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ORIGINAL ARTICLE

50 years of woody vegetation changes in the Ferlo (Senegal) assessed by high-resolution imagery and field surveys

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Abstract

Woody vegetation dynamics in the Sahel have been debated since the great droughts of the 1970s–1980s. Here, we combined high-resolution satellite and aerial imagery, field inventory, and historical botanical records to study woody vegetation trends over the years 1965, 1980, 2008, and 2018 in the Ferlo, the Sahelian sylvo-pastoral zone of Senegal. While tree density has decreased from 1965 (14.8 trees ha^{-1}) to 1980 (13.4 trees ha^{-1}) and 2008 (11.9 trees ha^{-1}), tree density has stabilized in 2018 (12.2 trees ha^{-1}). The relatively moderate decrease in tree density over 50 years characterized by extensive human pressure and droughts, as well as the rather stable woody cover following the drought years after the 1980s, do not support narratives of widespread desertification in this region. However, we observed a shift in the composition of species. While the drought-resistant tree *Balanites aegyptiaca* showed a stable abundance, *Acacia tortilis* showed strong increases and other species like *Sclerocarya birrea* and *Combretum glutinosum* decreased. In addition, recent field surveys show that the ratio between shrubs and trees has increased towards more shrubs. The observed loss of species diversity combined with the increase of drought-resistant species is in line with current observations for savanna ecosystems in the context of an increased aridity.

Keywords Woody vegetation · Senegal · Sahel · High-resolution imagery · Field inventory · Temporal trends

Introduction

The vegetation of savanna ecosystems is characterized by the coexistence of woody and herbaceous species. This is also the typical plant formation in the Sahel, a semiarid zone in West Africa delimited by 200 and 600 mm rainfall isohyets. Annual rainfall in the Sahel is concentrated during July–September and is characterized by a high spatial and inter-annual variability (Le Houérou 1989; Nicholson 2013). Most livelihoods in the Sahel are related to pastoralism, with varying strategies dealing with the variable vegetation resources (Thébaud and Batterbury 2001). Woody species provide fodder to livestock

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and also offer many others ecosystem services such as firewood, fruits, or traditional medicine (Lykke et al. 2004; Sop et al. 2012).

During the 1970s and 1980s, concerns were raised about the vegetation in this bioclimatic region, because the Sahel was hit by the most intense droughts of the twentieth century with annual rainfall decreasing down to 40% compared to the long-term mean (Nicholson 2001; Nicholson 2013). Many researches have focused on the impact of these droughts on vegetation in the region since then (Epule et al. 2014; Hiernaux et al. 2009; Maestre et al. 2012). A decrease in density and species richness of woody vegetation was reported in the West African Sahel/Senegal by field inventories, Earth observation datasets, or local interviews (e.g., Gonzalez 2001; Gonzalez et al. 2012; Poupon and Bille 1974; Vincke et al. 2010; Wezel and Lykke 2006). However, many studies based on remote sensing have shown that the Sahelian vegetation has experienced a recovery, also called "greening" (interpreted as an increase in gross primary productivity, Sellers 1985) since the end of the drought years (Anyamba and Tucker 2005; Dardel et al. 2014; Olsson et al. 2005). These studies have calculated NDVI (Normalized Difference Vegetation Index; Tucker 1979) from time series of NOAA AVHRR (National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) satellite images, allowing yearly estimates of vegetation productivity across the Sahel from 1982 to date. Until recently, it has been difficult to attribute this greening to the herbaceous or/and woody component of the vegetation, but new analyses of both satellite and field data have shown that the major part of the long-term greening could be associated with the woody part (Anchang et al. 2019; Brandt et al. 2019; Brandt et al. 2015).

Still, there are some limitations to these studies due to the focus on post-drought years only, and uncertainties remain in our understanding of the long-term vegetation dynamics of the region. First, the greening of the Sahel is not uniform (Brandt et al. 2017; Fensholt et al. 2013), and most satellite data available over a longer time period have a very coarse spatial resolution making it impossible to study single landscape features like trees. Second, the datasets used generally start in the 1980s, which coincides with the extreme drought period (Mbow et al. 2015). If viewed over a longer period, e.g. from the 1960s to date, only a few robust studies exist (e.g., Brandt et al. 2014; Hänke et al. 2016), due to the absence of relevant and homogeneous data-sources, allowing for a spatially and temporally coherent survey. Third, species and growth forms cannot be identified within satellite images. Moreover, ecosystem services are species dependent (Breman and Kessler 1995) and if the re-greening is driven by unpalatable woody species, the region's value as pastoral zone cannot be considered recovered. Field inventories thus remain crucial as complementary data source (Hänke et al. 2016; Herrmann et al. 2005). Unfortunately, there are only few long-term field monitoring sites that allow to study changes in woody species. The experimental trial of Miehe et al. (2010) shows a decrease in some tree species and an increase of bushes and spiny trees (Miehe 1994; Miehe 2002).

It is thus currently unclear if the vegetation recovery from the drought (the "greening") has led to pre-drought conditions, or if a real shift in vegetation patterns (change in growth form, density, etc.) and species has occurred. Additionally, local perceptions of land degradation/improvements often disagree with satellite-based analyses, and there is a need for more interdisciplinary studies to bridge the information provided by different methods (Herrmann et al. 2020; Herrmann et al. 2014; Mbow et al. 2015).

This study combines historical and recent satellite images with field data in order to document changes in woody vegetation for an area in the Ferlo (Senegal) between 1965 and 2018. The research includes the use of old de-classified Corona satellite images, which provide useful information about pre-drought conditions (Spiekermann et al. 2015) and historical field data that inform about changes in species compositions. We address three specific objectives: (i) investigate the changes in woody plant density between 1965 and 2018 and in woody cover between 1980 and 2008; (ii) determine if the observed changes in woody cover depend on relief and pastoral camps, a proxy for human activities; and (iii) investigate the changes in species composition and in species abundance between 1970 and 2017.

Material and methods

Study area and datasets

The study area is part of the Ferlo, located in the Sahelian and sylvo-pastoral zone of Senegal, mainly used by Fulani pastoralists. Human impact is limited to the effects of grazing and browsing, and fuel-wood collection, mainly for local uses. More specifically, the study focuses on an area of approximately 3700 km^2 (68 km × 55 km), in the surroundings of the deep wells Tessékéré (15.85° N, 15.06° W) and Widou Thiengoly (15.99° N, 15.32° W) (Fig. 1b).

