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Drought tolerant species dominate as rainfall and tree cover returns in the West African Sahel

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ABSTRACT

After the severe droughts in the 1970s and 1980s, and subsequent debates about desertification, analyses of satellite images reveal that the West African Sahel has become greener again. In this paper we report a study on changes in tree cover and tree species composition in three village landscapes in northern Burkina Faso, based on a combination of methods: tree density change detection using aerial photos and satellite images, a tree species inventory including size class distribution analysis, and interviews with local farmers about woody vegetation changes. Our results show a decrease in tree cover in the 1970s followed by an increase since the mid-1980s, a pattern correlating with the temporal trends in rainfall as well as remotely sensed greening in the region. However, both the inventory and interview data shows that the species composition has changed substantially towards a higher dominance of drought-resistant and exotic species. This shift, occurring during a period of increasing annual precipitation, points to the complexity of current landscape changes and questions rain as the sole primary driver of the increase in tree cover. We propose that the observed changes in woody vegetation (densities, species composition and spatial distribution) are mediated by changes in land use, including intensification and promotion of drought tolerant and fast growing species. Our findings, which indicate a rather surprising trajectory of land cover change, highlight the importance of studies that integrate evidence of changes in tree density and species composition to complement our understanding of land use and vegetation change trajectories in the Sahel obtained from satellite images. We conclude that a better understanding of the social-ecological relations and emerging land use trajectories that produce new types of agroforestry parklands in the region is of crucial importance for designing suitable policies for climate change adaptation, biodiversity conservation and the sustainable delivery of ecosystem services that benefit local livelihoods in one of the world's poorest regions.

1. Introduction

In a global perspective, the decline in rainfall over the Sahel during the 1970s and 1980s stands out as a particularly dramatic change in decadal means. Rainfall isohyets shifted 1–2° of latitude as compared to the wetter conditions during the 1930s to 1960s (Nicholson, 2013). The drought's disastrous effects on livelihoods and land use systems have received much attention from media, science, policy and civil society, and gave rise to extensive debates about desertification (Behnke and Mortimore, 2016; UNCCD, 1994). While desertification remains an influential science and policy framework, shaping e.g. climate change adaptation strategies (Mortimore and Turner, 2005; O'Connor and Ford, 2014), a different process of Sahelian environmental change has made the headlines more recently, as the region is reported to have become greener again since the 1980s (Brandt et al., 2015; Eklundh and Olsson, 2003; Herrmann et al., 2005; Kaptué et al., 2015).

The strongest greening signals, revealed from studies of satellite images and often measured as seasonal sums and maximum amplitudes of NDVI (Normalized Difference Vegetation Index), are seen in western Sudan to central Chad, in Southern Niger, around the border between northern Burkina Faso and Mali, and in South-

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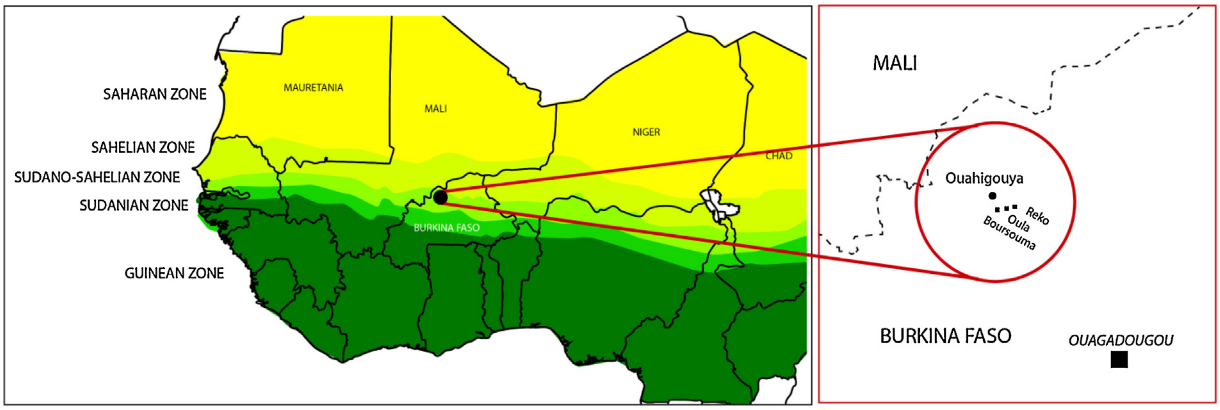

Fig. 1. Map of the study area. The left panel shows how the Saharian-, Sahelian-, Sudano–Sahelian-, Sudanian- and Guinean vegetation zones stretches across West Africa (Source: Arbonnier, 2004). The right panel zooms in on the three villages used in this case study – Boursouma, Oula and Reko—located close to the town of Ouahigouya in Northern Burkina Faso.

