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Woody vegetation and land cover changes in the Sahel of Mali (1967–2011)

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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 situation in 2011. High resolution panchromatic Corona imagery of 1967 and multispectral RapidEye imagery of 2011 form the basis of this regional scaled study, which is focused 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 farmer's 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.

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 (Brandt et al., 2014a). 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 an accelerating effect on rainfall variations (e.g. Kucharski et al., 2012; Paeth et al., 2009). These studies put changes in land cover into the focus again and justify the need for detailed investigations on the actual extent of environmental change.

After the droughts in the 1970s and 1980s, 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, almost no evidence of widespread degradation was found (e.g. Niemeijer and Mazzucato, 2002; Tiffen and Mortimore, 2002) and recent findings based on coarse-scaled analyses of satellite time series and ground data show an increase of vegetation greenness over most parts of the Sahel since the mid-1980s (e.g. Dardel et al., 2014; Brandt et al., 2014b; Herrmann et al., 2005; Olsson et al., 2005). 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.

High resolution imagery offers the possibility to detect single trees and large shrubs as objects. This has the major advantage that canopy cover can be directly mapped without the need to interpret mixed pixels by linear models (e.g. Herrmann et al., 2013; Larsson, 1993). 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

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analysis of time series (e.g. Brandt et al., 2014b; Anyamba 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., 2014a; 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 that 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., 2014a; Herrmann and Tappan, 2013; Gonzalez et al., 2012; Ruelland et al., 2010; Tappan et al., 2004; Elmqvist, 2004). These changes have significant effects on the ecosystem and people's daily lives. The dependence of the local population on the products from trees such as fire and construction wood, medicine and religious purposes (Maydell, 1990) is a factor of practical importance adding significance to regional-scaled environmental studies.

In greening and desertification debates, generalizations are commonly used, attempting to simplify a reality which is far more complex. We 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 Séno Plain in the Sahelian zone of Mali. The two major aims are:

1. To investigate and quantify land cover changes over 44 years including aspects of degradation and human expansion.
2. To analyze changes in woody cover between 1967 and 2011 and find explanations for these.

Materials and methods

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 Fig. 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.

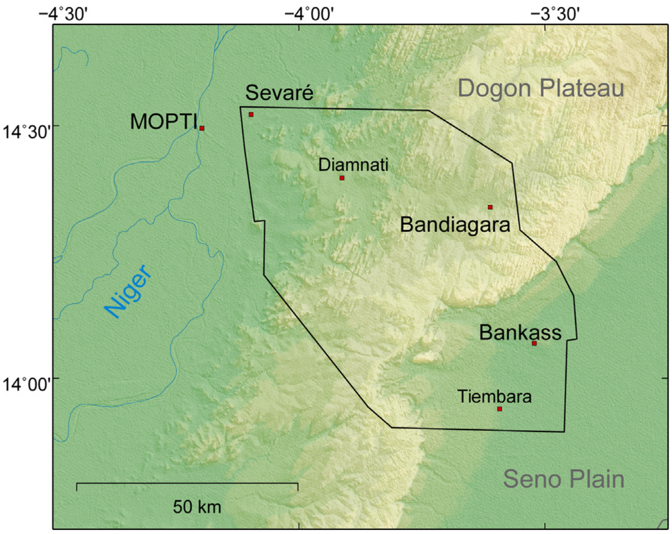

Fig. 1. The study area is located on the Malian Dogon Plateau and on the Seno Plain.

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 as they provide shade, soil nutrients, fruit, and wood (Brandt et al., 2014a). 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 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 (Brandt et al., 2014a; Allen, 2009; Yossi and Diakite, 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 Diakite, 2008). In general, the study area receives an average of 500–600 mm of annual precipitation, which falls entirely during the months of June–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., 2014a).

Data

Corona

Corona images belong to the very first U.S. earth observation satellites and provide a unique window into the past. The Corona KH-4B (mission 1102) took photographic images of the study area in Mali on 10th December 1967. 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 (Andersen, 2006). As raw images lack position data and any form of orthorectification, raw images were georeferenced manually using GoogleEarth as a reference. 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 (see Stein et al., 1999), rounding the input cell size to 2 m. The accuracy of each image was assessed visually with an overlay of RapidEye images.

