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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)