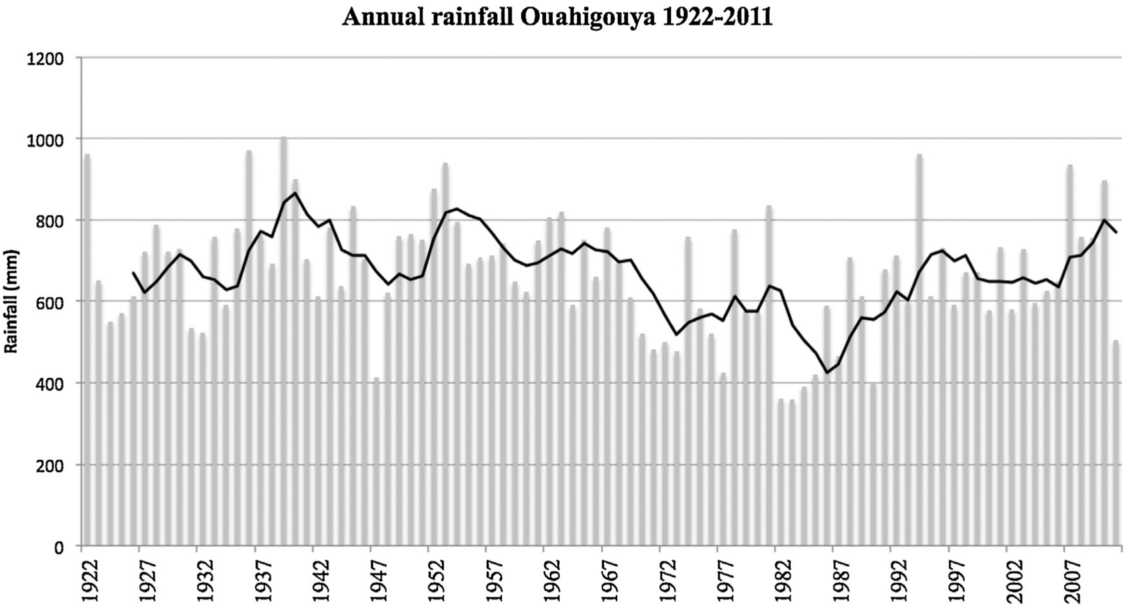

Fig. 2. Annual rainfall at the meteorological station in Ouahigoya, Burkina Faso, 1922–2011. The line shows how the 5-year moving average has changed over time. After the droughts in the 1970s and 1980s the rainfall now seems to have recovered close to pre-drought levels.

ern Mauretania (Bégué et al., 2011; Eklundh and Olsson, 2003; Herrmann et al., 2005; Olsson et al., 2005; Xiao and Moody, 2005). Increasing rainfall has been put forward as the major driver behind the observed vegetation changes, based on regional scale analyses (Brandt et al., 2015; Capecchi et al., 2008; Dardel et al., 2014; Herrmann et al., 2005; Hickler et al., 2005; Seaquist et al., 2009). In addition to the regional studies of NDVI, field based local studies conducted at various sites across the Sahel report increases in crop yields and/or tree density over the past 30 years (Haglund et al., 2011; Larwanou and Saadou, 2011; Sendzimir et al., 2011; Mortimore and Turner, 2005; Reij et al., 2005). These studies often cite land management (adoption of soil and water conservation practices and/or techniques for managing and pruning of trees) as likely factors contributing to that change. In parallel to the reports of remotely sensed re-greening and field assessments of increases in tree cover, there are also reports about declining woody species diversity across the Sahel. These are based on both botanical investigations (Brandt et al., 2015; Herrmann and Tappan, 2013; Lykke et al., 1999; Maranz, 2009) and studies of local perceptions (Herrmann et al., 2014; Lykke et al., 2004; Sop and Oldeland, 2013; Wezel, 2005; Wezel and Lykke, 2006). A number of studies also report a recent increase in drought-resistant woody vegetation across the Sahel (Gonzalez et al., 2012; Herrmann and Tappan, 2013; Herrmann et al., 2014; Hiernaux et al., 2009; Maranz, 2009; Sop et al., 2011; Sop and Oldeland, 2013).

Thus, several important processes of change seem to be involved in shaping contemporary Sahelian vegetation patterns. Understanding how these processes potentially interact and shape new types of landscapes is of crucial importance for local populations in the Sahel, who remain among the world's poorest. However, it is currently difficult to draw any robust conclusions about the vegetation trajectories that might arise. Part of the problem stems from a lack of integration between different scientific disciplines studying the different trends of vegetation change, which underscores the need to investigate patterns and processes of Sahelian vegetation change, from local to regional scales, in more detail and in more integrated ways (Bégué et al., 2011; Herrmann et al., 2014; Olsson et al., 2005; Seaquist et al., 2009). The rapid population increase in the region since the 1980s (Cour, 2001; World Bank, 2014) and rural communities' increased economic reliance on migration and diversified livelihoods (Mortimore, 2010; Nielsen and Reenberg, 2010) further highlight the importance of such integrative studies,

Table 1
Inventoried species, including their natural geographical distribution and population trends according to the SCD and interview survey.

