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An innovative approach to disentangling the effect of management and environment on tree cover and density of protected areas in African savanna

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ABSTRACT

In protected areas of the African savanna tree cover, structure and species composition are influenced by a combination of many different variables. These include complex and multi-scaled interplay of environmental factors such as water and nutrient availability, fire, herbivory and, when occurring, direct human disturbance. In this study, we conducted a comprehensive and comparative analysis of the spatial variability of tree cover and density in three neighboring Southern African National Parks (Kruger, Limpopo, and Gonarezhou) characterized by similar environmental conditions but different management plans. We sampled 3382 plots of 0.5 ha across the three parks using an innovative methodology defined as augmented visual interpretation, based on a free and open source software. This software, named Collect Earth, allows access to very high spatial and temporal resolution imagery archives. Spatial variability of tree cover and density was analyzed comparing the three parks and the two bioclimatic regions (semiarid and dry subhumid) characterizing them. The effect of relevant environmental variables such as edaphic factors, precipitation and fire frequency was also assessed. Kruger National Park is characterized by the lowest values of tree cover and density among the three Parks. Contrary to what was expected and the general trend of Southern Africa, the dry subhumid zone showed lower values of tree cover and density than the semiarid zone. Such variability is hypothesized to be related to the different managements of the three parks within the general environmental template characterizing the African savanna as well as differences in tree species composition between the two climatic zones.

1. Introduction

In protected areas of the African savanna the cover, structure and composition of woody vegetation are affected by the complex and multi-scale interplay of environmental factors such as water and nutrient availability, fire, herbivory and, when occurring, direct fuel wood harvesting by people (Van Langevelde et al., 2003; Holdo, 2007; Sankaran et al., 2008; Shannon et al., 2011; Vanak et al., 2012; Buitenwerf et al., 2012; Holdo et al., 2013). At regional and landscape scales, water availability, mainly related to rainfall regime, is considered the primary resource driver (Kerkhoff et al., 2004; Sankaran et al., 2005) defining the maximum potential tree cover (Coughenour and Ellis, 1993; Sankaran et al., 2005). As for soil nutrients (i.e. nitrogen), they are more limiting to grasses than to trees: a high soil nitrogen content promotes the growth of herbaceous species rather than tree seedlings, which in turn have negative effects on the establishment of the latter (Kraaij and Ward, 2006). Within this environmental template, the synergistic effect of fire regime and density of mega-herbivores (mainly elephants, *Loxodonta africana*) can have a significant impact on woody cover and structural diversity (Van Langevelde et al., 2003; Holdo et al., 2009; Asner and Levick, 2012; Levick and Asner, 2013). Natural and prescribed fires have a prominent role in maintaining the equilibrium between grasslands and woodlands in savanna ecosystems by reducing woody vegetation cover and density (Govender et al., 2006), especially in areas with higher precipitation rates (Devine et al., 2015). Similarly, the presence of herbivores generally leads to a reduction in woody cover due to browsing, grazing (Staver et al., 2009; Staver et al., 2011) and physical damage (Asner and Levick, 2012).

Despite the evolution of traits to resist or tolerate these disturbances, such as re-sprouting ability, storage in below ground organs,

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and fast height and diameter growth rates (Higgins et al., 2000; Midgley et al., 2010), fire (especially high intensity fires – Smit et al., 2016) and elephants are a lethal combination for woody plant limiting recruitment and transition processes (Levick et al., 2009; Midgley et al., 2010; Shannon et al., 2011). This effect is particularly evident in certain protected areas where the increasing density of elephant populations is causing a significant decline of large trees (Asner and Levick, 2012; Levick and Asner, 2013; O'Connor and Page, 2014). Given the range of ecosystem services that woody vegetation provides (e.g., soil protection, food for large herbivores, carbon sequestration) and the cascade effect that its change exerts on several important features of savanna ecosystems such as nutrient patterns (Ludwig et al., 2004; Treydte et al., 2007), habitat suitability (Cumming et al., 1997; Parr and Andersen, 2006), herbaceous biomass and fire (Smit and Prins, 2015), parks managers need to be supported by monitoring tools in order to allow for rapid and comprehensive woody vegetation assessments. In this context, remote sensing has been recognized as a fundamental tool for ecologists and a primary source of data for managers and policy makers. However, the application of conventional analysis techniques (e.g. semi-automated image classification) has proven to be challenging, especially in combination with very high resolution (VHR) satellite imagery, due to its high costs, low spatial extent and lack of global coverage (Bey et al., 2016). In this study, we used an innovative methodology (augmented visual interpretation) based on a free and open source software, Collect Earth, developed by the Food and Agriculture Organization of the United Nations (FAO). Such technology allows to perform land cover assessments through visual interpretation of freely accessible VHR satellite imagery archives (Bey et al., 2016).

The analysis was carried out in three national parks (NPs), which are part of the Great Limpopo Transfrontier Conservation Area: Kruger National Park (South Africa), Limpopo National Park (Mozambique) and Gonarezhou National Park (Zimbabwe), characterized by similar environmental conditions but different management capacities. Indeed, while Kruger NP is characterized by highly developed infrastructures and established wildlife and fire management regimes, Limpopo NP has none and Gonarezhou NP represents an intermediate situation. The aims of the study are: (1) to assess the spatial distribution of woody vegetation cover and density in the three parks by applying a novel methodology and (2) to estimate the relative influence of environmental drivers (i.e. precipitation and edaphic variables) and disturbance factors (i.e. fire frequency) on woody vegetation in the context of different management capacities. Data collected represent a baseline that can be used to assess future changes and the outcomes of the implementation of management strategies focused on fire, wildlife, climate change, and in the case of the Limpopo NP and Gonarezhou NP, respectively on old and newly established settlements.

