The influence of contrasting fire management practice on bush encroachment: Lessons from Bwabwata National Park, Namibia

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The influence of contrasting fire management practice on bush encroachment: lessons from Bwabwata National Park, Namibia.

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Abstract

Questions:

Bush encroachment, (i.e., disproportionate woody vegetation increase at the cost of grassland) has negative impacts for biodiversity conservation and tourism by homogenising habitat structure and decreasing grazing and game-viewing. While herbivory, rainfall, and CO2 all influence changes in woody vegetation cover, fire has the best potential for vegetation management. Changes in fire management can either encourage or suppress bush encroachment and a better understanding of how changes in fire regime affect vegetation structure is needed. Therefore, this study addressed three questions: (a) how has woody cover changed over two decades (1999 – 2019)? (b) what is the role of land use, rainfall, and fire in influencing woody cover change? (c) what are the management implications?

Location:
Bwabwata National Park (BNP), Namibia.

Methods:
The study used a novel combination of repeat ground photography and satellite-based remote sensing products to explore the change in woody vegetation in relation to rainfall, land use, and fire seasonality.

Results:

Woody vegetation has increased by 13% since 1999 in BNP. Change in vegetation structure differed in the east and west of the park. Early season burns in the east of the park were associated with an increase in trees over 3 m tall consisting primarily of *Dialium engleranum*, *Terminalia sericea* and *Burkea africana*. Repetitive late dry season fires in the west of the park were associated with an increase in shrubs under 3 m dominated by *Baphia massaiensis* and *Terminalia sericea*.

Conclusions:
Both early and late season fires are of value in management of bush encroachment. Early dry season fires appear to reduce the rate of bush encroachment and contribute to maintaining a heterogeneous vegetation structure. This fire management strategy reduces wildfire risk, conserves biodiversity, and promotes tourism and is, therefore, recommended for the park.

Key Words: woody vegetation, repeat photography, fire management, remote sensing, vegetation change, bush encroachment, savannas, MODIS, EVI

Introduction

A significant portion of Africa's growing human population, livestock and rangeland occurs within the savanna biome, which is home to high faunal and floral biodiversity and important for nature-based tourism (Scholes, 2003). Savannas are defined by their heterogeneity, comprising a layer of continuous grass with a discontinuous layer of trees or woody species of variable density that creates a range of habitats (O'Connor and Stevens, 2017). However, across southern Africa and indeed many parts of the globe, a trend of increasing woody vegetation at the cost of open, grass-dominated areas has been observed in savanna and grassland biomes (O'Connor and Stevens, 2017; O'Connor *et al.* 2014; Archer *et al.* 2017; Stevens *et. al.* 2017). This trend has been described as bush encroachment, but other terms such as woody thickening and woody plant encroachment, are used in reference to increasing density of indigenous woody plants (Archer *et al.* 2017; O'Connor *et al.* 2014). Bush encroachment and its process of homogenising habitat structure can cause a fundamental shift in ecosystem function through the reduction in open grassy areas. This, in turn, has widespread consequences for biodiversity and the services that ecosystems provide (Eldridge *et al.* 2011). Bush encroachment and homogenised habitat structure has impacts on species that are adapted to open areas (Sirami *et al.* 2009; Abreu *et al.* 2017), forage production and habitat modification (Archer *et al.* 2017; Smit and Prins, 2015), carbon sequestration (February *et al.* 2020), hydrology (Honda and Durigan, 2016) and erosion (Grellier *et al.* 2012). This process also has social consequences such as the loss of cultivatable land and fears about personal safety (Shackleton *et al.* 2013). Economic consequences include reduced visibility for tourists in game viewing areas and subsequent willingness to pay (Gray and Bond, 2013).

Change in woody vegetation is influenced by a range of factors. Some, such as grazing, rainfall and fire have a more local influence while others such as temperature and atmospheric CO_2 are more regional (Wigley *et al.* 2009) or even global in nature (Buitenwerf *et al.* 2012). On a regional and global scale an increase in temperature and CO_2 enables savanna trees to grow quicker and survive frequent fires (Higgins and Scheiter, 2012; Haverd *et al.* 2020; Wakeling *et al.* 2012). Studies have shown that the increase of woody vegetation has occurred across different land use types, disturbance regimes and climatic gradients (Buitenwerf *et al*. 2012; Wigley *et al.* 2009; O'Connor *et al.* 2014; Stevens *et al.* 2017). This evidence suggests that global drivers such as climate change and increasing atmospheric CO_2 are important drivers of the global phenomenon of woody plant encroachment (Higgins and Scheiter, 2012; Haverd *et al.* 2020).

However, local factors (herbivory and fire) also contribute to woody vegetation change and can sometimes be manipulated to manage the effects of global drivers of bush encroachment. For example, heavy grazing in a landscape favours the dominance of woody vegetation as grazing reduces the ability of grass to compete with woody vegetation for resources (O'Connor *et al.* 2014). Fire suppression allows woody vegetation to escape the flame zone or 'fire trap' (approximately 3 m) of savanna fires, thus favouring the thickening of woody vegetation (Higgins *et al.* 2000; van Wilgen *et al.* 2014). Fire seasonality also influences woody vegetation. For example, fires in the late dry season are generally larger, more intense, and harder to control than early dry season fires (van Wilgen *et al.* 2014; Govender *et al.* 2006). Early dry season fires are cooler, smaller, and more easily controlled. Thus, burning frequently in the early dry season reduces the risk of wildfire and creates a mosaic of patch burns which in turn promotes greater heterogeneity in the landscape (Govender *et al.* 2006; Humphrey *et al.* 2020; Brockett *et al*. 2001).

The primary aim of this study was to understand how fire, land use and rainfall have influenced woody cover change in Bwabwata National Park in north-eastern Namibia and how this knowledge can be used to manage vegetation in the region. We addressed three questions: (a) how has woody cover changed over two decades (1999 – 2019)? (b) what is the role of land use, rainfall, and fire in influencing woody cover change? (c) what are the management implications? To address these questions, we first described the nature, extent, and rate of woody cover change over the period 1999 to 2019 using a combination of repeat photography and remote sensing products. We then investigated the inter-decadal scale patterns in rainfall, fire, and land use at each of the repeat photography sites and explored their respective influence on observed woody cover change and structure. The use of these methods provides both a detailed ground-level assessment of measured woody species change (i.e., repeat photography and vegetation surveys) in combination with rainfall, and fire (remote sensing) at a larger scale. Finally, through utilising these integrated methods, we are able to reflect on the management and conservation implications of these findings.

