The role of humans, climate and vegetation in the complex fire regimes of north-east Namibia

Glynis Humphrey

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Declaration

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Glynis Humphrey (22nd July 2018)

Abstract

This thesis explores how interactions and feedbacks between environmental and socio-historical factors influenced fire management dynamics in north-east Namibia. Fires are mostly human ignited, but precipitation patterns influence when and where fires can occur, and there are feedbacks between fire, climate and vegetation cover. Yet, knowledge of historical and contemporary use of fire by societies is fragmented in southern Africa, and is therefore disputed. As a result, the complex interaction between climate, vegetation and human factors that influence fire dynamics remains poorly understood.

This thesis explores how the political history, livelihoods, land-use practices, policy changes, vegetation and climatic variation are relevant to present-day fire regimes and management. The study is located in Bwabwata National Park (BNP), north-eastern Namibia, which is managed for both conservation objectives and people's livelihoods. The park is inhabited by the Khwe (San), former hunter-gatherers, who have been using fire for millennia, and the Bantu-speaking Mbukushu people, who are agriculturalists and pastoralists. The area has been subject to colonial regimes, war, inter-ethnic conflict, social-political resettlement, conservation and associated changing fire management approaches since the 19th century. The vegetation includes omiramba grasslands, savanna-woodlands, Burkea shrublands and riparian types. For this study, qualitative semi-structured interviews with Namibian stakeholders, in combination with multi-year (2000 – 2015) remote sensing products, were used to understand the past and present fire regime characteristics.

Interviews with community stakeholders revealed that the Khwe and Mbukushu communities use fire for a diverse range of livelihood activities. Specifically, early season burning is used to assist in hunting, tracking and gathering of veld foods, and for improving forage for livestock. The traditional practice of early season burning is not only culturally and ecologically significant, but has positive consequences for Bwabwata National Park's conservation objectives, and fire policies, in terms of suppressing late season fires. However, explicit marginalisation of the Khwe since the C19th due to colonial regimes and cross-border wars has disrupted traditional fire management. Interviews with government and conservation stakeholders revealed recognition of the benefits of early season burning for biodiversity. Furthermore, despite the complex social-ecological history of the area, recent policy changes reveal an emerging willingness to incorporate traditional fire management into fire management policy.

Moderate Resolution Imaging Spectrometer (MODIS) data was used to analyse the fire regime (burned area, fire frequency, fire number and size, intensity, and seasonality), together with climate (El Niño Southern-Oscillation [ENSO] events; local rainfall patterns) and vegetation data in multiple use (inhabited) and core conservation areas, over a time period that covered a shift in policy from fire

suppression (2000-2005) to early season burning (2006-2015). Results from the analysis of the MODIS data revealed that a high frequency of early season burning in the inhabited areas of the park reduced the late season fires and dampened the local rainfall and burned area relationship. Nonetheless, grass growth (i.e. available biomass) during ENSO wet season events (La Niña) resulted in greater area burned and fire sizes in above average rainfall years in the early dry season in the community inhabited areas. In contrast, higher fire intensity and larger fire sizes were evident in the conservation core areas where people were not actively burning. Fire frequencies and burned areas were highest in the omiramba grasslands and savanna-woodlands, in the early dry season under the early burning policy in the east of the park, which reduced fire intensities in these vegetation types. In contrast, burning in the Burkea shrublands was frequent in the late dry season, at higher intensities in the Western conservation area under both policy phases. This study indicates that burned area depends on rainfall, ignitions and fire sizes in inhabited landscapes, where people practice early burning, which has consequences for decreasing the intensity and therefore spread and impact of fires on vegetation.

This study highlights the complex interactions between people, rainfall seasonality and fuel availability, as well as the need to incorporate historical factors. The study uses a pyrogeographic framework to integrate the social-cultural, climatic-biological, and topographic-environmental factors with fire. The synthesis reveals that the park communities are currently socially and ecologically vulnerable to global environmental change, given their dependence on fire for ecosystem services. However, the study also highlights how traditional fire management, and specifically early season burning, improves food security and contributes to livelihood subsistence and biodiversity conservation in the park.

BNP is characterised by complex historical and present-day social-ecological fire dynamics. The study highlights the importance of understanding the historical and political context of fire for determining and managing current spatial-temporal fire patterns. Respect for diverse fire knowledge and culture, communication and shared governance are central to improving community livelihoods and fire management strategies in BNP. Specifically, the shared interest in early season burning provides a point of confluence between diverse stakeholders in BNP and a basis for fire management policies that benefit biodiversity as well as livelihoods.

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Glossary

Agropastoralist: A person that herds livestock and cultivates crops for subsistence.

Ancestral territory: Natural territory of an inhabiting ethnic group in a geographic area.

Biomass connectivity: A continuous layer of vegetation (i.e. grass and tree biomass) available to burn in a landscape.

Community Based Natural Resource Management: Development programmes that emerged in the 1990s that sought to return the stewardship of biodiversity, and natural resources to local communities through participation, empowerment and decentralization.

Community Based integrated Fire Management (CBiFM): CBiFM programmes recognize the value of indigenous and/ or local communities fire knowledge, and aim to actively include communities into decision-making processes that involve fire management in an area.

Core Area: Conservation areas designated for special protection to support key government constitutional biodiversity objectives, and controlled tourism, which comprise the Kwando , Buffalo and Mahango core areas in Bwabwata National Park.

Early Burning Policy: The use of controlled fires in the early dry season (April – July) to reduce and fragment the vegetation to create a landscape of burnt and unburnt patches in Bwabwata National Park (2006 – 2015).

Early Dry Season Burns: Ignitions that are applied in the landscape in the early dry season between the months of April and July.

Early burning: Prescribed fire early in the dry season (April-July), before the leaves and undergrowth are completely dry, which is carried out as a precaution against more severe fire damage later in the dry season.

Ecosystem Services: Natural resources (e.g. food, water, climate regulation) that provide benefits to people.

El Niño Southern-Oscillation (ENSO): Is an irregular periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean. The warming phase is known as El Niño and is associated with a dry period and La Niña is associated with wet events (i.e. above average rainfall periods).

Fire ecology: The study of the interactions and relationships between fire and the biotic and abiotic environment.

Fire frequency: The number of fires that occur in a spatially defined area (e.g. in a pixel) and time period.

Fire intensity: Is a description of fire behaviour quantified by the temperature of, and heat emitted at the flaming front of a fire.

Fire management: Management or practice of controlling the fire regime for a specified desired outcome (e.g. reduce late season fires, regenerate vegetation, and / or reduce shrub layer).

Fire radiative power (FRP): The rate of radiant energy release measured in megawatts (MW) detected from actively burning fires from overhead earth observing satellites (e.g. MODIS).

Fire regime: Repeated characteristic patterns of fire in a spatially defined area, that include type of fire, severity, intensity, size and the frequency of fire.

Fire seasonality: The season of burn is defined by the time of fire, which is influenced by weather variables (e.g. rainfall, moisture content of the vegetation), temperature, wind, and humidity). People can choose when to burn (e.g. time of day, and the season [early or late dry season]).

Fire weather: High winds and temperature, in combination with low humidity that typically prevail during the late dry season (Aug – Nov).

Fuel load: The density of vegetation (i.e. biomass) available to burn.

Hunter-gatherer: a form of livelihood dependent on hunting animals, and gathering important 'veld foods' for subsistence.

Indigenous/traditional fire management: Fire related knowledge, beliefs and practices that have been developed and used for specific purposes by ancestral or tribal ethnic communities.

Induna: Village level traditional leaders (i.e. chief) that represent an ethnic community.

Late Dry Season Burns: Ignitions that naturally occur (i.e. caused by lightning strikes) and /or are applied in the landscape in the late dry season between the months of August and November.

Modern humans: Refers to members of our own species (*Homo sapiens* sapiens) who have lived since prehistoric times.

Multiple Use Area: An area zoned for inhabitant communities, community-based tourism, and trophy hunting, as well as the harvesting of natural resources vital to the communities livelihoods in Bwabwata National Park.

Omuramba: Palaeo-environmental feature that represents a low-lying fossil drainage area between dune crests that is typically characterised by grasslands in the Kalahari savanna-woodlands in Bwabwata National Park.

Patch mosaic burning: A fire pattern in the landscape that produces a range of different size patches with unique fire characteristics and histories. The use of this strategy results in variation in size, number, locality, seasonality and intensity of fires, and area burnt per year.

Pyrogeography: A discipline that integrates the socio-cultural, biological and geophysical aspects of fire regimes and recognizes the importance of these factors in making decisions for fire management that consider livelihoods, ecosystems and climate.

Rinderpest ('cattle plague'): An infectious viral disease of cattle and other even-toed ungulates (e.g. buffalo). It arrived in Africa in colonial times, and in 1887 resulted in the death of most cattle, resulting in famine and poverty in sub-Sharan Africa.

Social-ecological fire system: The interactions and feedbacks between climate, vegetation, people and fire in a defined system.

Stakeholder: A person, or community, and or institution who has an interest and a stake in fire management.

Suppression policy (SP): The prevention and suppression of fire from 2000 to 2005 in Bwabwata National Park.

Traditional Authority: Ethnic based leadership that requires recognition from the State in order to assume legally mandated roles, which may have not had formal leaders in the past.

Traditional: Is used to indicate indigenous concepts and practises used by the inhabitant communities in Bwabwata National Park.

Tribal homeland: a region created or considered by a State for a people of a particular ethnic origin.

Tsetse fly: A large biting fly found in the open woodlands in mid-continental Africa that feed on vertebrate blood, and transmit lethal diseases in animals and humans (e.g. sleeping sickness).

Veld food resources: Plant resources (e.g. fruits, seeds, leaves and underground tubers) that people consume for their livelihood subsistence as an ecosystem service.

List of Acronyms

Acquired Immune Deficiency Syndrome	AIDS
Area of interest	AOI
Bwabwata National Park	BNP
Core Area	CA
Computer assisted qualitative data analysis	CAQDA
Community Based Integrated Fire Management	CBiFM
Community Based Natural Resource Management	CBNRM
Community Game Guards	CGG
Community Resource Monitors	CRM
Caprivi Liberation Front	CLF
Directorate of Forestry	DoF
Early Burning Policy	EBP
Early Dry Season	EDS
Environmental information System	EIS
El Niño Southern Oscillation	ENSO
Earth Observing System	EOS
Exploratory spatial data analysis	ESDA
Environmental Systems Research Institute	ESRI
Food and Agricultural Organisation	FAO
Fire Danger Index	FDI
Fire Information for Resource Management Systems	FIRMS
Fire Management Plan	FMP
Fire radiative power	FRP
Georeferenced Tagged Image File Format	GeoTIFF
Global Fire Monitoring Centre	GFMC
Green House Gases	GHG
Geographical Information System	GIS
Government of the Republic of Namibia	GRN
Hierarchical digital format	HDF
Human Immunodeficiency Virus	HIV
Integrated Forest Fire Management Programme	IFFP
Integrated Fire Management	IFM
International Forest Fire News	IFFN
Integrated Rural Development and Nature Conservation	IRDNC
Intertropical convergence zone	ITCZ
Kyaramacan Association	KA
Kavango/Upper Zambezi Transboundary Conservation Area	KAZA-TFCA
Kruger National Park	KNP
Late Season Burning	LDS
Local indicators of spatial autocorrelation	LISA
MODIS global burned area product	MCD45A1
Multivariate ENSO index	MEI

Ministry of the Environment and Tourism	MET
Moderate Resolution Imaging Spectrometer	MODIS
Multiple Use Area	MUA
Ministry of Water, Agriculture and Forestry	MWAF
National Aeronautics and Space Administration	NASA
Namibian Defence Force	NDF
Namibian Finland Forestry Pilot project	NFFP
Namibian Forestry Strategic Plan	NFSP
Non-Government Organisation	NGO
National Oceanic & Atmospheric Administration	NOAA
Neal Real-Time	NRT
Protected Area	PA
Peoples Liberation of Namibia	PLAN
Polytechnic of Namibia	PoN
Participatory rural appraisal	PRA
Sound African Development Community	SADC
South African Defence Force	SADF
Suppression Policy	SP
Sea Surface Temperatures	SST
South West Africa	SWA
South West Africa Administration	SWAA
South West African Peoples' organisation	SWAPO
Traditional Authority	TA
University of Cape Town	UCT
University of Namibia	UNAM
National Union for the Total Independence of Angola	UNITA
United Nations University	UNU
Coordinated Universal Time	UTC
Universal Transverse Mercator	UTM
West African Standardized Time	WAST
World Geodetic System 1984	WGS84

Chapter 1 Introduction

Fire in context

Natural fires have been part of the Earth system for over 350 Myr. (Scott, 2000; Scott *et al.*, 2016). Historically, fire was driven by lightning ignitions in fire-prone ecosystems across the globe (Archibald *et al.*, 2013; Giglio *et al.*,2013; Scott *et al.*, 2014). Flammable ecosystems persisted with fire tolerant and/or fire resistant plant traits for millions of years before anthropogenic fires became prominent (Bond *et al.*, 2005). Consequently, evolutionary characteristics have arisen from the universal phenomenon of fire (Bowman & Murphy, 2011) pertaining to vegetation and humans. Significantly, fire has a deep cultural history in Africa (Pyne, 1998) as modern humans (*Homo sapiens*) co-evolved in a flaming savanna environment approx. 200, 000 yrs. ago (Scholes & Archer, 1997; Trollope & Trollope, 2004; Scott *et al.*, 2014). The date at which fire was first intentionally used by *Homo* is a matter of continuing controversy (Caldararo, 2002), although natural ignitions would have been used by modern humans to spread and/or contain fire over the last 200, 000 kya (Scott *et al.*, 2014).

Today, fire regimes are integral elements linking climate, vegetation, people and land-use across a range of spatial and temporal local, regional and continental scales (Lavorel *et al.*, 2007; Le Page *et al.*, 2010). During the last two decades, state of the art remote sensing techniques have augmented insight into global fire regimes, and prescribe that fires across the globe are largely increasing (Archibald *et al.*, 2010; Goldammer & de Rhonde, 2004). The burn estimates and the findings of these global level studies are widely cited, and they are extremely useful in providing a timely picture and analyses of the extent of fires across space and time (Dennis *et al.* 2005; Trigg & Roy, 2007). Remotely sensed data is a valuable tool for fire managers for monitoring fires (Flasse *et al.* 1998) and because resource managers require information to understand an areas fire history, the locations, trends and sizes of the areas burned (Trigg & Roy, 2007), as well as to decide what management strategy would be most effective in controlling fires (Frost, 1999; Parr & Brockett, 1999). However, more recently it has been found in savannas across the world, that fire regimes are changing over time and the area burned is decreasing (Laris *et al.*, 2018). The global expansion of agricultural, and the subsequent removal of grassy savannas are described as the major drivers of the observed decline in fire activity (Andela *et al.*, 2017).

Global datasets have shown that human presence in landscapes increases the number of ignition events over and above lightning strikes (Archibald, 2016). Thus, human-made fires are attributed to be the majority, whether accidental or deliberate (Andreae, 1992; Cahoon *et al.*, 1992; van Wilgen *et al.*, 2004; Dwyer *et al.*, 2010). Yet, human ignitions stem from diverse historical, cultural and societal contexts for a myriad of preferences that include livelihood subsistence and conservation management objectives. The combination of Africa's natural and human fire history in the fire-prone savannas and grasslands presents a distinctive opportunity for investigating people and fire patterns. Remarkably, research concerning indigenous groups of people who have maintained their cultural knowledge of fire resource patterns is scarce in the southern Africa region (Butz, 2009).

Over the last century, indigenous fire use patterns have been in conflict with complex colonial and national histories, as a result of contrasting objectives and perspectives of fire, leading to diverse fire management strategies and policies in southern Africa. Colonial policies emphasising fire suppression conflicted with traditional fire management and the ecological reality of fire adapted ecosystems. As we move out of the fire suppression era into a more inclusive approach to fire management that recognises the social and ecological benefits of fire (Coughlan & Petty, 2012; Archibald, 2016) novel paradigms have emerged that integrate an interdisciplinary understanding of climate-vegetation-fire-people dynamics in the Earth system (Lavorel *et al.,* 2007). For example, pyrogeography is a unifying discipline that integrates atmospheric, biological and social perspectives of fire (Bowman *et al.,* 2013).

Social-ecological-fire systems (i.e. the interactions and feedbacks between climate, vegetation, people and fires) are intrinsically complex, and fire regimes (i.e. repeated patterns of fire in an area) are in constant flux with variable global climatic systems (e.g. El Niño southern oscillation [ENSO]) (Andela & van der Werf, 2014) and local rainfall patterns in combination with people's actions, agendas and needs. These dynamic fire settings make generalisations and predictions challenging for fire scientists, reserve managers, and policy-makers, who customarily prescribe fire management practices. Equally, changes in fire management policies and environmental dynamics (e.g. climate) can threaten indigenous communities who depend on fire for ecosystem services (e.g. natural resources). However, in the last two decades the synthesis of data, methods and approaches to fire has led to a vastly improved understanding of the interactions between climate, human factors and the ecological implications of vegetation fires in southern Africa, West Africa, Australia, and in South and North America (Laris, 2002; Guyette *et al.,* 2002; Bowman *et al.,* 2004; Archibald *et al.,* 2010; Bilbao *et al.,* 2010; Walters, 2010; Russell-smith *et al.,* 2013; Bird *et al.,* 2016).

Climate-fire-vegetation-human interactions

Globally, it is widely reputed that climate is the major factor that underpins fire and ecology (response of the biotic and abiotic components of ecosystems) to fire regimes (Trollope & Trollope, 2004; Bond *et al.,* 2005). Ground-based and modelling vegetation studies have revealed the distinct association between climate and fire, and rainfall as the primary driver of biomass productivity and fire frequency (Bond *et al.,* 2005; Murphy *et al.,* 2011). Moreover, modelling studies have shown that African and South American savannas maintained without fire have the potential to form forests (Bond *et al.,* 2005).

Thus, today it is understood that fire decouples vegetation from climate in some areas, enabling the persistence of fire-prone grass-dominated landscapes in areas that have sufficient rainfall to support forests (Bowman & Murphy, 2011). Yet, fires are largely determined by the prevailing weather conditions and fuel characteristics (e.g. amount and dryness) (Bradstock, 2010; Scholes *et al.*, 2011), and typically burned area increases in fire seasons after higher rainfall, and decreases in times of drought (Archibald *et al.,* 2010). However, this only holds true in arid, but not mesic savannas with rainfall greater than 750 mm (Sankaran *et al.,* 2005; Staver *et al.*,2011). These ecological feedback systems alter the physiognomic characteristics of ecosystems, yet this theoretical understanding of climate-vegetation-fire interactions does not explicitly consider human activities, which can alter fire regimes through ignitions, fuel load and fuel connectivity. Nonetheless, the potential for people to alter fire patterns depends on climate and fuel availability (Whitlock *et al.,* 2010), and ecosystem characteristics (Parisien & Moritz, 2009), as well as the ecological knowledge, landscape condition, and the specific socio-economic settings, livelihoods, cultural values and management preferences (Coughlan, 2015).

Africa's tropical savannas provide the ideal climate, with both distinct wet and dry periods, that provide the fuel (i.e. fine flammable grass) for the occurrence of fires on the continent (Archibald *et al.,* 2013). Anthropogenic fire has long shaped landscapes and livelihoods in African savanna environments (Bond & Keeley, 2005; Kull & Laris, 2009). Today, anthropogenic fires extend savannas into areas beyond those created by lightning ignitions in some areas, while fire suppression allows forest expansion in others (Bond *et al.*, 2005; Shaffer, 2010). Thus, fire regimes are the collective outcome of multiple drivers, such as ignition patterns, climate and vegetation characteristics (Moritz *et al.,* 2009), however fire in turn profoundly influences people, climate and ecosystems (Moritz *et al.,* 2014; Archibald, 2016).

Inevitably, immense debate concerning climate and natural biomass ignitions versus anthropogenic burning abounds in the fire science and management literature (Bird & Cali, 1998; Pausas & Keeley, 2009; Archibald *et al.*, 2010; Holz & Veblen, 2011; Bowman *et al.,* 2011). Fire scientists primarily focus on understanding both the positive and negative aspects of fire on vegetation, herbivore and people interactions, within the context of a changing climate. However, governance systems frequently tend to give attention to the socio-economic impacts of fires (e.g. loss of high value forestry resources; wildlife mortality; tourism impacts), and thus the detrimental effects of people and fires, and infrequently refer to the biological controls of fires (e.g. climate-vegetation feedbacks), nor to traditional fire management practises and the benefits to biodiversity and livelihoods. Yet, rural communities are concerned with the cultural and traditional uses of fire for natural resource regeneration, and sustainability, primarily for a means of survival (Walters, 2010). Thus, to add to the complexity of disentangling human-climate-vegetation-fire interactions, the vigour of the on-going debate about how to manage fire arises out of contrasting historic and modern cultural values, professional identities, priorities and livelihood needs (Pyne, 2006). Thus, fire management inevitably involves diverse historical, cultural, political and ecological fire settings. Furthermore, decisions concerning fire management in savanna environments have become a territorial issue: who decides where, when and how to use fire, and with which information (Eloy *et al.*, 2018).

Fire regimes and fire management in African savannas

The extent of which vegetation changes in African savannas are related to anthropogenic fire is of current social-ecological interest among diverse stakeholder groups from local communities, to fire ecologists through to national policy makers (Bond & Archibald, 2003). Fire science typically involves studies of 'fire regimes' representing a particular combination of fire characteristics, such as frequency, size, intensity, severity, season, spread type (crown, surface, or ground fire) and extent (Gill, 1975; Bond & Keeley, 2005). Fires in southern African savannas (i.e. coexistence of grasses and trees) typically occur in the dry season and are differentiated as early [Apr – July] or late dry season fires [Aug – Oct] (Brockett *et al.*, 2001; Korontzi *et al.*, 2003). Laris *et al.* (2017) emphasised that the convention of ascribing fire as either early and late, is currently deeply embedded in savanna fire science and policy. Moreover, the arbitrary choice of the cut-off date of these fires is problematic because it reinforces the dominant view that impacts of fire on vegetation can be determined along the simple line of early or late (Laris *et al.*, 2017 for a review).

The fire regime in savannas determines vegetation cover (because it pertains to trees and grasses) with the effect that late season fires are more damaging to tree cover than early fires (Laris *et al.,* 2017). Thus, fire regimes are a critical determinant of tree cover because sporadic fires, and particularly the large late season fires prevent the transition of saplings and/or juveniles to mature trees (Sankaran *et al.*, 2004; Bond & Zaloumis, 2016). However, even though size and recurring fires are important, multiple factors require consideration in the assessment of the impact of fire seasonality, for example plant phenology and response to varying fire intensity (Laris *et al.*, 2017). Fire regimes are also strongly coupled with grassy systems, and moisture availability (e.g. fires lit in the early dry season will be patchy due to remnant moisture from the previous rainfall season) (Govender *et al.*, 2006; Knapp *et al.*, 2004; Le Page *et al.,* 2010). Thus, understanding both the beneficial and negative ecological effects of fire seasonality (Le Page *et al.,* 2010) on ecosystems and biodiversity (Flasse *et al.,* 1998; Bowman *et al.,* 2011) is central to fire regime research.

Fire management strategies that aim to introduce heterogeneity into the landscape through the use of patchy burns (i.e. variable fire sizes distributed across the landscape) over successive fire seasons are referred to as 'patch mosaic burning' (Brockett *et al.*, 2001; Parr & Anderson, 2006). The patchy burns are used with the intent to create pyrodiversity (i.e. diverse fire patterns), because it is hypothesised that ignitions in different spatial and temporal locations will promote biodiversity in the form of a mosaic of different post-fire ages (Trollope, 2011). African fires fall into two defined pyromes (i.e. global units of fire), namely as frequent-intense-large, and frequent-small-cool fires (Archibald *et al.*, 2013). In densely populated areas in southern Africa, burned area mainly consists of many small fires (Scholes *et al.*, 2011). Though climate (i.e. precipitation) governs when, and where fires can occur from local to continental scales (Archibald *et al.*, 2010; Andela & van der Werf *et al.*, 2014). It is now widely understood, that humans play a key role in determining the seasonal occurrence and spatial extent of burned area on local-landscape scales. Therefore, it is important to acknowledge that fire regimes and fire management goals vary considerably over time and between cultures (Pyne, 1995), alongside climate-fire-vegetation feedbacks over varying spatial and temporal scales (Figure 1-1).

