 2007; Herrmann & Hutchinson, 2005).

Annual precipitation over the Sahel started to increase again in the 2000s, in some places exceeding pre-drought values in 2009/2010 (Giannini et al., 2013; Nicholson, 2013). Moreover, coarse-scale continuous satellite data, measuring vegetation greenness and starting in the year 1981, revealed a significant greening trend over the entire Sahel area (e.g. Anyamba & Tucker, 2005; Olsson et al., 2005; Eklundh & Sjöström, 2004). Even though precipitation is a major causative factor controlling annual vegetation fluctuations (Hickler et al., 2005), the overall greening trend can only partly be explained by the increase in rainfall (Herrmann et al., 2005). Thus, a new re-greening debate largely replaced the previous desertification paradigm in the scientific community (e.g. Hutchinson et al., 2005). However, the re-greening debate is based on a very coarse satellite product, and little is known about the actual processes on the ground. Although ground studies provide evidence of farmer and governmental managed reforestation, (Reij et al., 2009; Reij & Smaling, 2008), only few studies are available linking remote sensing to ground data and to people. Thus, the underlying causes of the observed long-term greening trends and the extent and existence of degradation (e.g. Herrmann & Tappan, 2013; Hiernaux et al., 2009b) are unclear. Therefore, many explanations found in literature are hypothetical or remain speculative.

There is no doubt that the vegetation in the Sahel is changing. In the 20th century, most natural bushland has been transformed into agricultural land with a remarkable loss in woody vegetation cover (e.g. Ruelland et al., 2010; Tappan et al., 2004). The loss of broad forests accelerated climatic feedbacks and is thus a causative factor for droughts and a decrease in rainfall (Kucharski et al., 2012; Paeth et al., 2009). However, the influence of land cover on climate is much lower than statements in the 1970s and 1980s claimed (Charney et al., 1975), and global models have shown that changes in oceanic sea surface temperatures are largely responsible for Sahelian droughts and rainfall fluctuations (Giannini et al., 2008; Giannini, 2003). Moreover, in spite of the recent high levels of annual rainfall, climate models predict a warmer and dryer African Sahel with prolonged dry spells and an increasing frequency of severe droughts for the coming 30 years (Paeth et al., 2009).

Long-term ground observations of vegetation are rare, and it is important to distinguish between short term variations and long-term changes (Miehe et al., 2010; Mbow et al., 2008). Even though a broad drought recovery is observed on the ground (e.g. Hiernaux et al., 2009b; Tappan et al., 2004), a shift to a more arid climate with a corresponding adaptation of species is progressing, and several studies show a massive decline in biodiversity (Herrmann & Tappan, 2013; Gonzalez et al., 2012; Gonzalez, 2001). This species impoverishment is consistently observed in several Sahelian countries and took place in spite of existing greening trends. Moreover, case studies provide information on a climate triggered herbaceous species change which leads to a greening effect due to an invasive species with high greenness (Mbow et al., 2013). These examples demonstrate the complexity of the underlying causes on satellite derived vegetation trends.

1.2 BACKGROUND: REMOTE SENSING STUDIES IN THE SAHEL

Remote sensing is an established methodology to monitor long-term changes in vegetation cover (Jones & Vaughan, 2010; Jong & Meer, 2004). The West African Sahel has been the subject of various earth observation studies dating back to the beginning of the 1980s (Tucker et al., 1983). Sahelian land cover changes have been mapped using high-resolution Ikonos, Landsat, Corona and Satellite Pour l'Observation de la Terre (SPOT) satellite imagery (e.g. Nutini et al., 2013; Ruelland et al., 2010; Mbow et al., 2008; Tappan & McGahuey, 2007; Tappan et al., 2004) with varying classification methods, but all showing the increasing influence of humans and an overall decrease in natural vegetation. However, as static satellite images are not able to adequately capture the Sahelian vegetation dynamics, time series of Normalized Difference Vegetation Index (NDVI) are widely used for monitoring broad scaled vegetation changes. The only available satellite data measuring vegetation at a high temporal frequency since the beginning of the 1980s, is the Advanced Very High Resolution Radiometer (AVHRR) sensor from National Oceanic and Atmospheric Administration (NOAA) satellites. It is processed by the Global Inventory Modeling and Mapping Studies (GIMMS) group to a global dataset with a spatial resolution of 8 km ranging from July 1981 to December 2006 (Tucker et al., 2005). The data of the different NOAA satellites (7–18) is adjusted to a consistent long time series; however, an atmospheric correction is not applied, except for the volcanic stratospheric aerosol periods in 1982–1984 and 1991–1994 (Tucker et al., 2005). The latest version is termed GIMMS-third Generation (3g) and extends the period to 2011 with improved calibration methods. Most studies analyzing vegetation in the Sahel rely on the GIMMS dataset (Herrmann & Tappan, 2013; Bégué et al., 2011; Fensholt et al., 2009; Heumann et al., 2007; Anyamba & Tucker, 2005; Herrmann et al., 2005; Olsson et al., 2005; Eklundh & Sjöström, 2004) and recently GIMMS-3g (Dardel et al., 2014; Fensholt et al., 2013). Finer scaled, high-quality data is available from SPOT-Vegetation (VGT) since 1998 (1 km) and Moderate Resolution Imaging Spectroradiometer (MODIS) since May 2000 (250 m). However, active degradation and environmental change are rarely spotted over the shorter time period and thus studies applying SPOT-VGT or MODIS on Sahelian regions are more rare (e.g. Herrmann et al., 2013; Bobée et al., 2012; Martinez et al., 2011; Budde et al., 2004; Fensholt et al., 2004). Higher resolution Local Area Coverage (LAC) AVHRR data is available since the 1980s from local receiving stations at 1.1 km resolution, however, the poor quality and availability hampers the use in scientific long-term studies in the Sahel (Dybkjaer et al., 2003; Diouf & Lambin, 2001; Fuller, 1998; Tucker et al., 1985). All studies using long-term time series agree that a widespread greening is observed all over the Sahel over the past 30 years and degradation is rarely detected.

Due to the coarse spatial resolution of GIMMS, a lack of local studies and long-term ground data, it is largely unknown what causes observed greenness trends at a local scale and if they are reflected in a realistic way. Only few studies go beyond conjecturing interpretations and explain environmental changes by means of locally observed ground data (e.g. Dardel et al., 2014; Herrmann & Tappan, 2013; Mbow et al., 2013; Hiernaux et al., 2009b,a; Mougin et al., 2009; Diouf & Lambin, 2001). Moreover, due to a lack of combined approaches, issues of scales, also known as Modifiable Areal Unit Problem (MAUP), are seldom addressed in Sahelian studies (Boschetti et al., 2013). Finally, the people living and acting within the pixels are rarely studied and linked to earth observation data (Reenberg et al., 2013; Mertz et al., 2010; Mbow et al., 2008; Tappan & McGahuey, 2007; Tschakert & Tappan, 2004). The lack of linking different data-sources leads to misleading interpretations of both earth observations and field data (Reenberg et al., 2013).

1.3 RESEARCH QUESTIONS AND HYPOTHESES

Against the background of global climate and vegetation change, the major aim of the present study is to assess and explain local vegetation changes in the Sahel area by means of global earth observation datasets, local ground data and interdisciplinary groundtruthing. This study thus breaks the scale down to a local perspective and bridges the gap between remote sensing and ground studies. This thesis aims therefore to contribute to an ongoing greening versus degradation discussion and provides further context for unraveling the challenges of land management in the Sahel.

Moreover, this study focuses on questions regarding the use of satellite imagery in arid lands. The local variability and complexity cannot be interpreted from coarse scale imagery and a multi-scale approach is presented to provide a better understanding of the actual processes of change in dryland ecosystems. The research is conducted in two study areas, located around Bandiagara (Sahel of Mali) and Linguère (Sahel of Senegal). Two major **research questions** frame the work:

1. Which environmental changes can be observed in the two study areas?
2. What are the causative factors for the observed environmental changes?

With consideration of the current knowledge in environmental research on the Sahel, these research questions led to three main hypotheses, which deal with the **extent** and **causation** of environmental changes as well as the **data issues** of assessing these:

hypothesis 1: Widespread desertification is nowadays replaced by a widespread greening Sahel phenomenon.

In the 1980s, droughts, clearance of bushland and a drop in annual precipitation were postulated to have led to widespread deforestation, erosion, and desertification. Large portions of the Sahel area have been branded as irreversibly degraded land (e.g. Oldeman et al., 1990; Dregne, 1985). Even though the desertification paradigm is still present in the past decade (e.g. Kandji et al., 2006; Hammer, 2005), it is largely replaced by a greening Sahel debate. The greening is observed in coarse satellite data and is reported to be widespread (e.g. Anyamba & Tucker, 2005; Olsson et al., 2005).

hypothesis 2: The greening phenomenon can only partly be explained by rainfall variability. A human signal is part of environmental changes observed in satellite data.

The impact and scale of human activities and climate as drivers of environmental changes remain largely unknown. Moreover, actual environmental changes are rarely identified at a local level. Besides increasing rainfall (e.g. Nicholson, 2013), it is largely unclear what is causing the greening of the Sahel and if an environmental improvement has transpired (e.g. Olsson et al., 2005). The greening phenomena might be caused by an herbaceous layer and a shift in species composition (e.g. Dardel et al., 2014; Mbow et al., 2013), concealing an ongoing reduction in tree cover and species impoverishment (e.g. Herrmann & Tappan, 2013; Gonzalez et al., 2012). On the other hand, the greening could also imply that woody vegetation of the Sahel is returning steadily to conditions similar to the pre-drought situation.

hypothesis 3: The ability to characterize the spatial variability of Sahelian vegetation trends is affected by the coarseness and quality of the satellite data used. Thus, degradation is obscured and greening overestimated.

GIMMS NDVI data has been widely used in Sahelian vegetation studies both at regional (e.g. Anyamba & Tucker, 2005) and local (e.g. Herrmann & Tappan, 2013) scale. With its coarse spatial resolution of 8 km pixel size using a sampling technique which resamples 1.1 km samples to 8 km grid cells (and omits the remaining samples), it is not clear if the heterogeneous pattern of land cover and vegetation changes in the Sahel are adequately captured. Degradation processes are very local and may not be detected or are neutralized. Scale and data quality are common issues in earth observation sciences (see Sheppard & McMaster, 2004). An impression of widespread greening might obscure active degradation. Moreover, human signals can mostly be observed at local scales, proposing that regionally scaled greenness trends are mainly driven by rainfall variability (Hickler et al., 2005).

The present study intends to dismiss existing paradigms and analyzes extent, complexity and spatial/temporal variations of environmental change at a local scale. Coarse scale satellite studies alone are incapable of establishing whether degradation is existing and what is causing greenness trends. In accordance with the recommendations of Herrmann et al. (2005), this dissertation uses a combination of approaches and finer resolution spatial data. By means of case studies and household surveys, the causation of observed greening and degradation trends is studied. Using a multi-scale and multi-source approach, we apply a variety of earth observation products in combination with intensive fieldwork to investigate the hypotheses in two Sahelian study areas.

2 MATERIALS AND METHODS

This chapter briefly introduces the two Sahelian study areas and summarizes the materials and methods necessary to test the hypotheses. Various satellite time series and high-resolution imagery are combined with ground data to assess local vegetation trend patterns and changes in the two study areas (research question 1). Explanations, validation and interpretation of observed trends are based on several ground-truthing methodologies (research question 2). The data and methods are explained in detail in part II in the corresponding manuscripts.

Still being a remote sensing study as such, the present dissertation intends to expand the field of established ground-truthing methodologies. By intensive collaboration with scientists from different disciplines and organizations, ecological and social-scientific fieldwork build the core of the ground-truthing and validation/interpretation processes. We thus follow approaches discussed in Crews & Walsh (2009), Fox (2003) and Liverman et al. (1998), linking remote sensing and social sciences, i.e. pixels and people. Multiple scales are addressed in earth observation and ground data to overcome the MAUP (see methods and discussions in Jong & Meer, 2004; Sheppard & McMaster, 2004).

2.1 STUDY AREAS

Our study is conducted in the Sahel zone of Mali and Senegal. The Sahel zone is a semi-arid area forming an ecological transition between the Sahara desert in the north and the tropical savanna in the south. Annual rainfall is around 200–600 mm with varying definitions in literature (Anyamba & Tucker, 2005).

Both study areas are approximately 4000 km^2 large (see Figure 1) and both regions can be divided into a sandy and a lateritic part. Droughts in the 1970s and 1980s had adverse effects on the woody vegetation in both study areas, and a remarkable reduction of tree cover was observed, especially on the shallow ferruginous soils of the lateritic regions (Tappan et al., 2004). The Malian study area includes the sandy Seno Plain around Bankass and the rocky Dogon Plateau stretching from Bandiagara to Sevaré. Mean annual rainfall is around 550 mm and rainfed cropping of millet and groundnut is practiced by Dogon farmers throughout the whole area. Irrigated vegetable gardens (mainly onions) line the valleys of the plateau.

Figure 1: The locations of our two West African study areas (Linguère - Sahel of Senegal and Bandiagara - Sahel of Mali) are encircled in red in this map.

The Senegalese study area is situated around the city of Linguère and is part of the silvo-pastoral Ferlo region. With around 400 mm mean annual rainfall and a significant inter-annual variability, most of the area is used for livestock herding by Fulani herders. Less than 15% of the study area is cultivated by Wolof farmers with millet and groundnut. The region is named after the Ferlo River and can be divided in the lateritic Ferlo in the east and the sandy Ferlo in the western parts. The eastern Ferlo is exclusively used for grazing and cropping is prohibited and not profitable on the shallow soils. Rainfed cultivation and small scale gardening is found in the sandy parts north, west, and south of Linguère. More detailed information on the two study areas is provided in chapters 3, 4, 5, 6 and 7.

2.2 ASSESSING ENVIRONMENTAL CHANGE AT A LOCAL SCALE

Beside climate parameters (rainfall and temperature), this study concentrates on the woody vegetation and neglects herbaceous species due to four reasons: (a) trees and shrubs play a major role in the daily life of the Sahelian population (e.g. religion, medicine, cooking, fodder (Maydell, 1990)). (b) Trees are long living and serve as an indicator for long-term changes. Furthermore, (c) trees are an important factor for a steady state of a savanna ecosystem. They counter soil erosion and are a proxy for ecosystem health. (d) Individual trees and shrubs are detectable in high-resolution satellite imagery. Most species keep their green leaves throughout the dry season and can thus be extracted and measured via infra-red sensors of modern satellites.

2.2.1 *Climate data*

Apart from the Linguère weather station, climate data used in this study is based on preprocessed gridded datasets which are globally available. Global Precipitation Climatology Center (GPCC) (Schneider et al., 2013) and Climate Research Unit (CRU) (Mitchell & Jones, 2005) datasets are interpolated to grid cells from reported station-data. Depending on the sources, a high inter-annual variation of the reporting stations is present, adding a factor of insecurity to this kind of data-source (Eklund et al., submitted). However, if used with consideration of the limitations of these datasets, GPCC v6 can be a reliable source for coarse long-term rainfall trends (Paeth et al., 2010). The same is true for CRU v3.1 regarding temperature data. Both are available at a 0.5° grid resolution for the period 1901–2010. Tropical Rainfall Measurement Mission (TRMM) precipitation is based on satellite measurements (Huffman et al., 2007) and has proven to be a stable product (Paeth et al., 2010) showing spatial variations at a resolution of 0.25° since 1998 (see Figure 2 and Table 1).

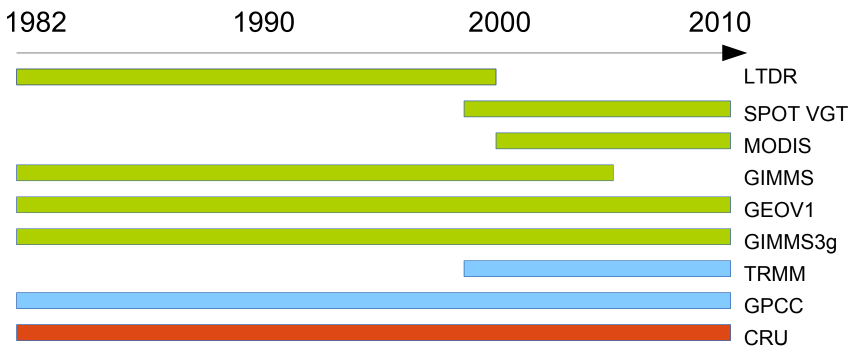


Figure 2: Global and continuous earth observation products used in this study. Green=vegetation greenness, blue=rainfall, red=temperature.

2.2.2 *Time series analysis*

Classical change analyses are ineffective to detect vegetation changes in the West African Sahel because a high inter-annual variability makes vegetation changes not a static but a very dynamic process. The Sahelian vegetation is mainly controlled by rainfall, which underlies an extreme inter- and intra-annual variability (Hickler et al., 2005; Nicholson & Webster, 2007). Individual years can vary extremely and do not represent a stable condition (see Figure 3).

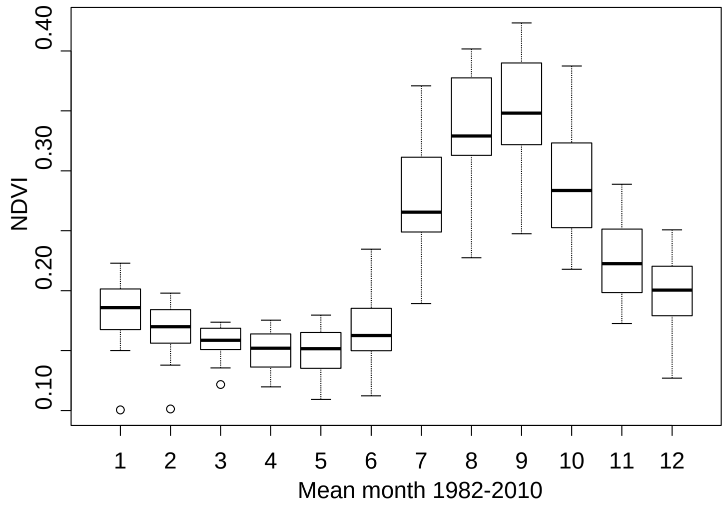


Figure 3: Boxplots for LTDR-SPOT NDVI for the period 1982–2010 averaged over the study area in Mali. Intra- and inter-annual variability is high.

DATASET	TIMEFRAME	SPATIAL RES.	TEMP. RES.	USE
LTDR v3	1982-2000	5 km	daily	NDVI
SPOT-VGT S10	1998-2010	1 km	10 days	NDVI
MODIS 13Q1	2000-2010	250 m	16 days	NDVI
GIMMS	1982-2006	8 km	16 days	NDVI
GEOV1	1982-2010	5 km	10 days	FAPAR
GIMMS3g	1982-2010	8 km	16 days	FAPAR
TRMM 2B42 v6	1998-2010	0.25°	daily	rainfall
GPCC v6	1901-2010	0.5°	monthly	rainfall
CRU v3.1	1901-2010	0.5°	monthly	temp.
Corona	Dec 1965/67	2 m	static	s/w
RapidEye	Dec 2010/11	6.5 m	static	5 bands
Landsat TM	1984-2010	30 m	static	7 bands
Biomass data	1987-2010	1 km	annual	biomass

Table 1: Spatial data used in the dissertation. Note the variety of different spatial and temporal scales ranging from 2 m to 50 km and daily to annual.

To monitor long-term vegetation trends, this study uses continuous greenness data (see Figure 2). The data is derived from AVHRR Global Area Coverage (GAC) sensor since 1982 at a coarse scale (5–8 km) and from MODIS and SPOT-VGT sensors since 2000 (1998, respectively) at a moderate scale (250 m/1 km). The time-line of AVHRR starts during the dry period in the 1980s and valuable information for vegetation development is provided since then. The data has a high temporal sampling rate [1], allowing further processing as a conventional time series. All processing and analyses were done pixel-wise, treating the z-values of each pixel with consistent x and y coordinates as a time series (see Figure 4). Each raster represents a constant step and covers a spatial region over a certain time-frame. All datasets offer a variety of different spatial resolutions, all capturing different levels of detail (see Figure 5 and Table 1). A coarse resolution merges a heterogeneous landscape and often neutralizes or masks important details, however, moderate and higher resolution data is only available for a shorter period and induces increased processing difficulties due to a larger data volume. Briefly summarized, the most important aspects regarding time series analysis in this work are:

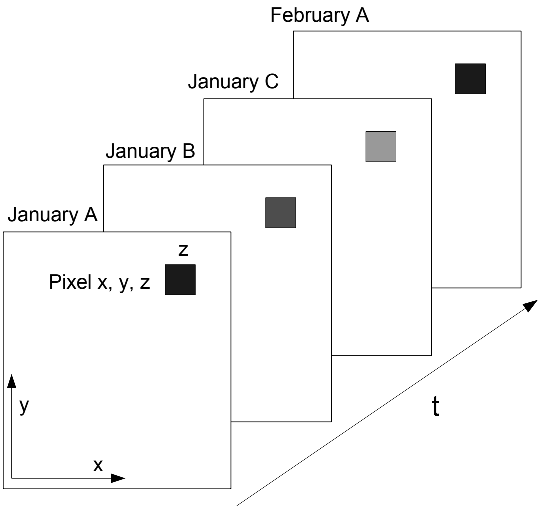
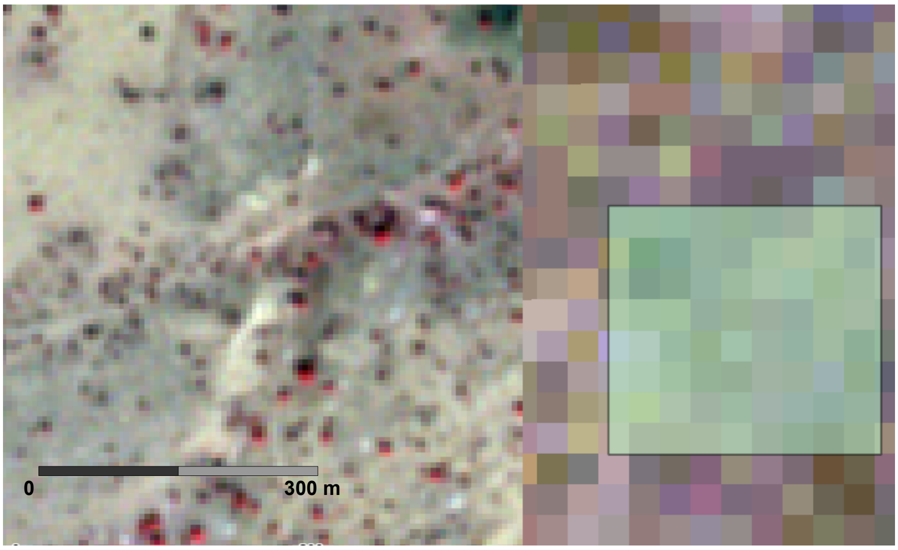


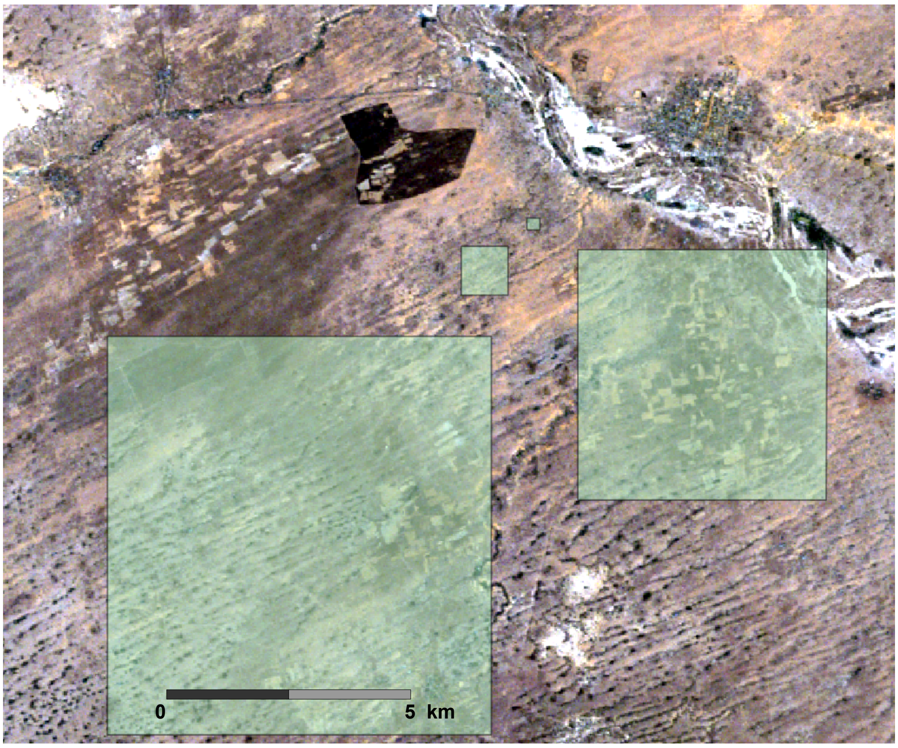
Figure 4: This figure shows the principles of pixel-wise time series analysis. Every pixel has consistent x and y coordinates and a varying z value which is treated as a conventional time series.

FILTERING AND SMOOTHING Even if modern remote sensing products like SPOT-VGT or MODIS pass procedures for corrections, permanent clouds and atmospheric disturbances are common during the rainy season in the semi-arid tropics and are thus problematic in all remote sensing datasets. Assuming that exceptionally low values are contaminated by clouds, Maximum Value Composite (MVC) [2] over a certain time period (10, 16 or 30 days) are constructed selecting only the highest pixel value within this time-frame. To further estimate the quality of each pixel, the datasets are delivered with quality assessment rasters for each image. These quality rasters are produced via algorithms and differ considerably between the datasets (Fensholt et al., 2009). By means of a key, the bit-pattern of quality flags was read and pixels of a quality below average masked. However, to avoid

1. raw data is available at a daily scale
2. see Holben (1986)



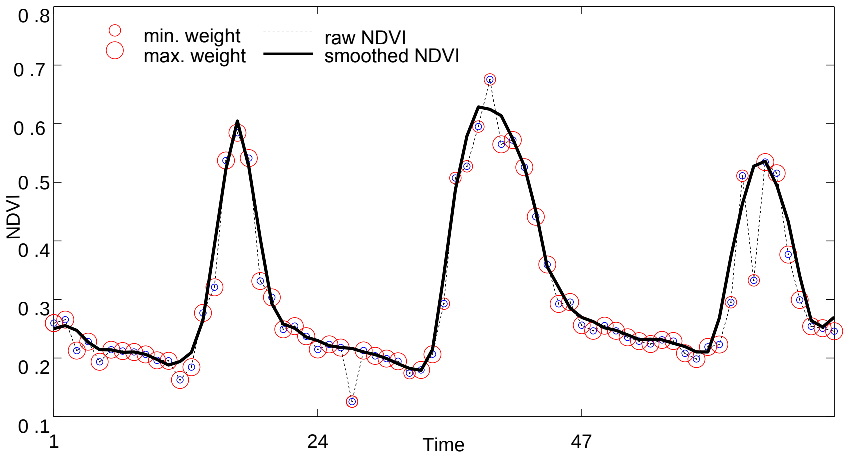
(a) Comparison between RapidEye (6.5 m, background), Landsat (30 m) and MODIS (250 m) pixel sizes (from smallest to largest pixel size).



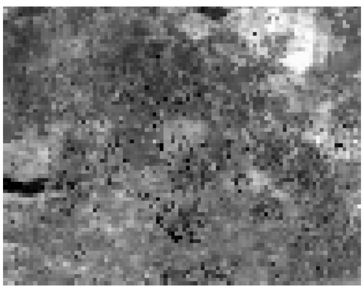
(b) Comparison between Landsat (30 m, background), MODIS (250 m), SPOT-VGT (1 km), LTDR (5 km) and GIMMS (8 km) pixel sizes (from smallest to largest pixel size).

Figure 5: Pixel comparisons south of Linguère, Senegal.

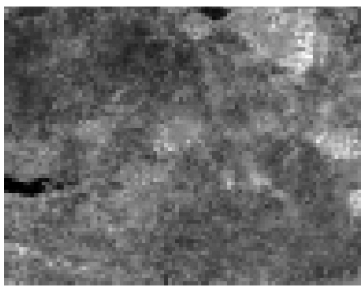
gaps, time series can be smoothed and gaps filled according to the temporally previous and successive pixels. Julien & Sobrino (2010) evaluate the most popular techniques. Within the present thesis, the method of Chen et al. (2004) and Jonsson & Eklundh (2004) was chosen. Here, smoothing is based on a seven-step interpolation with a Savitzky Golay filter[3], which was applied pixel-wise on the time-series. The tight-fitting curve was able to follow complex changes and fits to the distinctive annual cycle of the Sahelian vegetation. According to the quality flags, each pixel was weighted when the new time-line was calculated. The number of iterations and the moving window size had to be individually adapted for each dataset. Figure 6 demonstrates that the quality was considerably improved by applying this method. Long Term Data Record (LTDR), SPOT-VGT and MODIS rasters were processed this way. More information on the individual datasets can be found in chapter 4.



(a) The smoothed line excludes low weighted outliers of this MODIS pixel series.



(b) Raw MODIS scene



(c) The same scene with applied filtering

Figure 6: The effect of the weighted Savitzky Golay filtering on MODIS data is demonstrated here for a region in Linguère, Senegal.

3. The adaptive Savitzky Golay filter uses a polynomial regression to smooth the curve. The window size can be adjusted to determine the degree of smoothing and the ability to follow changes (Jonsson & Eklundh, 2004)

TREND ANALYSIS BASED ON SEASONAL DECOMPOSITION Trend analysis based on linear regression contains errors based on autocorrelation, seasonal fluctuations and erroneous data (e.g. artifacts). Even if slope parameters remain largely unbiased and linear, De Beurs & Henebry (2005) state that most image time series are temporarily correlated, resulting in unreliable significance parameters. Thus, a seasonal trend decomposition based on a local regression (Loess) [4] was used in this study to filter remaining noise and decompose the time series into seasonal and yearly (i.e. trend) components (see Figure 7). This robust technique was able to deal with noisy data containing missing values and is more stable and reliable for trend analysis. Additionally, the yearly component served as a proxy for the evergreen woody layer (Lu et al., 2003; Roderick et al., 1999), as the short lasting seasonal herbaceous layer was isolated and low-weighted. The yearly component was extracted and further used for linear regression analysis with the yearly component as response variable and time as explanatory variable. The slope was extracted and recalculated to the appropriate unit to give information on magnitude, direction and spatial pattern of vegetation change. Each pixel-series was tested for significance and only pixels with a confidence level of 95% were further processed. The rest was masked as Not Available (NA). The STL method produced more significant and reliable trends than conventional techniques and detected more subtle, gradual vegetation changes. The methodology is further described in chapter 4 and 5. Furthermore, the Loess method was applied to rainfall data to detect and visualize dynamic annual trends.

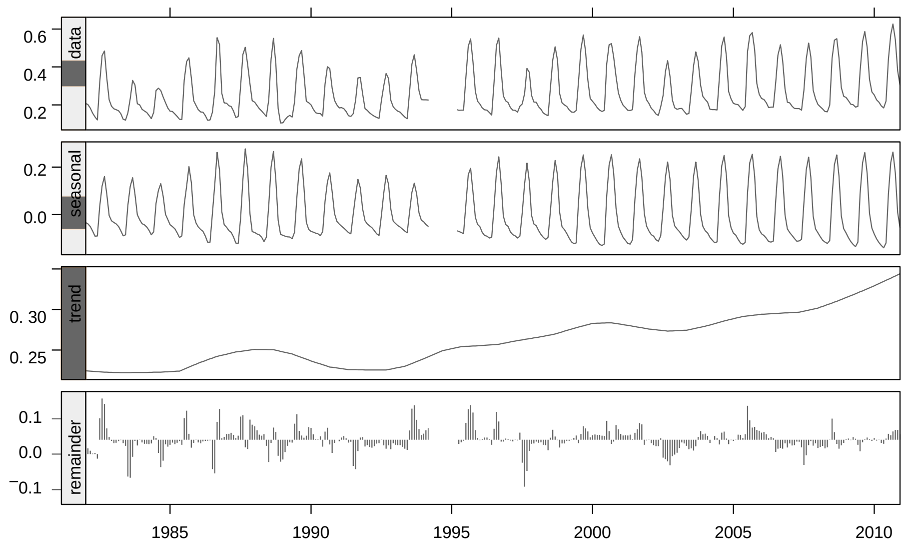


Figure 7: LTDR-SPOT time series averaged over the study area in Senegal and decomposed into seasonal, trend and noise components (seasonal window 4, trend window 80). The trend component is a proxy for the evergreen woody vegetation and further used for trend analysis.

4. Seasonal Trend decomposition based on Loess (STL), see Cleveland et al. (1990)

LTDR-SPOT LONG TIME SERIES A new time series was created by combining daily LTDR[5] and 10-day SPOT-VGT[6] data. LTDR is rated to be a superior AVHRR based dataset (Beck et al., 2011), processed from four different GAC sensors. LTDR is available for the period 1981-1999 and SPOT-VGT from 1998 until present. The two overlapping years 1998 and 1999 (Figure 2) were used to obtain a statistical relationship between SPOT-VGT and LTDR and adjust them to each other. The new LTDR–SPOT time series provides a higher spatial (5 km) and temporal (10 day) resolution than GIMMS (8 km, 16 days) and is thus better suited for local studies. The new NDVI time series is from 1982 until 2010; 1994 was completely masked as NA due to poor quality. More information on its creation and trend analysis based on this time series can be found in chapter 4.

GEOV1 FAPAR LONG TIME SERIES Geoland Version 1 (GEOV1) Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)[7] is another LTDR and SPOT-VGT-based alternative for GIMMS data with a higher resolution (approximately 5 km) and an innovative gap filling and smoothing technology. This way, years of poor quality data (e.g. 1994) could be reconstructed making the time series more consistent and gap-free. The period used is the same as LTDR–SPOT time series (1982–2010). Compared with NDVI, FAPAR mitigates the impact of soil background for low vegetated areas and should thus represent an improvement in semi-arid areas. Algorithm development and data processing was conducted by Aleixandre Verger[8] within the geoland2 project[9]. Further details on the method and the potential of this dataset to detect local vegetation changes are provided in chapter 5, Baret et al. (2013) and Verger et al. (2012).

DECOUPLING VEGETATION TRENDS FROM RAINFALL The RESTREND methodology statistically combines NDVI and FAPAR time series with rainfall data (GPCC and TRMM) and predicts vegetation-trends decoupled from rainfall (Herrmann et al., 2005; Wessels et al., 2007). A linear regression with a 3-monthly cumulative rainfall as explanatory and monthly NDVI/FAPAR as the response variable obtained slope and intercept coefficients, which were used to model NDVI/FAPAR with monthly rainfall. The residues between observed and modeled NDVI/FAPAR are expected to be an anthropogenic factor. Calculating a regression slope of the residues minimized the effects of rainfall on vegetation changes and gave information on causative factors responsible for greening and degradation trends. The methodol-

5. distributed by the Goddard Space Center
6. distributed by VITO
7. a vegetation index comparable to NDVI, see Baret et al. (2013)
8. INRA-EMMAH, Avignon, France
9. http://www.gmes-geoland.info 21.08.2013

ogy was applied for all available datasets and is published in chapter 3 for GEOV1 FAPAR and GPCC rainfall data.

2.2.3 *High-resolution satellite imagery*

Time series analysis has two significant drawbacks: (1) the pixel resolution [10] is not capable to capture single trees and (2) all datasets start in the beginning of the 1980s, i.e. during the dry period. Thus, the environmental situation prior to the droughts of the 1970s and 1980s remains unclear. Moreover, it is not certain if the recent greening trend means a return to conditions similar to the 1960s. To compare the current situation with pre-drought conditions, panchromatic high-resolution Corona images from the 1960s (McDonald, 1995) are an invaluable window into the past, helping to reconstruct the pre-drought situation. Though being only panchromatic, the pixel resolution of about 2 m is able to detect single trees and large shrubs, and provide information on land cover and land use. To compare the environmental situation of the 1960s [11] with recent conditions, RapidEye imagery from December 2010 (Senegal) and December 2011 (Mali) were acquired. They provide a resolution of 6.5 m and five multispectral bands, ranging from natural colors to near infra-red. Both Corona and RapidEye were georeferenced to obtain overlapping mosaics for both study areas. A qualitative visual inspection of Corona/RapidEye image pairs was conducted for both study areas (Mali and Senegal) (see chapter 4), whereas quantitative classifications and change maps were calculated for the Malian study area only (see chapter 6 [12]):

VISUAL INSPECTION Visual inspection and on-screen comparisons were conducted with image pairs 1967/2011 for Mali (respectively 1965/2010 for Senegal) for selected case studies areas, which were identified by time series analysis. Focus was on land cover change, change in tree density and cover, signs of apparent degradation, anthropogenic influences as well as instances of no change. In cases the resolution of RapidEye was not sufficient, Google Earth was additionally used for visual analysis. Results and further descriptions of the imagery and methodology are presented in chapter 4.

TREE COVER CLASSIFICATIONS Tree density and tree cover maps for 1967 and 2011 were created for the Malian study area, based on an object-oriented classification approach. In combination with spectral properties, the feature extraction and classification operations

10. ranging from 250 m to 8 km
11. available for Dec. 1965 for the Senegalese study area and Dec. 1967 for Mali
12. conducted in collaboration with Raphael Spiekermann (Spiekermann, 2013)

included in *ERDAS* Imagine Objective were applied to analyze the datasets and map millions of individual trees and large shrubs.

LAND COVER CLASSIFICATIONS Land cover maps for 1967 and 2011 differentiating between dense and sparse woody vegetation were calculated. Densely vegetated areas are mostly areas of dense natural bushland which have not been deforested for cultivation or have been laid fallow for extended periods of time. Sparsely vegetated areas have been cleared from bushland and are usually used for cropping purposes.

CHANGE MAPS Change maps for the period 1967 and 2011 for land cover, tree density and tree cover were calculated. Although the different resolutions of Corona and RapidEye make a quantitative comparison difficult, the direction of change is certainly correct and provides valuable informations of change over 44 years.

2.2.4 *Assessing land degradation*

Land degradation is an important aspect when environmental issues are assessed. Recent studies highlight the importance of an interdisciplinary approach including ecological and social aspects (Reynolds et al., 2007; Herrmann & Hutchinson, 2005) and remote sensing can only be a first step to detect degradation. Moreover, the issues of varying temporal and spatial scales in spatial data are of utmost importance, as land degradation is a long-term process and appears very locally in most cases. Even though coarse remote sensing studies have contradicted the debate of widespread desertification, it remains unclear what happens at a local scale. For this study, barren, unvegetated areas providing no further agricultural use were defined as degraded. To detect and quantify degraded land, three methods were applied within this study:

PIXEL'S PRODUCTIVITY/SEASONAL AMPLITUDE The seasonal amplitude of time series, i.e. the difference between the highest and lowest greenness value over one season, provides evidence of the productivity of a pixel. To avoid seasonal effects caused by rainfall variability, insects, bush fires and human impact, a mean value over several years was used. This methodology was applied to fitted MODIS data for the period 2000–2010 and identified unproductive pixels at a resolution of 250 m. The high temporal sampling of MODIS (23 images each year) over a period of 11 years provided a reliable seasonal amplitude. This methodology is further described and applied in chapter 4.

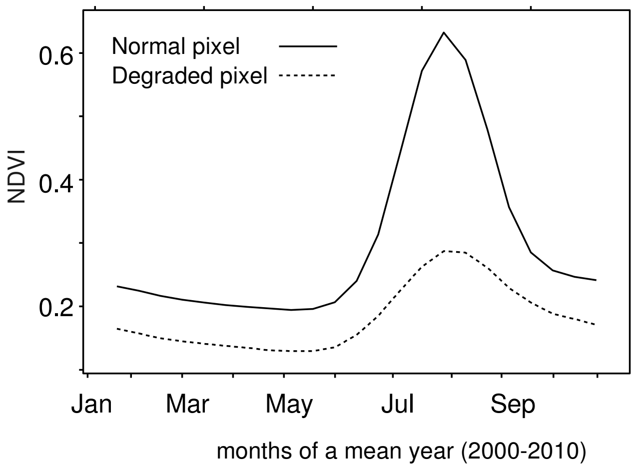


Figure 8: These two MODIS pixels in Senegal show areas with a high and a low greenness productivity.

LONG-TERM TREND ANALYSIS As all long-term time series start at the beginning of the 1980s, i.e. during a dry period, and end in a wet period (2010), degraded and unproductive areas were expected to show no positive trend, despite of increasing rainfall. Further details on the beginning and time-frame of the degradation process could be detected in the temporal profiles of the corresponding pixels. This methodology was applied to all long-term datasets (LTDR–SPOT NDVI, GIMMS-3g FAPAR and GEOV1 FAPAR) available, resulting in major variations. Results using LTDR–SPOT are presented in chapter 4 and GEOV1 FAPAR and GIMMS-3g FAPAR in chapter 5.

MODEL DEFORESTATION VIA WOODY COVER A loss of woody cover leads to soil erosion and a loss of productivity. Therefore, woody cover was modeled via training sites and Landsat dry-season images (mean of four images between 2000 and 2010) for both study areas. The model was derived using Reduced Major Axis (RMA) regression (Larsson, 1993) and featured continuous canopy cover in percent. Deforested areas clearly stand out and could be mapped at a resolution of 30 m. Aggregation up to 1000 m kept the spatial pattern and allowed linkages to time series data. Chapter 7 provides details on the methodology and includes the maps to illustrate deforested areas in the Senegal study area (the Malian study area was removed for the sake of brevity).

2.3 EXPLAINING ENVIRONMENTAL CHANGE AT A LOCAL SCALE

2.3.1 *Ground-truthing*

Both continuous time series data and high-resolution satellite imagery are neither capable of determining woody species nor finding explanations for trends, change and their spatial discrepancies. On the basis of observed remote sensing results, these issues were addressed via ground data collected by interdisciplinary ground-truthing, involving local people and vegetation- and soil surveys (see e.g. Fox, 2003). The ground-truthing process included four steps:

1. Hot-spot areas were identified via satellite time series analysis. Areas were marked where vegetation had either increased or decreased significantly; as were instances of no change. At this stage, trends were understood as change in biomass; what exactly caused this change was unclear.
2. Identified areas were further inspected by high-resolution Corona and RapidEye imagery. This way, the current situation (i.e. tree- and land cover) could be compared with pre-drought conditions at tree-level.
3. Local woody vegetation, land cover, soil and degradation processes were surveyed on the ground by line transects equally distributed throughout the two study areas but with focus on the hot-spot areas. All woody species along 145 line transects of approximately 200 m each were surveyed in 2011 and 2012. The transects gave information about species distribution, their abundance and use by humans as well as the condition and age pattern of trees. Altogether 3240 individuals including both trees and shrubs were documented. Additionally, 84 soil samples were taken and analyzed to investigate the interdependency of soil and woody vegetation.
4. Local people, village elders, governmental agencies and local scientists were interviewed using a retrospective approach (Fox, 2003). In collaboration with human geographers and social scientists [13], information on traditional and more recent land use systems were acquired. This includes pastoralism, use of trees and shrubs, cropping, land ownership and the history of several case study villages. Furthermore, the perception of local people as regards recent environmental conditions as well as changes in rainfall, temperature, soil fertility, woody cover and diversity, pasture and cropping capacities were addressed. Site visits and transect walks were conducted with villagers and results from ecological surveys included in the questions. Using a questionnaire, village elders were asked to identify changes in tree species composition over the past 40 years. A close collaboration with the Centre de Suivi Ecologique (CSE) and Institute d'Economie Rurale (IER) offered access to existing studies, data and knowledge. The information gathered is included in chapter 3, 4, 5, 6 and 7.