2. Material and methods

2.1. Study area

2.1.1. Gonarezhou National Park

Gonarezhou NP (Zimbabwe) was established in 1975 in the southeast of the country alongside the border with Mozambique, stretching between the Mwenezi and Save Rivers. It comprises a roughly rectangular strip of land of about 35 to 45 km wide and 135 km long, with an area of about 500 000 ha. Altitude ranges from 160 m asl at the Save-Runde junction to a maximum of 578 m asl on the Chiwonja hills. Mean annual rainfall over a 29-year period (from 1961 to 1990) was 515 mm. Morphologically, the Gonarezhou NP forms part of the Limpopo-Save Lowlands of Zimbabwe, extending across the southernmost part of the country in the form of a relatively flat plain that rises gently to the north from the Limpopo River. Vegetation is characterized by Miombo and Mopane vegetation types. The former is dominated by *Brachystegia tamarindoides* subsp. *torrei*, *Combretum celastroides* subsp. *celastroides*, *Combretum collinum* subsp. *collinum*, *Guibourtia conjugata* and *Julbernardia globiflora*. The mopane vegetation type is dominated by *Colophospermum mopane* and *Combretum apiculatum* (Martini et al., 2016).

2.1.2. Limpopo National Park

Limpopo NP (Mozambique) was proclaimed in 2002 and covers an area of 1 000 000 ha. The Kruger National Park in South Africa neighbors the Limpopo NP to the west, the Limpopo River forms the northern and eastern border, whereas the Olifants River (called Rio dos Elefantes in Portuguese) forms the southern boundary. Elevation ranges from 521 m asl in the north down to 45 m asl at the confluence of the Limpopo and Olifants rivers. Rainfall decreases from 500 mm near the Massingir Dam in the south to < 450 mm at Pafuri in the north. The dominant geological feature of the Limpopo NP is the extensive sandy cover along the northwest/southeast spine of the park. Calcareous sedimentary rocks have been exposed where this sand mantle has been eroded closer to the main drainage lines. Alluvial deposits are found along the main drainage lines (Limpopo, Olifants and Shingwedzi). Vegetation is characterized by Mopane woodlands dominated by *Colophospermum mopane*, *Combretum apiculatum* and *Terminalia sericea*, and other more localized types such as *Acacia tortilis* and *Acacia xanthophloea* forests along the Limpopo River, *Terminalia prunioides* thickets on shallow, stony soils and fragmented stands with *Androstachys johnsonii* on steep calcrete slopes (Stalmans et al., 2004).

2.1.3. Kruger National Park

Kruger NP (South Africa) covers almost 2 000 000 ha. The altitude ranges from 200 m in the east to 840 m asl in the south-west. There is a marked increase in mean annual precipitation from the north to the south of the park ranging from about 440 mm in the north to about 740 mm in the south (Venter and Gertenbach, 1986). The park is geologically divided into two main parts; granites and their erosion products to the west and basalts and their erosion products to the east. The vegetation in Kruger NP can be divided into 35 vegetation types, with the woody component largely dominated by *Colophospermum mopane* (in the north of the park), *Combretum apiculatum, Acacia nigrescens, Acacia tortilis, Terminalia sericea* and *Sclerocarya birrea* (Gertenbach, 1983).

2.2. Data set

In February 2016, 3382 plots of 0.5 ha were sampled using the augmented visual interpretation approach introduced above and described in detail in the following paragraphs. The plots were homogeneously distributed on a 3 km square-cell regular grid laid over the entire area of each NP, thus the number of plots sampled for each NP is proportional to its area (Kruger = 1875, Limpopo = 1031, Gonarezhou = 476). The plot size of 0.5 ha was chosen to be consistent with the FAO-FRA definition of forest, which has a tree cover ≥10% spanning an area of more than 0.5 ha that is not predominantly used for agriculture or urban activity, as well as areas in which tree cover is temporarily < 10% but is expected to recover (FAO, 2001).

The assessment was conducted using Open Foris Collect Earth, a new tool developed by FAO and based on recent developments in cloud computing systems, such as Google Earth Engine and the increasing availability of VHR satellite imagery. This innovative application was used for a global assessment of dryland forests (Bastin et al., 2017) and allows the assessment of land cover through visual interpretation of remote sensing imagery from DigitalGlobe libraries, accessed through Google Earth and Microsoft Bing Maps. The present study is based on interpretation of satellite imagery available at the time of the assessment (between February and March 2016) with a spatial resolution from ≤1 m (VHR; ~96% of plots) to ≤10 m (high resolution, e.g. SPOT, RapidEye and Sentinel 2; ~4% of plots) and to > 0–100 m (medium resolution, e.g. Landsat; < 1% of plots), coupled with the analysis of the Normalized Difference Vegetation Index (NDVI)