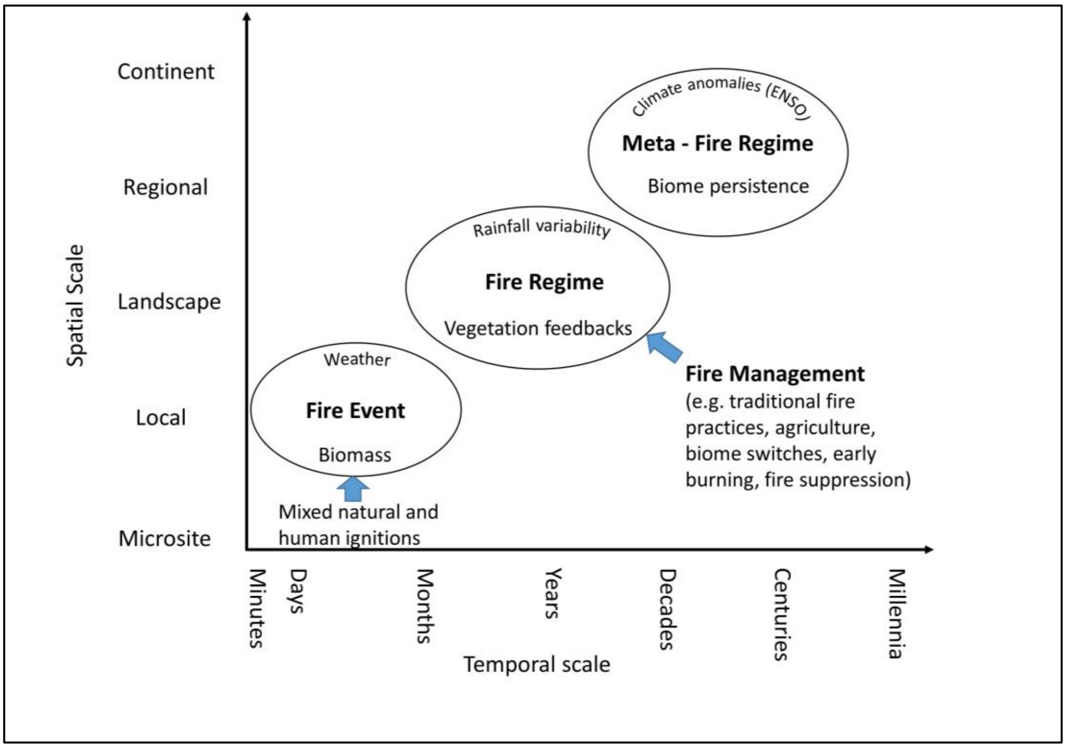


Figure 1-1: Controls of fire at multiple and temporal scales including the human dimension (adapted from Whitlock *et al.*, 2010, and Bowman *et al.*, 2011, in Gillson *et al.*, submitted).

It has often been assumed that direct human impacts, through ignition and suppression activities are what are driving current fire regimes, and these have been the focus of policy and management interventions (Kull, 2004; Archibald, 2016). Humans have changed the continuity of fuel loads (i.e.

density of biomass available to burn) by creating barriers to spread through the use of roads, cultivation and grazing activities, and by lighting fires during the early dry season (Mistry *et al.,* 2005; Russell-smith *et al.,* 2013), which reduces the frequency of fires during the late dry season (Archibald *et al.,* 2011).

Unequivocally, management in the form of fire suppression and/or bi-seasonal (early and late) burning strategies can have significant impacts on savanna structure, function and diversity, therefore understanding and controlling savanna fires has always been a priority for managers of these systems (Archibald *et al.,* 2017). Seasonal mosaic burning is recommended for its positive impacts on biodiversity, wildfire prevention and mitigation of carbon emissions (Russell-Smith *et al.,* 2013). Yet, for example, high intensity late season fires are also considered useful and are implemented in areas where bush thickening (i.e. woody plant invasion) is perceived as a management problem (Joubert *et al.,* 2012). Further, fires are typically ignited in the late season by people who want to prepare land for cultivation (before the rains start) to remove woody debris, and increase crop productivity (Frost, 1999). Policies of fire suppression only increase the likelihood of annual intense late season fires that may threaten rural people's livelihoods as they are dependent on natural resources in the grasslands and savannas in which they live (Lavorel *et al.,* 2007; Beatty, 2011).

The skilful manipulation of fire, through early season and patch mosaic burning is fundamental to peoples culture, beliefs and livelihood practises, as well as being vital for survival in remote regions (Laris, 2002; Walters, 2010; Huffman, 2013), as it has been for millennia. However, particularly in Africa, policies have been dominated by colonial Eurocentric notions of fire suppression, that originated in forested systems in the Northern Hemisphere. Colonial views typically perceived fire as evil and entrenched indigenous burning regimes as environmentally degrading (Eriksen, 2007; Laris & Wardell, 2006; Mistry, 2002), which resulted in the implementation of fire prevention, and suppressive policies that restricted indigenous fire use in the southern African landscape. Furthermore, traditional authorities (e.g. chiefs and headmen) and 'permit to burn systems' for controlling customary fires within communities have in some instances been removed (Beatty, 2015), which has resulted in the absence of the autonomous use of fire amid communities. The extensive misunderstanding between people who manage fires, and write fire policies, and people that depend on fire for livelihood subsistence leads to mismatches between fire policies rooted in classic (preservationist) conservation terms with colonial and national histories, and indigenous burning practises appropriate to specific contexts (Kull, 2008; Eloy *et al.,* 2018).

Walters (2010) emphasized that many international agencies send mixed messages about fire policy, and its impacts on the environment; alongside a growing recognition of the socio-ecological importance of fire, there is also concern about damage to property, loss of life and a legacy of perception of fire as damaging. There are a range of stakeholders involved in community fire management, which include civil society (e.g. Working on Fire), non-government organisations (NGOs), international agencies (e.g. The Nature Conservancy [TNC]; Food and Agricultural Organisation [FAO]), environmental consultancies, as well as local and national government. The majority of the aforementioned stakeholder initiatives are embedded in the concept of 'Integrated Fire Management (IFM) that emerged in parallel with Community Based integrated Fire Management (CBiFM) in the 1990s in Indonesia and Namibia (Moore *et al.*, 2002; Lineal & Laituri, 2010). IFM and CBiFM are centred on integrating communities into decision-making, and recognizes the positive potential role of this knowledge in fire management to prevent, control and utilize fire (Hoffman, 2013). However, IFM programmes tend to consider local knowledge mainly for identifying 'local demands' and 'local habits', rather than integrating local fire and landscape knowledge in the scientific understanding of fire behaviour and of the impact of different fire regimes on the ecosystem (Eloy *et al.,* 2018). Further, IFM programmes also tend to focus on 'training' the communities in how to use fire, and prevent fire with modern tools (e.g. fire beaters), instead of understanding the cultural use of fire for a variety of ecosystem services. However, rural communities burn patches for a range of objectives (ecosystem services, wildfire prevention, landscape management) that also need to be considered in fire management plans (Laris, 2002; Kull, 2004; Eloy *et al.*, 2018). Furthermore, traditional fire management systems that produce seasonal mosaic landscapes are characterised by opportunistic burning throughout the whole year linked to various cultural, ecological and spiritual purposes, (Bilbao *et al.,* 2010; Laris *et al.,* 2015; Eloy *et al.,* 2018).

Fire and livelihoods

There is mounting evidence to show the critical role of indigenous communities in effective fire management (Russell-smith *et al.,* 2013; Trauernicht *et al.,* 2015; Laris *et al.*, 2017). Historically, indigenous communities used fire for hunting, gathering, grazing and agriculture activities associated with land use amongst various other reasons (e.g. pest management, long distance communication) (Andreae, 1992; Laris, 2002; Kull, 2004; Burrows *et al.*, 2006). Ultimately, indigenous populations have evolved with and adapted to the use of fire for thousands of years (Wrangham & Carmody, 2010; Scott *et al.,* 2014). However, fire's contribution to livelihoods has been altered over time (Walters, 2010). The balance between people, fire, wildlife and plant resource regeneration and use has been disrupted due to changing histories, power regimes, demographics, land-use, climate change and conflicting policies about the environment, and the enduring negative perception of indigenous fire use on vegetation (Laris, 2002; Mistry *et al.*, 2005; Eriksen, 2007; Shaffer, 2010; Huffman, 2013). The complexity of these challenges have resulted in a breakdown of traditional fire knowledge (Huffman, 2013), and cessation of traditional norms over time, in combination with more recent shifts to modern westernized needs and monetarized lifestyles (Inglehart & Baker, 2000). Moreover, it is important to acknowledge that today there are only remnant indigenous or traditional groups of people remaining in southern Africa savanna landscapes. The result of three centuries of colonial history, has led to subsequent changes to society, and land-use systems that has had severe consequences for indigenous peoples culture, livelihoods, and ways of living. Nevertheless, today's fire-setting practices continue to be important to livelihoods (Walters, 2010), particularly where people are dependent on fire to sustain natural resources in the environment. In this sense, current fire ecology studies need to be centred within the context of understanding culture, land-use, vegetation, and burning practices (Walters, 2010; Coughlan, 2015), alongside the site specific historical circumstances, conservation objectives and livelihood concerns.

Traditional fire management systems in savanna environments are still poorly understood by western science standards that focus only on quantitative fire ecology (Kull & Laris, 2009; Mistry *et al.*, 2018). Typically, understanding of fire regimes are reflected through western scientific approaches (fire science academics; reserve/park fire managers; NGOs), environmental aid consultancies, and in the political arena (e.g. national policies') to the exclusion of indigenous fire knowledge. Largely, indigenous communities situated in remote settings rarely have a role in fire management decisions, or the opportunity to contribute to ecological fire knowledge without the support of CBiFM/IFM programmes to facilitate engagement and awareness (Taylor, 2012). These circumstances are commonly complicated by various human-centred factors, for example, authoritarian government roles, hierarchical park management structures and polices, and local inter-ethnic conflict, which result in the hindrance of traditional authority arrangements (e.g. laws) in place for community representation, and council (Hitchcock & Vinding, 2004).

On the other hand, in some instances, CBiFM and IFM programmes have integrated indigenous communities' ecological fire knowledge into current fire management practises (Russell-Smith *et al.*, 2013; Beatty, 2015), and significantly, ecological understanding (Trollope, 2011). Consequently, concerted efforts by fire scientists and managers have focused on the application of traditional early dry season fires into western fire management strategies, and have been applying these approaches to contemporary global problems in South and West Africa, South American and Australia (Brockett *et al.*, 2001; Trollope, 2011; Laris *et al.*, 2015; Russell-Smith *et al.*, 2013; Mistry *et al.*, 2018; Perry *et al.*, 2018). The 21st century has seen a far greater number of studies concerning indigenous people and fire use and the reasons for burning in southern Africa (Cassidy, 2003 [Botswana]; Kull, 2004 [Madagascar]; Sheuyange *et al.*, 2005 [Namibia]; Eriksen, 2007 [Zambia]; Butz, 2009 [Tanzania]; Marambaushe & Nyamadzawo, 2018 [Zimbabwe]). Yet, the successful integration of traditional and scientific fire management knowledge into management policies is still controversial (Eloy *et al.*, 2018), and remains mismanaged in southern Africa.

To understand the complexities of these circumstances it is necessary to analyse the aims and the objectives related to individuals or particular groups utilization of fire as a land management tool (Eriksen, 2007), and the multiple interests of different people in the environment, and how they make decisions about natural resource management (Agrawal & Gibson, 1999). This has important implications for future research and policy making communities, and creative ways are needed that address the unique circumstances of the observed fire regimes and the ensuing impacts on people and ecosystem services in the savanna fire-prone biomes in southern Africa. The ever-increasing reliance on savannas for ecosystem services (e.g. food resources; carbon sequestration; soil fertility) and livelihoods highlights the values of these savanna resources, especially among economically and socio-politically marginalised indigenous peoples inhabiting savannas (Per Doe, 2008). Thus, it is critical to understand the vulnerability of land-use systems and livelihoods to fire (Lavorel *et al.,* 2007), and develop adaptive management strategies in times of susceptibility (e.g. ENSO events) for people and biodiversity conservation in this era of global environmental change.

Thesis approach

Over the last two decades, the use of remote sensing data has provided an extremely useful and novel lens by which to monitor the spatial extent and timing of fires in the landscape with geospatial technologies as accessible and useable datasets (e.g. MODIS). However, the complex interplay between climate, vegetation and human factors that influence fire regimes remains poorly understood, and is infrequently assimilated into current management policies in southern Africa. Furthermore, the reliance on geospatial technologies (i.e. satellite data) to inform fire management policies tends to result in the exclusion of local knowledge and power over decision-making (Carmenta *et al.,* 2013). Fire happens on the ground, however a large portion of fire regime studies in southern Africa have focused on remote sensing applications and statistics to derive information on fire regimes and land-use changes (Archibald *et al.*, 2010; le Roux, 2011). The exclusion of ground-based data, both social and ecological (e.g. fire regime perceptions and understanding, vegetation dynamics, land-use, policies, and cultural knowledge) could result in cascading social-ecological implications, such as the suppression of early season burning and large detrimental fires that threaten ecosystems, and the people and the ecosystem services they depend on (Pyne,1998).

The majority of studies in southern Africa concerning indigenous groups of people (e.g. 'Bushmen', identified collectively as the Khoi-San) took place in the late 20th century by anthropologists (e.g. Marshall, 1976; Lee, 1979; Lee & Devore, 1981; Silberbauer, 1981), who primarily focused on social organization and diet. Subsequently, two seminal archaeological studies by Mills (1986), compared hunter-gatherer subsistence strategies and prescribed burning, and by Scherjon *et al.* (2015) documented Palaeolithic hunter-gatherer site fires. Notably, examples of indigenous fire use from the African continent were rare in the latter two studies.

Laris (2002) iterated that to move beyond only identifying the spatial patterns and land use systems, that it is important to understand the seasonal fire regime, which highlights the differences between early and late burning fires, and the *reasons* for them. Understanding the seasonal pattern of burning has important implications for research and policy-making communities (Laris, 2002), as well as for communities who depend on fire for their livelihood subsistence, and ecosystem services. New interdisciplinary perspectives of the study of fire (e.g. pyrogeography) has resulted in the integration of available methodologies, and greater scope for research on fire and people dynamics across the globe.

Therefore the present study combines ground studies that analyse how and why different stakeholder groups (e.g. traditional communities, government, and other conservation interest groups) use and perceive fire, alongside geo-spatial technologies (i.e. MODIS datasets) to look at spatial and seasonal patterns of burning. A pyrogeographic framework is then used to integrate these methodologies into coherent narratives of fire use and management.

Pinpointing a social-ecological site: Bwabwata National Park

This thesis uses the context of Bwabwata National Park (BNP) in the north-east of Namibia to examine the historical and current social dynamics of fire management and the effects on the current fire regime (2000 – 2015). Here, former hunter-gatherers, the Khwe (San) and Mbukushu inhabitants (Bantu-speaking people) who are renowned as agriculturalists and pastoralists are situated in the bounds of a national park, and living with fire on a daily basis in the savanna-woodlands. Moreover, recent research using genomics revealed that the Khwe are the oldest human population, and are descendants of the earliest human ancestors from which all other groups of Africans branch (Tishkoff *et al*., 2009). Thus, the people in this region have been using fire for many thousands of years in BNP (Brown & Jones, 1994; Owen-Smith, 2017), and the area falls within their ancestral and tribal territory in southern Africa

(Suzman, 2001). Thus, the Khwe and Mbukushu were identified as exemplary communities' to engage with to investigate the past and present cultural function of fire in the park. Furthermore, Namibia, since the late 19th century (1888) has been under a policy of fire suppression, however in 2006 the suppression policy changed to one of early burning in the park, which offered a unique occasion to investigate the fire regime and changes across both policy periods. Spatially, the park has community inhabited multiple use areas and conservation core park areas, where people are excluded, providing an opportunity to compare fire regimes in inhabited and uninhabited areas. BNP is also situated within the nexus of a fire hotspot within southern Africa in the Kavango/Upper Zambezi Transboundary Conservation Area (KAZA-TFCA) region that is bounded by Angola to the North, and by Zambia and Zimbabwe to the north-east, and Botswana to the south. Thus, ecologically the park is situated within the broad leave tree-shrub savanna biome of the 'Miombo Eco-region' of southern Africa (Timberlake *et al.*, 2018), an important vegetation type threatened by the extent of fire, and human activities (Frost, 1999).

This study is aimed at integrating local ecological fire knowledge of Namibian stakeholders with remote sensing data to understand past and present fire dynamics in the landscape. Multi-year (2000 – 2015) remote sensing fire products (MODIS) together with the Namibian stakeholders knowledge derived from interviews, in combination with secondary data sources (e.g. national policies) are used to understand the determinants and dynamics of the historic and existing fire regime in the study area. In this dissertation, the social findings are presented separately from the remote sensing chapters, in order to examine why people burn. Then remotely sensed data is presented and interpreted in terms of comparisons between different land-uses (core conservation and multiple use) both before and after the change from fire suppression to an early burning policy. Multiple working hypotheses are used with the aim of understanding the ecological, and social-political influences on the fire regime by integrating local people's knowledge about fire collectively with the climatic and vegetation data to elucidate the determinants of the contemporary fire regime in the park. Accordingly, the social and ecological implications of the results are considered in the discussion of each chapter. Thus, I have attempted to apply an interdisciplinary pyrogeographic approach (Bowman *et al.*, 2013) throughout this thesis. Chapter 6 is a synthesis which draws together and summarises the integration of the social and remote sensing findings and conclusions from all the chapters herein.

Research questions and objectives

The overarching objective of this research was to explore the interface of social-ecological fire systems, past and present, linkages to theory, and to understand how this influences community livelihoods, policy development, fire occurrence, and conservation practise in north-east Namibia.

This study addresses the following questions in Bwabwata National Park:

1. What ecological and social factors affect the spatio-temporal distribution of fires in BNP?
2. How has the historical context, and current social factors (e.g. local ecological knowledge; fire use and perceptions; changing policy and land-use) influenced the fire regime in BNP?

The specific objectives of this study were:

1. To identify spatial and temporal fire trends in relation to land use and transformation and vegetation and fire, through the use of remote sensing fire products and local ecological knowledge surveys.
2. To explore the relationships between livelihoods, land-use, policy, biodiversity conservation and the fire regime through stakeholder interviews.
3. To explore and identify factors influencing the current fire regime through the conceptual synthesis of the remote sensing and local ecological knowledge surveys using a pyrogeographic framework.

Thesis structure and chapter outline

This introduction chapter serves to explain the background and rationale for an interdisciplinary study of people and fire in a southern Africa context. **Chapter 2** covers the study area, and provides details concerning the historical context of north-east Namibia, ecological status, people, and policy developments from the 19^{th} century to the present.

Chapter 3 uses stakeholder interviews and literature review to examine the Namibian stakeholders (community and government and non-government) historical and current fire use strategies, and perceptions about past and present changes in the fire regime in the park. The interactions and feedbacks between fire management and the community (Khwe and Mbukushu people) and the government and non-government stakeholders are explored respectively.

Chapter 4 uses MODIS data to explore the relationship between burned area, El Niño southern oscillation (ENSO) events and antecedent rainfall, in association with fire seasonality, the number of ignitions, and fire sizes in the different land-use areas during the suppression and early burning policy change in BNP from 2000 - 2015. Comparisons are made using the multivariate ENSO index (MEI) and identified El Niño and La Niña events, in combination with antecedent rainfall patterns and above and below rainfall periods for the park, and the number of seasonal ignitions, fire sizes and area burned. Inter-annual variation is assessed between the two policy phases (suppression and early burning) in burned area, seasonal burning patterns (early and late seasons), the number of ignitions and associated fire sizes occurring across the entire BNP landscape, and in the four land use areas. The relationship between the climate data, fire regime variables and inter-annual variation under the two policy phases within the land-use areas is explored.

Chapter 5 uses MODIS data to examine fire occurrence and distribution (i.e. fire frequency using burned area extent), fire seasonality, and fire intensity as represented by fire radiative power (FRP) in four different vegetation types, and land use areas under the suppression and early burning policy periods from 2000 – 2015 in BNP. The relationships between fire frequency, burned area, seasonality, and fire intensity for different vegetation types in strictly protected areas, and areas inhabited by people (Multiple Use Area [MUA]) before and after a change in fire management policy is explored.

Chapter 6 explores the social fire history, contemporary fire regime patterns and fire management implications for Bwabwata National Park. Here, I integrate the findings from the historical context **(Chapter 2)**, the reasons for the use of fire and perceptions from both the stakeholder groups interviewed **(Chapter 3)** in combination with the remote sensing **Chapters 4 and 5** in a conceptual synthesis using a sequence of pyrogeographic models. I discuss how applicable current theory on savanna fire regimes is in landscapes where people manipulate fire at the local scale using an interdisciplinary perspective, and thus consider and detail the social-ecological implications, and outcomes of this dissertation. Therefore, the conclusions stemming from each chapter are summarised in this integrative synthesis chapter. In addition, I weigh up possible study limitations, highlight policy recommendations, and ideas for future research.

Chapters 3, 4 and **5** are written in a format suitable for submitting to a journal with each consisting of an abstract, introduction, methods, results, discussion, and a conclusion section so that each chapter can be read in isolation. Therefore some repetition between the chapters is inevitable. **Chapter 2** covers the study area information for each respective chapter in this thesis. **Chapter 6** comprises the synthesis of **Chapters 2, 3, 4** and **5,** and conclusions of this research. The references for all the chapters are available in a single bibliography section at the end of this thesis, together with the appendices.

Chapter 2 Study area: Cultural, political and ecological context

Introduction

For decades, explorers, colonialists, journalists and academics described the region as the exotic other, a peripheral and an inaccessible territory in the core of southern Africa (Zeller & Kangumu, 2007; Taylor, 2012). The historical narrative of the north-east of Namibia differs starkly from the rest of the country because of its geopolitical position as a military frontier (Kangumu, 2008), and as the locale of a colonial insurgent war (1966 -1989), which led to Namibia's independence (1990) (Wallace, 2011). The region, in relation to the rest of Namibia is also characterised by a distinct climate, tropical ecosystem, as well as people from diverse cultures (Fisch, 1999; Kangumu, 2008; Lenggenhager, 2015). Bwabwata National Park has been shaped by flooding regimes, fire-vegetation-wildlife dynamics, conservation re-proclamations and wars, and thus, has a complex human history, including both traditional landscape settings and international political interests (Ministry of Environment and Tourism [MET], 2013). Thus, understanding the park today requires the integration of several influential historical layers of interacting ecological and social aspects. To understand the social-ecological context of this study, it is useful to discuss the historical political context, alongside the ancestral and tribal people inhabiting the park, the Khwe (grouped by anthropologists as the 'San' or 'Bushmen') and Mbukushu (Bantu-speaking people) respectively, and the evolution of fire policies in the north-east of Namibia. The unfolding narrative of the greater region and the study area are closely tied to political events, which have strongly influenced conservation development of the park over the last half century (1963 – 2015) (Lenggenhager, 2015).

The region in which BNP is embedded has a long history of hunter-gatherer, and agropastoralism cultures, and over a century of colonial occupation (Germany and South Africa) through to Namibian independence (1884 – 1990). Therefore, the region and the park has successively experienced various name changes[1] associated with colonial occupation and conservation re-proclamations and policies (MET, 2013). The greater region in earlier times (1900s) under German administration (German South West Africa; 1884 – 1914) was known as *Caprivi Zipfel*, and also as *German Barotseland*, and the *German Zambezi region* (until 1908) (Fisch, 1999). During South African rule (1915 - 1989), it was named the *Caprivi Region*, *Caprivi strip* (English) or *strook* in the Afrikaans language, and officially as South West Africa (SWA). The study area (BNP) during the German colonial era was known as the *Hukwe-veld*, which means the "people who were left behind" (Brenzinger & Harms 2001:17), and during the South African era (1915- 1989) as the *western Caprivi*. In 2007 the park was re-proclaimed

[1] In this chapter, the names for each historical period of the greater region, and study area are maintained in keeping with the referenced literature for the relevant time period.

as Bwabwata National Park. The park is named after a village on its northern boundary, which means the 'sound of bubbling water' in Khwé-dàm (Khwe language). In 2005, Namibia's ministries changed their names (Taylor, 2012), and the Ministry of Wildlife, Conservation and Tourism was changed to the Ministry of Environment and Tourism (MET), who has mandate over BNP (Brown & Jones, 1994). Further, country elections in 2013 resulted in the colonial names of Namibia's regions and constituencies boundaries being re-evaluated, and renamed to indigenous titles, and thus BNP was sub-divided into the Kavango East and the Zambezi Regions (Immanuel, 2013).

Environmental context

Study area: Bwabwata National Park

Namibia is a large country on the south-western seaboard of Africa covering an area of 823 678 km², and straddles the Tropic of Capricorn. This study is situated in north-east of Namibia in Bwabwata National Park (18.1157° S, 21.6696° E; 627, 412 ha) in the Kavango East and Zambezi Regions, and is bordered to the north by Luiana Partial Reserve in Angola, and to the south by the Okavango Delta in Botswana (Figure 2-1). BNP extends 200 km from the west to the east between the Okavango and Kwando Rivers, and is 32 km in width from north to south (Brown & Jones, 1994). BNP has the highest rainfall in the country (average of 650 mm) relative to the rest of the country, and thus supports a tropical ecosystem associated with major rivers, floodplains, wetlands systems, dry Kalahari forests, and savanna-woodlands together with a high biodiversity (Mendelsohn *et al.*, 2009). The park also falls with the southern limit of the 'Miombo Eco-region' since it comprises high species diversity, large mammal diversity, endemism, as well as endangered species (Timberlake *et al.*, 2018). BNP lies at the nexus of the Kavango Zambezi – Transfrontier Conservation Area (KAZA-TFCA; 440 000 km²), one of the world's largest transfrontier conservation areas (Figure 2-1), which holds the territory of the largest global transboundary elephant concentration and harbours half of Africa's elephants (Lindsay *et al.*, 2017). The park has been identified as one of the important protected areas within the KAZA-TFCA where the borders of Angola, Botswana, Namibia, Zambia and Zimbabwe converge (Pricope & Binford, 2012; Lindsay *et al.*, 2017). Its central position in the KAZA-TFCA places it in an ideal locality for contributing to environmental protection in southern Africa (Mendelsohn, 2007). The park is located 200 km east of the town of Rundu, and is accessible along the Trans-Zambezi Highway (B8) that links Namibia to Botswana and runs the length of the park to the eastern perimeter, the Kwando River. BNP management is viewed as a cornerstone accomplishment in Namibia, as the designation of core conservation and multiple use areas allows both people and wildlife to co-exist in the park, a situation that offers benefits to both conservation and rural communities (Ministry of Environment and Tourism [MET], 2010).