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For more information on the ground-truthing methodology of the four steps, as well as the results, see chapter 4. The sampling technique used for the woody vegetation and soil is described in chapter 7. Chapters 3, 5, 6 and 7 provide the results achieved by the presented methods.

2.3.2 *Interpretation and validation*

This study uses several techniques to interpret the observed greenness trends. This includes ground data provided by African colleagues, qualitative and quantitative field-data collected by ground-truthing of the research team, and classification schemes derived from data analyses. Using a variety of survey and remote sensing products at different scales includes a variety of potential errors, e.g. erroneous data, processing mistakes, scale issues and misinterpretation. Methods successfully applied in one region do not necessarily fit to another. Therefore, the following methods serve not only for interpretation, but provide further material for validation of observed environmental trends:

A QUALITATIVE APPROACH The qualitative approach is based on case studies within the study areas. The case studies are mostly situated in hot-spot areas and were thus chosen as a result of time series analysis, a comparison of Corona and RapidEye imagery and site visits. Further in-depth knowledge was acquired during six field trips and close contact to local scientists and experts. In combination with high-resolution data and >5000 GPS-referenced landscape photos, the knowledge of the 145 transects could be extrapolated to the entire study areas. Moreover, field observations and ethnographic fieldwork (conducted by project colleagues) provided interpretations and explanations for observed trends and spatial patterns. Chapters 4 and 5 describe the chosen sites and present the results in a descriptive manner, whereas chapter 3 summarizes case study results for the entire study areas.

A QUANTITATIVE APPROACH The quantitative approach is based on time series of rainfall data and annual biomass observations [14], available from 1987 until 2010 at three sites [15] in Senegal. For biomass observations, trees and shrubs as well as the herbaceous layer were surveyed with a stratified sampling method based on transects and quadrats to estimate the green biomass for the woody and herbaceous layer (Diouf & Lambin, 2001). Using allometric relations, the leaf and herbaceous biomass are calculated for each year since 1987. In

14. collected by the CSE in Senegal
15. C3L5, C2L4, C2L5

consideration of the limitations of comparing above-ground biomass data with satellite derived greenness data (Diallo et al., 1991; Diouf & Lambin, 2001), the comparison was expected to provide evidence if direction, magnitude and the spatial pattern of NDVI/FAPAR trends are realistic and if trees or grass are the main drivers of trends. Results and further information are presented in chapter 5.

AN APPROACH BASED ON CLASSIFICATION SCHEMES Within the Senegalese study area, 84 soil samples were taken along with the vegetation survey. Statistical analysis of soil revealed four classes which correspond with local Wolof denotations and have predominant woody vegetation compositions[16]. These soil classes were extrapolated to the whole study area using Landsat, a Digital Elevation Model (DEM) and a Random Forest classifier. Based on this classification and the vegetation surveys, woody vegetation statistics were calculated. Furthermore, climatic vulnerability, environmental changes and resilience of the classified units were discussed using data gathered by interviews and surveys (see chapter 7).

OBJECT-BASED MAPPING An approach based on results of object-based mapping using high-resolution images provide details at tree level for the Malian study area. Chapter 6 discusses the results and observed patterns of change in combination with qualitative data gathered by the field trips.

INTER-COMPARISONS All data products were matched in temporal and spatial resolution and compared against each other. This includes continuous vegetation data (LTDR, SPOT-VGT, GIMMS, GIMMS-3g FAPAR, GEOV1 FAPAR, MODIS), rainfall data (GPCC, TRMM, station data) as well as static imagery (Landsat, RapidEye). Moreover, degradation assessments and land cover classifications gave information on the plausibility of spatial discrepancies in coarse scaled maps.

The flowcharts of Figure 9 and Figure 10 briefly summarize the applied methods which represent the backbone of the study to assess local phenomena of environmental change.

2.4 SOFTWARE

Apart from the object-based analysis which was done with *ERDAS* by Raphael Spiekermann, this dissertation was conducted with free and open software. Geo-spatial data management and analysis, raster processing, (geo-)statistics, modeling, visualization and mapping were conducted with *GDAL*, *QGIS*, *GRASS GIS*, *R* and *GMT*,

16. Soil sampling, laboratory and statistical analysis were conducted by Tobias Grau within his master thesis (Grau, 2013)

which proved to be more useful than merely an alternative to commercial products.

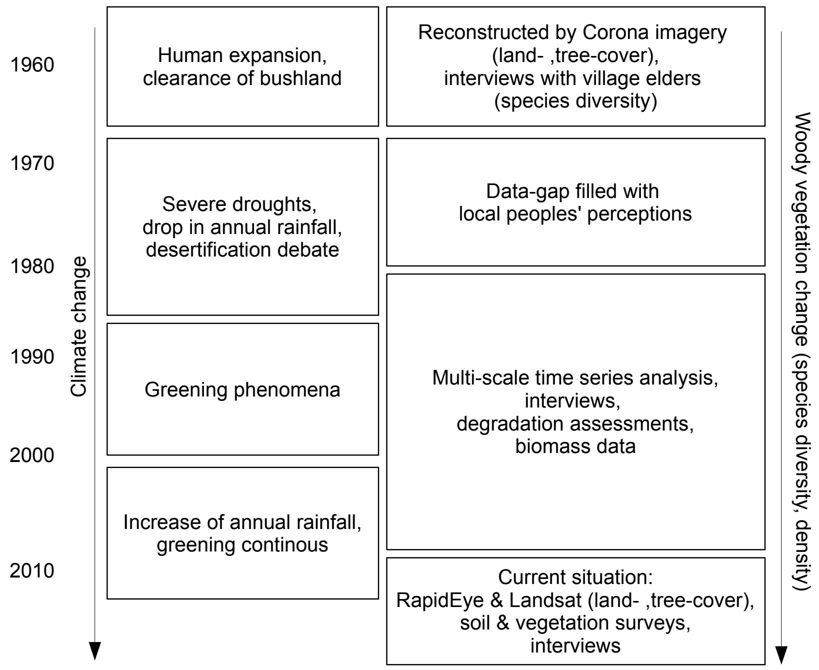

Figure 9: This chart shows the chronological order of events in the West African Sahel and the corresponding assessment methods applied in this study.

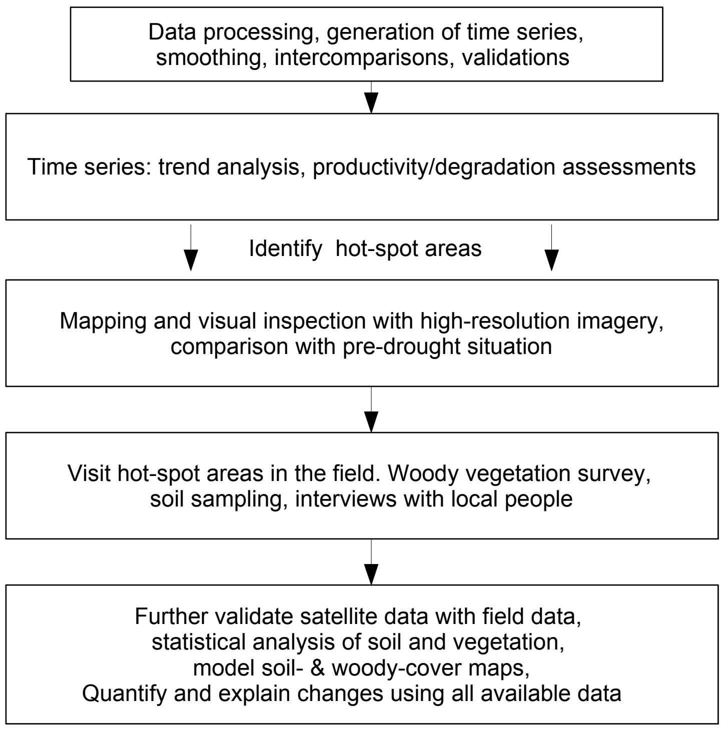

Figure 10: This chart gives a brief overview of the applied core methods in chronological order.

2.5 LIST OF MANUSCRIPTS

The approach taken to test the presented hypotheses rests upon five peer-reviewed manuscripts:

Manuscript 1 *Chapter:* 3
Authors: Brandt, M. (major); Paeth, H. (major); Samimi, C. (major)
Title: Vegetationsveränderungen in Westafrika – Spiegel von Klimawandel und Landnutzung
Journal: **Geopgrafische Rundschau** 9 2013, Pages 36–42.
Own contribution: equal: data acquisition and analysis, figures, concept, writing and discussion (33 %)

Manuscript 2 *Chapter:* 4
Authors: Brandt, M. (major); Romankiewcz, C. (minor); Spiekermann, R. (minor); Samimi, C. (minor)
Title: Environmnetal change in time series - An interdisciplinary study in the Sahel of Mali and Senegal
Journal: **Journal of Arid Environments**, 105 (6), 2014, Pages 52–63.
Own contribution: corresponding author, predominant: data acquisition and analysis (80 %), figures (100%), writing (80%), concept and discussion (80 %)

Manuscript 3 *Chapter:* 5
Authors: Brandt, M. (major); Verger, A. (major); Diouf, A.A. (minor); Baret, F. (minor); Samimi, C. (minor)
Title: Local Vegetation Trends in the Sahel of Mali and Senegal using Long Time Series FAPAR Satellite Products and Field Measurement (1982–2010)
Journal: **Remote Sensing**, 6(3), 2014, Pages 2408–2434.
Own contribution: corresponding author, predominant: data acquisition and analysis (80 %), figures (90%), writing (70%), concept and discussion (50 %)

Manuscript 4 *Chapter:* 6
Authors: Spiekermann, R. (major); Brandt, M. (major); Samimi, C. (minor)
Title: **50 years of woody vegetation and land cover changes in the Sahel of Mali**
Journal: **International Journal of Applied Earth Observation and Geoinformation**, under review
Own contribution: corresponding author, equal: data acquisition and analysis (40 %), figures (50%), writing (50%), concept and discussion (50 %)

Manuscript 5 *Chapter:* 7
Authors: Brandt, M (major); Grau, T. (major); Mbow, C. (minor); Samimi, C. (minor)
Title: **Modeling soil and woody vegetation in the Senegalese Sahel in the context of environmental change**
Journal: **Land**, under review
Own contribution: corresponding author, equal: data acquisition and analysis (50 %), figures (70%), writing (70%), concept and discussion (60 %)

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Part II

PUBLICATIONS

3

VEGETATION CHANGE IN WEST AFRICA IN THE CONTEXT OF CLIMATE CHANGE AND LAND USE

Vegetationsveränderungen in Westafrika – Spiegel von Klimawandel und Landnutzung

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Hypotheses 1 and 2 are dealt with in this chapter, providing an overview of extent and causation of environmental change in West Africa and the role of humans.

This chapter briefly describes the West African vegetation and climate. Furthermore, regional trends of climate and vegetation change are discussed and an outlook in future climate scenarios is given. Local case studies provide further details of vegetation changes and highlight the role of human impact on greening and degradation trends. It is exemplified how land use leads to diverse vegetation developments.

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Vegetationsveränderungen in Westafrika – Spiegel von Klimawandel und Landnutzung

Der Sahel Westafrikas, aber auch die südlich bis zur Atlantikküste anschließenden Gebiete zählen zu den *Hotspot*-Regionen des Umwelt- und Klimawandels (vgl. z. B. WBGU 2008). Ausgelöst wurde diese Debatte durch die großen Dürrekatastrophen der 1970er und 80er Jahre und einen generellen Rückgang des Niederschlags seit dieser Zeit. Eng damit verbunden ist das Paradigma der Desertifikation (vgl. *Hammer* 2005).

Obwohl sich die Niederschlagssituation inzwischen etwas entspannt hat, stehen auch aktuell immer wieder klimatische Extremereignisse im Zentrum der wissenschaftlichen und öffentlichen Diskussion, in den Medien oft übertrieben dargestellt (vgl. *Samimi* et al. 2012). Neben dem Diskurs über Klimaveränderungen stehen Fragen der Landnutzungsänderungen, die enge Kopplungen mit dem Klimasystem aufweisen im Fokus, da als mögliche Konsequenzen des Umweltwandels sogenannte Umweltflüchtlingen konstatiert werden. Leider erfolgt auch diese Debatte oft undifferenziert und positive Prozesse der Umweltveränderung, die auch entkoppelt von der Klimavariabilität ablaufen, finden wenig Beachtung.

Klima und Vegetation Westafrikas

Das Klima Westafrikas ist ein monsunales Klima, das von hohem Luftdruck des St. Helena-Hochs über dem Atlantik und relativ dazu tiefem Luftdruck über Westafrika gesteuert wird. Der Trog tiefen Luftdrucks, die sogenannte Innertropische Konvergenzzone (ITCZ), markiert die Nordgrenze der Kongo-Luftmasse. Sie wandert mit dem Sonnenstand im Nordsommer nach Norden bis maximal etwa 20° Nord. In den Wintermonaten liegt die ITCZ entlang der Küste des Golfs von Guinea. Diese saisonale Konfiguration führt dazu, dass die Niederschläge im Bereich der Küste des Golfs von Guinea ganzjährig fallen, ohne ausgeprägte Trockenzeit. Dies liegt daran, dass der Küstenbereich ganzjährig von der Kongoluftmasse umschlossen ist, also feuchte Luftmassen vom Atlantik auf den Kontinent geführt werden. Nach Norden wird die Zeitspanne mit Niederschlägen immer kürzer und die Regenmenge nimmt von maximal etwa 3 000 mm an der Küste von Liberia, Sierra Leone und Guinea und ähnlich hohen Werten in Nigeria auf unter 100 mm im Norden der Sahelzone bzw. beim Übergang in die Sahara ab (vgl. *Abb. 1*).

Insbesondere in Ghana, Togo und Benin erreichen die Niederschläge, bedingt durch lokale Zirkulationsbesonderheiten (vgl. *Lauer* und *Bendix* 2006), auch an

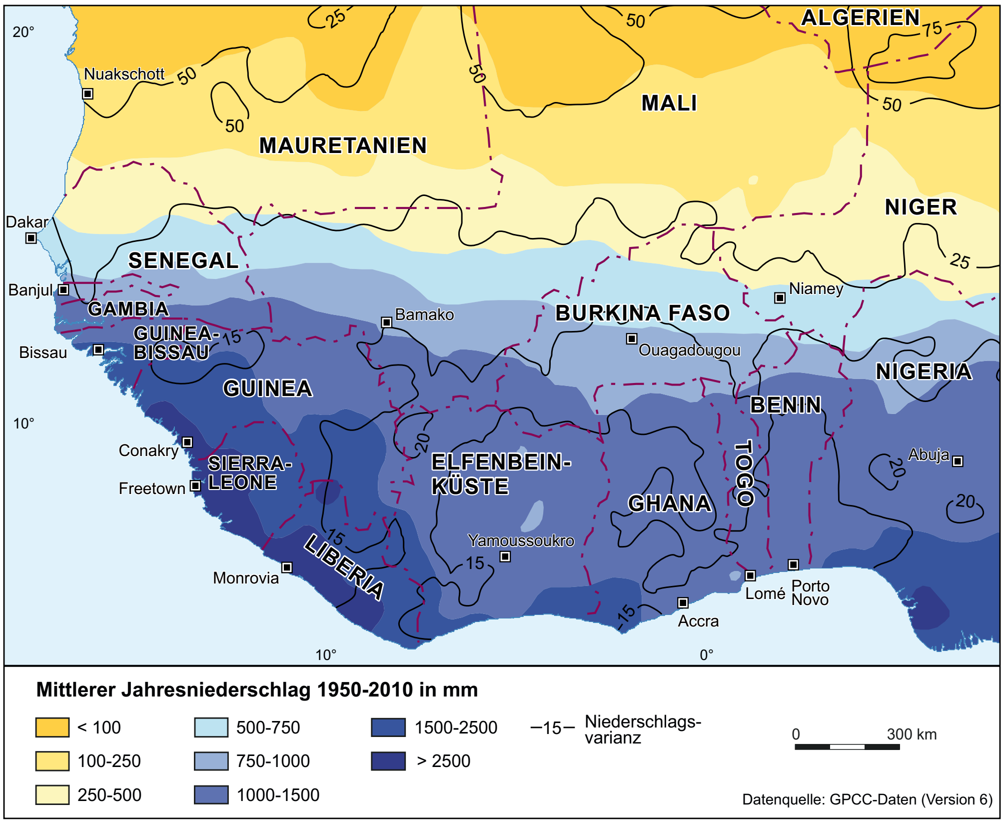

Abb. 1: Jahresniederschlag und Varianz des Jahresniederschlags

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der Küste keine 1 500 mm; man spricht vom Dahomey Gap. Mit abnehmenden Niederschlägen nimmt ihre Variabilität, dargestellt über den Variationskoeffizienten (vgl. *Abb. 1*), im Norden deutlich zu und damit die Planungsunsicherheit für Ackerbau und Viehzucht. In der unten dargestellten Beispielregion Linguère schwankt beispielsweise bei einem Variationskoeffizienten von ca. 30 % der Jahresniederschlag zwischen etwa 200 und 800 mm. Diese große raumzeitliche Variabilität ist insbesondere in den semiariden und ariden Gebieten Westafrikas darauf zurückzuführen, dass Regenfälle vor allem beim Durchzug von Squall Lines entstehen, die zwar frontähnlich sind, aber sehr punktuell zu Instabilitäten in der Atmosphäre mit Starkniederschlägen führen (vgl. *Weischet* und *Endlicher* 2000). Gesteuert wird diese Dynamik, die in die großräumige Monsunzirkulation Westafrikas gebettet ist, durch Konstellationen der Meeresoberflächentemperaturen im Atlantik, Mittelmeer und Indischen Ozean und damit durch globale Telekonnektionen sowie dem Aerosolgehalt in der Region (vgl. z. B. *Nicholson* 2001). Diese raum-zeitliche Heterogenität erfordert eine flexible Reaktion in der Landnutzung, beispielsweise über die mobile Viehhaltung.

Entsprechend der klimatischen Situation, allerdings stark anthropogen überprägt, stellt sich die natürliche Vegetation in der Region dar. Der Tieflandregenwald, von dem es eine feuchte und eine trockene Variante gibt, ist teilweise nur noch in Resten anzutreffen (vgl. *Abb. 2* sowie *White* 1983). Häufig ist er sekundärem Grasland, Plantagen und Ackerflächen gewichen. Noch prekärer ist die Situation der küstenbegleitenden Mangroven und der küstennahen Sumpfwälder. Nach Norden folgt Trockenwald, der ebenfalls stark anthropogen überprägt ist. Ackerbau und Plantagen sind hier weit verbreitet. Die vorkommenden Baumarten haben große ökologische Amplituden, Endemismus ist im Vergleich zu den Trockenwäldern im südlichen Afrika eher selten (vgl. *White* 1983).

Von Nigeria bis Mali ist der Trockenwald unter natürlichen Bedingungen von Bäumen der Gattung *Isoberlina* dominiert. Diese Trockenwälder werden als verarmte Miombo-Varianten angesehen, obwohl typische Baumgattungen des Miombo, insbesondere *Brachystegia* und *Julbernardia* fast vollständig fehlen (vgl. *White* 1983). Bei ca. 200–500 mm Jahresniederschlag folgen nach Norden besonders auf sandigen Böden Akaziensavannen mit lockerem Gehölzbestand, wobei hier vor allem auf sandigen Böden die mobile Weidewirtschaft gegenüber dem Ackerbau an Bedeutung gewinnt. Unter 200 mm schließt lückige Gras- und Strauchvegetation an, die insgesamt schon als Halbwüste eingestuft wird. Akaziensavanne und Halbwüste werden nach *White* (1983) als Sahel-Übergangszone zusammengefasst, die dann in die Sahara überleitet.

Klimavariabilität und Klimawandel

Die Niederschläge im subsaharischen Westafrika unterliegen nicht nur einer großen räumlichen, sondern auch zeitlichen Variabilität. Dadurch ändern sich auch die klimatischen Randbedingungen der Vegetation auf Zeitskalen von Monaten bis Jahrzehnten. In diesem Zusammenhang sind vor allem die mehrjährigen Dürrephasen in der Sahelzone und der südlich angrenzenden Guineaküstenregion zu nennen, die wohl die prominentestete Klimaanomalie im 20. Jh. darstel-

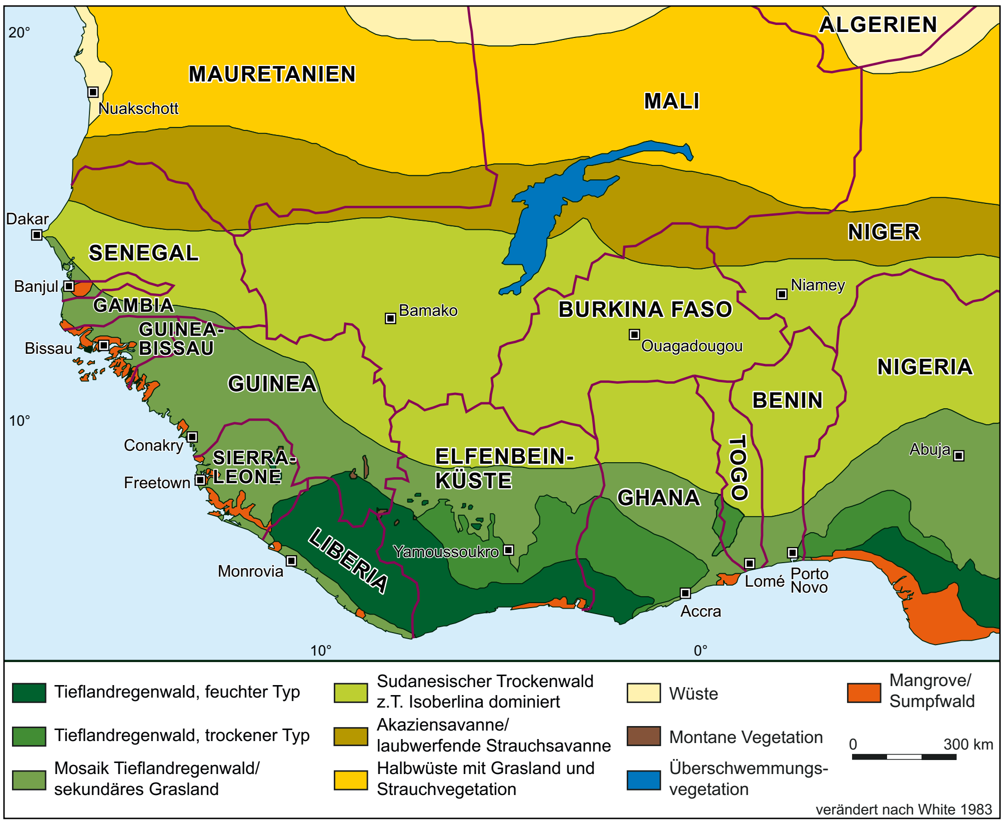

Abb. 2: Vegetation in Westafrika

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len (vgl. *Nicholson* 2001, *Mitchell* und *Jones* 2005). Nach einer relativ feuchten Phase in den 1950er und 1960er Jahren herrschen bis heute überwiegend negative Niederschlagsanomalien vor, obwohl die Niederschläge seit den extremen Dürren Mitte der 1970er und 80er Jahre wieder leicht zunehmen (vgl. *Abb. 3* unten).

Bezüglich der verursachenden Mechanismen besteht wissenschaftlicher Konsens, dass die westafrikanischen Dürren durch Schwankungen der Meeresoberflächentemperaturen ausgelöst und durch Wechselwirkungen mit der Landoberfläche verstärkt wurden (vgl. *Nicholson* 2001, *Paeth* und *Hense* 2004). *Los* et al. (2006) schätzen, dass sich die Niederschlagsvariabilität im subsaharischen Westafrika, insbesondere in der Sahelzone im Übergangbereich zwischen randtropischem, wechselfeuchtem und aridem Klima (vgl. *Abb. 1*), durch Vegetationseffekte um bis zu 30 % erhöht. Insofern bildet die Beziehung zwischen Atmosphäre und Vegetation in Westafrika ein Paradigma für die wechselseitige Beeinflussung im Klimasystem: Klimaschwankungen führen zu Vegetationsänderungen, welche wiederum auf längeren Zeitskalen auf die Atmosphäre rückkoppeln.

Die Frage nach der zukünftigen Vegetationsdynamik in Westafrika schließt somit unmittelbar die Frage nach dem mutmaßlichen anthropogenen Klimawandel ein. Das klassische Konzept der Projektion des zukünftigen Klimas besteht darin, Szenarien für die Emissionen von Treibhausgasen und Aerosolen als Randbedingung in Klimamodellen zu verwenden. Je nach Annahme über die demographische, technologische und sozioökonomische Entwicklung im 21. Jh. resultieren unterschiedliche Entwicklungspfade, die mit einem stärkeren (A1B-Szenario) oder schwächeren (B1-Szenario) Ausstoß von klimarelevanten Substanzen einhergehen und die Amplitude des globalen Klimawandels bestimmen (vgl. IPCC 2007 sowie *Abb. 3*). Vor diesem Hintergrund zeichnet der jüngste IPCC-Bericht ein diversifiziertes Bild der zukünftigen Niederschlagsänderungen in Westafrika mit mehr Niederschlag im Bereich der Tropen und Randtropen und trockeneren Bedingungen in semiariden und ariden Regionen (vgl. IPCC 2007). Somit verstärkt der Ausstoß von Treibhausgasen die natürlichen Gradienten der räumlichen Niederschlagsvariabilität, was zu einer noch stärkeren Ungleichverteilung von Wasserressourcen, zu Beeinflussung von Migrationsbewegungen und zu politischen Implikationen führen könnte.

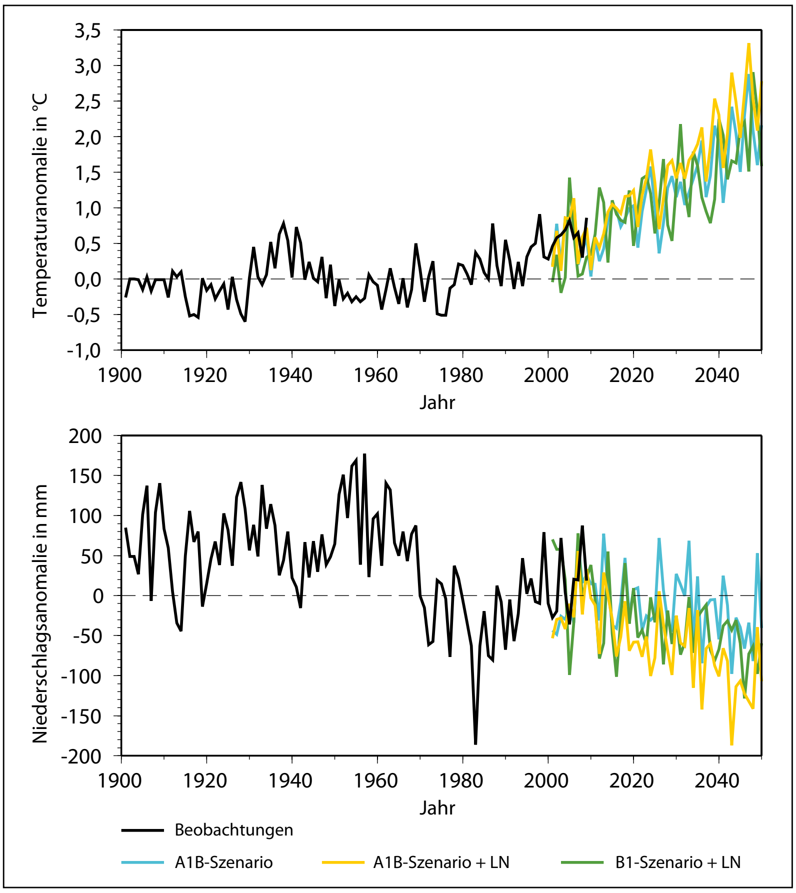

Abb. 3: Trends der Temperatur (oben) und des Niederschlags (unten) in Westafrika

Quelle: *Paeth* et al. 2009

Nun beschränken sich die klimarelevanten Aktivitäten des Menschen nicht auf die Emission von Treibhausgasen und Aerosolen. Durch die seit Jahrtausenden stattfindende und in den letzten Jahrzehnten in Afrika beschleunigt ablaufende, oben schon angesprochene Transformation von natürlicher Landbedeckung hin zu agrarischen und pastoralen Nutzungssystemen verändert der Mensch die physikalischen Eigenschaften der Landoberfläche, was sich auf den Strahlungs- und Energiehaushalt, den Wasserkreislauf, die Turbulenz und schließlich die Bodenfeuchte und den Abfluss auswirkt (vgl. *Feddema* et al. 2005). Um diesen Prozessen gerecht zu werden, wurden mit dem regionalen Klimamodell REMO Zukunftsprojektionen des westafrikanischen Klimas erstellt, die sowohl eine Erhöhung der atmosphärischen Treibhausgaskonzentrationen nach den oben genannten Szenarien als auch zukünftige Landnutzungsänderungen berücksichtigen (vgl. *Paeth* et al. 2009).

Die Modelle kommen zu eindeutigen Ergebnissen: Unter den Vorgaben fortführender menschlicher Aktivität wird das Klima im subsaharischen Westafrika deutlich wärmer und vor allem trockener werden, ein Trend, der sich für die Temperaturen schon heute zeigt (vgl. *Abb. 3*). Dabei hat die Landnutzungsänderung sowohl bei der Erwärmungsrate als auch beim Niederschlagsrückgang einen verstärkenden Effekt. In der Konsequenz würden sich Dürreereignisse wie in den 1970er und 80er Jahren in Zukunft häufen und in ihrem Ausmaß sogar noch verstärken. *Paeth* et al. (2009) haben ferner gezeigt, dass nicht nur die Gesamtsumme der Niederschläge rückläufig ist, sondern auch die Trockenphasen innerhalb der Sommermonsunperiode länger werden. Beides hätte direkte Auswirkungen auf die natürliche Vegetation und die land- und viehwirtschaftliche Inwertsetzung im subsaharischen Westafrika.

Großräumige Vegetationsveränderungen

Die Zusammenhänge zwischen Klimaschwankungen und Vegetation lassen sich im Detail nicht einfach quantifizieren. So genannte Erdsystemmodelle kön-

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nen zwar vielen Prozessen im gekoppelten System Atmosphäre-Landoberfläche Rechnung tragen, besitzen aber meist eine geringe räumliche Auflösung und decken nur kurze Modellzeiträume ab (vgl. IPCC 2007). Eine Alternative bieten statistische Modelle, bei denen die Vegetationsdynamik in Bezug zu einer Reihe von Klimavariablen gesetzt wird. Die Studie von Schmidt et al. (2013) basiert auf Klimavariablen des regionalen Klimamodells REMO und einem satellitenbasierten Vegetationsindex, die in einem multiplen Regressionsmodell gegenübergestellt werden. Es zeigt sich, dass das Klima zwar fast überall im subsaharischen Afrika einen signifikanten Einfluss auf die Vegetationsdynamik ausübt. Dieser Einfluss ist aber nur im Sahel, also im Übergangsbereich zwischen Randtropen und Sahara, zwingend. In den äquatornahen Regionen sind die klimatischen Randbedingungen fast immer vegetationsbegünstigend, in der Wüste existiert hingegen keine Vegetationsdynamik. In der Regel korrelieren die verschiedenen Vegetationstypen positiv mit dem Niederschlag und der relativen Luftfeuchte, wohingegen sich hohe Tagesmaxima der Temperatur und zunehmende Globalstrahlung eher negativ auswirken. Diese Wirkungszusammenhänge sind durchaus plausibel. Dennoch bleibt die Frage, wodurch sich die Vegetationsentwicklung im subsaharischen Afrika auszeichnet, wenn nicht vorwiegend durch die Veränderung der klimatischen Randbedingungen; wenngleich sich der leichte Anstieg der Niederschläge seit Mitte der 1980er Jahre auch in der Vegetationsdynamik niederzuschlagen scheint (vgl. *Los* et al. 2006).

Um den Anteil des Niederschlags aus dem Trend der Vegetationsveränderung heraus zu rechnen und so den Einfluss der Landnutzung sichtbar zu machen, wurden fAPAR-Daten, die ein Proxy für die Vegetationsdichte sind, mit Regendaten statistisch in Beziehung gesetzt. Die fAPAR-Daten sind im Projekt Geoland2 homogenisiert und stammen von 1981–2000 vom System NOAA-AVHRR, von 1999 bis heute von SPOT-VGT (GEOLAND2). Die VGT-Daten werden auf die 5x5 km umgerechnet und dann statistisch mit den AVHRR-Daten in Beziehung gesetzt, um so eine Datenreihe von 1982 bis heute zu generieren. Für die Verrechnung der fAPAR- mit den Niederschlagsdaten kam das Verfahren RESTREND zum Einsatz (vgl. *Wessels* et al. 2007). Man geht nach der Datenveränderung davon aus, dass der Einfluss des Niederschlags auf die Vegetationsentwicklung zumindest minimiert ist und sich so Landnutzungsänderungen besser erkennen lassen. Als Niederschlagsdaten standen GPCC-Daten (Version 6) zur Verfügung (vgl. *Rudolf* et al. 1991).

Die aus dem Verfahren resultierende Karte der Veränderung der Vegetationsdichte im Zeitraum 1982–2010 bestätigt die in der Literatur diskutierte Greening-Tendenz in Westafrika, wobei regionale Unterschiede deutlich werden (vgl. *Abb. 4*). Die Dichtezunahme sagt zudem nichts über den Vegetationstyp aus. Es müssen also beispielsweise nicht Gehölzpflanzen dominanter werden, sondern es können sich auch die Wuchsbedingungen für Gräser oder Kulturpflanzen verbessern. Die schwache Zunahme im Norden des Gebietsausschnitts (21,9 % der Gebietsfläche) ist statistisch zwar signifikant, bedeutet aber in diesem ariden Raum nur eine sehr leichte Zunahme der Vegetation. Südlich anschließend im Sahel und dann noch weiter nach Süden nahm die Vegetation auf über 75 % des gesamten Ausschnitts zu, wobei etwa 52 % sich eher schwach positiv und 23 % positiv entwickelten.

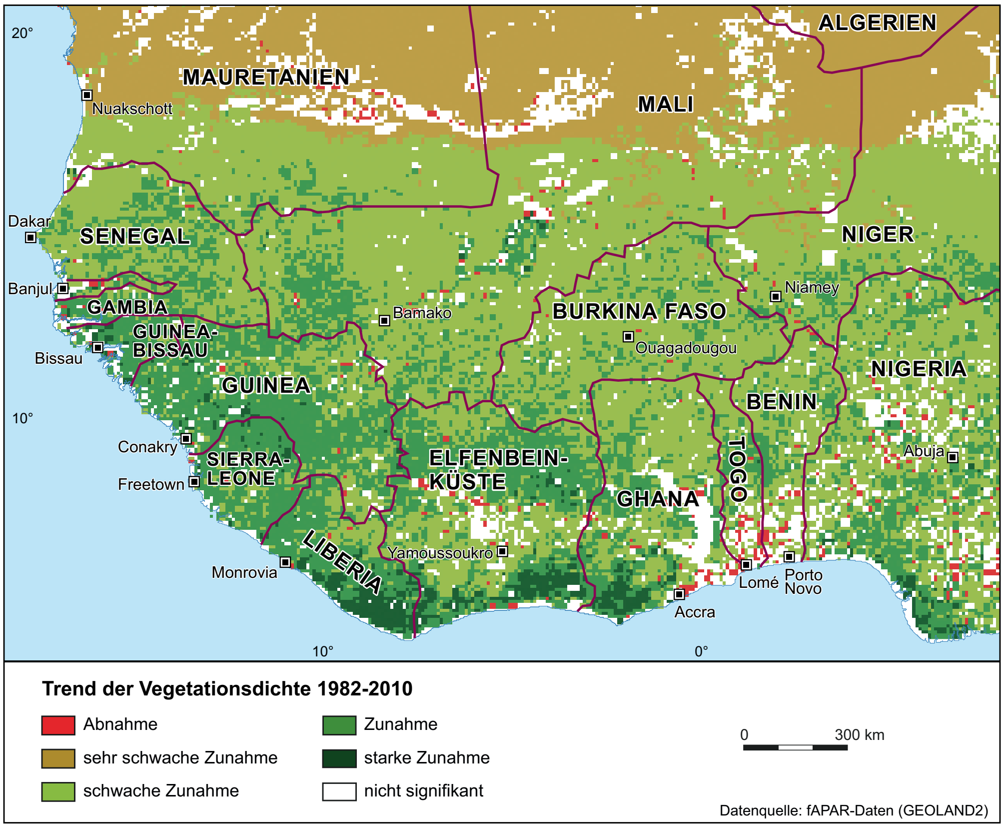

Abb. 4: Veränderung der Vegetationsdichte

Die positive Tendenz der Vegetationsdichte ist in allen Sahelländern gleichermaßen zu beobachten, wobei sie besonders im Senegal und im Westen Malis stärker ist als in den östlichen Sahelländern. Verlässt man den Sahel Richtung Südwesten, dominiert die Klasse „Zunahme" in den Ländern Guinea-Bissau, Guinea, Sierra Leone und Liberia. In Liberia kommt es in weiten Teilen des Landes sogar zu einer starken Erhöhung der Vegetationsdichte. In der Elfenbeinküste setzt sich küstennah die sehr starke Zunahme fort, im Zentrum des Landes verringert sich die Dichte dafür teilweise bzw. stagniert ohne signifikante Änderung. In Benin, Togo und einigen Regionen Ghanas, aber auch in Nigeria nimmt hingegen die Vegetationsdichte signifikant ab bzw. ändert sich nicht.

Betrachtet man aber die Statistiken der Waldentwicklung in den Ländern Westafrikas, fällt auf, dass außer in der Elfenbeinküste und in Gambia in allen anderen Ländern die Waldbedeckung stark zurückgeht (vgl. *Abb. 5*), also ein Zunahme der Vegetationsdichte durchaus trotzdem einen Waldverlust bedeuten kann. Besonders dramatisch ist der Waldverlust in Togo und Nigeria. Hingegen zeichnet sich im Niger eine eindrucksvolle Verlangsamung des Waldschwundes ab. Betrug die jährliche Entwaldungsrate von 1990 bis 2000 noch über 3,5 %, liegt sie für die Zeitspanne 2005 bis 2010 nur noch bei 1 %.

Fallbeispiele aus Mali und dem Senegal

Um die großräumigen Trends der Vegetationsentwicklung auf die lokale Maßstabsebene herunterzubrechen und die Frage des Einflusses der Niederschlagsvariabilität und der Landnutzung näher zu betrachten, werden zwei Fallstudien in der Sahelzone vorgestellt. Dabei stehen zwei Fragen im Mittelpunkt:

- Wie stellen sich die großräumigen teils stark positiven Vegetationstrends auf lokaler Ebene dar?
- Erfolgt tatsächlich eine Rückkehr zu einer Vegetationsstruktur, wie sie vor den großen Sahel-Dürren anzutreffen war?

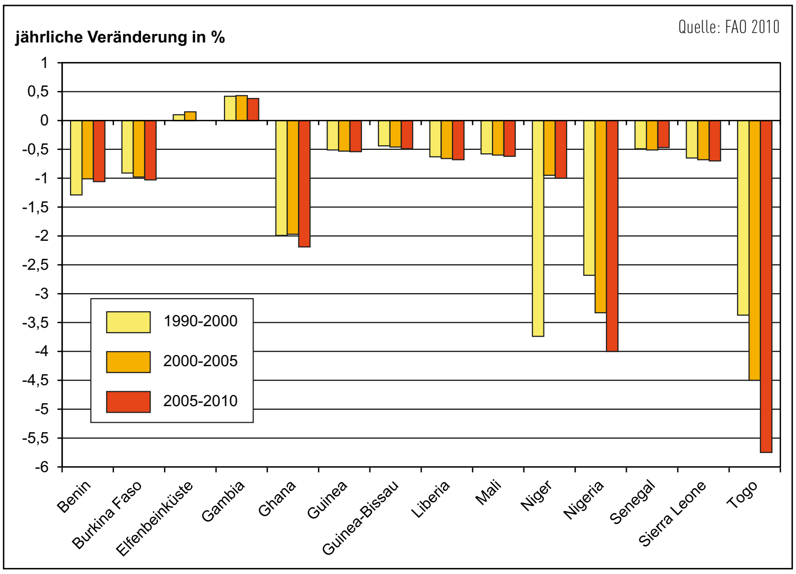

Abb. 5: Jährliche Waldveränderung in Westafrika 1990–2010

Das erste Gebiet liegt in Mali etwa 50 km südöstlich von Mopti und ist mit Jahresniederschlägen von etwa 550 mm im südlichen Sahel gelegen. Das Dogon Plateau um Bandiagara in Mali ist durch eine felsige Landschaft geprägt, wovon etwa 10 % nicht für Ackerbau nutzbar sind. Der Rest wird überwiegend von Dogon ackerbaulich bewirtschaftet. Direkt an das Plateau schließen die Seno Plains an. Waren in den 1960er Jahren noch 40 % der Seno Plains mit dichter Buschlandschaft bedeckt, sind es heute lediglich 25 % (vgl. *Spiekermann* 2013). Dieser Rückgang bedeutet nicht nur einen Verlust an Vegetationsdichte, sondern auch das Aussterben zahlreicher Baum- und Buscharten, welche lange Zeit fester Bestandteil des täglichen Lebens der örtlichen Bevölkerung waren (vgl. *Brandt* et al. 2013).

Gründe für diese Transformation sind im Bevölkerungswachstum, dem Mangel an Niederschlag selbst, aber auch in den damit verbundenen Konsequenzen für die Menschen zu suchen. So sorgen Dürreperioden für einen erhöhten Bedarf an Holz, welches zur Kompensation schlechter Ernten auf Märkten verkauft wird. Einst unbegehbare Gebiete sind heute komplett für Ackerbau und Viehzucht zugänglich, Dörfer breiten sich aus und Kulturlandschaften bestimmen das heutige Landschaftsbild. Der hiermit verbundene Verlust an Vegetation kann zu Degradierung führen (knapp 10 % des Plateaus), jedoch zeigen große Teile heute stark positive Vegetationstrends, welche nur zum Teil durch einen Anstieg der Niederschläge und Ausbleiben größerer Dürren zu erklären sind. Vielmehr entsteht ein neues, artenarmes aber durchaus vegetationsreiches Landschaftsbild, geprägt durch robuste Arten, allen voran *Balanites aegyptiaca* und *Combretum glutinosum*. Diese Arten verbreiten sich rasch, widerstehen Weidedruck und niederschlagsarmen Perioden und bilden heute einen Großteil der Baum- und Strauchvegetation, während laut Befragungen 22 Arten lokal ausgestorben oder stark zurückgegangen sind (vgl. *Brandt* et al. 2013).

