Executive Summary

How has Bwabwata National Park's woody vegetation changed in response to fire, rainfall and land use?

Conor Eastment (MSc Conservation Biology)

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Abstract

Bush encroachment or the thickening of woody vegetation is a phenomenon occurring throughout savannas, which tends to be more pronounced in small protected areas. The consequences of bush encroachment are often negative for the conservation of biodiversity, promotion of tourism and prevention of wildfires. Hence, effective monitoring of woody vegetation and the factors which influence its spread are essential. This is particularly the case for protected areas such as that of Bwabwata National Park (BNP) in north-east Namibia. With a complex land use history and different fire management approaches being adopted throughout the area, the effect of fire on woody vegetation in BNP is currently poorly understood. This study used a 20-year-old repeat photography monitoring project and satellite-based remote sensing products to explore woody cover dynamics within the context of rainfall, land use and fire in BNP (1999 – 2019). Results revealed that woody cover has increased by 13% since 1999 in BNP. Furthermore, the results show differences in the structure of woody vegetation. Repeated late dry season fires in the west of the park have driven an increasing dominance of < 3 m woody cover which is unable to escape the 'fire-trap'. *Terminalia sericea* and *Baphia massaiensis* are considered as primary species involved in the encroachment. A combination of the rainfall gradient from west to east and shorter fire return intervals resulting in less late dry season fires has driven an increase in woody cover > 3 m in eastern sections of the park. The influence of different fire regimes spatially across BNP, suggests that local fire management is a significant determinant of woody vegetation change. Woody vegetation change differs spatially across BNP due to frequent late dry season fires prevailing in the west and less frequent earlier season fires occurring in the east. Therefore, in order to reduce the mortality of woody species and conserve heterogenous height structure in the west, a reduction of frequent late dry season fires is recommended. Early dry season fires are shown to reduce the rate of increasing total woody cover change and, therefore, this fire management strategy arguably contributes towards the reduction of wildfire risk, conservation of biodiversity and promotion of tourism.

Key Words: woody vegetation change, repeat photography, fire management

Introduction:

Savannas and Bush Encroachment:

A significant portion of the continent's growing human population, livestock and rangeland occurs within the savanna biome, which is home to high faunal and floral biodiversity (Scholes & Archer 1997; O'Connor & Stevens 2017). Savannas are defined by a continuous grass layer with a discontinuous layer of trees or woody species (O'Connor & Stevens 2017). However, across southern Africa and indeed many parts of the globe, a trend of increasing woody vegetation has been observed in savanna and grassland biomes. 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 & Stevens 2017; O'Connor et al. 2014).

Bush encroachment, depending on its rate and extent, can give rise to a fundamental shift in ecosystem structure. This, in turn, has widespread consequences for the services (e.g. food, water, climate regulation) that ecosystems provide (Eldridge et al. 2011):

1. The process reduces primary production of herbs and grasses by shading out the ground layer which has multiple knock on effects for secondary production such as reduced habitat for grazers (Archer et al. 2017; Scholes 2003; Smit 2004; Smit & Prins 2015; Walker et al. 1972).
2. The higher levels of woody biomass may reduce the likelihood of fires being started (Hoffmann et al. 2005) but they simultaneously increase the risk and size of wildfires (van Wilgen et al. 2014).
3. Soil carbon has been shown to increase in encroached systems (Jackson et al. 2002; Hudak et al. 2003; Knapp et al. 2008). However, while this might decrease climate warming, the increased albedo of dense woody areas could alternatively increase it (Bonan 2008).
4. Loss of ground layer vegetation and increased woody vegetation is associated with higher erosion risk and rainfall interception, (Honda & Durigan et al. 2016; Huxman et al. 2005; Zou et al. 2014)
5. Dominance of woody species and alteration of vegetation structure has multiple negative impacts on species richness in savanna and grassland systems (Smit & Prins 2015; Sirami et al. 2009; Ratajczak et al. 2012; Blaum et al. 2007; Baez & Collins et al. 2008). This creates subsequent effects on tourism viability and the conservation of biodiversity.
6. Encroachment, in some cases has been shown to reduce visibility in conservation areas making wildlife viewing difficult (Gray & Bond 2013). Increased difficulty of viewing reduces tourist perception of the conservation area which impacts their willingness to pay park fees. This is a source of income directly linked to sustainable community livelihoods and resources used for the conservation of biodiversity (Gray & Bond 2013).

Local and Global Drivers of Woody Vegetation:

Woody vegetation is influenced by local factors of competition, demographic bottlenecks and global drivers such as atmospheric carbon dioxide (CO_2) . Understanding changes in woody vegetation such as bush encroachment requires investigating the dynamics of these drivers.

The competition-based model of change attributes co-existence of trees and grasses in savannas to a separation of rooting niches (O'Connor et al. 2014; Walter 1971). In this case, a site with heavy grazing would favour dominance of woody vegetation as grazers reduce grasses' ability to compete with woody vegetation for resources.

The demographic bottleneck model attributes change to disturbance events such as fire. For example, a fire suppression policy allows woody vegetation to escape the flame zone (approximately 3m) of savanna fires, thus favouring the thickening of woody vegetation which has led to bush encroachment in many areas of southern Africa (Higgins et al. 2000; O'Connor et al. 2014; van Wilgen et al. 2014).

Higher concentrations of CO_2 in the atmosphere are a global driver of woody vegetation in savannas (Higgins & Scheiter 2012; Haverd et al. 2020). CO_2 decreases stomatal conductance and transpiration rates of woody species facilitating faster growth rates and recovery from disturbance events (Kgope et al. 2010). Multiple studies have shown that the increase of woody vegetation is occurring across different land use types, disturbance regimes and climatic gradients (Buitenwerf et al. 2012; Wigley et al. 2009; O'Connor et al. 2014). This evidence suggests that while local factors emphasised by the competition based and demographic bottleneck models influence encroachment, it is global drivers such as climate change and increasing CO2 which are primarily responsible for the global phenomenon of woody species encroachment (Higgins & Scheiter 2012; Haverd et al. 2020).

Monitoring Woody Vegetation Change:

The primary methods used to assess change in woody vegetation over time and space include aerial photography, ground-based repeat photography, field surveys, satellite-based remote sensing and palaeo methods (O'Connor & Stevens. 2017). These methods are used to understand how change happening now compares to change that has happened in the past. This allows managers to understand whether current change is of concern or part of normal fluctuations.

Satellite-based remote sensing datasets (e.g. Landsat or Moderate Resolution Imaging Spectrometer [MODIS]) provide large spatial scale and detail, within decadal time scales (Chuvieco 2009). Ground-based repeat photography (i.e. fixed point, repeat or 'matched' photography) also provides decadal scales of change, but at a smaller scale which provides information not achievable with remote sensing such as height structure and species presence (Webb et al. 2010). When ground photos are repeated with exactly the same frame during the same time of year as the original photo, woody vegetation change and it's rate can be measured with insight into the species responsible for that change and how height

structure has changed over the period of time (Webb et al. 2010; Rohde et al. 2019; Hoffman et al. 2010).