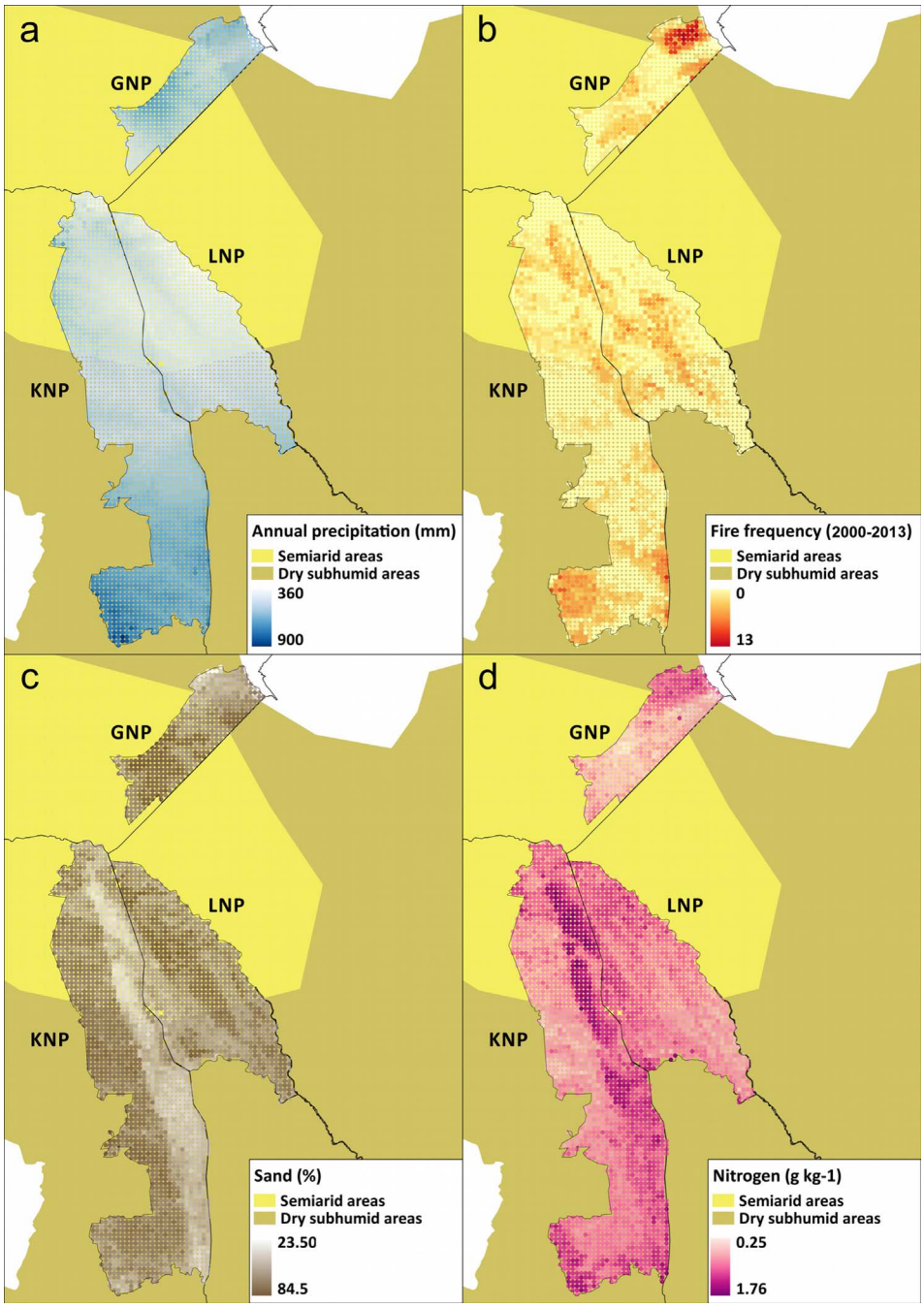

Fig. 1. Distribution of annual precipitation (a), fire frequency (b), percentage of sand in soils (c) and soil nitrogen content (d) in the 3382 plots across the three parks (Gonarezhou – GNP; Limpopo – LNP and Kruger – KNP) and the two bioclimatic zones.

computed using Landsat 8 data (Bey et al., 2016). The acquisition date of the satellite images spans from 2003 to 2016, although most of them (84%) were acquired in 2013 or later. This method is particularly suited for woody cover assessments in drylands where estimates based on low-to-high resolution satellite imagery are biased by the sparse tree density of open landscapes, the dominance of solar radiation reflected from bare soil and grassland, and the darkening effect of crown shadows (Ringrose et al., 1989; Lambin, 1999).

The survey consisted of the visual estimation of land cover elements within the plots. The biggest challenge was the distinction between multi-stemmed trees and shrubs, which was based on local knowledge of vegetation crown size and shape, evaluating crown shadows to account for vegetation height and using available georeferenced ground-based photography. Trees were restricted to vegetation with a crown spread ≥3 m when shadows or ground photographs were not available to augment visual interpretation (FAO, 2016). In order to assist in the visual interpretation, 49 2 m × 2 m sampling points were placed on 0.5 ha grid within each plot and were used to assess element cover, which was calculated by counting the number of sampling points that touched a certain element. The sampled data consisted of 14 classes of minimum percentage cover (0, 2, 4, 6, 8, 10, 20, 30, 40, 50, 60, 70, 80 and 90%) and 6 classes of minimum tree count (0, 1, 5, 10, 20, and 30 or more elements). The upper limit of 30 trees was defined as the maximum number of trees that could be clearly distinguished within each 0.5 ha plot at the available imagery spatial resolution.