The major landform of the Ferlo is composed of fossil eolian sand dunes intersected by large plains of 1 to 5 km (Le Houérou 1989). Soils are sandy with a slight differentiation according to the landform: on the dunes, ferruginous tropical soils dominate, and in the plains, sub-arid red and brown red soils dominate. Small depressions occur on both plains and dunes but they are more frequent and larger in plains, where they form temporary ponds at the end of the rainy season. This local topography (depressions vs. dune tops) influences woody vegetation, which preferably grows in depressions where water availability and soil fertility (due

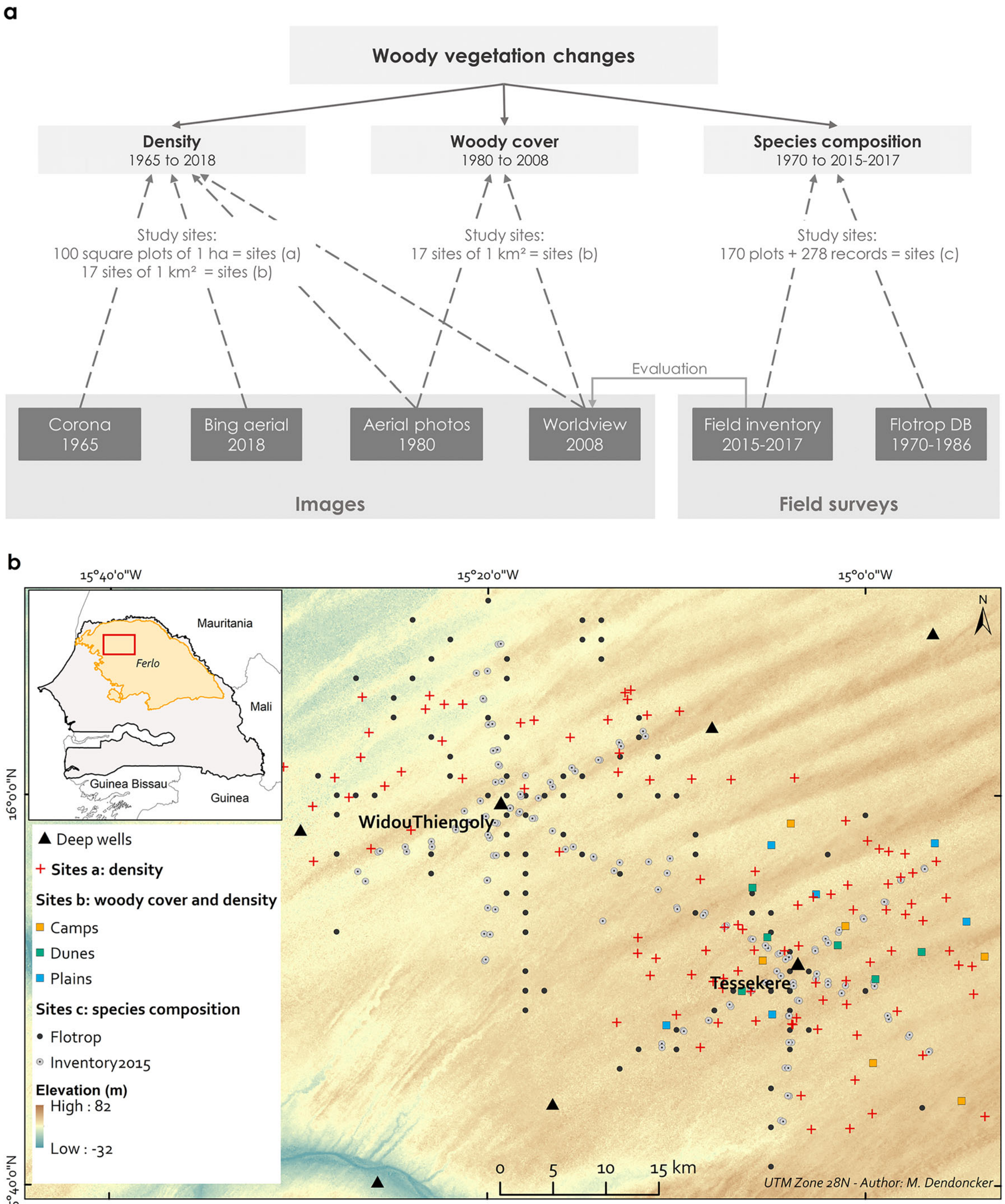

Fig. 1 Methodology to assess woody vegetation change and location of the study sites. **a** Relationships between the indicators calculated to assess woody vegetation dynamics, the datasets (images and field surveys) and study sites. **b** Location of the studied sites. The red crosses represent the 100 random plots of 1 ha on which woody plant density was assessed (sites a). The squares are the 17 study sites of 1 km^2 on which woody cover and density were assessed (sites b). The circles represent the field plots from the Flotrop database and the field inventory (2015) (sites c)

to cattle feces and clayey soils) are higher (Dendoncker and Vincke 2020).

The Ferlo region experienced major changes during the past 50 years. First, permanent water points (deep wells) were installed during the 1950s, providing access to water for population and livestock throughout the year (Le Houérou 1989). Prior to the 1950s, the region was used only in the rainy season when temporary ponds allowed transhumant pastoralists to enter the region. As ponds dried out during the dry season beginning in November, pastoralists returned to the Senegal River valley or to farming regions in south (Touré 1990). Second, partly due to the enhanced access to water, both human population and livestock increased. As an example, the density of Fulani camps in a radius of 15 km around the deep well of Tessékéré increased from 0.1 camps km^{-2} in 1980 to 0.23 camps km^{-2} in 2008 (Dendoncker, unpublished data). This has raised concerns about the increased pressure of livestock, associated with opening area for year-round use (Le Houérou 1989). Third, the area suffered from the severe drought years in the 1970s and 1980s, as it was the case for the entire Sahel region. The average rainfall between 1990 and 2007 in the West African Sahel (10° and 15° longitude west) was equivalent to the average of 1970–1989 (Nicholson 2013), which does not indicate a recovery of the rains to the same degree as for the entire Sahel.

This research assesses woody vegetation changes through four indicators obtained from multiple datasets (Fig. 1a). The indicators are (i) the woody plant density (i.e., the number of individuals per ha), (ii) the woody cover (i.e., the percentage of the ground covered by crowns), (iii) the species composition (i.e., the species list per period), and (iv) the frequency of the species (i.e., the percentage of the surveys in which the species are present). The Earth observation datasets are used to study woody cover and woody plant density, whereas recent and historical field inventories enabled us to study the species composition and frequency.