The Role of Policy and Local Fire Management:

The stated primary objectives of the management authority (Ministry of Environment and Tourism) within the study area, Bwabwata National Park (BNP) are the preservation of biodiversity and to improve economic development through the principle of sustainable utilisation (MET 2013). BNP occurs within the greater Kavango Zambezi - Transfrontier Conservation Area (KAZA - TFCA) and the movement of game is relatively unrestricted by fences. Therefore, the primary method of controlling woody vegetation is through the use of fire by local management authorities. The objectives of BNP's fire management strategy are to minimise the risk of wildfire, enhance park use and to improve ecosystems and habitats (MET 2013). Thus, some of the goals of BNP may be compromised by the consequences of increased woody vegetation and the efficiency of their fire management strategy is crucial in achieving the stated park objectives.

In order to implement an effective fire management strategy, monitoring of variables which influence the nature of fires is vital (van Wilgen et al. 2014). Seasons of high rainfall promote increased levels of grass growth and cover, subsequently increasing fire activity (Archibald et al. 2009; van Wilgen et al. 2014; Sankaran et al. 2005). Grass and tree fuel load determine the size and intensity of fires (Govender et al. 2006). Low grass cover and high tree cover generally would mean a low risk of fire ignition but a high risk of wildfire once ignition occurs. High grass cover and low tree cover would mean a high chance of ignition but a lower chance of wildfire (Govender et al. 2006; Archibald et al. 2009; Archibald et al. 2010). 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). Monitoring antecedent rainfall (generally the previous 18 months of rainfall (Archibald et al. 2009; Archibald et al. 2010) is thus important for fire management as it predicts grass density (i.e. fuel for fires) and plays a role in the rate and extent of burnt area in savanna woodlands (Archibald et al. 2009; Archibald et al. 2010).

Historically, a policy of fire suppression was adopted by many protected areas including that of BNP (Humphrey 2018). However, fire suppression has subsequently been found to contribute to bush encroachment across many study sites (O'Connor et al. 2014; O'Connor & Stevens 2017). Globally, this has prompted an increased recognition of the important role that fire management plays in managing woody vegetation. This management involves monitoring variables and the state of woody vegetation so that a policy of early dry season (EDS) or late dry season (LDS) burning can be used to achieve the desired balance of grassy and woody vegetation, characteristic of the savanna biome. LDS season burning involves intense, large and rapidly spreading fires which are effective at reducing woody vegetation but are hard to control (van Wilgen et al. 2014; Govender et al. 2006). In contrast, EDS burning (practiced by BNP communities for millennia, involves cool, small and controlled fires which create a mosaic of patch burns promoting habitat heterogeneity (Brocket et al. 2001; Govender et al. 2006; Humphrey. 2018; Humphrey et al. 2020).

Study Aim and Objectives:

The primary aim of this study is to understand how fire, land use and rainfall have influenced woody cover change in BNP and how this knowledge can be used to manage vegetation of the region.

Objectives:

1. To investigate the nature, extent and rate of woody cover change (1999 – 2019) using repeat photography and remote sensing products.
2. To investigate inter-decadal scale patterns in rainfall, fire and land use at repeat photography sites.
3. To investigate how fire seasonality, frequency, land use and rainfall influence woody cover change and structure.
4. To explore the management and conservation implications of results from objectives 1-3.

Study Site:

BNP is situated in a semi tropical climate (west ≤ 550 mm – east > 650 mm). A rainfall gradient exists from west to east with average annual rainfall (calculated from '96/'97- '18/'19) from Namibia's meteorological station (http://www.meteona.com) in Rundu (180 km west of BNP) of 554 mm and Katima Mulilo (110 km east of BNP) of 610 mm. Temperatures reach seasonal maximum at the end of the dry season (October) and seasonal minimum during mid-winter (June-July) (http://www.meteona.com). The temperature and rainfall seasons influence the timing of what is considered early dry season (EDS: April -July) and late dry season burning (LDS: August - October) in BNP (Mendelsohn & Roberts 1997; Humphrey. 2018; Humphrey et al. 2020; Govender et al. 2006).

The landscape is characterised by SE-NW oriented sand dunes and ancient river valleys (Figure 1). Valleys, known as Omirambas, contain nutrient-rich sandy clay-loam soils, a higher water table and are characterised by Omiramba Grassland as defined by Mendelsohn and Roberts (1997). Omirambas hold the most promise for agricultural practice due to their nutrient and water availability and thus are selectively transformed into fields near settlements in the park (Mendelsohn & Roberts 1997). On the crest of the dunes, the sediment is characterised by a lower nutrient sandy composition which facilitates higher levels of drainage than the lower-lying Omirambas. The lower water table favours the root system of woodland tree species and thus the dune crests are characterised by woody cover. The characteristic savanna mosaic between grassland in the Omirambas and woodland on dune crests forms the broader vegetation unit of BNP known as Kalahari woodland (Mendelsohn & Roberts 1997).

There are two land-use types in BNP, Multiple Use Areas (MUAs), where people reside, and Core Conservation Areas (CCAs), which are dedicated to biodiversity conservation (Figure 1). The MUAs were split into East and West as a result of differing human population densities and cultural practices (Humphrey et al. 2020).The two core conservation areas considered in

this study are Buffalo to the east of the Kavango river and Kwando to the west of the Kwando river.

Methods:

Objective 1: Investigating the nature, extent and rate of change in woody cover (1999 – 2019) using repeat photography and remote sensing products.

In November 1999, 38 repeat photo sites (Figure 1) were established by Garth Owen-Smith and Lynn Halstead of Integrated Rural Development and Nature Conservation (IRDNC), as part of a fire and vegetation monitoring project. Thirty-seven of the sites were revisited in late September and early October 2019 to recapture the photos taken in 1999. At each site, a field vegetation survey was conducted assessing height structure, woody species cover and composition. This infield survey was used to score total woody cover, and cover > 3m and < 3m for photos taken in 2019 and 1999. In order to establish the reliability of this technique, change from 1999 to 2019 as derived from photos was tested against change from the satellite monitoring product Enhanced Vegetation Index (EVI). Using Google Earth Engine, EVI for each site was derived from the Landsat satellite (Huete et al. 2002; Moore et al. 2016; Chander, Markham & Helder 2009, Zander et al. 2020). Therefore, a woody cover value from 1999 and 2019 from both photos and satellite monitoring was used to investigate change.

Objective 2: Describing inter-decadal scale patterns in rainfall, fire, and land use at repeat photography sites.

