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

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ABSTRACT

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).

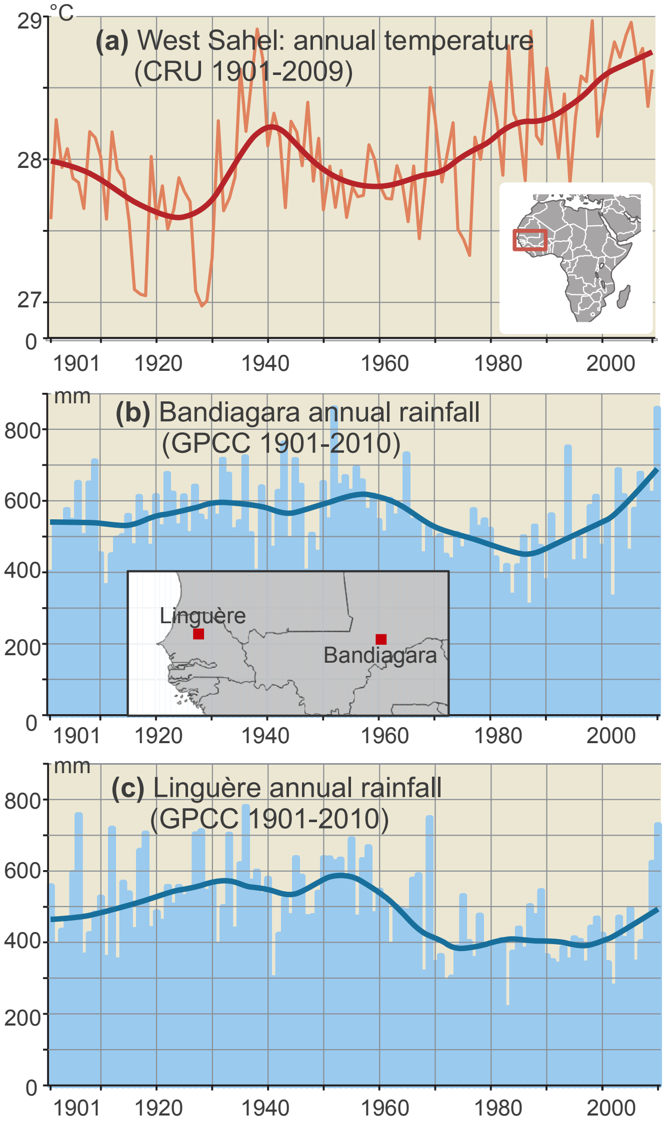

Fig. 1. Mean annual temperature 1901–2009 averaged over West Africa (a) and annual rainfall 1901–2010 averaged over the Bandiagara (b) and Linguère (c) research area. The location of the study areas can be seen in (b).