Data quality was controlled through a semi-automated cleaning procedure (Bastin et al., 2017) which highlighted potential inconsistencies (e.g. presence of tree cover with no trees recorded, high tree

cover with low tree count) to be manually reassessed. The identification of inconsistencies was based on the particular structure of the survey created for the assessment: many fields of the data insertion mask were mutually related (e.g. tree cover and tree count), in order to make possible errors more evident through the creation of incompatibilities easy to isolate through an automated routine.

Besides quality control, validation should entail a ground-truth assessment of land and tree cover. This was the case of the global dryland assessment, where a subsample of plots was surveyed in the field to evaluate the performance of the augmented visual interpretation technique: the root-mean-square difference of tree cover between the interpreted and the ground-controlled plot was 8.32% (Bastin et al., 2017). In the present study, whose aim is mainly to test the effectiveness of the novel methodology based on Collect Earth in providing data for the management of woody vegetation, an indirect validation approach was taken, by comparing the visual assessment of tree cover with Normalized Difference Vegetation Index (NDVI) values as a proxy for aboveground biomass (Brüser et al., 2014, Meroni et al., 2014). We calculated the NDVI based on LANDSAT 8 OLI (https://landsat.usgs.gov/landsat-8) 2013 Annual Greenest Pixel top-of-atmosphere reflectance composites. We used Greenest Pixel (created from all the images throughout the year, with the greenest pixel as the composite value) to avoid bias caused by shifts in seasonality between different vegetation types and taking into account the peak of productivity. We then executed a multiple regression analysis, using *lm* and *anova* functions from *stats* package in R (R Core Team, 2016), between mean plot NDVI values and interpreted woody vegetation percentage cover for all the plots assessed, expecting higher NDVI values for higher cover. For this analysis, we excluded croplands, wetlands and settlements (approx. 60 total plots), for which NDVI values could easily be biased (Broge and Leblanc, 2001).

2.3. Statistical analyses

One of the aims of the present study was to estimate the relative influence of environmental drivers and disturbance factors on woody vegetation in the context of different management capacities. To do so, we selected those environmental variables that have proved to exert a significant influence on plant growth in savanna ecosystems (Sankaran et al., 2005, 2008; Fig. 1a–d). We considered: (1) annual precipitation as a measure of water availability, which is known to be the primary determinant of woody cover (Walter, 1971; Walker and Noy-Meir, 1982). The data was derived from the World Clim data set (Hijmans et al., 2005); (2) Fire frequency, being fire one of the main factors affecting structure, cover and species composition of savanna ecosystems (Bond et al., 2003; Higgins et al., 2012). We used a fire count map for the period 2000–2013 based on MODIS MCD64 burnt area product (Giglio et al., 2009); (3) Soil parameters such as percentage of sand as a measure of soil texture, as well as the nitrogen content of soils at a depth of 20 cm obtained from the AfSIS Africa Soil Map at spatial resolution of 250 m (Hengl et al., 2015).

Furthermore, we took into account the division of the parks into different dryland zones as defined by an aridity index used by the United Nations Environment Programme (1992) in the elaboration of the World Atlas of Desertification. The aridity index is a measure of the ratio between average annual precipitation and total annual potential evapotranspiration. Our study area was divided into semiarid (0.20–0.50 aridity index) and dry subhumid (0.50–0.65 aridity index) zones. The plot grids were then superimposed on the environmental variables maps and the relevant information extrapolated using QGIS version 2.14 – (QGIS Development Team, 2016). Nitrogen was strongly negatively correlated with sand percentage ($R = -0.75$, $p < 0.001$) and thus excluded from the analyses. Tree cover and density, recorded according to interval classes, were then modeled conditionally on two factors (park, dryland zone) and three environmental and disturbance variables (annual precipitation, fire frequency and percentage of sand) (Table 1). The 'park' factor was considered as a proxy to the different management activities carried out in the three parks, which affect large mammals populations and fires distribution, hence woody vegetation.

Table 1
Description of predictor and response variables used in the ordered logistic regression models. Tree cover and density are analyzed against two factors (park and dryland zone) and three environmental variables). GNP: Gonarzhou National Park; KNP: Kruger National Park; LNP: Limpopo National Park; DS: dry subhumid; SA: semiarid.

Variable	Type	Range/Levels	Source
Response			
Tree cover (%)	Ordinal	0–100 (14 classes)	Assessed through visual interpretation
Tree cover (number of trees)	Ordinal	0–30 + (6 classes)	Assessed through visual interpretation
Predictors			
Park	Factor	KNP, LNP, GNP	IUCN, UNEP-WCMC (2017)
Dryland zone	Factor	DS, SA	UNEP (1992)
Annual Precipitation (mm)	Continuous	365–888 mm	Hijmans et al. (2005)
Fire frequency (number of fires)	Integer	0–13	Giglio et al. (2009)
Sand percentage (%)	Continuous	23.5–84.5	Hengl et al. (2015)

Due to the ordinal nature of our response variables (tree cover and density categories) we performed ordered logistic regression models using *MASS* (Venables and Ripley, 2002) and *car* (Fox and Weisberg, 2011) packages running in *R* (R Core Team, 2016). Environmental variables were standardized prior to modeling, in order to compare regression coefficients and assess the relative importance of the environmental factors. We also checked for significant interactions between the park and dryland zone factors in the models and constructed separate regressions when needed. We calculated McFadden's pseudo R^2 as a measure of goodness of fit for the logistic models. Finally, Post-hoc pairwise Bonferroni-adjusted Wilcoxon Rank Sum tests were carried out when appropriate.