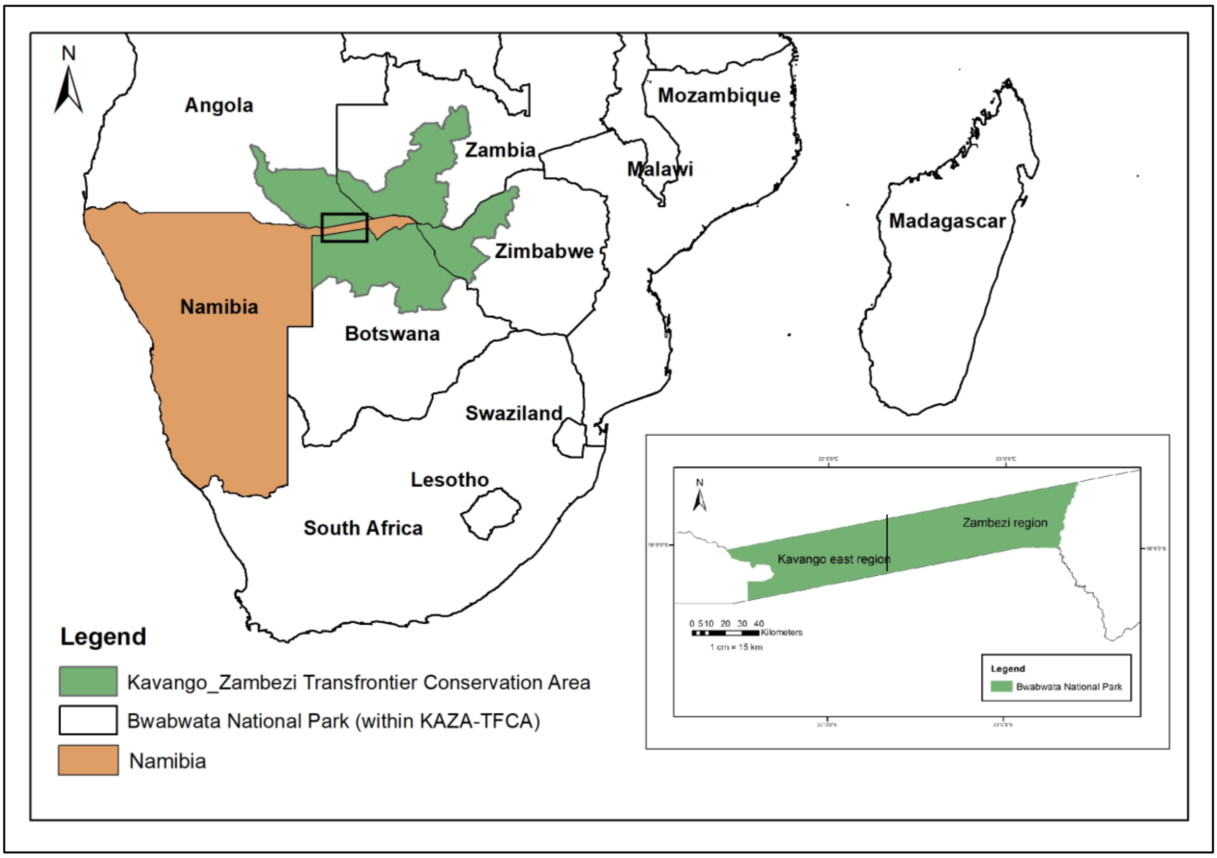


Figure 2-1: Map of southern Africa showing the location of Namibia, and Bwabwata National park centred within the nexus of the Kavango Zambezi – Transfrontier Conservation Area (KAZA-TFCA). The solid black box indicates the locality of Bwabwata National Park in Namibia, and the KAZA-TFCA . The boundary between the Kavango East and Zambezi Regions is shown with the vertical black line within the park in the second map in the bottom right hand corner.

Fire in north-east Namibia

Generally, the fire affected areas in Namibia are confined to the central and north-eastern regions of the country, and follow an approximate SW to NE rainfall gradient (Figure 2-2), with the consequential increase in fuel loads (i.e. grasses) – the ignition source for fire in these savanna woodlands (le Roux, 2011). Thus, the northern regions experience frequent, intense and extensive fires while in the south and west, fires are rare. The vast majority of these fires occur as surface fires that spread in the grass and shrub layer (Trigg & le Roux, 2001).

The Kavango East and Zambezi Regions are at the nexus of a fire hotspot regime in the KAZA-TFCA, and have experienced fire regimes characterised by early (May to July) and late dry season fires (August – November) (Mubongo *et al.,* 2011; MET, 2016). However, communal lands have experienced low fire frequency around settlements and higher frequencies away from settled areas (Mubongo *et al*., 2011). Data analysis in the region of BNP by le Roux (2011) revealed the locale to be characterised by a fire regime with a return period of every one to two years, with the burn season extending over 2 – 6 months of the year. The Kavango East and Zambezi Regions have experienced significant increases in fire frequencies prior to and following 2006, when an early-dry season mosaic burn policy was instigated through a combined effort by governmental fire managers and a Namibian non-government organisation (NGO) (Pricope & Binford, 2012). Pricope & Binford (2012) suggested that the underlying causes for the changes in the frequencies in the region to be attributed to climatic changes and variability, particularly in dry years and warm El Nino Southern Oscillation (ENSO) phases (Gaughan & Waylen, 2012). While climate, especially precipitation has been found to maintain fire activity in the mesic savannas of southern Africa, the feedbacks with human systems lack generalisation (Mayr *et al.*, 2018).

Fire information at the national level is of importance as the negative aspect of uncontrolled fires threaten people's livelihoods causing damage to property, reducing land potential and destroying valuable resources such as wildlife, grazing and thatching grass and other valuable timber and non-timber products (Goldammer, 1998). These factors impact on the government, the national economy and the local human population. However, fire is a natural and regular occurrence in BNP and plays a fundamental role in the vegetation, wildlife and land use of the region (Beatty, 2011).

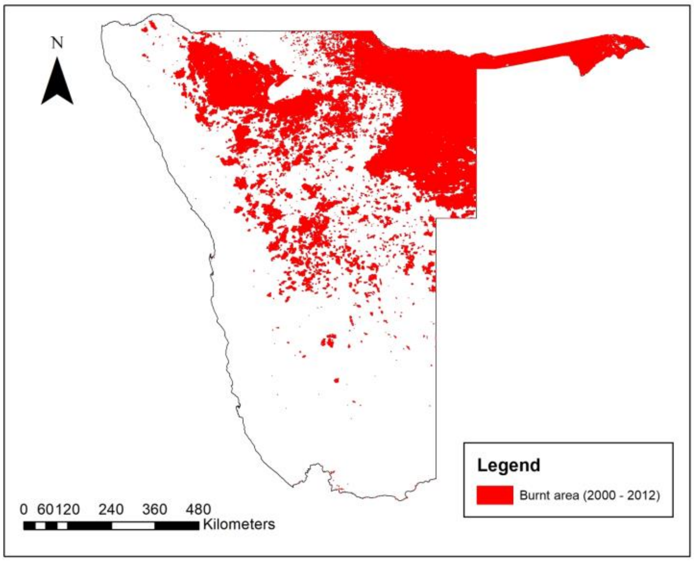


Figure 2-2: Map showing the concentration of all burnt area in central and north-eastern parts of Namibia, 2000 - 2012 (Data source: Ministry of Water, Agriculture, Forestry, 2013).

Climate and rainfall

Bwabwata National Park is located in the region of tropical dry climates characterised by alternating dry and wet seasons, and tropical thunderstorms that occur in the summer months (Tinley, 1966). Thus, precipitation is seasonal and is influenced by the Intertropical Convergence Zone (ITCZ), with the wet season occurring between November (typically peaking in January) and April. Even though BNP is located in the wettest part of the country, it is still subject to annual rainfall variation (30 %), and experiences serious droughts from time to time (Mendelsohn *et al.*, 2009; Kapolo, 2013). Mean annual rainfall declines from 550 mm in the east to 500 mm in the west (Mendelsohn *et al.*, 2009), however an average of 650 mm is frequently reported for the region (Tinley, 1966) (Figure 2-3). The rate of evaporation from surface water is about three times the annual rainfall. Despite a scarcity of weather stations in the area, localised variation in rainfall trends are reported from the north and south and from east to west across the Caprivi (Mendelsohn & Roberts, 1997). The period between April to October, marks the dry season, when the mean maximum and mean minimum monthly temperatures range between 14 °C and 39 °C respectively, with October being the hottest month (Pricope & Binford, 2012). July is the coldest month, with a monthly mean maximum of 30 °C and mean minimum of 4 °C (Barnes, 2001). Fire weather, for example high winds and temperatures that occur late in the dry season, can increase the frequency and spread of fires in the savanna-woodlands in the region. Figure 2-4 illustrates the minimum and maximum temperatures (°C) for the early dry season (EDS) (April – July) and the late dry season (LDS) (Aug – Oct) for BNP, 2000 -2015. The prevailing wind direction is easterly dry season winds that cross over from Botswana and Zambia (Verlinden & Laamanen, 2006).

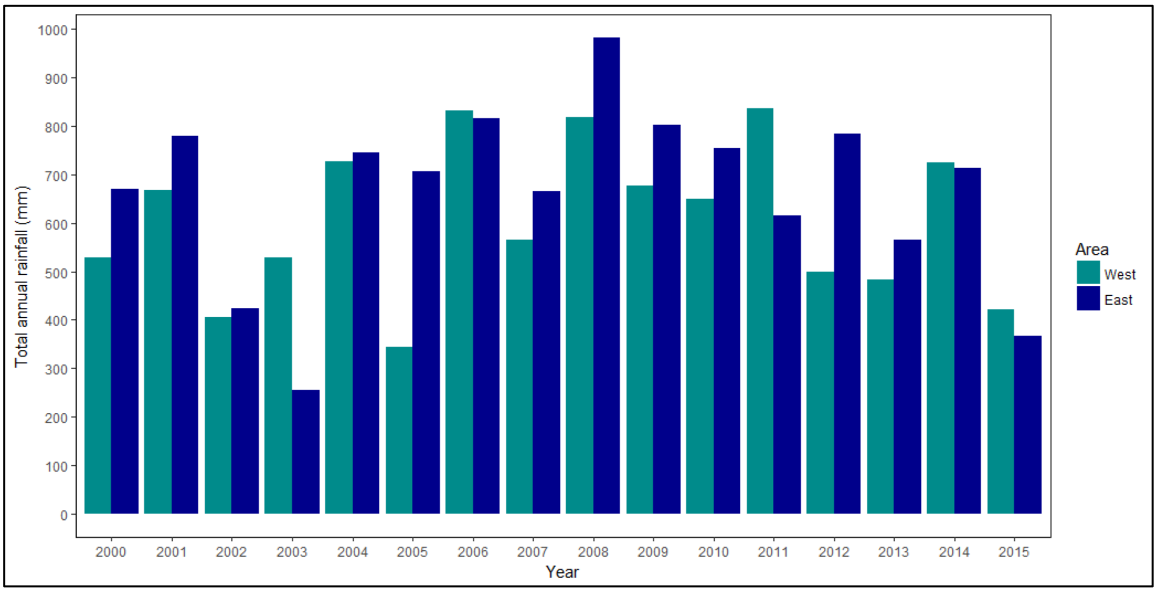


Figure 2-3: Total annual rainfall (mm) for the east (Katima Mulilo station), and the west (Rundu station) for Bwabwata National Park, 2000 - 2015. Data source: Namibia metrological station, Windhoek.

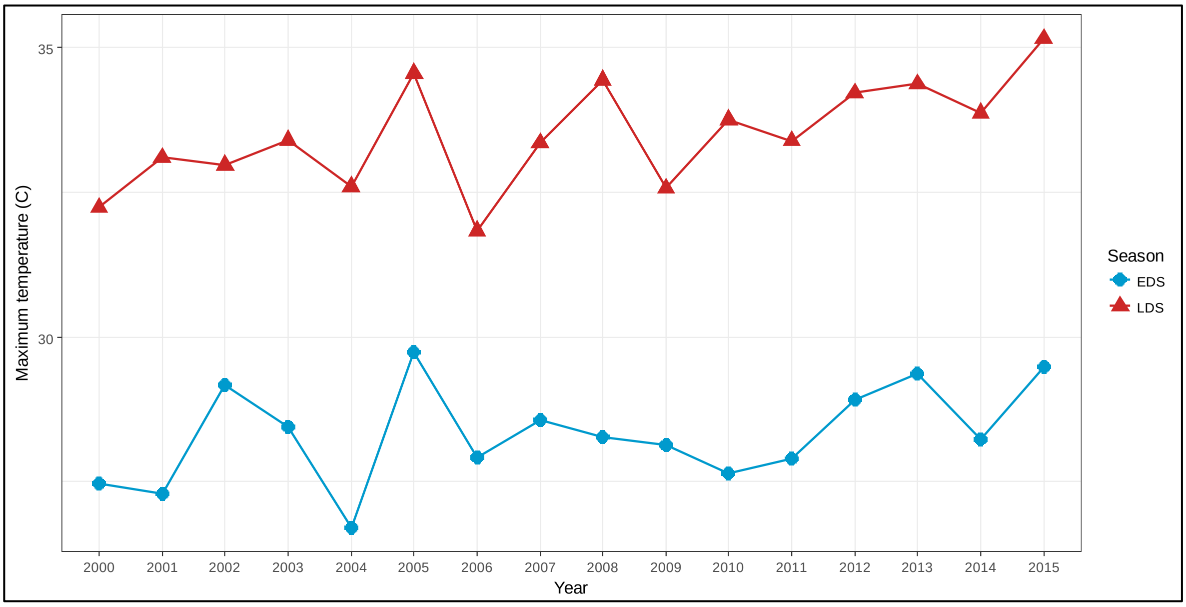


Figure 2-4: Mean maximum temperature (°C) for the early dry season (EDS) (April – July) and the late dry season (LDS) (Aug – Oct) for Bwabwata National Park, 2000 -2015. Data are presented as the mean calculated for the two weather stations, namely (Rundu [west]; Katima Mulilo [east]); Source: Namibia meteorological station, Windhoek (2013).

Geology, topography, drainage and soils

The region lies at the southern limit of the Kalahari Basin that formed some 130-180 million yrs. ago (Mendelsohn & Roberts, 1997). BNP falls within the Kavango – Zambezi River basins of southern Africa, and is surrounded by the substantial floodplains of the Zambezi, Kwando-Linyanti and Okavango Rivers (Figure 2-5). Historical flooding regimes that have occurred for over hundreds and thousands of years have resulted in the formation of remnant fossil drainage areas, the ‘omiramba’ in the landscape (Mendelsohn & Roberts, 1997). Therefore, the general topography comprises a flat landscape approximately 1000 metres above sea level (Trollope & Trollope, 1999), and falls within the Mega-Kalahari sand sea that reflects major relic linear dunes (i.e. plural: omiramba; singular: omuramba) with roughly an east-west orientation (Moore *et al.*, 2012). The only permanent surface waters are in the Okavango and Kwando perennial rivers, which rise in the Angolan Highlands in a rainfall belt of 1200-1550 mm per year (Brown & Jones, 1994). However, the omiramba are characterised by numerous seasonal, rain-filled pans that may hold water for up to five months after the last rains (Tinley, 1966). Historically, the dunes were thought to stand at ~ 90 m (Grove, 1969), however today they rise about 10 – 25 m above the intervening omiramba (MacFarlane *et al.*, 2005).

The soils in the valley areas of the region have largely been carried down from the drainage areas in Angola and Zambia, as well as by wind, and are therefore generally poor in nutrients and capacity to hold water (Mendelsohn, 2007). Thus, the deep aeolian Kalahari Sands are typically acidic and poor in essential elements such as phosphorous, while those of the omirmabas are heterogonous, alkaline grey clay soils or slightly acidic red or grey compact sands (Brown & Jones, 1994). Soil types in the region have been classified on the basis of their textures, and consist of varying amounts of sand and clay (Mendelsohn & Roberts, 1997) (Figure 2-6). The geology and the drainage of the Mega-Kalahari Basin have predominantly influenced both the regions soils and the vegetation on the dune crests and lower lying omiramba features (Mendelsohn, 2007).

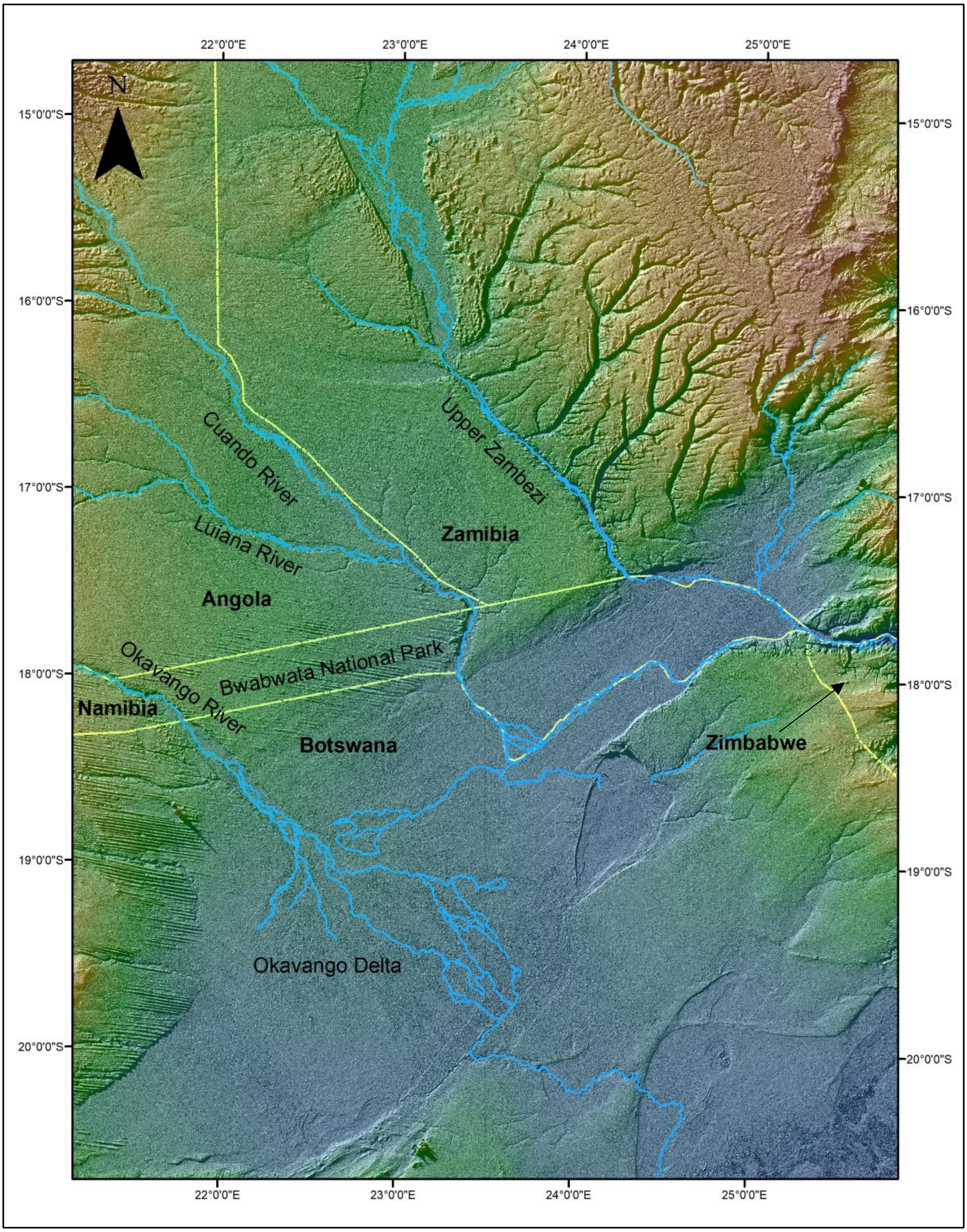


Figure 2-5.The subtle topography relief of the Kalahari Plateau using side-shaded shuttle radar topography mission (SRTM)-4 imagery showing Bwabwata National Park within the Okavango and Upper Zambezi River Basins shared by Namibia, Angola, Botswana, Zambia and Zimbabwe (adapted from Moore *et al.*, 2012).

Today, the dune crests are highly degraded, and in places only diagnosable by vegetation contrasts between the crests, which support dry broadleaved savanna and woodlands separated by grass intervening omiramba (MacFarlane & Eckhart, 2007; Brown & Jones, 1994). Floods restrict the growth of most woody plants in the omiramba because the roots cannot tolerate the water inundation (Mendelsohn & Roberts, 1997). For this reason, the low-lying omiramba features are dominated by grasslands, and the dune crests by tall densely woodlands, with large root systems (Figure A1; Appendix A).

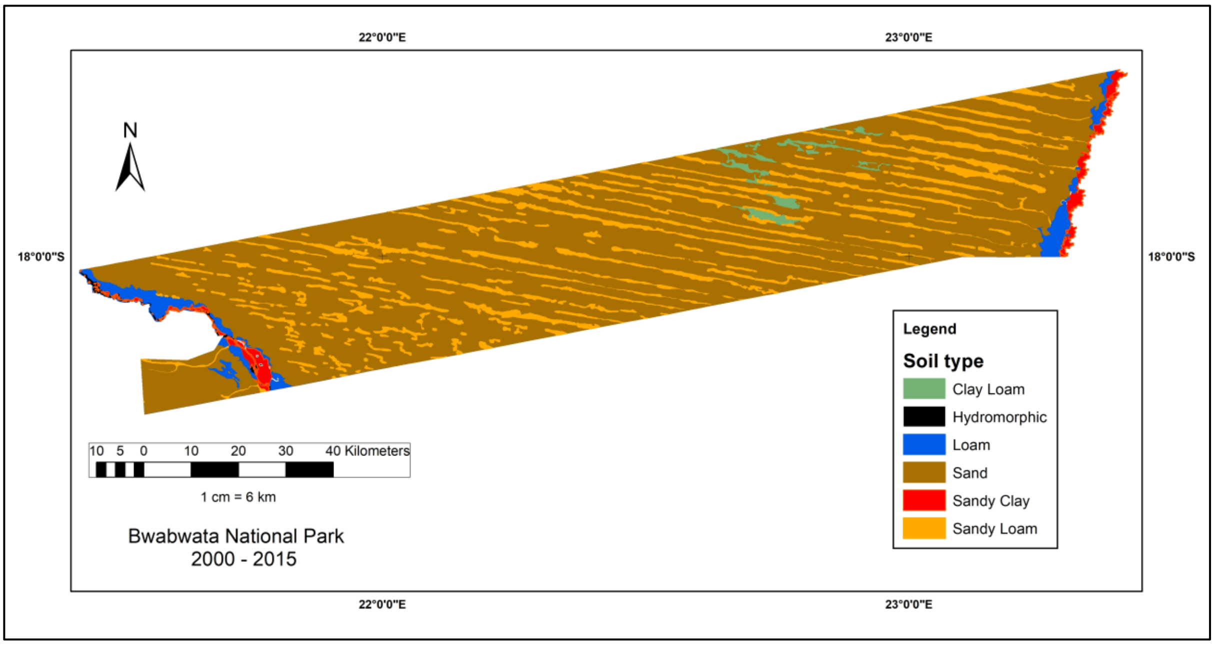


Figure 2-6. The distribution of soil types in Bwabwata National Park (data derived from Mendelsohn & Roberts, 1997).

The primary drivers of the ecological patterns are the flooding regimes, soil types and fire in BNP (Mendelsohn & Roberts, 1997). The park is composed of three distinct physiographic features, i) the perennial Okavango and Kwando Rivers, their floodplains and associated riparian vegetation; and ii) the parallel system of fossil drainage lines (omirmaba) that trend ESE – WNW between the perennial rivers, which contain mostly grassland, and iii) the parallel palaeo-dune crests between each drainage line (i.e. omuramba) supporting wooded savanna (Tinley, 1966) (Figure 2-7;
Figure 2-8). The Kwando River has an extensive network of floodplains that range between 2 - 5 km in width, with numerous backwaters and oxbow lakes, whereas the Okavango floodplain is generally narrow (1 - 2 km wide) (Brown & Jones, 1994).

Figure 2-7: Aerial view of the palaeodune field showing the vegetated Kalahari dune crests and the grass laden fossil drainage lines (omirmaba) with active fires in Bwabwata National Park. (Photo: Diganta Sarma, 2015).