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 (Funk et al. 2015). Mean Annual Precipitation (MAP) from 1996 – 2019 for each pair of sites along the B8 was calculated using CHIRPS extracted from Google Earth Engine (GEE) (Figure 2). Due to the uni-modal summer rainfall season (i.e. only one rainfall peak [i.e., 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 the following year September.

MODIS collection 6 burned area product (https://modis-land.gsfc.nasa.gov/burn) was used to calculate the frequency (fire return interval (FRI) or number of years between fires) and seasonality of fire (% burnt area in EDS vs LDS) (Giglio et al. 2018). The resolution of this MODIS fire product is 0.25 km^2 allowing individual fire history to be determined for each photo site. Sites were split into the four respective land use categories (CCA Buffalo, MUA West, MUA East and CCA Kwando) to test whether fire management differs between the land use areas.

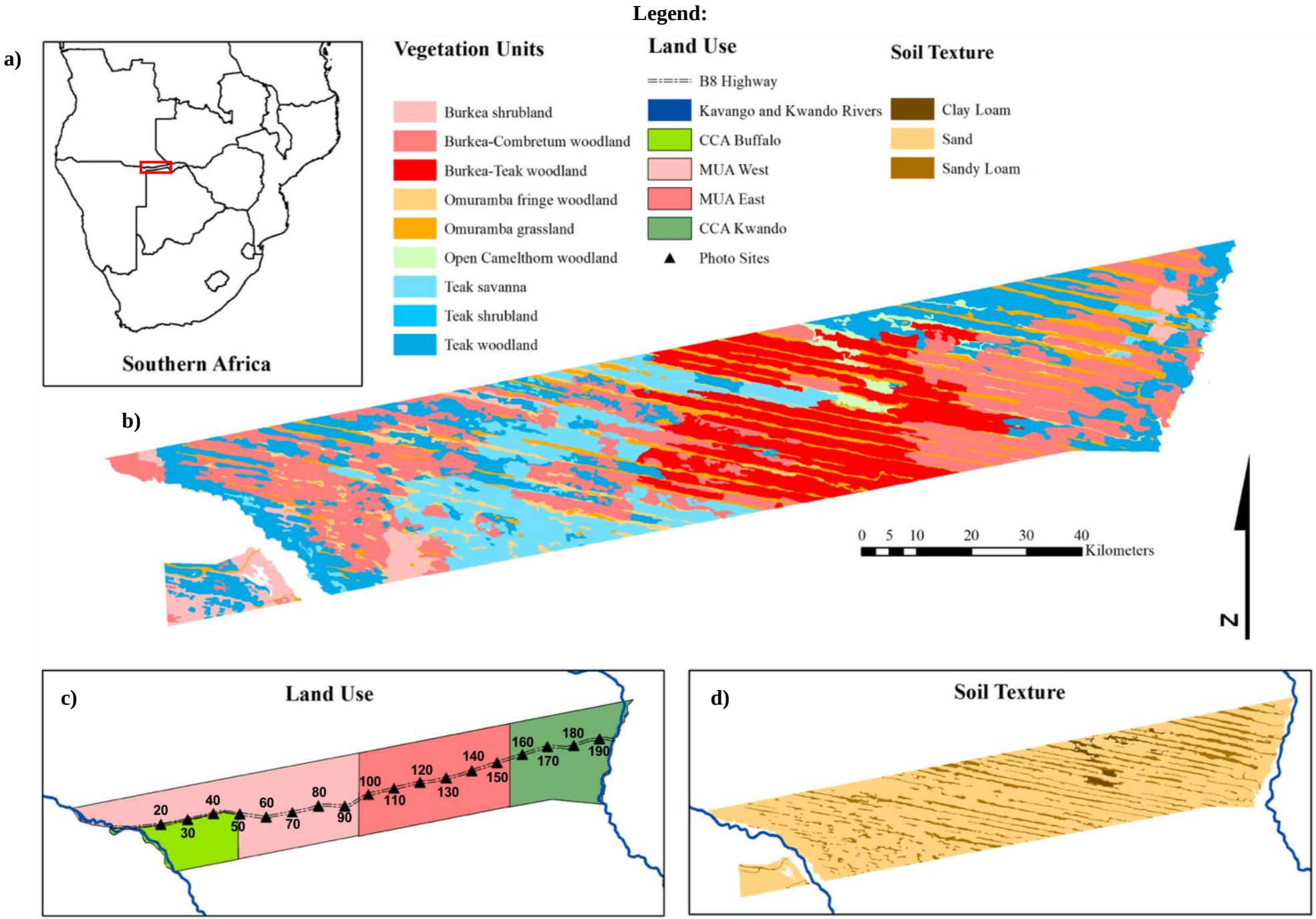
Legend:
a)
Southern Africa
Vegetation Units
Burkea shrubland
Burkea-Combretum woodland
Burkea-Teak woodland
Omuramba fringe woodland
Omuramba grassland
Open Camelthorn woodland
Teak savanna
Teak shrubland
Teak woodland
Land Use
B8 Highway
Kavango and Kwando Rivers
CCA Buffalo
MUA West
MUA East
CCA Kwando
Photo Sites
Soil Texture
Clay Loam
Sand
Sandy Loam
b)
0 5 10 20 30 40
Kilometers
N
c)
Land Use
20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
d)
Soil Texture

Figure 1: *a) Continental perspective of the location of Bwabwata National Park in southern Africa, b) vegetation units. c) The fixed-point repeat photography sites are distributed within the inland section of the park between the Okavango and Kwando River systems and land use units. d) Soil texture map (correspondence between Omuramba grassland and sandy loam soil type and the occurrence of woodland on sandy soil is evident) (data derived from Mendelsohn and Roberts. 1997).*

Objective 3: Investigate how fire seasonality, frequency, land use and rainfall drive woody cover change and structure.

A Generalised Linear Mixed Model (GLMM) was used to test the effects of fire, rainfall and land use on woody vegetation. Change in woody vegetation was considered as the response variable and FRI, MAP, EDSBA, LDSBA and land use category were explanatory variables. Due to sites being situated close to one another, position was added as another explanatory variable which controls for the lack of independence between sites.

Results:

Objective 1: The Nature and Extent of Change in Woody Cover (1999 – 2019).

Total woody cover in BNP has increased by 13% since 1999 (Figure 2 & 3). The majority of this occurred within the < 3 m woody cover category, which has increased by 9% across the whole of BNP. Less than 3 m woody cover increased at almost twice the rate of > 3 m woody cover which showed a 4% increase. The majority of < 3 m woody cover increase took place in the west of the park and > 3 m in the east of the park (Figure 2 and 3). Confidence in woody cover change results is supported by the high correlation (R^2 = 0.67; p=<0.001) of change from EVI and photos.