3. Results

Our assessment of tree cover and density via visual interpretation of VHR satellite images highlighted fundamental differences in their spatial distribution among the three parks and in the two climatic zones within each park (Fig. 2a and b). Kruger NP seems to exhibit the lowest overall tree cover, especially in the most southern area in the dry subhumid zone. A similar trend is shown within Gonarezhou NP, despite a generally higher cover, while Limpopo NP presents intermediate tree cover values, with a less clear distinction between the two climatic zones. Tree density (Fig. 2b) follows the same pattern of tree cover as for its spatial distribution, with a major exception in Kruger NP, where density, unlike cover, appears to be very similar to Gonarezhou NP's and Limpopo NP's. However, this could be a mere sampling artifact due to saturation of the tree count, for which an upper threshold of 30 trees was defined.

When examining the aggregated values per park, tree cover is higher for Gonarezhou NP and Limpopo NP than Kruger NP; 57% and 43% of plots in Gonarezhou NP and Limpopo NP, respectively, were above 60% tree cover as compared to only 8% of plots in Kruger NP (Fig. 3). On the other hand, 35% of plots in Kruger NP were characterized by intermediate tree cover values between 20 and 60%, and 19% showed no tree cover. Less than 10% of the plots in Gonarezhou NP and Limpopo NP were unforested. More than 57 000 trees were recorded in the survey, giving an average density of about 34 trees per hectare, or 17 trees per plot. When examining tree densities, Kruger NP shows the lowest tree density among the parks, with about 30 trees per hectare (15 trees per plot). Limpopo NP had higher tree density than Kruger NP, with nearly 40 trees per hectare and 20 trees per plot, and Gonarezhou NP shows the highest density of all, with 42 trees per

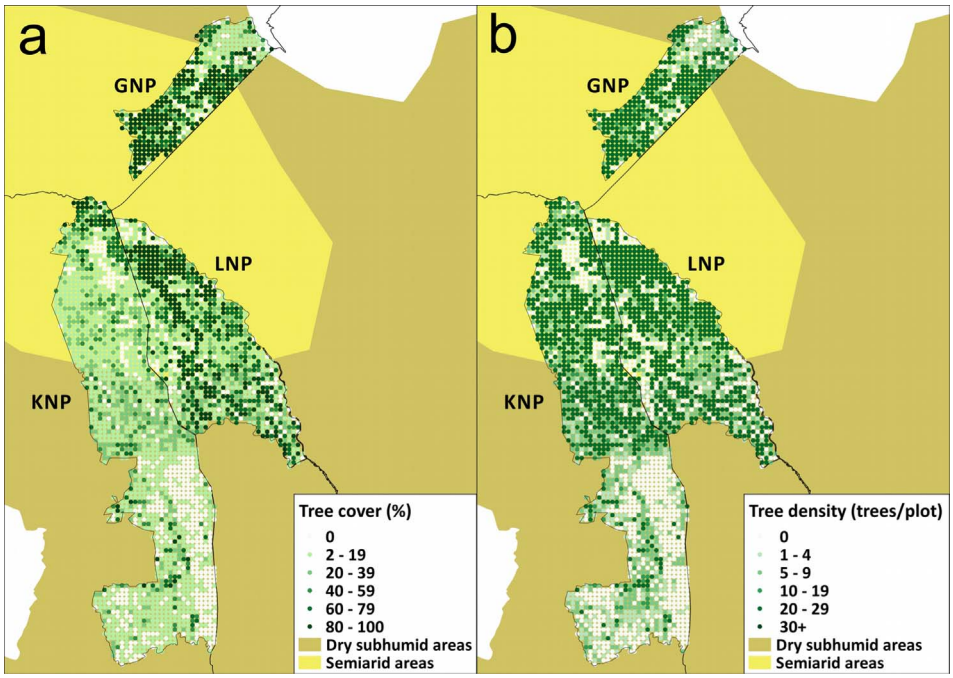

Fig. 2. Tree cover (a) and tree density (b) in the 3382 plots across the tree parks (Gonarezhou - GNP, Limpopo - LNP and Kruger - KNP) and the two bioclimatic zones (semiarid and dry subhumid).

hectare and nearly 21 trees per plot. Based on these figures we estimated about 58 million trees for Kruger NP, 39 million trees for Limpopo NP, and 21 million trees for Gonarezhou NP, giving a total estimation of 118 million trees for the three parks combined. Notably, being Kruger NP the largest among the parks, it has the highest tree number estimate despite presenting the lowest mean tree density. In terms of tree density classes Gonarezhou NP and Limpopo NP are quite similar, with 56% and 55% of plots with 30 or more trees, respectively. In Kruger NP the percentage of plots belonging to the same density class is 32% (Fig. 3).

The semiarid zone is characterized by higher values of tree cover and density than the dry subhumid zone, with the exception of tree cover in Limpopo NP for which no difference was highlighted (Table 2, Fig. 2a and b). Among the parks, Kruger NP has significantly less tree cover and density than the others. Conversely, Gonarezhou NP has higher values in the semiarid zone than Limpopo NP, and the opposite for the dry subhumid zone (Table 2).