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. 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 remain green during the dry season. The RapidEye images were delivered as digital numbers (DN) and then converted to reflectance values.

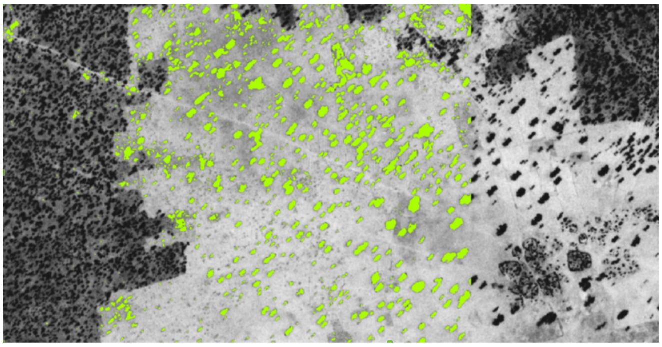

Fig. 2. This figure shows the two classes used in the 1967 classification as well as how individual trees are mapped (green). The bright area around the village represents an area of sparse woody vegetation, whereas the dark area in the west is an example for dense woody vegetation which had not been cleared for cultivation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Methods

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 RapidEye. The two main classes are "sparse woody vegetation" and "dense woody vegetation", seen in Figs. 2 and 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

Fig. 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 (December 2011).

outcrops did not change significantly during the studied period and are thus masked for both datasets. Due to the additional multispectral information, the classification for 2011 introduced a class for 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.

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 (2011), Erikson and Olofsson (2005), San 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 Fig. 2). For detailed information on the feature extraction of woody vegetation we refer to Chepkochei (2011).

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 gray values to the target pixels (woody vegetation) in a cropland area. For RapidEye imagery, the adjacency effect adds further uncertainty. 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. Moreover, to improve the comparison between Corona and RapidEye, small trees (canopy cover <4 m^2) were omitted in the mapping algorithm for Corona.

For the accuracy assessment, 200 random points were scattered over the study area and for each point it was determined if it represents woody cover in 1967/2011 or not. This was then compared with the detected woody cover polygons to calculate the percentage of accurately classified random points. The woody vegetation cover was then calculated as the area of woody vegetation objects per 250 m × 250 m pixel in percent. 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.

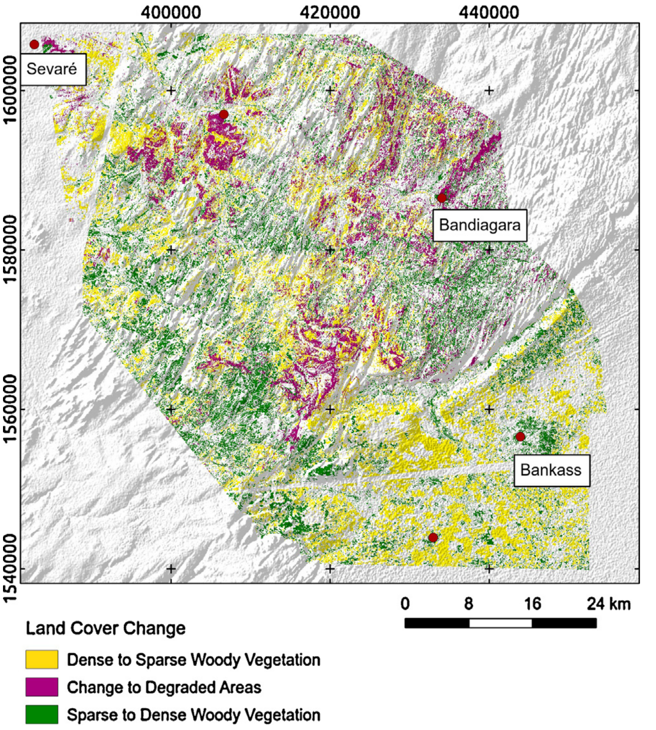

Fig. 4. Land cover change map 1967–2011. Areas of no change/rock/no data are displayed transparent.