Doch auch der Mensch zeigt sich direkt für „greening trends" verantwortlich. So ist das Fällen und Beschneiden der meisten Baumarten strikt verboten und zahlreiche Aufforstungsmaßnahmen zeigen Erfolge. Darüber hinaus besitzen einheimische Bauern umfassendes Wissen über die ertragsfördernde und vor Erosion schützende Wirkung gesunder Bäume. Hinzu kommen rituelle und ernährungstechnische Bedeutungen zahlreicher Baum- und Straucharten (vgl. *Bruijn* et al. 2005). All dies führt zum Schutz und somit einer stetigen Zunahme der Baumdichte auf permanent ackerbaulich genutzten Flächen, nicht erst nach den Dürrejahren (vgl. *Abb. 6*). Jedoch beschränkt sich diese Zunahme überwiegend auf Felder in Dorfnähe. Busch-, Brach- und Weideflächen sind hingegen auch heute noch eine Quelle für legalen und illegalen Holzschlag und werden oft nur unzureichend geschützt.

Das zweite Gebiet befindet sich im Senegal nördlich der Stadt Linguère und gehört zu der überwiegend von Fulbegruppen weidewirtschaftlich genutzten Ferlo-Region. Die Jahresniederschläge liegen bei etwa 400 mm. Ähnlich wie in Mali ist auch hier eine fast vollstän-

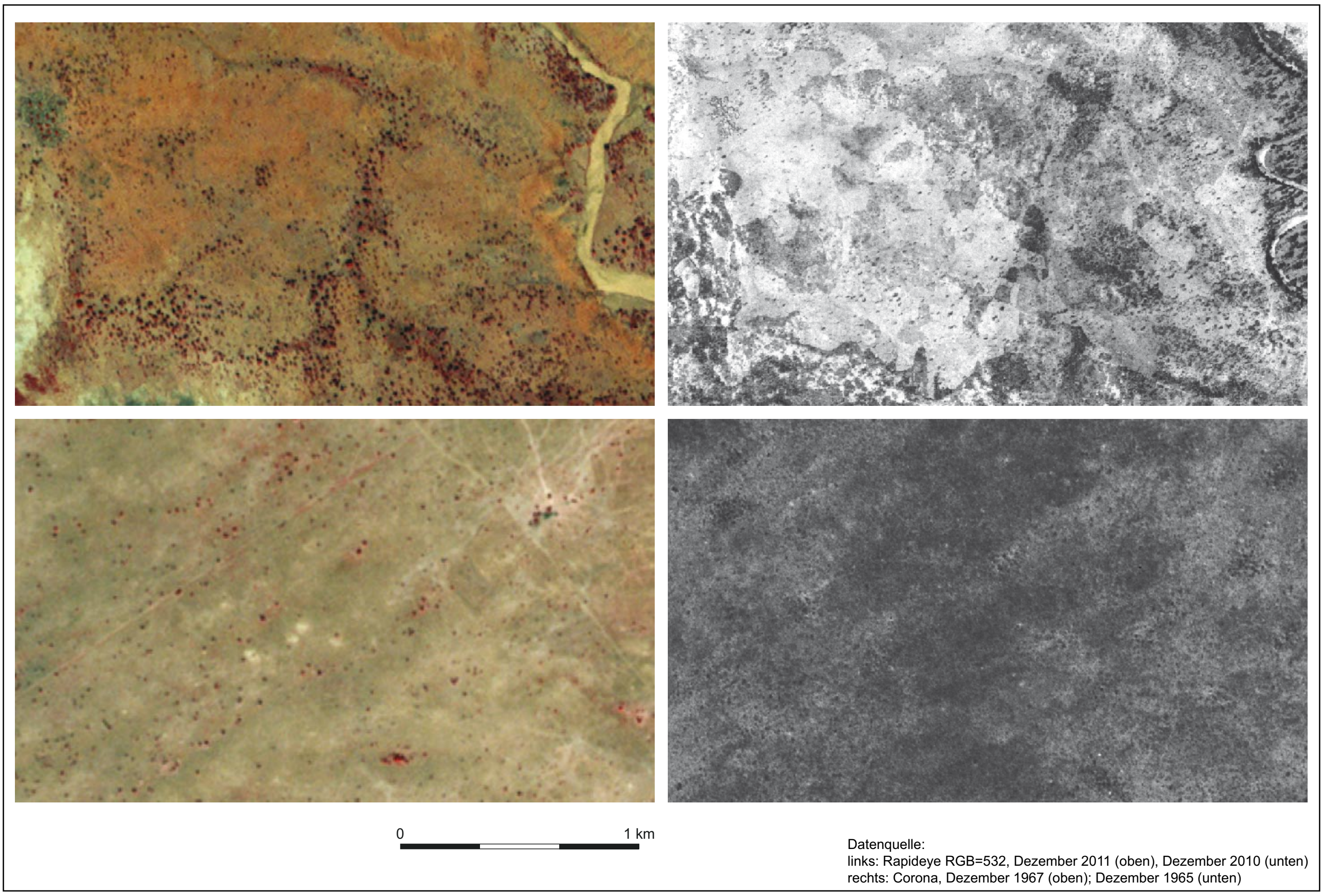

Abb. 6: Baumzuwachs auf den Feldern des Dogon-Dorfes Diamnati von 1967 bis 2011 (oben)
Transformation von dichter Buschlandschaft zu offener Baum und-Strauchsavanne im Ferlo (Senegal), 1965–2010 (unten)

dige Transformation zu einer Kulturlandschaft zu beobachten, mit dem Unterschied, dass heute nur sehr kleine Teile ackerbaulich genutzt werden. Dies liegt zum einen an den geringeren Jahresniederschlägen, vor allem aber an der traditionellen Ausübung des Weidenomadismus der Fulbe. Doch auch diese sylvopastorale Zone ist heute unverkennbar durch Menschen gestaltet und Ursachen für Veränderung ähneln stark dem weit entfernten Dogon Plateau. Schon vor den großen Sahel-Dürren kam es zur großräumigen Rodung natürlicher Vegetation (vgl. *Abb. 6*). Ab 1973 sorgten Dürreereignisse gefolgt von niederschlagsarmen Jahren für eine weitere Reduktion der Baumdichte, sowie dem Rückgang zahlreicher Arten. Und auch hier ist nicht nur der geringe Jahresniederschlag, sondern auch der Eingriff des Menschen entscheidend: zwar besitzen Bäume traditionell einen sehr hohen Stellenwert, noch wichtiger sind den Fulbe jedoch ihre Tiere. So werden in trockenen Jahren durch den Mangel an Gras zahlreiche Äste und ganze Bäume geschnitten, um die Tiere mit Blättern zu versorgen.

Zwar ist mittlerweile ein Anstieg des Niederschlags zu beobachten, viele Baumarten sind jedoch nicht in der Lage, sich von diesen Eingriffen zu erholen, da Sprösslinge ohne Schutzmaßnahmen dem Weidedruck nicht standhalten können. Befragungen ergaben für die vergangenen 30 Jahre einen starken Rückgang von 23 Arten, während lediglich vier Arten eine Zunahme aufweisen (vgl. *Brandt* et al. 2013). Diese ist jedoch beachtlich, und so machen heute *Balanites aegyptiaca*, *Acacia tortilis* und *Combretum glutinosum* 73 % der gesamten Baumvegetation aus. Diese Arten sind robust gegenüber intensiver Beweidung, verbreiten sich schnell und verursachen somit einen *„greening trend"*, welcher das Aussterben zahlreicher Arten verschleiert. Unterstützt wird diese natürliche Verbreitung durch staatlichen Schutz, drastische Strafen, sowie Aufforstungsmaßnahmen. So finden sich alleine im nahen Umkreis von Linguère mehr als 5 000 ha teils eingezäunte Flächen mit gepflanzten *Acacia senegal*. Ausgewiesene Feuerholzgebiete beschränken den legalen Einschlag auf kleine Zonen und fördern so die Regeneration von Gehölzpflanzen.

Allerdings sind im Raum Linguère auch heute nicht nur positive Entwicklungen zu beobachten. Morphopedologisch benachteiligte und stark übernutzte Gebiete zeigen komplett entwaldete und degradierte Böden, welche nur sehr schwer wieder regenerierbar sind. Diese Flächen machen 3 % um Linguère aus und haben sich in den vergangenen 50 Jahren stark ausgebreitet (vgl. *Tappan* et al. 2004).

Fazit

Insbesondere die semi-ariden und ariden Gebiete Westafrikas, aber auch die feuchteren Regionen waren

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schon immer durch Klimavariabilität geprägt, die seit den Dürren der 1970er und 80er Jahre möglicherweise zunimmt (vgl. IPCC 2007). Auch die Szenarien des Klimawandels verheißen Änderungen, die für die Landnutzungen noch problematischer werden könnten. Die Entwicklung der Vegetation der letzten Jahrzehnte zeigt wiederum, dass durchaus positive Trends möglich sind, die unabhängig von der Klimaentwicklung stattfinden. Die häufig undifferenzierte und einseitige Diskussion der Desertifikation, die im Zuge der Dürresituation und Trockenperiode stattfand, wird heute vom Paradigma des *„Greening Sahel"* abgelöst. Auch diese Debatte verallgemeinert oft zu stark und nivelliert regionale und lokale Differenzen des Umweltwandels. Problematisch könnte im Kontext des Umweltwandels vor allem eines sich möglicherweise verschärfenden Klimawandels die anhaltend hohe und weiter steigende Bevölkerungszahl sein, die Handlungsoptionen der lokalen Bevölkerung einschränken könnte. Die Anpassungsfähigkeit der Bevölkerung, die sich in den letzten Dekaden gezeigt hat und die die positiven Entwicklungstendenzen eingeleitet hat, sollte Anlass zur Hoffnung geben, dass auch eine Adaption an zu erwartende Umweltveränderungen möglich sein könnte. III

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SUMMARY

Vegetation change in West Africa in the context of Climate Change and Land Use

by Martin Brandt, Heiko Paeth, Cyrus Samimi

Western Africa has been discussed as a hot spot of environmental change. In the 1970ies and 80ies a drastic decrease in precipitation and severe droughts occurred in the Sahel. The degradation of the vegetation led to the desertification paradigm. But also in wetter regions south of the Sahel vegetation changes, mainly forest losses have happened. Since the 90ies the precipitation stabilized somewhat and a greening trend can be observed. Both paradigms, desertification and greening, tend to neglect regional and local differences. These differences are often decoupled from rainfall and are linked to land use practices. The article gives an overview about regional trends of vegetation and climate change and emphasize on decoupling precipitation and vegetation. Local examples show how land use leads to diverse vegetation developments.

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4

ENVIRONMENTAL CHANGE IN TIME SERIES – AN INTERDISCIPLINARY STUDY IN THE SAHEL OF MALI AND SENEGAL

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Cyrus Samimi[1]

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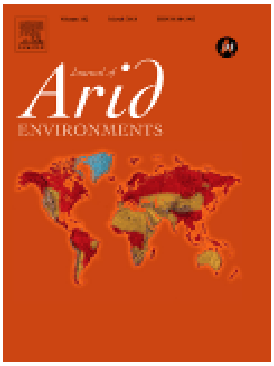

This publication represents the core of the present dissertation, addressing hypotheses 1, 2 and 3: A multi-level, multi-site, multi-method and interdisciplinary research design is applied to analyze extent and causation of greening and degradation (i.e. environmental change) in both study areas. The approach is based on qualitative rather than quantitative assessments.

The chapter deals with detecting and explaining vegetation trends in the Sahel of Mali and Senegal. The manuscript outlines the use of both coarse and fine-scaled satellite data, including both long-term comparisons via high-resolution imagery and more recent time series. These are combined with field data and household surveys to assess vegetation dynamics over the past 50 years. The research concludes that greening trends and degradation in the Sahel are due to a combination of both climatic and anthropogenic factors. These are heterogeneous and explained by means of several case study sites in both study areas.

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Environmental change in time series – An interdisciplinary study in the Sahel of Mali and Senegal

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A B S T R A C T

Climatic changes and human activities have caused major environmental change in the Sahel. Remote sensing studies detect various vegetation trends; however, explanations are rarely studied in detail. We present a methodology using time series, high-resolution imagery and fieldwork to validate trend analyses for two regions in the Sahel of Mali and Senegal. Both study areas show significant greening trends from 1982 to 2010. Reasons can be very site-specific, but several factors are valid for both research areas: (1) farmer-managed agro-forestry, (2) planting programs and protection laws, (3) widespread dispersion of robust species, which replace the former diverse woody vegetation and simulate a greening which conceals a shift in biodiversity and (4) an increase of annual rainfall. However, the situation is still far from the pre-drought conditions, which are reconstructed by Corona imagery (1965) and interviews with the local population. Rather a transformation is observed: a decrease in natural vegetation, tree density and diversity. Reasons are climatic and anthropogenic: (1) drought events, less rain and higher temperatures, (2) increased demand for cropping areas and wood, especially in times of droughts. Our example validates that climatic factors are important drivers of change, but much of today's environment and vegetation composition is controlled by humans.

1. Introduction

During the 1970s and 1980s severe droughts occurred in the West African Sahel followed by a considerable decrease of mean rainfall (e.g. Zeng, 2003). Together with financial and political instability and regional conflicts, the droughts contributed to famines and sparked not only concern at global scale by politicians and development organizations, but also an increasing scientific interest in the causation and extent of the observed environmental change in the Sahel (Hutchinson, 1996).

Initial assertions acclaimed widespread irreversible desertification (Lamprey, 1988) caused by deforestation and atmospheric reactions which led to the droughts and decline in rainfall (Charney et al., 1975). Combined with a southward encroachment of the Sahara desert much of the Sahel was expected to become degraded, unusable land (e.g. Kandji et al., 2006; Oldeman et al., 1990). The Sahel region has thus been branded as one of the "hot spots" of global environmental change (e.g. Kandji et al., 2006). Several studies have shown that primarily oceanic surface temperature controls Sahelian rainfall (e.g. Giannini et al., 2008). Land cover changes merely play a secondary role when explaining changes in rainfall patterns (Paeth et al., 2011). Moreover, further assessments did not find evidence of widespread degradation, which has led to a discussion of the term "degradation" itself and also to a questioning of the causes and existence of irreversible land degradation (e.g. Hutchinson, 1996; Tiffen and Mortimore, 2002).

Remote sensing has always been a valuable tool to assess environmental changes in the Sahel. The Global Inventory Modeling and Mapping Studies (GIMMS) dataset (Tucker et al., 2005) has been used to monitor Normalized Difference Vegetation Index (NDVI) time series since 1981. Various studies did not find evidence of widespread degradation but rather a considerable greening trend in most parts of the Sahel (e.g. Anyamba and Tucker, 2005; Olsson et al., 2005). Even if the correlation of vegetation and rainfall is high, a study by Herrmann et al. (2005) demonstrated that much of the observed greening is decoupled from rainfall. Attempts to assess land degradation with remote sensing tools are still popular (e.g. Fensholt and Rasmussen, 2011; Martinez et al., 2011), but a changing context in the desertification debate

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highlights the importance of an interdisciplinary approach which includes ecological and social aspects (Herrmann and Hutchinson, 2005; Reynolds et al., 2007).

There is no doubt that the Sahelian environment is changing. Anthropogenic disturbances and varying rainfall have massive effects on flora, fauna and soil. It is not easy to distinguish between human-induced and climate-driven dynamics, between short-term fluctuations and long-term changes (Mbow et al., 2008; Miehe et al., 2010; Wessels et al., 2007). Long-term studies indicate an overall decrease in natural vegetation and an increase in agricultural areas (e.g. Mougin et al., 2009; Tappan et al., 2004). Tree density has decreased but depending on morpho-pedological conditions, there is a moderate recovery since the droughts, which confirms the resilience of Sahelian vegetation (Hiernaux et al., 2009; Tappan et al., 2004). Detailed ground studies (e.g. Reij and Smaling, 2008; Yossi and Diakite, 2008), often supported by remote sensing tools, describe several success stories where farmer managed natural regeneration (FMNR) lead to a massive greening in several Sahelian countries but rather degradation is also detected (Miehe et al., 2010). Several investigators agree that there is a shift and decline of tree species diversity in the West African Sahel that is related to a more arid climate (Gonzalez, 2001; Gonzalez et al., 2012; Herrmann and Tappan, 2013; Hiernaux et al., 2009; Vincke et al., 2010).

Many investigators used coarse-scale time series to detect environmental trends and changes and to show the dynamic nature of the Sahelian ecosystem. However, detailed explanations for these trends remain largely unknown or speculative. Studies at tree/village level remain local and are rarely embedded into global datasets.

Our study in Mali and Senegal aims to find explanations for vegetation trends and therefore contributes to an ongoing greening vs. degradation discussion. Coarse resolution studies on the Sahel are incapable of establishing whether the “greening trend is a return to pre-drought conditions or simply a transition to a new equilibrium state with a different vegetation composition” (Herrmann et al., 2005 p. 402). In accordance with the recommendation of Herrmann et al. (2005), we use detailed fieldwork at a local scale and analyses of finer resolution spatial data. Multiple datasets and methodologies over different periods are used and their application to various spatial and temporal scales is explored. Global remote sensing techniques are broken down to a local scale and combined with high-resolution images to visually identify hot spot areas. Based on the image interpretation, explanations for a sample of both positive and negative hot spots by means of several case studies are discussed. Natural- and social scientific methods are combined to assess the current environmental setting, reconstruct pre-drought conditions and find explanations for trends and changes.

Several studies that overlap our own research areas form the basis of our work. For Senegal, these studies are manifold (CSE, 2008; CSE, 2009; Diouf and Lambin, 2001; Martinez et al., 2011; Mertz et al., 2009; ROSELT, 2005; Stancioff, 1984; Tappan et al., 2004) and contrast to Mali where only few related studies are available (e.g. Bruijn et al., 2005; IPE-Mali, 2009; Yossi and Diakite, 2008). Until now, only the Gourma region to the north of our study area has been the object of detailed environmental research (e.g. Hiernaux et al., 2009; Mougin et al., 2009).

2. Materials and methods

2.1. Study areas

The study areas are located in Senegal around Linguère and in Mali around Bandiagara (see Fig. 1a, b). The research area around Linguère is located in the semi-arid Sahel with mean annual precipitation around 400 mm (1950–2010) which mainly falls between July and September with extreme inter- and intra-annual variations (coefficient of variation is 28 mm for the period 1950–2010). Even though this research area is small (about 50 × 50 km), there is a steep north-south gradient and mean annual rainfall is 60 mm higher in the southern part compared to the northern part. The region is named after the seasonal Ferlo River, a traditionally silvo-pastoral zone, mainly inhabited by semi-nomadic Fulani pastoralists. Around Linguère cropping represents an important occupation by Wolof and also Fulani farmers. The sandy soils are suited for the cultivation of millet and groundnut, followed by fallow periods to preserve soil fertility. The woody vegetation is characterized by an open tree and shrub savanna with low vegetation diversity. Small depressions with clayey and temporarily flooded soils are widespread in this area. Droughts have caused considerable damage to the vegetation, especially in the lateritic eastern part where tree cover has decreased from 10–20% to 5–15% in the past 50 years (Tappan et al., 2004).

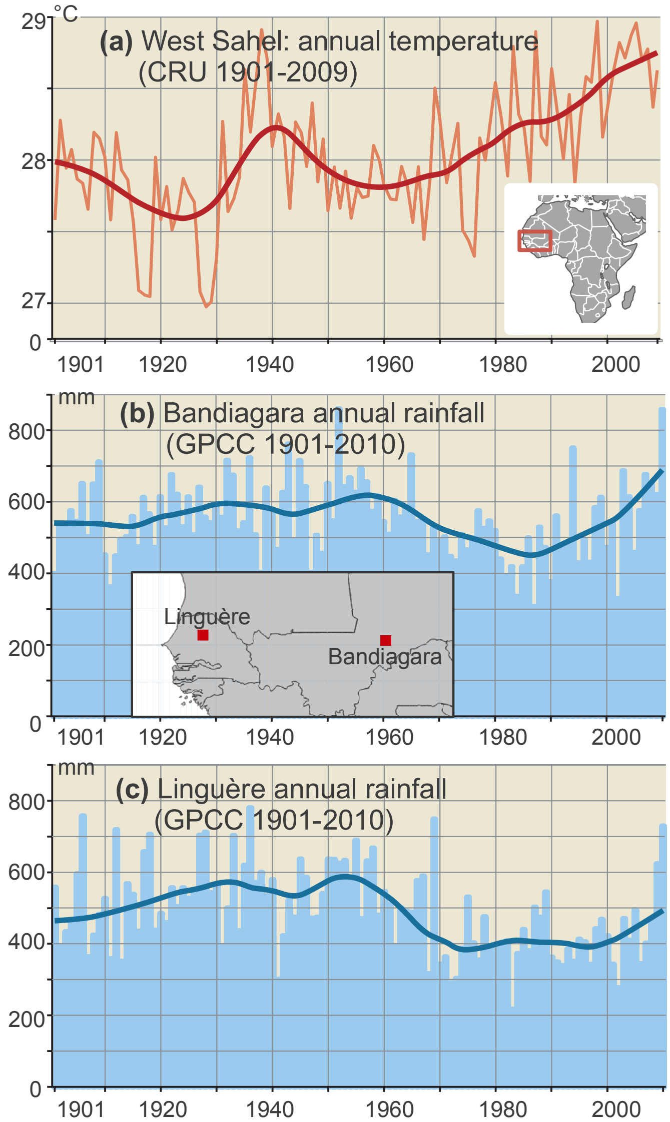

Fig. 1. Mean annual temperature 1901–2009 averaged over West Africa (a) and annual rainfall 1901–2010 averaged over the Bandiagara (b) and Linguère (c) research area. The location of the study areas can be seen in (b).

The Malian research area around the town of Bandiagara is inhabited by Dogon farmers and to a much lesser extent by Fulani pastoralists. Rainfed agriculture (millet, groundnut and sorghum) and vegetable gardening (mainly onions) are the main economic activities. Soils on the plateau between the towns Sevaré and Bandiagara are sandy, lateritic and in places with rocky sandstones, cultivation is challenging. Valleys are mainly used for cropping and onion plantations are found where irrigation is possible. The Séno Plain around Bankass stretches southwards from the Bandiagara escarpment and represents a different morphological zone. Sands are deep and infertile but more than 90% of the whole area is used for rotational cropping. Annual rainfall is around 500 mm (1950–2010), which mainly falls between June and October with a considerable inter- and intra-annual variability (coefficient of variation is 23 mm for the period 1950–2010).

In both study areas, trees and shrubs play a major role in peoples' daily life. Besides being the main source for firewood, they fulfill a variety of traditional functions related to cooking, medicine, religion and for constructions. Leaves and fruits also represent an important source of animal fodder. Selling firewood and charcoal is a common practice and constitutes a considerable income for the local population but requires purchasing an official permission from the Governmental Forest Agency. However, traditional landowner rights and control mechanisms largely determine access and exploitation of woody resources.

2.2. Data

Data of different spatial and temporal scales were used to assess and evaluate changes at different levels (Table 1). Land long Term Data Record (LTDR) and SPOT-Vegetation (VGT) coarse-scale time series provided long-term NDVI trends from 1982 to 2010 and Moderate Resolution Imaging Spectroradiometer (MODIS) moderate resolution time series contribute short-term trends at a much higher spatial resolution with more details for the period 2000–2010. Several hot spot areas were identified in which pre-drought conditions were reconstructed at tree level by high-resolution Corona-imagery (1965–67) and by information from the local population. Recent conditions were monitored at the same level by field surveys and RapidEye imagery. Climate data from different sources gave information about rainfall and temperature trends and changes.

2.2.1. LTDR–SPOT long term time series

SPOT-VGT (S) data were downloaded at a temporal scale of 10 days and a spatial resolution of 1 km. The time-frame is 1998–2010. This product consists of an unfiltered 10 day Maximum Value Composite (MVC) NDVI and a corresponding quality flag, which uses a bit pattern to rate the quality of every pixel in 5 classes. The MVC method selects the highest value within 10 days, thus excluding clouds with low values. After extracting the area of interest, a Savitzky Golay filter was applied to smooth the time series pixel-wise. For more information on the method we refer to Chen et al. (2004). The filter implements a local polynomial regression to filter out bad values mainly caused by clouds and atmospheric disturbances. According to the quality file, every pixel attained a particular weight, which was used to calculate the new time series. This is an extremely important procedure since clouds are a major problem during the rainy season and are often obstructive for more than 10 days.

Table 1
Continuous coarse and moderate resolution data products used in this study.

Product	Spatial resolution	Time-frame	Temporal resolution	Variable
MODIS MOD13Q1 v5	250 m	2000–2010	16 days	NDVI
SPOT VGT-S	1 km	1998–2010	10 days	NDVI
LTDR v3	0.05°	1982–1999	Daily	NDVI
GPCC v6	0.5°	1901–2010	Monthly	Precipitation
CRU v3.1	0.5°	1901–2009	Monthly	Temperature

LTDR is an AVHRR (Advanced Very High Resolution Radiometer) derived product, which uses new methods to obtain a daily high quality NDVI product at a spatial resolution of 0.05° (approximately 5 km). As of yet, the years from 1982 to 1999 are available in Version 3 and are distributed by the Goddard space flight center. Quality flags are processed for every pixel using methods, which are comparable with the MODIS program. After downloading daily images, 10 day MVCs were created which match the SPOT VGT periods. The quality flag points out the day used in the MVC and marks pixels of low quality. In a further step, the NDVI time series was smoothed with a Savitzky Golay filter and weighted with the respective quality flags. Due to bad quality, 1994 was completely masked as not available (NA).

Global LTDR and SPOT-VGT NDVI images were used to create a NDVI time series from 1982 until 2010 at a spatial resolution of 0.05° and a temporal resolution of 10 days. SPOT-VGT was aggregated to the spatial resolution of the LTDR images using a median filter. Then a pixel-wise regression was carried out for the two overlapping years 1998 and 1999 for the two research areas separately. R^2 is 0.94 in the Linguère- and 0.92 in the Bandiagara region. The next step was to model and adjust the LTDR time series to the SPOT-VGT series via the regression coefficients of the two overlapping years. This was necessary due to the different sensor specifications of both products. After combining the two series to the new LTDR–SPOT, comparisons were made with the often-used GIMMS showing a good agreement in our research areas. Due to the improved methods and the better temporal and spatial resolution, the new series proved to be of superior quality to GIMMS showing much more details and a more reliable time-line.

2.2.2. Terra MODIS short term time series

The product used was MOD13Q1 with a temporal resolution of 16 days and a spatial resolution of 250 m, which is available since March 2000. The individual images were delivered with a quality file, rating each pixel between 0 (highest quality) and 15 (not produced). Only pixels with values below 8 (below average) were further processed. The NDVI time series was then smoothed with a Savitzky Golay filter weighted with the corresponding quality files. Pixels were weighted by their quality to produce a smooth line and to eliminate clouds and atmospheric disturbances.

2.2.3. High resolution imagery

Corona satellite images were declassified by the U.S. Geological Survey (USGS) (McDonald, 1995) and in most cases represent the only available source that offers an impression of pre-drought conditions of the research areas in the 1960s. Images are panchromatic with a resolution of about 2 m. Available Corona Images in the Senegal are dated at December 1965 (KH-4A 1028) and in Mali December 1967 (KH-4B 1102). They were manually georeferenced using Google Earth as reference and almost 500 control points for each study area.

Twenty-two RapidEye images from December 2010 (Senegal) and 2011 (Mali) complement the high-resolution Corona images and were acquired for both research areas to monitor change at tree level. RapidEye provides multi-spectral data at spatial resolution of 6.5 m. In this paper we use a RGB composition with the bands 532 (infrared, red, green) to highlight single trees from their surrounding. Vegetation appears red in these images, whereas the panchromatic Corona displays vegetation in dark gray and black colors. In cases where features were not detectable in RapidEye, Google Earth was additionally used for visual analysis. The Google Earth data used in our study area was delivered by DigitalGlobe and consists of Quickbird satellite imagery from the dry seasons of the years 2005–2009. A table of the Corona and RapidEye scenes used in this study is provided in Appendix 1, electronic version only.

2.2.4. Climate data

GPCC (v6) (Global Precipitation Climatology Centre, Rudolf et al., 1991) and CRU (v3.1) data (Climate Research Unit, Mitchell and Jones, 2005) interpolate monthly stationary data at 0.5° resolution and fully depend on reported station data, which can vary extremely from year to year. We compared GPCC with station data, and GPCP (Global Precipitation Climatology Project, Adler et al., 2003) in our study areas and came to the conclusion that GPCC was a good source for annual rainfall as was CRU for mean temperature if used with consideration of the limitations of these datasets. For the period 1933–2010, R^2 between yearly station data and GPCC rainfall is 0.82 over the Linguère weather station.

2.3. Methodology

This study follows a multi-level, multi-site, multi-method and interdisciplinary research design. After vegetation trends were identified by time series, we visually compared high-resolution imagery from 2010/2011 (RapidEye) respectively 2005–2009 (Google Earth) and the past (1967, Corona) in areas of interest. Based on the assessments of this comparison, specific areas were selected and visited in the field. Besides detailed vegetation measurements, interviews were conducted with local people from nearby villages. This study concentrates on the woody vegetation as trees and shrubs are an important factor in steady states of savanna ecosystems and in peoples' daily life (Croll and Parkin, 1992). Additionally trees are long-lived and therefore changes in tree populations are an indicator of long-term changes. Another reason is the fact that most of the trees remain green over the dry period and hence infrared satellite imagery can be used to detect and quantify trees over large areas. NDVI was used as an indicator for green vegetation as it is a robust and comparable index (e.g. Anyamba and Tucker, 2005). It is important to emphasize that an increase in NDVI over large areas does not necessarily mean an increase in tree density, as crown cover varies inter- and intra-annually. Therefore, positive trends are understood to mean an increase in overall biomass. What exactly causes the increase in NDVI needs to be examined.

2.3.1. Time series analysis with coarse and high resolution data

Filtered LTDR–SPOT and MODIS NDVI time series were used to perform trend analysis at different spatial scales. Regression analysis extracted significant ($p < 0.05$) slope values, which were recalculated to NDVI to express the total change over 29 years. To estimate the herbaceous and woody layer separately, a Seasonal Trend decomposition based on Loess (STL) was done (Cleveland et al., 1990). This method uses a local regression to separate the seasonal component from the yearly component in a time series. As most trees remain green during the dry season, the yearly component could be used to estimate the foliage production and therefore trends caused by the tree layer (Roderick et al., 1999). In the following, only the yearly component was used for trend analysis. We eliminated seasonal fluctuations by calculating a mean year using 11 years of MODIS images. The amplitude of the mean year was taken to quantify a pixel's productivity (Appendix 2, electronic version only). NDVI amplitudes smaller than 0.2 were allocated as degraded or unproductive land. The threshold was calibrated by test sites consisting of barren and unvegetated land.

2.3.2. High resolution satellite imagery

Areas identified by time series were compared with pre-drought Corona-imagery using RapidEye and if needed, Google Earth, for visual analyses. This offered a detailed overview of the environmental change at tree level i.e. a scale at which trees are clearly visible. Individual shrubs and small trees could not always be clearly identified on Corona and RapidEye images, however, single tree detection and quantification was not the scope of this study. Rather, tree density and land cover were observed and changes of nearly 50 years compared. After testing automated methods like object-based tree counting and supervised as well as unsupervised classifications, manual approaches i.e. visual inspection were rated more as reliable due to reasons mentioned in Tappan et al. (2004) and due to the fact that only hot spot regions and not the whole study area had to be compared. Areas with changes like loss of trees, transformation of land cover and increased woody vegetation as well as instances of no changes were identified by visual comparison of RapidEye and georeferenced Corona images. These places were then visited and validated in the field.

2.3.3. Fieldwork

Fieldwork was carried out during the dry seasons 2011 and 2012 (February and March) as well as in the rainy season 2012 (September) and provided information on land use systems, vegetation composition and the current environmental conditions. Guided by the data of the previous steps, i.e. conspicuous NDVI trends and changes in land cover and tree density, 145 transects (60 in Mali, 85 in Senegal) of approximately 200 m each were surveyed. Altogether 3301 individuals of trees and shrubs were identified after Maydell (1990) and surveyed along randomly selected line transects (see Herrick et al., 2005). Start and ending points of the transects were marked with a GPS. Further, all surveyed trees and shrubs were rated according their condition and usage (1–5) and classified in large (>4 m) and small (<4 m) to obtain comparable data to other studies (e.g. Tappan et al., 2004). These transects gave information about species distribution, abundance and their use by humans and livestock as well as trees' condition and age pattern. For several tree species, the relation between large and small trees can be taken as an indicator for the vitality of a species. Soil durability, degradation and erosion occurrence and processes were documented after Stocking and Murnaghan (2001). Additionally 5275 GPS-referenced landscape photos were taken in color with a digital camera. They documented visited areas and were the basis for ground validation of satellite imagery.

Most ethnographic fieldwork was conducted along with the ecological fieldwork. In the villages, the initial contact was carried out by a semi-structured interview with the chief or a group of elders and revealed a rough overview of the village's historical development. Apart from a few exceptions, an interpreter supported the communication. Further semi-structured individual and group interviews and key informant interviews were conducted to allow people to identify and assess changes in local climatic and environmental conditions. Questions addressed changes in rainfall, temperature, soil fertility, woody cover, the diversity of tree population, capacities of pasture, and crop yields (e.g. Mertz et al., 2009; Roncoli, 2006). Village elders gave valuable information regarding pre-drought conditions and long-term changes in natural resource and farm-management. Additionally, transect walks and site visits were conducted with villagers in the surroundings of settlements. First, observation results of the ecological fieldwork were considered in interview questions that focused on local people's interpretations and explanations of specific phenomena in

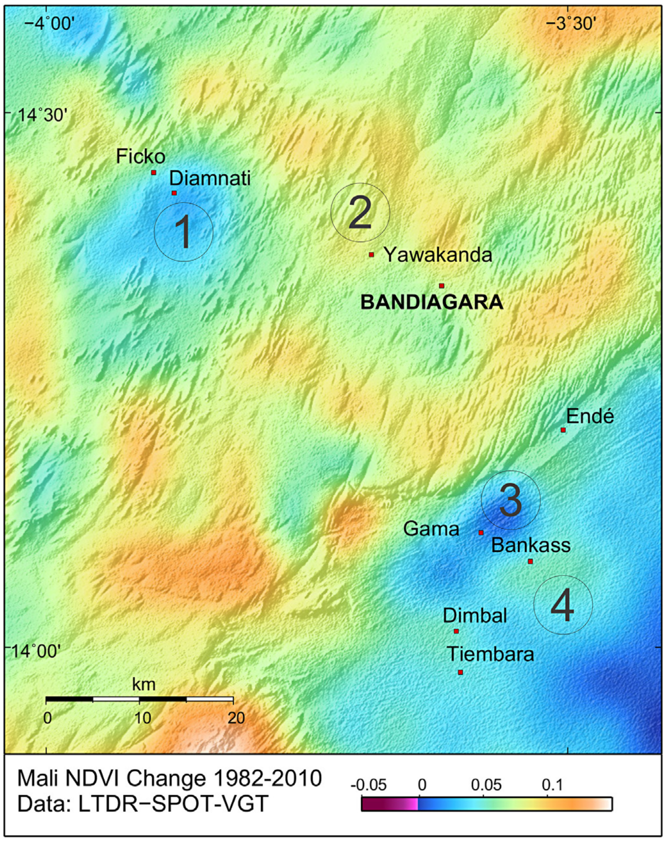

Fig. 2. LTDR–SPOT time series NDVI change from 1982 to 2010 in Mali. The numbers indicate the case study sites which are further explained within Chapter 3.2. Since the time series starts in times of droughts, no negative change can be observed. However, several areas do not follow the overall greening trend. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the proximity of the respective villages. With the help of a village questionnaire, a local tree species inventory was developed and elders were able to identify trends in changing tree species composition of the past 50 years. For methods on local assessment of identified vegetation changes, see for example Gonzalez (2001).

3. Results and discussion

3.1. Rainfall trends

Trends of coarse-scale monthly products (GPCC and CRU) show that during the 70s and 80s of the 20th century the rainfall of our research areas dropped far below average (Fig. 1). Combined with a simultaneous increase in temperature (Fig. 1a), a shift to more arid climatic conditions was observed by Gonzalez et al. (2012) in several Sahelian regions. Annual rainfall in Linguère during 1970–2010 (390 mm) was only 75% of the 1930–1970 mean of 520 mm. In Bandiagara, the mean annual rainfall between 1970 and 2010 (501 mm) decreased by 13% compared to 1930–1970 (579 mm). According to Fig. 1, annual rainfall seems to be recovering in both research areas with extraordinary wet years in 2009 and 2010. In Mali, annual rainfall levels have almost reached pre-drought values in 2010, whereas in Senegal, the increase is much slower.

3.2. Mali case studies

Vegetation trends in the study area of Mali are positive, but major spatial discrepancies can be observed in Fig. 2. In the following, several hot-spot areas are chosen around the Dogon villages Diamnati, Yawakanda, Gama, Bankass and Tiembara.

3.2.1. Diamnati/Mali (1)

South of Ficko the large blue area stands out which is marked with 1 in Fig. 2. This seems to be an area which does not show greening trends (0.03 whereas 0.08 is the mean for the area) despite increasing rainfall. MODIS data show variations within small areas (Fig. 3) indicating that positive and negative NDVI trends are local and still active since 2000. A comparison with pre-drought Corona imagery (1967) shows major land use changes: What used to be dense bush-cover has partially been converted to farmer-managed agro-forestry and a significant proportion is now degraded land (Fig. 4). Furthermore, an increase of tree cover on the fields can be detected. Fieldwork validated suspected soil erosion and ongoing loss of trees and shrubs outside the fields used for farming purposes (Fig. 4). On the fields surrounding the village, many useful trees of all sizes were identified. Observations and interviews revealed that villagers actively protect seedlings of selected tree species (e.g. *Faidherbia albida*, *Balanites aegyptiaca*, *Borassus aethiopum*, *Adansonia digitata*) on cropland against animal grazing, trampling and cutting with the help of thorny branches. This has led to an increase of tree cover and improved soil conditions. Farmers have profound knowledge of benefits of trees on

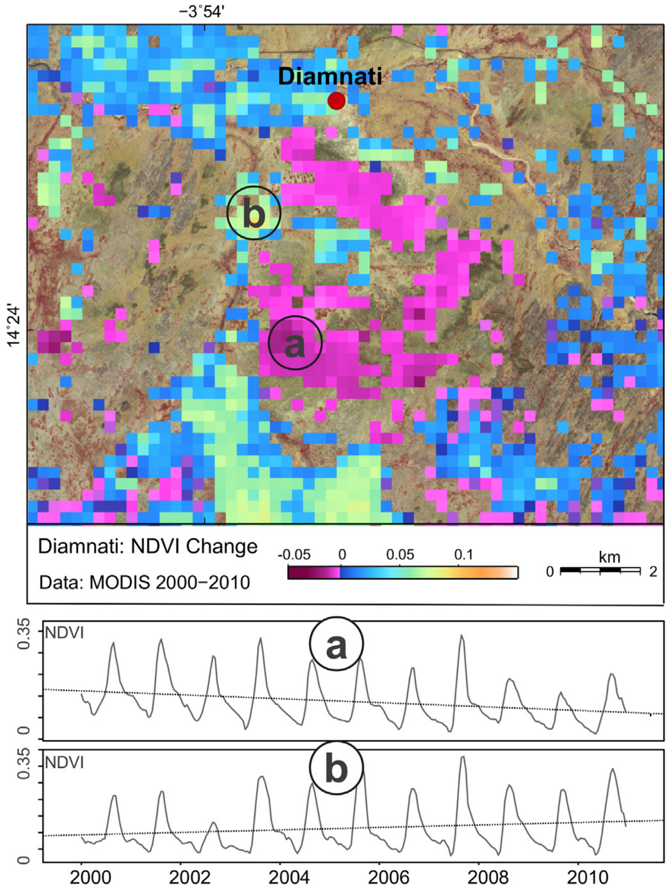

Fig. 3. The area marked with 1 in Fig. 2 appears homogeneous in the LTDR image (Fig. 2). The spatial scale of MODIS (250 m) is able to record heterogeneity within this region by identifying negative and positive vegetation trends (transparent areas stand for no significant trends). While positive NDVI change can be observed near Diamnati village, active degradation is visible in the surroundings. The temporal profiles of the pixels marked with "a" and "b" are shown below. The background map is a RapidEye 532 composite from December 2011. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

farmland. The owner of a field may pollard his trees sustainably but cutting them down is persecuted. The land outside the current farming area is highly degraded, which is explained by the following points:

1. the severe droughts in the 1970s and 1980s,
2. several years of insufficient rainfall since the droughts,
3. increased felling of trees/cutting of branches by the local population during and after the droughts to compensate for harvest losses by selling wood on markets and to feed animals respectively,
4. a lack of villagers to restrain strangers from cutting/felling due to missing ownership (latecomer) and the existence of individual cutting permits issued by the Governmental Forest Agency,
5. increased livestock numbers that put pressure on soils and vegetation.

Due to the declining vegetation cover and supported by the unfavorable morphology of the rocky plateau, the susceptibility to soil erosion by wind and water increases. Many useful trees and shrubs have become very rare or disappeared altogether (e.g. *Butyrospermum parkii*, *Crataeva adansonii*, *Combretum micranthum*, *Piliostigma reticulatum*, *Pterocarpus lucens*, *Sclerocarya birrea*, etc.).

3.2.2. Yawakanda/Mali (2)

This area is an example for a FMNR program on the Dogon Plateau (see Yossi and Diakite, 2008). Supported by dispersion of *Combretum glutinosum* and increasing rainfall, this causes a positive NDVI change, marked with 2 in Fig. 2. Elders reported that there was dense natural woody vegetation, which they started to clear for farmland and their houses at least 60 years ago when the village was founded. A comparison of Corona imagery with RapidEye and Google Earth shows that there is a significant increase of trees on the fields used for cropping. However, a major difference is that the species composition has changed. While according to the interviews several species like *F. albida*, *B. aegyptiaca*, *B. aethiopum*, *C. glutinosum* and *S. birrea* have increased, many species such as *Annona senegalensis*, *Detarium microcarpum*, *Diospyros mespiliformis*, *Khaya senegalensis*, *Lannea acida*, etc. have almost vanished during the last 30 years. Thus, the findings of Yossi and Diakite (2008) are supported.

The differences between regularly used and mostly fallow land are striking (Appendix 3, electronic version only). The active fields are covered with healthy trees and plowed soil aided by deep-rooting vegetation. The village chief mentioned the occasional unapproved cutting of branches by foreign herdsmen to make fodder available for their animals. The fallow/bush areas are exploited for firewood and the lack of regular cultivation leads to hard and crusted soils. This is a very local phenomenon, which is not visible at a scale of 5 km (Fig. 2) and sometimes not even at 250 m. High resolution at tree level imagery and fieldwork is needed to understand local land cover patterns.

The area around Yawakanda not only serves as an example for tree protection managed by farmers, trends are also influenced by small dams which are used to irrigate the vegetable cultivation in proximity to the Yame river. The dams were built by German development projects in 1996, 1999 and 2005 and represent only three of more than 80 dams on the plateau of the Cercle de Bandiagara. Areas around these dams often stay green months after the end of the rainy season.