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

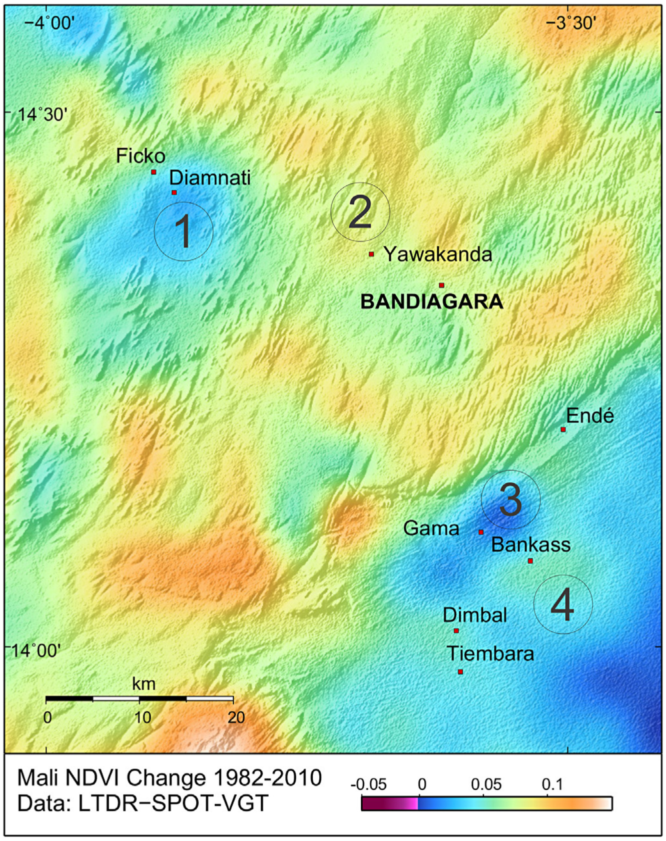

Fig. 2. LTDR–SPOT time series NDVI change from 1982 to 2010 in Mali. The numbers indicate the case study sites which are further explained within Chapter 3.2. Since the time series starts in times of droughts, no negative change can be observed. However, several areas do not follow the overall greening 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

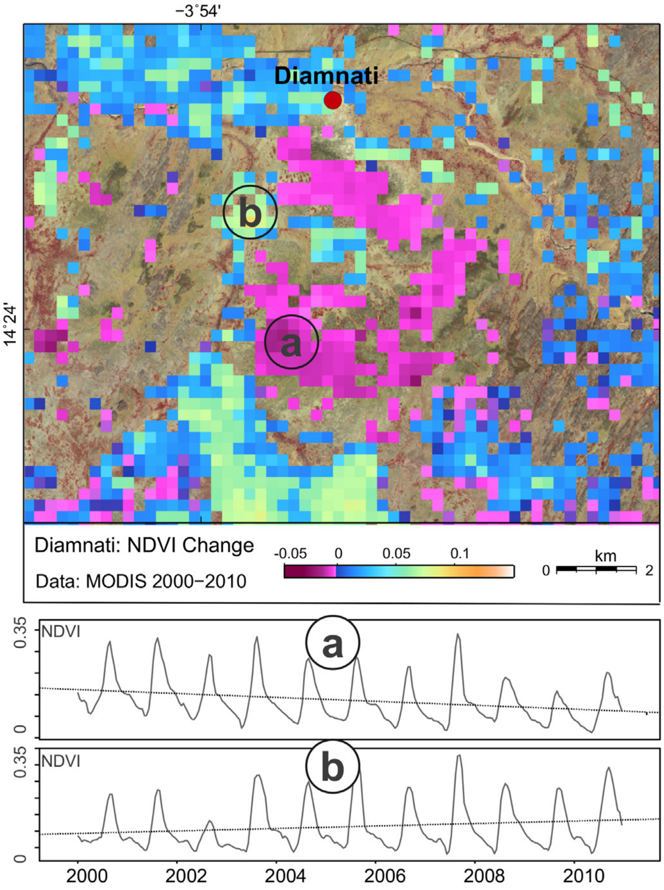

Fig. 3. The area marked with 1 in Fig. 2 appears homogeneous in the LTDR image (Fig. 2). The spatial scale of MODIS (250 m) is able to record heterogeneity within this region by identifying negative and positive vegetation trends (transparent areas stand for no significant trends). While positive NDVI 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