Study Area and Methods

Study area

Bwabwata National Park (BNP; 18.1157° S, 21.6696° E) occurs within the Kavango Zambezi-Transfrontier Conservation Area (KAZA-TFCA) in north-east Namibia (Figure 1a). KAZA-TFCA and BNP, are a major tourism destination owing to the concentration and diversity of wildlife which the landscape supports. The BNP landscape is characterised by SE-NW oriented palaeo dunes and ancient river valleys known locally as omuramba (Figure 1b) that are now stabilised by vegetation (MacFarlane and Eckardt, 2007). These latter features contain nutrient-rich soils and a higher water table than the dunes, and for these reasons are often used for cultivation by the local population who are concentrated in the centre of the park where game activity is lowest (Table 1). On the crest of the dunes, sediment is characterised by a lower nutrient sandy composition facilitating higher levels of drainage than the lower-lying omiramba. The lower water table is accessible to woodland tree species and the dune crests are, therefore, characterised by a higher cover of woody plants such as *Burkea africana*, *Baikea plurijuga*, *Combretum* spp. and *Terminalia sericea* amongst others (Mendelsohn and Roberts, 1997). The omuramba grassland and dune crest woodland together form the heterogenous savanna mosaic of BNP known as Kalahari woodland (Mendelsohn and Roberts, 1997). The climate is sub-tropical with a gradient in rainfall from about 550 mm in the western part of the park to about 650 mm in the east (Mendelsohn and Roberts, 1997). BNP experiences unimodal rainfall during summer (November to April), rendering winter months as dry and fire prone.

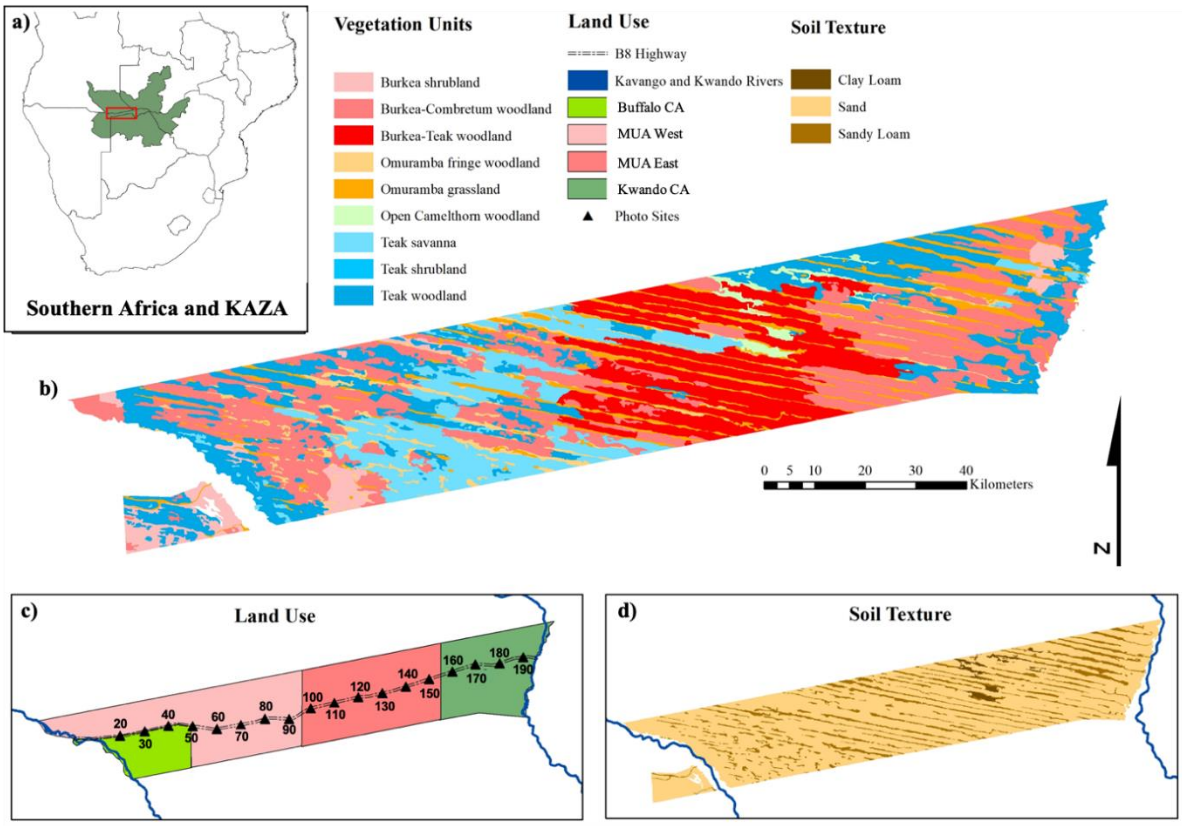


Figure 1. a) Bwabwata National Park within southern Africa in the centre of the Kavango Zambezi-Transfrontier Conservation Area (KFCA-TFCA). The location of the park is outlined by the red box; b) Vegetation units; c) Fixed-point repeat photography sites labelled at 10km intervals within land use areas d) Soil texture with river systems on east (Kwando River) and west (Kavango River) border of park (Mendelsohn and Roberts, 1997)

Land use

There are two main land use types in BNP. These are the Multiple Use Areas (MUAs), where people reside in villages and practice agropastoralism, and Core Areas (CAs) which are protected areas and are dedicated to biodiversity conservation and controlled tourism (Figure 1c; Table 1). There are two MUAs i.e., MUA West (2446 km^2) and MUA East (1609 km^2), which lie in the centre of the park. While the exact human population of each of the MUAs is not known, most of the total population of about 5500 people live in the MUA West. The major land use activities in both MUAs include cultivation with some hunting of small game and wild food gathering (i.e. plant food resources) as well as community-based tourism and trophy hunting. There is a relatively low concentration of game in the MUAs with the wet season being the period of greatest activity. Surface water in the omuramba pans increases in availability during this time of year drawing game inland and away from the river systems. There is a localised population of cattle primarily in the west of the park close to Omega 1 village (Suzman, 2001). The two CAs comprises of Buffalo (629 km^2) adjacent to the Okavango River in the west and Kwando (1345 km^2) on the Kwando River in the east which support a relatively high concentration of game especially along these river systems in the dry season.