Woody cover and density changes

Earth observations datasets and sampling

Woody cover and plant density were derived from four Earth observation datasets. The first dataset are Corona images available from the US Geological Survey for December 1965 at 2-m resolution. The second dataset are aerial photos taken in January or February 1980, by the Teledyne society for the OMVS (Guissé et al. 1987). The original scale is 1/50000. The third and fourth datasets are WorldView-1 images from April 2008 (© 2015 DigitalGlobe, Inc. Licensed under NextView) at 0.5 m and Bing map satellite images (© Bing Map Microsoft) from 2018. Even though the spatial resolutions of the data sources are in the same order of magnitude, the different sensors and processing techniques make the detectability of trees and shrubs in the different data sets challenging to be directly compared. Figure 2 illustrates the differences and shows that only larger trees can be reliably detected in the older data sets (Corona and aerial photos). These differences make automatic tree detection difficult, and we thus decided for a manual visual interpretation of the images.

The Corona and the aerial photos both required georeferencing prior to their use. This was performed using a third-order polynomial transformation using large trees as ground control points (at least 40 points per image). The implementation of a geometric correction of the aerial photos was not possible given that the flight information necessary to do such a correction were not available. For that reason, we chose to work only in the central part of the photos (inside a square area of 64 km^2) to avoid geometric distortions, which are more pronounced towards the sides.

Two types of sites were sampled. The first type aimed at evaluating the overall trends in woody plant density. Here, we randomly selected 100 plots of 1 ha within the overlapping areas of Corona images, the aerial photos and WorldView-1 images (sites a, Fig. 1). The second sampling aimed at testing the influence of human impact (using the presence of pastoral camps as indicator) and relief (i.e., dune and plains) on woody plant density and cover. We assume that the long-term presence of a pastoral camp induces a higher grazing intensity and woody and non-woody product collection on the surrounding vegetation. We selected 17 sites of 1 km^2 around the deep well of Tessékéré (sites b, Fig. 1 and Fig. 3). Five sites are centered on a Fulani camp present from 1980 (visible on aerial photos) to 2018 (visible on WorldView-1 and Bing images). As Fulani camps are located in plains, no camp sites in dunes could be selected. Additionally, we selected 12 more sites: six on dunes and six in the interdunal plains, all located at a minimum distance of 1 km from camps. To facilitate the reading, we will further refer to the type of site (camp, dune, or plain sites) reflecting human activity and the relief.

Woody cover and density measurements

Woody plant density reflects the number of woody plants per hectare that are visible in all the imagery used. The detectability of small shrubs and bushes was limited by the data source of poorest quality, being the Corona images. Smaller crowns were thus omitted in all the imagery (Fig. 2). Density was assessed in the 100 plots of 1 ha (sites a, Fig. 1) by manually counting the woody individuals visible in the Corona images, the aerial photos, the WorldView-1, and the Bing images. We also performed the same density analysis on the 17 sites of 1 km^2 (sites b, Fig. 1) for three image acquisition periods: 1980, 2008, and 2018. We counted woody individuals inside a grid of 100 m × 100 m squares that divided each site into 100 cells.

Woody cover expresses the fraction of the ground covered by the sum of the woody plant crowns. This indicator was only calculated for images with a comparable resolution (i.e., aerial photos and WorldView-1 images). Woody cover changes were studied between 1980 and 2008 on the 17 sites of 1 km^2 (sites b), using the same grid as for the density (the quality of Corona images was not sufficient for this analysis). We used a threshold gray-scale value to classify the pixels into tree and no-tree. The threshold determination was based on trial and error. Masks were created for the camp sites to exclude the areas occupied by houses and the immediate surroundings of bare soil as their pixel values fell within range of tree pixel values. To validate the thresholds and to be able to estimate a detection error rate, we randomly distributed 100

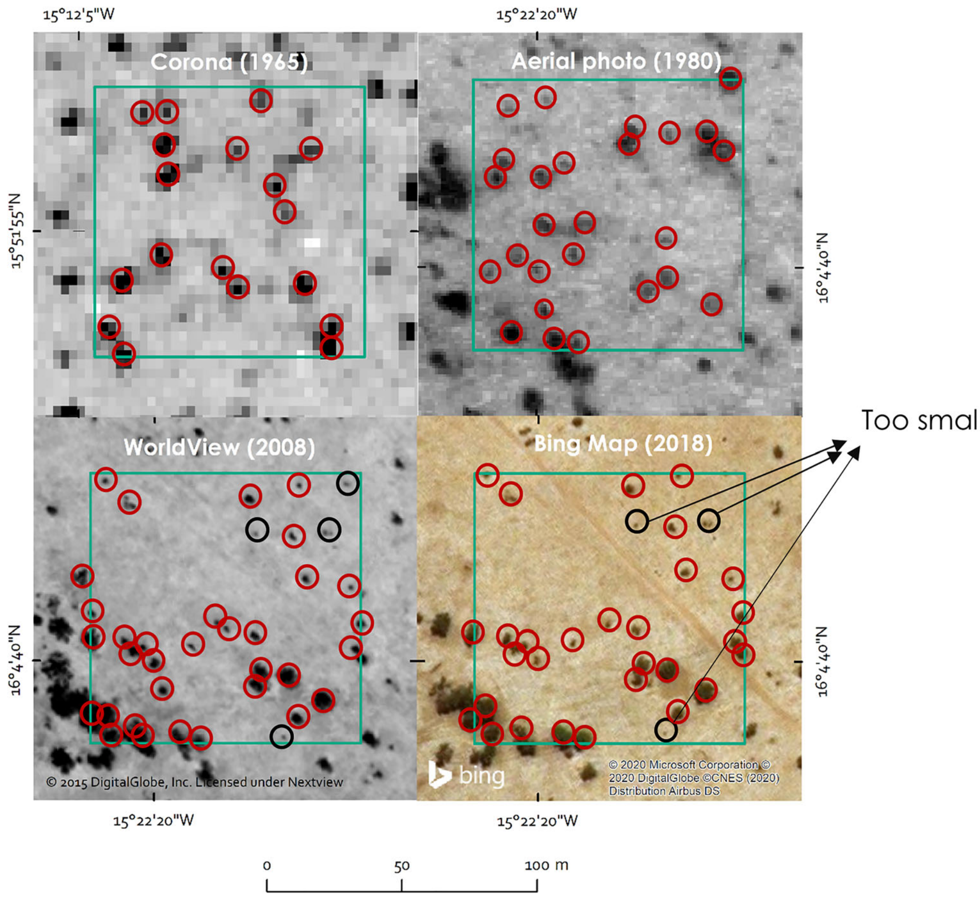

Fig. 2 Quality of the four datasets (not the same location except for WorldView and Bing map). The red circles identify woody individuals inside the 1-ha plot in green. The black circles highlight the individuals that were omitted in the WorldView-1 and Bing map imagery because their size was too small to be detectable in the older data sets

points within each of the 17 sites. As woody cover usually ranges from 5 to 10% in our study area (Tappan et al. 2004), we allocated 10 points to the "tree" class and 90 points to the "no tree" class per site. We then visually verified if these points were correctly assigned to the "tree" or the "no tree" class.