Field work

Ground-truthing is essential for remote sensing studies, as many forms of information 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. Dialogs with local farmers often provided invaluable information and clarification of events and changes to woody vegetation (Brandt et al., 2014a). 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 (Brandt et al., 2014a).

Results and discussion

Land cover change

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

Table 1
Land cover change 1967–2011 in hectare and percent. DV, dense woody vegetation; SV, sparse woody vegetation; D, degraded.

Change Code	Dogon Plateau change (ha)	Dogon Plateau change (%)	Seno Plain Change (ha)	Seno Plain Change (%)
DV->SV	32,362.1	13	24,487.3	26.6
DV->D	8764.7	3.5	0	NA
SV->DV	35,157.5	14.1	11,623.3	12.6
SV->D	15,495.5	6.2	0	NA
Rest	157,361.1	63.2	55,881.2	60.8
Total	249,140.9	100	91,991.8	100

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 Endé, 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 which most is located in proximity to paved major roads.

Case studies of tree cover change

Tiembara

Tiembara is a Dogon village located on the Seno Plain in the far south of the study area (marked in Fig. 1). Tiembara has had no external influence by projects such as the areas surrounding Bankass and Endé. 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 Fig. 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 period of half a century, as seen in Fig. 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 Fig. 5). This is why tree cover here has increased by 10–20%, whereas tree cover further away decreased by up to 30% (see Fig. 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 (Fig. 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 (Fig. 5).

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 Fig. 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. 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 Fig. 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 Fig. 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., 2014a). Fig. 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 increase 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 (Fig. 6). The woody vegetation cover ranged between 0 and 10% on cropland areas and 10 and 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 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.

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. Table 3 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 20 a negative tendency. *Faidherbia albida* (formally *Acacia albida*) provides nutrients