There are important differences in the fire regime in BNP which are related to land use type. For example, in Buffalo CA and MUA West, fires are generally inconsistent in their frequency and occur mostly in the late dry season (Table 1). By contrast, fires in MUA East and Kwando CA are relatively consistent in their frequency and occur mostly in the early dry season. As a result, there is a reduction in the number and extent of uncontrolled fires in the latter two areas (Humphrey *et al.* 2020). In this study, we refer to early dry season (EDS) fires which occur from April - July and late dry season (LDS) fires from August – October (Humphrey *et al*. 2020).

Table 1: Summary of dominant characteristics relevant to the study, defining the land use categories of BNP (Ministry of Environment and Tourism (MET), 2013; MET, 2016).

Traits	Buffalo Core Area	Multiple Use Area (West)	Multiple Use Area (East)	Kwando Core Area
Size (km^2)	629	2446	1609	1345
Land use	Protected Area	Settlement area	Settlement area	Protected Area
Human Population Size	0	Not known – vast majority of total MUA population of approximately 5500 (MET. 2016)	Not known – small minority of total MUA population of approximately 5500 (MET. 2016)	0
Dominant Activities (MET. 2013)	Biodiversity conservation and controlled tourism	Mostly agro-pastoral with some hunter gathering, small mammal hunting and floral gathering, community-based tourism, and trophy hunting. Clearing fields for agricultural purposes. Limited use of woody species for construction.	Hunter gathering and agro-pastoral, small mammal hunting and floral gathering, community-based tourism, and trophy hunting. Clearing fields for agricultural purposes. Limited use of woody species for construction.	Biodiversity conservation and controlled tourism
Fire management (MET. 2016)	Inconsistent, uncontrolled, mostly late dry season fires.	Inconsistent, uncontrolled, late dry season fires are dominant.	Consistent, early dry season burning occurs.	Consistent, reduced uncontrolled fires, early dry season burning occurs.
Game activity (MET. 2013)	River system concentration predominantly in the dry season (e.g., elephants).	Low concentration - wet season is highest activity period.	Low concentration - wet season is highest activity period.	River system concentration predominantly in the dry season (e.g., elephants).
Domestic Animals	NA	Cattle, goats, donkeys, chickens, and dogs.	Cattle, goats, donkeys, chickens, and dogs.	NA

Repeat photography, remote sensing, and the assessment of change in woody plant cover

In November 1999, 38 repeat photo sites (Figure 1c) were established by the Integrated Rural Development and Nature Conservation (IRDNC), as part of a vegetation monitoring project. The design of the project consisted of a pair of repeat photograph sites established every 10 km situated approximately 200 m north and south of the road along the B8 Highway which runs through BNP from west to east for 200 km (Figure S1). At each location, which was marked with a metal pole, a photograph was taken in each of the four cardinal directions (north, east, south, and west). This resulted in a total of 152 photographs established in 1999 of the vegetation in BNP.

Thirty-seven of the sites were revisited in the dry season in late September and early October 2019 to re-photograph the images taken in 1999. One site was severely disturbed and was therefore not re-photographed. The repeat photographs were taken with a Canon 5D MkII digital camera mounted on a tripod. In addition to the photographs that were repeated at each site, an ocular vegetation survey (Rohde & Hoffmann 2010) was carried out in 2019. This was done by walking through the main vista represented in the photograph, listing vegetation percentage cover and the height of dominant species. Notes on major changes in species composition, cover of species, browsing and fire evidence were recorded at each site. Cover estimates were made in the field using the comparison chart in Anderson (1983) to calibrate the scores. A ranging rod was placed in the middle of each photo to estimate the cover for all woody plants < 3 m and > 3 m in height. Dominant woody species were also recorded at each site. These estimates obtained in the field survey were used to assist in the estimates made of total woody cover, and cover < 3 m and > 3 m observed in the photographs taken in the dry season of 1999 and 2019.

To assess vegetation change over time, each of the 1999 and 2019 photo comparisons were placed on a large computer screen alongside each other. Woody cover above and below three metres were assessed, alongside grass and bare ground. Photos being assessed were compared to a representative photo sheet of example sites with a range of cover values to ensure cover estimates were consistent.

To establish the reliability of the estimates of woody cover change from 1999 to 2019, derived from the repeat photographs, the values were correlated with values obtained from remotely sensed indices. The satellite monitoring product Landsat 8 and 4 collection 1, Enhanced Vegetation Index (EVI) (resolution of $0.25km^2$) was utilised to provide a relative measure of change in productivity from the same time photos were taken in 1999 and 2019. Using Google Earth Engine, bi-weekly values of EVI were extracted as close as possible to the photo dates from 1999 and 2019 for each site (Venter *et al.* 2020). Therefore, a woody cover value from 1999 and 2019 from both repeat photos and the EVI dataset were used for comparative purposes and to investigate change.

A pairwise t-test was performed on photo cover scores for all sites across BNP to establish if woody cover differed over the 20 years from 1999 to 2019. This test was performed separately for total woody cover, woody cover <3 m and woody cover >3 m. All statistical analyses were performed in R (R Development Core Team, 2017). Photo cover scores from each cardinal direction at a site were averaged to obtain one mean value of woody cover for each site for the year of interest. Each site was considered independent and thus the sample size for the test of woody cover change was n= 37 over the whole BNP. In order to understand if there were differences in woody cover change across the land use categories a pairwise t-test (was also performed for each land use category: Buffalo CA, MUA West, MUA East and Kwando CA.