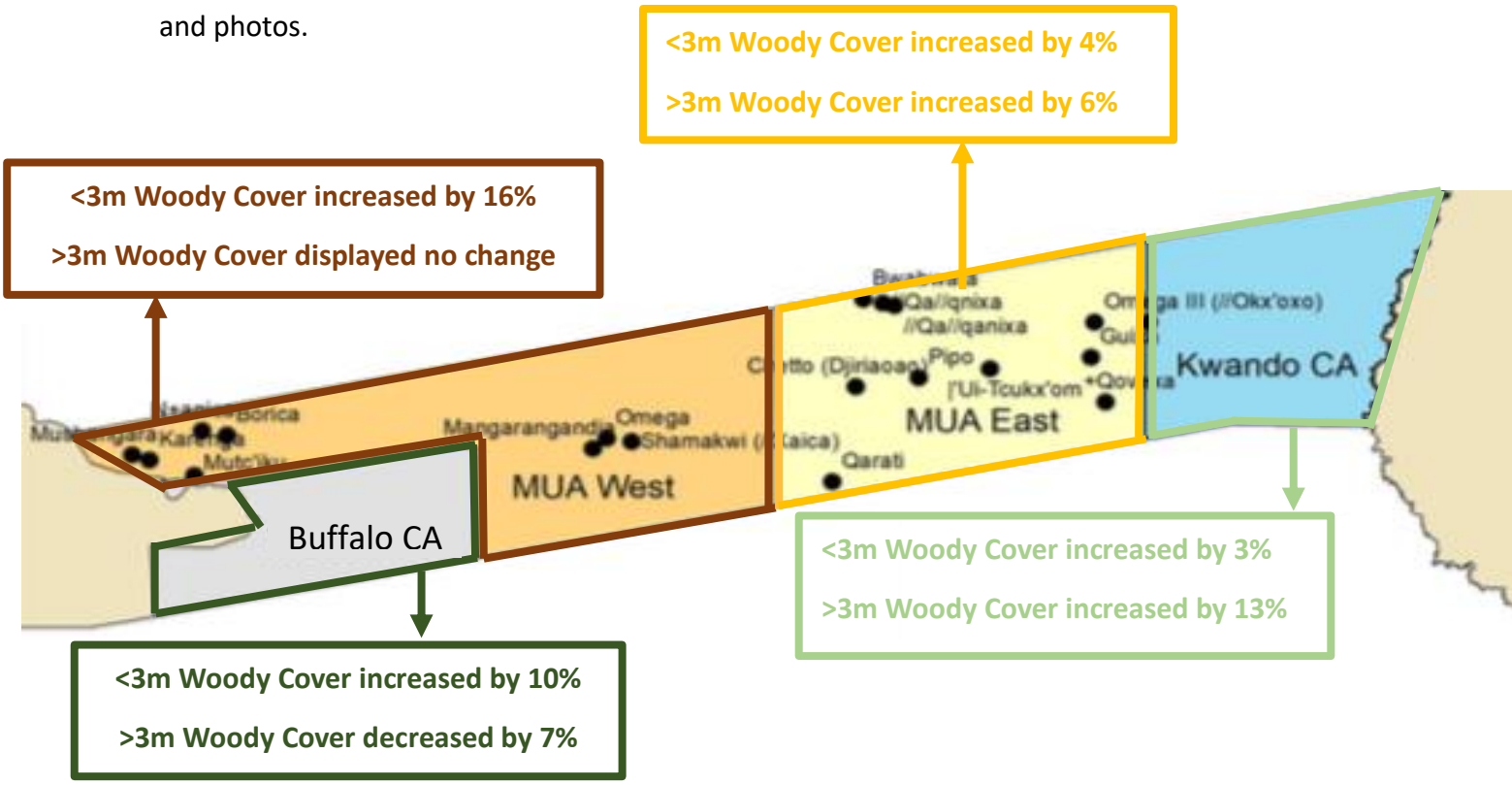

Figure 2: *Woody vegetation change in height categories summarised between land use areas. Change is calculated as difference of the means from 1999 – 2019. The majority of < 3 m increase took place in the west of the park and increases in > 3 m were predominant in the east.*