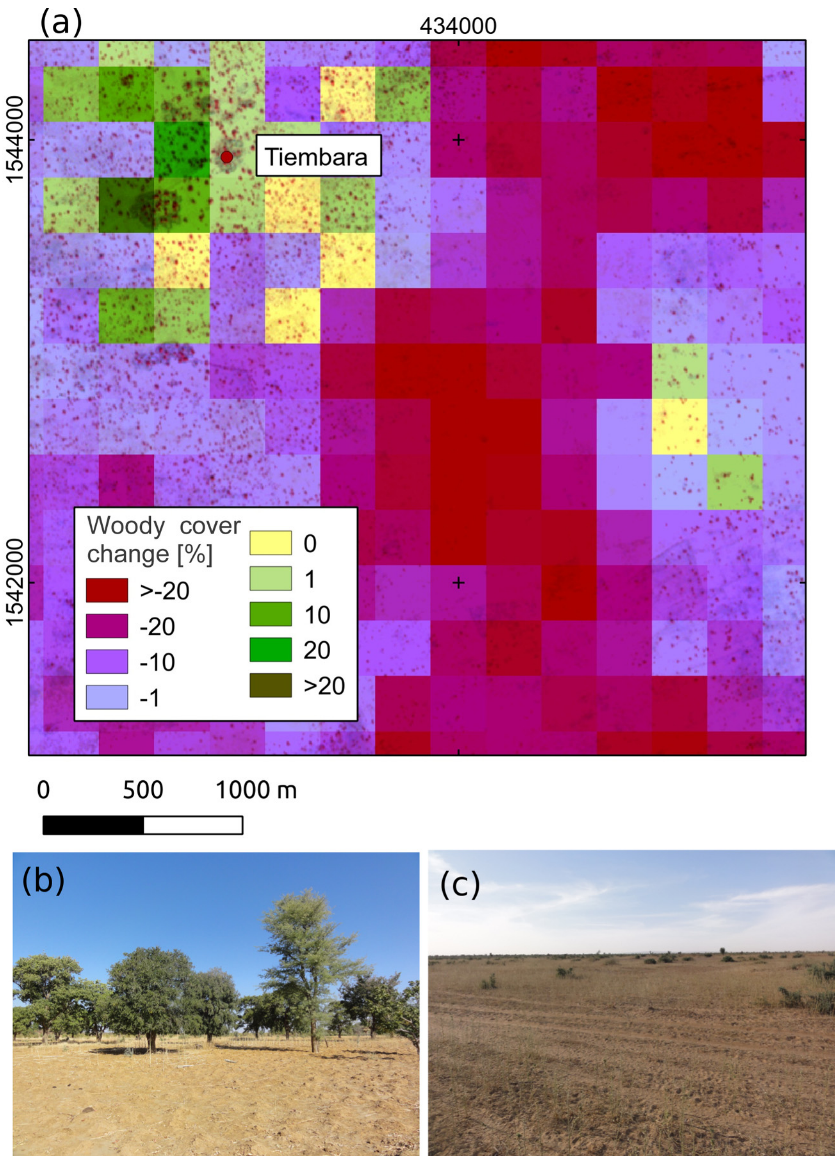

Fig. 5. Woody cover change in percent around the Dogon village Tiembara (Seno Plain) for 1967–2011, with RapidEye as background (a). Note that a total reverse of tree cover has occurred in the space of half a century. A dense woody vegetation can be found on the fields surrounding Tiembara (b). What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

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.

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. (2010), 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 cover by approximately 4% in the Seno Plain (with ca. 7% in 2011), mainly caused by anthropogenic disturbances (Tables 1 and 2). The change on the Dogon Plateau is not as large, primarily due to the rough morphology and difficulty of expanding agriculturally used areas (Tables 1 and 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

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

Woody cover	Dogon Plateau	Seno Plain
No. Pixels (250 m × 250 m)	40,885	14,957
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