Tree species	Plant family	Ecoregion	Norhtern/Southern/Exotic	Interview (%)	Slope value*	R	P	Total sample >5 cm	Total sample <5 cm
Acacia albida	Mimosoideae	Sahelo-Sudanese	N	−12	−0.751	0.761	0.170	56	18
_Acacia gourmaensis_*	_Mimosoideae_	_Sahelo-Sudanese_	_N_	_10_				_32_	_21_
_Acacia macrostachya_*	_Mimosoideae_	_Sahelo-Sudanese_	_N_	_6_				_11_	_4_
Acacia nilotica	Mimosoideae	Sahelian	N	8	−1.920	0.891	0.001	47	2
Acacia senegal	Mimosoideae	Sahelo-Saharian	N	17				0	4
Acacia seyal	Mimosoideae	Sahelo-Saharian	N	6	−1.783	0.881	0,002	63	33
Acacia sieberiana	Mimosoideae	Sudano-Guinean	S	9	−1.159	0.865	0.003	25	7
Adansonia digitata	Bombaceae	Sahelo-Sudanese	N	−15	−1.510	0.917	<0.001	63	34
Anogeissus leiocarpus	Combreataceae	Sudano-Guinean	S	−6	−0.587	0.657	0.550	14	0
Azardirachta indica	Meliaceae	Exotic	E	96	−2.790	0.954	<0.001	231	202
Balanites ægyptiaca	Balanitaceae	Sahelo-Sudanese	N	6	−1.907	0.951	<0.001	97	97
Bombax costatum	Bombaceae	Sudano-Guinean	S	−14	0.250	0.580	0.882	1	39
Calotropsis procera	Asclepiadaceae	Sahelian	N		−1.061	0.932	0.071	1	1
Cassia sieberiana	Caesalpinioideae	Sahelo-Sudanese	N	8	−1.855	0.957	<0.001	53	161
_Combretum glutinosium_*	_Combreataceae_	_Sahelo-Sudanese_	_N_	_6_				_2_	_1_
_Combretum micranthum_*	_Combreataceae_	_Sahelo-Sudanese_	_N_	_9_				_30_	_871_
Diospyros mespilif.	Ebenaceae	Sahelo-Sudanese	N	6	−1.720	0.941	<0.001	48	88
Enatda africana	Mimosoideae	Sudano-Guinean	S					0	8
Eucalyptus camal.	Myrtaceae	Exotic	E	49	−1.480	0.962	<0.001	3	0
Feretia apodanthera	Rubiaceae	Sahelo-Sudanese	N					0	12
Ficus sycomorus	Moraceae	Sudanese	S	−6					
Gardenia sokotensis	Rubiaceae	Sudano-Guinean	S	−6					
_Guiera senegalensis_*	_Combreataceae_	_Sahelo-Sudanese_	_N_	_7_				_7_	_1344_
Khaya senegalensis	Meliaceae	Sudanese	S	−37	0.131	0.391	0.292	1	0
Lannea acida	Anacardiaceae	Sudano-Guinean	S	−27	−1.158	0.798	0.011	104	9
Mangifera indica	Anacardiaceae	Sudan (Exotic)	S	−6	−0.176	0.270	0.483	12	0
Mitragyna inermis	Rubiaceae	Sahelo-Sudanese	N	6	−1.218	0.909	0.015	8	2
Parkia biglobosa	Mimosoideae	Sudano-Guinean	S	−56	−0.320	0.630	0.660	4	0
_Piliostigma spec._*	_Caesalpinioideae_	_Sahelo-Sudanese_	_N_	_15_				_54_	_241_
Proposis africana	Mimosoideae	Sudano-Guinean	S	−6	−0.140	0.578	0.378	1	0
Pterocarpus erinaceus	Fabaceae	Sudano-Guinean	S	−16					
Pterocarpus lucens	Fabaceae	Sudanese	S	−18					
Saba senegalensis	Apocynaceae	Sudano-Guinean	S	−6	−0.341	0.748	0.321	2	0
Sclerocarya birrea	Anacardiaceae	Sahelo-Sudanese	N	10	−2.013	0.879	0.002	122	1
Securidaca longepedunculata	Polygalaceae	Sudano-Guinean	S	−6					
Sterculia setigera	Sterculiaceae	Sahelo-Sudanese	N	−9					
Tamarindus indica	Caesalpinioideae	Exotic	E	−6	−0.290	0.498	0.173	9	5
Terminalia avicen.	Combreataceae	Sahelo-Sudanese	N	6				0	17
_Terminalia macroptera_*	_Combreataceae_	_Sudano-Guinean_	_S_					_2_	_3_
Viteralleria paradoxa	Sapotaceae	Sudano-Guinean	S	−56	0.351	0.317	0.405	33	0
Vitex doniana	Verbenaceae	Sudano-Guinean	S	−7					
Ximenia americana	Olacaceae	Guinean	S	−9	−0.570	0.450	0.311	10	6
Ziziphus mauritania	Rhamnaceae	Sahelian	N	9	−1.287	0.874	0.002	21	38

Notes: Columns show tree species; plant family; natural distribution in different ecoregions; classification into Northern, Southern (based on the ecoregions) or Exotic species; percentage of interview respondents who cited a particular species as increasing (positive value) or decreasing (negative value); SCD-slope values; R values and P values from the correlation tests between abundances and size classes; and total number of trees sampled for each species (one column for each size class). Missing values in the table are due to the fact that a few species were not listed in the interviews and that SCD-slopes could not be calculated for the species that had less than 10 samples, only had regeneration, occurred as shrubs, or were totally absent from the inventory. A strong negative SCD-slope indicates a lot of regeneration of new trees while a shallower slope indicates an overrepresentation of mature trees. Species written in italic and containing * are shrubs.

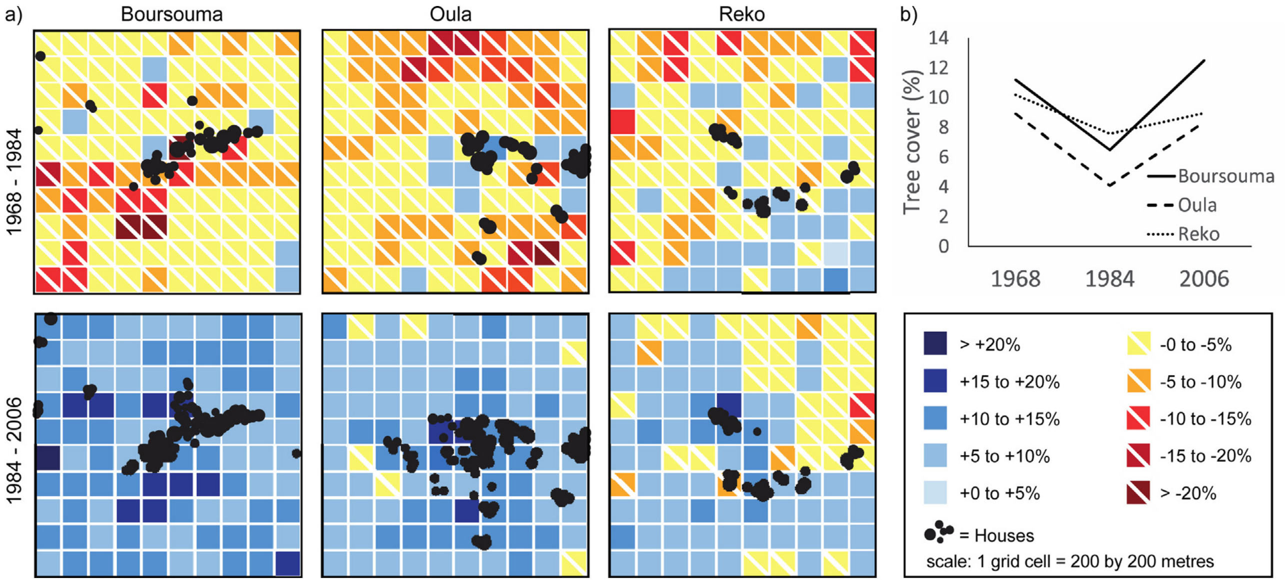

Fig. 3. Tree cover changes in two periods 1968–84 and 1984–2006 for 200 × 200 m grid cells across 2 × 2 km areas in three landscapes. The left panel (a) show the data across space and with the houses in 1984 and 2006, respectively, and the right panel (b) shows the total tree cover change (in%) for each village over time.