Changes in rainfall, fire, and land use

Climate Hazards Group and InfraRed Precipitation with Station (CHIRPS) is a rainfall dataset which uses satellites and observations to provide precipitation values from 1981 – present, globally at a scale of 2.25 km^2. Mean Annual Precipitation (MAP) from 1996 – 2019 for each pair of sites along the B8 Highway was calculated using CHIRPS extracted from Google Earth Engine (GEE). Due to the uni-modal summer rainfall season (i.e. only one rainfall peak with no alternation of humid and dry months within the wet season), years were calculated from the beginning of the rainy season in October to the end of the dry season in September of the following year. Antecedent rainfall (i.e. previous 2 years of accumulated rainfall) of each photo year (1999 and 2019) was calculated to account for the possible influence of high and low rainfall seasons on vegetation change (Sankaran *et al.* 2005).

MODIS collection 6 burned area product (https://modis-land.gsfc.nasa.gov/burn.html) (MCD64A1) was used to calculate the frequency and seasonality of fire (Giglio *et al.* 2018). Fire Return Interval (FRI) represents the number of years it takes for a fire to return to a site. Short Fire Return Interval represents higher fire frequency and longer Fire Return Interval represents lower fire frequency. Early Dry Season Burnt Area (EDSBA) is the percentage of a site burnt during the early dry season (April – July). Late Dry Season Burnt Area (LDSBA) is the percentage of a site burnt during the late dry season (August – October). The resolution of this MODIS fire product is 0.25 km^2 allowing for the individual fire history to be determined for each photo site from the period 2000 – 2018 with an unfortunate gap in data due to a sensor outage from May – July 2001 and 2019 being an incomplete year. Throughout this paper the key fire regime and rainfall variables are capitalised.

Sites were split into the four respective land use categories (Buffalo CA, MUA West, MUA East and Kwando CA; Figure 1c) and a one-way ANOVA (*dplyr* package: Wickham *et al.* 2018) was used to test whether fire seasonality and frequency differs between the land use areas. A post-hoc Tukey Honest Significance of Difference test was used to assess differences between land use categories in fire seasonality and fire frequency.

The effect of rainfall, fire, and land use on the change in woody cover

A Generalised Linear Mixed Model (GLMM) was selected to investigate the effect of rainfall, fire, and land use on woody cover change with the use of the *lme4* package available in R (Bates *et al.* 2015). Change in woody vegetation was considered as the response variable and Mean Annual Precipitation (MAP), Fire Return Interval, Early Dry Season Burnt Area, Late Dry Season Burnt Area, and land use category as explanatory variables. Due to the sites being situated relatively close to one another (approximately 500 m), each of the four cardinal directions at a site were included as crossed random effects creating four random effects per site. Residuals of the model were tested for spatial autocorrelation and none was detected (Moran's I: $p > 0.1$; SD = 0.017164). The formula for the model fitted by maximum likelihood was:

Woody Cover Change ~ Fire Return Interval + Mean Annual Precipitation + *Early Dry Season Burnt Area + Late Dry Season Burnt Area + Land Use + (1 | Position)*

The distribution of the response variables was tested using the *car* package (Fox and Weisburg, 2019). Changes in total woody cover and woody cover > 3 m were fitted with a normal distribution. Change in the < 3 m woody cover category was transformed using the log link function for a normal distribution.

Results

Repeat photography and the change in woody plant cover

Total woody cover in BNP increased by 13% over the period 1999-2019 ($p<0.001$; df= 35; Figure 2 & 3). Most change occurred within the < 3 m woody cover category, which increased by 9% across the whole of BNP ($p<0.001$; df = 35). Woody cover <3 m increased at almost twice the rate as >3 m which showed a 4% increase ($p<0.05$; df=35). MUA West experienced the largest change in <3 m woody cover with a 16% increase ($p<0.001$; df 13) and no change in >3 m. Kwando CA experienced the largest increase in >3m woody cover with a 13% change ($p<0.001$; df=7). MUA East displayed a similar increase in both <3 m (4%; $p<0.001$; df=7) and >3 m (6%; $p<0.001$; df=7).

The results showed a difference in the change in woody cover structure between the west and the east of the park. The majority of woody cover increase <3 m took place in the west of the park and >3 m in the east of the park (Figure 3). Confidence in woody cover change results is supported by the strong correlation (R^2 = 0.67; p=<0.001) of change between the EVI values and those derived from the repeat photo comparisons (Supplementary material Figure S4).