When comparing Fig. 1 to Fig. 2 it is possible to infer the relationships between environmental variables, fire and woody vegetation cover across all sites, as revealed by the results of the logistic regression models (Tables 3–5). As for soil variables trees seem to follow a coherent pattern in all the three parks and dryland zones, with sandy (hence nitrogen-poor) soils corresponding to generally higher cover and density values (Coeff 0.45/0.48; $p < 0.001$). On the other hand, the relationship between woody vegetation, mean annual precipitation and fire frequency is more complex. For instance, despite in the southern part of Kruger NP precipitations are higher than anywhere else in the study area, tree cover shows values that are among the lowest, while high precipitations in Gonarezhou NP seem to positively affect cover and density. Indeed, the general model highlighted differences in tree cover and density among the three parks and between the two bioclimatic zones as for the response to environmental variables (Table 3). The interaction term park × dryland zone was also found significant, meaning that at least one environmental factors has different effects in different parks and in the two bioclimatic zones within each park. Indeed, annual precipitation has a significant negative effect only in the dry subhumid zone (Table 5). As far as fire frequency is concerned, a strong relationship can be observed between the high number of fires in the northern part of Gonarezhou NP and the low tree cover values in the same area. A similar pattern can be detected in Limpopo NP and in the

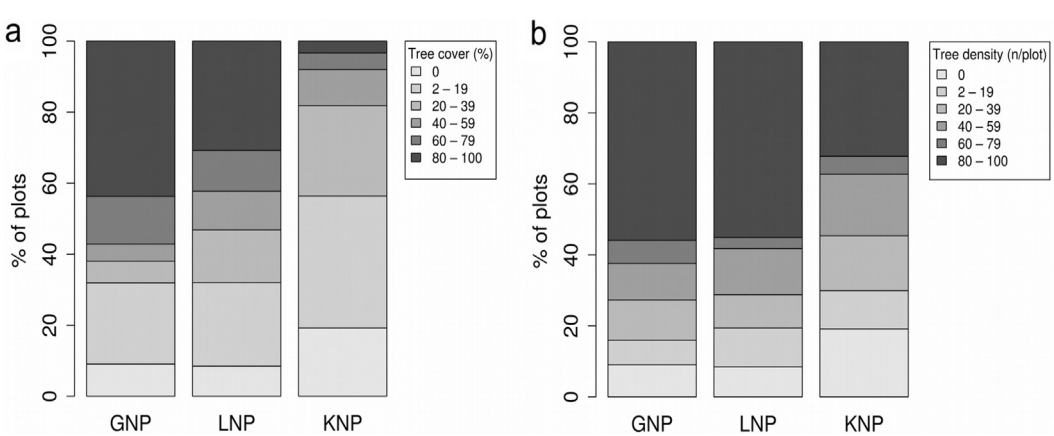

Fig. 3. Percentage of plots assessed in each of the three National Parks included in the study area, classified according to tree cover (a) and tree density (b) intervals. GNP: Gonarzhou National Park; KNP: Kruger National Park; LNP: Limpopo National Park.

Table 2
Mean and standard deviation of tree vegetation cover and density in the two dryland zones (Semiarid – SA; Dry subhumid – DS) of Gonarezhou National Park (GNP), Limpopo National Park (LNP) and Kruger National Park (KNP). The significance (Sig) of the Wilcoxon rank sum test is reported. The results of the pair-wise tests are indicated by the superscripts: k: different from KNP; l: different from LNP; g: different from GNP. Significance codes: (*) $p < 0.05$, (**) $p < 0.01$; (***) $p < 0.001$; Ns: Not significant.

	Tree cover (%)			Tree density (trees/plot)		
	SA	DS	Sig.	SA	DS	Sig.
KNP	$26.2^{g,l}$ (± 23.7)	$15.9^{g,l}$ (± 19.0)	***	19.8^{g} (± 12.4)	$10.1^{g,l}$ (± 11.1)	***
LNP	$46.4^{k,g}$ (± 35.0)	$41.8^{k,g}$ (± 34.2)	*	20.3 (± 12.5)	16.8^{k} (± 12.8)	***
GNP	$62.3^{k,l}$ (± 35.1)	$31.8^{k,l}$ (± 33.1)	***	22.3^{k} (± 11.4)	13.6^{k} (± 12.4)	***

Table 3
Anova table of the ordered logistic regression model for tree cover and density. KNP: Kruger National Park; LNP: Limpopo National Park; SA: Semiarid. Significance codes: (*) $p < 0.05$, (**) $p < 0.01$; (***) $p < 0.001$; Ns: Not significant.

	Coeff	Tree cover (pseudo $R^2 = 0.07$)				Coeff	Tree density (pseudo $R^2 = 0.09$)			
		LR Chisq	Df	Pr(> Chisq)	Sig.		LR Chisq	Df	Pr(> Chisq)	Sig.
Park (KNP)	−1.80	349.08	2	< 2.2e−16	***	−1.20	67.52	2	2.18e−15	***
Park (LNP)	−0.72					−0.95				
Dryland (SA)	0.69	42.67	1	6.49e−11	***	0.42	49.26	1	2.24e−12	***
Fire frequency	−0.45	164.95	1	< 2.2e−16	***	−0.35	87.42	1	< 2.2e−16	***
Annual Prec.	−0.27	32.50	1	1.20e−08	***	−0.51	97.82	1	< 2.2e−16	***
Sand%	0.47	213.70	1	< 2.2e−16	***	0.50	224.18	1	< 2.2e−16	***
Park (KNP)* Dryland (SA)	−0.03	16.35	2	2.82e−04	***	0.56	29.70	2	3.55e−07	***
Park (LNP)* Dryland (SA)	−0.61					−0.23				

Table 4
Ordered logistic regression model coefficients, standard errors and P values for tree cover and density in the semiarid zone. KNP: Kruger National Park; LNP: Limpopo National Park. Significance codes: (*) $p < 0.05$, (**) $p < 0.01$; (***) $p < 0.001$; Ns: Not significant.