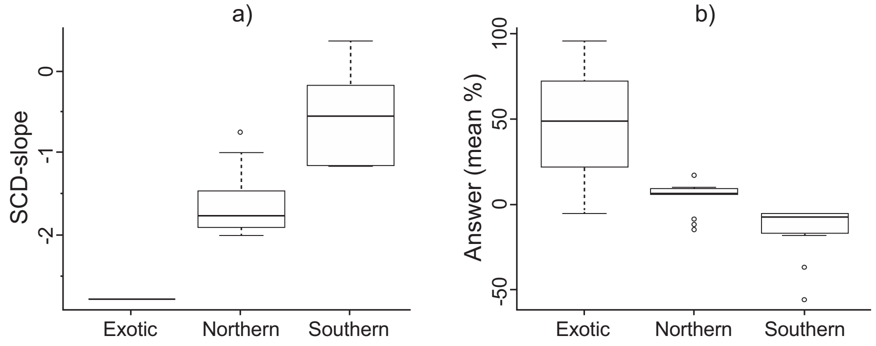

Fig. 4. Median and variation in SCD-slopes and interview answers shown for three groups of tree species. Data based on SCD-slopes are shown in the left panel (a). The interview data illustrated in the right panel (b) denote for each species group the percentage of respondents assigning a species to a change category. For species classifications see Table 1. A strong negative SCD-slope indicates a lot of regeneration of new trees, while a more shallow or positive slope indicates an over-representation of established trees and declining populations (see 2.3.3). The boxplots show the median, 50% of the data inside the box, 1.5 times the interquartile distance, plus outliers outside that distance.

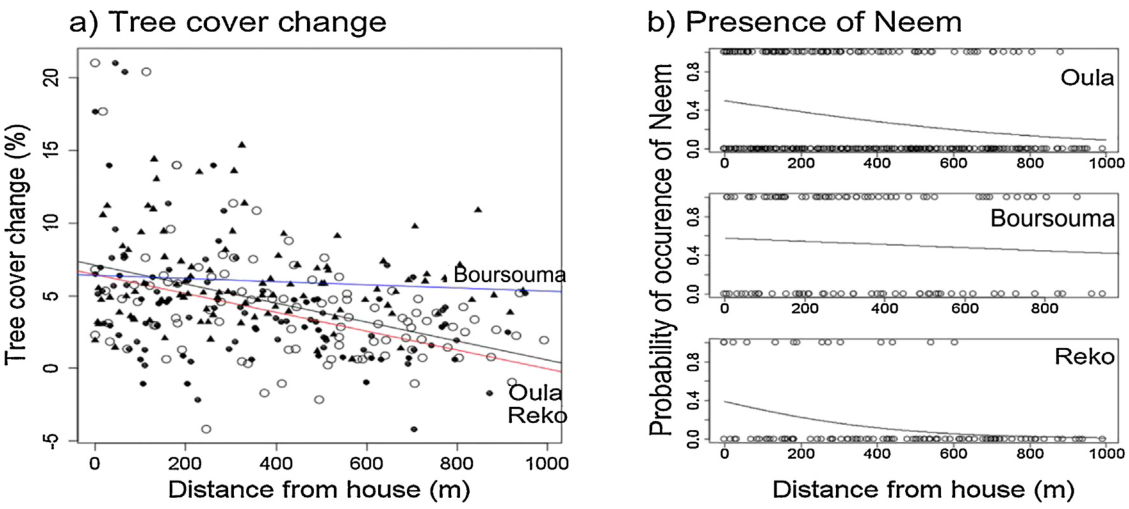

Fig. 5. Change in tree cover and presence of Neem correlated with distance to houses. The left panel (a) show tree cover change between 1984 and 2006 and the right panel (b) show presence of the Neem tree as a function of distance to the nearest house in 2006. In (a) data and linear trendlines are shown for the three villages and in (b) logistic regression lines are shown for the three villages separately (see methods).

to understand which social-ecological interactions now emerge in the region.

In this paper we take a step in this direction, reporting on a study of three village landscapes (Boursouma, Oula and Reko, (see Fig. 1) in Northern Burkina Faso, where we have connected the question of tree cover change to that of changes in tree species composition. We do this by combining three different methods, 1) remote sensing, in which we used high resolution images to assess trends in tree cover before, during and after the droughts in the 1970s and 1980s; 2) woody vegetation inventories (trees and shrubs) on the main land cover classes (residential land, cultivated fields, and bush land), from which we could draw conclusions about regeneration patterns of species associated with different climatic zones (drought tolerant species vs. species which would be favored by higher rainfall), and 3) an interview survey documenting local knowledge regarding the historical trends of tree- and shrub species abundances. The study area we focus on is reported to have become both greener (in terms of increasing NDVI) and wetter (in terms of increasing annual precipitation) since the 1980s (Herrmann et al., 2005; Nicholson, 2013; Fig. 2).

A specific focus on trees and shrubs is interesting for several reasons: trees are key features of Sahelian agroforestry parklands[1] and village landscapes, woody species are a cornerstone for biodiversity in the region and they generate a range of ecosystem services on which local livelihoods depend (Boffa, 1999; Sinare and Gordon, 2015). The relative importance of woody vegetation (vis-à-vis other types of vegetation) for the recent Sahelian re-greening is, however, still uncertain (Herrmann and Tappan, 2013; Herrmann et al., 2014; Larwanou and Saadou, 2011; Reij et al., 2005).

2. Materials and methods

2.1. Study site

This paper is based on a case study of three village landscapes in the Ouahigouya region of Northern Burkina Faso in the western Sahel. The Ouahigouya region was chosen since it is representative of areas that appear to have become greener over the past decades, in studies based on changes in NDVI (Herrmann et al., 2005). Annual average rainfall is highly variable, with a long-term rainfall average of about 600 mm per year, and a trend of increasing rainfall since the exceptionally dry 1970s and 1980s that follow the general trend reported from the western Sahel (Nicholson, 2013; Fig. 2). The study area is located in the transition zone between the Sahel and the Sudano-Sahelian zone (Fig. 1).