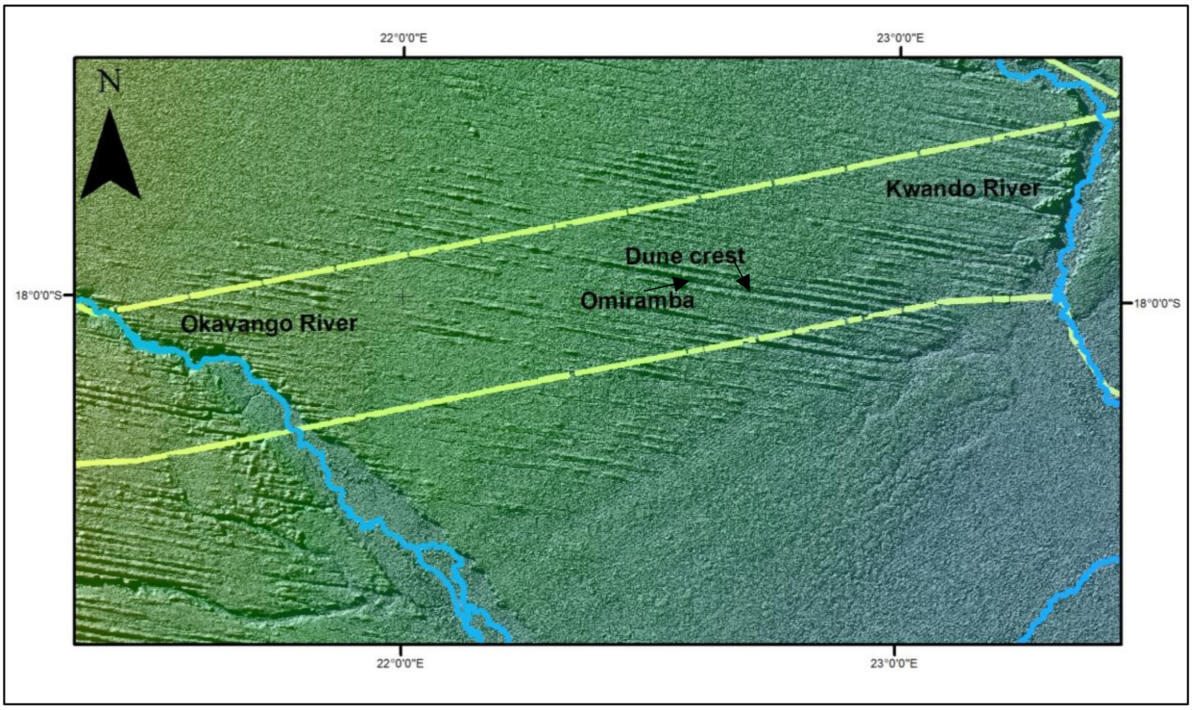


Figure 2-8: The subtle topography relief of the Kalahari Plateau using side-shaded SRTM-4 imagery across a portion of the Mega-Kalahari sand sea showing the major relic dunes (i.e. omirmaba) that trend ESE – WNW between the Okavango and Kwando Rivers in Bwabwata National Park (Adapted from Moore *et al.*, 2012).

Vegetation

Bwabwata National Park lies within the Zambezian domain of the Sudano-Zambezian Floristic region (White, 1983), and is classified as tropical savanna (Tinley, 1966). As a region, the Kavango East and Zambezi Regions have the highest density and variety of trees and plants in Namibia (Ashley & La Franchi, 1997). The vegetation type is described as dry deciduous woodlands and transitions from dry forest savanna in the east (MWAF, 2011) to dry scrub savanna of the Kalahari in the west, and is situated within the southern limit of broadleaved tree-shrub savanna biome of the 'Miombo Eco-region' of southern Africa (Timberlake *et al.*,2018).

The vegetation is influenced by five factors, namely climate, soils, floods, fire (Trollope & Trollope, 1999), and human activities. The vegetation structure is often determined by the relative frequency and intensity of fires, as well as impacts associated with elephants (Massyn *et al.*, 2009). It is reputed that huge areas of these woodlands continue to be lost as a result of frequent burning, particularly in the eastern Caprivi and in the west of the region in BNP (Mendelsohn, 2009). At present, vast areas of the forests and woodlands have been converted to shrublands, and there is concern that most remaining trees will disappear if the frequent burns are allowed to continue (Mendelsohn & el Obeid, 2005). There have also been suggestions that fires were associated with the war-time activities in the 1980s (Burke, 2002), and explicitly a 1 km fire-free zone was created along the Angolan border during the South African Defence Force (SADF) occupation (World Wildlife Fund [WWF], 1997), which indicates that fires were frequent elsewhere in the region during the war.

Vegetation types

In this study, Geographic Information System (GIS) layers resulting from analyses of satellite imagery and ground surveys by Mendelsohn & Roberts (1997) were used to delineate the main vegetation types and landscape features in BNP. Spatial data from the Environmental profile of the Caprivi (Mendelsohn & Roberts, 1997) was obtained from (http://www.the-eis.com/). The 13 vegetation classes in the vegetation map of Mendelsohn & Robert's (1997) were reclassified into four major broad types, namely: (1) savanna-woodlands (82. 35 %), (2) omiramba grasslands (9. 40 %) (3) riparian (4. 39 %), and (4) Burkea shrublands (3. 86 %) (Figure 2-9; Figure 2-10 a - d). Since the omiramba grasslands and Burkea shrublands are characterised as distinctive, as they differ from the other aforementioned types in BNP, they were not grouped with any other vegetation types occurring in the park.

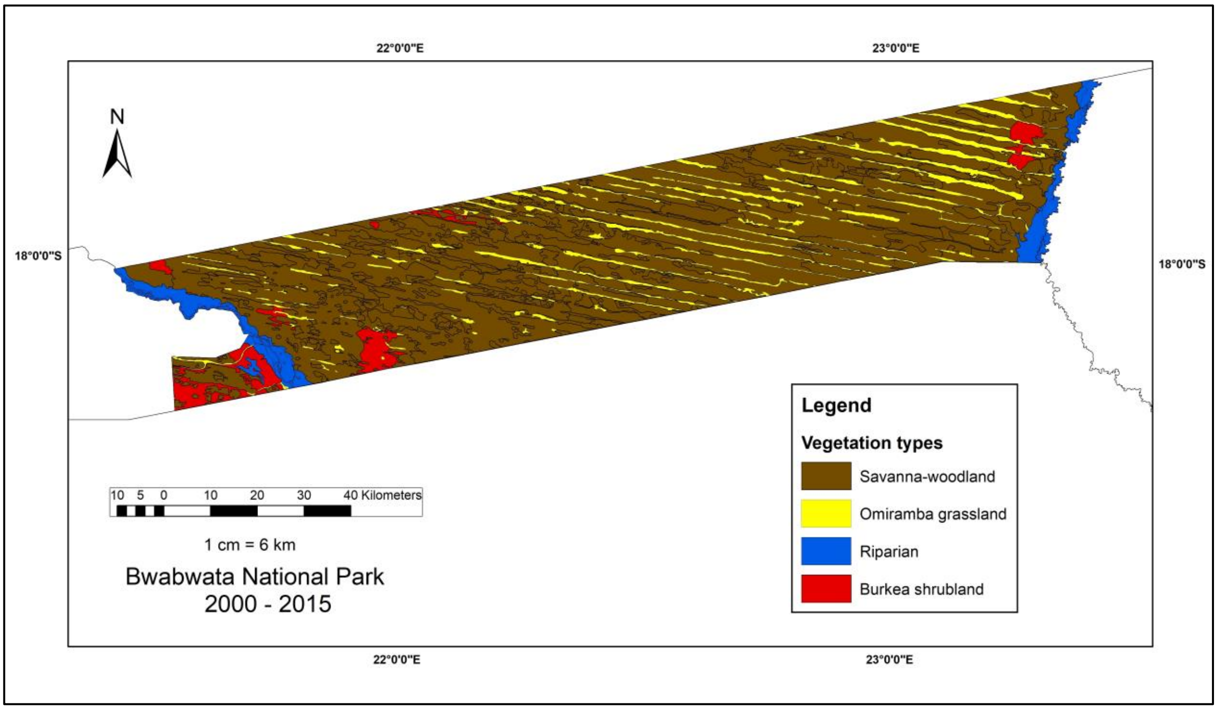


Figure 2-9. Vegetation map showing the four vegetation types in Bwabwata National Park. (Data derived from Mendelsohn & Roberts, 1997). Refer to text for details.

Savanna-woodlands

The savanna-woodlands were reclassified based on grouping the following woodland types characterised in Mendelsohn & Roberts (1997): open-camelthorn woodland, teak savanna, teak woodland, Burkea-teak woodland, Burkea-Combretum woodlands and omirmaba fringe woodlands, which constitute mixed open woodland vegetation in BNP. The broadleaved woodlands are considered to be less sensitive and scarce (MET, 2013). Characteristic species include *Burkea africana, Baikiaea plurijuga, Guibourtia colesperma, Ochna pulcra, Terminalia sericea, Erythrophleum africanum, Combretum hereoense, Schinziophyton rautanenii*, *C. collinum* and *Pterocarpus angolensis* (Tinley, 1966). The woodlands represent a catenary sequence with the tops of the dune crest lined with dense woodland to the lower edaphic grasslands in the omiramba (Brown & Jones, 1994). Further, these woodlands are composed of several species that yield fruits, seeds, tubers and leaves, which are important to the Khwe in the subsistence of their diet (Brown & Jones, 1994).

Omiramba grasslands

The omiramba grasslands fall within a distinct palaeodune feature in BNP and are fossil drainage lines covered in grassland that lie between each remnant dune crest, which form part of the savanna-woodlands coverage in the park throughout the Kalahari sand areas. Tinley (1966) described the grass cover within the omiramba, as diverse, with each omuramba comprising a different suite of grass composition. However, is some cases, mostly tall, coarse, sour perennial grasses are present in the drainage areas. The omiramba are fringed by woodlands which dominate along the omiramba margins and are characterised by *Combretum psidioides*, *C. zeyheri* , *Philenoptera violacea*, *Dialium engleranum*, *Senegalia nigrescens*, and *Euclea divinorum* (Tinley, 1966; Mendelsohn & Roberts, 1997). The grass *Imperata cylindrica* dominates the wetter areas while a variety of palatable species grow in the drier areas, such as *Schmidtia papppophoroides, Brachiaria nigropedata, Digitaria eriantha* and *Anthephora pubescens* (Mendelsohn & Roberts, 1997). Evidence of the encroachment of thorny species in some of the omiramba has occurred from the edges to the centre of the drainage lines (Brown & Jones, 1994). The biodiversity of the omiramba and associated fringe woodlands are considered to be moderately sensitive and scarce (MET, 2013), and provide some of the best grazing resources in the Kalahari sand areas (Mendelsohn & Roberts, 1997). These low lying drainage areas are frequently used by the Khwe and Mbukushu for cultivating crop fields in BNP.

Burkea shrublands

The Burkea shrublands represent a degraded form of teak woodland (trees over 4 metres are rare), and are characterised by a shrub layer that can cover up to 50 % of the extent of this vegetation type (Mendelsohn & Roberts, 1997). The shrub layer is generally characterised by *Terminalia sericea, Philenoptera nelsii, Bauhinia petersiana, Baphia massaiensis*, *Burkea africana* and *Grewia retinervis* (Mendelsohn & Roberts, 1997). Other common species included *Erythrophleum africanum, Combretum zeyheri*, *Ochna pulchra*, *Croton gratissimus* and *Gymnosporia senegalensis* (Tinley, 1966).

Riparian

The riparian vegetation was characterised by grouping the okavango-kwando valley woodland, okavango-kwando grassland, and rivers and open water vegetation types. The riparian areas are characterised by tall marginal woodlands that line the river edges, which are comprised predominantly of *Garcinia livingstonei, Ficus sycamorus, Diospyros mespiliformis, Senegalia nigrescens, Syzygium cordatum,* and *Combretum imberbe* (pers.observation). The Kwando floodplain is covered mainly in tall Phragmites reedbeds with patches of papyrus and grassland, which grades from permanently inundated to seasonally inundated tracts, and the species physiognomy and composition changes accordingly (Tinely, 1966). The biodiversity in the riparian woodlands and floodplains are considered to be highly sensitive and scarce (MET, 2013).

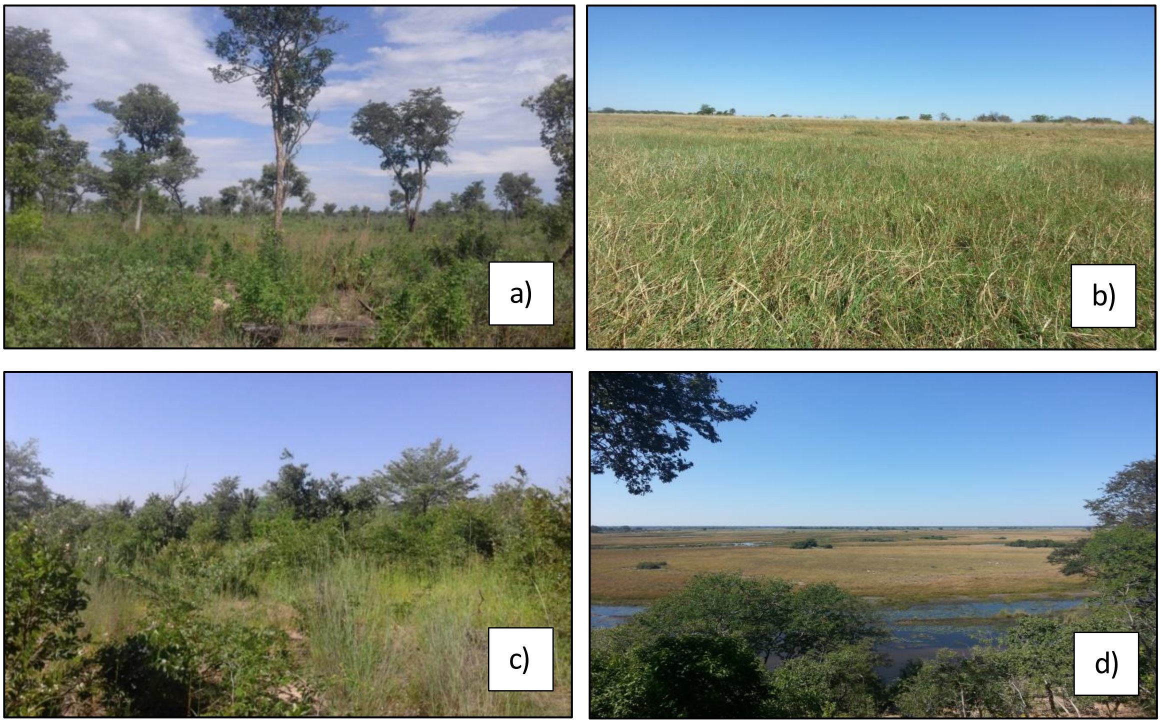


Figure 2-10: The four major vegetation types in Bwabwata National Park (BNP): a) Savanna-woodlands, b) Omiramba-grasslands, c) Burkea-shrublands, and d) Riparian.

Biological diversity

The park area between the major two river systems forms a dry-land link, and is the largest section of Kalahari woodland in Namibia (MET, 2013). The region has faunistic affinities with both the Southern African Biotic region and the Zambeziacan Biotic region (Brown & Jones, 1994), and thus a high number of large mammal and bird species occur in the park that are rare nationally. Ninety seven mammal species are known to occur in the park, however the faunal diversity remains understudied. Forty four percent of these mammals are classified as Red Data species because of their association with the wetlands of the Kwando and Okavango River systems that are predisposed to human disturbance (Brown & Jones, 1994). BNP supports 9 predators, and 10 lesser known smaller predators, 23 herbivores, and 3 primates species (Tinley, 1966). The savanna-woodlands and rocky areas of the park contain 51 species (71 %) of mammals, and support 6 endangered mammals, which include Cheetah (*Acinonyx jubatus*), Wild Dog (*Lycaon pictus*), Roan Antelope (*Hippotragus equinus*), however all the remaining Black Rhino (*Diceros bicornis*) were captured and relocated to safety. The riparian forests and termitaria further provide important microhabitat for small mammals, and reptiles (Timberlake *et al.*, 2018).

There is a bi-annual large mammal concentration in BNP (Tinley, 1966). The Kwando and Okavango Rivers and associated floodplains are important water sources during the dry season (July – October) for Elephants (*Loxodonta africana*), and Buffalo (*Syncerus caffer*) (Figure 2-11a), as well as several water dependent antelope, for example, Waterbuck (*Kobus ellipsiprymnus*), and Sitatunga (*Tragelaphus spekii*). The floodplains provide important habitat for the Red Lechwe (*Kobus leche*) and Common reedbuck (*Redunca arundinum*). The omiramba (fossil drainage areas) and their associated grasslands between the woodland habitats of the park form important habitat for Roan (*H. equinus*), Sable (*H. niger*) and Tsessebe (*Damaliscus lunatus*) antelope (Massyn *et al.,* 2009). After sufficient rainfall (Nov - Mar), the omiramba pans provide water sources for woodland inhabiting fauna through the dry season between the river systems (Figure 2-11b). Over a 1000 Buffalo occur between the Buffalo and Mahango core areas of the park (MET, 2010).

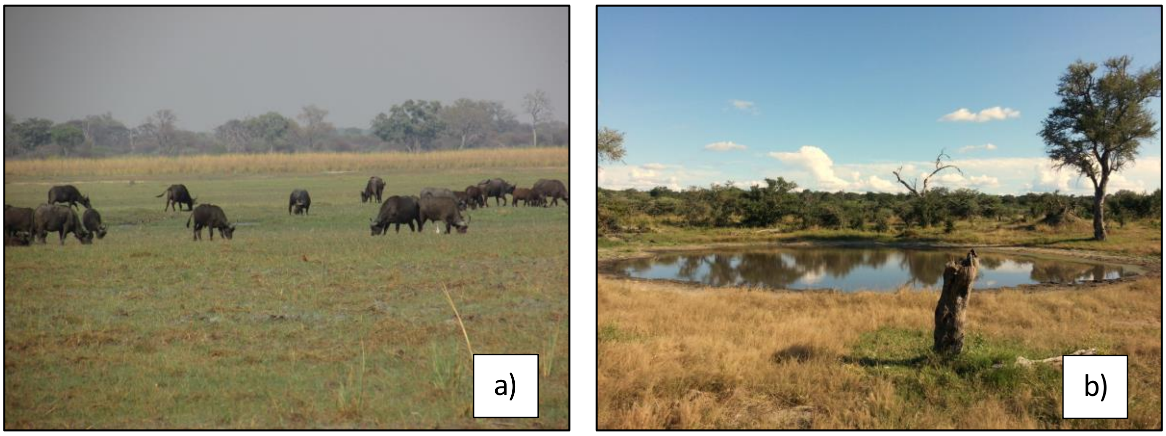


Figure 2-11: a) Buffalo grazing on the Kwando floodplain, and b) rain-filled 'omuramba' pan in Bwabwata National Park.

The Mahango core area (CA) within the Western CA is an internationally important bird area, which supports globally threatened species. A total of 417 bird species have been recorded on the Okavango River system, and 430 for the east Caprivi (Kwando area) (Brown & Jones, 1994). The park is a prime bird watching area, with 70 % of all bird species found in Namibia being recorded in the region (Kangumu 2008). The Okavango River systems support a rich fish diversity of 73 species (Skelton *et al.,* 1985).

The South African military's entanglement in nature conservation from 1966 – 1989 (see below), heralded population declines in elephant numbers (Brown & Jones, 1994), and thousands were killed in the region for their ivory (Lenggenhager, 2016), and presumably meat (Chase & Griffin 2009). Botswana also erected veterinary fences (1991 – 1997) on the border of Namibian and Botswana (135 km), which would have limited large mammal movement between the Okavango Delta and BNP. Recent estimates for the elephant population in the KAZA-TFCA are approximately 202, 000 and based on the tracking of individual elephants (Lindsay *et al.,* 2017) they move largely into and out of the Western and Kwando CAs of the park from Angola and Zambia. However, these elephant populations are also largely threatened because they are the current target of poachers[2] driven by the Asian demand for ivory, and the corridor areas between BNP, Angola and Zambia are notably being avoided by elephants (Pinnock, 2014).

Land use within BNP

Bwabwata National Park is comprised of three core wildlife areas designated for special protection to support key government constitutional biodiversity objectives, and controlled tourism, which comprise Kwando (134, 481 ha) , Buffalo (62, 921 ha) and Mahango (24, 479 ha) core areas (Figure 2-12). A central Multiple Use Area (MUA; 405, 531 ha) is zoned for community-based tourism, trophy hunting, human settlement and development and the harvesting of natural resources vital to the livelihoods of BNPs surrounding and resident communities, the Khwe and Mbukushu (MET, 2009). The MUA is home to an extensive village network (19), and the park also contains schools, clinics, fields, housing, and a Catholic Mission which are remnant structures left from the SADF occupation. In 1995, the Government of the Republic of Namibia (GRN) established a prison farm (Divundu Rehabilitation Centre) on the banks of the Okavango River (Koot, 2013). The distribution of settlements today in BNP is a result of past settlement patterns, wars, and ecological, economic and political circumstances (Brenzinger & Harms, 2001).

The Khwe (former hunter-gatherers) are predominantly settled in the west, centre and east of the park, whereas the west is mainly populated by the Mbukushu agropastoralist people, and therefore represents a mixed population of both Khwe and Mbukushu inhabitants. For the purposes of this study, the MUA was divided into the MUA East (218, 700 ha) and MUA West (186, 700 ha) because of the density, and different ethnic populations residing in the respective areas. The official core protected areas in the west (Buffalo and Mahango) were combined in this study due to their small surface areas, and are hereafter called the Western core area (CA; 87, 400 ha), and the Kwando area in the east is referred to as the Kwando core area (CA: 134, 500 ha) (Figure 2-13).

[2] Fires were also described as being lit to conceal tracks in the vegetation after poachers has passed through an area (Stakeholder interviews, 2014 and 2015).

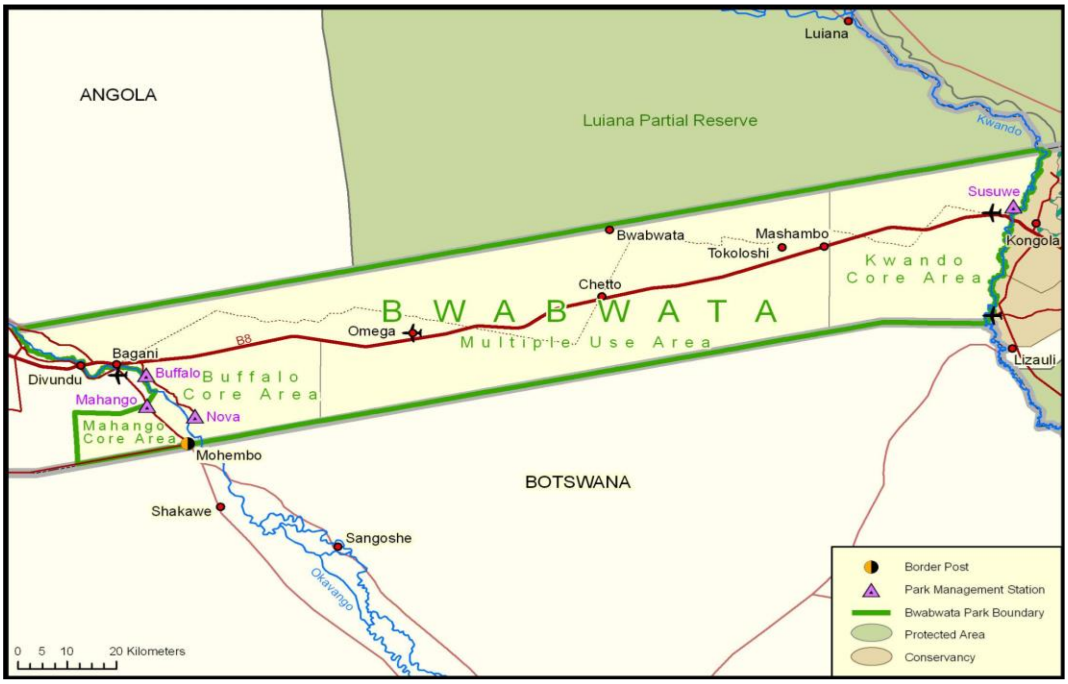


Figure 2-12: Map showing the formally designated conservation core areas (Mahango; Buffalo; and Kwando core areas) in Bwabwata National Park (BNP) (MET, 2011).