The accuracy of satellite-based woody cover values was evaluated by field data (see Online Resource 1 for coordinates). Thirty square plots of 0.25 ha each were inventoried in 2017 in the area around Tessékéré. The field plots were randomly located inside the 1-km^2 sites (sites b). We recorded every living individual woody plant with a crown diameter larger than 0.5 m ($n = 572$) to match with the resolution of the WorldView-1 sensor. We identified the species and measured two perpendicular crown diameters for each plant. The percentage of overlapping crowns was visually estimated so that the field woody cover would reflect the actual proportion of the ground covered by the vertical projections of the crowns. Field measured woody cover was calculated from the field data of 2017 by summing the crown cover of all individuals corrected for overlapping canopies. For the same 30 plots, woody cover was assessed in the WorldView-1 images by applying the threshold method. A linear regression was then performed between field woody cover and satellite estimated woody cover to evaluate the consistency of the values.

Changes from 1965 to 2018 and influence of human impact and relief

To study changes in woody plant density from 1965 to 2018, we compared the density in the 100 square plots (sites a) using multiple Student means comparisons and Holm's method (Holm 1979) as p value adjustment. Due to varying accuracy in georeferencing and distortion of the images, it cannot be guaranteed that the 100 plots perfectly overlay between 1965 and 2018. However, the large number of plots is assumed to be representative for the whole study region so the average values over the plots are comparable.

Changes in woody cover between 1980 and 2008 and in density between 1980 and 2018 for the 17 sites of 1 km^2 were assessed using linear mixed models with Satterthwaite degrees of freedom (Zuur et al. 2009), fitted with the "lmerTest" package in R software (Kuznetsova et al. 2017; R core team 2018). The response variables were either the density or the woody cover values obtained at the grid scale (i.e., 1700 cells of 1 ha). Site location was used as random effect and we included the type of site as variable with fixed

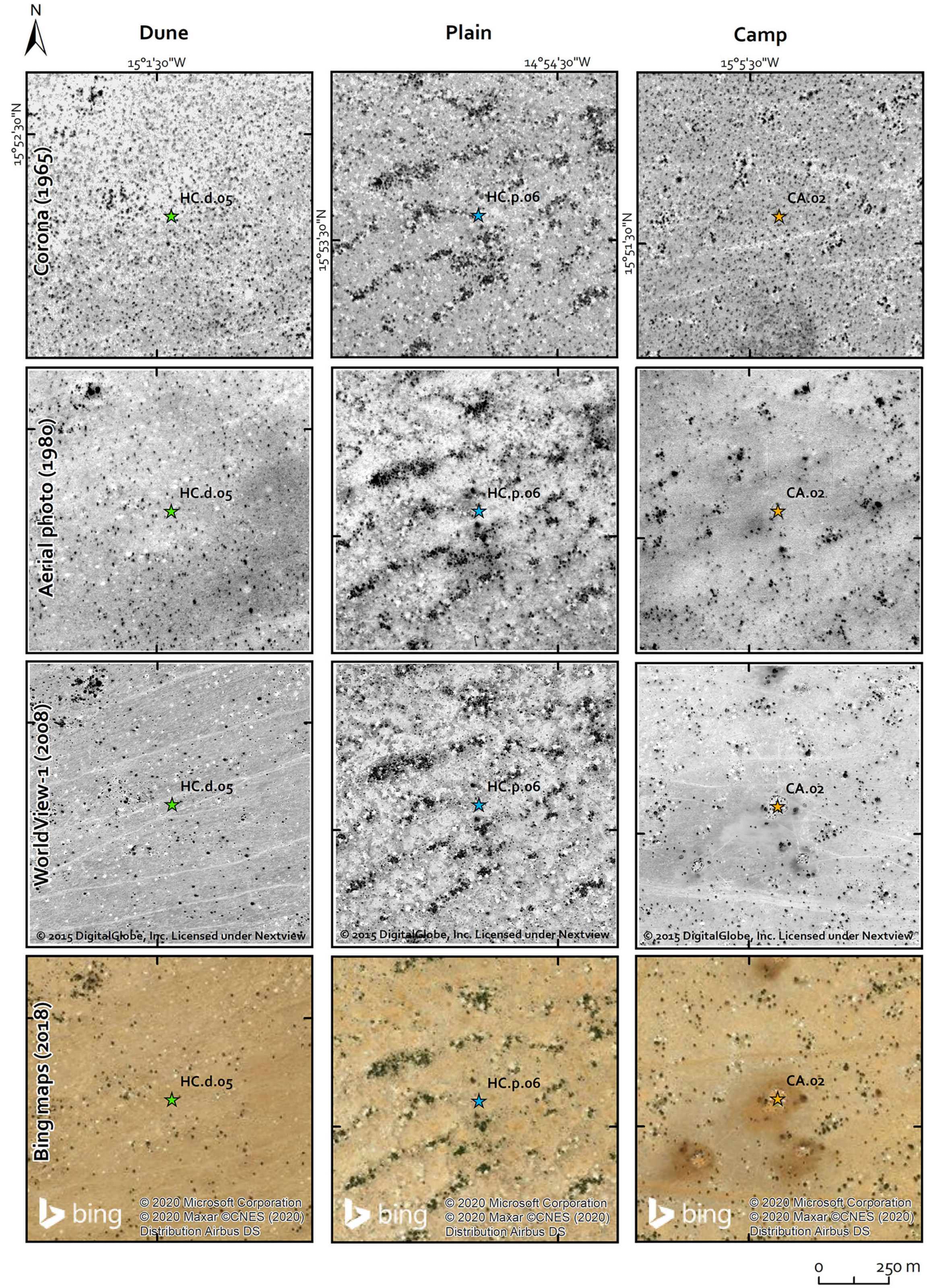

Fig. 3 Time series of Earth observation datasets from 1965 to 2018 for each type of site. Rows: the four datasets and columns: the type of site, with the center marked by a star (a dune site, HC.d.05; a plain site, HC.p.06; and a site near a camp, CA.02)

effect (See Online Resource 2 for details). For both woody cover and density, the first model applied aimed to test for significant changes during the studied period (effect of year) and the general effect of the site type. If the effect of the year was confirmed, we calculated four new variables "delta" to further study the changes and the potential influence of relief and human impact. One delta variable was computed for the woody cover: the cover of 2008 minus the cover of 1980 for each cell and three deltas for the density: density in 2018 minus density in 2008, density in 2008 minus density in 1980, and density in 2018 minus density in 1980. As the datasets from 1980 to 2008 overlaid precisely, we directly compared the presence or absence of tree between the two dates. This allowed us to obtain, for each site, the proportion of trees that were already present in 1980, which is important for studying age structure of woody plants in the region.