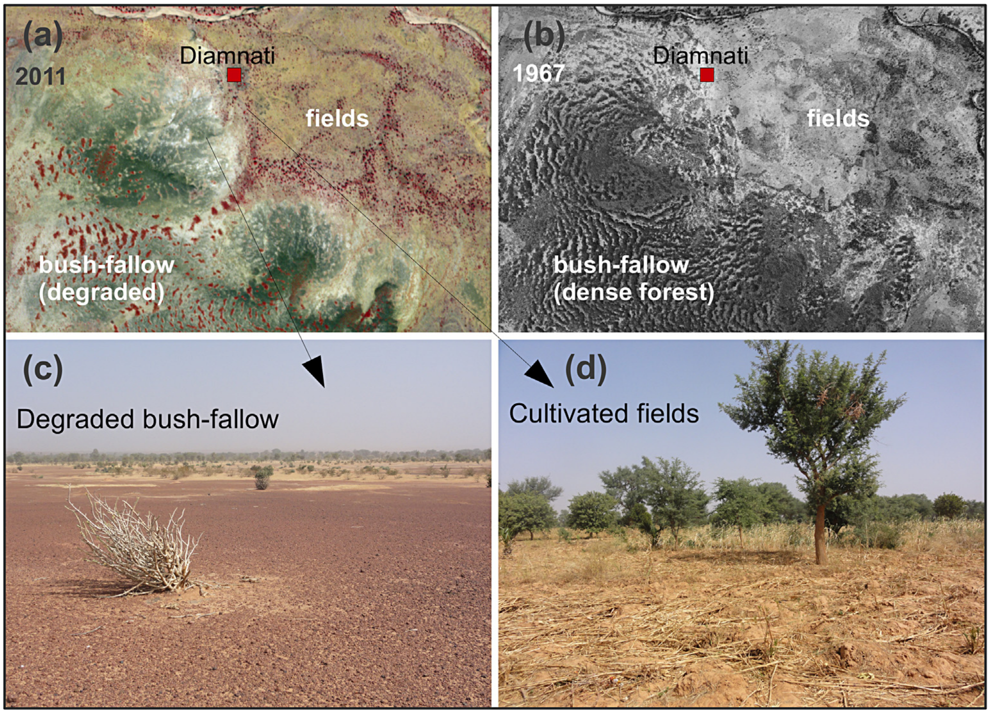

Fig. 4. The first image pair (a + b) shows exactly the same area compared over a period of 44 years. The area around Diamnati shows degradation and greening phenomena the same time. The Corona image from 1967 (b) shows formerly dense tiger-bush formations in the south-west (dark black areas), of which 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

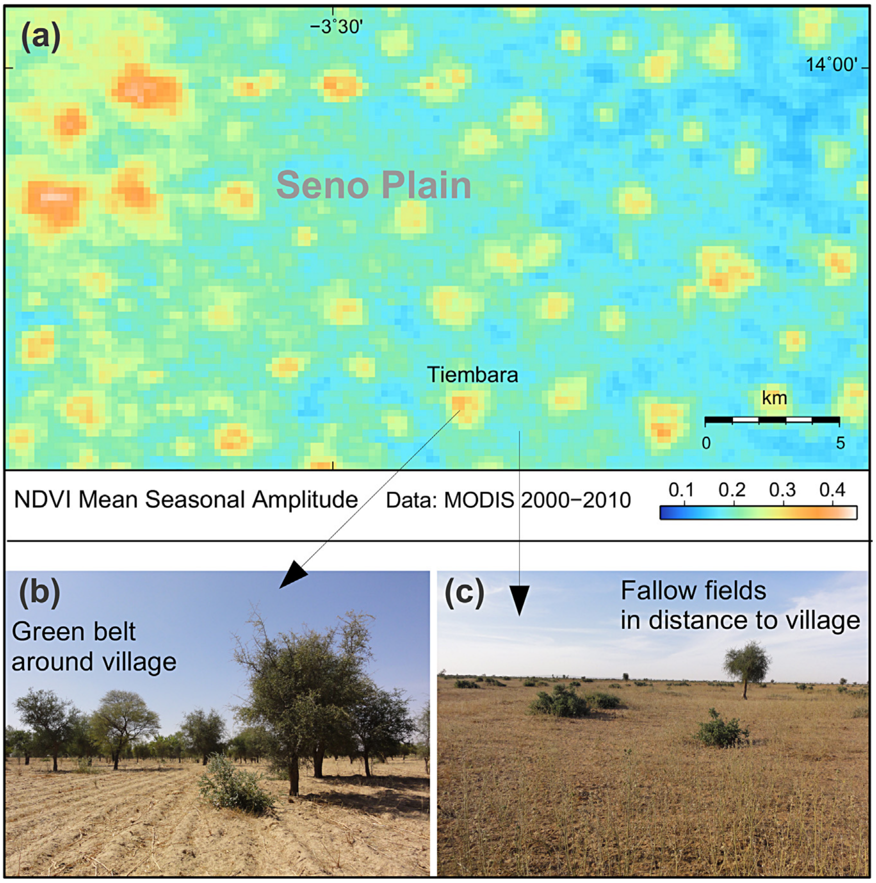

Fig. 5. MODIS mean amplitude identifies green productive belts (high values) represented by yellow and red colors around the villages in the Séno Plain (a). These fields are regularly cultivated and fertilized. Moreover, trees are protected. Photos from the Dogon village Tiembara show the difference 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.)