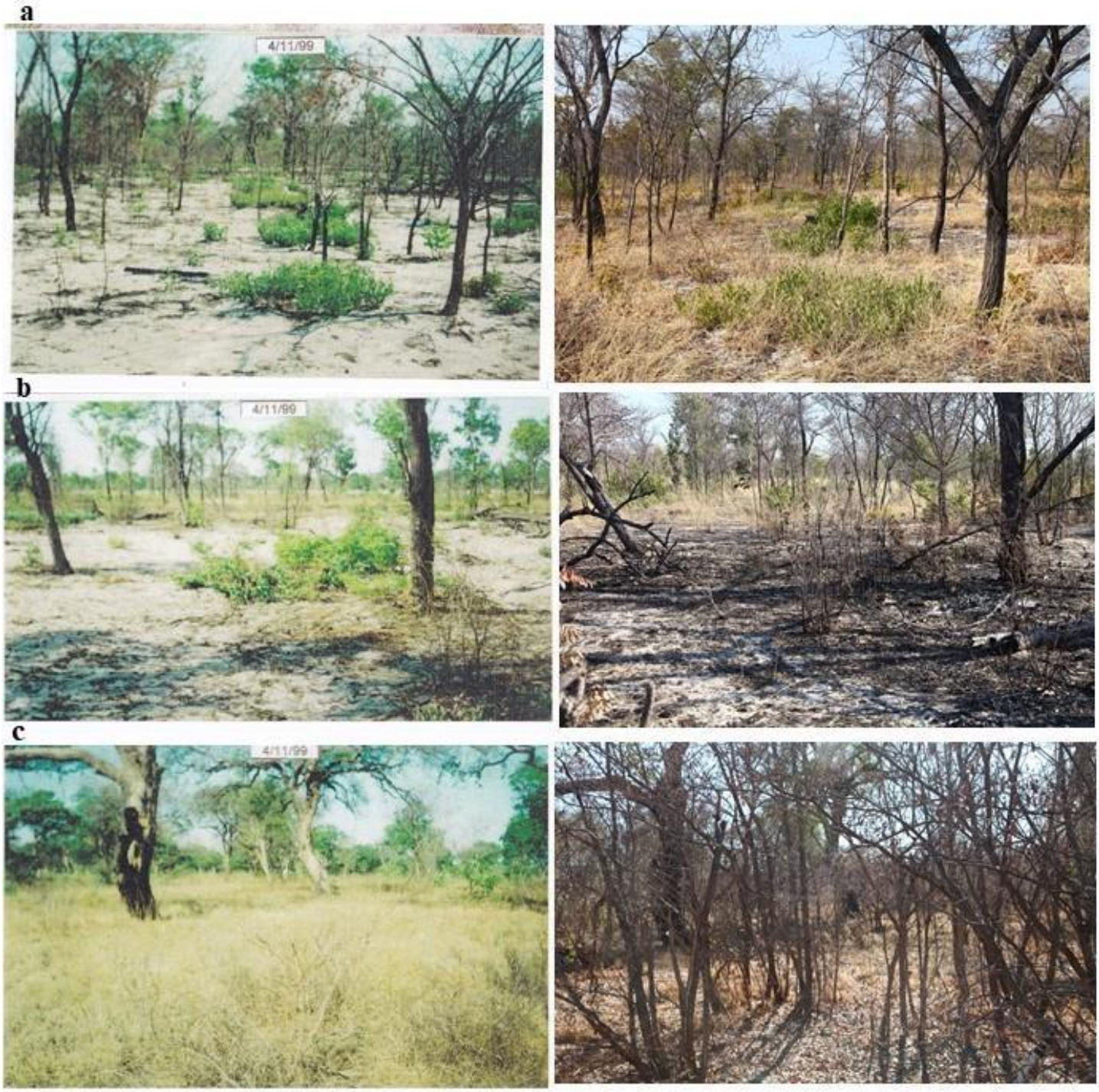

Figure 3 *Examples of woody vegetation change seen at repeat photography sites on a scale from minimal change (a) to maximum change (c). Photos on the left are taken in November 1999 and photos on the right are taken in October 2019. Photo a represents a site where an increase in woody cover of 3% was found due to a marginal increase in Terminalia sericea individuals in the mid-ground. Photo b is an example of below average (10% increase in total woody cover) change with the whole of BNP seeing an average increase of 13%. The majority of change in photo b is as a result of T. sericea thickening in the mid-ground. Photo c represents a maximum amount of change found at photo sites (36% increase in total woody cover). The two large Guibourtia coleosperma individuals are still present but are much more difficult to see as a result of an intense thickening of T. sericea which can be considered to have shaded out the swath of grass cover seen in the '99 image.*

The most dominant species was *Terminalia sericea* which covered 20% (predominantly in the west) of the surveyed area (Figure 2). The 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). Sixty percent of *T. sericea* surveyed occurred between 1 – 8 m. in height. Hundred percent of *B. massaiensis* and 70% of *O. pulcra* was < 3 m. *D. engleranum, B. plurijuga* and *B. Africana* varied in height.

Objective 2: Describing inter-decadal scale patterns in rainfall, fire and land use across repeat photography sites.

Rainfall:

MAP in the period '96/'97 – '18/'19 for pairs of sites displays a gradient of increasing rainfall from west to east (Figure 4).

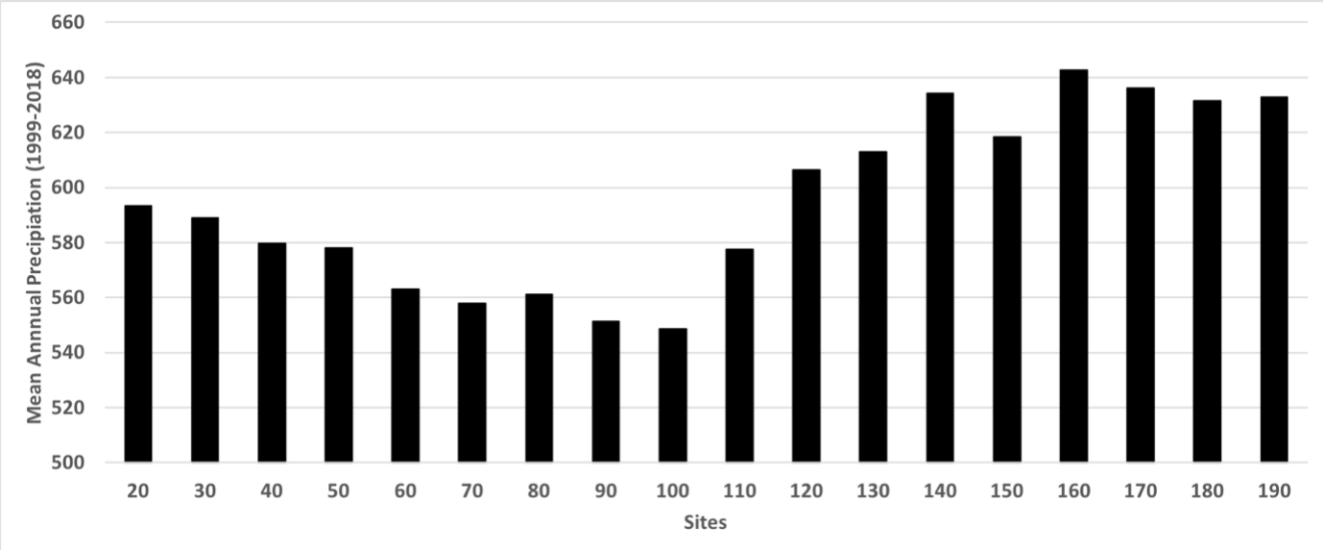

Figure 4 *Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) derived Mean Annual Precipitation (MAP; mm) for each pair of sites for the period '96/'97 – '18/'19. Sites (x-axis) are shown in pairs from west to east of Bwabwata National.*

Photo year '18/'19 received 300mm less rainfall than photo year '98/'99 and has the lowest recorded rainfall since the '96/'97 rainfall season (Figure 5). The two year antecedent rainfall total for photo year '18/'19 is 920 mm and for photo year '98/'99 is 1010 mm. Considering the difference (90mm) in antecedent rainfall to photo years (920 and 1010 mm), the potential influence of a contrast in rainfall between photo years influencing the results of woody vegetation change analysis is low, however, this difference may influence the fire return interval for the respective years.

Confidence in the accuracy of rainfall as derived from the CHIRPS dataset is high. 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)