Within the Ouahigouya region, we selected three village landscapes (Boursouma, Oula and Reko) to represent typical conditions in the region. They differ somewhat in population size according to the 2005 census, which report 597 inhabitants for Boursouma, 1380 for Oula and 587 for Reko. Houses are clustered in settlements (or residential areas) at the center of the village territory, which are surrounded by cultivated fields and grazing land (bush land). The sizes of the village territories vary from 7.1 km^2 to 8.4 km^2, but we have investigated the same area in all village landscapes. Inhabitants belong to the *Mossi* ethnic group, and practice rain-fed farming of particularly millet and sorghum as their main livelihood source. Many farmers also combine this with livestock keeping. Gardening is an important additional livelihood source, as well as a range of off-farm provisioning ecosystem services, including firewood, construction materials, wild foods, and medicines provided by the agroforestry parklands (Boffa, 1999; Sinare and Gordon, 2015). Many households also receive income from different non-farm activities, such as seasonal labor migration and small-scale trading.

2.2. Methodological approach

In this study we combined three different methods: remote sensing, woody species inventories including size class distribution analysis (SCD) of trees, and interviews with local villagers about trends in woody species vegetation.

2.2.1. Remote sensing

Historical change in tree cover was investigated with a visual quantitative interpretation of CORONA satellite images from 1968, aerial photos from 1984 and satellite images from Google Earth Pro in 2006. The resolutions of these images were 2.5 m, 1.6 m, and 0.8 m. The historical data was geo-referenced using the most recent images as basis layer, geo-corrections were applied and all images were converted to the UTM projection system. After the geo-referencing process, image accuracy was <5 m. The change detection was performed on a square of 2 × 2 km centering on the main settlement in each village. The square was divided up in one hundred grid cells à 200 × 200 m, and an 8-m distance dot grid was inserted in each grid cell. Dots were counted as dichotomous variables (tree/no tree), and the total number of tree-matching dots was divided by the total number of dots in order to calculate % tree cover. The same procedure was followed for all three sets of images. Due to the lower resolution of CORONA images, only trees with crowns larger than 5 m^2 were counted, to ensure that data were comparable. This method resulted in a complete sample of trees in the investigated areas.

2.2.2. Woody species inventory

The tree inventory was performed in October–December 2011. In each village we did a systematic stratified sampling of tree species, size and regeneration in the same 2 × 2 km area as in the remote sensing analysis. We conducted the sampling in two nested circles centered in each of the 200 × 200 m grid cells, the larger with a radius of 17.84 m (=1000 m^2), and the smaller with a radius of 12.62 m (=500 m^2). Within the larger sub-plot, we inventoried all trees with a diameter at breast height (DBH) larger than 5 cm, measured their DBH and noted the land use with the help of local residents. Within the smaller sub-plots, all woody species with a DBH smaller than 5 cm were inventoried, which included regenerating trees as well as shrub species. Land use and land cover were identified together with local informants and classified into four broad land cover classes: *residential land* (where houses and gardens are located), *cultivated fields* (including fallow land), *bush land* (land dominated by shrubs, grass and woody vegetation which is mainly used for grazing), and *sacred forests* (locally protected patches of dense woody and shrubby vegetation used for diverse cultural and religious ceremonies). We were allowed to enter five sacred forests in two different villages. However, due to the small number of plots, the inventory data from the sacred forests could not be interpreted with a sufficient degree of confidence and was therefore omitted from the analyses of trends in the separate land cover classes. Although we analyzed a total of 1137 established trees (>5 cm DBH) and 3238 regenerating trees and shrubs (<5 cm DBH), many species were represented by relatively few individuals (see Table 1).

2.2.3. Tree species interview survey

We interviewed 30 people in each village (total n = 90) about changes in tree and shrub species composition in the landscape. The informants were selected based on the criteria that men and women should be represented to the same extent, they should be between 20 and 65 years old, and have agro-pastoral activities

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[1] Agroforestry parklands are the main land cover form in the West African Sahel and represent an integrative system of agriculture, trees and pasture (Boffa, 1999).

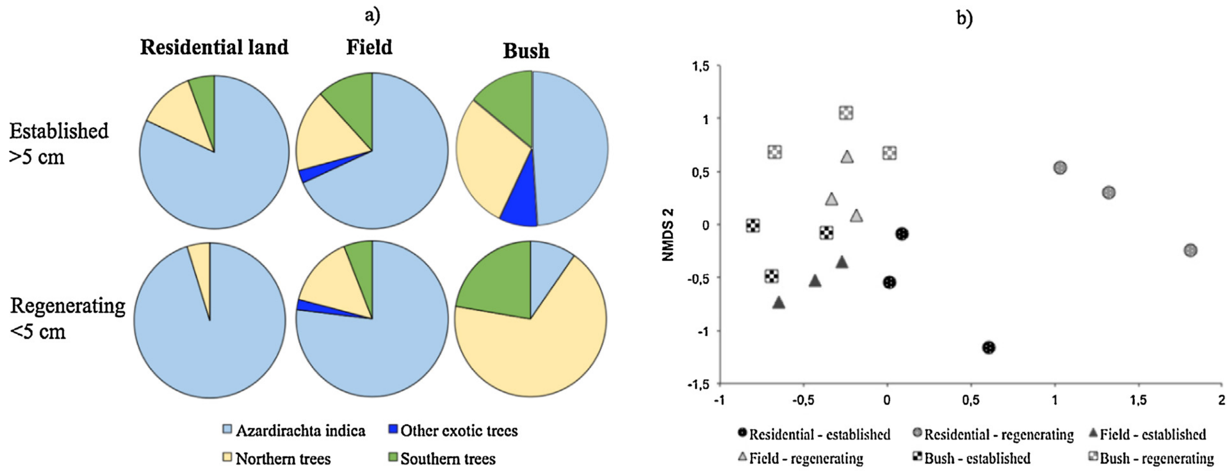

Fig. 6. Changes in tree species composition. The left panel (a) show proportion of the number of stems of different categories of species in the different land use types shown for both the established (>5 cm DBH) and regenerating (<5 cm DBH) strata of trees. The right panel (b) show an ordination plot (NMDS, stress = 0.11) with scores of the different landscape/land cover combinations for both the established (>5 cm DBH) and regenerating (<5 cm DBH) strata of trees. The species compositions in two coordinates that are close denote similar composition while distant points in the graph denote dissimilar compositions (the axes have not been analyzed in relation to any environmental variables).

as their main livelihood source (to capture informants that were knowledgeable about the local landscape and its dynamics over time). Interviews contained a combination of quantitative and qualitative questions. Perceptions of species abundance and population trends were obtained through free-listing questions, that is, no predefined list of species was presented to the informants. Species were identified through local names, pictures and when necessary they were botanically identified using two botanical books (Arbonnier, 2004; Von Maydell, 1986). The data gathered from each respondent thus consists of a list of species and the perceived trend for each species. These trends were subsequently summed over all respondents and expressed as the percentage of respondents who cited a given species as increasing or decreasing. This could be justified since no single species were recorded by some respondents as increasing and by others as decreasing.