Dynamics in species composition

Field surveys (sites c, Fig. 1) include records from three different sources. First, the 30 plots that were inventoried (see 2.3.2). Second, we used the data from 139 plots inventoried in 2015 in the same area and using a similar field methodology to the inventory of 2017 (Dendoncker and Vincke 2020). Third, 278 records, dating from 1970 to 1986 and located within an area of 20 km around the deep wells of Widou Thiengoly and Tessékéré, were extracted from the Flotrop database (Taugourdeau et al. 2019). For 143 of these records, the species abundances were recorded using Braun-Blanquet coefficients (Braun-Blanquet 1932). These coefficients were transformed on relative abundances by dividing each abundance by the sum of the individual abundances. The remaining 135 records contained only information about the presence of species.

The species frequencies in the Flotrop database were compared with the species frequencies in 2015–2017. Species with more than five occurrences in the database (among the 278 records) were classified in three groups: (i) increasing species, i.e., species with a relative difference in frequency > 30%; (ii) decreasing species, i.e., species with a relative difference in frequency < −30%; and (iii) stable species. For the field survey of 2017, we calculated the density ratio between trees and shrubs. Species considered shrubs were *Boscia senegalensis* (Pers.) Lam. ex Poir., *Calotropis procera* (Ait.) Ait. f.), *Feretia apodanthera* Del., *Guiera senegalensis* J. F. Gmel., and *Leptadenia pyrotechnica* (Forssk.) Decne. Species composition was established for dunes and plains separately.

To study change in the botanical composition between 1970 and 2015–2017, all the abundances of the field surveys were pooled into a matrix with rows as records and columns as the relative species abundances. We then performed a principal coordinates analysis (PCoA) on a Bray-Curtis distance matrix using the "vegan" package in R software (Oksanen et al. 2019). Records were classified in three separate periods: 1970–1971 (corresponding to the early stage of the great drought, $n = 78$), 1972–1986 (during the drought, $n = 65$), and 2015–2017 (the current situation, $n = 169$). The influence of the period on the first two axes of the PCoA was tested by an ANOVA and Tukey's test.

Results

Woody plant density

During the period 1965 to 2018, woody plant density decreased from 14.8 ± 5.0 trees ha^{-1} (mean ± s.d.) in 1965 to 13.4 ± 5.1 trees ha^{-1} in 1980 ($P = 0.215$) and reached 11.9 ± 5.7 trees ha^{-1} in 2008 in the 100 random plots (sites a, Fig. 4). No marked differences occurred during the last period with a density of 12.2 ± 5.7 trees ha^{-1} recorded in 2018. The pattern was confirmed for the 17 sites (sites b). The first linear mixed model highlighted an effect of the year (Online Resource 2), with density values decreasing from an average value (least square means, with a standard error of 0.55) of 14.5 trees ha^{-1} in 1980 to 12.3 trees ha^{-1} in 2008 but increased to 13.6 trees ha^{-1} in 2018 (Fig. 4.). The Tukey test on the least square means differences confirms this trend ($P < 0.001$).

The type of site influences the woody plant density, regardless of the year, as shown by the first model. Plain sites showed the highest woody plant density value with a least square mean of 16.4 trees ha^{-1} against 14.5 and 9.5 trees ha^{-1} for the camps sites and the dune sites, respectively. However, these differences are only significant between plains and dunes, and camps and dunes (Tukey test, $P < 0.05$). Looking at the changes between 1980, 2008, and 2018 according to the type of site, the woody plant density around camps changed from 14 to 13.5 to 15.8 trees ha^{-1}, respectively. On dunes, woody plant density changes from 11.2 (1980) to 8.2 (2008) to 9.0 (2018) trees ha^{-1}, and in plains from 18 (1980) to 15.3 (2008) to 16 (2018) trees ha^{-1}. Relative changes between 1980 and 2008 showed a pronounced decrease for dunes (− 26.8%), which was less strong in plains (− 15%) and camps sites (− 3.6%) (Fig. 4). However, these differences in density changes between the different types of sites are not statistically different according to the three other models (($P > 0.05$; Online Resource 2).

Woody cover

Evaluation of the WorldView-1 woody cover using field woody cover

The WorldView-1 estimated woody cover from 2008 is highly correlated with the woody cover measured in the field in 2017 (Fig. 5, $R^2 = 0.807$, slope = 0.89, mean absolute error = 0.6%), although the time period is different. Woody cover in depressions is generally higher in the satellite assessment as compared to field data, whereas the values are lower on dune