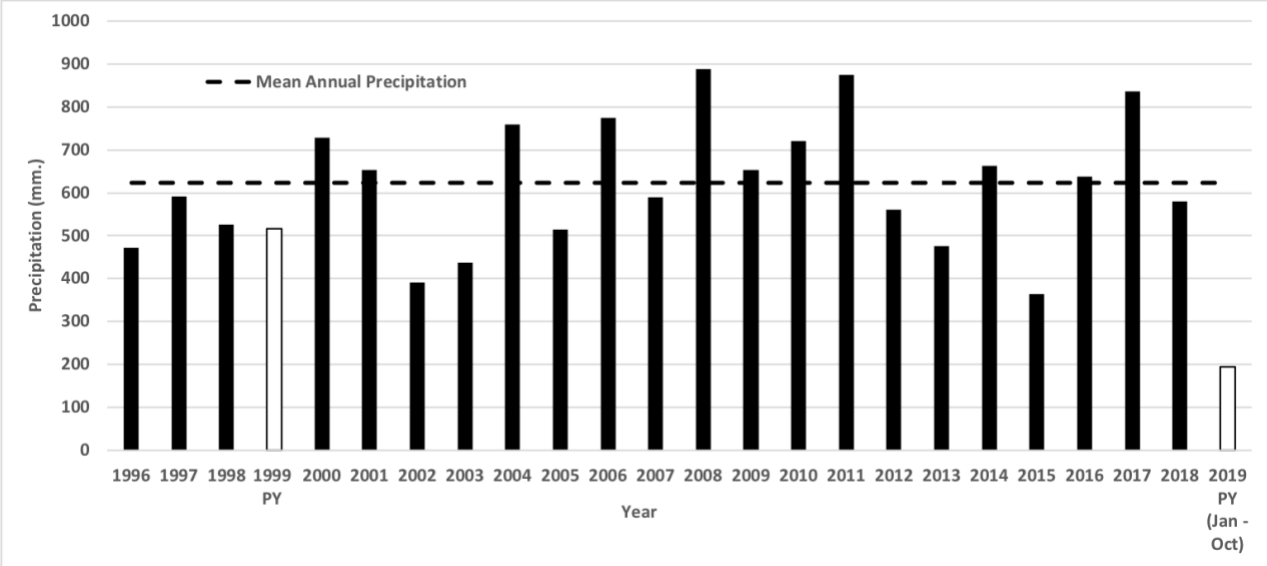

Figure 5 *Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) derived total annual rainfall for Bwabwata National Park from October – September rainy season '96/'97 – '18/'19. The '98/'99 and '18/'19 season when photos were taken are marked with white bars. The Mean Annual Precipitation (MAP) is marked with a dashed line in order to place antecedent rainfall of photo years into context.*

Fire and Land Use:

The average FRI for all sites is seven years with sites in the MUA East displaying above average FRI and the majority in MUA West displaying below average FRI (Figure 6). The average EDSBA across BNP is much lower than LDSBA as only 8% of site area was burnt in the EDS as compared to 26% during the LDS (1999 - 2019). Sites within the eastern portion of the park (MUA East and Kwando CCA) display below average LDSBA compared to most sites in the west of the park where LDSBA is above average.

All three fire variables differed significantly among land use categories (Figure 6, FRI: $F=38.86$, $p=<0.001$; EDSBA: $F=5.35$, $p=<0.001$; LDSBA: $F=30.17$, $p=<0.001$). LDSBA varied the most between land use categories. The western land use categories (MUA West and Buffalo CCA) displayed significantly higher LDSBA than the eastern categories (MUA East and Kwando CCA). The most extreme difference in LDSBA was found for MUA West and MUA East where the portions of a site burnt in the LDS differed by an average of 27%. FRI was similar for the two CCAs but the MUA East and MUA West contrasted significantly with an average of 9 years difference in the time taken for fires to return to a site in each land use area. EDSBA displayed less significant differences between land use areas. Kwando CCA displayed the highest portion of EDSBA and Buffalo CCA the lowest. There is a significant difference between land use areas in terms of fire management application and this difference is most evident between the categories of MUA West and MUA East.

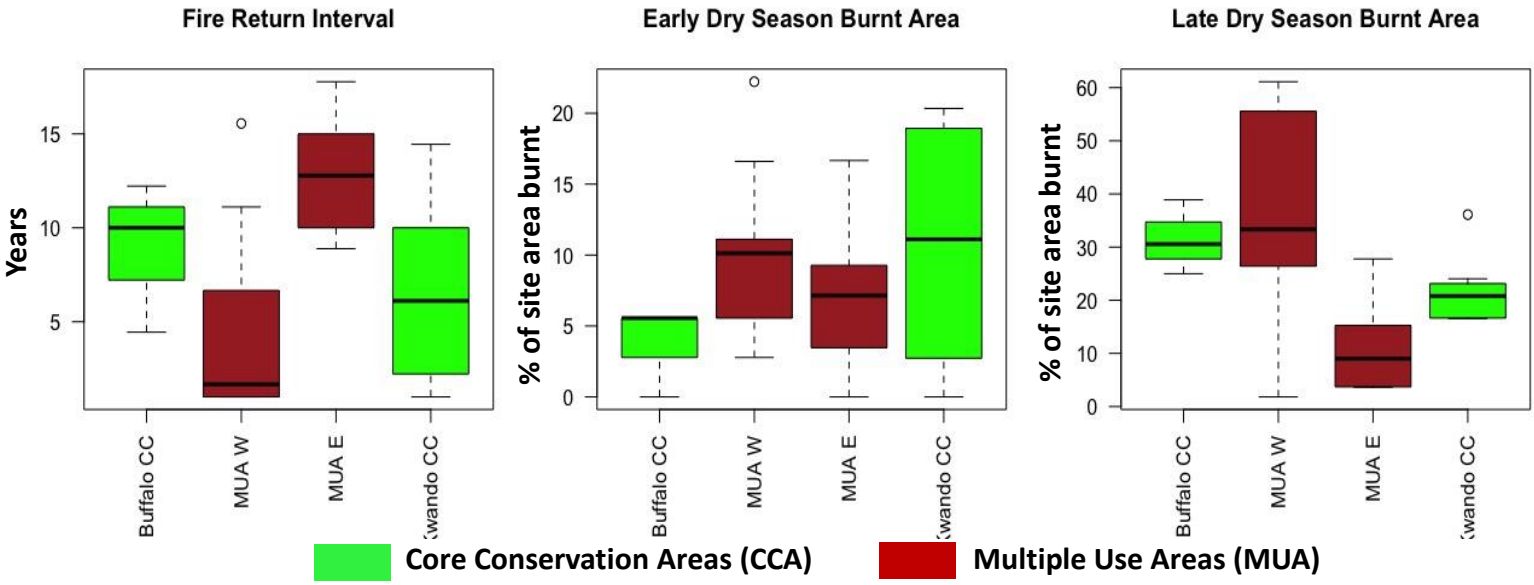

Figure 6 *Box and whisker diagrams of the three fire regime variables (FRI, Early Dry Season Burnt Area, Late Dry Season Burnt Area) derived from MODIS Burned Area product (2000 – 2018), grouped by the BNP land use categories (CCA Buffalo, MUA West, MUA East and CCA Kwando). Fire Return Interval displays the number of years it takes for a fire to return to a site. Early Dry Season Burnt Area displays the percentage of a site which burns during the early dry season (April – July). Late Dry Season Burnt Area displays the percentage of a site which burns during the late dry season (August – October). The CCA protected areas in BNP are highlighted in green and the MUA East and West in red.*

Objective 3: Investigating how fire seasonality, frequency, land use and rainfall drive woody cover change and structure.