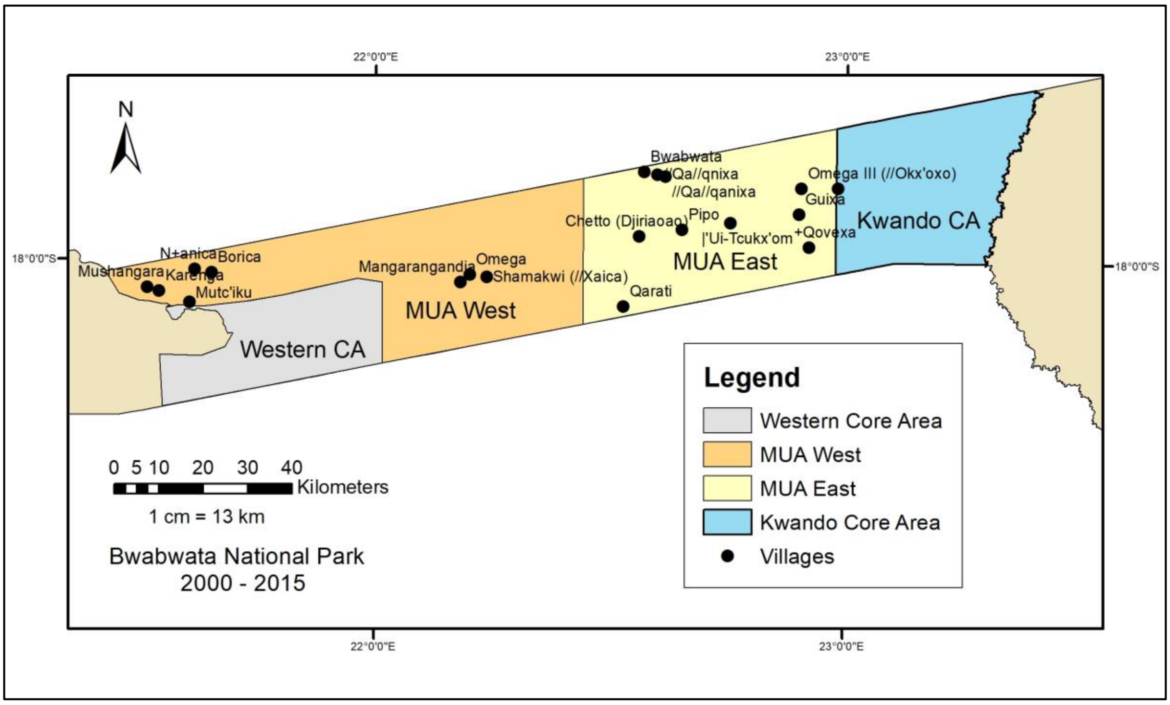


Figure 2-13: Map showing the location of the four land use areas (Western CA; MUA West; MUA East and Kwando CA) and villages in Bwabwata National Park.

Historical and social context

Early human occupation

The first known hominoid (*Otavipithecus namibiensis*) in Namibia was found in the Berg Aukas, near Grootfontein, which was dated to the late Middle Miocene (~ 13 Ma) (Conroy *et al.*, 1992). The earliest evidence of stone tools was produced by hominoids (of the genus '*Homo*') over the last 1.8 million years in Namibia (late Pleistocene) (Mendelsohn *et al.,* 2009; Kinahan, 2011). Other Namibian Early Stone Age tool sites have been estimated at 800,000 years (Orange River), 500,000 years (Namib IV situated on the western Namibian escarpment), and the most recent site is the Apollo XI cave in the Huns Mountains, where the earliest rock art was dated at 19,000 – 26, 000 years ago (Mendelsohn *et al.*, 2009). Thus, the first archaeological sequence in Namibia, starts with the Miocene (Conroy *et al.,* 1992), and is followed by "late Pleistocene evidence of the Early, and Middle Stone Age, with Later Stone Age evidence first appearing before the Last Glacial Maximum" (Kinahan, 2011: 19). Namibia has been arid for millions of years, and historically, human settlement patterns were limited by water distribution (Kinahan, 2011), and people moved frequently and covered large distances (Mendelsohn *et al.,* 2009).

Hunter-gatherers: Holocene (10, 000 years ago - present)

Overall, the history of human occupation of Bwabwata National Park is poorly understood, in part due to the geology and landscape features, since many archaeological sites have been covered by Kalahari sand (Kinahan, 1996; Mendelsohn *et al.,* 2009). Furthermore, during the Liberation war (1960s – 1989), access was restricted, which limited research possibilities (Kinahan, 2011). Thus, it is an incomplete history, pieced together from archaeology (Kinahan 2011), anthropology and most recently with genomic data (Suzman, 2018). Recent genetic evidence suggests that the Khwe people in the north-east of Namibia are the oldest inhabitant population and are representative of an ancestral group of modern humans (Tishkoff *et al.*, 2009; Henn *et al.,* 2011). Thus, the southern African 'Bushmen' groups involve the history of modern humans (*Homo sapiens*) in sub-Sharan Africa, through to the agricultural revolution and today (Suzman, 2018). During the Holocene (i.e. the last 10,000 years) people were still classic hunter-gatherers (Kinahan, 2011), and in BNP, the Khwe were still practising traditional hunting and gathering livelihood strategies up until the 1960s (about 60 years ago) (Diemer, 1996).

Before colonial boundaries were drawn (1886) (Fisch, 1999), historical sources indicate the Khwe's territory straddled the dense bush in what is now south-eastern Angola, south-western Zambia, and northern Botswana (Suzman, 2001; Robbins, 2007; Taylor, 2012). Notably, Tinley (1966) observed an influx of Khwe people from Angola and Botswana (1960s), who were then settling in the low lying drainage areas, locally called 'omiramba' in the western Caprivi. Brenzinger (2010: 26) emphasised that the West Caprivi is the ''core land" of the Khwe (Figure 2-14) since it has always been the centre of their ''migration territory", and secondly because other areas were occupied by other groups (Angola), or were inaccessible. The colonial administration also increasingly recognised the West Caprivi as a 'Bushmen area' (Suzman, 2001; Taylor, 2012).

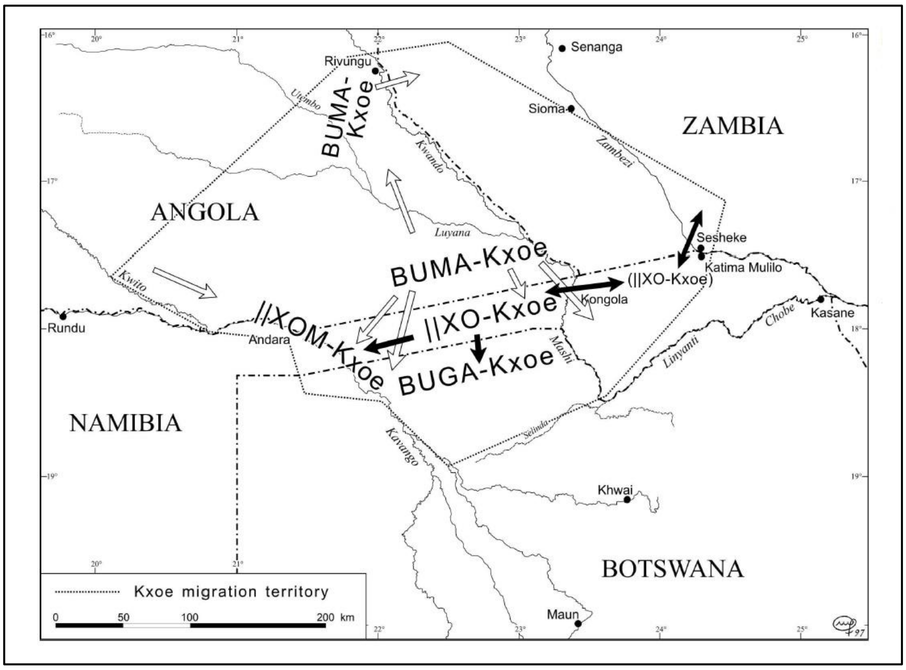


Figure 2-14: The Khwe "migration territory" prior to 1965 derived from the distribution of Kxoe 'dialects' in central southern African (Brenzinger, 2010:12). The arrows indicate the directions of the Khwe migrations.

Historically, the Khwe were highly mobile hunter-gatherers who lived in small family bands up to 30 people (Uys, 2015), separated from each other by long distances (Brenzinger & Harms, 2001; Rousset, 2003). The Khwe people are renowned for their bush knowledge of plants and animals, which is associated with their hunting and tracking skills. They have been burning the vegetation for hundreds of thousands of years (Brown & Jones, 1994; Owen-smith, 2017). Further, the harvesting of veld food resources (e.g. fruits, seeds, underground tubers, firewood) is an important livelihood activity of the Khwe, which is said to contribute to 75 % of their diet, although there is some evidence that this may be changing (Diemer, 1996; Massyn *et al.,* 2009).

Agropastoralism from the last 2,000 years – present

The last 2,000 years coincided with more specialised and complex tools (e.g. bone, arrows, stones). In the study area, the oldest agro-pastoral sites with pottery date from 2, 200 to 2, 000 years ago, which indicate crop cultivation, since the clay pots were used to store grain. Late Stone Age (850 AD) implements (pottery, bone and iron fragments) were found between the Okavango and Kwando Rivers (Tinley 1966; Kinahan, 2011). The artefacts found on the Okavango River belonged to the farming Bantu-speaking peoples (Huffman, 2007) that migrated into this area, and constituted the settled farming community then, as today, where rainfall conditions were suitable for pastoralism alongside staple cereals of millet, sorghum and recently maize (Mendelsohn *et al.,* 2009). Thus, the Holocene period, which was mainly characterised by the Late Stone Age record, also includes the first appearance of domestic livestock, ceramics, metallurgy and farming in the last 2, 000 years (Vogelsang *et al.,* 2002; Kinahan, 2011; 2013). At this time, the area was already inhabited by hunter-gatherer peoples who acquired pottery skills and spread them over a wide area prior to the establishment of the Bantu farming settlements (Kinahan, 1986; Kose, 2009).

Mostly, Bantu-speaking peoples in southern Africa are recognised as agropastoralists and are not typically associated with hunting activities, and the knowledge of these traditions as part of their culture remain limited (Eckl, 2007; Fisch, 2008). The Bantu-speaking Mbukushu who arrived in the late 18th century in West Caprivi were described as having a 'semi-sedentary lifestyle' and were spread over a similar area to that of the Khwe, but were concentrated along the river systems (Brenzinger, 2010). From the brief historical records, it is known that at least for the last 200 years, the Mbukushu have lived along the middle Zambezi, lower Kwando and Okavango Rivers of SWA, and in the Okavango Delta of Botswana (Larson, 1970). They first settled in south-west Zambia (1750) (Larson, 1970), and then along the Okavango River (around 1800 or in the late 18th century) along the margins of the Okavango Delta that penetrates south into Botswana (Bock & Johnson, 2002). Here, they encountered the Khwe, Macanigwe River Bushmen, and the Kung! Bushmen, who were sparsely distributed in the landscape (1800s) (Tinley, 1966), owing to a lack of surface water (Fisch, 2008).

Early explorers (mid-15th to 19th century)

The first known explorers and seafarers of Namibia, along the Skeleton coast on the African West coast were the Portuguese, Diogo Cào (1445) in Walvis Bay, and Bartholomeu Dias (1488) in Lüdertiz. Remarkably, the first map produced of the northern part of Namibia was by the Swedish-English hunter and explorer, Sir Charles John Andersson in 1852 (Blomstrand, 2008) (Figure 2-15). According to Larson (1970), Andersson attempted to reach the Mbukushu capital at Andara on the Okavango River, but had to turn back due to severe attacks of malaria. However, in 1856, a trader, Frederick Green, and a Swedish zoologist Professor Wahlberg, were the first Europeans to make contact with the Mbukushu (Larson, 1970). Nonetheless, the Khwe people have long been acknowledged as the first inhabitants in the study area, after which the Bantu-speaking people, namely the Mbukushu people, and various other groups of Bantu descent (Mafwe and Mayeye) migrated into the greater Caprivi region from Central Africa in the late 18th century (1790 – 1800s) (Tinley, 1966). The West Caprivi is also home to a small number of !Xũ San, also known as the *Vasekele* who originated from Angola (Suzman, 2001; Taylor, 2012).

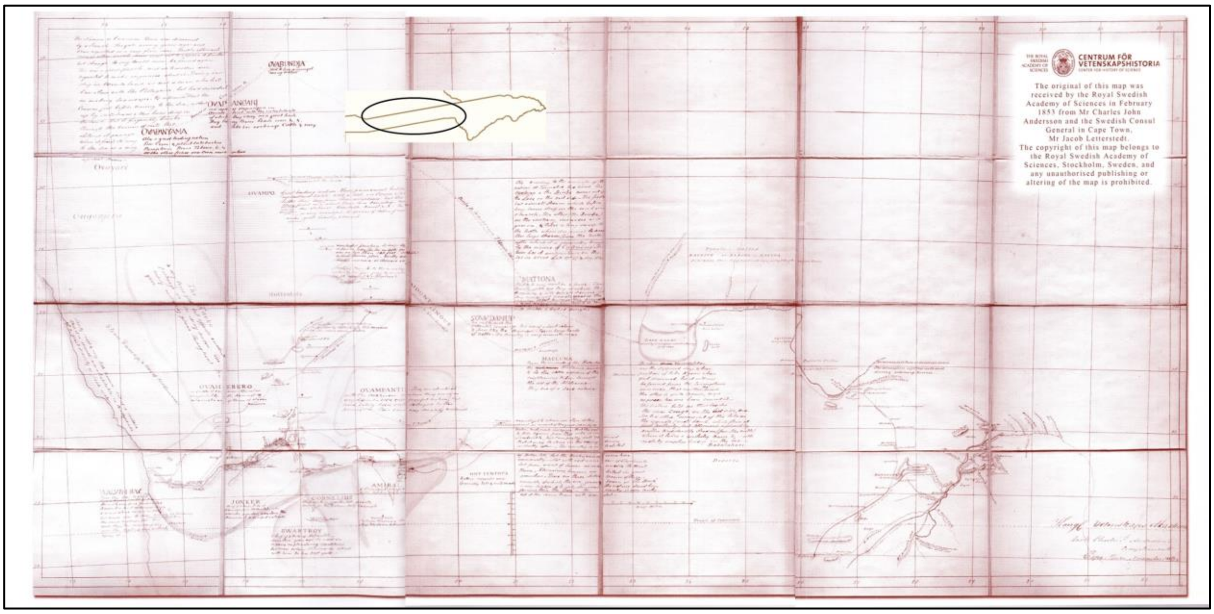


Figure 2-15: An early exploration map produced by Sir John Charles Andersson in 1852 of north-east of Namibia (Blomstrand, 2008). The black oval circle indicates the location of the West Caprivi. *This map lay hidden in a vault for 154 years, until its discovery in 2004, and is available at the Royal Academy of Sciences, Sweden. Reproduced with permission from the Royal Academy of Sciences.

Colonial history and the rise of conservation (1884-1990)

Namibia has a chequered history prior to its independence on the 21st March 1990, with colonial influences involving Britain, Portugal, Germany and South Africa in the north-east of the country. Namibia was first under German administration (1884 – 1914), and called German South West Africa, and later South West Africa (SWA) under South African rule (1915 – 1989). After the end of the First World War, the League of Nations at the Treaty of Versailles (1919) placed SWA under a British mandate and was declared a South African protectorate, as South Africa had become part of the British Empire in 1910 (Mendelsohn *et al.*, 2009; Wallace, 2011). Thus, South Africa's direct political and military rule over SWA began with the defeat of the former German colony during World War I. After the country's two decade (1966 – 1989) armed resistance struggle against South African rule in the Namibian War of Liberation, the SWA administration ended after 75 years with the founding of the Government of the Republic of Namibia (GRN) in 1990 (Mendelsohn & el Obeid, 2005; Lenggenhager, 2015). The region persisted for over a century as the most internationally strategic area in the country at the nexus of four neighbouring countries (Bronkhorst, 1991), with an insurgent war (1966 – 1989), that would later become the frontline for resistance against communism during the Cold War (Kangumu, 2008).

In the late 19th century, two major agreements between three colonial powers, namely Britain, Portugal and Germany, defined the colonial border of the Caprivi Region (Fisch, 1999; Lenggenhager, 2015). In 1886, the Portuguese-German Convention demarcated the northern boundary with Angola (Portuguese colony) of imperial Germany's area of influence to open up access to the east African coast (Wallace, 2011). Four years later, in 1890, an Anglo-German agreement created the feature of the *Caprivi Strip* on Africa's political map (Zeller & Kangumu, 2008); a jutting slice into the Zambezi region, which defined the eastern and southern boundaries as part of the colonial 'Scramble for Africa' (Kangumu, 2008). The regions boundaries have been described as 'one of the most unusual colonial boundary legacies in Africa' (WWF,1997: 10), as European regimes drew a narrow strip (32 km wide) from the west to the east, wedged between four countries (Angola, Zambia, Botswana and Zimbabwe) (Figure 2-1). In the late 19th century, the Kingdom of Barotseland was under the influence of British colonial administration, encompassing Bechuanaland (Botswana), Northern Rhodesia (Zambia), and Southern Rhodesia (Zimbabwe), with the Caprivi strip neighbouring these countries. In 1890 the British signed the Heligoland-Zanzibar treaty, conceding the strip of land between the Okavango and the Zambezi to Germany to access their territories in East Africa along the Zambezi River (Fisch, 1999). However, the Zambezi River could not be sailed by ships for long stretches due to the extensive rapids en route, and thus the acquisition of the thin strip of land lost a part of its significance to Germany (Fisch, 1999). German colonial powers left the most significant legacy – 'the determination of the boundaries' (Boden, 2009: 12), which set the course for multifarious significant cultural and decolonisation turmoil in the years to come. Yet, South African rule left the greatest mark, a two decade war (1966 – 1989), which significantly shaped today's social-ecological circumstances in the park.

In response to rising anti-colonial resistance during the 1960s in southern Africa, SWA was considered an area of 'utmost strategic military importance' by the South Africans (Kangumu, 2008). Thus, the area was developed as a military base for the control of the border region and as a base for cross-border attacks into neighbouring countries (i.e. Angola and Zambia). Namibia's South West Africa People's Organisation (SWAPO) and its military wing, Peoples Liberation of Namibia (PLAN) was founded in response to the country's resistance against South Africa's apartheid policies, and liberation struggle for independence since the early 1960s (Wallace, 2011). The emergence of SWAPO and PLAN as a significant military organisation precipitated a far larger South African presence in the Caprivi Strip and northern Namibia as a whole.

Northern Namibia was beheld by the South West Africa Administration (SWAA) as having great potential for its labour force, and natural resources with economic benefits for South Africa (Lenggenhager, 2015). Explicitly, South Africa's presence in the country resulted in the intensification of 'apartheid' (based on the principle of social, economic and social organisation), and thus the rolling out of the Odendall Commission (1963) leading to the identification of independent black 'homelands' (Wallace, 2011). Although it was originally agreed that the western Caprivi be set aside for the 'Bushmen' in the area, the area being rich in wildlife, it was declared a Nature Park in 1963, and upgraded to a Game Park in 1968[3] (Suzman, 2001; Rodwell *et al.*, 1995). However, despite its new status as a Game Park, the Khwe people were allowed to continue to live there, as well as hunt with traditional weapons (e.g. bow and arrow) (Boden, 2009). This decision was based on the Odendall Commission that recognised the needs of the San and other minorities living in the park, and their need to harvest wildlife and veld food resources (Massyn *et al.*, 2009). However, these circumstances soon changed with an emerging war (1966 – 1989). Instead, the majority of the Mbukushu (1970) were removed from the park, and placed on the western bank of the Okavango River (WWF, 1997). Furthermore, shortly after the designation of the area to a Nature Park, the war began, and the SADF cleared the western Caprivi (BNP) for use as a military zone (i.e. closed zone) (Legal Assistance Centre [LAC],2006). The SADF had a great interest in the 'Bushmen' occupying the area at the time as soldier recruits. Furthermore, the Portuguese-Angolan civil war was coming to an end in Angola in 1975, and the Khwe people who were trained as soldiers in Angola, were escaping into the West Caprivi in fear of retaliation from the new political parties (Robbins, 2007; Boden , 2009).

The SADF regime immediately recruited the influx of Khwe from Angola into their forces, to fight against SWAPO and Namibia (Brenzinger, 2010). Thus, the Khwe men were used as trackers and soldiers by the SADF for the duration of war, and were romanticised as 'Bushmen soldiers' due to their renowned tracking and bush skills (Suzman, 2001). By the late 1980s, the Bushmen held the unique distinction as being one of the most militarised ethnic groups in the world (Gordon, 2018). Oral histories indicate that the Khwe did not enlist in the SADF for political or ideological reasons, but for economic reasons (Taylor, 2012). However, two decades prior to the SADF presence in the West Caprivi, many Khwe worked on the Gold mines (Witwatersrand Reef) in South Africa, and came to rely on a cash economy (Boden, 2009). However, in 1975 Botswana closed its southern border (Mahango) with

[3] In 1966, Ken Tinley, a state ecologist, was requested to survey the wildlife status and the Kalahari woodlands 'to ascertain whether anything of natural and unique value would be lost to SWA' if the terrain was to be developed along the lines envisaged for the 'Okavango Native Territory' (i.e. Bushman Reserve') (Tinley, 1966: 1). Tinley's survey revealed the significant ecological value of the area, which influenced and elevated the conservation status of the area (MET, 2013).

Namibia, preventing the Khwe's movement to work on the mines in South Africa (Brenzinger, 2010). This event, together with the declaration of the area as a Game Park (1963), and later when the Khwe were concentrated into army camps between 1975 - 1989, and forbidden their freedom (Brenzinger, 2010), were left with little choice but to join the SADF forces who paid appealing high salaries (Suzman, 2001). Thus, before the arrival of the SADF, the Khwe and Mbukushu engaged in variety of livelihood strategies: hunting/trapping, veld food gathering, cultivation (millet, maize and vegetables) and fishing along both rivers in the park (Jones & Dieckmann, 2014). The presence of the SADF in the region precipitated a war related economic boom of airports, schools, clinics, infrastructure, and administration (Lenggenhager, 2015). Thus, the SADF placed considerable effort into the socio-economic development of northern Namibia, which included propaganda campaigns among its population aimed at persuading the people of the SADFs good intentions and undermining support for SWAPO amongst their Namibian recruits (de Visser, 2011). The Khwe, then employed as soldiers, rapidly became dependent on financial support, and especially food supplies provided by the SADF (Diemer, 1996).

Explicitly, the cordoned West Caprivi park landscape was used by the SADF to train soldiers and 'Reconnaissance Commandos' (Boden, 2009). For two decades, Namibian conservation officials were denied access to the area (Brown & Jones, 1994). Thus, the Namibian War of Liberation (also known as the 'South African Border War', 'Namibian Border War' and/or the 'Angolan Bush War') intercepted the parks conservation proclamation (1963), and hence, progress in this regard was thwarted, and terminated for political motives. The SWAA decision to promote the conservation status of the park was driven by its strategic geopolitical importance on the boundary of four countries with independence struggles starting in Angola, Zambia, and in Namibia in the 1960s (Rousset, 2003; Taylor, 2012; MET, 2013). Thus, equally the abundance of wildlife and the country's political boundary dynamics (1960s) led to its protected area status (Lenggenhager, 2015).

Conservation, unrest and land-use after independence (1990)

Following independence in 1990, the Ministry returned to the park for the first time, and a set of biological inventory surveys were carried out (e.g. social-ecological survey of the West Caprivi [Brown & Jones, 1994], and a wildlife aerial census (Rodwell *et al.*, 1995) to assess sustainable development options. In addition, the GRN settled the Khwe into agricultural schemes in the area, but the Khwe were reluctant about accepting these schemes, and settled in other areas of the park (Brenzinger & Harms, 2003; Boden, 2008). The Caprivi region as a whole is highly valued by the GRN due to its biological resources, which holds most of the economically valuable wildlife species in the region (Rodwell *et al.*, 1995), together with forests (Mendelsohn & el Obeid, 2005). Thus, the area was ear-marked to support the emerging Community Based Natural Resource Management (CBNRM) initiatives, conservation and development projects in the 1990s. In 1997, Mendelsohn & Roberts produced a seminal environmental profile (i.e. Atlas) of the Caprivi region, detailing the socio-economic, land-use potential and ecological status. Furthermore, in 1998, Namibia's Ministry of Environment and Tourism (MET) introduced a conservation and tourism development plan for the Caprivi Game Reserve, which was to improve management and nature conservation in the area (Rousset, 2003). One of the objectives of the conservation plan was to allow for the inhabitant communities to benefit equally form wildlife and tourism. The Integrated Rural Development and Nature Conservation (IRDNC), a Namibian NGO assisted the MET with managing the integration of communities living in the park in conservation efforts after Independence (Rousset, 2003). The MET vision involved the segregation of land, which resulted in the planning of different land use types, and thus the Multiple Use Area (MUA) was created for the use of inhabiting communities, along with two core conservation areas, the Kwando and Buffalo core areas, which were uninhabited. Table 2-1 shows the chronological development of the conservation status of the park from 1963, including incorporation within the greater KAZA-TFCA in 2003, and re-proclamation as Bwabwata National Park in 2007. Further, in 2007, the smaller Mahango core area on the border of Botswana (Mohembo) was integrated into the park's area (Figure 2-12). Yet, Rousset (2003) reported that even though the park vison planning was underway, the security situation had not yet stabilised in the region.

Table 2-1: Evolution of the conservation status of the western Caprivi to Bwabwata National Park (1963 – 2007).

Year	Conservation status
1963	West Caprivi Nature Park
1968	Caprivi Game Park
1999	The Bwabwata National Park Vision
2003	BNP incorporated into the KAZA-TFCA
2007	Bwabwata National Park officially re-proclaimed

Caprivi Secessionist Movement (1999 – 2002)

The year 1999 saw the eruption of internal and cross-border political unrest and the rise of the Caprivi Secessionist movement. This was an armed conflict between the GRN and the Caprivi Liberation Front (CLF), a rebel group that tried to seize the eastern Caprivi region. In 2000, Namibia allowed Angola to utilise the region to attack The National Union for the Total Independence of Angola (UNITA) in the southern parts of Angola, which resulted in the GRN accusing the Khwe of collaborating with UNITA rebels as enemies of the State (1998 – 2002) (Boden, 2008; Taylor, 2009). A number of people were attacked during this time, causing the Khwe to flee across the border into Botswana (Rousset, 2003). In early 2002, the death of Jonas Savimbi, the UNITA leader, resulted in the stabilisation of the security in the region. Thus, the secessionist situation overshadowed and interfered with development and conservation plans at the time (Rousset, 2003). Kangumu (2008) emphasised in his thesis called "*Contested Caprivi",* a distinct history of neglect, which has been characterised by having wildlife preservation more to heart than human welfare, but with politics clearly at the top of the agenda.