3.2.3. Gama/Mali (3)

This area stands out with a weak positive trend because the time series starts in 1982, during the severe droughts. It would probably

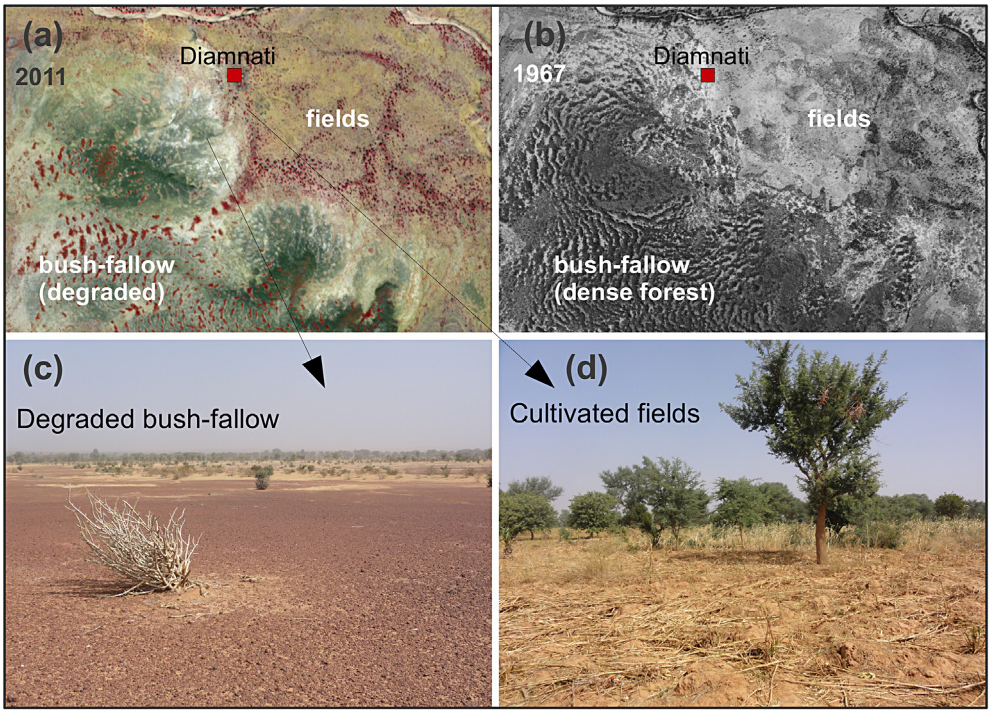

Fig. 4. The first image pair (a + b) shows exactly the same area compared over a period of 44 years. The area around Diamnati shows degradation and greening phenomena the same time. The Corona image from 1967 (b) shows formerly dense tiger-bush formations in the south-west (dark black areas), of which only small parts are left in 2011 (a, RapidEye), visible as red spots. Most parts are degraded land with exposed laterite, visible as dark areas on RapidEye. Farmers' fields around Diamnati in the north-east (bright on Corona) show a totally different development. Almost no trees (black dots) can be seen in 1967, whereas in 2011 fields are densely covered with trees (red dots). The obvious difference in vegetation cover of adjacent areas used for grazing (c) and farming (d) is illustrated by field-fotos (photos M. Brandt, Nov. 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

be negative if the time series would start before the droughts. It is marked with 3 in Fig. 2. RapidEye imagery and fieldwork revealed a fossil dune area near the Bandiagara cliffs, which suffers considerably under the severe effects of soil erosion (Appendix 4, electronic version only). Compared to pre-drought conditions, most trees are lost and there is no recovery. Fieldwork showed that *D. microcarpum* often is the only species left. The sandy dunes fail to store moisture for extended periods, which is the reason why most of the trees died off during the drought periods in the 1970s and 1980s. Prior to the droughts, the trees performed soil stability functions through their deep rooting systems. Because of the lacking vegetation cover, the dunes are very susceptible to soil erosion, especially during intensive rainfall periods. This has led to the formation of extensive gully systems, which are increasing in size from year to year, as little can be done to stop the regressive erosion during the rainy season. The gullies reduce the size of cropping fields and make access to farmland more difficult. No evidence of prevention techniques to divert or reduce run-off in these areas were observed.

3.2.4. Séno Plain around Bankass, Tiembara/Mali (4)

Tree planting and protection programs have been introduced on the outskirts of Dimbal and Bankass. RapidEye imagery and fieldwork show improvements in tree density (Appendix 5, electronic version only) and a positive NDVI change can thus be observed around the villages, e.g. in the area marked with 4 in Fig. 2. Projects encouraging planting and protection of trees on fields are widespread in the Séno Plain (e.g. Allen, 2009). Higher resolution MODIS time series trends are influenced too much by cropping and fallow periods in this area. The herbaceous and shrub vegetation on fields, which lie fallow, often produce a higher NDVI than crops, especially peanuts and beans. A change from fallow to active cropping often results in a negative trend, whereas the opposite leads to greening and frequent land cover change results in no significant trends at all.

Vegetation diversity and tree density in the Séno Plain vary. Many healthy individuals of various species around the villages can be seen (e.g. *F. albida*, *Acacia nilotica*, *Acacia seyal*, *A. digitata*, *B. parkii*, *D. microcarpum*, *P. reticulatum*, *Prosopis africana*, *S. birrea*, etc.). These green tree belts also exist around smaller villages, but cannot be detected in LTDR–SPOT images. The MODIS mean seasonal amplitude exposes these green productive belts around the villages indicating active fields with a dense woody vegetation (see Fig. 5). These primary fields are kept fertile with natural and artificial fertilizers and are rarely fallow. Beyond this belt, the fields are used rotationally. Distant fallow fields serve as main source for firewood and for grazing. This is a traditional practice (Croll and Parkin, 1992), but due to lack of space for more fields, the soils on these secondary fields are overused because of shortened fallow periods. Because of the infertility of the soils around the green belt, fields are mostly used for only 3 years before being left fallow for the same period. Traditionally, at least 5 years of fallow would be needed to allow a sufficient recovery for the soils and avoid nutrient leaching. Many stumps are visible and the remaining

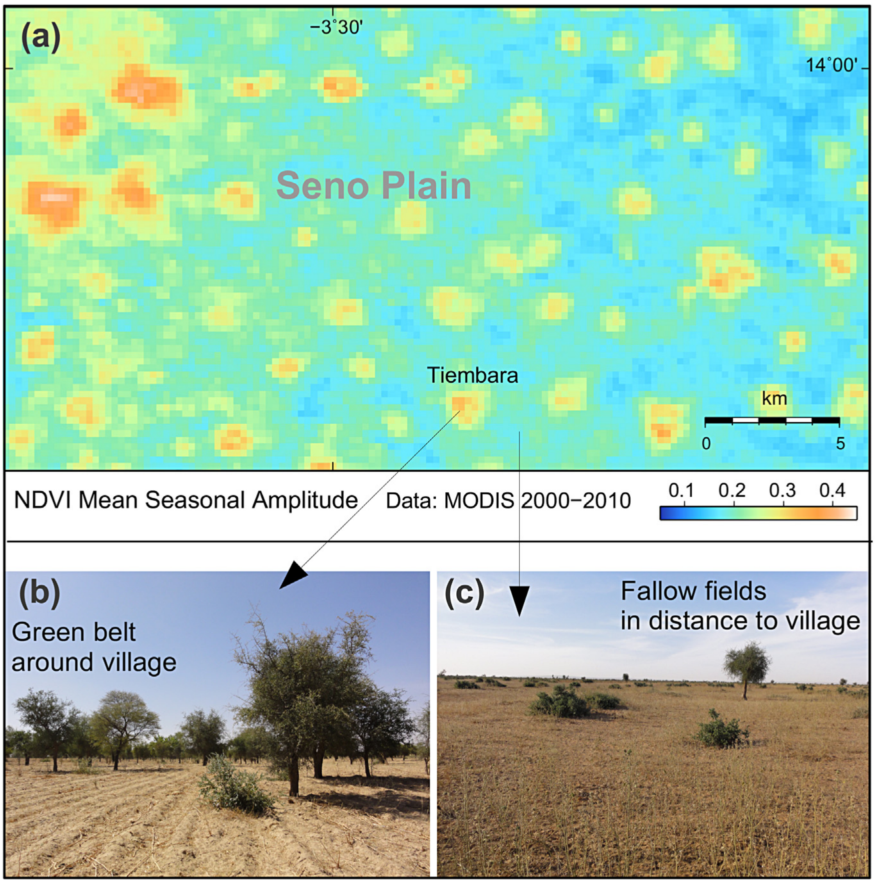

Fig. 5. MODIS mean amplitude identifies green productive belts (high values) represented by yellow and red colors around the villages in the Séno Plain (a). These fields are regularly cultivated and fertilized. Moreover, trees are protected. Photos from the Dogon village Tiembara show the difference between a regularly cultivated field near a village (b) and a mostly fallow field further away (c) (photos taken Nov. 2011). *Guiera senegalensis* is the prevalent species on the fallows. *Balanites aegyptiaca*, *Faidherbia albida* and *Sclerocarya birrea* dominate on fields. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

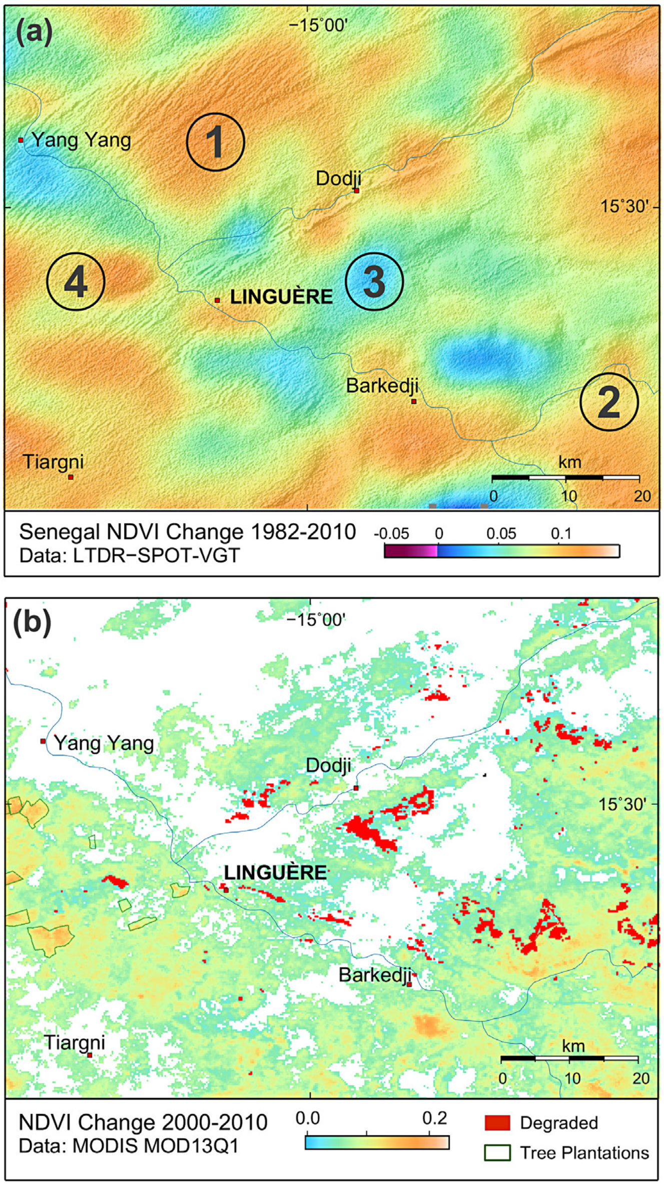

Fig. 6. LTDR–SPOT NDVI time series NDVI change from 1982 to 2010 in Senegal (a). The numbers indicate the case study sites which are further explained within Chapter 3.3. While positive MODIS trends (b) (2000–2010) in the west of Linguère are mainly caused by large tree plantations, positive changes in the east are caused by the shrubby vegetation of the lateritic Ferlo which reacts positively to increasing rainfall. Large parts of the eastern Ferlo produce insignificant trends (white) due to a huge bush-fire in 2010. Degraded areas identified by the mean seasonal NDVI amplitude (below 0.2) are marked in red, tree plantations of *Acacia senegal* are encircled in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

woody vegetation in these areas can be clearly recognized by severely trimmed trees and shrubs, signifying a lower prioritization or capacity for protection in these areas (see Fig. 5). The cropping period is too short for the trees to recover from the overuse during fallow periods.

Today most of the trees are small and rarely older than 20 years, indicating a good recovery since the extreme droughts. Generally, species like *B. aegyptiaca*, *C. glutinosum*, *F. albida* and *P. africana* increased while *D. microcarpum*, *Gardenia ternifolia* and *Vitellaria paradoxa* either decreased or disappeared.

3.3. Senegal case studies

Long-term time series show significant positive vegetation change in the Ferlo around Linguère. Even though the Senegal study area is smaller than the one in Mali, several zones based on ecological characteristics (see also Tappan et al., 2004) can be differentiated.

3.3.1. Northern zone (1)

In the northern zone (number 1 in Fig. 6a), dense bush formations can be observed on Corona-imagery of 1965 but current images show a complete transformation to an open tree and shrub savanna which is partly and irregularly used for cropping (Fig. 7a, b). Rainfall and drought-recovery are causative factors for prominent positive biomass trends in this area of our time-series (1982–2010). According to local people, a fire burned nearly all vegetation in this area in the times after the droughts. Although small bush fires are not an exception in this region of the Ferlo, the dimension of this event, according to the interviewees, had never been seen before or since. The drought of 1984 removed most of the animals by either migration or starvation. The following years were wet and forage accumulated in the absence of livestock. This vast fuel load caused a severe fire that burned almost all woody vegetation. Today *B. aegyptiaca*, mostly of similar age, make up more than 80% of the species.

3.3.2. Ferruginous zone (2)/(3)

This ferruginous pastoral zone forms the eastern Ferlo and has been seriously affected by severe droughts in the 1970s and 80s and by the overall drop of annual rainfall (Tappan et al., 2004). Today, considerable parts show a good recovery and react positively to increasing rainfall, as evidenced by a positive NDVI change (2 in Fig. 6a) and vegetation dominated by *P. lucens* and *Guiera senegalensis*. MODIS reveals that the recovery is widespread and that the density of the vegetation has particularly increased in the last five years (Fig. 6b). These findings coincide with local people's statements. However, other areas do not follow the strong positive trends (example areas are marked with 3 in Fig. 6a). Thus, the range of MODIS mean seasonal amplitude (see 2.3.1) was used to identify unproductive pixels, which represent degraded land. Almost 3% of the research area is degraded, barren land (red in Fig. 6b), a result similar to Budde et al. (2004). According to Tappan et al. (2004), the portion of degraded land has been spreading rapidly in this region during the last 50 years. As seen on Corona-imagery, these areas used to be covered with dense woody vegetation (Appendix 6, electronic version only). Most local inhabitants confirmed this by explaining the loss of woody vegetation by overuse of humans, but also droughts, lack of rain, and unfavorable soils were mentioned. Once vegetation is lost, soils become susceptible to erosion. Topsoils are washed away and laterite-crusts are exposed so that the remaining soil becomes impenetrable – a process very similar to certain places on the Dogon Plateau in Mali. In all visited areas many species (e.g. *Anogeissus leiocarpus*, *C. micranthum*, *D. mespiliformis*, *Grewia bicolor*, *S. birrea*, *Sterculia setigera*, *Terminalia avicennioides*) have disappeared or are only left in few numbers.

3.3.3. Cropping zone (4)

Although this area belongs to the silvo-pastoral region, large parts of this zone 4 in Fig. 6a are used for cropping. Farmers reported that when bushland was cleared during the 20th century, only trees of a particular height or certain species regardless of age were not felled (e.g. *F. albida*, *A. nilotica*, *Acacia sieberiana*, *Acacia raddiana*, *A. leiocarpus*, *Combretum nigricans*, *L. acida*, *S. setigera*, *T. avicennioides*, *Ziziphus mauritiana*). However, most of these have vanished due to lack of rain within the past 35 years. Regular

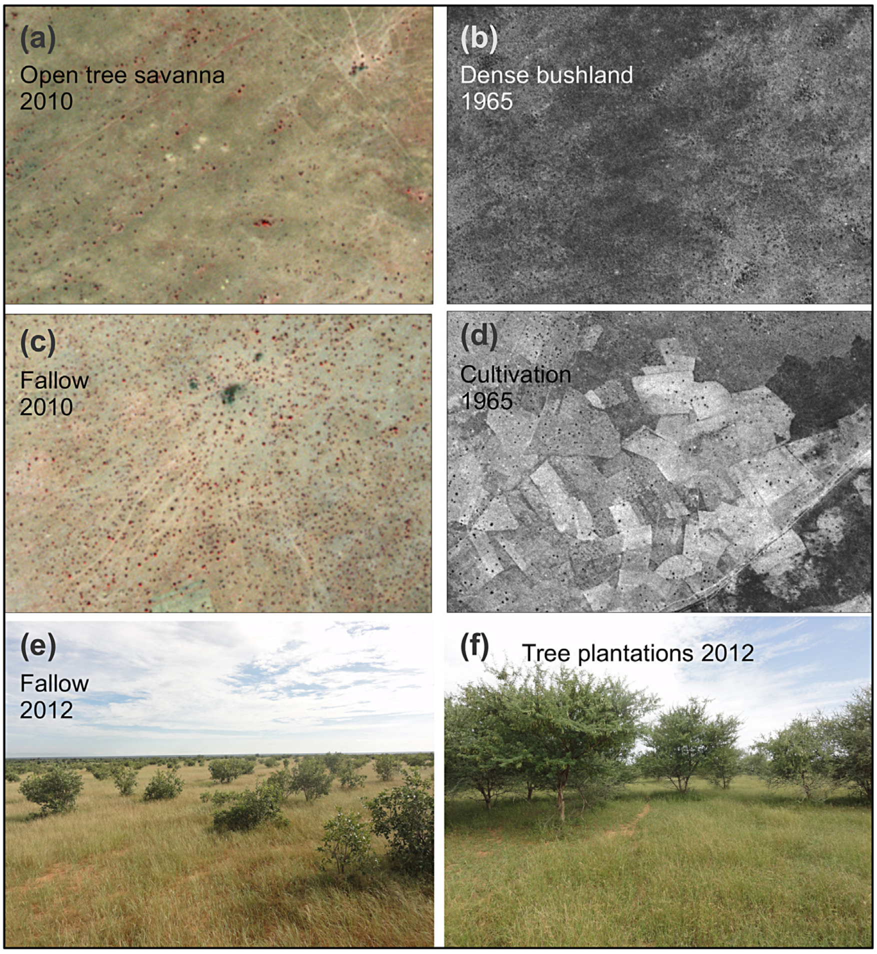

Fig. 7. The dark gray and black areas in the Corona image (b) (1965) represent dense bushland, which was common 1965 and dominated by *Guiera senegalensis*. The bushland was cleared before the beginning of our time series. Today, this area is a peanut fallow with an open *Balanites aegyptiaca* vegetation, seen as red dots on the RapidEye image (a) (2010). Formerly regularly cultivated with a sparse woody vegetation (1965 Corona), the fields near Doundodji seen in (d) are peanut fallows with a dense woody vegetation in 2010 (c) (RapidEye). *Combretum glutinosum* shrubs, dense grass on peanut fallows (e) and large reforestation areas with *Acacia senegal* trees (f) induce a positive trend west of Linguère (photos taken Sept. 2012). The trees seen in (f) were planted in 2000 and are part of a gum plantation near the villages Kamb and Ndodj. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cultivation keeps the soil penetrable and farmers are aware of the benefits of trees in their fields. Thus, some species are regenerating by means of protection and planting but most of them are still very young and vulnerable to livestock. However, the explanations for large parts of the greening are of a different nature: (1) according to interviewees, cropping encroached rapidly since the 1960s (see also Tappan et al., 2004), while today many fields are fallow due to the lack of rain in the past decades (Fig. 7c–e). This is particularly true for the northern parts of the zone. Shrubs and trees (*C. glutinosum* on soft, and *B. aegyptiaca* on harder sand), which were usually cut down on the former active fields, are able to spread and cause a greening which is supported by herbaceous vegetation with a high NDVI. Furthermore, (2) reforestation areas maintained by farmers and supported by the Governmental Forest Agency fill up large parts of this area as can be seen by positive MODIS trends in Fig. 6b (see also CSE, 2009). Thousands of *Acacia senegal* (Fig. 7f) are planted in fenced areas which in some cases are partly used for cropping by the responsible village. Livestock is only allowed to enter in the end of the dry season for a fee, which is used to maintain the protected area. However, the purpose is not always exclusively environmental protection, as large parts of these areas serve as gum plantations for a private investor.

3.4. Overall vegetation trends

Although inter-annual variability is a common phenomenon in the Sahel, LTDR–SPOT time series reveal significant NDVI greening trends from 1982–2010 in most areas (Fig. 8). Mean changes in NDVI are 0.07 with a maximum of 0.12 in Mali and 0.08 with a maximum of 0.11 in Senegal. Our case studies have shown that reasons can be very local but several factors apply to both research areas:

1. farmer-managed agro-forestry,
2. planting programs and strict protection laws,
3. widespread dispersion of robust species, especially *B. aegyptiaca* and *C. glutinosum*, which replace the former diverse woody vegetation and simulate a greening which in fact conceals a shift in biodiversity,
4. an increase of annual rainfall and recovery from the droughts.

However, woody vegetation is far from pre-drought conditions, which have been reconstructed by Corona-imagery and information from village elders. In 1967, dense bushland covered about half of the Séno Plain (Mali) and also large areas of the Ferlo (Senegal).

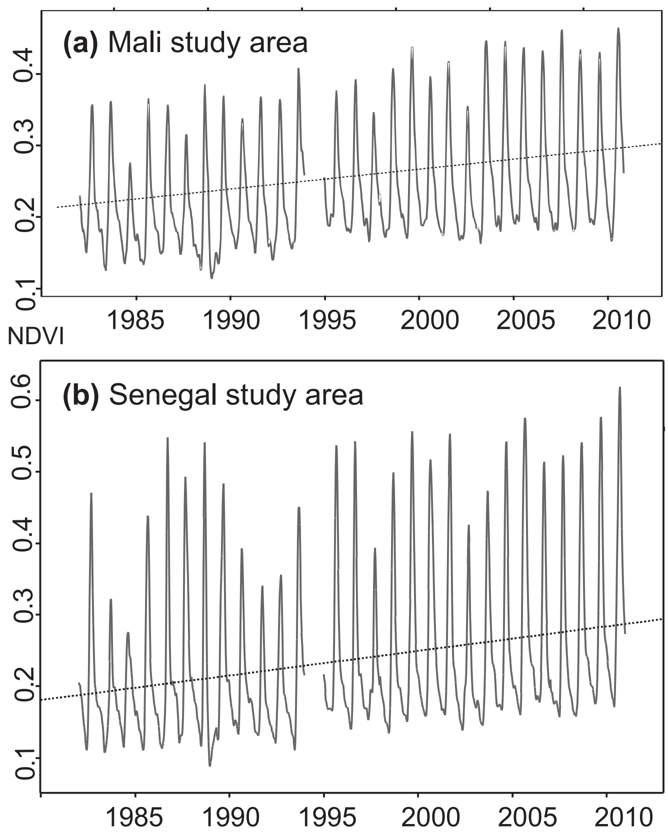

Fig. 8. LTDR–SPOT NDVI time series from 1982 to 2010 averaged for the Bandiagara (a) study area and for the Linguère (b) study area.

Since the 1960s, the natural vegetation has been completely transformed and today many trees and shrubs have become rare or disappeared (Fig. 9a) due to climatic and anthropogenic reasons: (1) the 1970s and 1980s drought events have caused the death of individuals of various tree and shrub species. During the following decades, the amount of annual rainfall remained below pre-drought levels and the mean temperature increased. These new climatic conditions largely contributed to a decrease in the diversity of woody species and at the same time, favored increasing numbers of certain robust tree varieties (Fig. 9a). (2) Initially, natural population growth and to some extent in-migration contributed to agricultural extensification and clearing of forests for farming purposes. This led to rising livestock numbers and demand for fuel-wood. Cutting living trees and selling the wood is a well-established strategy to generate income and to economically compensate harvest losses. In the pastoral regions of the Ferlo, branches are cut to feed animals with leaves. These activities increase during droughts putting pressure on the woody vegetation. In areas with a decrease of woody coverage, soil becomes more vulnerable to erosion and desertification.

Fig. 9b shows that species richness changed dramatically in Senegal after many species died due to a lack of soil moisture and increased cutting. Today *B. aegyptiaca*, *C. glutinosum* and *A. raddiana* make up 73% of all woody vegetation. Most other species are left in few numbers in clayey depressions. Considering the age structure of the trees, the dominance of these few species will even increase in the near future. The share of young trees (smaller 4 m) among the population of the three above-mentioned species is around 50% while among species like *S. birrea* or *A. nilotica* small trees barely make up 5%. Local people explained that the drought in 1973 was a starting point from which many favored species (e.g. *A. leiocarpus*, *L. acida*, *S. setigera*, *G. senegalensis*, *G. bicolor*, *T. avicennioides*) slowly vanished in some regions due to lack of water and increased cutting of living trees.

In Mali the situation is more diverse and site specific (Fig. 9a), due to morphological differences within the larger study area. While several species have disappeared in many areas (e.g. *A. leiocarpus*, *C. adansonii*, *G. bicolor*, *P. lucens*, etc.), others have taken their place (e.g. *B. aegyptiaca*, *Eucalyptus camaldulensis*). Much depends on local site conditions, management and external influence. We observed that protection and planting of trees only takes place near villages, while fields and fallows at greater distances are heavily exploited for fuel-wood. The study area has seen an increase of village numbers, particularly during the past 50 years, as seen on Corona images. New settlements caused an initial decrease of the vegetation due to land use change (bushland to fields). However, we hypothesize that the increase in village density at the same time led to a certain recovery of vegetation by the conservation of useful trees on farmland in proximity to villages resulting in a higher density, diversity and vitality of trees. Villagers encourage growth of the trees by protecting them on their actively used fields, preventing the unsustainable exploitation of the woody vegetation. Furthermore, regular treatment keeps soils penetrable and counters erosion and degradation.

4. Conclusion

Coarse-scale time series have proven to be a good indicator for long-term vegetation change. Trends were clearly positive, indicating an increase in biomass. Because this time series starts in times of droughts, degraded areas could clearly be identified because they do not follow the overall greening trend. The initiation of the degradation processes thus began prior to the period covered by the time series (1982–2010).

MODIS trend analysis revealed greening and degradation at a local level. However, fine-scale information often proved being irrelevant when trying to confirm regional patterns, i.e. trends were often caused by local irrigated plantations and fallows. The time line of MODIS often is too short to follow short-term processes. Active degradation is rarely spotted within 10 years and events such as bush-fires, floods or frequent crop rotation make trends often insignificant. The mean seasonal amplitude reliably identified productivity per pixels at a relevant scale that is valuable when identifying degraded or productive areas at field level.

The results of the time series analysis led to various hypothetical explanations of trends, which were verified by ground-truthing. Despite of their different climatic and social conditions, both research areas have many similarities when explaining environmental changes. Many of them coincide with other findings, confirming woody vegetation recovery (Hiernaux et al., 2009; Tappan et al., 2004), but also species impoverishment (Gonzalez et al., 2012; Herrmann and Tappan, 2013) and a spreading of degraded areas (Budde et al., 2004; CSE, 2009; Tappan et al., 2004) were discovered. Greening and degradation are spatially heterogeneous and caused by a combination of both anthropogenic and climatic factors. Even if droughts and a decrease of rainfall contributed to the extinction of many tree species, humans increasingly control the tree density and species composition today.

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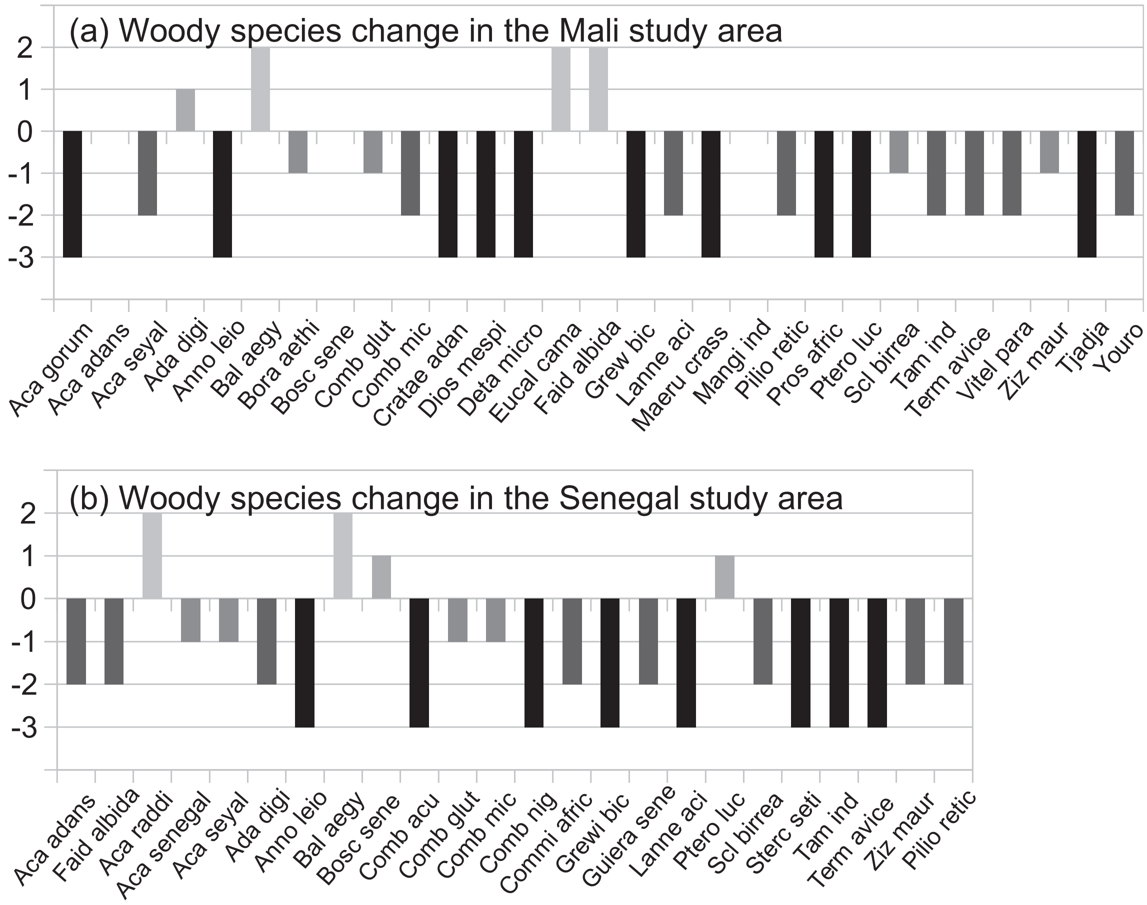

Fig. 9. Local people's perception of changes in tree species composition in the Bandiagara (a) and Linguère (b) study areas in the past 40 years. −3 very strong decline or disappeared, −2 strong decline, −1 decline, 0 stable, 1 increase, 2 strong increase. More information and complete scientific, Dogon and Wolof names can be found in Appendix 7 and 8, electronic version only.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2014.02.019.

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5

LOCAL VEGETATION TRENDS IN THE SAHEL OF MALI AND SENEGAL USING LONG TIME SERIES FAPAR SATELLITE PRODUCTS AND FIELD MEASUREMENT (1982–2010)

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This publication assesses local vegetation trends by means of long time series of satellite and ground data. Moreover, validation and interpretation of coarse FAPAR time series addresses data quality and scale issues, i.e. hypotheses 1, 2 and especially 3 are addressed.

Long FAPAR time series (GEOV1 and GIMMS-3g) are compared with ground measured biomass data over 29 years. Thus, the capacity of GEOV1 (5 km) and GIMMS-3g (8 km) to capture long-term vegetation trends at a local scale is assessed, validated and interpreted. Both satellite and ground-based datasets provide valuable information on environmental changes since the 1980s, shedding more light on the processes responsible for greening/degradation. Rainfall is identified to explain large parts of the inter-annual variability, however, in-depth knowledge and site visits help explaining a heterogeneous pattern at a local scale. The different spatial resolutions and processing lines of the datasets provide varying results, making the choice of the dataset an important factor.

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Article

Local Vegetation Trends in the Sahel of Mali and Senegal Using Long Time Series FAPAR Satellite Products and Field Measurement (1982–2010)

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Abstract: Local vegetation trends in the Sahel of Mali and Senegal from Geoland Version 1 (GEOV1) (5 km) and the third generation Global Inventory Modeling and Mapping Studies (GIMMS3g) (8 km) Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) time series are studied over 29 years. For validation and interpretation of observed greenness trends, two methods are applied: (1) a qualitative approach using in-depth knowledge of the study areas and (2) a quantitative approach by time series of biomass observations and rainfall data. Significant greening trends from 1982 to 2010 are consistently observed in both GEOV1 and GIMMS3g FAPAR datasets. Annual rainfall increased significantly during the observed time period, explaining large parts of FAPAR variations at a regional scale. Locally, GEOV1 data reveals a heterogeneous pattern of vegetation change, which is confirmed by long-term ground data and site visits. The spatial variability in the observed vegetation trends in the Sahel area are mainly caused by varying tree- and land-cover, which are controlled by human impact, soil and drought resilience. A large proportion of the positive trends are caused by the increment in leaf biomass of woody species that has almost doubled since the 1980s due to a tree cover regeneration after a dry-period. This confirms the re-greening of the

Sahel, however, degradation is also present and sometimes obscured by greening. GEOV1 as compared to GIMMS3g made it possible to better characterize the spatial pattern of trends and identify the degraded areas in the study region.

Keywords: land degradation; greening; drought; Sahel; FAPAR time series; GIMMS3g; Geoland; biomass observations; Senegal; Mali

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1. Introduction

The West African Sahel is an area that has experienced recent climatic and environmental changes (e.g., [1,2]). After severe droughts in the 1970s and 1980s, large areas were branded as degraded land (e.g., [3]). However, satellite time series starting in 1981 revealed a significant greening trend, which can only be partly explained by increasing rainfall [4]. Thus, a new re-greening debate largely replaced the previous degradation paradigm (e.g., [5,6]), although evidence of actual greening and increasing tree densities does not always correlate with greening trends derived from satellite time series [7]. Recently, Brandt *et al.* [8] and Herrmann & Tappan [7] highlighted how diverse processes on a local scale can be, and that a positive vegetation trend does not necessarily mean an environmental improvement, as a remarkable species impoverishment was detected in both studies.

Time series analyses based on moderate and coarse resolution satellite data are widely used for monitoring vegetation. In regions with high intra- and inter-seasonal vegetation dynamics, mainly caused by rainfall variability, traditional change detection methods fail to succeed, making continuous data over a long time period irreplaceable. Remote sensing products have been tested against each other and found to be highly consistent for the entire Sahel [9,10]. Recent studies are scaled from global [11] to local [7] dimensions. Short term trends at a moderate scale (250 m–1 km) are studied with SPOT VEGETATION (VGT) (starting 1998) and Moderate Resolution Imaging Spectroradiometer (MODIS) (starting 2000) [12,13]. In Africa, continuous moderate resolution data of years prior to 1998 are only regionally available at 1.1 km from LAC (Local Area Coverage) AVHRR (Advanced Very High Resolution Radiometer) receiving stations [14–16]. However, poor quality, difficulties in data processing and availability hampers the use in the West African Sahel. Alternatively, the Normalized Difference Vegetation Index (NDVI) Global Inventory Modeling and Mapping Studies (GIMMS) time series starting in the year 1981 with 8 km spatial resolution derived from the AVHRR global GAC (Global Area Coverage) dataset [17] has been widely used for long-term trends [4,18–20]. The latest version, termed the third generation GIMMS3g dataset has been recently produced for the period July 1981 to December 2011 with AVHRR sensor data from NOAA (National Oceanic and Atmospheric Administration) 7–18 satellites with an improved calibration. In addition to the NDVI, Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) and Leaf Area Index (LAI) products have been derived from GIMMS3g dataset to provide quantitative information of the state of earth's vegetation at 8 km resolution and 15-day intervals [21]. The recently delivered Geoland Version 1 (GEOV1) time series of FAPAR, LAI and Fraction of Vegetation Cover (FCOVER) based on AVHRR LTDR (Long Term Data Record) dataset combined with SPOT VGT offer a spatial resolution of approximately 5 km for the period

1981–1998 and 1 km from 1999 to present [22,23]. Although the main problem of these long-term time series is their very coarse resolution, merging heterogeneous processes and characteristics on the ground into one single pixel, the higher spatial resolution of the GEOV1 dataset as compared to GIMMS3g may contribute to improve local trend analysis. In the Sahel, long term vegetation trend studies using GEOV1 have not been conducted so far. GIMMS3g is mostly used at a global scale [24–26] and studies are rarely located in the Sahel [9,27].

Ground-truthing of vegetation trends in the Sahel can be extremely difficult, as landscapes and human activities are not uniform and even if the region is well known, (1) the actual causes of trends remain unclear and (2) degradation or greening can be obscured or neutralized by mixed spectral information from changes of adjacent objects. So far, ground-truthing has rarely been linked to long-term trend studies in the Sahel. Only few studies go beyond hypothetical interpretations of the trends. Herrmann & Tappan [7] use botanic inventory sites over 27 years, while Brandt *et al.* [8] present an interdisciplinary and descriptive approach. Bégué *et al.* [18] related greening trends to land-cover changes, finding some correlations in the Sahel. Dardel *et al.* [9] compared long-term field observations with GIMMS3g NDVI data, finding a good consistency of positive vegetation trends in Mali (R^2 = 0.59) and negative trends in Niger (R^2 = 0.38).

This study uses FAPAR time series instead of NDVI. FAPAR is defined as the fraction of radiation absorbed by the canopy in the 400–700 nm spectral domain under specified illumination conditions [28]. It is directly related to the photosynthesis and it is used as an input in light use efficiency models. The relationship between NDVI and FAPAR has been found to be linear for green vegetation, particularly in the semi-arid environment of the Sahel. A number of satellite-related (including atmospheric effects and view-sun angle geometry) and canopy-related (including leaf angle distribution, canopy heterogeneity, brown elements and soil color) factors are found to influence the parameters of this linear relation which is site-specific and often only valid when calibrated for a given soil type [13]. Compared with NDVI, the FAPAR satellite products mitigate the impact of soil background for low vegetated canopies and the saturation effects for high vegetation amount [29].

The purpose of this study is to assess local vegetation trends in the Sahel of Mali and Senegal in the period 1982–2010 by combining long-term FAPAR satellite datasets with ground based data. The potential of GEOV1 and GIMMS3g time series for trend detection is assessed and validated with biomass observations, rainfall data and site visits. This study is designed to better understand the processes responsible for satellite derived trends and, thus, to shed more light on the re-greening debate of the Sahel area.

2. Materials and Methods

Our study uses coarse scale GEOV1 and GIMMS3g FAPAR satellite time series to examine local vegetation trend patterns in two Sahelian study areas. Validation and interpretation of the spatial pattern and magnitude of observed vegetation trends is based on two methodologies: (1) a qualitative approach using in-depth knowledge of the regions and (2) a quantitative approach through the comparison with biomass field measurements and rainfall data.

2.1. Study Areas

The study areas are located in the Sahel of Mali and Senegal, an area with evidence of significant environmental changes over the studied time period. Greening and degradation have both been observed in the study areas, offering a heterogeneous pattern of vegetation change [2,8,30,31]. Human impact, morpho-pedology as well as rainfall variability have shaped a diversified landscape. Six test sites with oppositional land-cover trends were chosen for further analysis (*MALdeg, MALpos, C3L5, C2L5, C2L4, Ldeg*, shown in Table 1 and illustrated in Figure 1). The two study areas and the location of the six test sites are shown in Figure 2.

Table 1. Location and site characteristics for the Sahelian test sites presented in this study.

Sites	Location	Coordinates (Long./Lat.)	Site Characteristics
MALdeg	Mali, Dogon Plateau	−3.8738 14.4276	Tree-, shrub savanna, degraded bushland, crops, ferruginous, shallow soils
MALpos	Mali, Dogon Plateau	−3.5312 14.3253	Tree-, shrub savanna, cropping and onion plantations line the valleys, dams and irrigation structures
C3L5	Senegal, ferruginous Ferlo	−14.5815 15.2463	Shrub-, tree savanna, dense bushland, ferruginous, spots of bare soil, shallow soils, pasture
C2L5	Senegal, southern sandy Ferlo	−15.2032 15.2309	Tree-, shrub savanna, sandy, intersected by clayey depressions, pasture and small scale cropping
C2L4	Senegal. northern Ferlo	−15.2857 15.6035	Open tree-, shrub savanna, sandy, pasture and small scale cropping, fallow fields
Ldeg	Senegal, ferruginous Ferlo	−14.9444 15.4718	Tree-, shrub savanna, ferruginous, laterite, shallow soils, degraded, intersected with woody depressions

2.1.1. Bandiagara (Sahel of Mali)

In Mali, the focus is on the Dogon Plateau around Bandiagara, east of Mopti. Around 10% of the rocky and ferruginous plateau are not suitable for agriculture, while most of the remaining portion is used for rainfed cropping by Dogon farmers and livestock herding by Fulani pastoralists. In the past 50 years, droughts and human expansion have caused a considerable loss of natural woody vegetation, resulting in degraded land and an increase of cultivated areas [31]. Prevailing woody species are *Balanites aegyptiaca, Combretum glutinosum, Guiera senegalensis*, and especially on fields *Faidherbia albida*. The plateau is represented by two case study sites (see Figure 1 and Table 1): large portions of the area around *MALdeg* are highly degraded with exposed laterite and only scattered spots of grass and woody vegetation remaining (Figure 1a). On the contrary, *MALpos* represents an area with large scale onion plantations and fertile fields (Figure 1b), surrounded by a dense shrubby vegetation on rocks.

Figure 1. Study sites in Mali (**a**,**b**) and Senegal (**c**–**f**); illustrated by RapidEye images [32] (bands 532, December 2010) and photos, taken in December 2011 (**a**,**b**); March 2012 (**d**) and September 2012 (**c**,**e**,**f**). Site (**a**) is located on the lateritic Dogon Plateau with small spots of bushland left, visible as red spots in RapidEye. Degradation (dark color) fills up most parts of the image. Onion plantations (bright red) are present at (**b**) and stay green into the dry season due to irrigation. The rocky surroundings are covered by *Combretum micranthum* shrubs. Site (**c**) illustrates the ferruginous Ferlo with a dense shrubby vegetation dominated by *Pterocarpus lucens, Guiera senegalensis* and *Boscia senegalensis* but also unvegetated spots; (**d**) represents the southern sandy Ferlo, intersected by forested depressions. *Sclerocarya birrea* and *Balanites aegyptiaca* are seen on the dry season photo; Site (**e**) is located in the northern sandy Ferlo with an open tree and shrub savanna. Small *Combretum glutinosum* and *Balanites aegyptiaca*, severely cut by humans can be seen on the photo; Site (**f**) reveals different details in different resolutions: while the GIMMS pixel (blue grid) mixes the degraded area with peanut-fields further north, the GEOV1 (red grid) pixel captures the largely degraded area.