Mean Annual Precipitation (MAP), LDSBA and FRI displayed the most significant effects on all woody cover categories (Figure 7). Specifically, LDSBA showed contrasting effects on < 3 m and > 3 m woody cover categories. The < 3 m woody cover was shown to increase and the > 3 m woody cover to decrease with the more LDSBA . The LDSBA was also shown to decrease total woody cover. The FRI had the same effect on all categories of woody cover. Increasing FRI (i.e. the less frequent a fire visited a site), the less change in woody cover occurred. Higher MAP decreased < 3 m woody cover and increased > 3 m woody cover. As expected, higher MAP resulted in a higher total woody cover.

EDSBA's strongest effect was on < 3 m woody cover. As the portion of a site burnt in the EDS increased, < 3 m woody cover significantly decreased. EDSBA has the same effect for all woody cover categories, however, the level of significance was not high for total and > 3 m woody cover

The most significant effect of land use category was that of MUA West on < 3 m woody cover and > 3 m woody cover. This land use area displayed a negative effect on woody cover > 3 m and a positive effect on < 3 m woody cover.

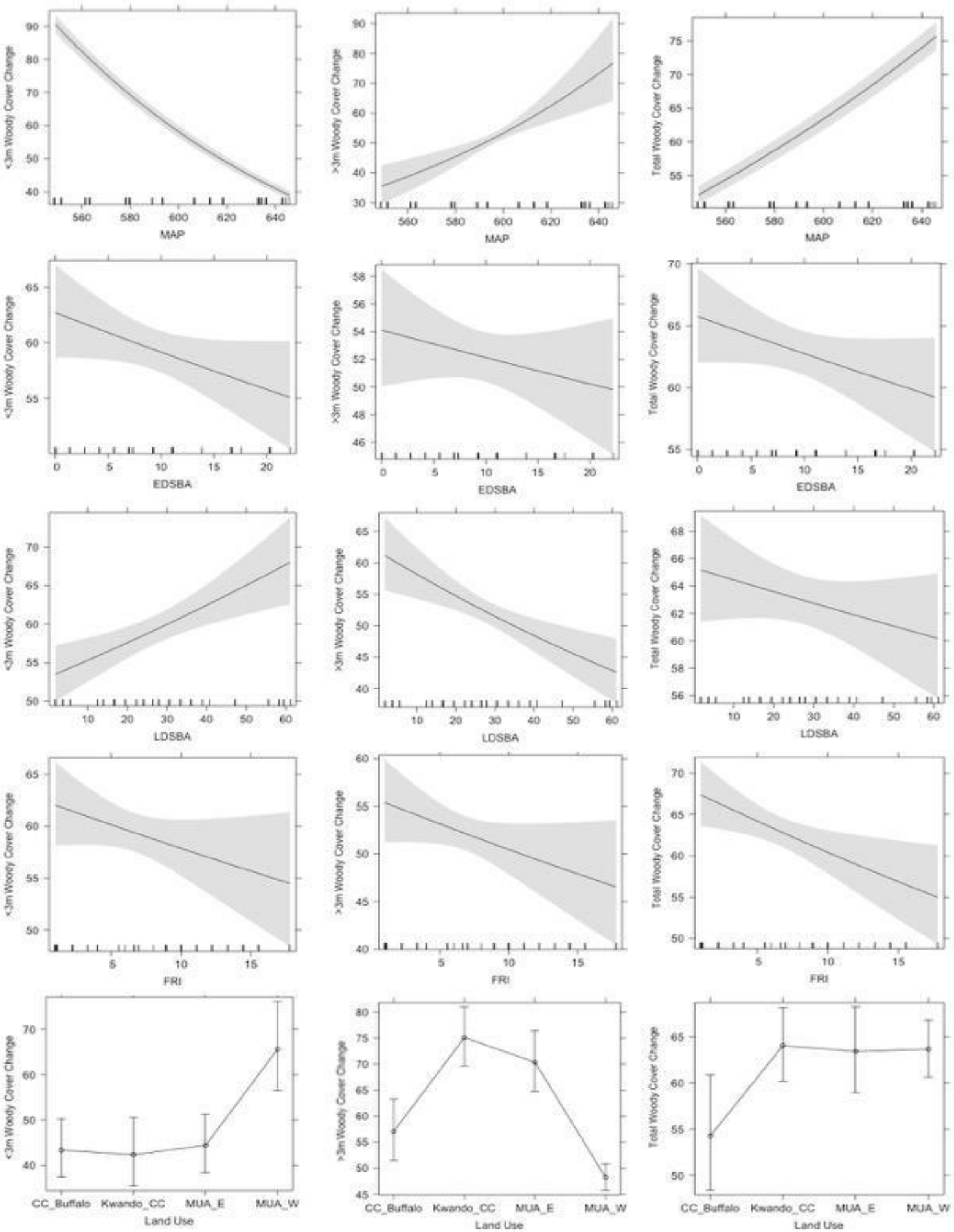
<3m Woody Cover Change
>3m Woody Cover Change
Total Woody Cover Change
MAP
EDSBA
LDSBA
FRI
CC_Buffalo
Kwando_CC
MUA_E
MUA_W
Land Use

Figure 7: *Fitted regression functions for predicted effects of MAP, land use and fire on woody cover. Derived from the Generalised Linear Mixed Model with untransformed data and slope angle indicating direction of change. Each explanatory variable (x-axis), Mean Annual Precipitation, Early Dry Season Burnt Area (EDSBA), Late Dry Season Burnt Area (LDSBA), Fire Return Interval (FRI) and Land Use category is arranged per row. Predicted effects are plotted for each response variable (y-axis; % change), < 3 m Woody Cover Change, > 3 m Woody Cover Change and Total Woody Cover Change in columns regardless of size or significance of effect. Y axis scales may differ according to the range of response observed for each category of woody cover change. The size of grey area around slope lines indicates the accuracy of fit for predicted effects. Dispersion of raw data is indicated in upper and lower quartiles for explanatory variable of land use - for the rest of the explanatory variables, the x-axis contains short vertical lines with thicker lines indicating a density of raw data points.*

Discussion:

Objective 1: Bush Encroachment and Homogenisation of Vegetation Structure.

Woody vegetation cover (canopy cover) increased by a total of 13% over the period 1999 – 2019, 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). These results provide evidence for the occurrence of bush encroachment in BNP. The majority of encroachment occurred within < 3 m woody cover, comprising 9% of the total 13% increase, suggesting a change in vegetation structure towards shrubs rather than large trees. The increase in < 3 m was predominant in the western section of the park (Buffalo CCA and MUA West) with the eastern sections (MUA East and Kwando CCA) displaying a predominant increase in > 3 m cover. This suggests that there is homogenisation of the vegetation structure to shrub cover occurring particularly in the west of BNP. Such a phenomenon should warrant concern considering the important role of heterogenous vegetation structure on biodiversity and thus tourism (Sirami et al. 2009; Benton et al. 2003).