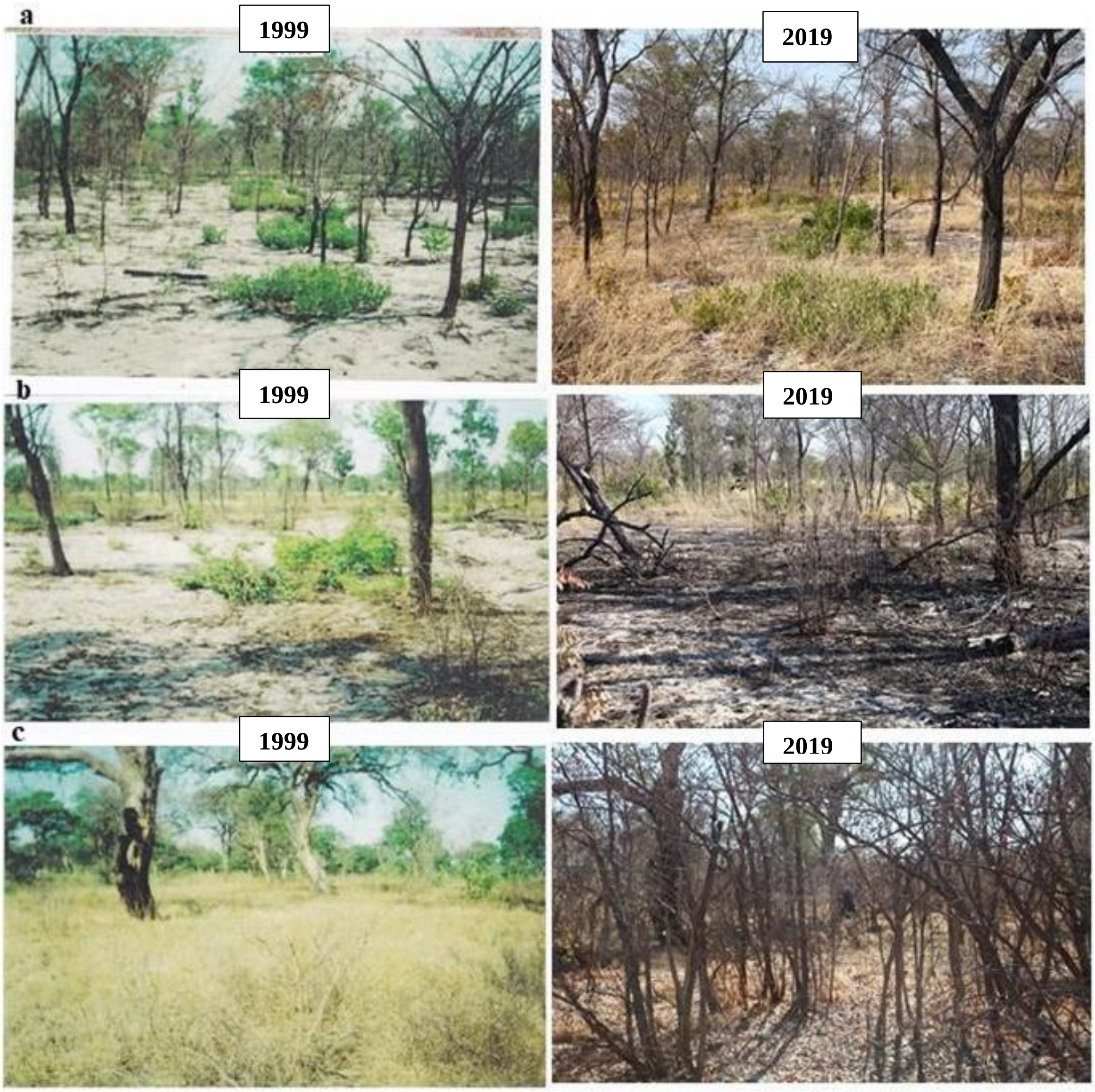
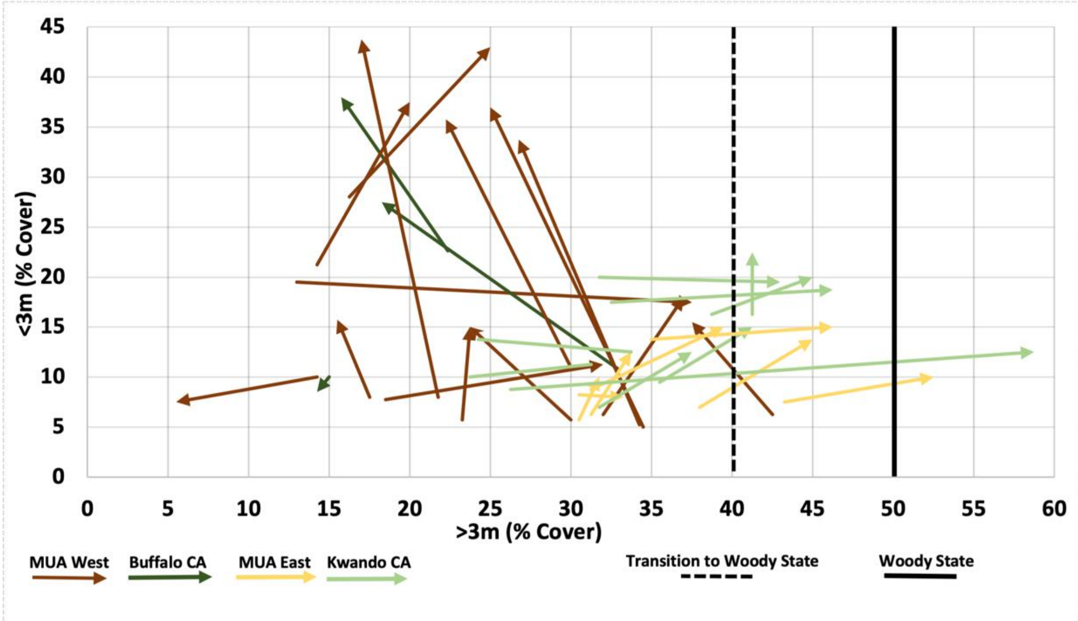


Figure 2. Examples of woody vegetation change between 1999 and 2019 seen at repeat photography sites on a scale from minimal change (a) to maximum change (c). a) Represents an increase in woody cover of 3% due to a marginal increase in *Terminalia sericea* in the mid-ground. b) Shows a 10% increase in woody cover with the majority occurring as a result of *T. sericea* thickening. c) Represents the maximum change recorded (36% increase in total woody cover). Two large *Guibourtia coleosperma* trees are still present but are much more difficult to see in 2019 due to the increase in the number of *T. sericea* individuals in the foreground.



12

Figure 3. Trajectory of change for the 37 repeat photo sites with arrows indicating direction of change from 1999 to 2019. Colours represent the respective land use category with lighter colours (i.e., yellow and green) representing the eastern section, where there was more increase in larger size classes and darker colours (i.e., green and brown) the western section of BNP, where increases took place in woody plants <3 m. Vertical lines (solid and dashed) on the x-axis (% woody cover >3 m in height considered as a proxy for tree) represent transition values from grassy to woody savanna states as defined by Staver *et al.* 2011.

Results of vegetation surveys

The most dominant species recorded in the vegetation surveys was *Terminalia sericea* which covered 20% (predominantly in the west) of the surveyed area (see Table S1, S2 and Figure S2 in supplementary material for a complete species list). Other dominant species were *Ochna pulcra* (5%) *Dialium engleranum* (9%; predominantly in the east.), *Burkea africana* (7%; predominantly in the east), *Baphia massaiensis* (10%; predominantly in the west), and *Baikea plurijuga* (9%; predominantly in the west).All *B. massaiensis* individuals and 70% of *O. pulcra* individuals were <3 m. *T. sericea*, *D. engleranum*, *B. plurijuga* and *B. africana* varied in height from 1 to 8m.