		Tree cover (pseudo $R^2 = 0.05$)				Tree density (pseudo $R^2 = 0.04$)			
		Coeff	Std. Error	LR Chisq	Pr(> Chisq)	Coeff	Std. Error	LR Chisq	Pr(> Chisq)
Park	KNP	−1.57	0.16	116.64	***	−0.13	0.17	5.29	Ns
	LNP	−0.98	0.21			−0.20	0.22		
Fire frequency		−0.59	0.06	110.42	***	−0.43	0.06	48.66	***
Annual Prec.		−0.09	0.11	0.74	Ns	−0.08	0.12	0.44	Ns
Sand%		0.45	0.05	68.16	***	0.55	0.06	81.18	***

Table 5
Ordered logistic regression model coefficients, standard errors and P values for tree cover and density in the dry subhumid zone. KNP: Kruger National Park; LNP: Limpopo National Park. Significance codes: (*) $p < 0.05$, (**) $p < 0.01$; (***) $p < 0.001$; Ns: Not significant.

		Tree cover (pseudo $R^2 = 0.06$)				Tree density (pseudo $R^2 = 0.08$)			
		Coeff	Std. Error	LR Chisq	Pr(> Chisq)	Coeff	Std. Error	LR Chisq	Pr(> Chisq)
Park	KNP	−1.65	0.19	122.41	***	−1.06	0.19	32.26	***
	LNP	−0.55	0.20			−0.93	0.20		
Fire frequency		−0.36	0.05	65.48	***	−0.29	0.05	40.65	***
Annual Prec.		−0.38	0.06	46.00	***	−0.69	0.06	138.84	***
Sand%		0.48	0.04	127.15	***	0.48	0.04	119.28	***

southern part of Kruger NP (Figs. 1 and 2). This was confirmed both by the general and the dryland zone specific models (Coeffs −0.35/−0.59; $p < 0.001$).

As for data quality control, the regression model between mean plot NDVI values and woody vegetation cover lead to an Adjusted R^2 of 0.291. This low value can be explained by the variability in the contribution of different vegetation elements (e.g. seasonal grasses, trees, shrubs) to the NDVI. Despite this, the fit showed high significance ($P < 0.001$), thus confirming the relationship between NDVI and estimated tree cover and density, as well as the quality of the data obtained from the augmented visual interpretation.

4. Discussion

Trees in African savannas generate a wealth of environmental services including habitats for biodiversity, protection against water and wind erosion and desertification, amelioration of water infiltration in the soils, and contribution to soil fertility. Complex interactions between biotic and abiotic, and static and dynamic factors, including precipitation, soil, fire, and herbivory (particularly by elephants) determines the cover, structure and species composition of woody cover (Scholes and Archer, 1997). Large scale, high resolution remote sensing techniques have been advocated as useful tools to monitor spatial and temporal changes. Recently, airborne LiDAR (Light Detection And

Ranging) has been extensively used to this purpose, highlighting the predominant role of elephants in shaping woody vegetation structure in both Kruger (Asner and Levick, 2012; Asner et al., 2016) and Serengeti (Morrison et al., 2016) protected areas, and the importance of different management practices on the savanna woody vegetation structure (Wessels et al., 2011; Fisher et al., 2014). Our approach is in line with such studies; using the Collect Earth tool which allows the visual interpretation of freely available VHR satellite images, we performed a comprehensive and comparative assessment of the tree cover and density of three Southern African national parks, providing new insights on the spatial variation of such parameters and the first estimation of the number of trees in the National Parks of the Limpopo basin.

According to our findings, Kruger NP is characterized by the lowest values of tree cover and density (Fig. 3, Table 2). Several factors might have contributed to that: after the end of culling activities in 1994 the elephant population increased exponentially up to about 16 000 animals in 2012 (Source data: Scientific Services, South African National Parks – 2012 census), and this is having a significant effect on tree cover and density (Asner and Levick, 2012), with an estimated mean biennial treefall rate of 8 trees or 12% per hectare (Asner et al., 2016). However, Gonarezhou NP has higher overall values of tree cover than the other parks (Fig. 3, Table 2) despite an estimated elephant density (9100 animals, 1.84 per $km^{2;}$ (Dunham et al., 2010) which is more than twofold that of Kruger NP (16 000 animals, 0.85 per km^2) and ten times the estimated elephant density in Limpopo NP (about 1500 individuals, 0.13 per km^2) (Source data: Parque Nacional do Limpopo, Aerial Wildilife Census, 2010). This suggests that the presence of elephants alone is not the main driver of reduction of woody vegetation cover in African savannas, but rather one of the multiple disturbance factors (i.e. herbivory, fires) whose mutual interactions affect the presence and the spatial distribution of trees. Furthermore, significant differences exist between the two bioclimatic zones, with greater values of tree cover and density for the three parks in the semiarid zone and the opposite for the dry subhumid (Table 2). This result was rather unexpected considering the general trend for semiarid and dry subhumid zones (FAO, 2016), as well as the wide evidence of the decline of tree species such as *Brachystegia tamarindoides* and *Acacia tortilis,* and tree cover due to the effect of elephants, fire and drought, especially in Gonarezhou NP (Tafangenyasha, 1997, 2001; Gandiwa and Kativu, 2009; Gandiwa et al., 2011; Zisadza-Gandiwa et al., 2013).