The dominant increase of < 3 m woody cover in the western land use areas indicates that there is currently a high fuel load within the flame zone of grass and ground layer fires (van Wilgen et al. 2014; Govender et al. 2014). An increase in woody vegetation is associated with the shading out of the grass layer with less grass available to start fires (Hoffmann et al. 2005). However, in the case of reduced grass fuel load, there would likely be a concomitant increase in dry and dead woody vegetation on the ground layer of a similarly flammable property to that of grass (van Wilgen et al. 2014; Govender et al. 2014). Therefore, it is possible to conclude that the risk of wildfire in the west of the park has increased since 1999.

The dominance of *T. sericea* (covered 20% of sites at varying heights) and *B. massaiensis* (covered 10% of sites at < 3 m) in the west of the park provides potential evidence for their classification as indigenous encroachers (Curtis and Mannheimer, 2005). Both species have been observed to coppice and resprout at higher rates than other woody species following disturbance such as fire (Nefabas & Gambiza 2007; Holdo 2005). 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 *B. plurijuga* or a comparison of *B. massaiensis* and *T. sericea* cover cannot be concluded.

The comparison of the repeat photography derived woody cover change estimates and the EVI derived productivity change between 1999 and 2019 returned a significantly high correlation (R2=0.67; p<0.001). Though repeat photography is sometimes criticised as a qualitative or subjective analysis and not as replicable as remote sensing based change studies (Webb et al. 2010), these results show that repeat photography returns reliable woody cover change estimates (as also shown by Rohde et al. 2019; Hoffman et al. 2010; Venter et al. 2020 and others).

Objective 2: Spatial and Temporal Patterns of Rainfall and Fire across BNP.

Rainfall as derived from the CHIRPS dataset correlated significantly with observed rainfall experienced at the nearest weather stations to BNP (Katima Mulilo: R^2=0.93 and p=<0.001; Rundu: R^2=0.88 and p=<0.001). Thus, it is concluded that the CHIRPS dataset can reliably be used to determine rainfall variables in areas where weather station data is not available.

Analysis of CHIRPS derived MAP for each pair of photo sites revealed a decreasing gradient of rainfall from east to west of BNP. On average, in the order of 40mm more rainfall per annum occurs in the east of the park than the west. This may explain why there is a greater increase in > 3 m woody cover in the east of the park. Woody species in the east seem to have a resource advantage allowing them to grow above the ground fire layer faster than woody species in the west.

The fire analyses revealed significant differences in FRI and LDSBA between MUA West and MUA East. MUA West contained significantly higher LDSBA (34%) and a lower FRI (every 2 years) at photo sites compared to MUA East (7%; 13 years). This may explain the divergence of woody cover change between the two land use areas. Due to the association of late season fires with high intensity fires (Govender et al. 2006), this result suggests that fires in MUA West are hotter and larger than fires in MUA East and thus can be considered as high risk and hard to control (Humphrey 2018; Govender et al. 2006; van Wilgen et al. 2014). The significant difference in fire seasonality and frequency between the two areas despite relatively close proximity and similar vegetation suggests that there is a discrepancy in fire management practiced by the associated communities.

Objective 3: Investigating how fire seasonality, frequency, land use and rainfall drive woody cover change and structure.

Results of the GLMM model suggest that rainfall (MAP), fire frequency (FRI) and seasonality (LDSBA and to some extent EDSBA) are primary drivers of woody vegetation in BNP considering their highly significant correlation with woody cover change. However, the drivers which influence the vegetation height categories of woody cover between land use areas differ.

Increased LDSBA reduces > 3 m woody cover as found by van Wilgen et al. (2014) and others. Lower LDSBA increases > 3 m woody cover. Therefore, the higher cover of < 3 m woody vegetation in MUA West can be attributed to the land use area's practice of LDSBA fire management.

A high FRI (i.e. less frequent fires) at photo sites reduced change between 1999 to 2019 in all woody cover categories. This result supports the central role which fire plays in vegetation change. 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).

Higher MAP was associated with higher total woody cover change and > 3 m woody cover. This effect was opposite on < 3 m woody cover, thus supporting the assumption that higher > 3 m woody cover in the east and < 3 m cover in the west can be attributed to the west-east rainfall gradient. If MAP is the primary driver of vegetation change in BNP then considering the association of increased MAP and total woody cover (Sankaran et al. 2005), one would expect that rainfall would have been above average over the last 20 years and this could perhaps explain the 13% increase in woody vegetation. However, antecedent rainfall is relatively similar for both photo years (Figure 5). The fact that the fire variables differ across the land use areas, but bush encroachment has occurred across BNP suggests that there are larger scale drivers such as increasing atmospheric carbon dioxide (CO_2) at play.

Objective 4: Management Implications and Conservation Concerns

In order to effectively achieve BNP's primary objectives of biodiversity preservation and sustainable economic development, an understanding of the state of woody vegetation and its change is important. Woody vegetation forms an essential component of the services which an ecosystem can provide in terms of biodiversity and livelihood preservation (Eldrige et al. 2011). This study has supported the idea that fire is a key determinant of the nature, extent and rate of woody vegetation change and importantly, that local management makes a difference to these factors. Due to BNP occurring within the greater KAZA-TFCA, controlling herbivory as a means of managing vegetation change is particularly difficult. Thus, the efficient implementation of park fire management policy informed by monitoring is one of the most important actions which can be taken to achieve their primary goals.

While the impact of herbivory on post fire recovery of vegetation was not part of the scope of this study, this impact requires investigation. Domestic livestock and game herbivore density will decrease the rate at which vegetation is able to recover from fire (e.g. Roques et al. 2016). MUA West contains a denser human population (predominantly around Omega 1 village) than MUA East (MET 2013 & 2016) and during fieldwork for this project it was observed that settlements in the area are accompanied by a concentration of domestic livestock (predominantly cows). Future research and monitoring should quantify livestock concentrations across BNP and assess the possible impact which it might have on woody species post fire recovery.

The increasing cover of woody vegetation in BNP is consistent with the trend of bush encroachment in savannas found elsewhere. Due to the relatively low antecedent rainfall received by the region before the 2019 study period compared with the 23 year MAP (Figure 5) it is likely that other drivers of bush encroachment such as atmospheric carbon dioxide concentrations are at play (O'Connor et al. 2014; Skowno et al. 2017; Stevens et al. 2016;

Higgins & Scheiter 2012; Haverd et al. 2020). This highlights how management on a park level is influenced by global as well as local drivers and any potential contribution to such global or larger scale drivers (e.g. CO_2 emissions) needs to be considered.

The proliferation 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 area of LDS burning is recommended.

With an increasing total woody cover across the park, one would also anticipate a reduction in grass and herb production (Scholes 2003; Smit 2004; Walker et al. 1972). This would alter the ecosystems primary and secondary production chains. Therefore, it is important for management to monitor how this encroachment has and will influence faunal abundance and movement as determined by primary production of grass and herb layers.

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