Changes in rainfall, fire, and land use

Mean Annual Precipitation varied between 430 mm and 890 mm over the 20-year period (Figure S3), with a mean of 612 mm and no clear trend of change over the study period. The two-year antecedent rainfall total for 2018/19 and 1998/99 was very similar (920 mm vs 1010 mm, respectively). However, rainfall in the year prior to the 2019 photo survey was 300 mm less than rainfall in the year prior to the 1998/1999 photo survey (Figure S3. Correlation of observed rainfall from Katima Mulilo and Rundu Meteorological stations with CHIRPS data for the weather station locations was significant (Katima Mulilo: R^2=0.93 and p=<0.001; Rundu: R^2 =0.88 and p=<0.001; Figure S3). Therefore, confidence in the accuracy of rainfall as derived from the CHIRPS dataset is high.

Seasonal burned area, fire return interval and land use

Early Dry Season Burnt Area, Late Dry Season Burnt area and Fire Return Interval differed significantly among land use categories (Early Dry Season Burnt Area: F=5.35, *p*=<0.001; Late Dry Season Burnt Area: F=30.17, *p*=<0.001; Fire Return Interval: F=38.86, *p*=<0.001 (Table S3)). Late Dry Season Burnt Area and Fire Return Interval varied the most between land use categories. The average Fire Return Interval for all sites was seven years with sites in the MUA West displaying below average (i.e., short interval) and the majority in MUA East displaying above average (i.e., long interval) Fire Return Interval (Figure 4 & Figure S5). The MUA East and MUA West differed when compared to the park CA areas with an average of nine years for fires to return to a site in each land use area.

Eight percent of BNP was burnt in the early dry season as compared to 26% in the late dry season (1999 - 2019). Sites in the east of the park (MUA East and Kwando CA) displayed below average Late Dry Season Burnt Area compared to sites in the west of the park (Buffalo CA and MUA West). The most extreme difference in Late Dry Season Burnt Area was found between the MUA West and MUA East where the portions of a site burnt in the LDS differed by an average of 27% (Figure 4). There was significantly more burning in the early dry season in Kwando CA than in the eastern Multiple Use Area and the Buffalo CA.

Thus, there is a significant difference between land use areas in terms of fire seasonality and frequency. The MUA East showed higher fire frequency (i.e., lower than average Fire Return Interval) and higher than average late season burn area, whereas the opposite was found in the eastern MUA West.

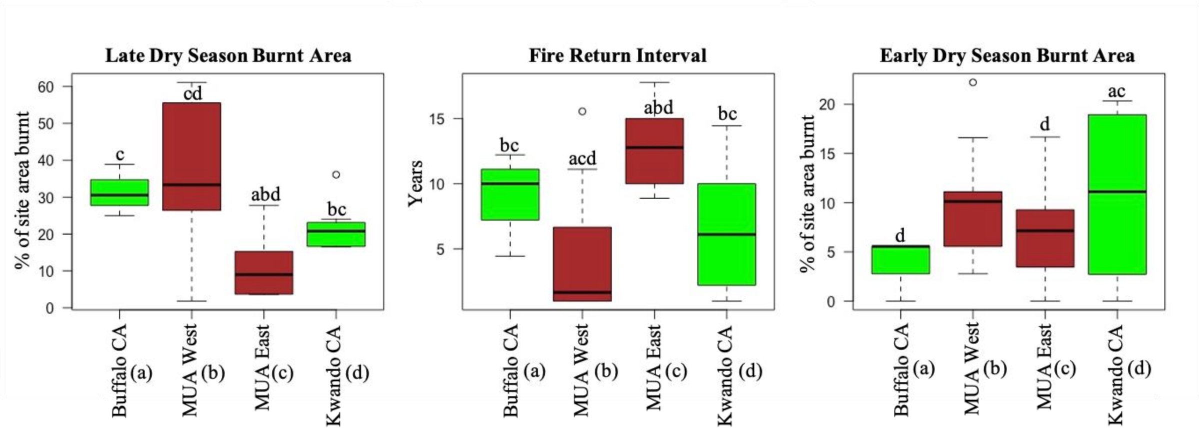


Figure 4. Box and whisker diagram (median values are displayed per category by the bold black line with the upper and lower box representing the upper and lower quartile and bars the minimum and maximum values) of fire regime variables (Fire Return Interval, Early Dry Season Burnt Area, Late Dry Season Burnt Area) from MODIS Burned Area (2000 – 2018), grouped by land use categories (Buffalo CA, MUA West, MUA East and Kwando Core Area). The Core Areas in BNP are highlighted in green and the MUAs in red.. Letters are associated with land use categories and if displayed in graph, represent significant differences (Table S2).

The effect of rainfall, fire, and land use on the change in woody vegetation structure

Across all woody cover categories, the GLMM revealed that Late Dry Season Burnt Area and rainfall (Mean Annual Precipitation), displayed significant effects (Table 2). Late Dry Season Burn Area was also associated with decreased total woody cover. Fire Return Interval s was significant in relation to Late Dry Season Burn Area and the > 3m woody cover category. However, Late Dry Season Burn Area showed contrasting effects in the <3 m and >3 m woody cover categories. Specifically, increasing area of late season burns was associated with increasing < 3m woody cover was and decreasing >3 m woody cover.

The most significant effect of land use category was that of MUA West increasing <3 m woody cover and decreasing >3 m woody cover. The effect of fire on woody cover was most pronounced in the MUA West which displayed a negative effect on woody cover >3 m and a positive effect on <3 m woody cover.

Higher Mean Annual Precipitation was associated with higher total woody cover. Higher Mean Annual Precipitation was associated with decreased <3 m woody cover and increased >3 m woody cover. While the GLMM identified Mean Annual Precipitation as a significant driver of woody vegetation change, the difference in antecedent rainfall between photo years (90 mm) and between photo sites (40 mm difference from east to west) was not significant and thus cannot fully explain the variation in woody vegetation change across categories.