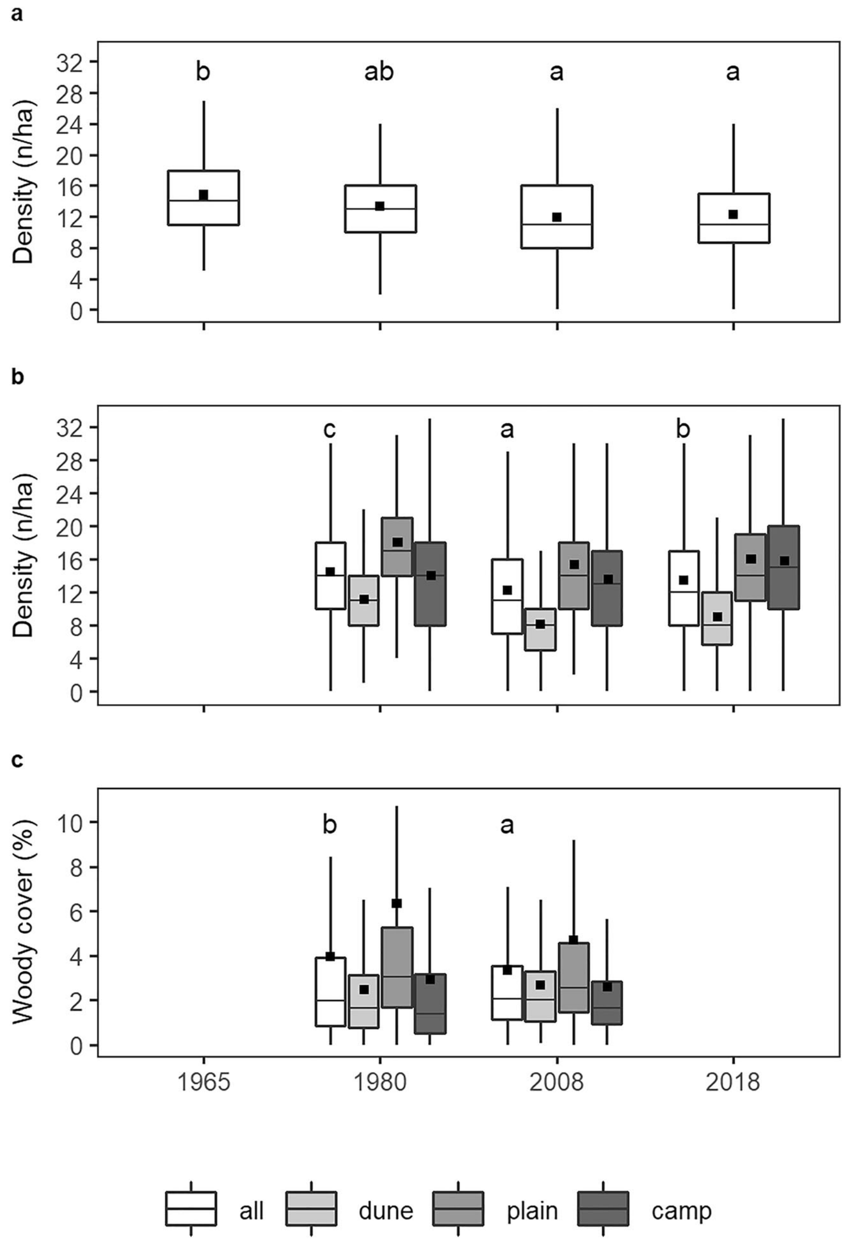

Fig. 4 Density and woody cover changes (medians and quartiles; means are represented by the black squares). The letters above the white boxplots indicate whether the values are significantly different ($P < 0.01$). **a** Tree density between 1965 and 2018 on the 100 random plots of 1 ha (sites a). **b** Tree density on the 17 sites of 1 km^2 (sites b). **c** Woody cover between 1980 and 2008 on the 17 sites of 1 km^2 (sites b)

tops and slopes. Trees with overlapping crowns in depressions form closed canopy areas. This can lead to the formation of clumps when a threshold is applied (Fig. 3), and might explain the overestimation of woody cover observed here, in particular in older imagery of lower quality.

An independent validation of the threshold-based woody cover estimation showed that in total, 81.2% of the points for the WorldView-1 images and 90.6% for the aerial photos distributed among the "tree" class were correctly classified (Online Resource 3). As for the "no tree" class, 97.4% of the points for the WorldView and 98.4% for the aerial photos were correctly assigned. To assess whether the observed changes in woody cover are larger than the uncertainty caused by classification errors, we derived a mean error rate of 14.1% from the validation procedure by taking the mean (in %) of the tree points wrongly classified as tree. Changes below this threshold are considered as uncertain.

Woody cover changes

The woody cover values for the 17 sites for both image acquisitions are found to be influenced by two factors, as tested by a linear mixed model. The type of site influences woody cover values ($P < 0.001$), independent of the year. Tukey HSD test shows that woody cover values in plains are on average 1.5% higher (least square mean) than woody cover at camp sites. Woody cover values for dune sites are in-between and not significantly different from the plains and the camps.

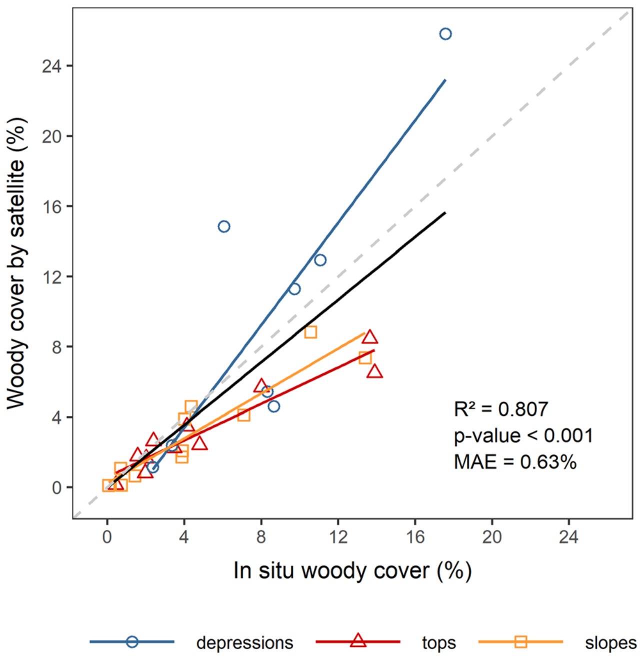

Fig. 5 Evaluation of woody cover derived from WorldView-1 using field data ($n = 30$, slope = 0.89). The black line represents the linear regression for all plots, whereas the symbols and the colored lines separate the plots according to topography

Mean woody cover slightly decreased from 1980 (3.9% cover) to 2008 (3.3% cover). The major changes occurred for plains sites, where woody cover decreased from 6.3 to 4.7% whereas for dunes and camps sites, woody cover was stable with 2.5 and 2.9% in 1980 and 2.7 and 2.6% in 2008, respectively. However, these differences between the types of site are not significant according to the linear mixed model ($P > 0.05$; Online Resource 2). The analysis of the presence or absence of tree pixels between 1980 and 2008 (Online Resource 4) reveals that for the whole area (represented by the 17 sites), 47.9% of the trees remained unchanged. This means that nearly half of the trees present in 2008 were already visible in 1980.

Species composition dynamics

We recorded 17 species in the 30 inventoried plots (sites c; see Online Resource 5 for the complete list of inventoried species). Among these, 15 are found in the plains and 9 on dunes. The most frequent ones are *Boscia senegalensis*, found in 96% of the plots, followed by *Balanites aegyptiaca* (L.) Del. and *Sclerocarya birrea* (A. Rich.) Hochst. both found in 33% of the plots. Less frequent species but still present in more than 10% of the plots are *Acacia senegal* (L.) Willd., *Acacia tortilis subsp. raddiana* (Savi) Brenan, *Calotropis procera*, *Combretum glutinosum* Perr. ex DC., *Guiera senegalensis* J. F. Gmel., and *Leptadenia pyrotechnica*. The proportion of shrubs is higher for plains (67%) than for dunes (56%).

The botanical composition has changed from 1970 to 2017. Indeed, the PCoA shows a clear separation between the records of the first two periods (1970–1971 and 1972–1986) and the records from 2015 to 2017 (Fig. 6a). The Tukey test on the first axis coordinates confirms this trend ($P < 0.001$), indicating that the communities' assemblages (i.e., species that are found together) present in 1970–1971 and in 1972–1986 are not the same as the communities in 2015–2017. Another finding concerns the currently abundant shrubs species *Boscia senegalensis*, *Calotropis procera*, and *Leptadenia pyrotechnica* (field inventory 2015–2017). Both species are located on the right side of the graph, which means that they are more related to the recent field inventory.