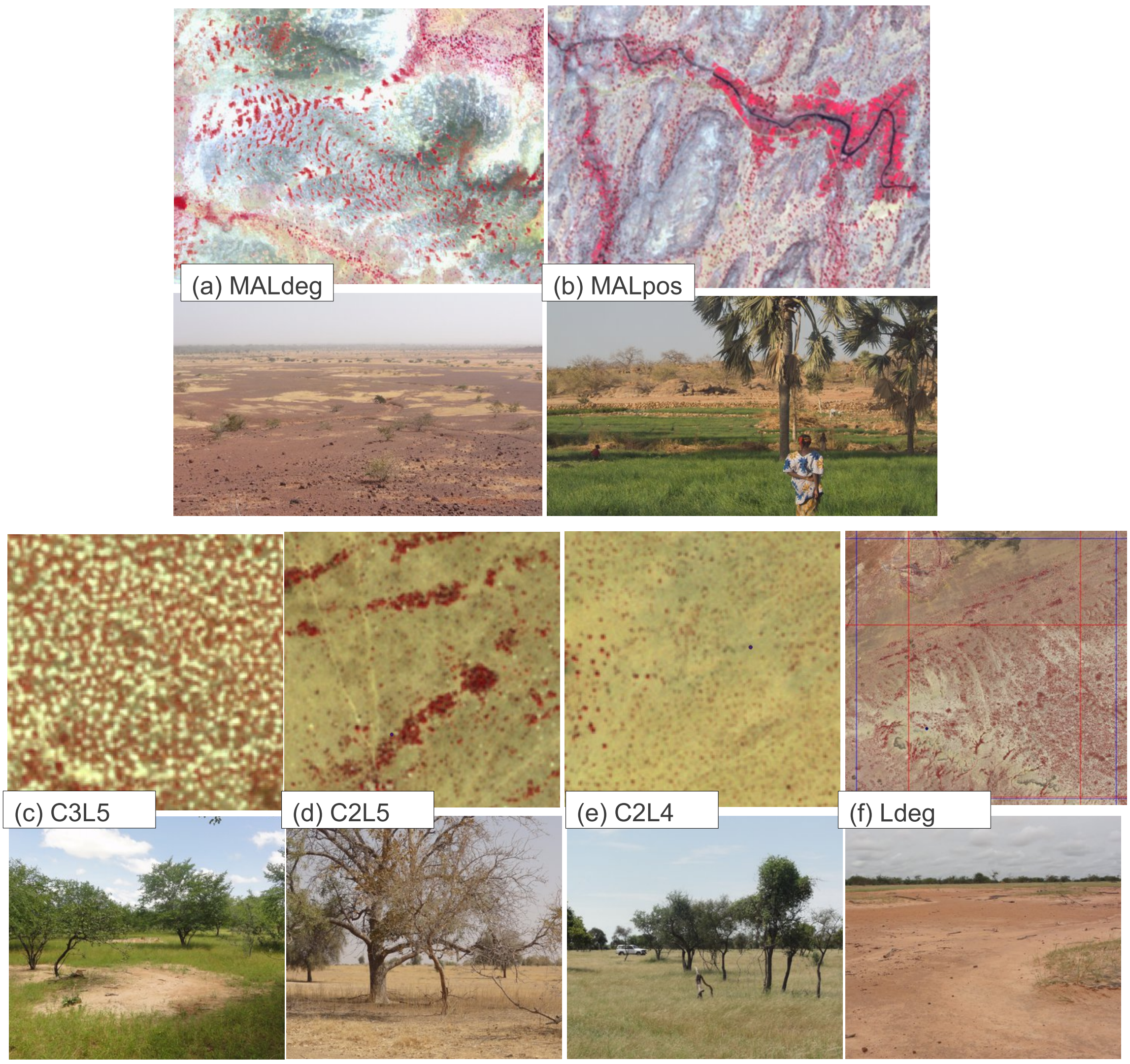
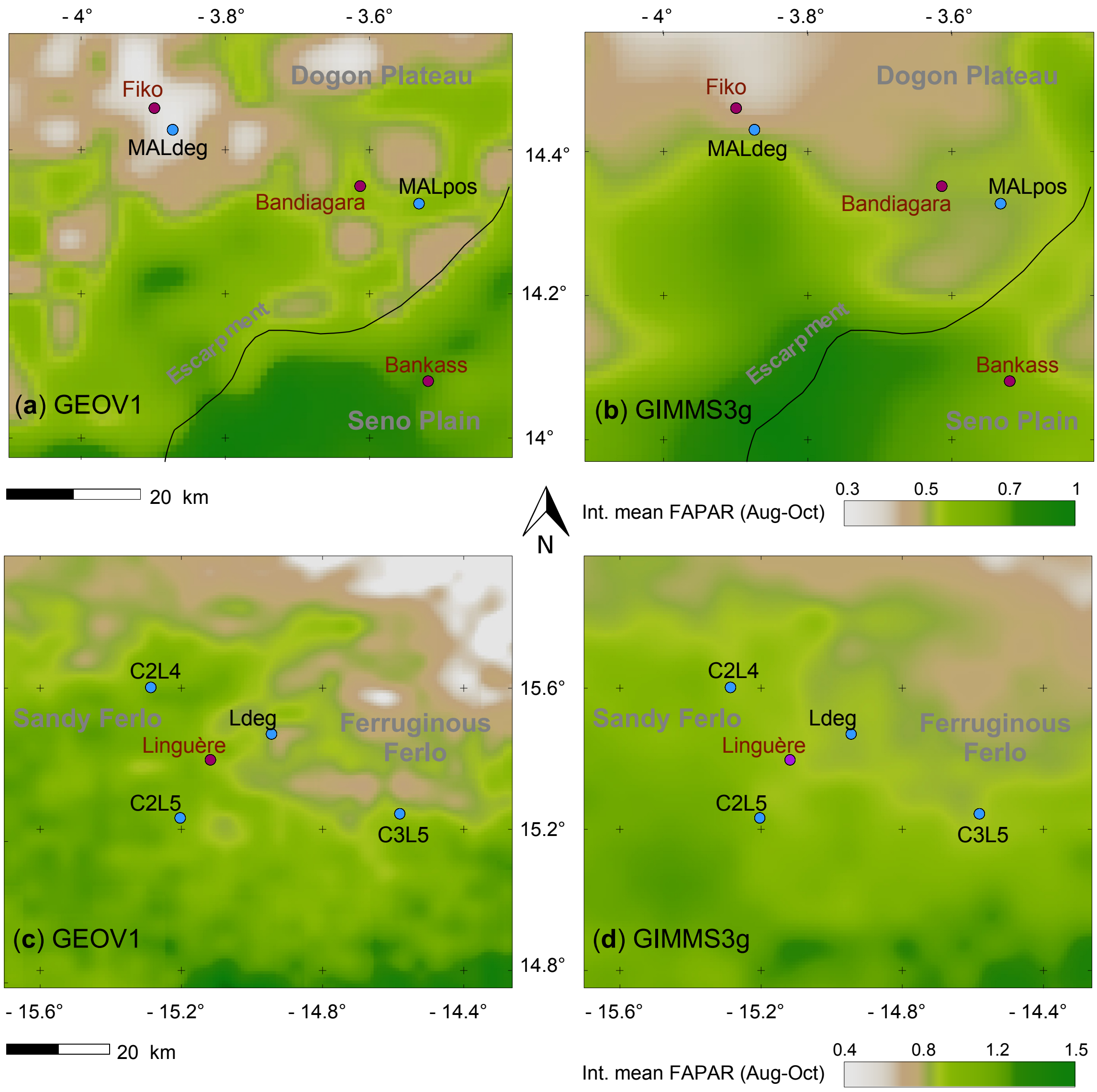


Figure 2. Accumulated FAPAR for mean rainy season (August-October) of GEOV1 FAPAR (left) and GIMMS3g FAPAR (right) from 1982 to 2010. Banidgara (**a**,**b**) and Linguère (**c**,**d**) regions both show a good agreement between the two datasets with more details in GEOV1. Sandy areas can be distinguished from lateritic sections (Dogon Plateau in Mali and ferruginous Ferlo in Senegal). In Mali, the Bandiagara escarpment separates the Dogon Plateau from the Seno Plain around Bankass. All rasters were interpolated to a spatial resolution of 1 km by a bicubic interpolation method for a better visual inspection and interpretation. No quantitative information is lost nor added by applying this method.



South-east of the Bandiagara escarpment, the Seno Plain represents a different morphological zone (Figure 2). In the absence of rocks and laterite, Dogon and Fulani farmers cultivate almost 90% of its deep sandy soils. In 1967, about 40% were still covered by dense bushland, which was cleared due to human expansion and the need for cropping land [31].

2.1.2. Linguère (Sahel of Senegal)

The Ferlo region around the Senegalese city Linguère forms our second study area. The ferruginous part lies east of Linguère and was severely affected by droughts in the 1970s and 1980s with a remarkable reduction of tree density [2]. Especially in the past 10 years, the vegetation has been recovering with increasing rainfall, but deforestation and degradation are also apparent, mainly along ancient valleys and in proximity to wells and villages [8]. The region has shallow and unfertile soils with laterite exposed at many sites. It belongs to the silvo-pastoral zone and therefore agriculture and settlements are rare in the whole area, which is used by Fulani herders for livestock grazing. Much of the dense bushland has never been cleared and woody vegetation is a shrub and tree savanna with *Pterocarpus lucens, Guiera senegalensis* and *Boscia senegalensis* prevailing. Test sites *C3L5* and *Ldeg* both lie within this area, representing oppositional stages of degradation. While *C3L5* consists of a relatively dense woody vegetation (Figure 1c), *Ldeg* is seriously degraded (Figure 1f). As most of the trees were felled or died during droughts, soil erosion caused a loss of upper soil and remaining vegetation can only be found in small clayey depressions.

The sandy Ferlo west, south and north of Linguère is infrequently used for cropping and strongly influenced by human activities. It consists of sandy fossil dune soils, of which approximately 15% are cultivated by Wolof farmers. Most of the bushland has been cleared in the 20th century and the current woody vegetation is an open tree and shrub savanna dominated by *Balanites aegyptiaca, Acacia raddiana* and *Combretum glutinosum*. Drought resilience of these species growing on sandy soils is good, thus overall tree mortality was moderate during the dry period (1970s–1990s). Test sites *C2L5* and *C2L4* are both situated within this area. South of Linguère, *C2L5* represents the southern part of the sandy Ferlo, which is dissected with clayey and forested depressions and mainly used for pasture purposes and small scale cropping (Figure 1c, Table 1). *C2L4* is located north of Linguère. Parts of the region used to be cultivated but recently lie fallow due to a lack of rain. Trees and shrubs in this area are severely affected by human impact (Figure 1d, Table 1).

2.2. FAPAR Time Series

Global GEOV1 FAPAR time series derived from AVHRR LTDR (1981–2000) and from VGT (1999-present) data have been recently delivered within the Geoland2 project. Products are freely available at 10-day time intervals and approximately 5 km (1 km) for AVHRR (VGT). The GEOV1 VGT FAPAR product is based on a combination of already existing products to take advantage of their specific performances while limiting the situations where products show deficiencies. In line with the published literature on products validation, the MODIS and CYCLOPES [28] products are selected since they provide higher level of consistency [33]. The selected products are combined and eventually scaled to compute the fused product that is expected to provide the best performances globally. Neural networks are then calibrated to relate the fused products to the corresponding VGT L3a top of canopy directionally normalized reflectances [34]. The GEOV1 AVHRR algorithm aims to ensure robustness and consistency of the derived FAPAR product with GEOV1 VGT. The approach is based on the use of neural networks to mimic the GEOV1 VGT product using AVHRR LTDR reflectances and dedicated temporal smoothing and gap filing techniques to improve the consistency and continuity of the derived time series. Further information are available in Baret *et al.* [22] and Verger *et al.* [23].

Similarly as in GEOV1, the principles used for the generation of GIMMS3g FAPAR are based on the use of neural networks to mimic an existing product, in this case, the MODIS FAPAR [21,34]. A neural network algorithm is first trained using both the NDVI GIMMS3g and MODIS FAPAR products over the overlapping period 2000–2009. The trained neural network algorithm is then applied using the land-cover class, pixel-center latitude, pixel-center longitude, and NDVI3g as inputs to generate time series of FAPAR from July 1981 to December 2011 at 15-day temporal steps and 1/12 degree (about 8 km) spatial resolution over the globe. For further information, we refer to Zhu *et al.* [21].

For this study, monthly MVCs (Maximum Value Composites) were produced for both FAPAR datasets to derive temporally identical time series and to further eliminate contamination by clouds and atmospheric disturbances. With the assumption that exceptional low values are contaminated, the highest value of each month was selected. Figure 2 presents the accumulated GEOV1 FAPAR and GIMMS3g FAPAR over the period 1982 to 2010 for the mean rainy season (August-October) in the Bandiagara and Linguère regions. Here, the spatial pattern and range of values for both products show a good agreement for both study areas. Ferruginous zones (Dogon Plateau in Mali and ferruginous Ferlo in Senegal, see Figure 2) can be distinguished from sandy zones, which are more productive and thus have a higher FAPAR. GEOV1 reveals more details and illustrates more spatial heterogeneity within these zones.

2.3. Time Series Analysis

Prior to the trend analysis, a pixel-wise Durbin-Watson test was carried out, which revealed significant autocorrelation in the monthly time series of both FAPAR datasets (values between 0.5 and 0.8 ($p \leq 0.05$)). Therefore, in order to correct for autocorrelation and to filter out remaining noise, we applied a Seasonal Trend decomposition based on Loess (STL) to the monthly MVCs [35]. Here, a local regression was used to decompose a times series into seasonal, yearly and noise components. For every pixel and each year, the yearly component was extracted and further processed. Using the de-noised yearly component has the additional advantage that singular seasonal effects are not overestimated and adds focus on the evergreen woody layer [36]. This produces trends that are more significant and detects subtle gradual changes. A linear regression was applied for each pixel to the preprocessed datasets with the yearly components for the period 1982–2010. The slope of the yearly components was derived to quantify the direction and magnitude of the overall trend. Slope values were recalculated to FAPAR units by multiplication with the number of years to express the total change over time. Only pixels with a confidence level of 95% ($p \leq 0.05$) were further processed.

For reasons of comparability and to avoid unit inconsistencies, annual anomalies in percent were calculated for rainfall, integrated FAPAR and biomass data for the period 1987 to 2010 by dividing each individual year through the long-term mean. Here, annually integrated FAPAR is used instead of decomposed components to obtain comparable results with previous studies [37].

2.4. Validation and Interpretation Data and Methods

2.4.1. Qualitative Information

Fieldwork was conducted during the dry seasons 2011 and 2012 (February–April) and the rainy season 2012 (September, October). In close collaboration with local scholars, several natural scientists visited the two study areas and collected qualitative and quantitative information on woody coverage and species composition [38], soil erosion and degradation processes [39] as well as impact of humans and livestock on soil and vegetation. In addition, several social scientists conducted interviews in nearby villages to gather information on people's perception on the local climate, environment in general, woody cover and species, crop yields and capacities of pasture. Local people were questioned regarding recent conditions as well as environmental change over the past 30 and 50 years. Within the present study, this qualitative information strengthened the knowledge about the study areas and offered explanations on the causative factors for vegetation trends. More details on interview techniques and the applied field-methods can be found in Brandt *et al.* [8].

2.4.2. Quantitative Information

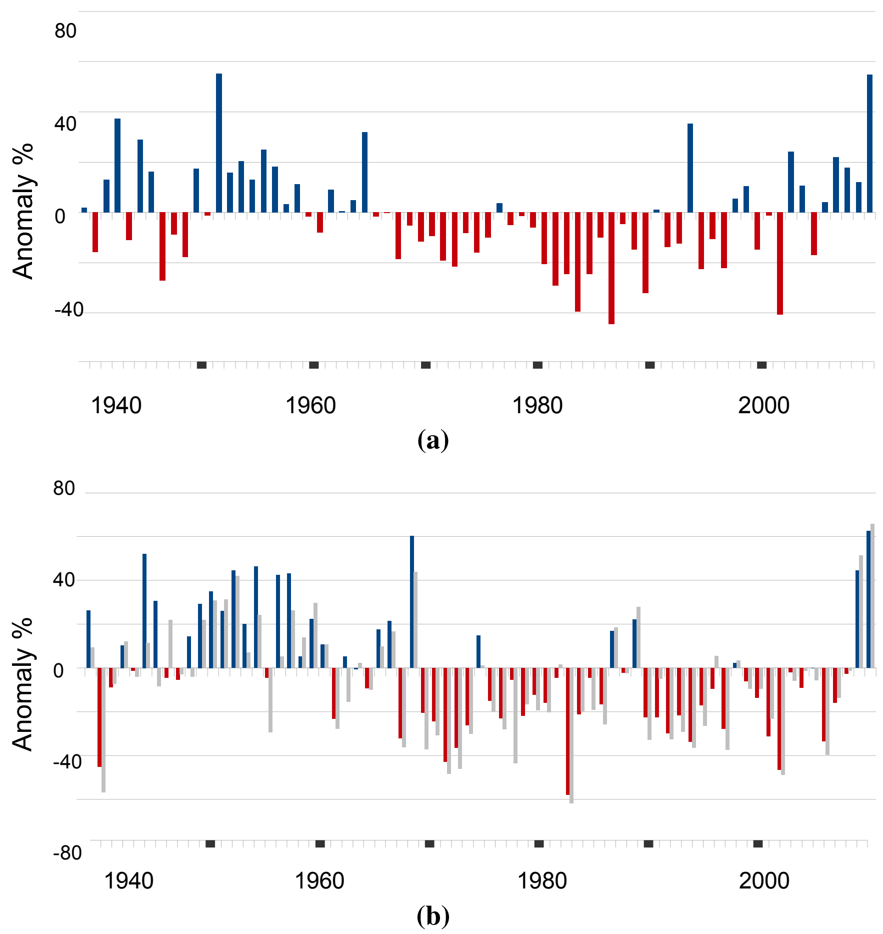
Biomass Observations

In the Bandiagara region, no long-term field data is available but the Gourma region further north has been the object of detailed studies. Dardel *et al.* [9] have shown that a good correlation between GIMMS3g NDVI time series and 27 years of field observations is present in Gourma (R^2 = 0.57). The CSE (Centre de Suivi Ecologique) collects biomass data throughout Senegal each year at the end of the rainy season at 36 sites, although only three are located in our study area (*C3L5*, *C2L5* and *C2L4*). Most of the sites date back to 1987, representing areas of relatively homogeneous vegetation and soil. Trees, shrubs as well as the herbaceous layer were surveyed with a stratified sampling method based on transects and quadrats in an area of about 3 × 3 km to calculate green biomass in kg DM (Dry Matter) / ha for the woody and herbaceous layer separately. The stratification for the herbaceous production was based on the estimated production level of a vegetation type. Depending on the heterogeneity, up to 50 samples along a 1 km transect were collected. In a second step, 200 g samples were collected for each production level of green biomass and dried in an oven. The leaf production of trees was calculated using four quadrats of up to 1 ha which were placed along the line transect. Within the quadrats, trees were surveyed and woody production estimated by allometric relationships relating trunk circumference with typical production values of the species. Leaf production variations of individuals were calibrated by the ratio of leaf dry-weight of branches divided by standard branch values. After drying of samples and calculation of dry matter (herbaceous and leaves), the biomass production was estimated and extrapolated using a linear regression equation between dry matter samples and integrated NDVI (SPOT VGT). For information on data collection and biomass calculation methodologies, we refer to Diouf & Lambin [37] and Diallo *et al.* [40].

Although the comparison of field measured above-ground biomass with remotely sensed greenness indexes (e.g., NDVI or FAPAR) is not trivial, several studies agree that a strong relationship exists. Fensholt *et al.* [41] compared 13 of the CSE sites throughout Senegal with integrated MODIS MOD15

FAPAR for the year 2001, finding a good consistency (R^2 = 0.72). Diouf & Lambin [37] correlated integrated NDVI from a local AVHRR receiving station with 12 CSE biomass monitoring sites between 1987 and 1997. They conclude that a strong relationship exists (R^2 = 0.68 in average), however, with large inter-annual variations, making NDVI a reasonable but not a robust proxy for biomass estimation in the Senegalese Sahel. Mbow *et al.* [42] discovered that species composition has a significant effect on the relationship between NDVI and biomass at a test site near Dahra, west of Linguère. The spatial unit size differences between ground sample areas and AVHRR pixels constitutes another source of error. The scope of this study is not a 1:1 comparison but to find investigate if (1) the direction; (2) the magnitude and (3) spatial discrepancies of long-term FAPAR trends correspond with ground data.

Figure 3. GPCC annual rainfall anomalies in percent for the period 1940–2010 averaged over the study areas of (**a**) Mali and (**b**) Senegal. Linguère weather-station data is included in (**b**), indicating that gridded GPCC data corresponds well with ground-measured station data (grey columns). Note the extraordinary dry period in the 1970s and 1980s. Data after Schneider *et al.* [45]. (**a**) Mali; (**b**) Senegal.



Rainfall Data

In the Sahel, annual vegetation fluctuations are largely controlled by precipitation [43]. To better interpret the detected trends in FAPAR, rainfall data from local meteorological stations and from the Global

Precipitation Climatology Centre (GPCC) dataset was included. The data is available for the Linguère weather station since 1933 [44] and since 1901 at a 0.5° grid from the GPCC precipitation database v6. The 0.5° grids are created by interpolating station data over approximately 90.000 weather stations globally [45]. GPCC data is consistent with local station data (see Figure 3b) and thus suited for further analysis. The two considered regions around Bandiagara in Mali (Figure 3a) and Linguère in Senegal (Figure 3b) have considerable intra- and inter-seasonal rainfall variability with almost the entire annual rainfall falling between June and October. After a wet period in the 1950s and 1960s, rainfall dropped far below average in both study areas from the 1970s to the 1990s. Since then, annual precipitation is increasing again, in Bandiagara more rapidly than in Linguère. Recently, mean annual rainfall lies around 430 mm in Linguère and 550 mm in Bandiagara.

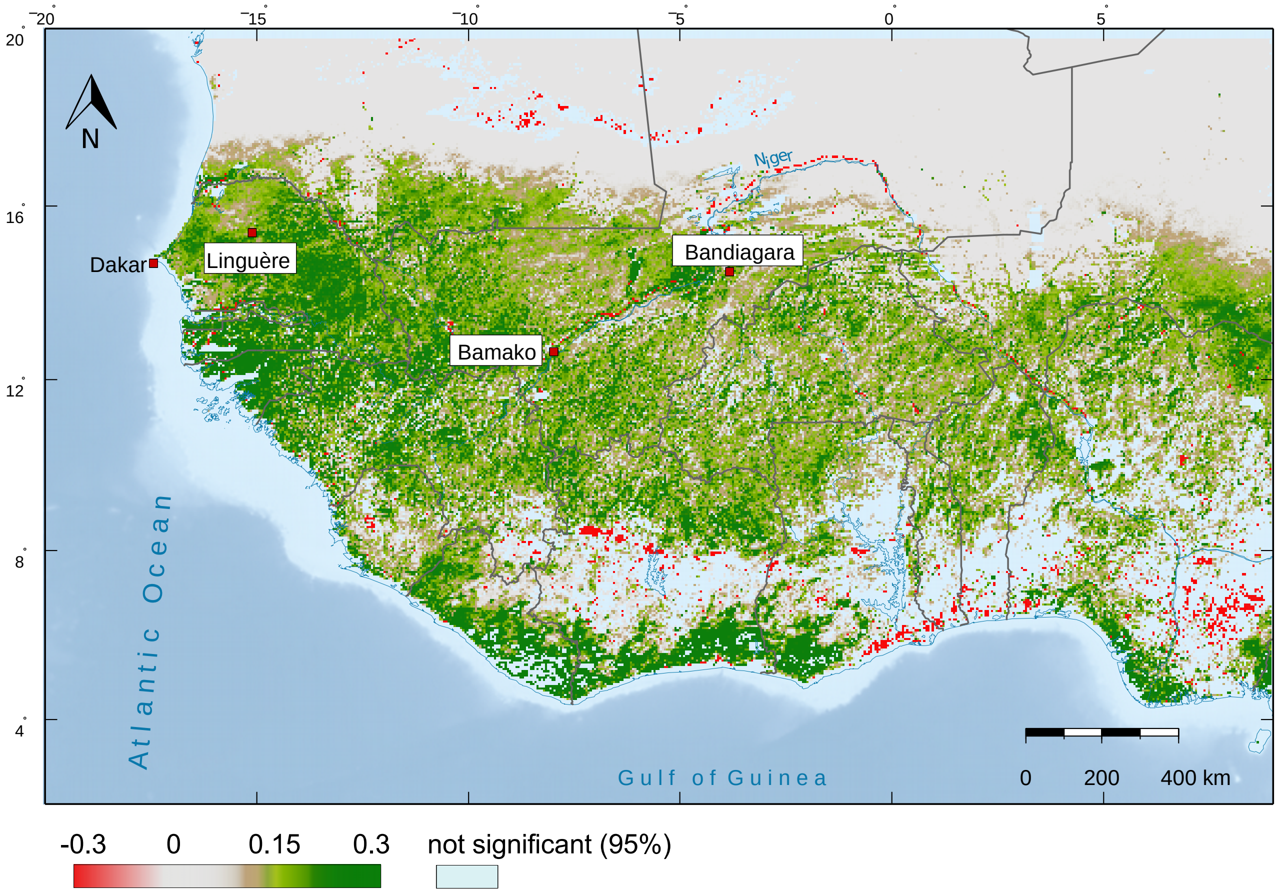
3. Results

We first present results of FAPAR trend analysis on a continental level showing vegetation change for Western Africa. We then move on to a regional level choosing two Sahelian study areas, one around Bandiagara (Mali) and one around Linguère (Senegal). The trend patterns in the study areas are examined by means of six local case study sites and supported by qualitative and quantitative ground data.

3.1. Trend Analysis of Western Africa

Figure 4 illustrates significant FAPAR change for Western Africa using the GEOV1 product. Especially in the south, large areas remain insignificant due to permanent clouds in the VGT data, while the processing of AVHRR proves to be more stable here [23]. Large parts of the Sahel and Western Africa reveal significant positive change (about 65%), confirming the re-greening hypothesis [9], but also negative change is detected (about 1%). Negative change mostly correspond to large areas of deforestation, vegetation loss and land-cover change, especially in Nigeria, Togo and Ghana [46,47]. FAO statistics detect an annual deforestation rate of up to 4% between 1990 and 2010 in these countries [47], providing a possible explanation for the negative change. On the other hand, a positive change does not necessarily mean an increase in forest-cover but in biomass, which crops and grass can also cause. In 12 of 14 countries, forest-cover is decreasing, whereas most of them have a positive trend within the same time frame [46,47]. For a better understanding of the processes behind changes, it is inevitable to break down the scale to a local level.

Figure 4. GEOV1 FAPAR change map of Western Africa (1982–2010). The map shows the slope of a linear regression with monthly MVCs multiplied by their number. Study areas are located around Linguère and Bandiagara.



3.2. Local Trend Patterns

3.2.1. Bandiagara (Sahel of Mali)

Corresponding to increasing rainfall (Figure 3a), the Malian study area has a general positive greenness trend with major spatial discrepancies seen in Figure 5a,b. The magnitude and spatial distribution of changes differ between the two FAPAR data products. However, both GIMMS3g and GEOV1 FAPAR agree that (1) stronger positive areas are present on the Dogon Plateau around Bandiagara (Figure 5a,b); and (2) neutral or slightly positive trends indicating less productive areas are located in a large area south of Fiko (marked with *MALdeg* in Figure 5a,b). Around *MALdeg*, most parts of the formerly dense tiger-bush were cleared by human expansions and the need for cropping land in the 1960s but abandoned few decades later becoming bush-fallows again [30]. Beyond the currently active fields, bush-fallows are used for tree cutting with and without permits. This increased in times of drought and little rainfall, as selling trees is an established compensation for harvest losses. In combination with droughts, dry periods, floods and large livestock numbers, *MALdeg* has turned into a desert-like vast-land (see Figure 1a), which is recognized in the trend maps but spatially overestimated in GIMMS3g

(Figure 5a,b). The temporal profiles of *MALdeg* in Figure 6a provide evidence of the low productivity and demonstrate that the degradation process began prior to the start of the time series (1982). However, degradation is still active, as FAPAR has decreased in the past decade, despite increasing precipitation (Figure 3a).

Figure 5. FAPAR change in the Bandiagara (**a**,**b**) and Linguère (**c**,**d**) region from 1982 to 2010 as evaluated with the GEOV1 FAPAR product (left), as well with the GIMMS3g FAPAR product (right). Trends were derived using the STL method and reveal a very heterogeneous pattern. The important differences in the magnitude of change for GIMMS3g and GEOV1 prevents the use of the same color bar. Lateritic areas show a much higher change than sandy ones in both study areas and degraded and deforested spots can be identified in GEOV1 change maps. Those spots are merged in GIMMS3g.

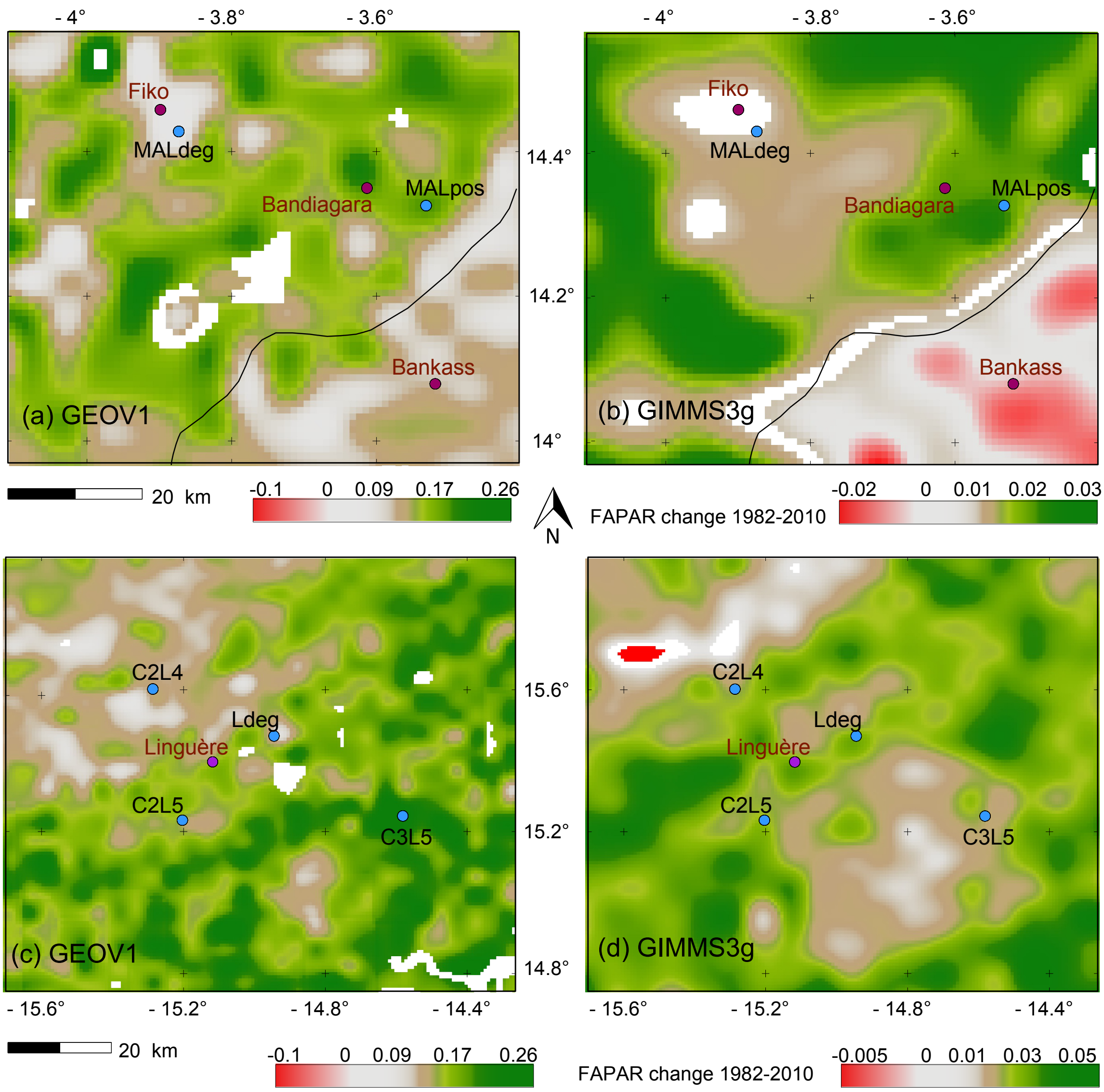
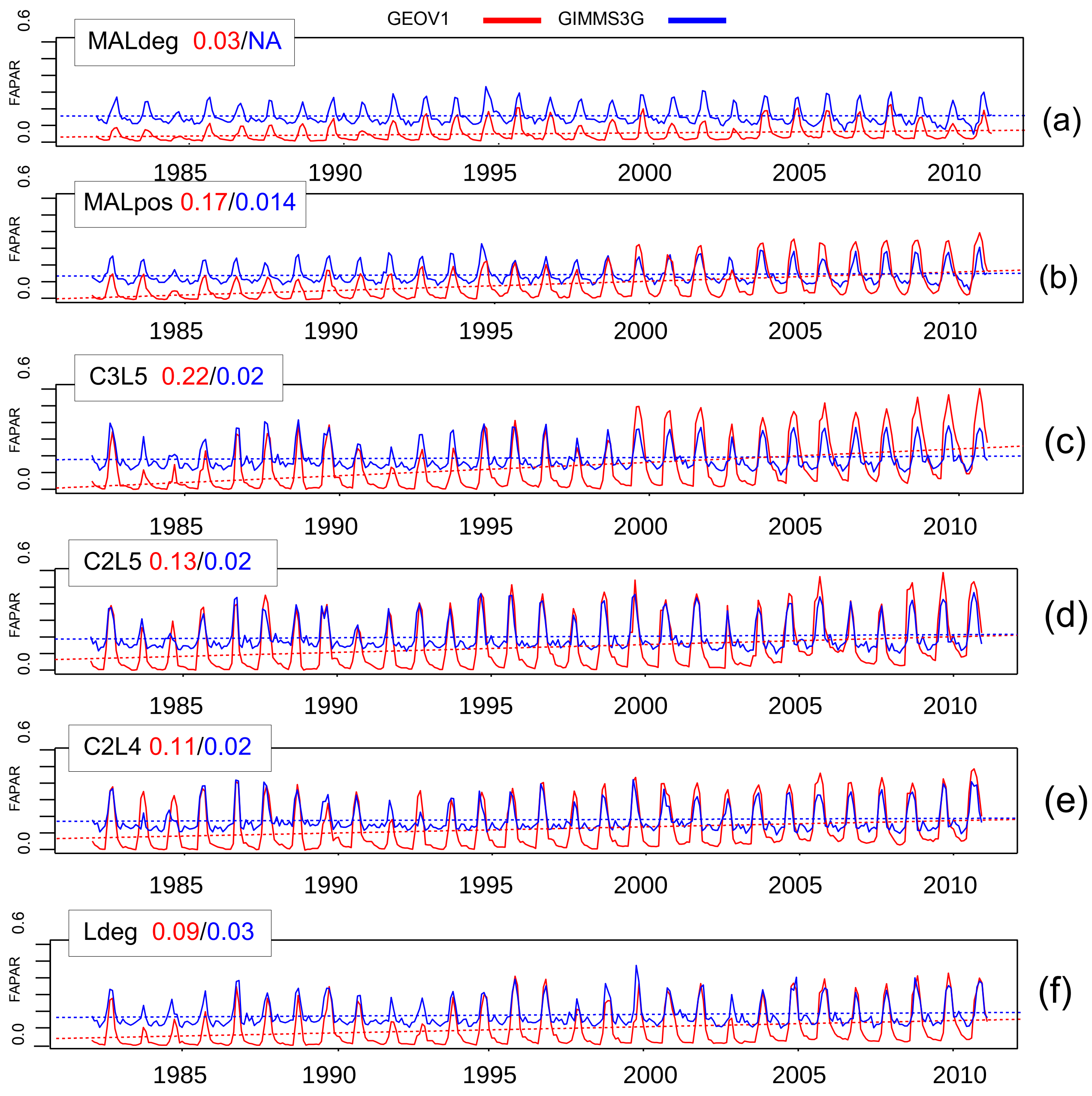


Figure 6. Temporal profiles extracted from the pixel overlaying two sites near Bandiagara (**a**,**b**) and four sites around Linguère (**c–f**) from 1982 to 2010. The numbers (top left) indicate change in FAPAR units. Profiles (a) show a large degraded area, which is the reason for a very small positive trend in GEOV1 and insignificy in GIMMS3g, despite of increasing rainfall; Profiles (**b**) are extracted over onion plantations, which were established after the year 2000 and therefore a strong positive trend can be observed in GEOV1. Site *C3L5* (**c**) reacts to rainfall changes and therefore had a strong positive trend in the past decade. Drought years (especially 1983 & 1984) and the related damage on vegetation are clearly visible. The open tree savannas (**d**,**e**) have a moderate positive trend. Drought years are tempered better than in all profiles with lateritic soils. Temporal profiles (**f**) show a largely deforested and degraded area with a slightly positive trend.



As an example of positive change on the plateau, an area east of Bandiagara was chosen. Onion plantations were established around *MALpos* after the year 2000 (see Figures 1b and 6b). These fields stay green long into the dry season due to irrigation. Cultivation activities in combination with drought-regeneration of semi-natural bushland, agro-forestry on fields, reforestation and tree protection laws, strongly influence the overlaying FAPAR pixels causing positive changes and prevailing greening areas on the entire Dogon Plateau. However, a share of almost 10% are deforested and seriously degraded [31], not following the greening trend. GEOV1 (Figure 4a) reveals more spatial discrepancies and details than GIMMS3g FAPAR, showing a variety of adjacent degraded and greening areas northeast of the escarpment (Figure 5a). According to the prevailing trend, those heterogeneous areas are merged in GIMMS3g to large areas of greening, irrespective of the degradation (Figure 5b).

On the Seno Plain around Bankass, droughts caused less damage to the woody vegetation on deep sandy soils as compared to the rocky plateau around Bandiagara. Nevertheless, human expansion and impact has been much greater. Thus, natural regeneration and greening is generally lower in the Seno Plain as observed in Figure 5a,b. However, trends of GIMMS3g and GEOV1 FAPAR show different directions of change with a slightly positive trend in GEOV1 and a negative trend in GIMMS3g data. As most clearing of the dense bushland ended prior to the start of the time series, a positive trend is expected here as supported by several studies reporting large scale plantings, regeneration after droughts and an overall increase of tree cover in the last decade [8,31,48].

3.2.2. Linguère (Sahel of Senegal)

Depending on soil, morphology, land-cover, human impact and drought resilience, areas react differently to rainfall changes, causing different magnitudes of trends (see Figure 5c,d). As rainfall is increasing over the past years (see Figure 3b), negative trends are almost not observed in both time series products. Clear differences in changes between the lateritic eastern and the sandy western areas exist. Droughts and dry years in the 1980s but also 1990s caused considerable damage to trees and shrubs on shallow lateritic soils in the east, visible in the temporal profiles of Figure 6c,f. The sandy soils in the west have a larger water storage capacity helping to temper the effects of droughts [2]. This can also be seen in the profiles of Figure 6d,e. Regeneration and therefore trends are thus much higher on lateritic soils (Figure 5c,d).

Despite the overall regeneration, the GIMMS3g FAPAR trend map shows that areas of less positive trends exist in the eastern region (see Figure 5d). GEOV1 FAPAR has a clearer spatial pattern than GIMMS3g, better differentiating between deforested and densely vegetated zones east of Linguère (Figure 5c). Thus the spatial pattern between the GIMMS3g and GEOV1 products is similar, but still critical disagreements are found at local scale.

Two oppositional test sites were chosen, one with an obvious positive woody vegetation trend (*C3L5*), and one with a large share of degraded land (*Ldeg*). The temporal profiles in Figure 6f confirm that since 1982 the trend at *Ldeg* is slightly positive due to small forested depressions which react to increasing rainfall. The monitored area is small (around 5 $\times$ 5 km) and surrounded by dense bushland in the east and peanut fields in the north and west. The RapidEye image in Figure 1f shows that an 8 km grid is incapable of capturing this area correctly. In a pixel of 8 km spatial resolution the degraded area is mixed with adjacent land cover which explains the positive pattern around *Ldeg* in

Figure 5d (GIMMS3g). Site visits showed that site *Ldeg* is an example for a degraded area where woody coverage is now only found in small clayey depressions. In the year 1965 the area was still covered by dense bushland [8] but nowadays most of the shallow soil is washed away and woody and herbaceous vegetation is very scarce here (see Figure 1f). Along with the unfavorable morphopedological characteristics and the proximity to several larger villages (e.g., Kol Kol, Kadji, Dodji), excessive browsing, cutting of living trees and livestock grazing are responsible for this development.

On the contrary, *C3L5* has a positive trend (Figure 6c), caused by a denser woody vegetation. GIMMS3g does not capture this area correctly, as it is merged with a degraded area south of Barkedji, which is spatially overestimated in GIMMS3g. Information gathered in interviews confirm that tree mortality was high during the droughts in the 1980s and 1990s, also seen in Figure 6c. Additionally, the proximity to the national road makes this site vulnerable to the exploitation of woody products and thus this site was reported as degraded with a massive reduction in tree cover in the 1990s [37]. However, temporal profiles in Figure 6c and site visits (Figure 1c) reveal a dense woody vegetation and positive trend for the past decade.

3.3. Validation and Interpretation of Trends by Ground Observations

3.3.1. Validation and Interpretation by Biomass Data

CSE biomass data at *C3L5* provides evidence of increasing leaf biomass between 1987 and 2010 (see Figure 7a) and thus proves that the GEOV1 trend (Figure 5c) and temporal profile (Figure 6c) are realistic. Inter-annual variability is very high, but after low values in the 1990s, leaf production is increasing rapidly (see Table 2), especially in the past decade, and corresponds well with integrated GEOV1 FAPAR (Figure 7a and Table 2). This phenomenon can not only be observed at the ferruginous test site *C3L5* but also at the sandy sites *C2L5* (Figure 7b) and *C2L4* (Figure 7c) with significant leaf biomass increases. Again, this can be confirmed by GEOV1 FAPAR with similar increases at *C2L5* and *C2L4* (Table 2). Since leaf biomass of woody species has almost doubled at our test sites, this is a clear sign of regeneration after an extraordinary dry period and its related consequences, beginning in the 1970s until the late 1990s (see Figure 7 and Table 2).

In contrast to the steep positive trend of the woody layer, a significant trend cannot be detected regarding the herbaceous biomass at all three test sites (see Figure 7a–c). Instead, major inter-annual fluctuations are observed, with a negative tendency at all three sites (see Table 2). This is obscured by the woody layer, which causes an overall positive trend. This is particularly true for *C3L5*, with a strong positive trend in total biomass and FAPAR, but an insignificant negative trend in herbaceous biomass, in spite of increasing rainfall (see Figure 7a and Table 2). This is explained by soil erosion caused by water and livestock, leading to a spreading of bare soil at this site. Currently, it only affects the herbaceous layer. This phenomenon is hidden in our time series by a dense woody canopy cover and is an example for erosion and degradation obscured by greening. At the sandy test sites *C2L5* and *C2L4*, the negative trends in herbaceous biomass are mainly caused by extraordinary high values at the end of the 1980s (Figure 7b,c). Those herbaceous biomass peaks often occur after drought years and are caused by (1) the absence of livestock after severe drought years and the subsequent accumulation of biomass;

(2) fertilization by dead-wood and (3) accumulation of seeds. Moreover, a change in the herbaceous species composition could be responsible for inter-annual biomass fluctuations [42].