Table 2. A summary of the Generalised Linear Mixed Model (GLMM) effects in relation to fire regime variables and woody cover categories (estimate of effect and associated standard error (SE), t-value and p-value [**bold** = significant]). Values for explanatory variables of Mean Annual Precipitation (MAP), Early Dry Season Burnt Area EDSBA, Late Dry Season Burnt Area (LDSBA), Fire Return Interval (FRI) and land use categories with adequate sample size were included, thus Buffalo CA (n=3) was excluded.

Response Variable	Explanatory Variable	Estimate	Standard Error (SE)	T value	P-value
< 3 m Woody Cover	MAP	-0.008	0.000	-144.400	**<0.001**
	EDSBA	-0.005	0.003	-1.824	0. 927
	LDSBA	0.004	0.001	3.477	**<0.001**
	FRI	-0.007	0.005	1.503	0.148
	MUA West	-0.168	0.056	-2.982	**<0.050**
	MUA East	0.210	0.068	3.105	**<0.010**
	Kwando CA	0.275	0.066	4.178	**<0.001**
> 3 m Woody Cover	MAP	0.007	0.001	4.309	**<0.001**
	EDSBA	-0.003	0.003	-1.011	0.329
	LDSBA	-0.006	0.001	-3.539	**<0.016**
	FRI	0.010	0.006	-1.672	**<0.050**
	MUA West	0.415	0.082	5.008	**<0.001**
	MUA East	0.023	0.121	0.196	**<0.050**
	Kwando CA	-0.022	0.139	-0.166	0.311
Total Woody Cover	MAP	-0.001	0.000	-29.262	**<0.001**
	EDSBA	-0.004	0.002	-1.666	0.661
	LDSBA	-0.001	0.001	-1.283	**<0.010**
	FRI	-0.012	0.004	-29.262	0.063
	MUA West	0.160	0.061	2.611	**<0.010**
	MUA East	0.156	0.069	2.248	0.166
	Kwando CA	0.166	0.067	2.481	**<0.050**

Discussion

Increase in woody plant cover and change in vegetation structure

The trend of bush encroachment in BNP is occurring at a rate of increase of 0.5% per annum, which is consistent with other findings in southern African savannas (O'Connor *et al.* 2014; Skowno *et al.* 2017; Stevens *et al.* 2016). Most of the increase occurred within the <3 m woody cover category, which comprised 9% of the total 13% increase, and occurred predominantly in the west of the park. The <3 m woody cover category includes coppicing and resprouting plants and thus this increase is likely related to post-fire vegetation responses (Higgins *et al.* 2000). This suggests greater homogenisation of vegetation structure in Buffalo CA and MUA West when compared to MUA East and Kwando CA which displayed a greater increase in the >3 m woody cover category. Such homogenisation (increasing dominance of woody vegetation at the cost of grass and herb production) in the west should warrant concern (Scholes, 2003; Smit, 2004). The heterogenous makeup of savanna vegetation supports biodiversity and thus tourism

(Sirami *et al.* 2009; Brenton *et al.* 2003). This likely reduction in grass and herb productivity would have cascading effects on herbivore guilds and monitoring of this shift is recommended (Schwarz *et al.* 2018).

The dominance of *Terminalia. sericea* (which covered 20% of sites at varying heights) and *Baphia massaiensis* (which covered 10% of sites in the <3 m woody cover category) in the west of the park provides support for their classification as indigenous encroachers by the Namibian Tree Atlas Project (Curtis and Mannheimer, 2005). Both species have been observed to coppice and resprout at higher rates than other woody species following disturbances such as fire (Nefabas and Gambiza, 2007; Holdo, 2005; Smit *et al.* 2016). Unfortunately, due to the lack of species-specific information from the 1999 photo survey period, the potential decline of protected and or threatened species such as *Baikea plurijuga* or a comparison of *B. massaiensis* and *T. sericea* cover cannot be determined.

Comparison of the repeat photography derived woody cover change estimates and the EVI derived productivity change between 1999 and 2019 returned a significant positive correlation (R^2=0.67; p<0.001). This suggests that vegetation change analysis can gain confidence in results by combining repeat photography and satellite-based methods. While EVI is a measure of productivity which includes grass, both measurements used in 1999 and 2019 were taken during the end of the dry season when grass productivity is at its lowest. The use of a trained remote sensing product that excludes grass in its measurement would have been beneficial, however was beyond the scope of the project. Yet, the lack of remote sensing measurements would have reduced the reliability of the results and therefore EVI was used. While there are controversies around the use of both methods (late dry season EVI use [Galvão *et al.* 2011]) and the qualitative nature of repeat photography (Webb, 2010), the correlation shown in this study potentially identifies the value of combining these datasets in future studies.

Drivers of the divergence in woody vegetation change between east and west

Analysis of satellite imagery revealed significant differences in fire frequency (Fire Return Interval) and fire seasonality (area burned in early or late season) between east and west of the park (Figure 4; Table S3). In the west of the park, increased Late Dry Season Burnt Area was associated with reduced >3 m woody cover and increased <3m woody vegetation cover. In the east of the park, lower Late Dry Season Burnt Area was associated with a significant increase in >3 m woody cover, in combination with Mean Annual Precipitation (Table 2; Figure 4). Therefore, the higher cover of <3 m woody cover in MUA West is attributed to the difference in rainfall, and fire management practices between land use areas, which affect fire seasonality. In other words, the lack of early season burning in the west of the park comes at a cost to tall trees and a homogenisation of vegetation structure (Smit *et al.* 2016).

The presence of frequent fires in the late dry season, in the absence of early dry season management burns in the MUA West is contributing towards increased risk of perpetual late season wildfires in the park. Due to the association of late season fires with high intensities (Govender *et al.* 2006), fires in MUA West are hotter and larger than fires in MUA East, and thus are considered as high risk and hard to control (Humphrey *et al.* 2020; Govender *et al.* 2006; van Wilgen *et al.* 2014). Smit *et al.* (2016) emphasized in a study in Kruger National Park in South Africa that high intensity fires are more effective than low intensity fires in reducing woody cover in the short height classes, yet only in the short term. These findings are consistent with this study and suggests that frequent, repetitive, late season fires will maintain the short woody shrub cover structure (<3 m).