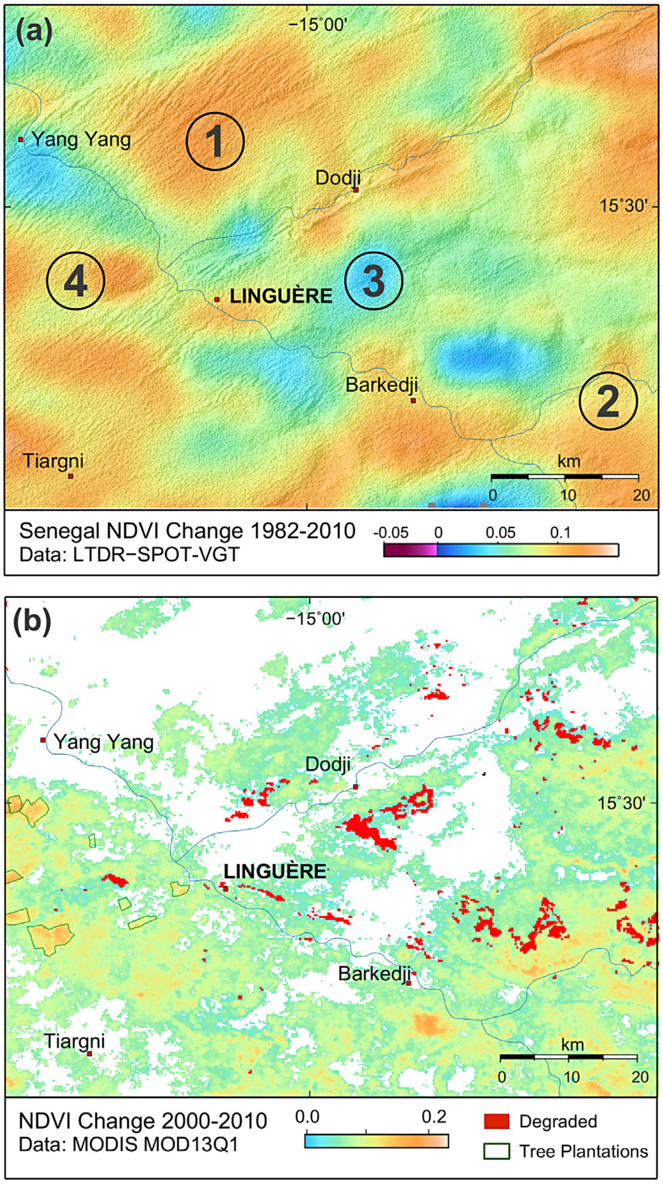

Fig. 6. LTDR–SPOT NDVI time series NDVI change from 1982 to 2010 in Senegal (a). The numbers indicate the case study sites which are further explained within Chapter 3.3. While positive MODIS trends (b) (2000–2010) in the west of Linguère are mainly caused by large tree plantations, positive changes 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