Figure 7. Anomalies of CSE biomass at monitoring sites *C3L5* (**a**); *C2L5* (**b**) and *C2L4* (**c**) and integrated GEOV1 FAPAR from 1987 to 2010. Note that biomass data is not available for each year. The plots give evidence of important conclusions: (1) large inter-annual discrepancies between biomass and FAPAR are not an exception; (2) the leaf biomass shows a strongly positive trend at all three sites and thus supports the FAPAR trend. Most leaf biomass and FAPAR anomalies before 2000 are negative, whereas they are mostly positive after 2000. This is an obvious sign for drought recovery; (3) No clear trends can be observed concerning the herbaceous biomass. Rather degradation is observed, especially at *C3L5*, as it does not increase with rainfall.

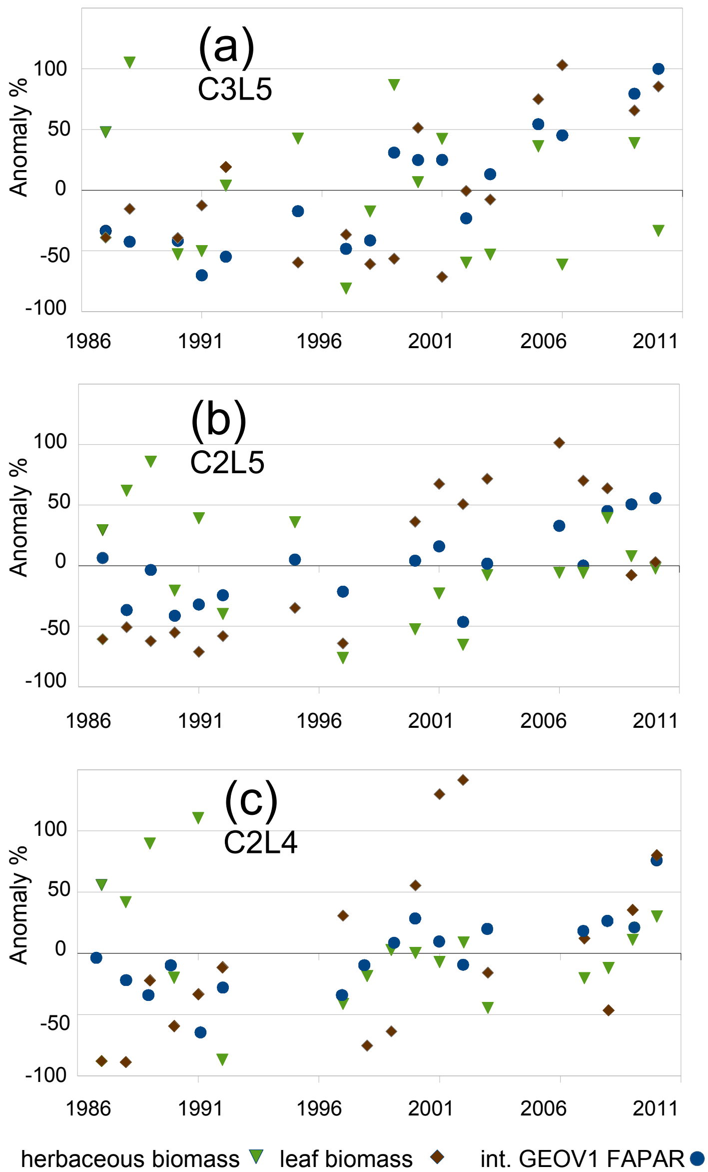
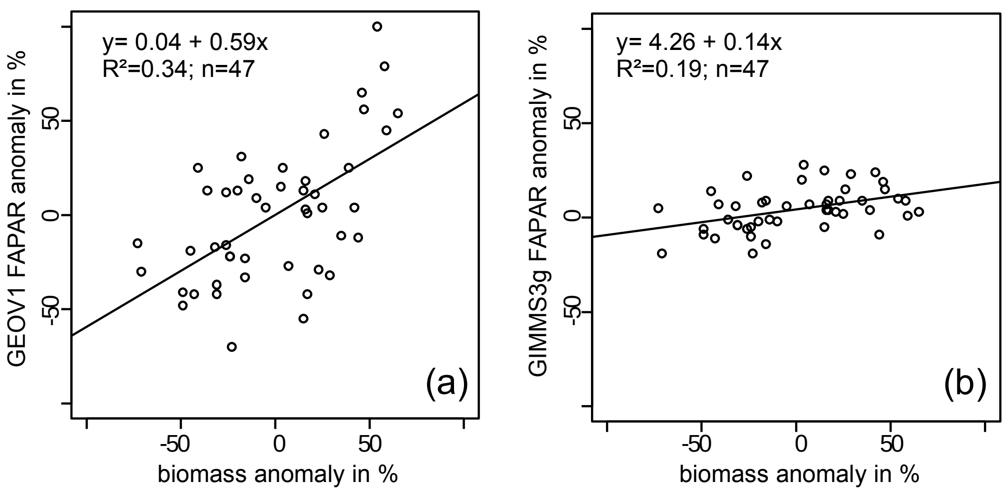


Table 2. The first four rows show vegetation change derived from linear regression for sites around Linguère (Senegal) for the period 1987–2010. ** = significant at 95%; * = significant at 90% confidence level. Units are FAPAR and DM kg/ha. The change is calculated as the slope of annual values and multiplied by the number of years. It is further divided by the long-term mean to derive change in percent, shown in brackets. Note that a relationship between GEOV1 FAPAR and biomass trends is present and that FAPAR change increases with mean leaf biomass present.

	C3L5	**C2L5**	**C2L4**	**Ldeg**
GEOV1 FAPAR change	+0.22 [104%] **	+0.12 [55%] **	+0.11 [38%] **	+0.09 [8%] **
GIMMS3g FAPAR change	+0.011 [7%]	+0.012 [3%]	+0.012 [4%] **	+0.017 [10%] *
total biomass change	+1025 [59%] *	+149 [10%]	+140 [13%]	
leaf biomass change	+1172 [93%] **	+462 [101%] **	+174 [78%] *	
herb. biomass change	−147 [−30%]	−313 [−28%]	−34 [−4%]	
mean leaf biomass	1254	457	222	
mean herb. biomass	485	1085	865	

By correlating integrated FAPAR with the total biomass for the monitoring sites *C3L5*, *C2L5* and *C2L4*, a highly significant relationship ($p \leq 0.01$) for both FAPAR products (Figure 8) is obtained. For these sites, GEOV1 proves to be somewhat more reliable (Figure 8a; $R^2 = 0.34$) than GIMMS3g (Figure 8b; $R^2 = 0.19$). However, even if a relationship between both FAPAR products and above-ground biomass observations is given, neither GEOV1 nor GIMMS3g prove to be robust proxies for biomass estimation in this area.

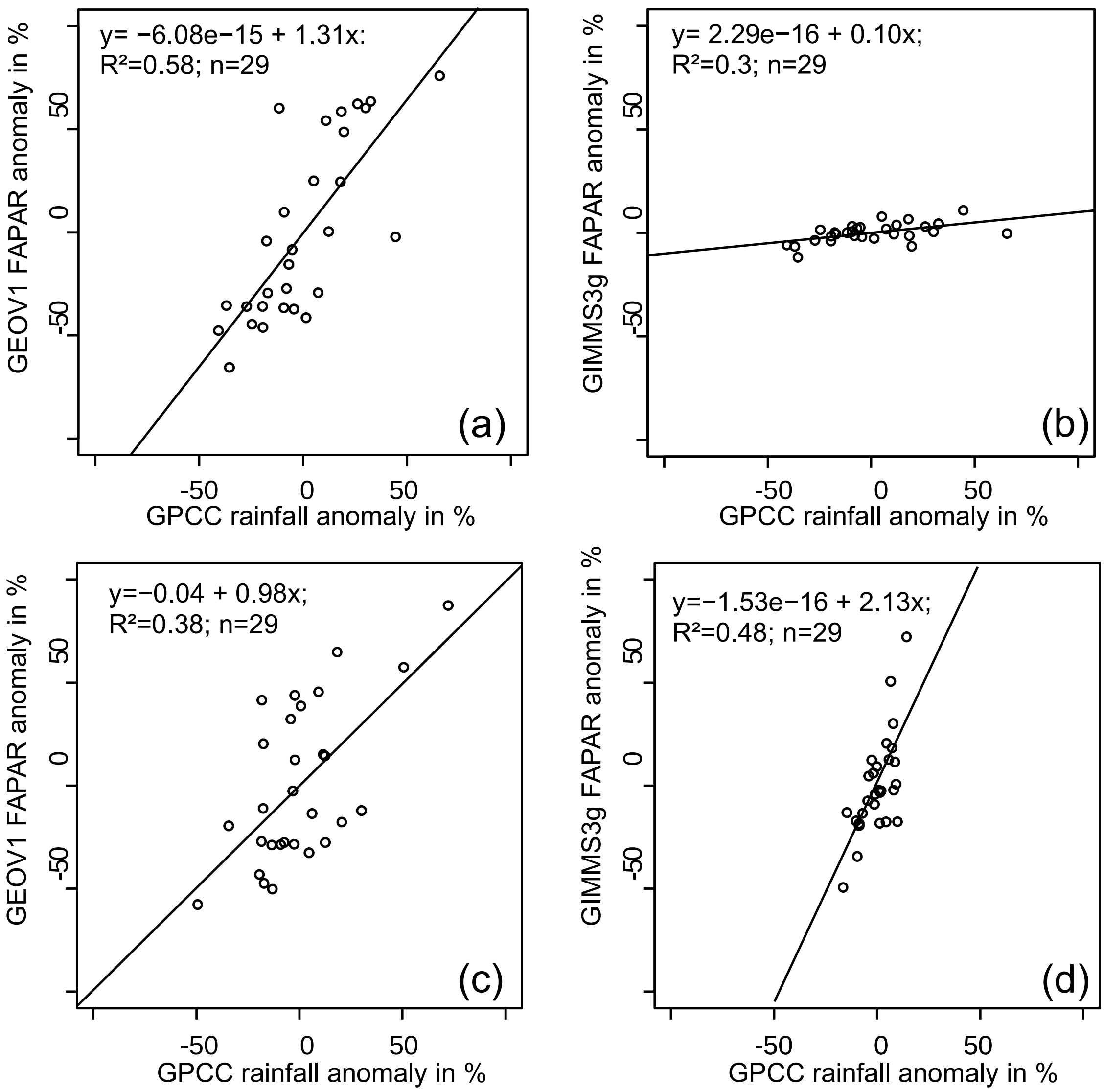
Figure 8. Scatterplots between ground based biomass (sites *C3L5*, *C2L5*, *C2L4*) and GEOV1(**a**)/GIMMS3g (**b**) pixel values obtained over the monitoring sites from 1987 to 2010. The relationships are not strong, but highly significant ($p \leq 0.01$). Inter-annual discrepancies between observed biomass and satellite derived FAPAR are high, thus neither GEOV1 nor GIMMS3g FAPAR are robust proxies for biomass estimation.



3.3.2. Validation and Interpretation by Rainfall Data

In the period 1982–2010, rainfall around Bandiagara shows a considerable increase which is significant at the 99% confidence level (+281 mm; 54%; $p \leq 0.01$). According to Figure 9a,b, a relationship between annual rainfall and annual FAPAR exists over the entire Malian study area, explaining 58% (GEOV1) and 30% (GIMMS3g) of the variability. This is confirmed by the second study area around Linguère, where rainfall increased by +142 mm (34%; $p \leq 0.1$) over the same time period with 38% (GEOV1) and 48% (GIMMS3g) of annual FAPAR anomalies being explained by annual rainfall fluctuations (Figure 9c,d respectively). These numbers give evidence that at regional scale precipitation explains much of the FAPAR variations.

Figure 9. Scatterplots showing relationships between annual rainfall (GPCC) and annual FAPAR anomalies averaged over the study areas around Bandiagara (**a**,**b**) and Linguère (**c**,**d**) for the period 1982–2010 (29 years).



Correlating yearly CSE biomass *vs.* annual precipitation anomalies (1987–2010) verifies that rainfall is a causative factor for local vegetation change and variations (R^2 = 0.22; $p \leq 0.01$) at the sites *C3L5*, *C2L5* and *C2L4*. Exactly the same result is obtained when correlating integrated GEOV1 FAPAR pixel values from the same sites against annual precipitation (R^2 = 0.22; $p \leq 0.01$), confirming the weak but highly significant relation. The weak correlation can be partly explained by local rainfall variations and the distance to the weather station. Moreover, Diouf & Lambin [37] state that locally the response to rainfall is controlled by soil type, terrain, presence of plant seeds, variations in rain-use efficiency, species composition, the intra-annual distribution of rainfall as well as land-use practices. If the three biomass monitoring sites are averaged, the correlation is much stronger (R^2 = 0.55; $p \leq 0.01$).

4. Discussion

The spatial pattern of trend analysis of GEOV1 and GIMMS3g FAPAR shows significant discrepancies in our Sahelian study areas. Initially it is not clear if trends realistically reflect patterns on the ground or are caused/accentuated by sensor-, processing- or scale issues. A combination of good data-sources, ground-truthing and local knowledge of the area are important factors that facilitate a sound interpretation and explanation of satellite derived trend maps.

Annual rainfall has significantly increased over the studied time period in both study areas, following the overall upward trend of Sahelian rainfall [49,50]. At a regional scale, this explains large parts of the observed positive vegetation trends [43] in the entire Sahel [9,27]. However, at a local scale, numerous variations exist, forming a heterogeneous pattern of vegetation trends [8]. A higher resolution clearly improves the capability to assess these discrepancies.

Our results show that the spatial pattern seen in satellite trend maps show regional differences that can partly be explained by soil and land-cover differences [9,51]. The sandy Seno Plain in Mali can be distinguished from the rocky Dogon Plateau. The same applies for the ferrugieous and the sandy Ferlo in Senegal (see Figure 5). Considering our Senegalese case studies, most of the positive trends are caused by leaf biomass, which has almost doubled at the three monitoring sites (*C3L5*, *C2L5* and *C2L4*) since 1987. Local trend variations, *i.e.*, areas of non-change or only weak change, are mostly caused by deforested and degraded areas. The droughts in the 1970s and 1980s caused considerable harm to trees. Additionally, people increasingly cut living trees in times of droughts as an alternative source for income and fodder. Trees and shrubs on sandy soils withstood the stress much better than those on shallow lateritic soils [2]. Although recovery of trees and shrubs from droughts is obvious in the biomass observations in Figure 9, Brandt *et al.* [8] state that strict laws, farmer managed protection, reforestation programs and the dispersion of robust species (especially *Balanites aegyptiaca* and *Acacia raddiana*) contribute to a large scale greening and increase in leaf biomass in both study areas in Mali and Senegal.

Our examples further demonstrate that both greening and degradation are present at a local scale in the West African Sahel, supporting the findings of Dardel *et al.* [9], Spiekermann [30], Nutini *et al.* [52] and Martinez *et al.* [12]. Neither greening nor desertification can be generalized. Our study detected degraded areas not following the greening trend, which is invoked by rainfall increases. However, neither is degradation irreversible, nor is greening an always positive phenomenon. In Mali, farmers were observed using traditional methods like stonewalls or holes with manure to recapture degraded soils near Fiko. Tree planting programs and farmer managed agro-forestry were observed all over the study areas in Mali and Senegal, confirming reports by Allen [48] and Reij *et al.* [53]. In addition, greening can mask degradation, as in both regions a remarkable species impoverishment was detected despite positive woody vegetation trends [8], a fact that coincides with other Sahelian studies [7,54]. In addition, areas seriously affected by soil erosion and spreading of bare soils can be concealed behind a greening trend caused by the woody layer (see *C3L5*).

The moderate correlation and major inter-annual discrepancies between biomass and satellite derived greenness data (Figures 7 and 8) confirm the findings of Diouf & Lambin [37] and Diallo *et al.* [40]. As this study uses only three monitoring sites, the obtained relationships are weaker (see Figure 8a,b). Furthermore, the spatial resolution is much coarser (about 5 km compared to 1.1 km). However, the biomass data at the observed sites gives clear evidence that the direction, the spatial discrepancies as well as the magnitude of FAPAR trend maps are largely realistic in this area. It further shows that woody vegetation is the main driver of positive FAPAR trends seen in Figure 5.

Although the two data products show good spatial consistency at an annual and regional scale (see Figure 2), the local pattern and magnitude of trends strongly differs. Degrading GEOV1 to 8 km resolution (results not shown for brevity) reduces the details but keeps the spatial pattern with apparent differences to GIMMS3g trend maps. Both datasets are created by sampled 1.1 km AVHRR data which are resampled to a 8 km (5 km) grid cell by selecting subsets, while omitting other subsets [13]. The whole processing line of the FAPAR data causes significant variations and the choice of the dataset may have significant effects on the results [33,55–57]. In GEOV1 FAPAR data, the values of the VGT period are sometimes higher in densely vegetated areas than the AVHRR period, causing trends to be overestimated. On the contrary, trends in GIMMS3g FAPAR are too weak and significantly underestimated. The base levels of GIMMS3g FAPAR are much higher than those of GEOV1 FAPAR. Our comparison with ground data showed that the reality lies in between the two products, but closer to GEOV1. These differences in the processing line may influence the magnitude of trend analysis and bias the significance test, but the spatial pattern of GEOV1 trends shows agreement with ground observations (Table 3).

Table 3. This table presents significant ($p \leq 0.01$) changes (see Table 2 for methodology) for the period 1987–2010. ++50%–105%, +10%–50%, o <10%.

Sites	GEOV1	GIMMS3g	Leaf Biomass	Observations	Rainfall
MALdeg	o	not significant	NA	active degradation	++
MALpos	++	o	NA	new plantations	++
C3L5	++	not significant	++	drought recovery	+
C2L5	++	not significant	++	drought recovery	+
C2L4	+	o	++	drought recovery	+
Ldeg	o	+	NA	degradation	+

5. Conclusions

This study focused on the local vegetation trends in drylands of Western Africa (Sahel of Mali and Senegal) over the 1982–2010 period. Two long-term satellite datasets of Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) derived from Advanced Very High Resolution Radiometer (AVHRR) data were considered: Geoland Version 1 (GEOV1) and the third generation Global Inventory Modeling and Mapping Studies (GIMMS3g). Biomass ground measurements and rainfall data supported a quantitative validation of detected trends in satellite products. Auxiliary information and expert knowledge of the study areas allowed a qualitative validation and interpretation of the local observed trends.

Our results show that the choice of the dataset has significant impact on the results. The study seems to indicate that, compared to GIMMS3g, the spatial pattern of GEOV1 trends show a better agreement with ground data, rainfall pattern, land-cover, land management of the two study areas in the Sahel of Mali and Senegal. The differences in the processing lines (input reflectances and retrieval algorithms) seem to play a role in the observed differences rather beside the differences in their spatial resolution. Note however that our conclusions on the accuracy of GEOV1 and GIMMS3g time series for trend detection analysis are limited to the study areas. An extensive validation and comparison of both datasets at global scale should be addressed in a forthcoming study. This study shows the potential of GEOV1 for local trend detection. However, some inconsistencies have been detected in the GEOV1 dataset and are being to be corrected. Correction will be achieved through a second version of Geoland Version 2 (GEOV2) products from VEGETATION (VGT) and AVHRR sensors which is expected to contribute to global climate monitoring and earth science modelling applications.

The inter-annual correlation between FAPAR and annual rainfall is significant over the study areas, explaining around 50% of the variability in vegetation changes. Spatial discrepancies are mainly caused by land- and tree-cover, which are controlled by soil, human and drought resilience. As precipitation in the Sahel was very low when the time series started in 1982 and gradually increased, a positive greening trend is mostly observed in the study area. However, deforested and degraded areas clearly stand out in GEOV1 trend maps while they are hardly visible in GIMMS3g. The positive trends of the three case study sites in Senegal (*C3L5*, *C2L5* and *C2L4*) are caused by the woody layer recovering from droughts/dry periods and its consequences.

These local patterns have shown that both greening and degradation are present in the Sahel of Mali and Senegal, but also greening can hide degradation. Neither the re-greening nor the desertification paradigm can be generalized as both are present at a local level.

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Author Contributions

The conception of the research approach and development of the methods was done by M. Brandt, A. Verger and C. Samimi. The data was collected and prepared by A. Diouf (CSE), F. Baret, A. Verger (both Geoland2) and M. Brandt. The research was conducted by M. Brandt. Analysis and interpretation was done by M. Brandt and A. Verger and discussed with all authors. The manuscript was written by M. Brandt and A. Verger with contributions from all authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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6

50 YEARS OF WOODY VEGETATION AND LAND COVER CHANGES IN THE SAHEL OF MALI

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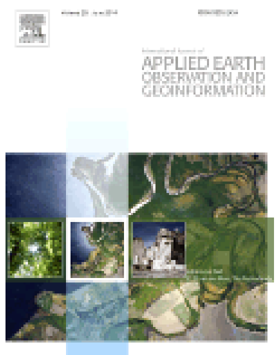

This publication has the focus on hypothesis 1, quantifying tree- and land cover changes over 50 years; on hypothesis 2, explaining the pattern of change with anthropogenic disturbances; and finally on hypothesis 3 by assessing environmental changes at tree level and thus discovering a pattern which is hidden in coarse scale satellite data.

The chapter aims to reconstruct the woody vegetation and land cover in the Malian study area before the severe droughts in the 1970s and 1980s using high resolution (2 m) Corona imagery from 1967. The resulting maps are compared with the current situation which is derived from RapidEye imagery (2011) with a spatial resolution of 5 m. Moreover, woody species change over the same time period is assessed by interviews with village elders. Results show a significant reduction of dense natural vegetation, an extensive species impoverishment, an increase in agricultural land as well as an increase of trees on actively used fields.

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50 years of woody vegetation and land cover changes in the Sahel of Mali

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Abstract

In the past 50 years, the Sahel has experienced significant tree- and land cover changes accelerated by human expansion and prolonged droughts during the 1970s and 1980s. This study uses remote sensing techniques, supplemented by ground truth data to compare pre-drought woody vegetation and land cover with the current situation. High resolution panchromatic Corona imagery of 1967 and multi-spectral RapidEye imagery of 2011 form the basis of this regional scaled study, which is located on the Dogon Plateau and the Seno Plain in the Sahel zone of Mali. Object-based feature extraction and classifications are used to analyze the datasets and map land cover and woody vegetation changes over 44 years. Interviews add information about changes in species compositions. Results show a significant increase of cultivated land, a reduction of dense natural vegetation as well as an increase of trees on farmers fields. Mean woody cover decreased in the plains (–4%) but is stable on the plateau (+1%) although stark spatial discrepancies exist. Species decline and encroachment of degraded land are observed. However, the direction of change is not always negative and a variety of spatial variations are shown. Although the impact of climate is obvious, we demonstrate that anthropogenic activities have been the main drivers of change.

Keywords: Sahel, degradation, greening, Dogon Plateau, Seno Plain, RapidEye, Corona, environmental change

1. Introduction

The Sahel has been acclaimed as one of the hot spots of global environmental change in the last decades. As the 20th century progressed, settlements spread over the Sahel and most forests were cleared for agricultural purposes and an ever growing demand for wood (U.S. Congress, Office of Technology Assessment, 1986). The degradation of the environmental conditions was accelerated by prolonged droughts in the region during the 1970s and 1980s and an overall decrease in annual precipitation (e.g. L'Hote et al., 2002). Scientists claimed deforestation to be the main causative factor for these climatic changes (Charney et al., 1975). However, several studies have shown that sea surface temperatures largely control Sahelian rainfall fluctuations (e.g. Giannini et al., 2008). Recently, investigators demonstrated again that land cover changes can have a strong accelerating effect on rainfall variations (e.g. Kucharski et al., 2013; Paeth et al., 2009). These studies put changes in land cover into the focus again and justify the need for more detailed investigations on the actual extent of environmental change.

After the droughts, the observed loss of woody vegetation cover was often considered as irreversible desertification and large parts of the Sahel were designated as degraded land (e.g. Kandji et al., 2006; Oldeman et al., 1990; Lamprey, 1988). However, even though degradation is locally apparent (e.g. Miehe et al., 2010; CSE, 2009), almost no evidence of widespread degradation was found (e.g. Niemeijer and Mazzucato, 2002; Tiffen and Mortimore, 2002). Recent findings based on coarse-scaled analyses of satellite time series even show an increase of vegetation greenness over most parts of the Sahel since the mid-1980s (e.g. Herrmann et al., 2005; Olsson et al., 2005). Ground data collected over almost 30 years provide evidence that supports these observations. The increase in green biomass is thus not a data issue but indeed an undeniable real-

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ity (Dardel et al., 2014) and often caused by the woody layer regenerating from the droughts (Brandt et al. 2013). However, due to a lack of historical data, it remains largely unclear if this is a return to pre-drought conditions or a transformation of land cover to a new equilibrium state.

The present study intends to compare the pre-drought woody vegetation and land cover with the current situation for a study area approximately 3600 km^2 large. The two major aims are:

1. To investigate and quantify land cover changes over almost 50 years including aspects of degradation and human expansion.
2. To analyze changes in woody cover between 1967 and 2011 and find explanations for these.

Greening and desertification debates are both generalizations attempting to simplify a reality which is far more complex. We thus dismiss these paradigms and show the complexity and spatial variations on a local scale. High resolution panchromatic Corona imagery of 1967 and multispectral RapidEye imagery of 2011 form the basis of this study, which includes parts of the Dogon Plateau and the Sno Plain in the Sahelian zone of Mali.

1.1. Background

High resolution imagery offers the possibility to detect single trees and large shrubs as objects. This has the major advantage that tree density and tree cover can be directly mapped without the need to interpret mixed pixels by linear models (e.g. Herrmann et al, 2013; Larsson, 1996). This is an important factor, as the Sahelian vegetation largely depends on rainfall (Hickler et al., 2005) causing huge inter-annual variations in mixed pixels and making conventional change detection methods unreliable. This problem was often solved by trend analysis of time series (see e.g. Martinez et al., 2011; Anayamba and Tucker, 2005). However, these datasets begin in the 1980s and do not provide any information on the situation prior to the severe Sahel droughts. Beside aerial photography, Corona imagery from the 1960s is a source that offers unique pre-drought information on the Sahel. Moreover, it documents a time of beginning human expansion and clearance of natural bushland. So far, many studies use a qualitative approach, applying case studies and/or visual inspection to reconstruct the pre-drought Sahel with aerial photos and Corona imagery (e.g. Herrmann et al, 2013; Brandt et al., 2013; Tappan et al., 2004; Gonzalez, 2001). Land- and tree-cover changes have also been mapped (e.g. San Emeterio and Mering 2012; Ruelland et al., 2010; Tappan and McGahuey 2007; Elmqvist, 2004; Tappan et al., 2000) using a variety of methods (see Ruelland et al., 2011). The studies revealed drastic environmental change, as most of the former bushland has been transformed to agricultural land and a significant reduction of tree density has been observed with a spreading of barren land and considerable impoverishment of woody species (Brandt et al., 2013; Herrmann and Tappan, 2013; Gonzalez et al., 2012; Ruelland et al., 2010; Tappan et al., 2004; Elmqvist, 2004). Brandt et al. (2013) point out that drivers of change can be both climatic and human-induced, modified by differences in soil and morphology.

Overall, a shift to a more arid climate with an adapted species composition is observed in case studies throughout the African Sahel (Herrmann and Tappan, 2013; Hiernaux et al., 2009; Gonzalez, 2001). These changes to the woody vegetation cover and diversity have significant effects on the ecosystem and people's daily lives. Furthermore, an expansion of erosion and degradation has been detected as the result of droughts and excessive deforestation, which has in turn lead to a loss of arable land (Brandt et al., 2013). The dependence of the local population on the products form trees as fire and construction wood, medicine and religious purposes (Maydell, 1990) is a factor of practical importance adding significance to regional-scaled environmental studies.

2. Materials and Methods

2.1. Study Area

The study area is located in the Mopti Region in Mali. It is approximately 3600 km^2 large, featuring the towns of Sevaré in the north-west, and Bandiagara and Bankass in the east (see Figure 1). Generally, the study area can be divided in the Dogon Plateau (75%) and the Seno Plain (25%) with the steep Bandiagara escarpment dividing the rocky plateau in the north from the sandy plains to the south. The plateau is inhabited by Dogon farmers and is characterized by a complex and rough morphology with shallow and lateritic soils. Cropping and grazing areas are spread between the rocky outcrops in the valleys. The sandstones often restrict the expansion of cropland areas so that many such spaces are dominated by dense natural vegetation, with *Combretum micranthum*, *Combretum glutinosum* and *Guiera senegalensis* prevailing and in turn provide wood as an energy source. The main crops are millet, peanuts and sorghum. Onion plantations and gardens are found in close proximity to major streams, where the recent construction of small dams has enabled irrigation systems to be expanded.

The Seno Plain lies 200 m lower than the plateau at an altitude of 200–300 m with a plain morphology and sandy soils. The population density has increased during the past decades, which has had a significant impact on the land cover. Almost all areas of the Seno Plain are used for agricultural purposes today. Soils are deep sandy-loam which increase resilience to dry periods compared to the shallow soils on the plateau.

The villages on both the plateau and the plains have many large trees within the village borders and on fields in proximity to the village. These trees (mainly *Adansonia digitata*, *Balanites aegyptiaca*, *Borassus aethiopum*, *Faidherbia albida*) are carefully protected by villagers and provide shade, soil nutrients, fruit, and wood (Brandt et al., 2013). Farmers cut branches of trees within their own field, mostly by sustainable pollarding methods. More remote cropland is often laid fallow and trees on these fields often remain unprotected, as It is harder to patrol bush fields. Most species are officially protected and permits have to be bought from the forestry service to cut trees. However, the situation is very unclear and different interpretations of the forestry law exist. Within our study area, cutting and felling with and without permits was observed and reported by

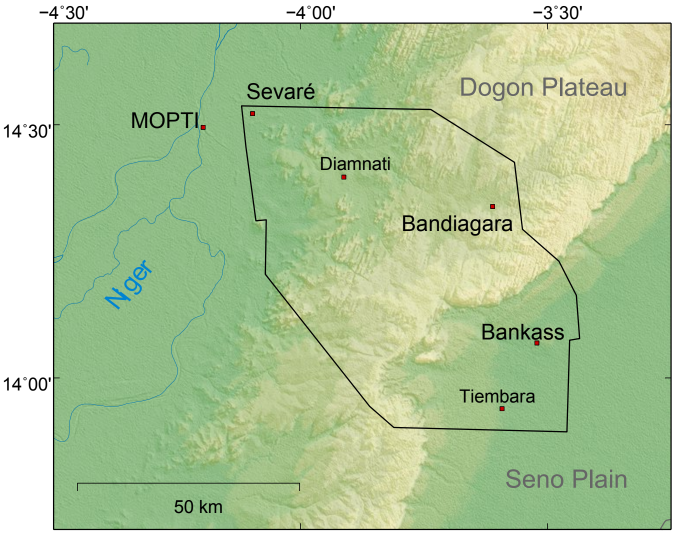


Figure 1: The study area is located on the Malian Dogon Plateau and on the Seno Plain

the local population. In both cases, the existence and degree of protection varies primarily according to species.

Various projects situated within the study area show the positive impact humans can have on woody vegetation. The areas around Bankass and Endé have particularly benefited from input by organizations like SahelEco and the inter-village association Barahogon (Allen, 2009, Yossi & Diakité, 2008) and many protected sites with dense tree growth exemplify the capabilities of trees to survive years with little rainfall and flourish in the long-term.

The Mopti region is covered in part by the North Sudanian zone (550–750 mm of average annual rainfall) and also by the Southern Sahel zone (350-550 mm average annual rainfall) (Yossi and Diakit 2008). In general, the study area receives an average of 500-600 mm of annual precipitation, which falls entirely during the months of June to October with a high inter- and intra-annual variability. The 1970s and 1980s have seen several severe droughts and an overall drop of annual rainfall. Since the 1990s, annual values are increasing again, almost reaching pre-drought values in 2010 (Brandt et al., 2013).

2.2. Data

2.2.1. Corona

Corona images belong to the very first U.S. earth observation satellites and provide a unique window into the past. The satellite which took photographic images of the study area in Mali on 10th December 1967 was named Corona KH-4B (mission 1102). Corona KH-4B was equipped with two panoramic rotator cameras with a focal length of 61 mm and a ground resolution of 1.8 m. Although panchromatic, the image is remarkably sharp and full of detail, so that single trees, grass- and barren land as well as settlements can be distinguished and extracted. Anderson (2006) successfully detected 70% of mapped trees using Corona imagery at 2.75 m resolution. As raw images lack position data and any form of orthorectification, all ten single images were georeferenced manually using GoogleEarth as a reference, as high resolution images were required for identifying control points. Due to the lack of infrastructure, control points needed to be chosen not only at intersections and at buildings, but also at edges of rocky outcrops and large old trees. For each of the ten Corona images, between 30 and 50 control points were acquired. Rectification was performed with the rubber sheet method, rounding the input cell size to 2 m. The accuracy of each image was assessed visually with an overlay of RapidEye images.

2.2.2. RapidEye

RapidEye satellites are equipped with a 5-band (red, green, blue, red edge, near infra-red) multi-spectral sensor. Images used here were delivered orthorectified and resampled to 5 m resolution and were acquired from the RapidEye Science Archive (RESA), provided by the Deutsches Zentrum fr Luft- und Raumfahrt (DLR) free of charge. The high resolution multi-spectral images of RapidEye provide a dataset to assess the situation in the study area for 2011 and cover a total area of 3501 km^2. The scene covering almost the entire study area is dated 26th December 2011 (made up of 13 tiles). The second scene covers only a small section in the north-west of the plateau and dates 7th December 2011. Both scenes correspond with the time spent in the field. The near infra-red channel facilitates the distinction between individual trees and their environment, as trees and shrubs are the only form of vegetation that remains green during the dry season. The RapidEye images were delivered as digital numbers (DN) and then converted to reflectance values. Furthermore, NDVI (Normalized Difference Vegetation Index) was calculated.

Before any analyses with the respective datasets could be carried out, the accuracy of the horizontal positioning of the two datasets, which differ in resolution, had to be verified and adjusted to allow spatial analyses and comparisons to be carried out. Adjustments were made after thorough on-screen visual inspection of the image pairs to reduce spatial disparities to a maximum of 20 m.

2.3. Methods

2.3.1. Land-cover classification

Land cover maps were created for 1967 and 2011 at a resolution of 20 m. An unsupervised classification (ISODATA) method was used for the Corona images and a supervised classification (maximum likelihood) for 2apidEye. The two main classes are sparse woody vegetation and dense woody vegetation, seen in Figure 5 and Figure 3. Areas of dense woody vegetation are areas, which have not been deforested for agriculture, or areas which have been laid fallow for extended periods of time and are now covered by shrubs and grass. Dense groups of large trees within croplands were also included in this class. Areas of sparse woody vegetation are usually used for agricultural purposes and include cultivated, fallow and grazing areas. Bare rocks form an additional class. The rocky outcrops did not change significantly during the studied period and are thus masked for both datasets. Due to the additional multi-spectral information, the classification for 2011 introduced a class for

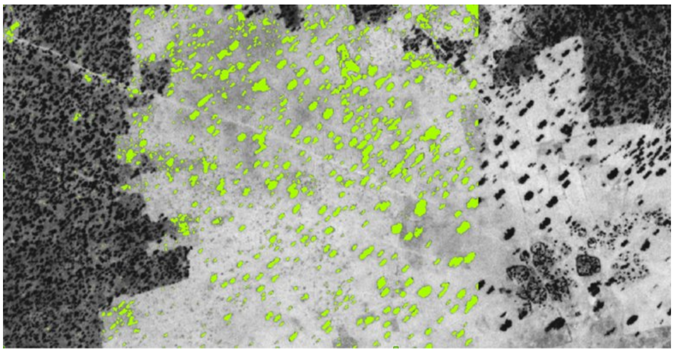


Figure 2: This figure shows the two classes used in the 1967 classification as well as how individual trees are mapped (green). The bright area around the village represents an area of sparse woody vegetation, whereas the dark area in the west is an example for dense woody vegetation which had not been cleared for cultivation.

degraded land with apparent soil erosion and exposed laterite. Visual inspection of Corona images showed that this class was almost not spatially explicit in 1967. For the supervised classification, 73 training areas were selected, in most cases covering sites visited in the field. The classifications were resampled to 20 m using a majority resample technique to equal the geometric resolutions of 1967 and 2011 and to smooth the results. To obtain changes over the whole time period, a change map was created showing differences and directions of change between the two classifications from 1967 and 2011. Further information on the classification methodology and validation is provided in Spiekermann (2013).

2.3.2. *Object based tree cover mapping*

The woody vegetation assessment maps trees and large shrubs using object-oriented, automatic mapping technology provided by IMAGINE Objective (Erdas Inc., 2008). Scientific literature on this topic is rare and includes studies by Chepkochei (2011), Leckie et al. (2005), Ke and Quackenbush (2012), Erikson and Olofsson (2005), Emeterio and Mering (2012) or Pouliot et al. (2002). Mapping at tree level guarantees a high degree of accuracy and certainty of results pertaining to changes to woody vegetation density and cover. The punctiform nature of the ligneous cover in the Sahelian savannah makes an object-oriented approach logical.

For this study, each feature model for the delineation and extraction of woody vegetation objects is a line of algorithms which consist of seven nodes and the corresponding input data. The process of automatic feature extraction is based on pixel cue metrics that use both spectral information, i.e., pixel level cues to identify color, texture, tone, and site, as well as spatial information, i.e., object level cues, to analyze shape, size and orientation (Erdas Inc., 2008). The outputs are shapefiles containing millions of polygons representing the woody cover (see Figure 2). For detailed information on the feature extraction of woody vegetation we refer to Chepkochei (2011) and Spiekermann (2013).

The detection of woody vegetation is mostly based on the spectral information of training samples for woody vegetation and background training samples, i.e., areas surrounding the woody vegetation. Background pixels may differ greatly between different land uses, especially between cropland and bush-fallows. This is true for both the Corona and the RapidEye datasets. In an area of dense natural vegetation, the areas between trees or large shrubs are often covered by herbaceous vegetation and shrubbery and have a much higher tree density than on cultivated land. For Corona, this means that the background pixels in natural vegetation areas may take on similar grey values to the target pixels (woody vegetation) in a cropland area. For RapidEye imagery, the adjacency effect adds further uncertainty (Liang et al., 2001). Tree crowns with a diameter of 10 m on the ground are not necessarily represented by the corresponding spectral characteristics of the tree in just four 5 m pixels. Rather the neighboring pixels are affected by the scattering reflection of the tree crown, which is especially true in areas of dense woody vegetation. To reduce the mentioned sources of error, the mapping of woody vegetation not only required singular processing of the Dogon Plateau and the Seno Plain, but was also carried out for the various classified land cover types separately (Spiekermann, 2013).

The woody vegetation cover was calculated as the area of woody vegetation objects per 250 m x 250 m pixel in percent (see Spiekermann, 2013). The coarse pixel size was chosen to reduce uncertainties and match MODIS (Moderate Resolution Imaging Spectroradiometer) to enable extrapolation to a larger area in future studies.

2.3.3. *Field Work*

Ground truthing is essential for remote sensing studies, as many forms of knowledge and understanding of processes seen on imagery can only be studied on the ground. Thus two field trips were undertaken, one in April 2010 and another six week trip during November to December 2011, matching the date of the RapidEye scenes. During the second field trip, 65 sites of interest were visited, previously selected by on-screen studying of the images. These sites were selected according to conspicuous tree cover change but also where site conditions and vegetation are representative for a larger region. Site visits provided information on land cover and land use, woody species composition, tree height and condition as well as on degradation processes. Dialogues with local farmers often provided invaluable information and clarification of events and changes to woody vegetation (see Brandt et al. 2013). Farmers as well as a local guide accompanied us on transect walks and provided information on the local use of trees and farmer management strategies. Village elders in 13 villages were asked to name favored woody species and their development over a period of approximately 40 years according to the following categories: strongly increased, increased, stable, decreased or vanished.

3. Results and Discussion

3.1. *Land Cover Change*

The land cover change map in Figure 4 displays changes that occurred between 1967 and 2011 for all overlapping areas of

Figure 3: Areas of sparse (a+b) and dense (d) woody vegetation as well as a degraded area (c) as seen on RapidEye (band combination 532) and on the ground (Dec. 2011).

the two datasets (see also Table 1). Large areas of the Seno Plain have been converted from dense woody vegetation to sparse woody vegetation. This reflects major land use changes in the Seno Plain during the twentieth century due to population increase and the spreading of settlements. During this time the land required for agriculture increased significantly so that large areas of natural bushland were deforested for cultivation purposes. Exceptions do exist, however, where the reverse is shown to be true. The areas surrounding Bankass and Ende, for example, show an increase of areas with dense woody vegetation caused by tree protection and planting programs, mostly in the past decade (Yossi and Diakite, 2008).

Changes observed on the Dogon Plateau are far more diverse. The land cover change between 1967 and 2011 is further summarized in Table 1 and shows the various changes that occurred during 44 years. 13% of the plateau area changed from dense to sparse woody vegetation. However, almost the same portion (14%) changed from sparse to dense woody vegetation land cover, including large areas to the southwest and east of the plateau. This signifies the spreading of shrubbery in remote areas, but also the ability of multi-spectral RapidEye data to better distinguish between shrubs and their rocky background. The 25,000 ha classified as degraded in 2011, originate from areas of dense and sparse woody vegetation alike, with 3.5% of the total area resulting from dense woody vegetation and 6.2% of all areas changing from sparse woody vegetation to degraded land. This makes up a share of almost 10% barren land, of

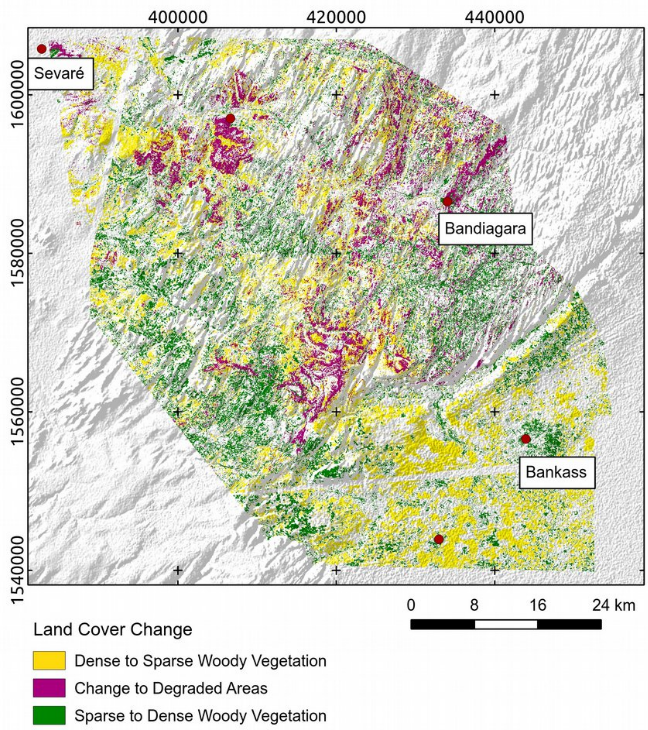


Figure 4: Land cover change map 1967-2011. Areas of no change/rock/no data are displayed transparent.