This result can be again explained by the converging effect of environment and different management strategies as for wildlife and fires among the parks, as well as the presence of human population in Gonarezhou NP and Limpopo NP. Although there is no difference in mean values of fire frequency in Kruger NP (semiarid = 2, dry subhumid = 2.1, $p = 0.69$), the occurrence of high intensity fires is significantly higher in the dry subhumid zone (Attorre et al., 2015). This is the key parameter that can contribute, together with the overriding impact of elephants, to the reduction of tree cover and density (Smit et al., 2010; Asner et al., 2016). Unfortunately, in our comparative analysis temporal and spatial data on fire intensity was available only for the Kruger NP, even though new developments in remote sensing technology could allow their inclusion in future studies (De Santis et al., 2010). Another potential explanation may be due to the differences in woody vegetation composition between the semi-arid zone (dominated by mopane trees) compared to *Combretum* and *Acacia* dominated landscapes of the dry subhumid zone (Venter and Gertenbach, 1986).

In Limpopo NP no difference emerged in mean fire frequency between the two bioclimatic zones (semiarid = 1.7, dry subhumid = 1.9, $p = 0.07$), but the dry subhumid zone is characterized by the presence of settlements, that are often located closer to the main rivers and, despite an ongoing translocation process, a few villages are still present. The lower densities of trees may therefore be attributed to two factors: the effect of heavier, less sandy soils, and the legacy of the past, when direct disturbances due to fuel wood harvesting and clearing for rain fed agriculture exerted their effects on woody vegetation (Stalmans et al., 2004).

In Gonarezhou NP, the dry subhumid zone is characterized by a high fire frequency and is highly impacted by recently established settlements and croplands (Dunham et al., 2010). These impacts are significantly transforming the area with the conversion of woodland vegetation into shrubland (Zisadza-Gandiwa et al., 2013) and with the majority of trees being multi-stemmed, a situation normally resulting from a vigorous re-sprouting in response to disturbances such as herbivory and frequent fires (Bond and Keeley, 2005).

When considering the general model (Table 3) and the partial models for the two bioclimatic zones (Tables 4 and 5), it appears that the variability of both tree cover and density is well explained by the environmental parameters considered as indicated by the values of pseudo R^2. Indeed, according to McFadden (1978), a pseudo R^2 around 0.1, as those obtained with our analyses, corresponds to an R^2 of about 0.5/0.6). This means that, besides the differences previously discussed among the three parks and between the two bioclimatic zones, all the environmental parameters are having a significant effect on tree cover and density. The only exception is represented by the annual precipitation in the semiarid zone, where rainfall is evenly scarce and woody vegetation is mainly affected by the other factors. Fire frequency has a negative effect as does the annual precipitation in the dry subhumid zone. The former result was expected (Levick et al., 2009), while the latter has been already explained considering that a higher precipitation can promote fires of higher intensity due to the greater amount and greater continuity of forest fuels, as in Kruger NP (Attorre et al., 2015), or support human activities as in Limpopo NP and Gonarezhou NP.

Sand percentage, which is negatively correlated with the nitrogen content of the soil, has a positive effect on both tree cover and density (Tables 3–5). This result confirms the findings of previous studies on the determinants of woody cover in the African savannas (Sankaran et al., 2008); sandier soils tend to be characterized by lower nutrient availability and facilitate water percolation, characteristics that promote a higher woody cover by reducing the competition from the herbaceous layer (Scholes and Walker, 1993; Walker and Langridge, 1997; Sankaran et al., 2008).

A better fit of the model would have probably been achieved by including as an explanatory variable an elephant density map, following Asner et al. (2016) in their analysis of several areas within the Kruger NP. Unfortunately, point-based elephant census records to use for interpolation are available only for this park, thus preventing any comparative analyses.

In conclusion, Collect Earth proved to be a useful tool to conduct comprehensive and comparative assessment and analysis of the spatial variability of tree cover and density in protected areas of African savanna. In this way, we were able to evaluate the differences in tree cover and density among the three national parks and to assess the influence of environmental and disturbance factors on woody vegetation. However, a true disentanglement of the effect of different environmental and disturbance factors in shaping the woody vegetation of African savanna is far from being achieved, mainly because of the lack of extensive georeferenced animal population and fire intensity data, which reflect the effects of park management initiatives. Indeed, despite some challenges in the estimation of tree cover and density through visual assessment (e.g. distinction between trees and shrubs, saturation of tree count) the main limit to our analysis was the unavailability of such information. Nevertheless, this study still provides a fundamental background for evaluating the outcomes of the different management practices carried out in each park. As a matter of fact, a baseline monitoring system has been established and future reassessments will allow to evaluate the effects of current and new management policies once the relative spatial-explicit data will have become available.

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