The Generalised Linear Model suggested that Late Dry Season Burnt Area was associated with a change in woody vegetation structure between 1999 to 2019. Further, there was an interactive effect of precipitation and fire, most likely mediated by changes in grass biomass (Archibald *et al.* 2010). However, the model was a relatively simple one and did not include the effects of global drivers such as CO_2. Mean Annual Precipitation varied between 430 mm and 890 mm over the 20-year period (Figure S3), with a mean of 612 mm and no clear trend of change over the study period. This probably had a larger influence on grass cover than on woody cover since tree cover is unlikely to be affected by annual differences in rainfall. Due to the relatively low antecedent rainfall received by the region before the 2019 study period compared with the 23-year Mean Annual Precipitation (Figure S3) it is likely that other drivers of bush encroachment such as atmospheric CO_2 concentrations are involved, that were not included in our model (Haverd *et al.* 2020). The model should therefore be considered as a useful exploratory tool and as a basis for further investigation.

The results support the central influence that fire has on woody vegetation cover and bush encroachment at the local scale, despite the effect of global drivers such as CO_2 concentrations (O'Connor *et al.* 2014; van Wilgen *et al.* 2014; Govender *et al.* 2006). Thus, any effort to control and understand vegetation change such as bush encroachment requires considering the role of fire and specifically fire seasonality (early versus late season burning practises) (Govender *et al.* 2006; van Wilgen *et al.* 2014). The occurrence of frequent LDS fires in the MUA West is damaging to trees and results in the proliferation of the most fire-resistant woody species (e.g. *T. sericea* and *B. massaiensis* (Nefabas and Gambiza, 2007; Holdo 2005). In contrast, EDS burning with non-cured grass creates cooler fires and can contribute towards habitat heterogeneity by creating a patchy distribution of burnt area allowing a broader selection of fire-resistant woody species to survive (Bond and Zaloumis, 2016). Thus, the process of EDS burning facilitates the management of wildfire risk and conservation of biodiversity.

Management implications

The increasing cover of woody vegetation in BNP is consistent with the trend of bush encroachment in savannas found elsewhere. Increasing total woody cover across the park is probably associated with a reduction in grass and herbaceous production (Scholes, 2003; Smit, 2004). This would alter the ecosystems primary of grass and herbaceous layers, with cascading effects on herbivore guilds. Therefore, it is important for management to monitor how this encroachment has and will influence faunal abundance and herbivore movement in the park (Schwarz *et al.* 2018).

The results suggest that early season burning in the east of the park seems to be effective in curbing the spread of woody shrubs and in maintaining heterogenous vegetation structure. The spread of <3 m woody cover and indigenous encroachers (*T. sericea* and *B. massaiensis*) in the west of the park poses a biodiversity, wildfire, and tourism risk. Further investigation and monitoring of this issue is required to understand potential consequences. In order to mitigate the homogenising of vegetation composition and structure in the western areas of the park a reduction in the frequency and size of LDS burning is recommended with the use of EDS fires as a management tool. Thus, any management intervention needs to recognise the value of a combination of seasonal fires that include the use of prescribed early season burning to create a mosaic of post-age fires in the landscape to restore the variability in height structure and species composition to encompass both grasses and woodland patches that would benefit biodiversity. This finding highlights how management of fire at the landscape or park scale can ameliorate the effect of global drivers, such as CO_2 emissions, which contribute to shrub encroachment.

Conclusions

This study used an integrated combination of methods to investigate bush encroachment and its drivers in the region of north- east Namibia in a protected area with multiple land use objectives. Repeat photography and remote sensing analyses from BNP in Namibia show that bush encroachment is occurring at a rate of 0.5% per year over the time-period 1999 – 2019. This trend is more evident in the western land use areas of the park where late dry season burning is promoting the increase of shrub cover and the homogenisation of the landscape at the cost of large trees. Eastern land use areas displayed a more balanced change in woody vegetation with trees and shrubs increasing at similar rates.

Results of generalised linear modelling, suggest that fire seasonality is a major driver of changes in woody vegetation during the study period. Divergence in woody vegetation change between east and west of the park can be explained by differing fire management practices between land use areas, specifically frequent LDS fires in the west and EDS burning in the east. Early season burning seems to be effective in reducing shrub encroachment and maintaining vegetation heterogeneity. The pattern of bush encroachment in the west of the park is likely to reduce the conservation of biodiversity and increase the risk of wildfire with these risks being particularly higher in the western land use areas. The results suggest that early dry season management fires are effective in creating patch mosaic vegetation patterns that has consequences for biodiversity.

The combination of these methods has shown that manipulation of fire seasonality provides a promising fire regime variable for managing bush encroachment in southern African savannas, specifically through the use of early season burning. Considering the widespread pattern of bush encroachment and impact on biodiversity, tourism, and wildfire risk, it is vital that replicable methods are established which allow authorities to monitor and manage vegetation change at the landscape scale.

To reduce this risk, the results suggest that implementation of early season burning policy would be beneficial. The study indicates how repeat photography in combination with remotely sensed data can be used to monitor woody savanna vegetation to inform fire management decisions and practice at the landscape scale. It also highlights the importance of monitoring changes in woody vegetation cover and structure and suggests that manipulation of fire seasonality provides a promising fire regime variable for managing bush encroachment in southern African savannas.

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Author contribution statement

TH, LG and GH conceived the research design. CE conducted the study. GH and CE conducted fieldwork and collected data. All authors discussed the results and commented on the manuscript.

Data availability statement

Data is publicly available on Zenodo DOI: 10.5281/zenodo.5783814

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Appendices:
Figure S1. Study design setup.

Table S1. Results of woody cover change (1999 – 2019) pairwise t-test.

Table S2. List of all species found in photo sites across Bwabwata National Park.

Figure S2: Relative percentage cover of dominant species across Bwabwata National Park.

Figure S3. Total annual rainfall for Bwabwata National Park (BNP) from October – September rainy season 1996/97–2018/19.

Table S3. Comparing fire seasonality and frequency across land use categories.

Figure S4. Correlation coefficient of change in woody cover calculated by EVI and photos.

Figure S5**.** Fire Return Interval (a) and burn seasonality (b) derived from MODIS burned area product for 2000-2018.