Livelihoods of Khwe and Mbukushu in BNP today

Today, the population of BNP is approximately 5, 500 people (Massyn *et al.*, 2009). BNP is now home to two major and distinct indigenous people; mainly the Khwe, and to a lesser extent the !Xũ or Vasekele people (from Angola) that comprise 82 % of population (LAC, 2006). The Mbukushu people make up 16 % of the BNPs population and are politically dominant in the area since they are the only indigenous group with a Traditional Authority (TA) recognised by government (Dain-Owens *et al.*, 2010) (Figure 2-16). Brenzinger (2010) showed in 1996 that the village of Mutc'iku was the major Khwe settlement, and 68 % of the Khwe population live to the west of Chetto village (more or less in the centre of the park), whereas 33 % of the Khwe live to the east of Chetto (Table A2; Appendix A). The only census figures available for the Mbukushu are historical, and in 1951 it was reported that 3, 000 Mbukushu were living in SWA, and in the 1970s, a conservative estimate of 4, 000 (Larson, 1970). Further, 200 Mbukushu, were said to be living along the Kwando River on the Zambian border in the 1970s (Larson, 1970). Today, the Mbukushu are predominately settled in the west of the park on the Okavango River (WWF, 1997).

The Khwe have had the most tumultuous and complex history of all the Namibian San, and have been severely marginalised, and are widely regarded as inferior by others (Brenzinger & Harms, 2001). Moreover, the history of the life of the Khwe still remains partial in literature, in comparison to other 'pure' San populations (Suzman, 2001; Boden, 2009; Gordon, 2009; Taylor, 2012). The Khwe people are cast as 'hybrids' or 'black Bushmen', and are therefore not seen to fit the stereotypical caricature deemed of anthropological interest of the pure and foraging unit of 'Bushmen' (Rousset, 2003; Boden, 2009; Hitchcock, 2012; Taylor, 2012). Moreover, these integrated traits were seen as beneficial by the South African army, and the Khwe who served as soldiers during the Namibian liberation war featured as 'crack soldiers' "combining the strength of the Black with the cunning of the Bushmen" (Uys, 2015: 10; Boden, 2009), which largely influenced their ethnic identity (see Battistoni & Taylor, 2009; Taylor, 2008). Ultimately, the South African army transformed the socio-political power between the Mbukushu and the Khwe, and affected both groups' access to natural resources during and after the war. The SADF were often in favour of the Khwe, which led to severe complications for the Khwe in the 21st century, related to ethnicity and identity factors (Taylor, 2008). Explicitly, the SADF's involvement with the Khwe during the war, fundamentally influenced post-independence government legislation on Traditional Authorities[4] (TA), and judgements involving the Khwe (Taylor, 2012).

During the South African rule (1915 - 1989), the Khwe were differentiated from the 'Bantus' as 'Bushmen' by the SADF in operation in the Western Caprivi (Taylor, 2008; 2009 ; Uys, 2015). The term 'Bushmen' is now widely regarded as disparaging (Fisch, 2008) and has been replaced by the word 'San', which is commonly used to designate the hunting and gathering people in southern African in the distant past (Brenzinger & Harms 2001). However, many people consider the 'San' more derogatory (Mendelsohn *et al.*, 2009). In this thesis, the 'Khwe-San' are referred to as the Khwe, as they call themselves (Taylor, 2012), meaning 'people' or 'human being' (Rousset, 2003) who speak a Khwe language called Khwé-dàm belonging to the Khoisan language family (Brenzinger & Harms, 2001). For the Khwe living in BNP, means 'to suffer', which they associate with their identity, because of the humiliation and hardships that they endure on a daily basis (Rousset, 2003). The Khwe, over the past century, have also been referred to as *Khoe, Kxoe, Kwe, Hukwe, Xukhwe,* and in some cases are still used (Taylor, 2012). Locally the Khwe were called *Barakwena* or *Barakwengo* by the neighbouring Bantu-speaking people (Brenzinger, 2010).

These latter names are disliked by the Khwe because of the former master-slave relationship with the Mbukushu (Brenzinger, 2010). The Khwe have sustained contact with the Mbukushu since their in-migration (1800s), and intermarriages were common (Brenzinger, 2010). The Khwe also became reliant on the Mbukushu for trading supplies (Boden, 2009), however according to several sources the Khwe were also enslaved for personal use as clients or servants or sold to slave traders in Angola by the Mbukushu (Taylor, 2008; 2009; Hitchcock, 2012). According to missionary and anthropological reports in the 1900s, the Khwe were frequently treated violently by the Mbukushu, which involved punishment for minor crimes, for instance, being drowned or buried alive (Taylor, 2008; 2009). Yet, the Khwe have maintained their own social organisation, language and distinct culture (Rousset, 2003; Brenzinger, 2003).

[4] The *Traditional Authorities Act* in Namibia explicitly makes provision for "traditional communities" that may not have had formal leadership in the past or for communities whose leadership structures were ignored and destroyed by the colonial regime (Hitchcock & Vinding, 2004).

The GRN requires under the *Traditional Authorities Act 17 of 1995* and *Traditional Authorities Act 25 of 2000* in Namibia) that traditional leaders apply for recognition before they can assume legally mandated roles in their respective communities (Hitchcock & Vinding, 2004). In the 1950s, the Khwe developed a more centralised mode of social and political organisation not dissimilar to the Mbukushu (Suzman, 2001). According to oral histories, Martin Ndumba was elected as the first Khwe chief in 1953, and was succeeded by his grandson, the Khwe Chief (Kipi) George in 1987 (Taylor, 2012). The Khwe TA in West Caprivi is purportedly one of the most established San traditional communities in Namibia (Suzman, 2001; Hitchcock & Vinding, 2004). However, in 2006, Chief Edwin Mbambo, the Mbukushu TA, claimed that the West Caprivi has been under his control since 1995 (Suzman, 2001). The state recognised the Khwe political authority up until the 1950s, however since independence, the GRN has been in favour of the Mbukushu TA, and has continued to refute the Khwe their own TA on the grounds that they already have Chief Mbambo (Iyambo, 2001 in Taylor, 2012). Since, the 1990s, the Mbukushu with permission from their chief, have been migrating into the Khwe territory with their cattle and clearing land, with ensuing impacts on the veld food resources used by the Khwe (WWF, 1997; Brenzinger, 2001). Therefore, the TA legislation in Namibia roused the ‘’resurgence of ethnicity”, which had significant implications for access to, and authority over land and resources (Taylor, 2012: 82). Today, food security and hunger are among the most severe problems mentioned by the Khwe (Brenzinger & Harms, 2003). Today, the Mbukushu remain politically dominant in the area, however few Khwe consider themselves the subjects of the Mbukushu TA (Suzman, 2001; Hitchcock & Vinding, 2004).

The Khwe community leaders have taken the TA issue to court, and have received legal support for claims (Brenzinger & Harms, 2003), although to no avail, as in 2001 their TA status was officially declined. The TA dispute has entered its third decade in Namibia, and remains unresolved today. These circumstances are consequences of the South African government forces in its military operations against Namibia’s liberation movement, when the Khwe fought as soldiers for the SADF, and the Khwe community themselves believe that they are victims of this political setting (Hitchcock & Vinding, 2004). The period of South African rule and the army occupation within the region, had a far-reaching impact on the lives of the Khwe (Taylor, 2012), and contributed fundamentally to the *disruption of their livelihood practises*. Today, the Khwe are considered ‘former’ hunter-gatherers (Brenzinger, 2003), and the basis of their sustenance in the park rests on the hunting of small animals, small-scale vegetable gardens, government food-aid, while veld food harvesting is still a vital part of their daily diet (Suzman, 2001; Dain-Owens *et al.*, 2010).

The Mbukushu tribe were described as the "deep water men" as they were accustomed to deep rivers for transport and hunted hippo from dugouts (i.e. canoes made from hollowed out trees) (Tinley, 1966: 29; Fisch, 2008). According to Larson (1970: 33), the Mbukushu "can be said to be truly a river people; the great Okavango is their highway". In addition, their economy, in the late 1800s, showed a strong hunter-gatherer component (Fleisch & Möhlig, 2002). Fisch (2008: 4) described their hunting ability 'to be almost on par with any San hunter', and recorded the Mbukushu exclusively hunting elephant, hippo, lion and monkey, which has rarely been recorded in the scientific literature. They became wealthy through the ivory and slave trade (Larson, 1970). The Mbukushu also cultivated crops and kept large herds of cattle until 1945, when a Tsetse fly invasion forced them to move further west (Tinley, 1966). Today, the Mbukushu are mainly associated with agricultural (millet, sorghum, maize) and pastoralism activities' (Fisch, 2008). Remarkably, in the 21st century there are few references that refer to the riparian and bush hunting prowess of the Mbukushu people, and their history remains neglected (Eckl, 2007). Today, their history and traditional culture is typically excluded from local reports. Possibly, the reason for the exclusion of the detail concerning the Mbukushu is because of the struggles over land, authority, and natural resources between the GRN, and the two ethnic groups (Taylor, 2008), and in particular NGOs support and intense focus on the Khwe, and their severe socio-economic and political marginalisation.

Currently, alcohol consumption is a major problem (Brenzinger & Harms, 2001), within both the Khwe and Mbukushu communities. Moreover, the Khwe population is also characterised by low education levels, illiteracy, and some of the highest HIV/AIDS rates (30 – 40 % of the adult population) in southern Africa (Brenzinger & Harms, 2001; le Roux & le Roux, 2010). Significantly, the war and politics have considerably affected the Khwe's relationship to the land and natural resources in the park since independence, and has resulted in both challenges for and innovations in conservation priorities in BNP (Taylor, 2012).

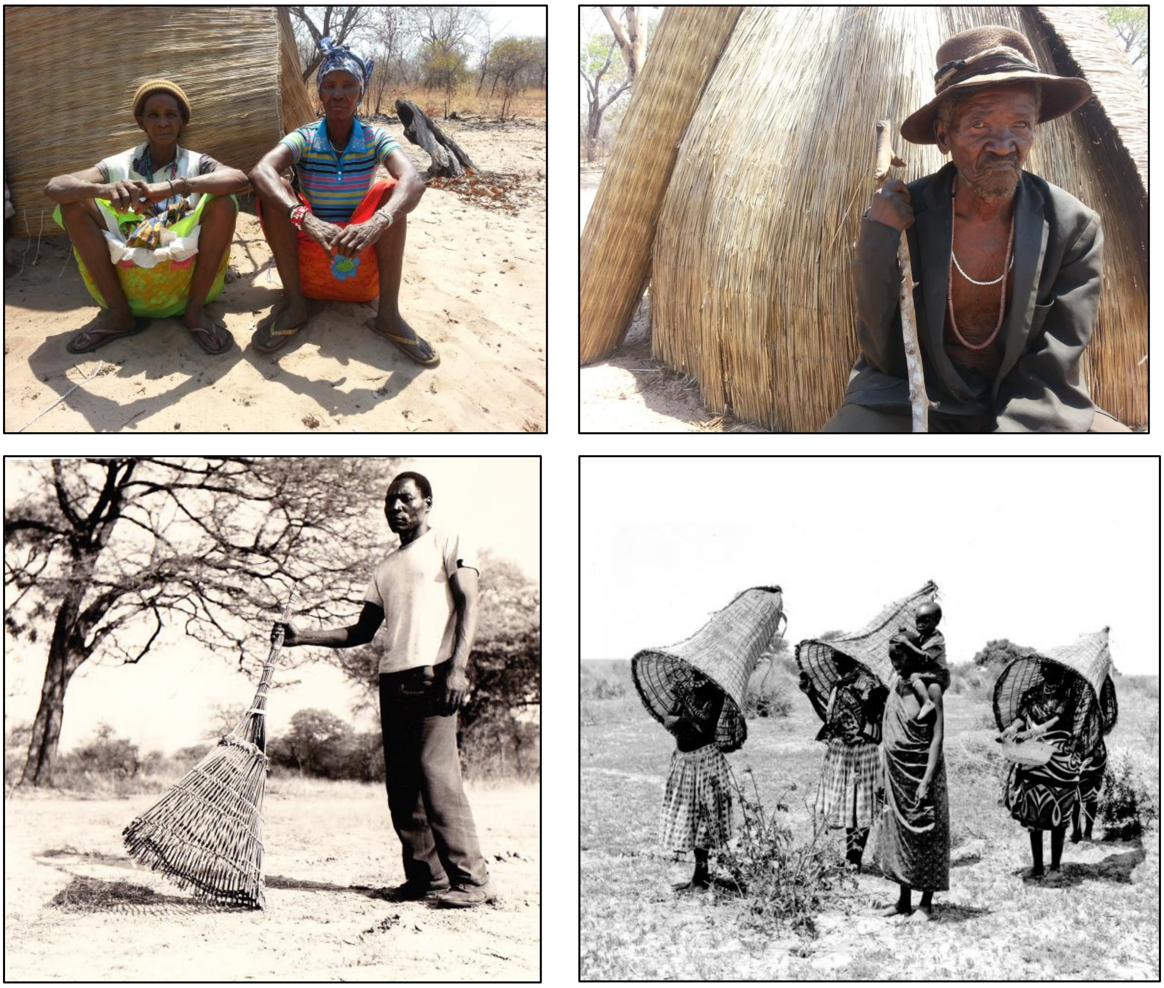


Figure 2-16. Khwe women and man (top images) (2015) and a Mbukushu man, women and children (bottom images) with a traditional fishing baskets in Bwabwata National Park, (Tinley, 1966).

Namibia's fire management policy framework: past and present

Namibia has been subject to Eurocentric forestry policies since the first inscribed policy in 1888. German colonial power (1890 – 1914) (Fisch, 1999) had significant and long-lasting effects through the definition of boundaries and became crucial in rendering activities illegal (Boden, 2009). In recent decades, Namibia has received input from Finland, Germany, South Africa, and more recently Australia concerning fire management policy and implementation.

The Directorate of Forestry (DoF) in Namibia has the mandate to monitor, manage and control forest fires (Kazapua *et al.*, 2009). The DoF currently regulates fire management through the Forestry Act (2001) (MWAF, 2001). Emphasis on fire suppression and prevention is pervasive in Namibia's Forest Act 12 of 2001 and the National Veld Forest and Veld Management Policy (Directorate of Forestry [DoF]-Namibia-Finland Forestry Programme, [NFFP], 2004). In 2015, a Government Gazette (No. 5801) was released with a schedule of the arrangement of Forest Regulations as part of the Forest Act of 2001, which stipulates '*measures to be taken for forest protection, prevention of fires, and protection of the soil and water resources'*. As yet, there is no proposed statement on the *use of* prescribed controlled burning in either of these documents, and to date there is no forest fire policy for Namibia, although the DoF produced a draft version in 2004 in collaboration with the Namibia-Finland Forestry Programme (DoF-NFFP, 2004; le Roux, 2010). However, in 2013, the Bwabwata National Park Management Plan was established, which stipulated the use of fire as a management tool, and early burning was prescribed (MET, 2013). Furthermore, in 2016, a Fire Management Strategy for Namibia's Protected Areas was developed, which similarly implemented a controlled fire management plan with early burning strategies in the CAs and in the MUA of BNP, and also incorporated aspects of traditional fire management for the first time (MET, 2016). Table A3 (Appendix A) provides a time line of policy events, which have influenced the evolution of fire management from the 19th – 21st century in Namibia. The following section provides an overview of the development of policy in relation to fire management in Namibia, and further details will be provided in successive chapters of this thesis.

Fire suppression and prevention period (1888 – 2005)

The first policy established under the rule of the *Deutsche Kolonialgeselllshaft fûr Sûdwestafrika* (German Colony for South West Africa) (1888) banned all fires because of the notion that deliberate burning destroyed forests and vegetation (Goldammer, 2001; le Roux, 2011). This fire suppression policy persisted until after independence. However, in 1998, the Namibia Finland Forestry Programme (NFFP) was assisted by the Global Fire Monitoring Centre (GFMC) to develop ''National Fire Policy and Guidelines on Fire Management in Namibia'' (Goldammer 1999). The GFMCs objective was to bridge technology transfer to fire management and policy development in collaboration with a fire ecology research group. The NFFP formulated the first national guidelines called the 'Eastern Caprivi Integrated Fire Management Project' (IFFP) to emphasise the potential for fire as a sustainable tool, if carefully timed and used (Goldammer, 2001). The foundation of the policy was to improve the environment and the living standards of local people (Beatty, 2011). However, it was unclear if the project was effective in improving rural livelihoods in the East Caprivi. Kamminga (2001) acknowledged that it is difficult to quantify the impacts of wildfires and the benefits of improved fire control among the communities.

The aforementioned policies revoked local burning practises and control of fire by the traditional authorities in the region (Beatty, 2011), and as a result, recognition of the importance of seasonal burning to communities as part of their local land management calendar was overlooked (le Roux, 2011). For example, the Namibia Forestry Strategic Plan (NFFP) (MET-DoF, 1996: 26) states ''the occurrence and severity of uncontrolled and accidental forest fires has to be reduced, and the policy of burning of patches to improve hunting grounds should be changed to one of only using fire as a controlled tool under specific circumstances''. Communities in the region subsequently requested both to restore their rights to practise controlled burning, and for the renewal of their community decision-making to achieve effective fire management (Beatty, 2011).

The Integrated Forest Fire Management Programme (IFFP) was an outcome of the NFFP, and the IFFPs main objective was to strengthen the coordination of *fire prevention and suppression* among government, private and community stakeholders (Beatty, 2011). Implementation activities discouraged burning through education and awareness campaigns, firebreak networks and community training in wildfire suppression (Beatty, 2011). Consequently, in the mid-1990s, even though controlled burning was acknowledged as a fire management tool, it was rarely integrated into planning or implementation in the region at this stage of policy development. The lighting of fires on communal land without authorization from the DoF was designated as illegal (Beatty, 2011), and if people were caught lighting fires they were then fined by DoF authorities. Starting a fire and allowing it to spread to a classified forest or protected area (PA), or failing to put out a fire under instruction of an official or as dictated in a fire management plan (FMP) could result in the offender being fined up to $4000 (Namibian dollars) or 6 months imprisonment (DoF, 2001). Tree cutting, hunting and deliberate burning are all prohibited within the PAs (Kamwi *et al.*, 2017).

In 1999, the NFFP was technically reviewed by southern Africa's fire ecologist, Professor Winston Trollope. Trollope & Trollope (1999) highly recommended that the IFFM be changed from fire suppression at the district level to a fire management program which includes controlled burning as an ecological necessity under certain circumstances. Further, it was recommended that the public awareness campaigns be adapted to differentiate between harmful effects of indiscriminate fires effecting the vegetation and the ecological necessity of using controlled burning. Trollope & Trollope (1999) stated that this would help restore the credibility of traditional knowledge developed over millennia concerning ecologically acceptable use of fire for managing natural vegetation.

Early burning (2006 – present)

In 2006, an Integrated Fire Management Programme was implemented within the context of Community Based integrated Fire Management (CBiFM) by the local NGO operating in the region, the Integrated Rural Development and Nature Conservation (IRDNC). This program resulted in the Caprivi Region Draft Integrated Fire Management Strategy and was developed by the DoF and

Community Forest in North Eastern Namibia in conjunction with the IRDNC Fire Management Specialist (Beatty, 2011). It was successfully carried out between 2006 – 2011 with the objective to support communities, national parks and forestry in the Caprivi Region. The CBiFM project entailed devolving the responsibility of fire management to the rural land owners in the region to enhance the adaptable strategy that embraces wildfire hazard reduction, maintains and enhances land use, and ecosystems and biodiversity (Beatty, 2011). Subsequently, the BNP Management Plan currently addresses the use of fire for actively maintaining and rehabilitating all habitats in the park, as well as the application of early dry season burning (MET, 2013). Thus, the three national parks created in the north-east of Namibia at independence, namely Bwabwata, Mudumu and Mamili National Parks, were managed according to a fire suppression program starting in 1996 and have been undergoing prescribed early-dry season burning programs since 2006, with the primary purpose of grass regeneration for wildlife and, secondarily, prevention of more extensive late-dry season wildfires which could endanger the ever-increasing human population living in the region (Beatty, 2011; Pricope & Binford, 2012).

In 2016, a workshop was convened that resulted in the attendance of GRN and associated ministries, researchers, and fire management specialists, and resulted in the production of a Fire Management Strategy for Namibia's Protected Areas (MET, 2016). This strategy now stipulates a Controlled Fire Management Programme using controlled burning to manipulate the park's ecosystem to enhance park management objectives. The programme implements an overarching strategic early dry season burning regime to establish a mosaic of interlinked burned patches and corridors, representing approximately 35 to 50 percent of the park area. This creates an early dry season firebreak network that minimises the occurrence and extent of late dry season fires. Furthermore, the specific location, timing, and method of controlled burning are all guided by park land-use and habitat requirements in identified fire management zones within BNP (MET, 2016). Significantly, the programme for the first time in Namibia's history, has recognised the importance of traditional fire management strategies carried out by the Khwe and Mbukushu communities inhabiting the MUA of the park.

Traditional fire management

Currently, traditional fire management includes the use of early dry season burns that are maintained for subsistence livelihoods, which include providing grass growth for cattle and wildlife, and to protect valuable natural resources, which provide ecosystem services (e.g. veld foods, medicinal plants) (Beatty 2014; Massyn *et al*., 2009). Further, fires in the late season (Oct-Nov) are used for cultivation purposes (slash-burn agriculture) by both the Khwe and Mbukushu communities in the MUA. Almost all fires are of anthropogenic origin in the park, and over the last decades burning of the burning within the savanna-woodlands has increased, alongside population growth, and fire management policy changes (Beatty, 2015).

Chapter 3 Complex social - ecological dynamics of fire use in north-east Namibia: consequences for the 21st century.

Abstract

The long history of anthropogenic fire in African savannas suggests that *historical and current traditional ecological fire knowledge* are relevant to understanding savanna-fire interactions. However, conceptual knowledge of historical and contemporary use of fire by societies is scarce in southern African savanna-woodland biomes.

Bwabwata National Park (BNP) (former *western Caprivi*) in north-east Namibia has been a conduit for colonial penetration, war, social-political resettlement, conservation and associated changing fire management approaches since the 19th century. This research aims to explore the human-ecological-fire regime interface, past and present, to understand the determinants of the fire regime, and how this influences conservation practice, particularly in the field of fire management, in BNP. This study draws on a qualitative approach, using 61 semi-structured interviews and participatory appraisal techniques (3 focus group meetings), to investigate how the inhabiting indigenous communities (Khwe [San] and Mbukushu [Bantu people]) and government and non-government stakeholders perceive and manage fire both historically and currently. Furthermore, this study investigates how these dynamics in combination with suppressive Eurocentric fire management policies (late 1900s) are related to recent changes to early burning policy initiatives in the park in the 21st century.

Results show that the inhabiting communities use fire for a diverse range of specific though interrelated livelihood activities. Historically, the use of *early season burning* was central to their cultural values, and is pertinent to current subsistence strategies. However, explicit marginalisation of the Khwe since the late 19th century due to colonial regimes and cross-border wars has created complex historical-social-political and ecological dynamics that are affecting contemporary fire management in BNP. Comparisons between the communities and government and non-government stakeholders perceptions of fire use revealed that both groups value and understand the benefits of early burning for similar reasons, specifically for the prevention of intense late season burns. Acknowledging the complexity of traditional burning alongside current fire management practises, and recognition of the preference for early burning as a possible area of congruence could strengthen stakeholder engagement, and enhance biodiversity conservation and social outcomes in BNP.

Introduction

Climate, humans, vegetation and fire are historically and presently inexorably interrelated (Scott *et al.*, 2014). Knowledge of the use of fire is considered imperative in the Anthropocene, in which historical disturbance regimes (i.e. occurrence of fire patterns caused by lightning) have been over-ridden by human fire management strategies (Bowman *et al.*, 2011; Coughlan & Petty, 2012). Throughout world history, fire has been entrenched in peoples' culture, and livelihood practises, and has been used as an effective tool, as part of informal or formal land management practises (Stewart, 1956; Kull, 2008; Scholes *et al.,* 2011; Scott *et al.,* 2014). The savannas and grasslands of Africa are highly affected by fires, due to a seasonal rainfall ideal for successive vegetation growth and drying (Trollope, 2011), and high ignition from widespread and diversified fire practises (Le Page *et al.,* 2010).