Among the 40 species recorded in the Flotrop database, half of them only have a few occurrences (< 5) and were therefore excluded from the following classification (See Online Resource 5 for the Flotrop species list). The trajectory of 6 species are classified as "stable," including *Balanites aegyptiaca* and *Adansonia digitata* L., 13 as "decreasing" and only one (*Acacia tortilis*) as increasing (Fig. 6b). While Fig. 6a highlighted the disappearance of some communities, this analysis illustrates a strong decrease in relative frequency of many species such as *Grewia bicolor* Juss. (− 40%), *Acacia seyal* Del. (− 47%), *Sclerocarya birrea* (− 48%), *Acacia senegal* (− 61%), *Combretum glutinosum* (− 70%), and *Commiphora africana* (A. Rich.) Engl. (− 96%).

Discussion

Our study shows several patterns regarding changes in woody vegetation in the Sahelian Ferlo over the past 50 years. First, woody plant density was higher in 1965, before the extreme Sahel droughts, which was also the case for woody cover in 1980, 3 years before the driest years of 1983–1984. This is in line with findings by Gonzalez (2001), and confirms that, over the long term, a decline in woody cover has taken place. However, a reduction from 14.8 trees ha^{-1} to 12.2 trees ha^{-1} over 50 years of extensive human expansion and severe droughts is not a dramatic figure. Besides, the exact magnitude of the change is difficult to establish, given the differences in spatial resolution of the datasets.

Second, only minor changes in woody cover not exceeding the classification uncertainty were observed over the past 4 decades. The relatively stable woody cover does on the one hand refute narratives about widespread desertification after the drought years exaggerated by increased livestock pressure. On the other hand, other studies reporting an increased woody cover at a larger scale (Anchang et al. 2019; Brandt et al. 2019) seem not to be supported at the study area scale. However, here one has to note that other studies start during or after the drought years, while our images were taken a few years before the driest years of 1983–1984. It is thus possible

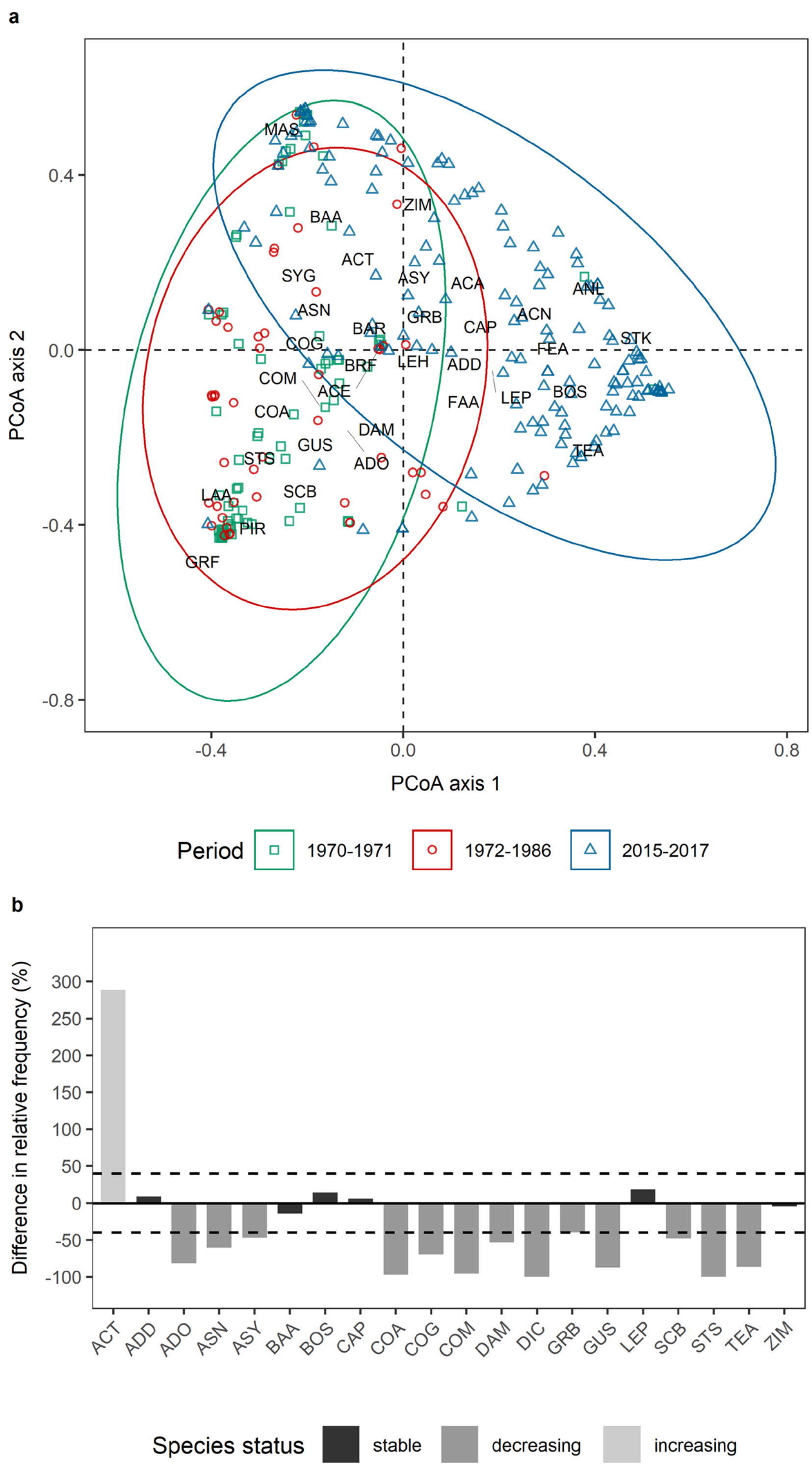

Fig. 6 Changes in species composition. **a** Principal coordinates analysis using a Bray-Curtis distance on the abundances matrix of Flotrop and field inventory (2015–2017). Ellipses show the confidence interval at 90% around the records of the three periods. **b** Changes in the relative frequency between 1970 and 2015–2017 for species with more than five occurrences in the Flotrop database. Species are displayed by a three letters acronym. ACA, *Acacia ataxacantha*; ACE, *Acacia erythrocalyx*; ACN, *Acacia nilotica*; ACT, *Acacia tortilis*; ADD, *Adansonia digitata*; ADO, *Adenium obesum*; ANL, *Anogeissus leiocarpa*; ASN, *Acacia senegal*; ASY, *Acacia seyal*; BAA, *Balanites aegyptiaca*; BAR, *Bauhinia rufescens*; BOS, *Boscia senegalensis*; BRF, *Bridelia ferruginea*; CAP, *Calotropis procera*; COA, *Combretum aculeatum*; COG, *Combretum glutinosum*; COM, *Commiphora africana*; DAM, *Dalbergia melanoxylon*; FAA, *Faidherbia albida*; FEA, *Feretia apodanthera*; GRB, *Grewia bicolor*; GRF, *Grewia flavescens*; GUS, *Guiera senegalensis*; LAA, *Lannea acida*; LEH, *Leptadenia hastata*; LEP, *Leptadenia pyrotechnica*; MAS, *Maytenus senegalensis*; PIR, *Piliostigma reticulatum*; SCB, *Sclerocarya birrea*; STK, *Stereospermum kunthianum*; STS, *Sterculia setigera*; SYG, *Syzygium guineense*; TEA, *Terminalia avicennioides*; ZIM, *Ziziphus mauritiana*

that a reduction in tree cover has taken place after 1984, which has been slowly recovering in the following decades.