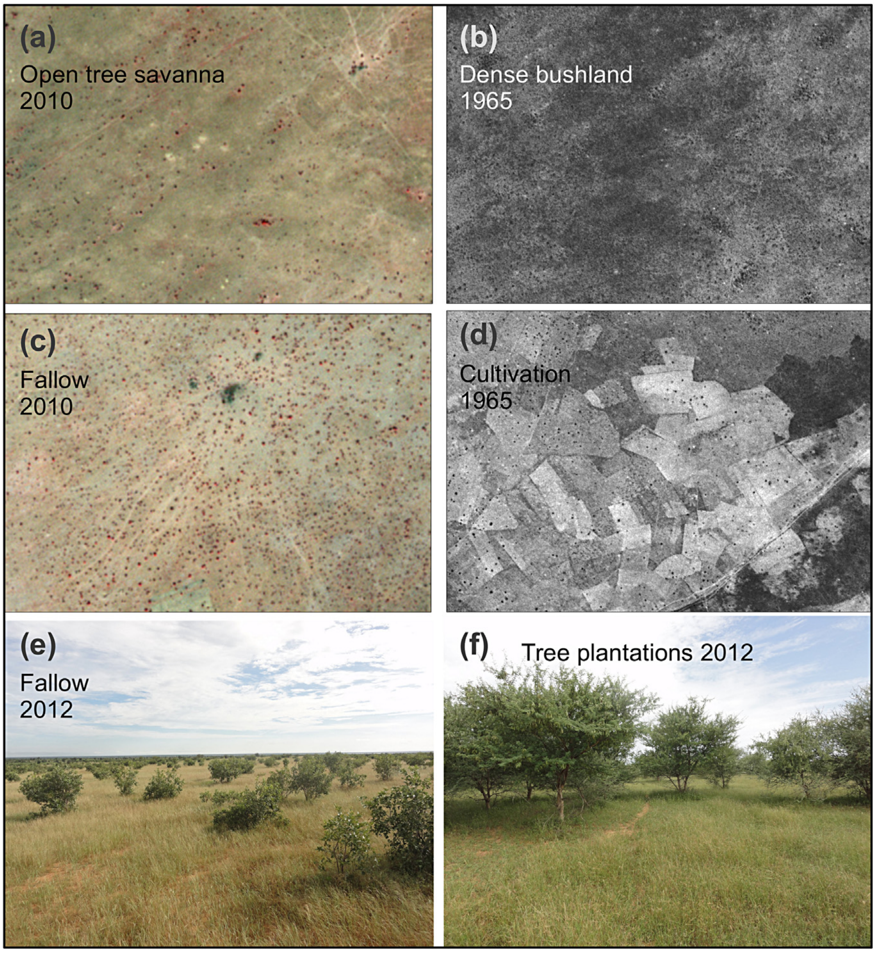

Fig. 7. The dark gray and black areas in the Corona image (b) (1965) represent dense bushland, which was common 1965 and dominated by *Guiera senegalensis*. The bushland was cleared before the beginning of our time series. Today, this area is a peanut fallow with an open *Balanites aegyptiaca* vegetation, 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).

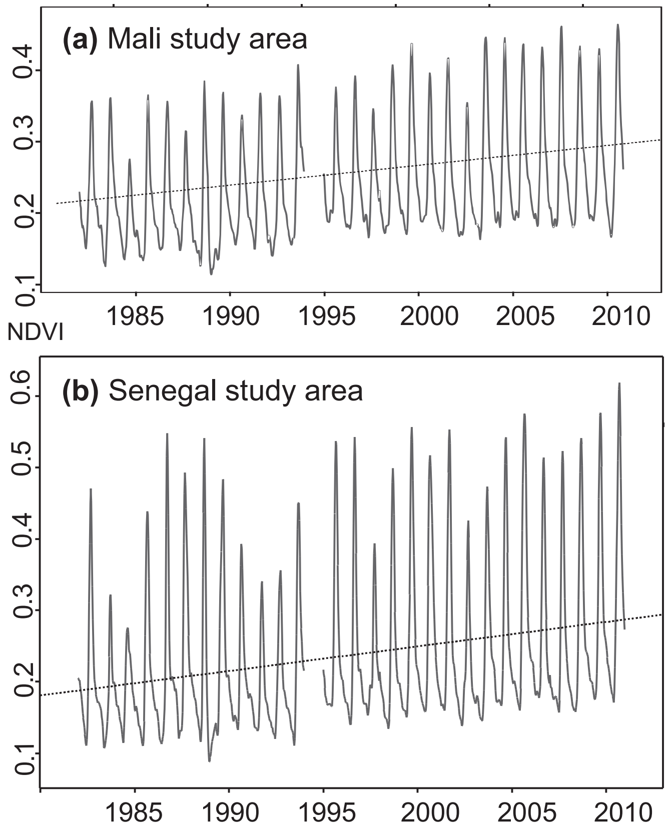

Fig. 8. LTDR–SPOT NDVI time series from 1982 to 2010 averaged for the Bandiagara (a) study area and for the Linguère (b) study area.