In southern Africa, hominid-induced fires have been documented for at least 1.5 million years (Brain & Sillen, 1988). Fire scientists recognised present-day aboriginal societies as having the ability to spread and contain fire from natural settings (Scott *et al.,* 2014). The Khwe people (referred to as 'Bushmen' and today known as 'San') who formerly lived as nomadic hunter-gatherers (Brenzinger, 2003) have been using fire for millennia (Powell, 1988; Owen-Smith, 2017), as have the Mbukushu tribe (fisherman, hunters, agriculturalists, pastoralists) of the Bantu-speaking people in the savanna-woodlands of north-east Namibia, where this study is situated. Thus, African savannas have likely been shaped by a long history of anthropogenic fire (Pyne, 1995), with modern human (i.e. *Homo sapiens*) occupation extending between 100, 000 to 200, 000 kya (Stringer, 2012; Scott *et al.*, 2014). This long history of anthropogenic fire in African savannas suggests that historical and current traditional ecological fire knowledge could provide insight into savanna-fire interactions (Shaffer, 2010). The recognition of this long history of fire practises could also be more intentionally drawn on for the management of fire for ecosystem services (Trollope, 2011).

Despite the historical importance of anthropogenic fires, controversy still prevails because of the perceived unsustainability of indigenous burning practises (Mistry *et al.*, 2005; Trollope, 2011; Pooley, 2014). Consequently, aboriginal communities are commonly perceived by fire scientists and national governments as 'major agents of wildfire' (Mbow *et al.,* 2000), because of land use practises and changes and ensuing environmental degradation and biodiversity loss (Laris & Wardell, 2006; Dwyer *et al.,* 2010; Pausas & Keeley 2009; Bowman *et al.,* 2011). However, the view that aboriginal burning benefits savanna systems has recently gained acceptance among some fire managers (Laris, 2002). Place-based studies have shown that indigenous communities have been instrumental in managing biodiversity by burning seasonal patch-mosaics, which facilitate habitat heterogeneity in West Africa

(Fairhead & Leach, 1996; Laris, 2002; Laris & Wardell, 2006) and in Australia (Braithwaite, 1996; Parr & Brockett, 1999; Bird *et al*., 2005), as well as in preventing the damaging effects of late season fires (Laris, 2002; Russell-smith *et al.*, 1997).

In addition, comprehensive social studies of indigenous people's use of fire have resulted in an insightful understanding of communities in relation to vegetation fires in Africa (Butz, 2009 [Tanzania]; Eriksen, 2007 [Zambia]; Hough, 1993 [Benin]; Kull, 2002 [Madagascar], Nyamadzawo *et al.*, 2013 [Zimbabwe]; Shaffer, 2010 [Mozambique], Walters, 2010 [Gabon]). Furthermore, anthropologists in southern Africa have contributed to an understanding of the Kalahari San hunter-gatherers social organisation, diet, ethnobotany, and have recorded the use of fire to attract game to grazing areas for hunting purposes (Lee & DeVore, 1976; Lee, 1979; Hall, 1984; Marshall, 1976; Schapera, 1930; Silberbauer, 1981). The first ethnographic record of the southern African San using fire to remove moribund grass and regenerating herbage for attracting game was by Burchell in 1811 on his travels on the highveld grasslands of West Griqualand (central South Africa, Northern Cape province) (Hall, 1984). These early anthropological observations provided the first link to understanding fire use and hunting among the San. Other anthropologists (Battistoni & Taylor, 2009; Boden, 2009; Gordon, 2009; Biesele & Hitchcock, 2011; Hitchcock, 2012; Koot, 2013; Rousset, 2003; Suzman, 2017) have concentrated on the San's extreme social, historical, political and economic marginalisation, and resulting changing ethnic-identities in southern Africa. Remarkably the keyword 'fire' is rarely encountered in hunter-gatherer studies (Scherjon *et al.*, 2015). Thus, few research efforts have been concentrated exclusively on the knowledge, observations, *needs* and *reasons why* people light fires amongst indigenous populations in the savannas of southern Africa (Archibald, 2010; Butz, 2009; Eriksen, 2007; le Roux, 2011; Bowman *et al.*, 2011; Sheuyange *et al.*, 2005; Trollope, 2011). Two exceptions are the global reviews of historical hunter-gatherer burning practises by Mills (1986), and Scherjon *et al.* (2015) from an archaeological perspective, although in these studies records from Africa were scarce. This chapter therefore contributes to addressing this gap in this literature. Notably, the burning of land by aboriginal hunter-gatherers are particularly well studied through ethnographic records from wider Australia and North America (Lewis, 1989; Russel-Smith *et al.*,1997; Stewart, 1951).

Historically, indigenous communities used fire for hunting, gathering (i.e. encourage and/ or discourage specific plant types), grazing and agriculture/cultivation activities, to locate wild tubers, flush out bees from hives, and see mineral outcrops, amongst many other reasons associated with land use and subsistence (Kull, 2008; Scherjon *et al.*, 2015; Walters, 2010). The San of Namibia are known to have used fire extensively to obtain a wide array of veld food resources and to maintain diverse ecosystems

(Powell, 1988; Jacobsohn & Owen-Smith, 2003). Today, many people still rely on fire for livelihood reasons, including the control of pests and diseases, for managing wildfires, and to attract game (Roques *et al.*, 2001; Kull, 2002; Shaffer, 2010). Fire has also been used as a conflict tool between communities over competition for resources, and towards governments due to restrictive fire management policies (Kull, 2002; Rodríguez, 2007).

Africa's fire policies have been influenced by European powers since the 19th century (Laris & Wardell, 2006). The prevailing colonial view was that fires were detrimental, and that indigenous burning regimes were environmentally degrading (Eriksen, 2007; Laris 2002; Mistry, 2002). This notion subsequently permeated African natural resource governance, and authorities have striven to reduce fire use in savanna-woodlands (Fairhead & Leach, 1996; Laris, 2002; Laris & Wardell, 2006; Pooley, 2018). Eriksen (2007) highlighted that the persistent colonial negative perceptions of fire and vegetation, conflicted with local inhabitants views of fire as positive for ecological and livelihood sustainability reasons (Trollope, 2011). However, during the late 20th century, fire policies enacted by protected area managers and national legislators throughout southern Africa began to change (Shaffer, 2010). For example, strict 'no burn' policies were enacted in areas settled by indigenous people, whereas policy for timber operations, and commercial agricultural were at first focused on suppression and later on prescribed (i.e. controlled) burning (van Wilgen *et al.*, 2004). A shift to prescribed burning occurred because it was eventually recognised that fire is an important ecological factor of grasslands and savannas on the continent (Trollope, 2011).

Further changes ensued in the 21st century, with a shift to understanding ecological systems as non-equilibrium states, heterogeneous and in constant flux (Eriksen, 2007; Kull, 2002; Laris, 2002; Parr & Andersen, 2006). Thus, with the acceptance of disturbance and non-equilibrium states in ecosystem management, dominant views linking degradation to indigenous fire management began to be reconceptualised (Fairhead & Leach, 1996; Kull, 2002). At the same time, patch mosaic burning (see Parr & Anderson, 2006 for a review) was gaining ground in academic literature and in fire management practises (Brockett *et al.,* 2001; Trollope, 2011; Russel-smith *et al.*, 2013). Indigenous burning patterns provided the foundational practise and knowledge for dry seasonal burns in Australia (Kakudu National Park), and in South Africa (Pilanesberg National Park) (Trollope, 2011), but local burning knowledge and practises continue to be largely unrecognized by national government officials in southern Africa. Furthermore, few studies have compared government and indigenous ecological understanding and reasons for burning in southern Africa (Eriksen, 2007; Trollope, 2011). This thesis argues that by investigating, and highlighting how indigenous and national government stakeholders think about fire, better consensus and understanding could be reached about the use and management of fire.

Over the last 120 years in southern Africa, power regimes, political governance, demography, land use and fire regimes have dramatically changed, as has the subsistence economy (Eriksen, 2007; Vaarzon-Morel & Grabys, 2009). For example, hunter-gatherer societies have experienced a transition to agricultural subsistence over the past 100 years (Newman, 1970). Longstanding civil and colonial wars in southern Africa have resulted in the disruption of indigenous practises (Shaffer, 2010; Suzman, 2001). In some instances, people were used as soldiers, resulting in long-term civil and inter-ethnic conflict, as is the case in north-east Namibia, where the Khwe people were used as trackers, and 'Bushmen soldiers' during the South African apartheid military during Namibia's Liberation War (Battistoni & Taylor, 2009; Suzman, 2001). The Khwe's alliance with the South African's during the war resulted in the government of the Republic of Namibia (GRN) refusing the Khwe people a Traditional Authority (TA) (Suzman, 2001; Hitchcock, 2012). Further, as a result of these wars, in parallel with colonial and changing national policies, population densities were lowered, hunting rights were restricted, and frequently people were re-settled (Robbins, 2007; Shaffer, 2010). Consequently, the affected indigenous communities had to establish alternative land-uses in typically poverty-stricken circumstances associated with a loss of land tenure, as well as natural resources (i.e. wildlife and plant resources) critical to sustaining their livelihoods (Koot, 2013; Suzman, 2017).

In the 1980s the imbalance between elite conservation agendas (e.g. tourism and conservation goals to the exclusion of people from parks) and conservationists, who realised that restrictions could be harmful to local social well-being, and undermine conservation objectives was recognised. As a result 'Community Based Natural Resource Management' (CBNRM) emerged. (see Dressler *et al.,* 2010 for a review). Following the growth of the CBNRM discourse (Food and Agricultural Organization [FAO], 2011; Lineal & Laituri, 2012), the concepts of 'Integrated Fire Management' (IFM) and 'Community Based integrated Fire Management' (CBiFM) emerged, and were first applied in Indonesia and Namibia (Moore *et al.,* 2002). These initiatives recognised the ecological dependence of specific ecosystems on fire, coupled with traditional land use activities by including local communities in fire management (FAO, 2011; The Nature Conservancy [TNC], 2011). The CBiFM concept gained leverage in the late 1990s, and subsequently there has been series of reports, analyses, case studies, training efforts and some peer reviewed papers (FAO, 2011). However to date there is limited critique (Lineal & Laituri, 2012), and little published literature, and moreover, limited evidence of the integration between fire science, IFM and CBiFM in Africa.

Recent departures from traditional cultural fire use in combination with global environmental change (e.g. climate and CO_2) have been associated with major shifts in ecological composition, ranging from local to regional and continental scale changes in vegetation, for example forest degradation and shrub encroachment (Trauernicht *et al.*, 2015). Furthermore, many social-ecological fire systems are poised to undergo adjustments due to global climate changes (Rodríguez & Pyne, 1999), which will alter the functioning of ecological systems and associated ecosystem services (Bowman *et al.*, 2011). Thus, understanding burning practises in terms of social-ecological, political and historical and environmental complexity is considered critical for for determining changes in fire regimes in the anthropic era of ensuing global environmental change and for developing adaptive fire management strategies and policies.

The objective of this research is to explore the human-ecological-fire regime interface, past and present, to understand the determinants of the fire regime, and how this influences conservation practice particularly in the field of fire management in BNP. This study is situated in the savanna-woodlands of Bwabwata National Park (BNP) (commonly known as *West Caprivi*) in north-east Namibia. Since the 19th century, this area and the inhabiting people have been subject to colonial penetration, two decades of war, inter-ethnic conflict, social-political resettlement, political violence, emergence of livestock diseases (e.g. Tsetse fly invasion; Pneumonic (lung) plague; rinderpest), religious influence, and changing land use and conservation plans, as well as associated varying fire management approaches. The management of fire in Namibia has been dominated by fire suppression policies for 118 years, since the first inception of fire policy in 1888, although in 2006 early burning strategies were implemented in BNP. A chronology of major historical events from the (1800s – 2016) relevant to the Khwe, Mbukushu and the government of Namibia (GoN), and events associated with the evolution of fire management Acts and policies in Namibia are presented in Table A1 & Table A3 (Appendix A). The study comprises interviews with the Khwe and the Mbukushu people (i.e. community stakeholders), as well as with Namibia's government and non-government stakeholders. Semi-structured interviews and participatory appraisal techniques formed the central component of this research. The objective of the community interviews was to garner an understanding of communities' knowledge and perceptions of the role and use of fire, historically and currently, and to establish in what way, and to what extent fire impacts on their livelihood resources in BNP. Interviews with governmental and non-governmental stakeholders were used to address aspects of their understanding and perceptions of early and late dry season burning, drivers of the fire regime (ecological and /or social factors), changes in the fire regime, and past fire suppression policy implications for the greater region, in which BNP is a nexus. Research techniques also included the use of the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectrometer (MODIS) satellite fire product data (MCD14ML), and other secondary data sources (e.g. reports and workshops).

The following research questions were addressed in this study.

Community stakeholders

i. What are the Khwe and Mbukushu people's historical and current perspectives on the use of fire?
ii. What resources are important to people's livelihoods in association with fire in BNP?

Government and non-government stakeholders

iii. What are the stakeholders observations concerning past fire policies and the current early dry season fire management strategies in BNP?
iv. What are the perceptions of the fire and vegetation history and associated fire regime changes in reference to the past Namibian policy of fire suppression?
v. What are stakeholders views and understanding of past and present traditional fire management of the Khwe and Mbukushu people?
vi. Are there similarities and/or differences in the use of and perception of fire between the government and non-government and community stakeholders?

Methodology

To document all stakeholder observations, knowledge and use of fire I used a combination of qualitative and quantitative methods. The social data collection involved a mixed approach of participant observations in the field, and qualitative methods in the form of participatory rural appraisal (PRA) methods (Chambers, 1994), such as focus group meetings, seasonal calendars, and quantitative methods in the form of informal interviews. For the purposes of this study, stakeholders were grouped into 'community' (Khwe and Mbukushu people), and 'government and non-government stakeholders'. Further, the satellite derived MODIS fire product (MCD14ML) was used as secondary data to establish the number of pixel hotspots (i.e. the number of pixels affected by fire in a spatially-gridded database), and the timing (i.e. season) of fires in BNP (2000 – 2015). Secondary data sources consisted of fire management polices (1800s to 2016), government and non-governmental organisation (NGO) reports, newspaper articles, and fire management workshops.

Field data collection

Data was collected over the course of 4 months in 2014 and 2015. In total 61 interviews and 3 focus group meetings were carried out (Table B1; Appendix B). These field work periods occurred within the two main dry seasons in BNP: early dry season (Apr – July) and late dry season (Aug – Nov). Wellrespected, non-political translators were selected in the community with the assistance of the Integrated Rural Development and Nature Conservation (IRDNC), a Namibian NGO which works with rural communities in the region. Thus, for all the community stakeholder interviews a translator was present to translate each question and response. Interviews were carried out in English and translated into Khwé-dàm (Khwe language) and Thimbukushu (Mbukushu language) with the assistance of local translators. The fact that I was unable to converse in Khwé-dàm or Thimbukushu had its limitations, however I was in a position to converse in Afrikaans, as many Khwe learnt the language during the Liberation War (Brenzinger, 2003). For the duration of the community data collection period I stayed within the villages in proximity to my translator's home and/or near the village headman's homestead.

Prior to carrying out field work within the BNP communities', ethics clearance was obtained from the University of Cape Town (UCT) (Figure B7; Appendix B). In the field the local headman from each village was consulted where I explained the objective of my research, and permission was requested, and obtained to carry out the data collection with the community inhabitants within the respective villages. All interviews were conducted with the consent of all individuals present, and prior to the interview, permission to record the dialogue was requested. Thus, all interview sessions were recorded with an audio recorder, and later transcribed to ensure that all ideas were accurately and completely captured. Further observations were obtained from walks and drives with the translators within the village perimeters, and surrounding area, which presented me with the opportunity to observe land management practises, recent burns, historical burnt patches, and possible differences between early and dry season burnt patches, and environmental determinants in the landscape (Butz, 2009).

The core of my study area was BNP, however I extended my interview survey area to include government and non-government stakeholders' from the Zambezi Region (former *eastern Caprivi*) because fire management in Namibia is under the mandate of the Directorate of Forestry (DoF). Further, the Namibian Finland Forestry Pilot project (NFFP) instigated in 1996, resulted in the Integrated Forest Fire Management Programme (IFFP) and development of the National Fire Policy and Guidelines on Fire Management for Namibia (Goldhammer, 2001). Furthermore, the Zambezi and the Kavango East Regions have been exposed to several external international influences (Finnish, German, South African, and Australian) concerning fire management (1888 to present), which subsequently resulted in different approaches to fire management at different time scales in Namibia (Table A3; Appendix A). Thus, although forest fire management strategies differ from savanna-woodland management due to different vegetation structure and environmental conditions (e.g. moisture availability), I obtained stakeholder perspectives from both BNP and the forestry sector for the aforementioned reasons. During the stakeholder interviews in the town of Katima Mulilo, I stayed with local residents which provided me with the opportunity to network and locate other stakeholders of interest within the ministries and other sectors involved in fire management in the region. Prior to my arrival in the area I notified all relevant ministry stakeholders of my research intentions and location within BNP, and in which communities I intended to work with for each of the two field trips under the required research permits issued by the Ministry of the Environment and Tourism (MET) in 2014 and 2015 (Figure B8; Figure B9; Appendix B).

Data sources

Satellite data: MODIS active fires

NASA's MODIS active fire data set (MCD14ML) was used to determine the locations and timing of pixels affected by fire (i.e. pixel hotspots) indicative of the presence of fires at overpass of the earth observing satellites (EOS), Terra (EOS AM) and the Aqua (EOS PM) between 2000 and 2015 in BNP. Each active fire location represents the centre of the 1 km pixel that is identified by an algorithm as having one or more fires within the pixel (Davies *et al.*, 2009). The MODIS Collection 5. 1 active fire product MCD14ML shapefiles were available from November 2000 to December 2015 for the present study via the University of Maryland and NASA's Fire Information for Resource Management System (FIRMS) archive data tool (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/active-fire-data). The acquisition date and time, latitude and longitude, satellite name, and the detection confidence (Giglio *et al.*, 2003; Giglio, 2010) were extracted from the FIRMS dataset. For the purpose of this study the low confidence pixels (< 30 %) were excluded, and only the nominal (30 – 80 %) and higher confidence level fire affected pixels (> 80 %) were selected (refer to Chapter 5: *Satellite fire data 2* for further details).

Community stakeholder interviews

Thirty-six in-depth semi-structured interviews were carried out with the Khwe and Mbukushu participants from 9 villages (Mut'ijuku, Pipo, Chetto, Poca, Mashambo, Tokoloshi, Omega III, Diye, and Mashshane) located in the Multiple Use Area (MUA) East and MUA West of BNP (Figure 2-13; Chapter 2). The interviews were structured into 4 themes, which included: i) cultural practices and beliefs; ii) fire management (how, where, when and how often fire is used), which included land use practises; iii) vegetation and fire history, and iv) livelihood resources (Table B2; Appendix B).

Twenty-six Khwe (72%), and 10 (28%) Mbukushu participants were interviewed (Table B4; Appendix B). The Khwe people are the majority, and the Mbukushu the minority population in the park (Suzman, 2001). Due to the sensitive nature of the use of fire in general, interviewee names are withheld to protect people's identities (Butz, 2009). Typically, the interviews lasted approximately an hour. The male of the homestead is regarded as the head of the household among the Khwe and Mbukushu, thus the majority of the interviews were carried out with men (81%), and 19 % with females amongst the community participants. Elderly community members were identified as interview participants because of my research focus on the historical use of fire, and thus over 90% of the respondents were over the age of 60. A locality map (1: 250 000) was used as a visual aid during the interviews to assist with the identification of where small and large fires occur in the BNP (Mistry, 1998) (Figure B1; Appendix B). The interview responses were used to create a database of when, how, where and how frequently fire is used, and how the vegetation burns, and how fire practises today differ from the past in BNP.

Government and non-government stakeholder interviews

Twenty five in-depth semi-structured interviews took place during two field visits in May – July (2014), and September and November (2015). The interviews were used to elicit stakeholder perceptions of early and late dry season burning in the BNP as a management practise, drivers of the fire regime (ecological and /or social factors), and past fire suppression policy implications (Table B3; Appendix B). Six diverse stakeholder categories were established (Figure B2; Table B5; Appendix B). Seven of the respondents were representative of the MET, 6 from the DoF, 5 were private consultants, 3 were from NGOs, and 3 from academia, and 2 were classified as other (e.g. State veterinarian and lodge owner) (Table B5; Appendix B). All the interviews were conducted in English, and therefore translators were not required. Interviews took place in BNP in proximity to the park stations (Buffalo, Mahango), the park headquarters in Suswe, Windhoek (capital), in the town of Katima Mulilo in the Zambezi region, and a single interview took place in Cape Town. Secondary data sources consisted of informal discussions with conservation and community-based organisations in Namibia, published reports in the region by governmental departments and NGOs, books, and archival records obtained from the Namibian Scientific Society, relevant newspaper and radio reports, and attendance of three fire management workshops held in Namibia between 2014 and 2016. These sources were critical both for providing a historical context of contemporary events in the area, for cross checking oral accounts (Taylor, 2012), and for observing changing fire management perceptions and policies in Namibia during this study.

Seasonal calendars

Indigenous ecological calendars, also known as seasonal calendars (Prober *et al.,* 2011) were used to document the Khwe and Mbukushu observations and historical knowledge of seasonal fire patterns and the effect of fire on natural resources (e.g. veld foods) after the interview sessions. To investigate annual environmental and seasonal land management changes the following themes were explored with the interview participants: fire regime, climate, land use, resource harvesting and cultural practices to produce a seasonal calendar. Furthermore, the calendar activity helped to clarify the participants answers to the questions following the interviews. Frequently the family members of the interview participant would join in during this activity, which resulted in debate and discussion concerning fire and resource use in the household, and village area (Figure B3; Appendix B). Laris (2002) emphasized that by asking people about the reasons for burning, people may give one answer and not the other, and suggested that by shifting the focus from specific to broader temporal and spatial categories of burning, the researcher could avoid this problem. Therefore, the seasonal calendars were useful for the purposes of asking people to describe their annual burning regime instead of asking specific questions about the use of fire.

Focus group meetings

Three unstructured community focus group meetings were held in Chetto village at informal gatherings in the MUA to engage a larger audience, build rapport within the community, and clarify information (Butz, 2009). The seasonal calendars were used to address the seasonal use of fire and resource use, and to elicit knowledge about the positive and negative impacts of fire on the plant resources in the park from the community resource monitors (CRMs) in attendance at these meetings. These focus group meetings only took place in Chetto village because this is where the core group of employed CRMs were resident in BNP. The community stakeholder interview themes were used as guide to lead the focus group meetings (Figure B4; Appendix B).

Data analysis and methods

MODIS active fires (i.e. pixel hotspots)

The MODIS FRIMS active fire dataset (MCD14ML) was clipped to the BNP boundary, and was used to identify the time of the day and the number of pixels (1 km x 1 km) affected by fire from 2000 to 2015 in BNP. I used the Temporal Analyst extension in ArcGIS to produce a data clock graph showing the time over 24 hours, the month, and the number of pixels affected by fire at satellite (Terra [AM] and Aqua [PM]) overpass. The purpose of this graph was to visually represent, and determine the frequency of active fire pixels (pixel hotspots) per month and time of day. This data was used alongside the interview scripts, to verify and triangulate what time of day, and in what month people typically use fire in BNP. Data was organised and analysed in ESRI ArcGIS v10.2 and was used to produce the data clock showing the timing and number of detected fire affected pixels in BNP (2000 – 2015).

Stakeholder interviews

Data analysis was centred on qualitative and quantitative data techniques. I selected a mixed method approach to reveal the context of the data with the use of grounded theory (Glaser, 2000), thematic analysis (Namey *et al.,* 2008), and participant quotations. Grounded theory is a methodology that is grounded in data systematically gathered and analysed (Strauss & Corbin, 1998). Theory evolves during the actual research, and this occurs through the iterative process from data collection, analysis, through to the conceptualization of the theory. This approach allows key concepts and their relationships to emerge through continuous coding analysis techniques (Birks *et al.*, 2008), and thus, it allows one to conceptualize the patterns emergent in the social data (Glaser, 2002). I used thematic content analysis to identify prevalent themes that were used to describe both implicit and explicit ideas in the data (Namey *et al.,* 2008). Even though, I had established *priori* themes to structure the collection of data of the community stakeholder interviews (Table B2; Appendix B) , I used an 'open coding system' (Strauss & Corbin, 1990), which resulted in the detailed formation of main themes and sub-themes for both stakeholder interview groups (Figure B5 and B6; Appendix B). Table B6 (community stakeholders) and Table B7 (government and non-government stakeholders) in Appendix (B) provide a description for each sub-theme used in this analyses. The qualitative and quantitative cycle of social data analysis used for this chapter is presented in Figure 3-1 below.