Change code	Dogon Plateau chance (ha)	Dogon Plateau change (%)	Seno Plain change (ha)	Seno Plain change (%)
DV–SV	32362.1	13	24487.3	26.6
DV–D	8764.7	3.5	0	NA
SV–DV	35157.5	14.1	11623.3	12.6
SV–D	15495.5	6.2	0	NA
REST	157361.1	63.2	55881.2	60.8
Total	249140.9	100	91991.8	100

Table 1: Land cover change 1967-2011 in hectare and percent. DV: Dense woody Vegetation; SV: Sparse woody Vegetation; D: Degraded

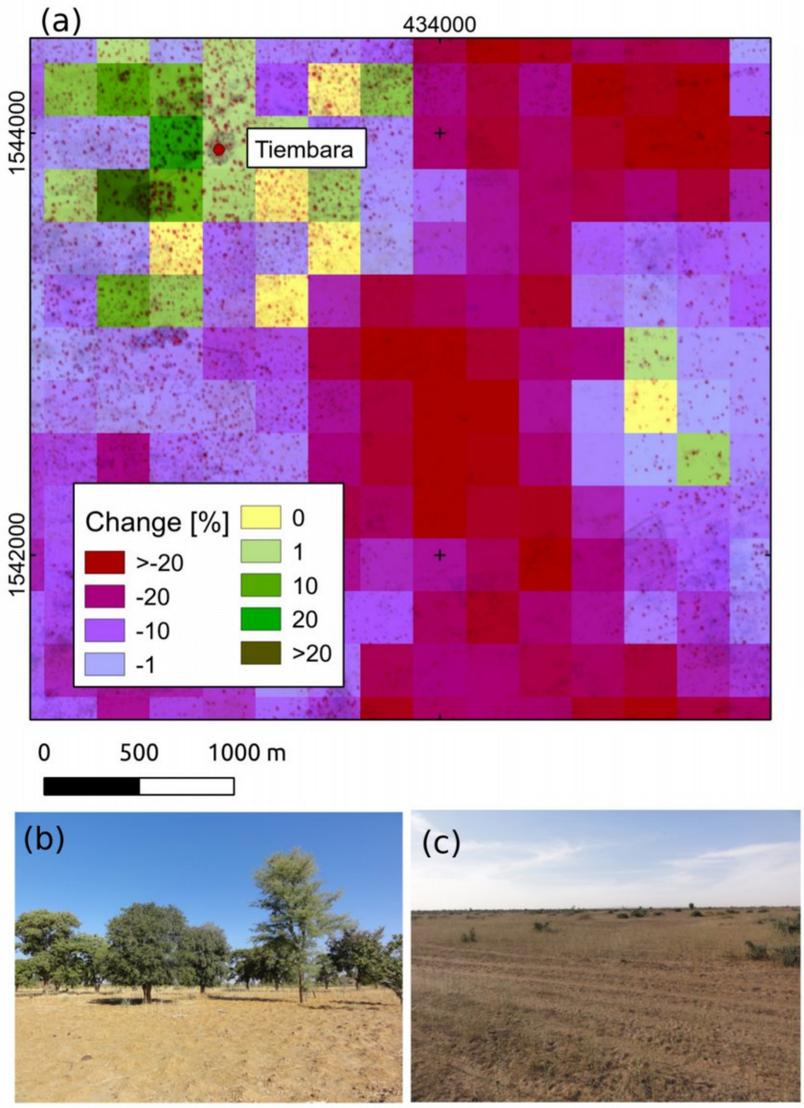


Figure 5: (a) Woody cover change around the Dogon village Tiembara (Seno Plain) for 1967-2011, with RapidEye as background. Note that a total reverse of tree cover has occurred in the space of half a century. (b) A dense woody vegetation can be found on the fields surrounding Tiembara. (c) What was natural bushland in 1967, now fields on the outskirts of Tiembara that are mostly fallow and serve as a source for firewood (Photos taken in December 2011).

which most is located in proximity to paved major roads.

3.2. Case studies of tree cover change

3.2.1. Tiembara

Tiembara is a Dogon village located on the Seno Plain in the far south of the study area (marked in Figure 1). Tiembara has had no external influence by projects such as the areas surrounding Bankass and End. Therefore, we assume that the development of the woody vegetation around the village area has progressed with limited outside disturbances. This case study intends to demonstrate the changes in tree cover that have occurred over 44 years and typifies the environmental change on the Seno Plain (see Figure 5). Bushland areas to the east and south of the village have been classified as dense woody vegetation with a woody cover of 20-30% in 1967. Due to anthropogenic disturbances, these areas no longer exist in 2011. However, due to an increase of woody vegetation on the cropping fields surrounding Tiembara, many of the cultivated areas show a much higher tree cover today and are thus partly classified as dense woody vegetation. A total reverse of land and tree cover has thus occurred in the space of half a century, as seen in Figure 5. While the bush-fallow areas were entirely deforested, tree growth has been encouraged and existing trees have been protected by villagers on their fields that surround the village and are regularly used for cropping (see Figure 5). This is why tree cover here has increased by 10-20%, whereas tree cover further away decreased by up to 30% (see Figure 5). Therefore, land use is not just the decisive factor for woody vegetation cover and change but particularly the subjective value given to their cultivated areas by farmers. The older fields in proximity to the village boast a large number of healthy trees (10-20%), whereas the newer fields further away have a very sparse tree cover (Figure 5) in 2011 (0-10%). These former bush-fallow areas were found to be fallow in December 2011 and are only used in a rotational cycle of three to six years. During the fallow period, the fallow fields serve as a source for firewood and as grazing land, which is the reason for their very low woody vegetation cover in 2011 (Figure 5).

3.2.2. Diamnati

To exemplify land- and tree cover change at a large scale on the Dogon Plateau, the area surrounding the village of Diamnati was chosen as a case study (marked in Figure 1). Diamnati was founded by families emigrating from the Seno Plain in 1954 in agreement with the nearby village of Fiko, which until today has rights to the land (Spiekermann, 2013). Corona images show that within thirteen years following the initial settlement, large areas of bushland had already been cleared for cropping purposes. In 2011, the RapidEye image shows the same fields to the east of the village with many large trees covering the still actively used fields (see Figure 6). What was once bushland to the southwest of Diamnati is now to a large extent deforested and represents a form of unvegetated barren land. Only remnants of the upper-soil and tiger-bush remain, seen as a skeleton-like pattern in the background of Figure 6. Even in the 1980s, the vegetation here was much denser than in 2011 and the erosion process is still active (see Brandt et al., 2013). Figure 6 displays changes to the woody cover for the area between 1967 and 2011 at a 250 m pixel scale. On the one hand, tree growth and agroforestry on fields have led to an increase of woody cover in proximity to the village. Bush-fallow areas in the southeast have been cleared and serve as a source for wood resulting in a decrease of woody cover and an increased of degraded areas. Almost half of the case study area is now degraded and cannot be used for agricultural purposes apart from livestock grazing during the wet season, where patches with a thin layer of soil enable herbaceous vegetation to grow (Figure 6).

The woody vegetation cover ranged between 0-10% on cropland areas and 10–30% in bush-fallow areas in 1967. As was shown, the degraded areas have lost most trees and shrubs and host very little woody vegetation in 2011 (a loss of up to 30%). However, the woody cover in fields directly surrounding Diamnati village has increased to 5–20%, which is an increase of approximately 10%, sometimes up to 20%. The situation is similar to the case study Tiembara, with the difference that (1) the rocky morphology of the deforested bushland accelerates erosion without vegetation protecting the soil and (2) the sandy soils of the Seno Plain help tempering drought effects much better.

3.3. Woody Species Change

Another open question of Sahelian environmental science is concerned with the current and recent change to the woody species composition. Not only the density and coverage of woody vegetation is important, but also which species are growing and favored by local people. Figure 7 shows the perception of village elders about change of favored woody species around 13 villages in the study area. According to these interviews, a clear loss in species diversity and transformation to a man-made environment is observed, with only four species showing a positive and 22 a negative tendency. *Faidherbia albida* (formally *Acacia albida*) provides nutrients and sheds its leaves during the rainy season. It is thus the most favored tree in cropping fields and thoroughly protected by farmers. *Balanites aegyptiaca* is a robust tree, withstanding droughts, dry periods and grazing pressure. It further acts as a pioneer, filling the place of lost vegetation. *Eucalyptus camaldulensis* is a robust, fast growing and frequently planted tree. However, its negative effects on soil properties raises questions regarding its large scale implementation, a process supported by governmental programs. Most other tree and shrub species strongly decreased or vanished locally within the past 40 years.

3.4. Extensive environmental changes over 44 years

The changing environment in our study area is in no way a return to the situation of the mid-1960s prior to the severe droughts. Extensive land use changes have characterized the past fifty years, confirming the studies of Ruelland et al. (2009), Tappan and McGahuey (2007) and Elmqvist (2004). Significant changes of the land cover include the stark rise of areas with sparse woody vegetation and the reduction of mean woody

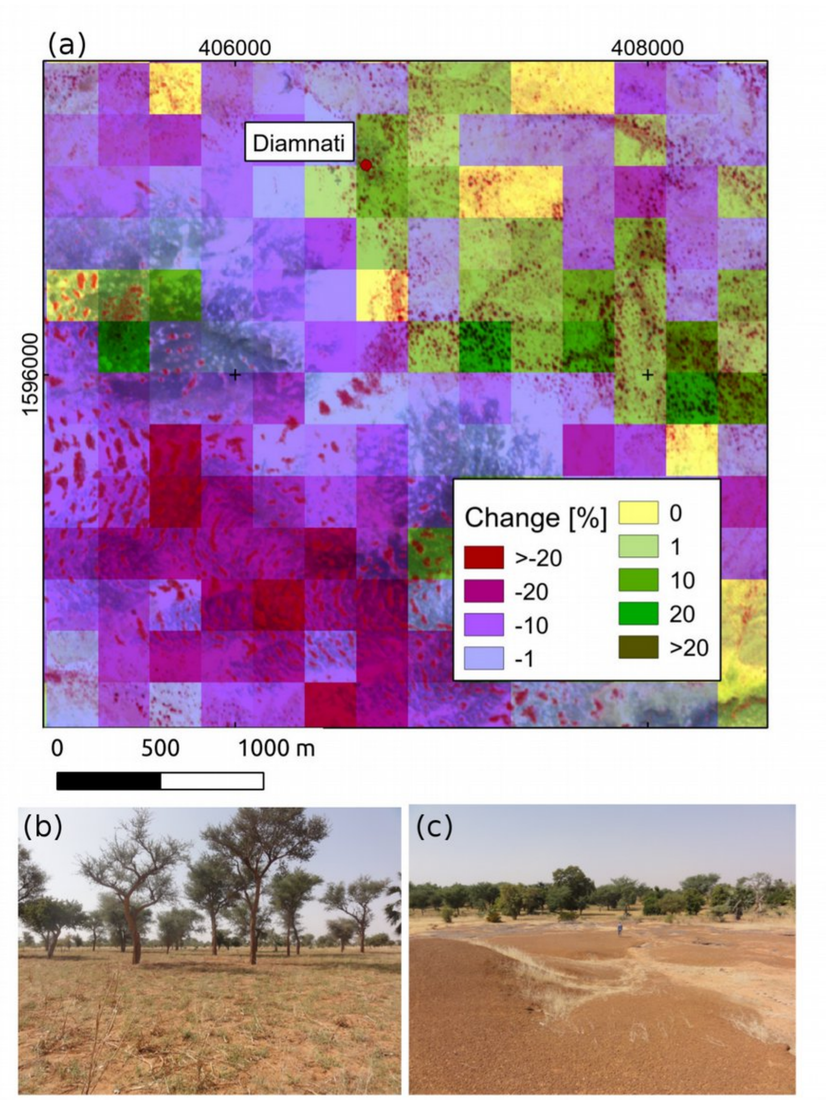
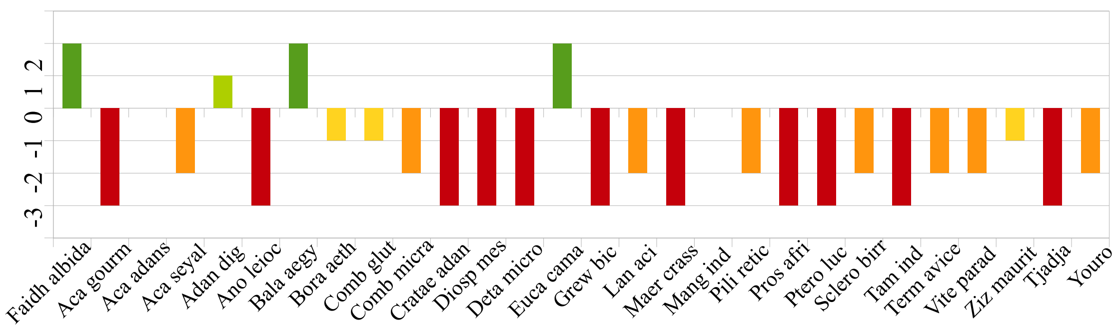


Figure 6: (a)Woody vegetation cover change around Diamnati (Dogon Plateau) 1967-2011 with RapidEye as background. Note the increase on cropping fields and the decrease on the formally densely vegetated bush-fallow. The decrease increases with distance to the village, with large areas highly degraded in 2011. (b) Healthy *Faidherbia albida* grow on the fields surrounding Diamnati (b, and background on the right photo), whereas the areas not used for cropping are deforested, eroded and highly degraded (c, foreground) (Photos taken in December 2011).



-3 vanished or very strong decrease, -2 decrease, -1 moderate decrease, 0 stable, 1 increase, 2 strong increase

Figure 7: Woody species change as reported by village elders in 13 villages on the Dogon Plateau and the Seno Plain

Woody cover	Dogon Plateau	Seno Plain
No. Pixels (250 m)	40885	14957
Mean woody cover 1967 (%)	10.1	11.2
Mean woody cover 2011 (%)	11.5	7.5
Positive change 1967-2011 (%)	44.9	25.4
Negative change 1967-2011 (%)	43.7	61.6
No change 1967-2011 (%)	11.4	13.0

Table 2: Mean woody cover and change 1967–2011 for 250 m pixels in percent

cover by approximately 4% in the Seno Plain (with ca. 7% in 2011), mainly caused by anthropogenic disturbances (Table 1 and Table 2). The change on the Dogon Plateau is not as large, primarily due to the rough morphology and difficulty of expanding agriculturally used areas (Table 1, Table 2); areas of positive change of woody cover equal areas of negative change (both about 45%, see Table 2), with an overall stable mean woody coverage of about 10% (+1%). In 2011, barren land comprised almost 10% of the total area of the Dogon Plateau, signifying a worrying portion of degraded land. The tree cover change corresponds well to land cover changes with an increase on primary fields and a decrease mapped in areas where the dense bushland areas of 1967 have been converted to secondary cropping fields. The spreading of barren land is often indirectly and directly related to the intense droughts of the 1970s and 80s. On the one hand, the shallow soils were not able to temper droughts, leading to a massive dying of trees and shrubs. On the other hand, cutting of living trees is an established source of income and increases during dry periods. Vegetation species have decreased due to an increasing need for cropland areas and the selective process of farmers in regard to which species are favored. Tree protection by-laws have been introduced and the awareness and knowledge of the advantages gained when protecting certain tree species, i.e., ensuring their sustainable use on farmland, has increased among local inhabitants. This led to an increase of woody vegetation in the immediate surroundings of settlements.

4. Conclusion

The research presented in this study offers detailed insight on the state of the environmental change in the West African Sahel at a regional/local scale. Quantitative information on the woody vegetation cover and its change over 44 years is provided. Remote sensing, making use of high resolution Corona and RapidEye images of the years 1967 and 2011, supported by ground truthing is shown to be a useful tool for quantifying and comparing the land and woody vegetation cover over the past fifty years at tree level. By means of an object-oriented approach, individual and groups of woody vegetation features could be extracted and displayed as woody vegetation cover maps.

The number of objects detected in the Corona images is greater than the number extracted from the RapidEye images. The reverse is true concerning the average area of the features, mainly due to the different pixel size (2 m compared to 5 m). Thus, there is an obvious dilemma in comparing these maps quantitatively. However, although the quantitative change of tree cover is not without error, the trend is certainly true, providing a sound basis for further interpretation. Improvements may be made by using very high resolution multi-spectral images such as World-View2 or GeoEye-2 imagery to gain greater accuracy although processing difficulties increase due to the data volume at regional scale. MODIS or Landsat data can further be used to extrapolate the current woody cover to a larger region in a future study.

Even though our results show that extensive land and tree cover changes exist, the direction of change is not always negative but is very heterogeneous on a local and regional scale. Although climate has had significant impacts on woody changes, the pattern obviously demonstrates that anthropogenic activities are the main drivers of change.

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7

MODELING SOIL AND WOODY VEGETATION IN THE SENEGALESE SAHEL IN THE CONTEXT OF ENVIRONMENTAL CHANGE

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The importance of soil on vegetation changes and degradation is often underrepresented. Thus, the main scope of this publication is on hypothesis 2, disentangling the effects of soil on woody vegetation and environmental changes.

The manuscript focuses on the Senegalese study area and works with data gathered by soil- and vegetation surveys as well as by qualitative interviews. The paper presents an analysis of soil properties and -types, and links both to woody vegetation cover and species. The authors combine field and laboratory soil and vegetation measurements with remotely-sensed satellite information to develop a statistically-based classification scheme that corresponds to locally used soil denotations. These are used to group a woody vegetation survey and are further discussed regarding environmental change, human impact, drought resilience and vulnerability. Results show that soil properties play a dominant role when explaining vegetation change and degradation in the Sahel.

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Article

Modeling soil and woody vegetation in the Senegalese Sahel in the context of environmental change

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Abstract: Climatic stress and anthropogenic disturbances have caused significant environmental changes in the Sahel. In this context, the importance of soil is often underrepresented. Thus, we analyze and discuss the interdependency of soil and vegetation by classifying soil types and its woody cover for a region in the Senegalese Ferlo. Clustering of 28 soil parameters lead to 4 soil types which correspond with local Wolof denotations: *Dek*, *Bowel*, *Dior* and *Bardial*. The soil types are confirmed by a Non-metric Multidimensional-Scaling (NMDS) ordination and extrapolated via a Random Forest classifier using 6 significant variables derived from Landsat imagery and a digital elevation model (out-of-bag error rate: 7.3%). In addition, canopy cover is modeled using Landsat and a Reduced-Major-Axis (RMA) regression (R^2 = 0.81). A woody vegetation survey shows that every soil type has its own species composition. However, 29% of *Bowel* regions are deforested (i.e. degraded) and interviews reveal extensive environmental changes with major differences between the soil types, showing that vegetation changes, degradation, resilience to climatic stress and human activities largely depend on soil properties. However, it is also reported that a more arid climate and overuse have led to an overall strong decline and local extinction of woody species.

Keywords: Sahel; degradation; environmental change; species change; NMDS; Random Forest; Senegal; Wolof; canopy cover

1. Introduction

The Sahel zone has undergone major environmental changes in the past 50 years [e.g. 1–3]. Severe droughts, a considerable drop in annual rainfall [e.g. 4] and increasing human activities have had massive impact on Sahelian ecosystems. Natural vegetation was rapidly declining and a shift in woody species composition is observed, adapting to a more arid climate [5–7].

Vegetation changes, degradation and re-greening in the Sahel have long been researched and discussed [e.g. 5,8–10] and studies agree that woody vegetation structure plays a decisive role as an indicator for ecosystem health. In addition, trees and shrubs are fundamental for people's daily life [11], particularly for food and mostly fodder in a short lasting herbaceous cover. Although rainfall and human management are prominent factors controlling tree and shrub growth, woody cover, species structure as well as its resilience mainly depend on morpho-pedological site conditions and thus primarily on soil properties [12]. For better understanding of past and ongoing processes, detailed classifications of soil and vegetation units are required.

Vegetation and soil studies in the Senegalese Sahel date back to 1965 and offer valuable pre-drought information [13–15]. Stancioff *et al.* [16] published maps of Senegal's geology, soil, morpho-pedology, vegetation and the agricultural suitability based on the assessments from 1965, field data and remote sensing imagery. Tappan *et al.* [1] divided Senegal in ecoregions partly based on Stancioff's maps. Several studies regarding woody vegetation change and degradation in the Ferlo exist. Vincke *et al.* [8] detected human and drought induced degradation and highlighted the importance of soil and topographic elements for species composition and tree density. Miehe *et al.* [17] conducted a long term study in Widou Thiengoly, monitoring vegetation in fenced and unfenced sites over 27 years. They observed degradation and species impoverishment induced by livestock grazing. Additionally, several reports by the CSE (Centre de Suivi Ecologique) are available including land-cover maps of the Ferlo as well as degradation assessments [e.g. 18]. Other international projects are located in Senegal's Sahel as well (e.g. LADA - Land Degradation Assessment in Drylands or ROSELT [19]).

To link vegetation changes to morpho-pedological site conditions, the present study suggests a statistical methodology to model soil types over an area in the Senegalese Ferlo by means of remote sensing products. Soils are classified according to their names in the local language (Wolof). Therefore, the objective of this study is to demonstrate that local soil types can be modeled and used to gain a sound scientific soil classification which (a) forms a basis for discussions on environmental change and vulnerability and (b) offers information on the predominant woody vegetation and agricultural suitability.

2. Materials and Methods

2.1. Study Area

The study area is located in the Senegalese Ferlo around the city of Linguère (Fig. 1). Mean annual rainfall is 450 mm with a high inter- and intra-annual variability and a steep north-south gradient. Severe droughts in the 1970s and 1980s combined with a remarkable decrease in annual rainfall are observed at the Linguère weather-station [20]. Due to this decline in precipitation and the presence of protected areas, only 15% of the study area are currently cultivated with millet and groundnut by Wolof farmers who live in larger villages around Linguère and Dahra. Semi-nomadic Fulani who practice animal husbandry with cattle, goats and sheep, settle in the region and make up 85% of the population in the Ferlo. Thus, the study area is known as a Fulani/Pular silvo-pastoral zone [21].

Tappan *et al.* [1] divided the study area in 3 ecoregions: the (a) northern and (b) southern sandy regions with aeolian sands and the (c) ferruginous pastoral region in the east, formed by a sandstone plateau which is dissected by ancient valleys. In general, 4 different types of soils can be distinguished in the region, summarized in Table 1 and illustrated in Figure 2 (1) *Dek*, (2) *Bowel*, (3) *Dior* and (4) *Bardial*. Small depressions with gray and clayey hydromorphic soils are spread throughout the Ferlo region and are called *Xour* and their clayey soils (1) *Dek* in Wolof. These Vertisols are formed by colluvial and alluvial sediments and characterized by standing water which often remains several months after the rainy season. Beneath the shallow clays with hydromorphic characteristics, sands and gravel form the basis of the soils. Woody vegetation is manifold and species composition and its density depend on the soil's grain size distribution. For herders and their livestock these sites are a valuable source for drinking water and fodder in form of leaves. Different perceptions of the terms *Xour* and *Dek* exist. In this study, heavy clayey soils with standing water are considered as *Dek*.

The eastern parts of the Ferlo are formed by clayey formations on the continental shelf of the Oligo-, Mio- or Pliocene [14]. These Regosols are stoney, shallow, poorly developed and laterite is often visible at the surface. This results in a great number of small unvegetated spots throughout the whole region which are called Karré in Wolof. Depressions with more loamy soils are widespread within this zone and standing water during the rainy season is common. Typical vegetation of this area is a shrub savanna mainly used for livestock grazing. Soils are susceptible to trampling, compaction and erosion through water and wind, thus degradation is apparent at many sites [16]. Large parts of the lateritic Ferlo are declared as protected area and agriculture is prohibited. In Wolof, the laterite soils are often called *souf bou khonk* (meaning reddish soil). However, as no clear and short expression exists, we use the Fulani (also used by Wolof) name for laterite: (2) *Bowel*.

The most predominant soil is a tropical soil developed on aeolian dune formations (Tound in Wolof) and is named (3) *Dior* in Wolof (also spelled joor). *Dior* soils are Arenosols with a good infiltration rate and a clay content not more than 6% [16]. Despite their moderate fertility, *Dior* have a great importance for cultivation of crops and as grazing land [14]. Ndiaye [22] further subdivides the Arenosols in (4) *Bardial* with differences in predominant vegetation and suitability for crops. According to Ndiaye [22], *Dior*s were cultivated with groundnuts, beans, millet and manioc until the droughts in the 1970s. However, in recent times mainly groundnuts and beans are cultivated. *Bardial* soils are characterized as more heavy, unsuited for groundnut and exclusively cultivated with millet.

Table 1. Pedological terms and units used in this study

Wolof Soil	Wolof Morphological Unit	Soil Characteristics	Soil Type	Usage
(1) *Dek*	*Xour*	clayey depression	Vertisol	pasture, drinking water
(2) *Bowel*	*All*	ferruginous/stony	Regosol	pasture
(3) *Dior*	*Tound*	sandy dune soil	Arenosol	cropping, pasture
(4) *Bardial*	*Tound*	heavy sandy dune soil	Arenosol	cropping, pasture

Figure 1. Position of the study area. The 84 training sites are located inside the circle around Linguère.

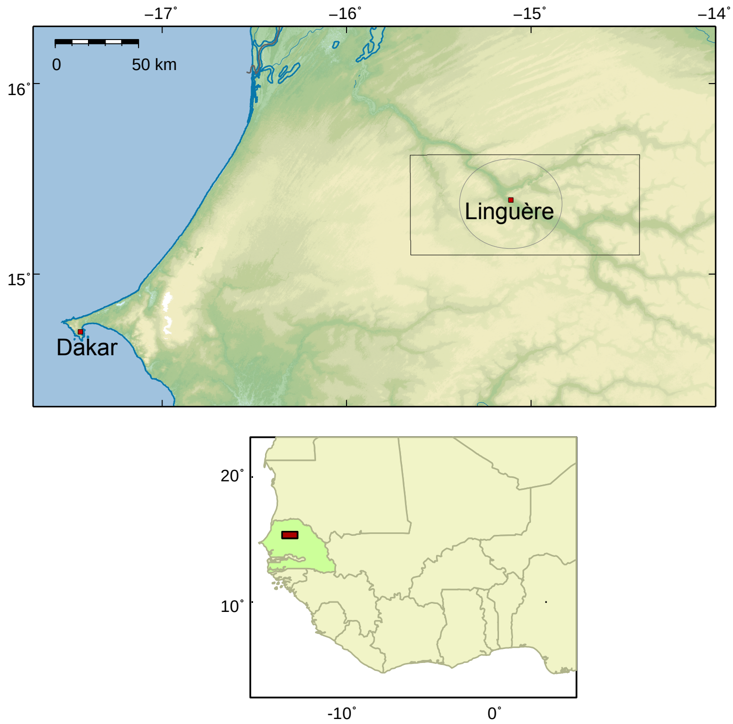
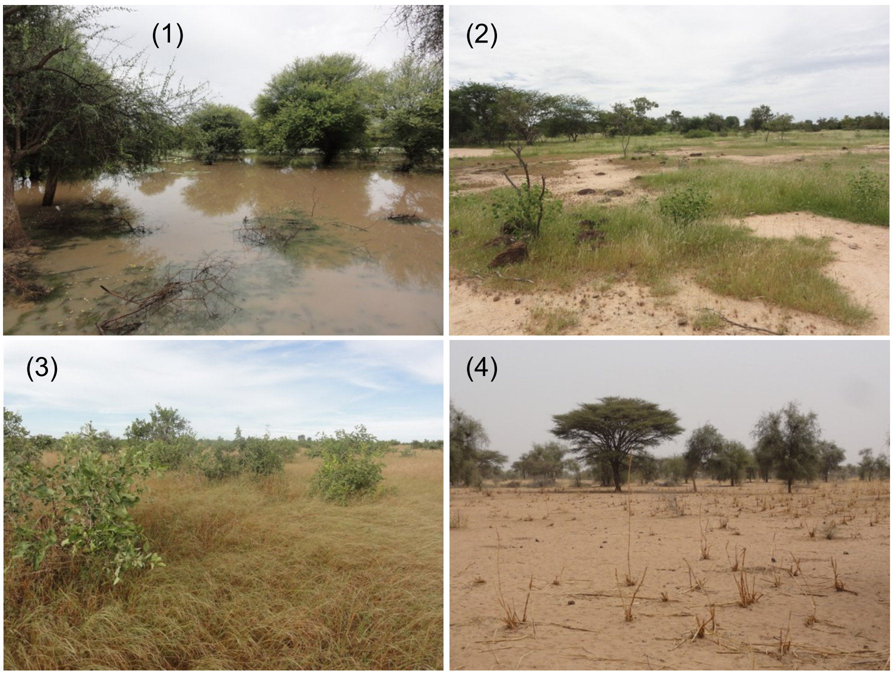


Figure 2. (**1**) A flooded *Xour* with *Dek* soils and large *Acacia tomentosa* trees; (**2**) *Bowel* region with exposed laterite; (**3**) a *Dior* peanut fallow with *Combretum glutinosum* shrubs; (**4**) a *Bardial* cultivated with millet and *Balanites aegyptiaca* trees. Also an *Acacia raddiana* can be seen here. Photos are taken in March (4) and September (1-3) 2012.



2.2. Data and Methodology

A detailed soil map derived from field work, multivariate statistics and remote sensing forms the basis of this study. Soil types, their properties and spatial dimensions as well as the occurring woody species growing on these soils were studied. Woody vegetation surveys and a modeled canopy cover map were grouped and explained according to the soil map. Interviews with the local population supported by existing literature were the basis for a discussion on environmental changes, climatic and erosion vulnerability for each soil type.

2.2.1. Fieldwork

Fieldwork was carried out during the dry (February, March) and the rainy season (September) of 2012 and the dry season of 2011 (February). In a first step, interviews with the local population were conducted in 6 Wolof villages and 3 Fulani settlements around Linguère to ascertain the local denotation of soil units as well as their agricultural use. Furthermore, information on the predominant woody vegetation growing on each unit was collected. This implied species abundance, its change over time and its use in people's daily life. Interviews were semi-structured with individuals, groups and key informants. More information on interview techniques are provided in Brandt *et al.* [2]. In the dry season 2012, vegetation and soil parameters on 84 representative and equally distributed test sites (2 ha each) were surveyed in the field. The sites were selected to represent all zones in existing soil- and vegetation maps [15,16]. All individuals of trees and shrubs along randomly chosen line transects (200 m) across the plots were identified in accordance with Maydell [11] and documented according to Herrick *et al.* [23]. Altogether, 2205 individuals of 24 tree and shrub species were surveyed within the 84 plots. Woody vegetation was differentiated in trees higher than 4 m and shrubs (including small trees) smaller than 4 m. This threshold was chosen to obtain comparable data to previous studies. Height, circumference (breast height), crown diameter, percentage of green leaves and canopy coverage for each tree >4 m were determined. Using high resolution imagery (RapidEye from December 27, 2010; see Brandt *et al.* [2]), trees and large shrubs (mostly >4 m) were manually counted on-screen for each 2 ha plot and validated by the field data of the transect line which crosses the plot. The total amount was divided by 2 to obtain the unit tree per hectare.

Finally, soil durability and degradation occurrence were noted according to [24]. Within the same plots, mixed soil samples and undisturbed samples were taken within the upper 20 cm (for sampling technique see [25,26]). The dried mixed samples were transported to a soil laboratory (see 2.2.2). Soil density and maximum water holding capacity (WCmax) were analyzed in-situ with undisturbed samples [25,26]. Additionally, soil stability was determined in accordance with Herrick et al. [23] and rated between 3 and 8 [27]).

2.2.2. Laboratory Analysis

The following soil parameters of all 84 mixed samples were analyzed in a laboratory: pH-value (H20), electrical conductivity [28], grain size distribution (fine-sand, medium-sand and coarse-sand, clay, silt), NO3-, NH^{4+}, PO43-, C/N, C, N, S, H^+, potential cation exchange capacity (CECpot) (Ca^{2+}, Mg^{2+},

Na^+, K^+, Al^{3+}, Fe^{3+}) and base saturation (BS) [26]. For information on techniques and equipment, see [25,26,28]. Available field capacity (FC) was estimated [25]. All parameters are listed in Appendix 1.

2.2.3. Statistics and Remote Sensing

To predict field data from test sites to the entire study area, a relation between field data and remote sensing products was obtained using two different statistical models, established to fit the needs of two different applications: (1) as conventional classification methods (e.g. maximum likelihood) are not suited for dealing with geographical data such as rainfall or a Digital Elevation Model (DEM) [29], Random Forest was chosen as a classifier to extrapolate local soil types over the study area. Therefore, the soil samples were grouped to soil types and a variety of predicting variables identified. (2) To model canopy cover at a continuous scale from 0 to 100%, a relation between one explaining variable and the test sites was established using a simple and robust regression method (Reduced Major Axis - RMA).

Model Soil Types

1. Group Soil Samples Soil types can often be distinguished by color, texture, predominant vegetation and agricultural use in the field. Local people confirmed this; however, a clear distinction was not always easy. To obtain an appropriate scientific classification based on physical and chemical soil properties, all 28 soil parameters (a listing can be found in Appendix 1) were used as input attributes for a clustering process using the Ward-algorithm and euclidean distance [30]. An ordination (Non-metric Multidimensional Scaling - NMDS) with 2 dimensions and a stress-value of 9.13% was then calculated using all 28 soil parameters. The NMDS is a very robust ordination, well suited for ordinally scaled and intercorrelated data [31]. As the 84 plots were grouped regarding their similarities, the NMDS was able to approve results from the clustering [27].

2. Identify Significant Remote Sensing Parameters As the final step is the area-wide extrapolation of soil types via remote sensing parameters, a variety of variables were fitted over the 2-dimensional space of the NMDS to identify significant relationships between grouped soil sites and remotely sensed raster values. Polygons were drawn over each of the 84 sites and averaged raster values underlying the polygons were extracted. In this way, a DEM derived from SRTM data offered the altitude in m a.s.l., TRMM (Tropical Rainfall Measurement Mission) rainfall data [32] provided the mean annual rainfall in mm (1998-2010), and the latitude and longitude gave the geographical position of each site. Multispectral and multitemporal Landsat TM (Thematic Mapper) data were acquired for 4 dates over 10 years and converted to reflectance values using a FLAASH (Fast Line-of-sight Atmospheric Analysis of Hypercubes) atmospheric correction (June 24, 2000; May 29, 2002; May 19, 2007; June 12, 2010). Each band was averaged pixel-wise using the 4 dates. This eliminated seasonal and atmospheric fluctuations which are common in this area. Furthermore, influences of bush fires and crop rotations were minimized by calculating mean values. The acquisition dates of the satellite images were during the late dry season in order to minimize the effects of photosynthetic active vegetation and to maximize reflectance values of soil properties. Moreover, at this time almost no grass and crop residues are left covering the ground. As dry bare soil reflects soil parameters best at wavelengths higher than 1.4 μm [33], band 5 (1.55-1.75

μm) and 7 (2.08-2.35 μm) were integrated into the NMDS. Band 2 (0.53-0.61 μm) added supplementary information on bare soil. The Normalized Difference Vegetation Index (NDVI) as a measurement for green vegetation [33], and the brightness coefficient of a Tasseled Cap (TC) transformation [34] as an additional parameter for soil reflectance, were also incorporated. A listing of all variables can be found in Appendix 2.

3. Extrapolate with Random Forest A Random Forest classifier was then used to extrapolate the clustered soil classes to the whole study area based on the training sites and significant environmental parameters, which were identified in the previous step. The Random Forest algorithm works with classification trees, of which each makes a class prediction based on various predictor variables. The trees are created using bootstrapping, a technique which holds back parts of the available objects and uses random subsets to grow various decision trees for each class. The final classification decision for each pixel is based on aggregation of the predictions of all random variable trees [29,35]. Depending on the scaling of the output variable, Random Forest models distinguish between regression- and classification-trees. Since our outcome variable has a nominal scale with 4 values representing 4 soil classes, the classification-tree method was obtained using the standard setting of 500 random trees. Validation of the model is called OOB (Out-Of-Bag) and is based on the bootstrapping. The classification-trees of random subsets are used to predict values which were previously held back and show an error matrix of the model quality [35]. Furthermore, a variable importance plot shows the importance of the individual input variables [35]. For a smoother result, the modeled image was filtered using a 3 x 3 pixel majority filter. For more information on Random Forest modeling we refer to Lawrence *et al.* [36], Pal [37] and Breimann [35].

Model Canopy Coverage

Polygons (about 200 m x 200 m) were drawn over 52 of the test sites. Using high resolution imagery (RapidEye from December 27, 2010), the crown-cover of all visible trees and large shrubs was painted black in a painting software at a scale of 1:1000 and a pencil size of 0.6 px. The output histogram of each polygon gave the exact value for the percentage of black within the image which corresponds with the canopy coverage in percent. This way, canopy cover in this study is defined by the whole area of woody objects, neglecting that a tree does not cover 100% of the ground. Also considering the spatial resolution of RapidEye (5 m), the actual cover may be lower than our modeling results. A model was then established using Landsat NDVI as the variable to explain canopy cover of the 52 training sites. The model was derived using the RMA regression method as suggested by [38]. In comparison to conventional linear regression models, the RMA method is more robust and can better handle sampling and measurements errors on both the x and y axis [38]. Since field work was carried out in February, no green grass and crop residues are left at this date and many of the woody vegetation keeps green leaves throughout the dry season, Landsat scenes of February were acquired and processed (FLAASH atmospheric correction) (February 22, 2002; March 13, 2003; February 28, 2007; February 20, 2010). Despite the drawback of vegetation change over 8 years which may influence single pixels, averaging the scenes over this time period has proven to deliver best results, as seasonal fluctuations and rainfall variability are minimized. The mean NDVI has a strong correlation with the painted canopy cover of the training sites (R^2 = 0.81; $p \leq 0.01$). Woody cover was then extrapolated to the whole study area via Landsat mean NDVI and the derived regression coefficients. Even though the percentage of green leaves is low for some tree species (e.g. *Acacia senegal, Pterocarpus lucens*), the reflectance signal of the bare soil is still suppressed due to the ligneous biomass cover. For more information on the methodology see Larsson [38]. Using the different soil types as masks, valuable information and quantification regarding the woody coverage of soil classes and degraded unvegetated regions could be obtained.

3. Results and Discussion

3.1. Soil Clustering Corresponds with Local Denotations

Clustering generated 4 soil classes at the 20% cutting-level which can be clearly validated by the elbow criterion [27]. These correspond with the soil types *Dek*, *Bowel*, *Dior* and *Bardial* which were denoted by the local population and are described in detail in chapter 2.1. In the following, the classes assigned by the soil clustering are used, as the demarcation in the field was not always clear. *Bowel* areas for example contain forested depressions or appear depression-like in *Dior* areas. However, their soil properties are more similar to *Bowel* than to a *Dek*, hence, they were included in the *Bowel* class and only heavy clayey sites were clustered as *Dek*. The Wolof names were applied to the corresponding clustered group. This way, each of the 84 plots obtained a value between 1 and 4 regarding its group.

3.2. Soil Types Significantly Differ in Properties

Soil properties differ between the 4 soil types. According to the FAO classification, *Dior* and *Bardial* are both Arenosols, *Dek* are hydromorphic soils (e.g. Vertisol) and *Bowel* regions are composed by Regosols [39].

Our results show that *Dek* sites are most clayey with a mean clay content of 26%, followed by the Regosols with 9%. *Dior* and *Bardial* Arenosols have an almost identical grain size distribution ($p \leq 0.05$) with a high portion of sand (85%) (see Fig. 3). However, at a confidence level of 10% *Bardial* have a significantly higher clay-content than *Dior* (6% compared to 5%). The pH-value differs significantly, too ($p \leq 0.05$). With 5.44, *Dior* have a 0.7 unit lower pH-value than *Bardial* (6.13). Linked to these differences are the lower base saturation and cation exchange capacity (Ca^{2+}, Mg^{2+} and K^+) on *Dior* (all significant at 5%).

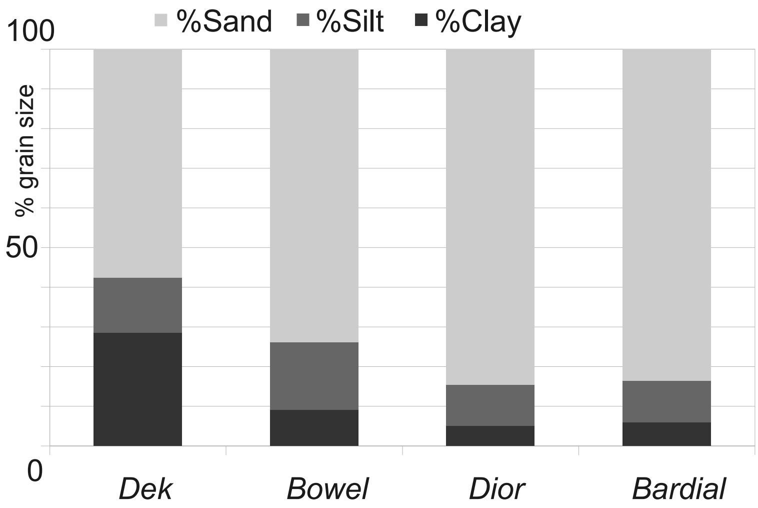
Mean organic carbon and humus are low (*Dek*) to very low (*Bowel*, *Dior*, *Bardial*) as are nitrogen and cation exchange capacity. Phosphate is rated within the lowest category for all soil types (<1 mg/kg), which is not surprising for tropical soils. *Dek* soils have the highest stability with 7.4, followed by *Bowel* Regosols (6.1) and both Arenosols (4.8 and 4.9). Available field capacity is high in the Regosols (22%), medium in *Dek* (20%) and low in *Dior* and *Bardial* Arenosols (9%). For detailed information and further statistics on soil properties, see Table 2.

3.3. Modeling Soil Types and Canopy Coverage

3.3.1. Soil Types

The NMDS confirmed the results of the soil clustering by grouping the sites in the same manner (see Fig. 4). Several significant predicting variables are identified. No evidence of a significant relationship between TRMM rainfall (R^2 = 0.045) / northing (R^2 = 0.06) and the soil properties can be verified at a confidence level of 10%. Both variables point into opposite directions, indicating that rainfall considerably decreases further north. On the contrary, Landsat's bands 5 (R^2 = 0.37), 7 (R^2 = 0.42),

Figure 3. Grain size distribution of the 4 soil types. Note that *Dior* and *Bardial* have an almost identical distribution.



as well as its TC brightness (R^2 = 0.29) are highly significant ($p \leq 0.01$) and point in the direction of the Arenosol sites *Dior* and *Bardial*, as does band 2 (R^2 = 0.09; $p \leq 0.05$). This can be explained by the low woody coverage of these soils and therefore the high spectral reflectance of the soil properties. NDVI (R^2 = 0.12), canopy cover (R^2 = 0.24) and especially trees/ha (R^2 = 0.48) are significant ($p \leq$ 0.05) and point in the direction of *Dek* and *Bowel* soils. Except from degraded sites, which are placed near the coordinate origin, these sites have a high vegetation density. In addition, significant ($p \leq 0.05$) relationships between easting (R^2 = 0.1) / altitude (R^2 = 0.14) and the soil types are observed.