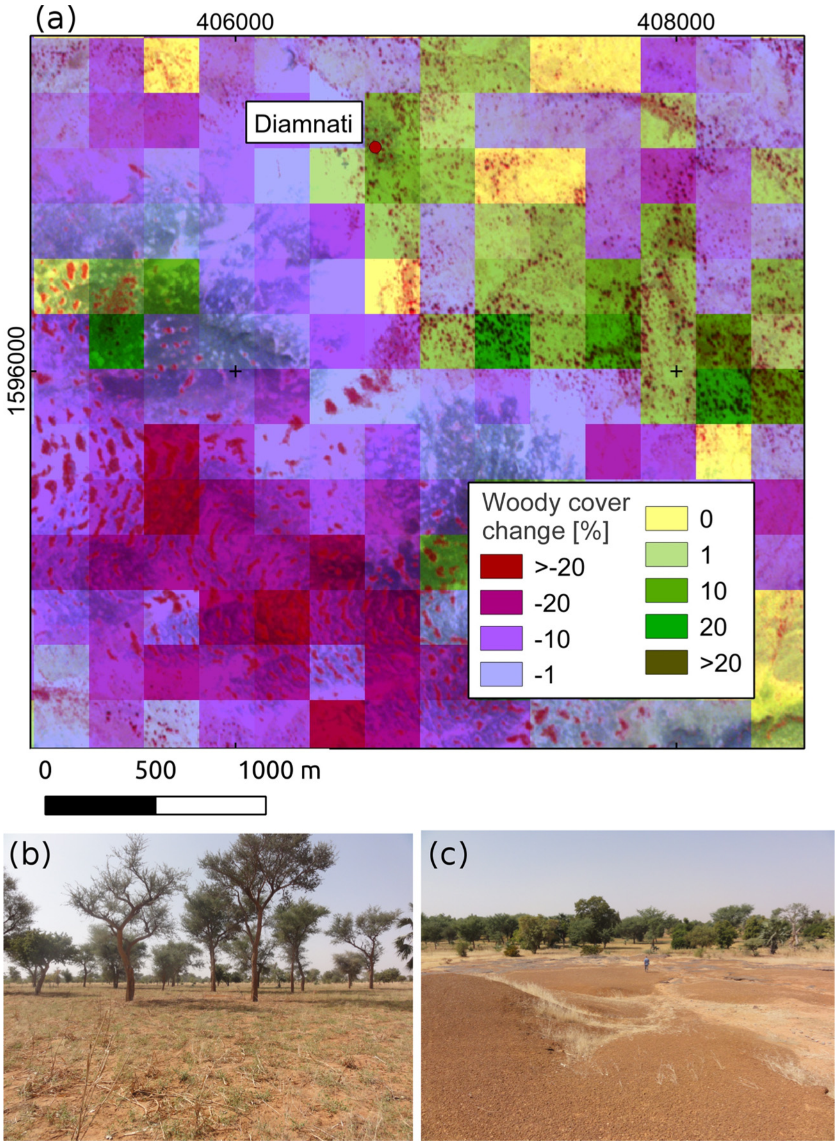

Fig. 6. Woody vegetation cover change in percent around Diamnati (Dogon Plateau) 1967–2011 with RapidEye as background (a). Note the increase on cropping fields and the decrease on the formally densely vegetated bush-fallow. The decrease increases with distance to the village, with large areas highly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

Table 3
Woody species change as reported by village elders in 13 villages on the Dogon Plateau and the Seno Plain, see also Brandt et al. (2014a) for Dogon names of the species and more details.

Strong increase	*Faidherbia albida*, *Balanites aegyptiaca*, *Eucalyptus camaraderies*
Increase	*Adansonia digitata*
Stable	*Acacia nilotica*, *Mangifera indica*
Decrease	*Borassus aethiopum*, *Combretum glutinosum*, *Ziziphus mauritiana* decrease *Acacia seyal*, *Combretum micranthum*, *Lannea acida*, *Piliostigma reticulatum*, *Sclerocarya birrea*, *Terminalia avicennioides*, *Vitellaria paradoxa*
Vanished or very strong decrease	*Acacia gourmaensis*, *Anogeissus leiocarpus*, *Crataeva adansonii*, *Diospyros mespiliformis*, *Detarium microcarpum*, *Grewia bicolor*, *Maerua crassifolia*, *Prosopis africana*, *Pterocarpus lucens*, *Tamarindus indica*

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.

Accuracy assessment and data uncertainties

For 1967, woody cover classification achieved an accuracy of 92%, with 67% of the random points representing tree cover being correctly classified. This detection rate is similar to a study by Andersen (2006), who detected 70% of mapped trees using Corona. The accuracy of RapidEye for 2011 is 88%, with 63% woody cover correctly recognized.

Although both classifications show a fairly good accuracy, there is an obvious dilemma when comparing maps of two different sensors with varying pixel size (Corona 2 m, RapidEye 5 m). More precise datasets (e.g. World-View2 or GeoEye-2) are needed to rigorously assess tree cover change in the Sahel. However, these datasets are expensive and processing at regional level is difficult with common hardware. Both Corona and RapidEye images have advantages and disadvantages: the shadows in the Corona images distort the true crown size and the fact that contrast of gray-scales is used to detect woody vegetation makes it difficult to assess whether or not vegetation is always the object mapped. RapidEye's spectral range ensures that only vegetation is mapped, but the larger pixel size means the capacity to delineate tree crowns accurately is reduced so that thickets or stands of shrubs and trees are often mapped as single objects.

Given the challenge in comparing Corona and RapidEye maps quantitatively, several steps minimize the error and justify a comparison: (1) small trees and shrubs play a minor role when estimating the woody cover for 250 m pixels and were omitted in the Corona detection algorithm. The remaining trees have a similar size in both datasets. (2) The wide range of the change classes minimizes uncertainties caused by the varying pixel sizes. (3) Although the exact change of tree cover is not without error, the observed direction of change is true and corresponds with observations by the local population. Hence, the results need to be considered as trends, providing a sound basis for further interpretation, which is the major focus of this study.

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 several decades 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. Even though future studies are needed to improve the accuracy, this initial approach provides a marked improvement to studies using coarse satellite data and opens a new time window, going back to the pre-drought situation. We showed that a tree cover assessment at tree level and regional scale is possible and provide more detailed results, particularly due to the integration of interdisciplinary field work, which allows a comprehensive interpretation of the results.

Even though our results show that extensive land and tree cover changes exist, the direction of change is not always negative. 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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