2.3. Data analyses

2.3.1. Species classification

Each species was classified into one of the following three categories based on their ecoregion according to botanical- and bio-geographical literature: northern species (Sudano-Sahelian, Sahelian and Sahelo-Saharian species), southern species (Sudano, Sudano-Guinean and Guinean species), or exotic species (Arbonnier, 2004; Von Maydell, 1986) (see also Fig. 1 and Table 1). The exotic category was included since one exotic species, the Neem tree (*Azadirachta indica),* was identified early on in the research process as a very common tree that deserved special attention.

2.3.2. Spatial variation in tree cover and Neem occurrence

For each of the village landscapes, we calculated the closest distance from the central point of each of the satellite Image 200 × 200 m grid cells (which also is the central point of the tree inventory plots) to the nearest house in 2006. We then run a linear model with distance to house and landscape identity (Oula, Reko or Boursouma) and their interaction as explanatory factors and tree cover in 2006 as response variable. We log-transformed the tree cover data in order to meet assumptions of homoscedasticity and normality. Also, we run a similar model with tree cover change between 1984 and 2006 as response variable. However, it was not possible to transform the data to fully meet the assumptions of the model. Therefore, we run separate Spearman correlations between tree cover change (%) and distance to house (meter) for the three village landscapes in order to check the robustness of the results. We found a clear interaction effect (significant slopes, $p = < 0.001$, for Reko and Oula but not, $p = 0.92$, for Boursouma) with this approach. Additionally, we run a general linear model (GLM) with a quasi-poisson error distribution (to account for over-dispersion) on number of Neem trees in a plot as a function of distance to the closest house and with landscape as a co-variable. Similarly, we run a GLM with a binomial error structure for only presence/absence of Neem in relation to the same variables.

2.3.3. SCD- analysis

To evaluate changes in tree species composition over time, we looked at the size class distribution (SCD) for each tree species inventoried in the larger sampling plots (shrubs were not included in this analysis). Since the species composition did not differ among the landscapes ($p = 0.15$, Adonis-test on each main land use type in the three landscapes using *vegan* package in R (R Development Core Team, 2013)), we pooled the data to get the largest possible sample for each tree species. For each species all sampled trees were assigned to one of the following DBH classes: 5–14.9 cm, 15–24.9 cm, 25–34.9 cm, 35–44.9 cm, 45–64.9 cm and 65–95 cm (Condit et al., 1998; Lykke, 1998). We then ran a linear regression on the log-transformed number of individuals per ha in each size class as a function of its class midpoint (Lykke, 1998). The number of individuals was log-transformed ($\log + 1$), as some classes had zero individuals (Lykke, 1998). We only calculated SCD-slopes for species with ≥10 individuals in total. This resulted in species specific SCD-slopes, ranging from strongly negative to strongly positive. Since larger size-classes normally have fewer individuals, slopes are usually negative, indicating a larger proportion of young (regenerating) to old (established) trees and thus regeneration. Weak-negative slopes and slope values around zero indicate a more even distribution of regenerating and established trees, signaling insufficient regeneration. Positive slope values indicate a larger proportion of established to regenerating trees, which signals a population in decline (Lykke, 1998; Mwavu and Witkowski, 2009; Obiri et al., 2002).

2.3.4. Interview data analysis

In order to document local knowledge about the historical trends of tree species, we calculated the percentage of respondents who cited a particular species as increasing or decreasing, pooling the interview data from the three different landscapes. Only species that were mentioned by at least 5% of the respondents were included in the results.

2.3.5. Comparing northern and southern species

We compared the SCD-slope values as well as the interview data (percentage cited as increasing or decreasing) between the two different categories of tree species (northern vs. southern) with a T-test. Furthermore, we also compared the outcome from the two approaches by correlating the two measures of increase and decrease with a Spearman-correlation test.

2.3.6. Tree species trends and land use types

To further characterize the trends of increasing and decreasing species, we investigated to what extent the species composition of the regenerating portion of trees (<5 cm DBH, excluding shrubs) was similar to the larger trees (>5 cm DBH) within each land use class. This was done by constructing a species-by-site matrix, similar to the one for the larger trees, but now including the regeneration (<5 cm sized trees from the smaller 500 m^2 plot) as separate rows for each land use type in each village. For each land use class in each village we calculated the density of trees inventoried at the two scales, which was used as input data. We tested if the species composition was related to land use class (in three categories) and age (in two categories) and their interaction with an Adonis-analysis in the program R (R Development Core Team, 2013). Moreover, we run an ordination of the same matrix (using the non-metric multidimensional scale method, NMDS with the meta-MDS function in the *vegan* package). This is a non-parametric indirect ordination, which can illustrate how different sites cluster- or differ- along axes according to their similarity or dissimilarity in species composition (McCune et al., 2002).

3. Results

3.1. Trends in tree density: 1968–1984–2006

The remote sensing analysis of tree density change revealed a consistent decrease in tree cover in all three villages between 1968 and 1984, from 9 to 11% to 4–8%, and a consistent increase in tree cover between 1984 and 2006, back to similar levels as in 1968 (8.5–12.5%) (Fig. 3a & b). Both the decline and recovery of woody vegetation was more pronounced in the village landscapes around Boursouma and Oula than in that around Reko. The tree cover in 2006 was higher close to houses (present in 2006) than far from houses in two (Oula and Reko) out of the three landscapes ($p < 0.001$ for the interaction between landscape and distance in a linear model). The tree cover change between 1984 and 2006 was also positively related to proximity to houses in the same two landscapes (Fig. 5a).