Figure 5 shows the result of the 4 soil types modeled with Random Forest via 84 test sites and 6 significant ($p \leq 0.05$) variables (DEM; Landsat bands 2, 5, 7; TC brightness; NDVI). Despite being significant, easting was excluded from modeling because a visual comparison showed that including the variable causes a loss of important details. In contrast to the NMDS which uses values averaged over the test sites (about 2 ha), Random Forest works pixel-wise at a resolution of 30 m. The model's variable importance plot identifies the DEM as the most important input parameter, followed by Landsat's bands 5 and 7 (see Appendix 3). Canopy cover is the least important variable and therefore excluded in the modeling process. The OOB confusion matrix attests a high model quality with an error rate of 7.3% (see Appendix 4). Visual analysis revealed that several sparsely vegetated river beds of the Ferlo valley are erroneously modeled as *Bowel* due to similar soil- and spectral-properties. Ferruginous *Bowel* soils are largely located on the sandstone plateau in the east of the study area, but several spots are spread throughout the sandy zones, especially south of Khogue, but also west of Linguère and north of Kadji. They constitute the largest category in the study area with 39% while *Dek* are the smallest with a portion of 2%. *Dek* are mainly situated inside and along recent and ancient river beds. *Dior* are the second predominant soil with a fraction of 31% equally distributed mainly along the northern and southern sandy ecoregion and sporadic along valleys in the east. *Bardial* soils are slightly less widespread (28%) and often found more closely to river beds. This explains the slightly higher clay content.

Neither the soil map of Maignien [15] nor the one of Stancioff *et al.* [16] distinguish between different Arenosols. Apart from that, the pattern and distribution of soil types in the modeled soil map show a good agreement with existing maps. Stancioff *et al.* [16] found 3 prevailing soils corresponding with our clustered classes: (1) hydromorphic soils are situated in river beds and ancient valleys (*Dek*/*Xour* areas), (2) Regosols are found in the east and agree with *Bowel*. (3) Sandy tropical ferruginous soils are located in the western part of the study area and agree with the distribution of *Dior* and *Bardial* Arenosols. Maignien [15] classified hydromorphic soils as weakly hydromorph sandy and clayey soils. In Maignien's soil map, the east of the study area (the *Bowel* region) is covered by weakly leached tropical ferruginous soils, characterized by solidification and crusts in the deep. Maignien [15] found two more soils in the zone modeled as *Dior*/*Bardial*: (1) ferruginous brown-red soils on siliceous sands situated around Kadji and in the northwest and west of the study area and (2) brown sub-arid soils, sometimes calcareous in the deep (south of Linguère).

By aggregating the modeled soil map to a coarser resolution (up to 1 km), the spatial pattern is preserved and still provides information on the predominant soil. This indirectly gives information on predominant woody vegetation and potential usage at a coarse scale. Local land cover maps [19,40] show a similar spatial pattern but the provided information differs. In comparison with MODIS global land cover maps, a much more realistic pattern can be observed on our soil map [27].

Figure 4. NMDS-ordination with grouped test sites (according to 28 soil parameters) and fitted variables. REF 2, 5, 7: Landsat reflectance June; TC: Tasseled Cap brightness; ALT: altitude; CAN-COV: canopy cover; TRMM: annual rainfall; LONG: longitude; LAT: latitude. The arrows show significant relationships between the soil samples and fitted variables by pointing into the respective direction. A longer arrow means a stronger relation.

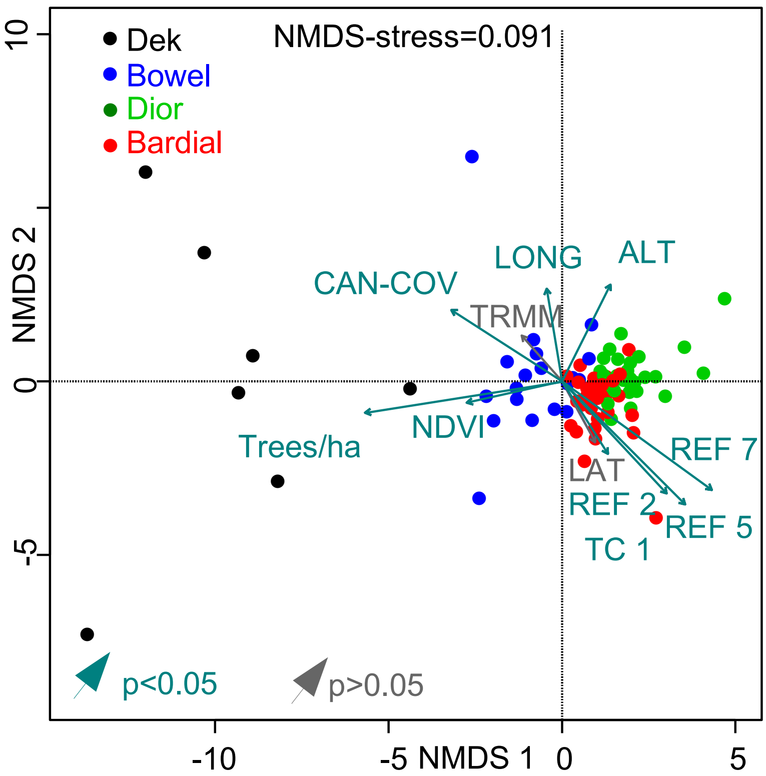
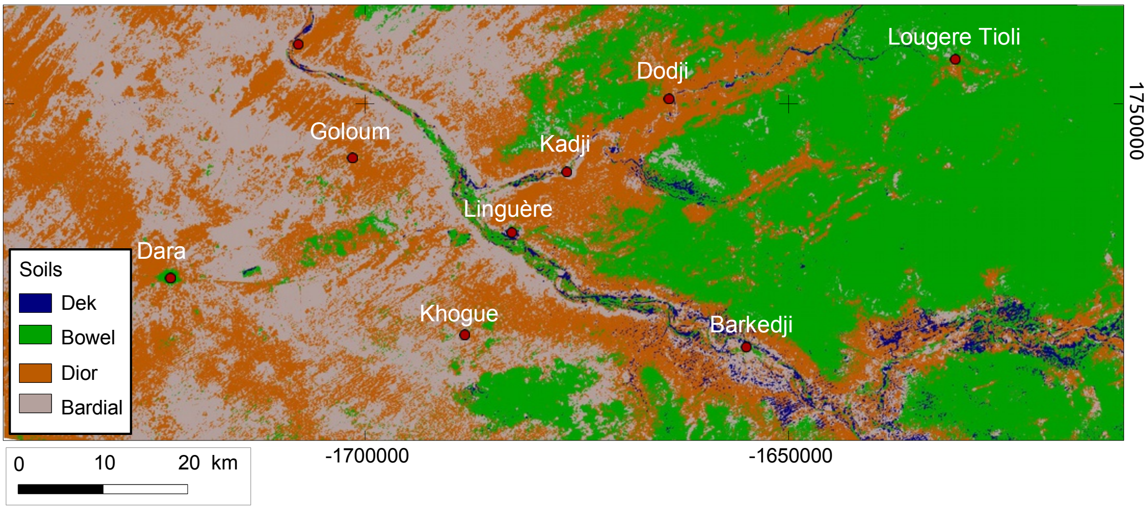


Figure 5. Modeled soil types in the Ferlo around Linguère. The legend shows the soil names in Wolof. For the corresponding scientific names, see Table 1. The area represents the square in Figure 1.



3.3.2. Canopy Coverage

Canopy coverage (Fig. 6) obviously differs between the 4 soil types and will be discussed in detail in chapter 3.4. It considerably decreases from west to east, indicating the geomorphological change from the sandy to the ferruginous Ferlo. Forested and deforested (i.e. degraded) areas are clearly visible in Figure 6 and Figure 7.

Figure 6. Modeled canopy cover for the whole study area. The area represents the square in Figure 1.

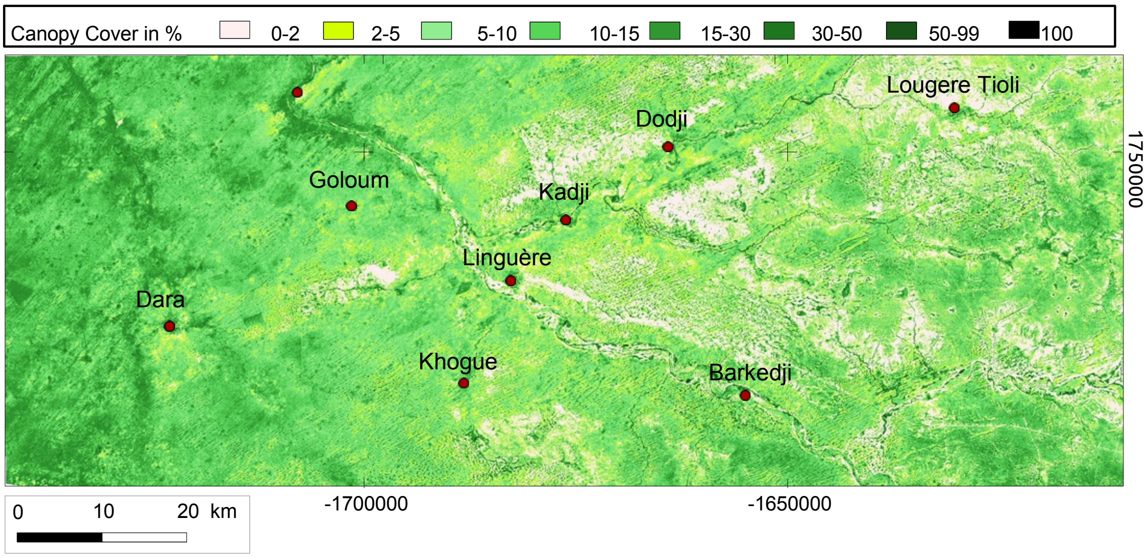
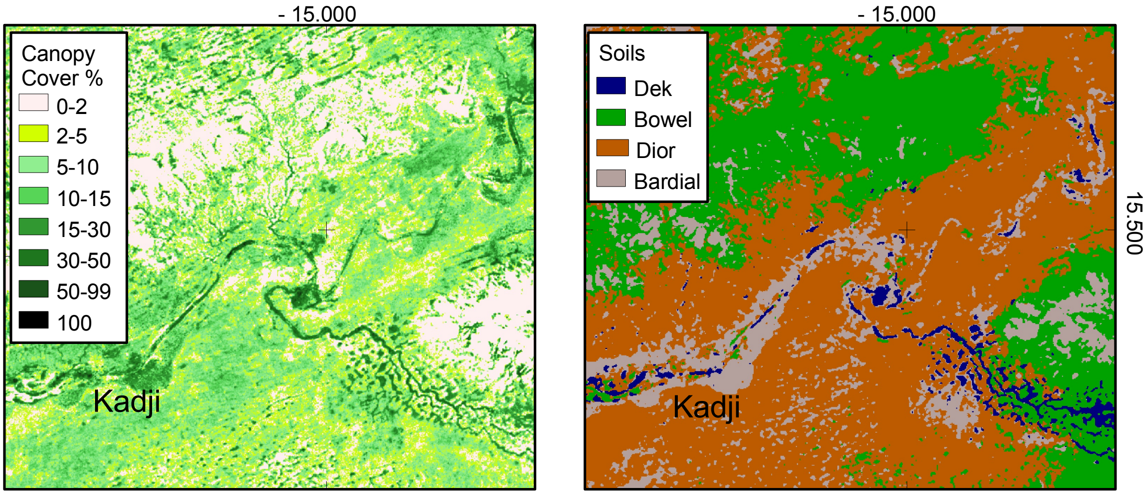


Figure 7. Woody cover (**left**) and soil types (**right**) around the Wolof villages Kadji and Kol Kol, north-east of Linguère. The *Dior* region with a sparse woody cover is mainly used for peanut cultivation while millet is grown on Bardial near the villages. Parts of the *Bowel* region are degraded and eroded with no woody vegetation left, as they are not suitable for cropping and thus serve as a source for fuel-wood. *Dek* are flooded during the rainy season.



3.3.3. Relationship between Soil and Woody Vegetation

This chapter describes and discusses woody species surveys and canopy coverage according the classes (1) *Dek*, (2) *Bowel*, (3) *Dior* and (4) *Bardial*. Results are summarized in Table 3 and Figure 8. Regarding species, trees and shrubs of all heights are included, whereas tree height, trunk circumference and trees/ha are only available for trees >4 m (see Tab. 3). The ratio tree/shrub counts the relation between trees >4 m and shrubs <4 m. At this point it has to be noted that much of today's woody species composition is strongly influenced by humans and livestock. However, a clear pattern can still be observed. Mostly dominating are *Balanites aegyptiaca* (43%), *Combretum glutinosum* (15%) and *Acacia raddiana* (15%) while 21 other species account for 27%.

(1) A majority of rare species such as *Mitragyna inermis* and *Acacia nilotica var. tomentosa* are found on *Dek* soils and are mostly absent in other classes (see Fig. 8). Especially the abundance of *Acacia seyal* is statistically significantly higher ($p \leq 0.05$) on *Dek* than in all other classes. Also mean tree height and trunk circumference of trees are greatest for the *Dek* group. The ratio of shrubs to trees is 34%, showing that large trees are more frequent on hydromorphic soils. Furthermore, trees/ha as well as mean canopy coverage outnumber all other classes. 87% of the classified *Dek* area exceeds a canopy cover of 10% (Tab. 3).

(2) As mentioned, it is not always easy to draw a strict boundary between a *Dek* soil within a *Xour* and a loamy *Bowel*. However, *Bowel* Regosols have a unique species composition with significantly higher portions of *Pterocarpus lucens, Guiera senegalensis, Combretum micranthum* and *Boscia senegalensis* than the other classes ($p \leq 0.05$). This composition follows the soil clustering, which generates only heavy clayey depressions with standing water as *Dek* and summarizes all lateritic and loamy sites including depressions (*Xour*) with above mentioned vegetation as *Bowel*. Species richness on *Bowel* Regosols is high (Fig. 8). Woody cover ranges from 0 to 89% with a mean of 6% due to a

very heterogeneous landscape (see Fig. 7). 28% of the zone can be considered as relatively dense non-degraded bushland with a canopy cover >10%, and 55% exceed a canopy cover of 5%. However, 29% of the *Bowel* soils are deforested, mostly a sign of degradation. Widespread degradation is mainly a problem of the *Bowel* class, as in all other soil classes combined, deforested areas account for merely 12%. Shrubs or small trees (<4 m) constitute 60% of the woody vegetation, which is evidence for the prevailing shrub savanna (Tab. 3).

(3) *Dior* sites have a significantly higher abundance of *Combretum glutinosum* ($p \leq 0.05$) than the other classes, most of them growing on peanut fallows and representing 24% of the woody population on *Dior*. Numbers in trees/ha, canopy cover, deforested areas and species diversity (Fig. 8) are strongly influenced by humans, as most shrubs are cut down when a field is changed from fallow to actively cultivated cropland. Thus, coverage is higher on fallows but still low, since farmers prefer not to have any large trees within their groundnut fields, as trees attract birds which subsist on crops during the harvest. Trees are not needed for fixing nitrogen, as groundnuts and beans are legumes as well. This is also expressed by the percentage of shrubs and small trees (<4 m), which is 77% on *Dior*. Mean tree height and trunk circumference are slightly lower than on *Bardial* Arenosols which are used for growing millet (Tab. 3).

(4) *Bardial* exceed *Dior* in trees/ha and canopy cover as well. Deforested areas are mostly nonexistent on *Bardial*. Moreover, most *Balanites aegyptiaca* are found on *Bardial* soils, but their abundance is not significantly higher than on *Dior* (see Tab. 3 and Fig. 8).

Figure 8. Distribution of the predominant species according to the 84 test sites (all heights). Note that *Balanites aegyptiaca* is dominant in all classes. Other: *Acacia nilotica var. adansonii, Acacia nilotica var. tomentosa, Acacia pennata, Adansonia digitata, Combretum aculeatum, Combretum nigricans, Commiphora africana, Bauhinia rufescens, Grewia bicolor, Piliostigma reticulatum, Sterculia setigera, Tamarindus indica, Ziziphus mauritiana.*

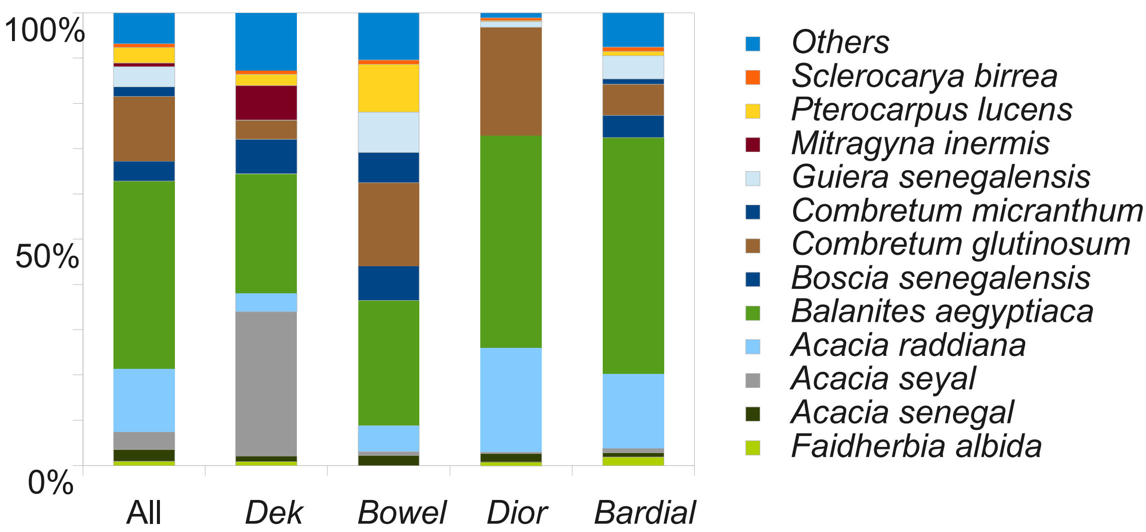


Table 2. Soil parameters classified according to the 4 clustered soil types derived from field and laboratory measurements. **Mean value**, range [min–max] and standard deviation are provided.

Parameter	*Dek*	*Bowel*	*Dior*	*Bardial*
Samples n	7	19	28	30
pH (H20)	**5.73** [4.4–8] 1.35	**6.17** [5.3–8.1] 0.58	**5.44** [4.9–6.4] 0.33	**6.13** [5.3–7.4] 0.43
Humus [%]	**1.56** [1.14–1.9] 0.25	**0.62** [0.38–0.97] 0.21	**0.34** [0.19–0.44] 0.06	**0.39** [0.24–0.68] 0.1
N [%]	**0.14** [0.12–0.18] 0.02	**0.08** [0.05–0.11] 0.02	**0.06** [0.04–0.08] 0.01	**0.06** [0.04–0.09] 0.01
CN	**6.8** [5.4–8.1] 0.9	**4.5** [3-6] 0.9	**3.4** [1.6–5.8] 0.9	**3.7** [2.2-5.3] 0.8
P [mg/kg]	**0.21** [0.1–0.5] 0.12	**0.22** [0.01–1.1] 0.28	**0.24** [0.04–0.62] 0.17	**0.48** [0.0–3.2] 0.71
CECpot [cmol/kg]	**9.04** [5.3–21] 5.61	**2.56** [1.51–4.5] 0.8	**1.33** [1–1.9] 0.23	**2.05** [1.1–4.3] 0.84
BS [%]	**97.8** [95.4–99.8] 1.71	**97.8** [95.5–99.6] 1.2	**92.7** [78.8–98] 3.75	**97.5** [95.2–99.6] 1.25
Ca [cmol/kg]	**6.26** [2.75–15.87] 4.68	**1.6** [0.81–3.32] 0.67	**0.67** [0.4–1.1] 0.16	**1.22** [0.63-2.5] 0.5
Mg [cmol/kg]	**1.83** [1.1–4.4] 1.16	**0.51** [0.25–0.83] 0.16	**0.24** [0.13–0.36] 0.05	**0.44** [0.2-1.08] 0.23
K [cmol/kg]	**0.5** [0.34–0.65] 0.11	**0.18** [0.09–0.27] 0.05	**0.12** [0.08–0.2] 0.03	**0.16** [0.06-0.28] 0.05
FC [% vol]	**19**	**22**	**8**	**8**
Sand [%]	**53** [32–65] 10	**71** [57–81] 7	**86** [79–92] 4	**85** [77–93] 4
Clay [%]	**26** [16–38] 7	**9** [4–20] 4	**5** [3–9] 1	**6** [3–10] 2
Stability (3–8)	**7.4** [6–8] 0.8	**6.1** [5–8] 0.9	**4.8** [3–7] 1	**4.9** [3–7] 1.1

Table 3. Mean vegetation parameters classified according to the 4 clustered soil types derived for test sites from field data (*) and for the whole study area from remote sensing products.

Parameter	*Dek*	*Bowel*	*Dior*	*Bardial*
% Spatial occurrence	2	38	31	29
Altitude [m]	24	46	39	40
NDVI (June)	0.19	0.15	0.16	0.17
Canopy cover [%]	18	6	7	10
Canopy cover <1% [%]	0	29	9	3
Trees / ha (>4 m) *	53	26	11	15
Tree height (>4 m) [m] *	8	7,62	7,2	7,8
Tree circumference (>4 m) [cm] *	70	34	59	63
% Shrubs	34	60	77	61

3.4. Extensive Environmental Changes are Reported on All Soil Types

Droughts, a general decrease in annual rainfall as well as human impact have taken a heavy toll on the woody vegetation in the Ferlo [1,2,8,17]. Tappan *et al.* [1] found a general decrease in mean tree cover from 10-20% to 5-15% within the past 50 years. Our data show that nowadays overall species diversity is low (Fig. 8) and village elders in our study area report an overall woody species and tree cover decline due to more arid conditions. These statements are statistically confirmed by the studies of Herrmann & Tappan [5], Gonzalez *et al.* [7] and Gonzalez [6]. Our interviews reveal that the 4 modeled soil types react differently to dry periods and rainfall change. Moreover, human impact differs between the classes. In this chapter, environmental changes are described and discussed according the classes (1) *Dek*, (2) *Bowel*, (3) *Dior* and (4) *Bardial*.

(1) Species richness and tree cover on clayey *Dek* is high, however, both are reported to have considerably declined in the past 50 years. In times of little rainfall, leaves of trees on *Dek* sites provide an important source of fodder throughout the dry season. These sites are exploited accordingly and often living trees are cut down to make leaves available to animals. Local people report that in combination with droughts and less rainfall, this has led to a strong decrease of large, old trees within *Xour* areas. Additionally, young trees struggle to survive due to massive numbers of animals who frequent the sites for drinking water, preventing rejuvenation.

(2) Most areas of lateritic Regosols (*Bowel*) belong to protected regions and are thus rarely used for cropping. Therefore, they were never cleared from bushland, although soil properties appear more fertile than those of *Dior* and *Bardial* Arenosols. However, the region is very heterogeneous, and often hard and impenetrable laterite is present near the surface. Local people and Tappan *et al.* [1] report that a poor infiltration rate and low water holding capacity make these areas vulnerable to droughts and little rainfall, leading to a decline or even local extinction of several species. E.g. *Anogeissus leiocarpus, Combretum micranthum, Commiphora africana, Grewia bicolor, Sterculia setigera* and *Terminalia avicennioides* are named to have strongly declined. The natural regeneration rate of other species (e.g. *Pterocarpus lucens, Guiera senegalensis*) is good and significant greening trends are observed within this region caused by an increment of the woody layer [41]. Elders report that 5 years after a drought the woody vegetation shows recovery under undisturbed conditions. In reality, over-exploitation by cutting, browsing and grazing as well as soil compaction by trampling leads to loss of vegetation and soil and hampers regeneration. Thus, an alarming figure of 29% of *Bowel* areas can be identified as deforested on our canopy cover map (Tab. 3 and Fig. 7). As observed by Brandt *et al.* [2] and Tappan *et al.* [1], these spots used to be covered by dense woody vegetation 50 years ago and are now eroded barren land. This is particularly the case in close proximity to villages, roads, boreholes and along fossil valleys.

(3+4) According to interviewees, large parts of the natural vegetation on *Dior* and *Bardial* Arenosols were cleared by humans in the 20th century for the purpose of cropping and grazing. Areas formerly covered by dense and sometimes inaccessible bushland dominated by *Guiera senegalensis* and inhabited by wild animals were cleared. Only large trees or favored species (e.g. *Faidherbia albida, Acacia nilotica, Acacia sieberiana, Anogeissus leiocarpus, Combretum nigricans, Lannea acida, Sterculia setigera, Terminalia avicennioides, Ziziphus mauritiana*) were not felled. However, most of them exist only in very small numbers today (see Fig. 8). Despite Arenosols having a large water storage capacity, which tempers the effects of dry years, some native species did not tolerate a general decrease in annual rainfall. Thus, local people report that the droughts in the 1970s and 1980s represent the starting point of a rapid increase of tree dying. Although a greening is observed which is caused by the woody layer [41], several species, which, according to village elders and older literature [13], were originally typical for this region and its soils, have now vanished (e.g. *Terminalia avicennioides*). They have been replaced by three prevailing species (*Acacia raddiana, Balanites aegyptiaca, Combretum glutinosum*) which account for a share of over 90% on our *Dior* and *Bardial* test sites (see Fig. 8). Although *Faidherbia albida* is a favored species and reported as being manifold on fields in former times, very few of these species larger than 4 m were found on Arenosols in 2012. However, various seedlings have been planted on cropland to reestablish *Faidherbia albida, Ziziphus mauritiana* and other useful species as well as thousands of *Acacia senegal* on huge tree plantations. However, the seedlings are vulnerable to extreme events and livestock and are not able to grow without protection. Villages like Nguith (3 km west of Linguère) and Goloum have their own fenced areas where trees are planted and protected. Only villagers from the corresponding village are allowed to enter and practice sustainable farming.

4. Conclusions

In this study we highlighted the importance of soil properties in the context of ecosystem resilience and environmental change. Native Wolof soil names (*Dek*, *Bowel*, *Dior*, *Bardial*) were used to classify soils and to statistically establish relationships between soil types and woody vegetation. Results were successfully modeled for a region in the Sahel and provide a soil map which corresponds well with existing maps. We thus demonstrated that local knowledge can be well combined with scientific classifications offering a concise and clear map. With its high spatial resolution and the use of local soil denotations, the map offers an easy usability and information on species distribution, potential usage and vulnerability to degradation. Moreover, the spatial degree of deforestation was assessed by modeling woody cover at a 30 m resolution.

Interviews with village elders revealed extensive environmental changes and a massive decline of woody species within the past 40 years with major differences between the modeled soil types. Droughts and a decrease in annual rainfall are reported to have led to a local extinction of several species on *Dior* and *Bardial* (e.g. *Terminalia avicennioides*), just as human activities and livestock grazing contributed to an overall decrease in woody cover. Our tree survey showed that nowadays few robust species (*Balanites aegyptiaca, Combretum glutinosum* and *Acacia raddiana*) make up approximately 80% of all surveyed trees and shrubs. Our canopy cover map identified large areas of deforested and degraded land restricted to *Bowel* regions (29%). This demonstrates that vegetation change, degradation, resilience to climatic stress and human activities significantly depend on soil properties.

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Author Contributions

The conception of the research approach and development of the methods was done by M. Brandt, T. Grau and C. Samimi. The data was collected and prepared by T. Grau (soil sampling, soil analyses, statistical soil analyses) and M. Brandt (remote sensing and modeling, vegetation survey and interviews). The research was conducted by M. Brandt and T. Grau. Analysis and interpretation was done by M. Brandt and T. Grau and discussed with all authors. The manuscript was written by M. Brandt with contributions from all authors.

Conflicts of Interest

The authors declare no conflict of interest.

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Part III

SYNTHESIS AND OUTLOOK

8 SYNTHESIS

The present study analyzed the spatio-temporal pattern of vegetation changes in two Sahelian study areas (Linguère in Senegal and Bandiagara in Mali). For the evaluation of the hypotheses a variety of datasets and interdisciplinary methods at different temporal and spatial scales were used. The main hypotheses of this study were:

1. **Widespread desertification is nowadays replaced by a greening Sahel phenomenon.**
2. **The greening phenomenon can only partly be explained by rainfall variability. A human signal is part of environmental changes observed in satellite data.**
3. **The ability to characterize the spatial variability of Sahelian vegetation trends is affected by the coarseness and quality of the satellite data used. Thus, degradation is obscured and greening overestimated.**

The approach taken to explore these hypotheses rests upon time series analyses (satellite derived greenness as well as rainfall), woody vegetation surveys and monitoring, high-resolution satellite imagery analyses (using visual inspection and object-oriented classifications), soil modeling, tree cover modeling, interviews with the local population and long time series biomass monitoring. The methods and results were presented and discussed in detail in five peer-review publications. Note however that our conclusions are limited to the study areas. Because of the direct linkage between the three hypotheses, they are not separately addressed in this synthesis. The main findings are the following:

Analysis of climate data (CRU) shows a significant and rapid increase in average annual temperature for whole Western Africa since the 1960s. GPCC, TRMM and station data rainfall trends reveal that annual rainfall was 15% lower in Linguère and 13% in Bandiagara for the period 1970–2010 compared to 1930–1970. However, both study areas have seen a significant increase over the period 1982–2010 (54% in Bandiagara and 34% in Linguère), signifying a strong recovery from the dry period since the 2000s. However, climate models predict an insecure future with a tendency towards prolonged dry spells, an increasing variability and a further decrease in rainfall (see chapter 4).

Multi-scale and mixed-method assessments in our study areas show that greening and degradation are spatially heterogeneous and caused by a combination of both anthropogenic and climatic factors. Neither extensive greening nor desertification is widespread and both paradigms cannot be generalized as both are present with varying occurrence at a local scale. In the year 2011, approximately 5–10% of each study area are considered to be degraded, whereas large parts of the remaining areas show a moderate and partially strong greening trend. The degraded areas were almost nonexistent in the 1960s. Anthropogenic disturbances and climatic factors (droughts, decline in rainfall), combined with unfavorable soil conditions have directly and indirectly led to desert-like vast-lands. However, the share of these areas is small and thus degradation has never been widespread, nor is it irreversible. Areas reported as seriously degraded in the late 1980s show a dense woody vegetation in the year 2012. In both study areas, farmer and governmental managed programs have been observed successfully combating degradation. This takes place within the framework of strict observance of legislation and by-laws and active protection against cutting of living trees. Agroforestry on fields and large scale reforestation areas have also been important drivers of increasing woody vegetation. In combination with an increase in rainfall and a strong tree cover regeneration after a dry-period, these activities have contributed to a large scale greening. Therefore, the greening Sahel phenomenon can be confirmed in both study areas with an average increase of approximately 30% in vegetation greenness since the beginning of the 1980s. However, our study also demonstrates that greening can hide degradation, as a dense tree cover can hide spreading of soil erosion on the ground. Moreover, areas of negative vegetation trends can still be observed, despite of an increase in annual rainfall.

Even though greening aspects prevail in both study areas, it is not a return to conditions similar to those prior to the severe droughts in the 1970s. Instead, extensive environmental changes were observed for the last 50 years in both study areas (see chapter 6). Depending on soil and morphology, much of the natural bushland vegetation has been cleared and has been replaced by an environment controlled by humans. Yet, even over the space of half a century, the direction of change is not exclusively negative. Agroforestry and protection of large trees on actively used fields have led to a tree cover increase in the immediate surroundings of villages. However, interviews with village elders and repeated measurements over approximately 30 years reveal a massive woody species decline both in Senegal and Mali (see chapter 4). Many species do not tolerate prolonged climatic and anthropogenic stress as well as the general decrease in annual precipitation. Thus, the current woody vegetation is composed of several robust species, which have dispersed all over the study areas (mainly *Balanites aegyptiaca*).

Environmental change is very much dependent on soil and its properties (see chapter 7). Soil controls human activities, drought resilience and regeneration capacities. Sandy dune soils were almost entirely cleared for cultivation purposes in the 20th century. Nowadays, tree cover is selective with only certain species on farmer's fields, often providing essential soil nutrients. Sandy soils temper the effects of droughts and human influence dominates here. Adverse impacts of dry periods were minimal on these soils so that the damage was low and thus the greening effects are only moderate, sometimes not significant. In contrast, woody vegetation on shallow soils paid a heavy toll during the droughts and dry periods in the 1970s and 1980s. Around 1/4 of these lateritic soils is nowadays deforested with apparent soil erosion and exposed laterite crusts. Not only is woody vegetation on this soil susceptible to droughts, but the lack of cultivation usage makes it a common source for firewood and livestock grazing, putting pressure on vegetation and soil. However, due to the large-scale tree dying at the beginning of the 1980s, areas with shallow soils nowadays show an extensive re-greening in both study areas, signifying a strong overall regeneration (chapter 5). This is mainly due to an increase in rainfall; the reduction of human pressure is also partly responsible.

Coarse-scale satellite time series have proven to be an appropriate indicator for monitoring long-term greenness change at a regional scale. Ground data and site visits show that much of the observed greening trends are a good reflection of the reality on the ground. As all available time series start during a dry period and end in a wet period, degraded areas are highlighted from their surroundings, as they do not show positive trends, in spite of the increasing rainfall. However, chapter 5 has shown that the spatial variability of vegetation cannot be adequately captured with coarse scale satellite datasets and we further demonstrate that apart from the pixel resolution the whole processing line (input reflectances and retrieval algorithms) of global datasets has significant effects on the results of trend analyses. Thus, not only the scale but also the choice of dataset has shown to be relevant and results have to be treated with caution.

Although all datasets are generally consistent at a regional scale, the magnitude, direction and spatial pattern of trends strongly differs at a local scale. In-depth knowledge of the areas is needed to verify derived vegetation trend maps. With a spatial resolution of 8 km, GIMMS data tends to generalize a heterogeneous landscape, obscuring important aspects. Moreover, the recent version of GIMMS-3g FAPAR contains errors and has to be used with caution. With a higher spatial resolution and different processing lines, GEOV1 FAPAR, MODIS and SPOT-VGT NDVI products made it possible to better characterize the spatial pattern and identify areas of degraded and re-greening land, which are hidden in GIMMS data. However, the GEOV1 product is still very coarse and inconsistencies have been detected within this study. At its current stage, GEOV1 is not free of errors which influence the analyses. Even though the spatial resolution of MODIS and SPOT-VGT is much higher than GIMMS and GEOV1, the temporal extent is often too short to identify areas of significant change. Unimportant short-term processes like bush-fires or crop rotations often have significant influence on the results of the fine scale analyses. However, in contrary to coarse data, MODIS analysis offers a trend pattern which is clearly affected by humans, identifying humankind as an important driver of change.

The major aim of this study was not an evaluation and quantitative assessment of data quality but to focus on interpretation of results. Thus, several limitations and uncertainties regarding data quality, scale issues and inconsistencies have been taken into account. The comparison of high-resolution imagery with two different resolutions (5 m and 2 m) is not without error. Moreover, the object-based mapping of RapidEye imagery needs improvement (see chapter 6). Both FAPAR products show inconsistencies. Thus, trend analysis conducted with GEOV1 and GIMMS-3g have to be considered with caution (see chapter 5). Climate data is based on very coarse and inhomogeneous global datasets. Sampling and processing of the gridded rainfall data is inaccurate and can only be an approximation of reality (Eklund et al., submitted). Moreover, a massive station decline is observed in West Africa since the 1980s making trend analyses with GPCC and CRU assailable. The author of this thesis provides more information on gridded data reliability in Eklund et al. (submitted) (not included in this dissertation). Furthermore, long term ground data of vegetation are only available for 3 monitoring sites in Senegal. Beside these sites, the long term interpretation results are based on interviews and are thus biased by personal perceptions of individuals. Moreover, beside the species survey, the interviews remain at a qualitative and descriptive level and restrict the results to small areas. However, the majority of remote sensing studies do not conduct any validation at local scale and even though the accuracy of our results may not always be entirely without error, the trend has shown to be correct.

Desertification and greening paradigms are both generalizations attempting to simplify a reality which is far more complex. Heterogeneity is an issue of scale and very coarse-scaled vegetation trend analysis mainly present a greening Sahel. However, locally-scaled trend maps are not uniform, exposing greening and degradation at the same time. Since rainfall is increasing over the observed time period, degraded and unproductive areas do not follow the overall greening trend. Even though rainfall explains large parts of regionally-scaled greenness trends, local explanations can be very site specific and we demonstrate by means of several case study sites that humans have a significant impact on locally observed vegetation trends. Moreover, today's woody vegetation density and composition in both study areas is increasingly controlled by humans, showing a clear pattern of anthropogenic activities and identifying humankind as a major driver of long term vegetation changes. This pattern is hidden in coarse scaled studies, so that high-resolution imagery, moderate resolution time series, field data and household surveys are needed in order to reliably identify and interpret environmental change. Critical attention to data reliability is essential to avoid erroneous interpretations.

9 OUTLOOK

Not all data collected in the past years could be utilized in the frame of the presented manuscripts and the dissertation. The studies remain very local and present a heterogeneous pattern of vegetation change which can differ in other areas. Thus, regionally scaled studies are necessary to offer further insights into vegetation change, scale issues and impact on humans. Moreover, this study remains largely descriptive when explaining environmental change. Long term ground data is very valuable, and available for 36 biomass monitoring sites throughout Senegal, of which only three were used within this thesis. Together with contacts established during the past years (Chekh Mbow, Abdoul Aziz Diouf, Aleixandre Verger) we prepare a new study using 24 of the biomass monitoring sites. The purpose of this study is to analyze the underlying causes of observed NDVI trends in the Sahel by disentangling trends in total biomass, herbaceous biomass and leaf biomass. 27 years of annual ground measurements at 24 monitoring sites distributed throughout Senegal are compared with coarse NDVI and rainfall data. The measurements cover a variety of different land cover types over the period 1987-2013.

Moreover, 48 sites of a woody species survey conducted in 1983 by Gray Tappan were revisited 2012/2013 all over northern Senegal. This data gives valuable information on woody species change over 30 years for a large region. Therefore, another objective will be to use woody species data to provide evidence for whether or not significant changes in woody species composition go along with observed greenness trends.

Furthermore, new satellite products will be available soon (GEOV2), providing a more accurate data basis. The issue of scale can be quantitatively addressed by statistical comparisons of multi-scale satellite data with ground observations, a task which has not yet been conducted in the Sahel. Again, for this purpose, the biomass monitoring sites can be very valuable. Another possibility of future work is the enclave in Widou Thiengoly, which is fenced off since the beginning of the 1980s and was visited twice within the project. Vegetation can be monitored in this area without the influence of grazing and cropping, providing valuable information on the impact of climate and environmental change on the vegetation composition and density. Furthermore, the quantitative comparison of Corona and RapidEye lacks accuracy. More work and higher resolution imagery is needed here to gain better information on vegetation changes over 50 years. Moreover, the human perspective, i.e. the impact of observed trends on humans was largely neglected in this study. A large part of the mentioned data has already been collected and is being processed beyond the present thesis and in close collaboration with the CSE. Finally, a review paper is currently being prepared in collaboration with Cécile Dardel. This short paper will summarize new insights of the greening/degradation debate achieved by new remote sensing datasets in combination with ground data.

Therefore, the author of this thesis will continue performing research in Western Africa and strengthen the knowledge of environmental change in the Sahel.

Part IV

APPENDIX

A LIST OF PUBLICATIONS AND PRESENTATIONS

Only publications and presentations related to the present thesis are listed here.

A.1 PEER-REVIEWED JOURNALS

1. Brandt, M., Verger, A., Diouf, A.A., Baret, F. & C. Samimi (**2014**): 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.
2. Spiekermann, R., Brandt, M. & C. Samimi: 50 years of woody vegetation and land cover changes in the Sahel of Mali. *International Journal of Applied Earth Observation and Geoinformation*, under review.
3. Brandt, M., Grau, T., Mbow, C. & C. Samimi: Modeling soil and woody vegetation in the Senegalese Sahel in the context of environmental change. *Land*, under review.
4. Brandt, M., Romankiewicz, C., Spiekermann, R. & C. Samimi (**2014**): Environmnetal change in time series - An interdisciplinary study in the Sahel of Mali and Senegal. *Journal of Arid Environments*, 105, 52-63.
5. Brandt, M., Paeth, H. & C. Samimi (**2013**): Vegetationsveränderungen in Westafrika – Spiegel von Klimawandel und Landnutzung. *Geographische Rundschau* 65(9), 36-42.
6. Eklund, L., Romankiewicz, C., Brandt, M. & C. Samimi: Issues of data and methods in linking environment and migration – A critical focus on scale. *Geographical Journal*, submitted.
7. Brandt, M., Verger, A., Diouf, A.A., Samimi, & C. Mbow: Three Decades of Vegetation Change in the Sahel Zone – Disentangling the Underlying Causes of NDVI Trends. In preparation.

A.2 CONFERENCE POSTERS AND PRESENTATIONS

1. Brandt, M., & C. Samimi (**2013**): La variabilité du climat et les changements environnementaux dans les régions exemplaires du Sénégal et du Mali. Stakeholder Workshop *micle* Project, Dakar.

2. Brandt, M., Verger, A., Baret, F. & C. Samimi (**2013**): 29 years of local vegetation trends in the Sahel of Senegal using long time series FAPAR satellite products and field measurements. *Deutscher Geographentag* 2013, Passau.
3. Spiekermann, R., Brandt, M. & C. Samimi (**2013**): Using high resolution imagery to detect woody vegetation and land-cover change over 50 years in the Sahel of Mali. *Geophysical Research Abstracts*, Vol. 15, EGU2013-11937, EGU General Assembly 2013.
4. Grau, T., Brandt, M. & C. Samimi (**2013**): Predicting local Soil- and Land-units with Random Forest in the Senegalese Sahel. Geophysical Research Abstracts, Vol. 15, EGU2013-10981, EGU General Assembly 2013.
5. Strommer, G., Brandt, M., Diongue-Niang, A. & C. Samimi (**2013**): Analysis of daily rainfall of the Sahelian weather-station Linguere (Senegal). Trends and its impacts on the local population. *Geophysical Research Abstracts*, Vol. 15, EGU2013-12716, EGU General Assembly 2013.
6. Brandt, M., Samimi, C., Romankiewicz, C. & R. Spiekermann (**2012**): Detecting environmental change using time series, high resolution imagery and field work – a case study in the Sahel of Mali. *Geophysical Research Abstracts*, Vol. 14, EGU2012-10583, EGU General Assembly 2012.

DECLARATION

(Eidesstattliche) Versicherungen und Erklärungen

(§5 Nr. 4 PromO)

Hiermit erkläre ich, dass keine Tatsachen vorliegen, die mich nach den gesetzlichen Bestimmungen über die Führung akademischer Grade zur Führung eines Doktorgrades unwürdig erscheinen lassen.

(§8 S.2 Nr. 5 PromO)

Hiermit erkläre ich mich damit einverstanden, dass die elektronische Fassung meiner Dissertation unter Wahrung meiner Urheberrechte und des Datenschutzes einer gesonderten Überprüfung hinsichtlich der eigenständigen Anfertigung der Dissertation unterzogen werden kann.

(§8 S.2 Nr. 7 PromO)

Hiermit erkläre ich eidesstattlich, dass ich die Dissertation selbständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe.

(§8 S.2 Nr. 8 PromO)

Ich habe die Dissertation nicht bereits zur Erlangung eines akademischen Grades anderweitig eingereicht und habe auch nicht bereits diese oder eine gleichartige Doktorprüfung endgültig nicht bestanden.

(§8 S.2 Nr. 9 PromO)

Hiermit erkläre ich, dass ich keine Hilfe von gewerbliche Promotionsberatern bzw. -vermittlern in Anspruch genommen habe und auch künftig nicht nehmen werde.

Bayreuth, April 2014

Martin Brandt