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 predrought 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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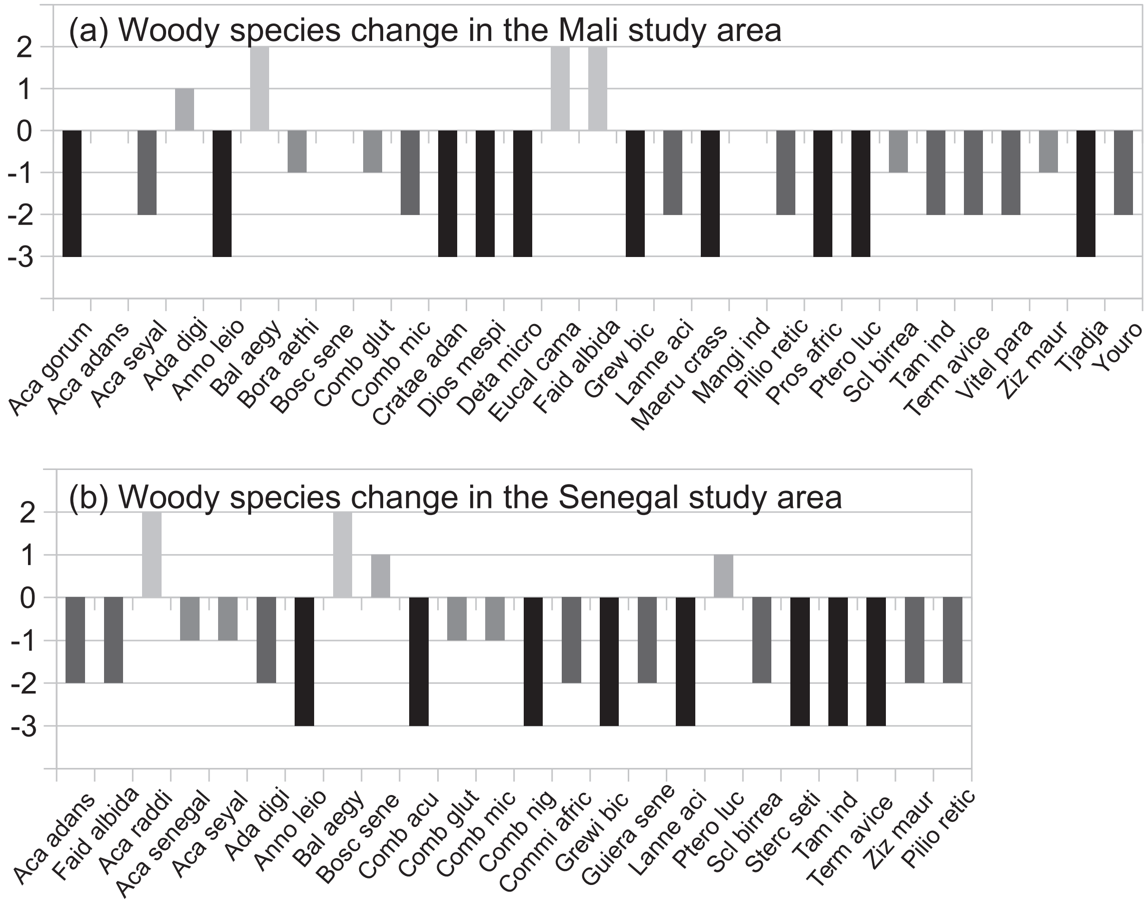

Fig. 9. Local people's perception of changes in tree species composition in the Bandiagara (a) and Linguère (b) study areas in the past 40 years. −3 very strong decline or disappeared, −2 strong decline, −1 decline, 0 stable, 1 increase, 2 strong increase. More information and complete scientific, Dogon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