This is supported by the increasing trends of density found between 2008 and 2018. Similar patterns (decrease in density and/or woody cover followed by stabilization or an increase) have been observed on sandy soils using field data from Mali (Hiernaux et al. 2009), as drought (1984)-induced woody plant mortality was followed by recruitment, though with different timing and magnitude according to the sites. Zwarts et al. (2018) also noted a decline in woody cover from 1965 to 2016 in south Mauritania and northern Senegal, but with no changes from 1965 to 1972 and a small increase from 2003 to 2016 (4.1 to 4.9%), suggesting that the decrease happened during the 1973–2002 period. The relief and the presence of camps impact the initial values of woody cover and density, with a higher density and cover in plains. The major decrease occurred in plains, though the difference with the dunes was not significant. Lykke et al. (1999) observed a similar phenomenon in Burkina Faso between 1955 and 1995, with the steepest decline of woody cover and density in valleys systems.

Third, we find a shift in the botanical composition towards more *Acacia tortilis* at the detriment of all other species. This supports a study by Brandt et al. (2014), which is based on interviews with the local population in Senegal. An increase of *Acacia tortilis* was also reported by interviewees from Burkina Faso who also perceived a decline of all other species (Lykke et al. 1999). Furthermore, species like *Sclerocarya birrea* are reported to be decreasing (Dendoncker and Vincke 2020; Miehe 2002) though it was once considered a dominant component of the woody vegetation for the center of the Ferlo, as mentioned in the vegetation classification of Tappan (1986). We also showed that shrubs species (*Boscia senegalensis*, *Calotropis procera*, and *Leptadenia pyrotechnica*) are more present in the recent inventories. This may indicate a shift in the growth form that took place during the “drought recovery.” Our findings are supported by studies from Widou Thiengoly, showing a decline of *Sclerocarya birrea*, *Combretum glutinosum*, and *Acacia senegal* and an increase of *Acacia tortilis* and *Boscia senegalensis* (Miehe 2002). As bushes provide different ecosystem services as compared to trees (e.g., carbon stocks, soil organic matter, fruits, and fodder), this shift is important to consider, in particular in the understanding of the regreening Sahel. If the greening is related with a shift towards more shrubs and less trees, the positive effects may be questioned. Distinguishing shrubs/bushes from trees is difficult using satellite and serial images, and the uses of field survey and historical records turned out to be critical in for this result.

Gonzalez et al. (2012) stated that the dominant factors of the observed vegetation changes are climatic, while acknowledging an influence of human activity on density and species richness at a more local scale. Experiments with study plots being fenced and not grazed over several decades confirmed that grazing induce a shift and a reduction in species diversity with grazing intensity (Miehe 2002). Yet, no evidence of a negative impact of livestock on woody or herbaceous vegetation cover was found by Rasmussen et al. (2018). On the contrary, one aspect of livestock impact is that it concentrates nutrients through dung decomposition around human settlements, which induces a higher productivity. Our results did not show differences in woody cover and density changes between the surroundings of camps sites and dunes or plains, supporting Rasmussen et al. (2018). Separating the causes (climatic or anthropogenic) of vegetation changes was beyond our objectives, but our results give no evidence that pastoral settlements impact on woody plant dynamics, at least not locally. Yet, we did not study the influence of camps on species composition.

The comparison of different panchromatic images from varying sensors covering five decades is challenging. Given these difficulties, the numbers reported here should be interpreted with caution. The image quality of current satellite systems is far superior to historic aerial and Corona photography. In particular, the Corona cameras were installed on satellites to gather information in times of the cold war, but never had the purpose of being accurate and being used for scientific purposes. Still these systems are a very rare image source from the very wet 1960s and provide valuable information on the times before the great drought.

Our numbers and also the trends are largely in line with Gonzalez (2001) who used aerial images from 1954, giving confidence in our results. We have chosen a visual approach based on the number of trees, as well as a digital classification approach based on the greyscale values. Both approaches include uncertainties. The manual counting and the choice of the threshold are subjective; however, a careful validation (field evaluation and classification validation) gives an estimation of the uncertainty of the approach. Moreover, the combination of a manual and automatic approach pointing both in the same direction shows that the results can be considered robust.

Conclusion

This research offers insight on long-term changes in woody vegetation (1965–2018) in the Senegalese Sahel using several indicators (density, woody cover, species composition, and species frequencies). They were derived from field records combined with satellite imagery, to acquire complementary information on ecosystem dynamics. Indeed, geotagged field data combined with a database such as Flotrop and historic Earth observations datasets (Corona images, aerial photos) proved to be very relevant for this topic. We therefore encourage future studies to further combine inter-disciplinary topics using field and satellite data (Herrmann et al. 2020; Herrmann et al. 2014; Mbow et al. 2015). Our results document a reduction in woody plant density from before to after the great droughts (1970s–1980s), with a slight recovery in recent years. While the decreasing trends of woody vegetation density and cover observed from 1965 to 2008 have stopped during the last decade (2008–2018), current communities are of different types than before the drought in terms of species composition and growth form. Indeed, the current trees-shrubs ratio tends towards more shrubs. Among the trees, we may be witnessing a shift towards drought-resistant species (*Acacia tortilis*) with a better ability to regenerate (*Balanites aegyptiaca*). Our results reflect the current trends reported at a global scale for savanna biomes with drought-induced vegetation diebacks, a more arid climate in drylands and losses in biodiversity towards drought-resistant shrub species (Berdugo et al. 2020; Sankaran 2019). These changes in structure and composition of savanna vegetation may bring major modification on ecosystem functioning and ecosystem services provided by savanna biomes (Osborne et al. 2018; Sankaran 2019).

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Author contributions MD, MB, RF and CV designed the study. MD conducted the analyses with support by MB and ST. MD collected the field data. JCT provided the VHR images. MD wrote the manuscript with contributions by all authors.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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