3.2. Trends in tree species composition based on tree inventories

The inventory of trees showed that the average density of established trees (>5 cm diameter at breast height (DBH)) was 30–60 stems/ha, with some differences between the three landscapes and land cover classes. In total, we found 32 woody species in Boursouma, 23 in Oula and 38 in Reko (see Table 1). We analyzed the size class distribution (SCD) of the inventoried trees (>5 cm in DBH) to reveal which species displayed a continuous regeneration and which had an underrepresentation of smaller size classes indicating a negative population trend.

The large majority of declining species belonged to the group of species which have a southern distribution with comparatively moister conditions (i.e. Guinean, Sudano-Guinean and Sudanese eco-regions, see methods, Fig. 1 and Table 1), whereas most increasing species belonged to the group of species with a northern distribution, which are rather drought tolerant (i.e. Sudano-Sahelian, Sahelian and Sahelo-Saharian distribution) (see Fig. 4a, *t*-test, $t = -4.1$, $p < 0.005$). Three tree species were exotic introduced species and all of them showed increasing trends according to the SDC-slopes (Fig. 4a and Table 1). One of them, Neem (*Azardirachta indica*), had the steepest negative SCD-slope (indicating that the increase and regeneration of this species is particularly prominent) and was likewise the tree most frequently found in the inventory (see Table 1). Moreover, the number of Neem-trees in plots increased significantly with proximity to houses in two (Oula and Reko) out of three landscapes ($p < 0.001$ for the interaction between distance to house and landscape) (see Fig. 5b).

The species composition differed significantly between land-use class and between the established (>5 cm DBH) and the regenerating trees (<5 cm DBH) (Adonis test; land use class, $F = 2.9$, $p = 0.001$ and age, $F = 6.3$, $p = 0.001$, no significant interaction effect). Specific patterns in the species compositional shift were that Neem trees (*A. indica)* had a much higher relative frequency among regenerating trees than among established trees on residential land and in the fields (Fig. 6a), while in the bush-land drought-tolerant species had a higher relative frequency in the regeneration class. The compositional changes were similar in the three different village landscapes as seen by the proximity of the different landscapes for each land cover category in a multivariate ordination space (Fig. 6b).

3.3. Trends in woody species composition based on interviews

The interview survey of 30 persons in each of the three landscapes (total $N = 90$) about perceived changes in the abundance of different woody species (see Table 1) also revealed significant differences in perceived change between the southern and northern groups of tree species ($t = 4.4$, $p < 0.001$, Fig. 4b). Neem was the tree most often cited as increasing in the survey (see Table 1). The two independent data sets (the tree inventory and the interviews) revealed a consistent pattern of the nature of the species compositional change as shown by the significant correlation between SCD-slopes and interview answers ($r = -0.81$, $p < 0.001$, Spearman's correlation), both indicating a shift in species composition towards more arid and northern species. Another pattern that the interviews revealed was that several shrubs increased, predominantly the family of *Combretaceae*, which also are considered to be northern species (e.g. *Guiera senegalensis* and *Combretum* spp., see Table 1).

4. Discussion

Our findings of an initial decline in woody vegetation between the 1960s and 1980s with a subsequent increase in tree cover correlate with the changes in greening signals measured as changed in NDVI, which is reported from this area. However, our results also show that the increase in tree cover has been accompanied by a change in tree species composition from a typical Sahelian agroforestry parkland flora towards a tree flora dominated by drought resistant and exotic species, and also more shrubs (see Table 1). This is a somewhat surprising finding, given the recent trends of increasing annual rainfall over the study area. Our results add nuance to the understanding of emerging landscape trajectories in the Sahel, as previous studies often have focused on singular dimensions of landscape change. In light of recent debates about desertification and greening of the Sahel, this confirms the need to e.g. investigate and differentiate between changes in vegetation density and species composition to be able to evaluate the processes that underlie such a transformation of the vegetation (Herrmann and Tappan, 2013; Herrmann et al., 2014), as well as its effects on the generation of ecosystem services and, associated with that, effects on local livelihoods (Haglund et al., 2011; Sinare and Gordon, 2015).

The shift in parkland flora towards more drought tolerant tree species seems paradoxical at first hand. Since the mid-1980s, data shows an increasing trend in annual precipitation over the Western Sahel (Nicholson, 2013), which is also reflected in our study area (see Fig. 2). While rainfall–vegetation dynamics admittedly are complex in semi-arid and dry sub-humid landscapes, this shift towards more drought tolerant woody vegetation, during a period of increasing annual rainfall, is surprising and leads us to question rainfall as the sole primary driver for the observed changes in woody vegetation in our study area. Based on our empirical findings, we propose that the change in species composition is mediated by changes in land use. The contribution of land management for tree cover increase is further indicated by our spatial analysis (Fig. 5), which show that increase in tree cover is more pronounced close to houses, i.e. in the more intensively managed parts of the village landscapes.

Without human intervention, vegetation would track changes in climate, with more drought tolerant species benefitting when climate gets drier and vice versa, but with a time lag (Fig. 7, center). However, people may decide to plant drought tolerant trees or use the land in a way that favors a more drought tolerant vegetation than what would be predicted by the actual rainfall conditions (Fig. 7, lower right corner). Also, with management, some species with a higher rainfall optimum, than what the actual climatic conditions reflect, can thrive with the help of for example watering or removal of competitive species (Fig. 7, upper left). While time lags between the onset of good conditions and the response of the vegetation are to be expected (Hylander and Ehrlén, 2013; Jackson and Sax, 2010), we found a stronger "drought-tolerant" signal among the regenerating portion of the trees and shrubs than among the established trees (see Fig. 6a) suggesting that extinction and colonization time lags are not the main drivers of the found pattern. Lack of seeds of southern species could be an important mechanism causing time lags in our study area, but since traditional management of the parklands has involved active promotion of these species and there still are available trees, albeit declining, this lag effect is not likely to have a strong impact on the observed change. However, seed sowing and transplantation experiments, combined with in-depth studies of current land management practices, would be an important next step to evaluate how different species perform under current conditions.

Our data shows that drought tolerant vegetation is dominating the regenerating portion of the woody vegetation in bush lands (see Fig. 6) as well as the shrubby vegetation in all land use classes. However, our data also shows that the Neem tree, which was introduced to the three village landscapes as late as in the early 1980s (interview data), is now very abundant in residential land as well as in the fields. Concerning the total tree regeneration, Neem makes up >75% in these two land cover classes. The dramatic increase in tree cover close to settlements in Oula and Reko (Fig. 2) is likely to be a Neem tree effect (Fig. 5). The lack of such an effect in Boursouma is likely to be an effect of a reforestation campaign conducted by OXFAM in the 1980s, which resulted in Neem trees being planted also in many places outside the residential lands, i.e. on cultivated fields and bush land. The Neem tree alone accounts for more than 50% of all trees >5 cm DBH in two of the villages. Other studies from Burkina Faso, Niger and Senegal, have documented similar trends, i.e. that increasing species were largely exotic trees (e.g. Neem and Eucalyptus) (Herrmann et al., 2014; Wezel and Lykke, 2006). Hence, increasing densities of this particular species might be one important driver behind the increased tree cover across at least some parts of the Sahel.

The Sahelian agroforestry parklands are domesticated landscapes that date back at least to the first millennium AD (Duvall, 2007; Höhn and Neumann, 2012; Maranz and Wiesman, 2003; Widgren, 2012). The documented shift in species composition thus suggests that current social-ecological relations are producing new and different types of parklands. Here we discuss some possible processes that together might contribute to the observed increases in tree cover and shifts in species composition in our study area, and that would be important to investigate in further detail to understand future development trajectories of these parklands. The first process is the intensified land use in the studied village landscapes. Farmers we interviewed consistently reported an increased frequency of tilling and an abandonment of fallowing as a result of rapid population growth and increased demand for land to cultivate, which generally corresponds to reports about increasing pressure on land from other parts of the Sahelian region (Cour, 2001; Mortimore, 2010; Van Vliet et al., 2013). As fallow areas were important sites for the regeneration of the southern Sudanian and Guinean tree species that farmers promoted in their fields (Boffa, 1999), the reduction/abandoning of fallow land likely contributes to these species' decline (Gijsbers et al., 1994; Schreckenberg, 1999). Our results show that shrubs belonging to the Sahelian *Combretaceae* family are very abundant and were also listed as increasing by interview respondents (Table 1). *Combretaceae* as well as Neem trees are able to produce root suckers and grow well through coppicing (Arbonnier, 2004; Hiernaux et al., 2009; Von Maydell, 1986), giving them a competitive advantage if fallowing is abandoned and the soil is permanently tilled. A second process reported by local farmers was an increasing trend in livestock rearing since the 1980s, which has also been reported from other Sahelian village landscapes (Herrmann et al., 2014; Rasmussen et al., 2014). Many of the indigenous species that we identify as increasing (e.g. *Combretaceae*) are indeed described as indicator species for heavy grazing and belong to the northern Sahelian environment (Arbonnier, 2004; Hiernaux et al., 2009; Von Maydell, 1986). Also, Neem is not eaten by livestock. A third factor, possibly accounting for the increase of the fast growing Neem tree is the demand for building material, shade and fuel wood to support the growing population. The Neem tree propagates naturally in the studied landscapes, but is also planted. Planting (e.g. for shade) most likely contribute to the abundance of Neem trees on residential land. Fourth, the Ouahigouya region has been subjected to large tree planting campaigns since the crisis period and deforestation during the 1970s and 1980s, which most likely have contributed to the dominance of Neem. The influence of reforestation programs is also indicated by Mertz et al. (2010) in a study across the Sudano-Sahelian zone of West Africa where farmers in the 500–700 mm rainfall zone regarded reforestation as a major strategy to ameliorate effects of negative trends in rain fed crop production. A fifth process that potentially could be contributing to the emerging landscape pattern is the social memory of the severe droughts and crisis period during the 1970s and 1980s, which may lead local farmers to adopt a bet-hedging strategy that favors species "that grow for sure". An important research frontier will be to further study how these kinds of processes interact with each other and with ongoing climate changes, to shape future landscape trajectories in the Sahel.

5. Conclusion

Based on a detailed multi-method case study, we show that woody vegetation in northern Burkina Faso is recovering after the devastating droughts in the 1970s and 1980s, a pattern correlating with the remotely sensed re-greening trend in the region since the 1980s. The increase in tree cover is, however, associated with an unexpected shift towards more drought tolerant woody vegetation. As precipitation shows an increasing trend during this period, the shift is difficult to explain as an exclusive rainfall effect. Instead, we suggest that the observed increase in tree cover might also be modified by an intensified land use system that includes a reduction in fallowing and thus more intensive cultivation and soil tilling, increased grazing pressure, and promotion of fast growing species for construction and fuel wood, (cf. Haglund et al., 2011; Herrmann and Tappan, 2013; Herrmann et al., 2014; Larwanou and Saadou, 2011; Rasmussen et al., 2014; Sinare and Gordon, 2015; Sop and Oldeland, 2013). Our findings provide new insights related to the Sahelian re-greening debate by indicating the emergence of new and complex trajectories of landscape change, or in other words that current social-ecological relations in the region are producing new types of agroforestry parklands—in our case a somehow unexpected shift to drought tolerant woody vegetation during a period of increasing rainfall. This points to the need for detailed and spatially explicit investigations that build on integrated analyses of societal and biophysical factors to better capture diversity and similarities between different change trajectories shaping contemporary Sahelian landscapes (Herrmann and Tappan, 2013; Kaptué et al., 2015; Karlson and Ostwald, 2016). A better understanding of these emerging trajectories is of crucial importance for designing suitable policies for climate change adaptation, biodiversity conservation and the sustainable delivery of ecosystem services that benefit local livelihoods in one of the world's poorest regions.

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