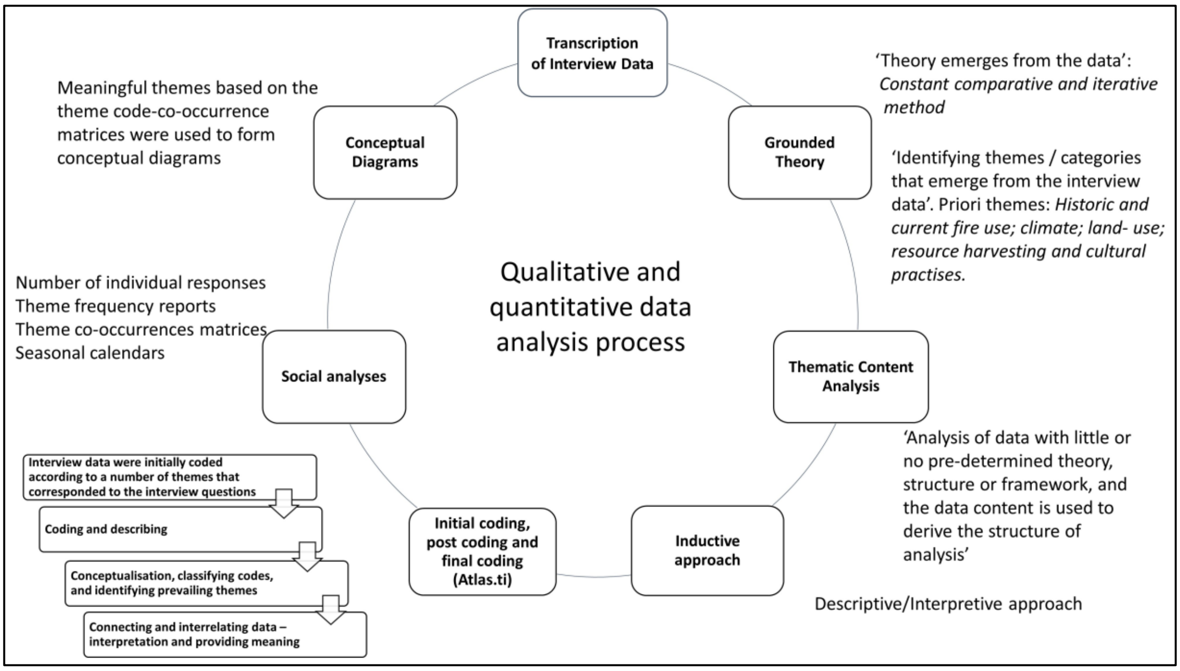


Figure 3-1: Schematic diagram showing the cycle of qualitative and quantitative data analysis for the stakeholder interview data beginning with the transcription of the interview data (2014 and 2015).

In dealing with large amounts of transcript interview data, computer assisted qualitative data analysis (CAQDA) programs assist one to systematically structure and organize the data for further analyses. Throughout my field work I kept detailed notes on my interviews, field observations, and research reflections which amounted to approximately 45, 000 words. With the use of CADQA, pieces of text (i.e. interview responses) were coded through continuous interpretation and analysis. The process is iterative, and involves the continual refinement of emerging themes within the data, as further insights are gained. The identified common themes were then aggregated into main themes and sub-themes, which assisted with the conceptualization and development of theory in this study. This process was enabled with the use of Atlas.ti (Version: 7.5.10), a qualitative software program that facilitates systematic analysis of data and assists in the process of categorization and coding, developing themes, and organizing data segments (Creswell, 2007). Atlas.ti was also used to count the number of recurring themes, and the number of respondents who provided a response. To quantify the frequencies of theme occurrence within the stakeholder interview data, Atlas.ti was used to produce a tabulation of theme frequencies. To determine the frequency of theme co-occurrences, I used the theme co-occurrence explorer table feature to quantify the number of times two themes co-occurred for each stakeholder respondent. The co-occurring themes were then organised into conceptual diagrams that maintained the respondents' descriptions of cause and effect, and the number of respondents reporting each sub-theme were included (Ray *et al.*, 2012; Namey *et al.*, 2012).

Results

Community stakeholder perspectives

Historical and current burning strategies of the Khwe and Mbukushu

The use of fire in Bwabwata National Park, both historically and currently, is entrenched in the tradition and culture of the Khwe and Mbukushu (Table 3-1). Analysis of the combined responses of the community interview data led to the emergence of 18 main themes, and 75 sub-themes (Figure B5; Appendix B) interrelated with the use, motives, causes, and general factors associated with fire observed by the community stakeholders in BNP. All respondents identified two distinct phases of savanna fire seasons: the earlier season in cooler conditions after the rainfall period when the grass is green, and the late dry season fires during dry, and hot conditions. Historically, the use of fire in the early dry season was fundamental to the Khwe's use of fire and was described as a fire that was lit between April and July, which was referred to as 'early burning' and/ or 'patch burning', and locally called "*txei txei*" (Khwé-dàm). "*Patch burning: starts in April surrounding the village, and in May patch burning in the bush. This is from the ancestors". Patch burning began when the elder people tell the young people to* *put fire close to the village and where to burn, and to be careful, and that the fire should not go further, and that they should stop it. Around for many years''* (Khwe; see Table B8 [Appendix B] for a list of exemplary quotations for the community stakeholders). The early season fires were described as small, and controlled fires close to villages, whereas the late seasons fires were perceived as being further away from their settlements, and uncontrolled fires, and/or transboundary fires coming across the border from Angola and Botswana.

Table 3-1: Summary of the reasons for burning as identified by the Khwe and Mbukushu stakeholders (n =36) associated with traditional - cultural fire knowledge and early burning practises (historically and present day) in Bwabwata National Park, 2014 - 2015.

	Reasons for burning
Traditional – cultural fire knowledge	
Creation of fire	Survival; traditional practise, and is regarded as a symbol of manhood.
Cooking, boiling water	Survival; food and nourishment.
Provision of light at night	Survival, and protection from dangerous animals at night.
Removal of vegetation	Close to the homestead for protection from the late season fires.
Protection from dangerous animals	Removal of dense vegetation whilst gathering veld food resources; and to open up an area for visibility (e.g. lion, elephant); chase snakes away.
Medicinal plants	Extract parts of a plant for healing properties (e.g. boiling and reducing roots).
Healing rituals/ceremonies	Promotion of a sick family member's health. Fire is transferred from the 'dwelling' of the sick to the healing ceremony.
Gender: Homestead	Male of the household will make the fire, and women typically can only use the fire for cooking.
Gender: Cultivation	Women typically make the fire in the cultivation fields for the purposes of burning of brush piles (i.e. vegetation debris) before planting seeds prior to the rainfall.
Spiritual purposes	Communication with ancestors (e.g. where to hunt).
Communication	To signal to distant family members in the bush to notify them of their location and success of a hunt.
Traditional use	Immediately light a fire as soon as the arrival at a location; fire also provided the means to move into remote areas.
Removal of parasites	Tick infestations.
Knowledge	Early burning was and is a planned activity; the elders of the community used to control who would burn and where; and people were taught how to burn.
Cultivation	Agricultural practises (removal of dry vegetation debris); increase the land productivity (i.e. crops grow rapidly after the use of fire).

Early burning: Historical and present day	
Regeneration of vegetation	Burning the old grass to generate new growth.
Protection of veld food resources	Protection of fruiting trees that provide vital veld food resources (particularly on dune crests); protection of the family's food resources.
Protection from the late season fires	Protection of the family, and village areas from large hot dry season fires.
Burning to source veld foods	Removal of the grass layer beneath trees in seed, since it's easier to locate fallen seeds on the ground.
Livestock grazing	Generate new growth of grass for cattle.
Hunting	Survival; generate growth of grass to attract wildlife (particularly in the grass laden Omiramba); flush smaller animals out from the grass (e.g. duikers, monitor lizards, tortoises); preparation of the meat for consumption.
Tracking	Clearing of vegetation to see the tracks on the ground after the fire for the ease of locating animal tracks in the remnant ash.

The associations related to the use of early burning strategies are illustrated in Figure 3-2, and reveal the interrelated reasons for the use of early season fire in the landscape of both the Khwe and the Mbukushu people. Appendix B (Table B9) provides a summary of the number of times participants referred to two sub-themes in association. Respondents revealed that the primary associations pertaining to the context of historical and current fire in BNP were related to the use of early burning for the maintenance and protection of veld food resources, prevention of the late season fires, hunting and tracking activities, and for livestock grazing purposes. Thus, the reasons why the Khwe used early burning practices included a number of *interrelated* favourable associations, which included stimulating grass growth to attract wildlife to grazing areas, opening up the vegetation for visibility for hunting and for the purpose of detecting animal tracks in the remnant fire ash, and for the protection from dangerous animals. The Khwe's fire use also differed according to the landscape feature and months of the year for a specific purpose. Reference was made to the use of fire in the ''forests'' (dune crests) earlier in the year during April and May for the purpose of regenerating veld foods located on the dunes, whereas, fire was historically used in the Omiramba (i.e. low lying grass laden areas between the dune crests) in August to October when the grass was typically drier for hunting larger animals where for example Kudu antelope (*Tragelaphus strepsiceros*) would browse on the ecotone of the omiramba fringe woodlands in BNP.

The Khwe in particular described early season fires as a deliberate management strategy as a planned and organised part of their burning practices associated with their forefathers' knowledge (sub-theme: *knowledge transmission*). The Khwe frequently referred to the decisions concerning the use of early burning, which belonged to the elders within the community who directed where and who would light fires (sub-theme: *authority to burn*). *''Any person cannot burn, and the elder people choose people to go and burn"* (Khwe). The younger members of the population would typically carry out the burning instructions during a hunting trip. Historically, punishment for accidental fires was instigated by the Traditional Authority (TA), the '*induna'* (chief of the village) and consisted of a fine of livestock (e.g. cow), but this system no longer exists amongst the BNP communities.

In-depth knowledge surrounding the use of historical fire practises were emphasised more by the Khwe, than the Mbukushu respondents. The Mbukushu people mainly made reference to the use of early burning practises for stimulating the germination of grasses for livestock grazing purposes, and only partially for regenerating veld foods (Figure 3-2). "*No late season fires as you will ruin the grass for the cattle; if there is burning it is because people don't know how to use fire; burn early season for the grass for cattle; if you burn early the grass starts to germinate"* (Mbukushu). And, although the Mbukushu made reference to the act of hunting, no references were made to the use of fire for tracking purposes. When asked whether early burning practises were still being employed, the majority (n = 33; 91 %) of the Khwe referred to the past, and others stated that early burning is still in use today (n = 19; 52 %). However, people may have been afraid to talk about their current fire practises, since it is typically prohibited in the park, and therefore they may have been hesitant to admit to present-day use. Further, whilst in the field (2014 and 2015), I observed a number of early dry season fires that were in proximity to the village areas in the months of May – June, and early as well as late dry season fires were evident in the satellite MODIS pixel hotspot data clock analysis (2000 – 2015) (Figure 3-3). The MODIS data clock revealed that the majority of fires were early season fires that took place between May and July, with the latter month experiencing the greatest number of pixels affected by fire between 14h00 and 15h00 in the afternoon in BNP. Further, the data clock showed that generally 50 % less pixels were burnt in the late dry season, of which were probably fires lit by the community for cultivation purposes. Further, notably the late season fires were typically lit between 10h00 and 11h00 in the morning in the late dry season.

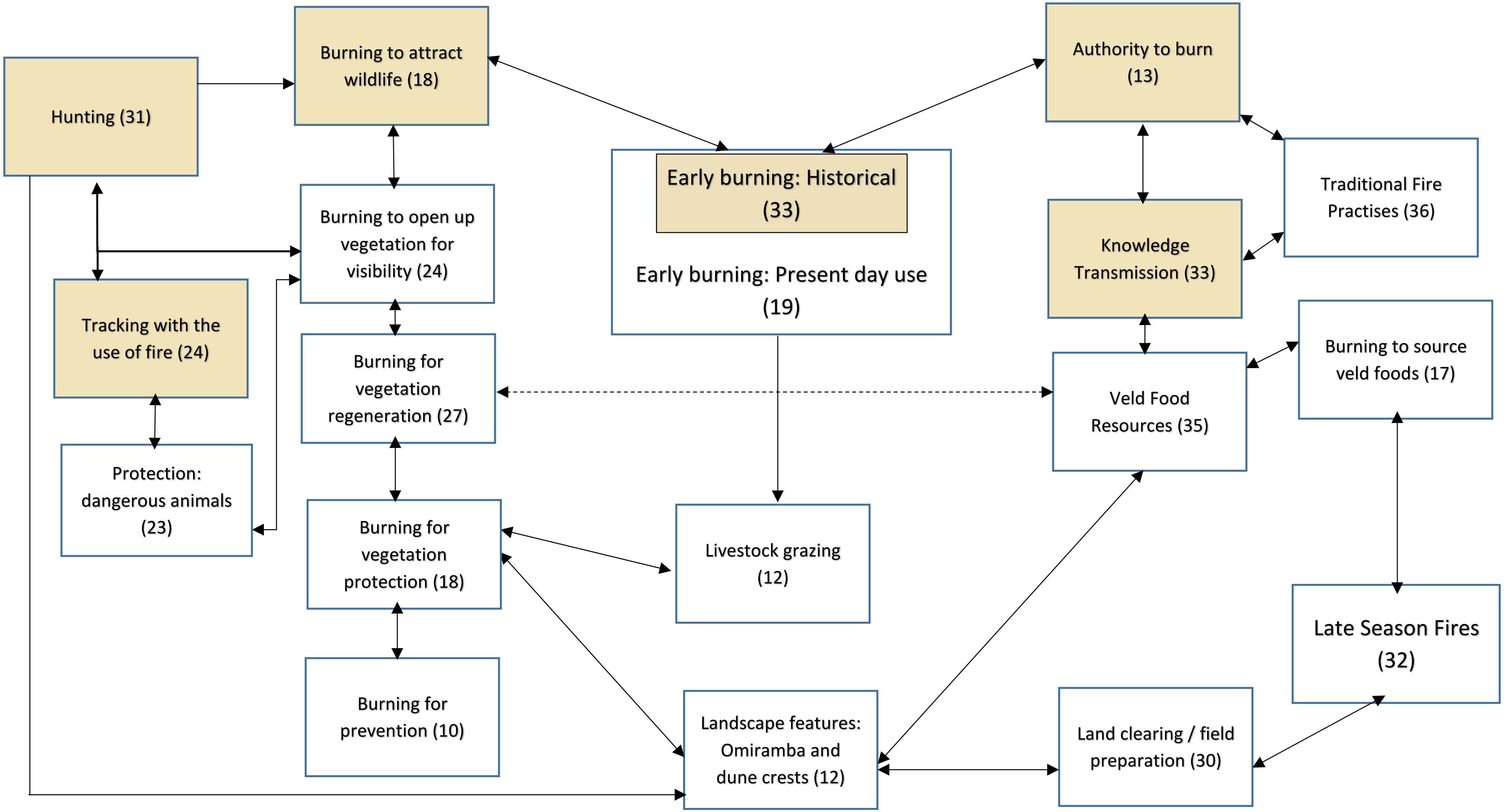


Figure 3-2: Conceptual diagram showing the associations between historical and current traditional-cultural practises by the BNP communities. *The numbers in parentheses refer to the number of participants who provided a response for each theme. The brown shaded boxes indicate the Khwe's historical practises in relation to early burning, which no longer take place today.

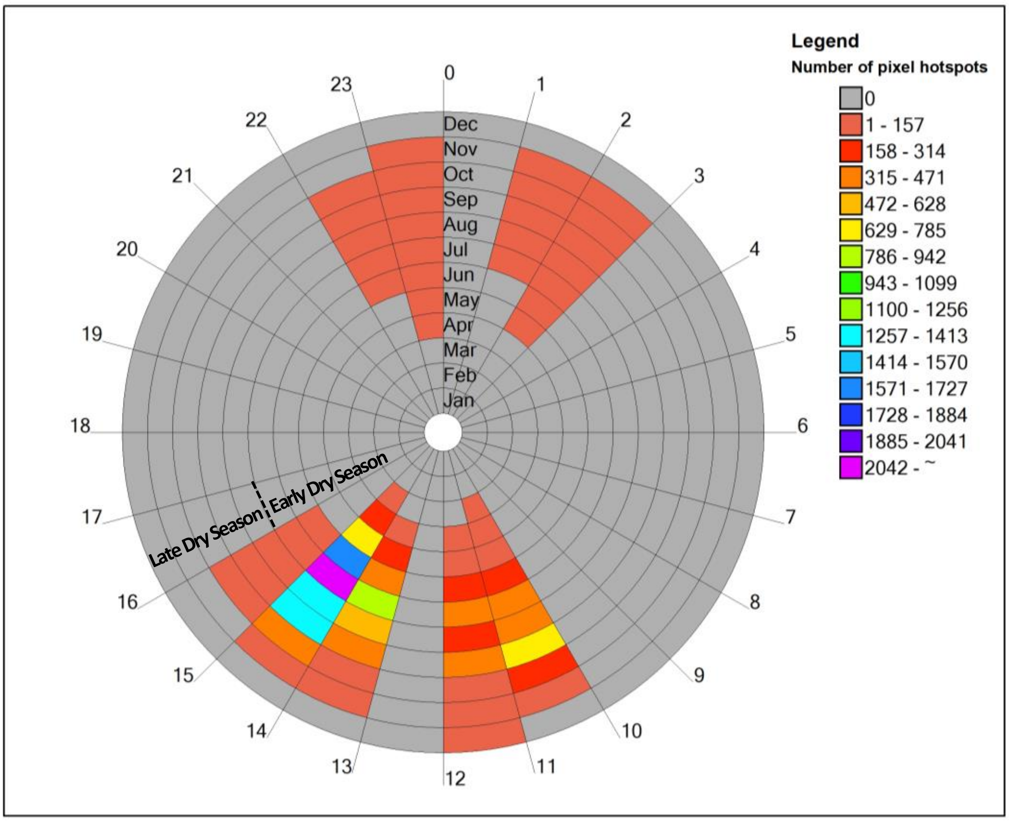


Figure 3-3. Data clock showing the number of MODIS active pixel hotspots per 1 km x 1 km pixel per month and hour of the day (24 hours) covering the early and late dry seasons in Bwabwata National Park, 2000 – 2015. Data derived from FIRMS MODIS MCD14ML. The dashed line indicates the division between the early and late dry seasons in BNP.

Currently, people in the BNP communities (n = 17; 47 %) associate early burning activities with government fire regulations being carried out by the community game guards (CGG) on patrol in BNP. Nowadays, the Khwe are hesitant to use fire due to the government fire regulations, and moreover the communities stated that they have been warned not to burn. Twenty (56 %) of the participants' referred to the loss of traditional knowledge concerning the use of fire (Figure B5; Appendix B). Moreover, the communities attributed a breakdown in fire knowledge due to the recent government fire regulations, and the ensuing effect of not being able to practise their traditional fire practises, which they suggested has resulted in the breakdown of communication between the elders and the youth concerning the use of fire. Respondents also associated a breakdown in the timing (e.g. early vs. late season) for the use of fire to a cessation in traditional norms within the community. The Khwe elders were reported as no longer communicating their fire practises to the youth, due to an absence of interest amongst the youth about local bush knowledge, which was attributed to the local attendance of school, parental restrictions in the villages enforcing the youth to stay closer to the homestead nowadays, as well as to a shift in the youth towards western needs. Concern was also expressed among the community respondents that the loss of traditional fire knowledge (n = 20; 56 %), together with the high frequency of late season fires, were affecting the veld food resources in BNP.

The late hot season fires which occur from September through to October in the region coincide with the community use of fire for cultivated crops (n = 28; 78 %) (sub-theme: *cultivation*) (Figure 3-4). Fire was described as being used to manage the brush piles, which consist of old branches from trees and dry grass, remaining after field clearing in preparation for the cultivation of crops, prior to the rainfall season in the late season (Oct – Nov). Inhabitants also stated that due to the brush piles being dry, it is easier to burn at this time of year and fires are usually of short duration, and typically the area is only burnt once prior to planting crops (theme: *Cultivation*). Burning at this time of year was also related to increasing the soil productivity, which was described as beneficial for the growth of crops. In BNP, during the dry season, the area in proximity to the settlements is conspicuously barren (pers. observation), which is likely due to human and animal movement, and because inhabitants clear the homestead area of vegetation because of the risk of fire at this time of year, and threat of snakes and scorpions entering their living areas. However, a few participants referred to the occurrence of runaway fires in the late season because of fires used for cultivation purposes.

The Khwe described their use of fields and fire and stated that their fields were typically far from villages and were not cultivated for long periods, since there has been in an increase in wildlife conflict (i.e. elephants damaging their crop fields), and for this reason, particularly in the east of BNP, cultivation has been decreasing as a form of subsistence. The Khwe were also resistant to a change in livelihood subsistence to cultivation, having been traditionally hunter-gatherers (sub-theme: *resistance to acculturation*), and emphasized the importance and their dependence on veld foods resources for their livelihoods (Figure 3-2; Figure B5; Appendix B). However, when asked about resource dependency, all respondents indicated that land-use associated with both crops and veld food resources were important for their livelihoods, though the Mbukushu indicated that the late season fires were generally impacting their grazing resources for their cattle, as they own more cattle than the Khwe community. Both the Khwe and Mbukushu people are reliant on a combination of land-use for cultivation, gathering veld foods, together with the hunting of small animals, and only a few respondents mentioned their reliance on government food aid (theme: *Land-use/Resource dependency*).

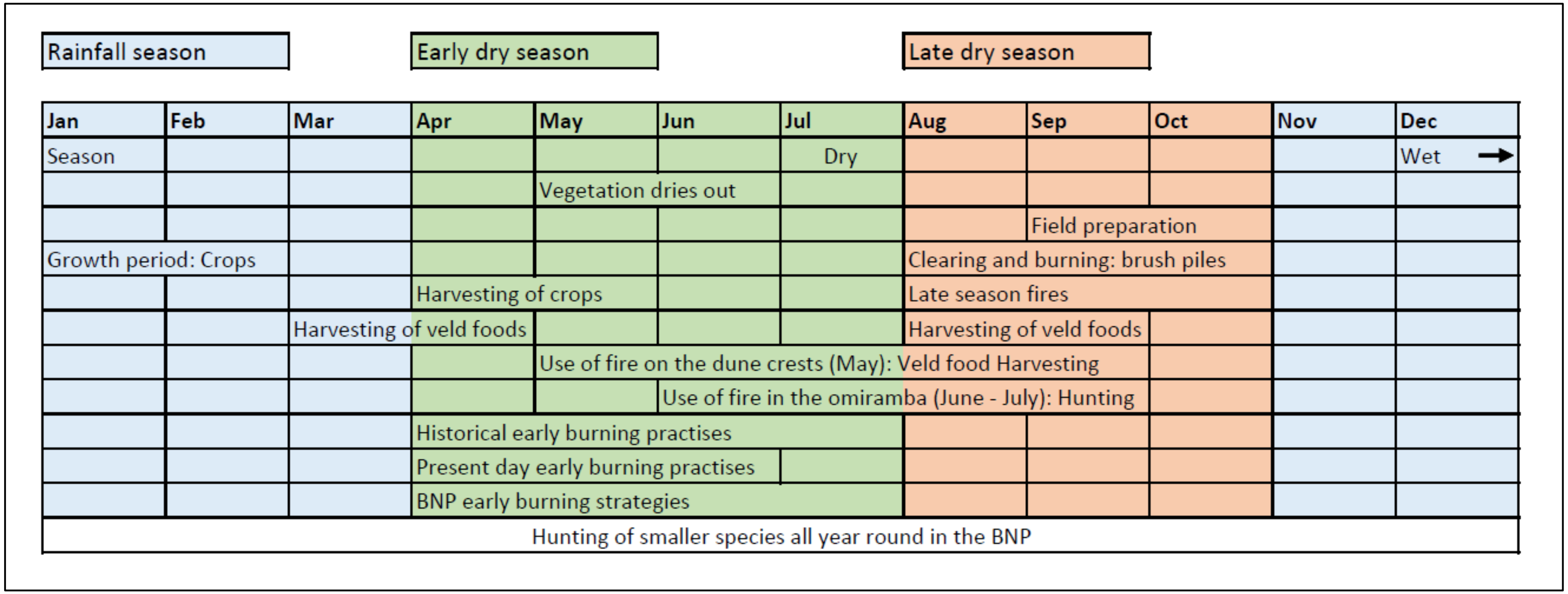


Figure 3-4: Seasonal calendar showing activities in relation to the use of fire amongst community and government and non-government stakeholders in Bwabwata National Park (2014, 2015).

Twenty four (67 %) of the respondents had a preference for using early season fires versus burning later in the season. Respondents were equally positive and negative about fire, however most were of the view that the late season fires should be stopped because of the detrimental effect on veld food resources (Figure 3-5). Thirty five (97 %) (Table B9; Appendix B) of the respondents stated that the late season fires were negatively affecting the availability and abundance of veld food resources, and suggested these late season fires should be prevented in the BNP landscape. '*'Sometimes burning has a negative side as the fires kill of veld foods; when the fire comes to the food plants - it will kill the food plants itself and you won't find that type of plants anymore*" (Khwe). Thus, reasons associated with a preference for early season burning were related to the negative impact fire has on veld food resources, and on the general vegetation, due to the late season fires (Figure 3-5 below; and Table B9; Appendix B). However, twenty eight (78 %) of the respondents amongst the BNP community had a positive perception of fires in general because of the benefits associated with early burning (Figure 3-5). All of the community respondents viewed the use of fire without purpose as negative. All of the respondents associated people as the cause of fire, including the presence of poachers in the park, and people being negligent, although nine respondents (25 %) also referred to the occurrence of natural causes of fire in BNP (i.e. lightning, and the presence of fires due to the previous year's rainfall and grass growth) (sub-theme: *natural causes*).

An increase in human population in the villages was also described as affecting the amount of and timing of burning, because of cultural differences and lack of understanding, and subsequent misuse of the use of fire in the landscape. The communities in the MUA West (Khwe respondents) reported an absence of power, and felt that their resources are being depleted because of the burning of important veld foods by meaningless burning attempts by the Mbukushu people, who were reported by the Khwe to burn any time of year. Thus, one of the effects of fire on veld food resources was described and attributed to cross-cultural conflict within the community between the Khwe and Mbukushu. The emergence of the cross-cultural conflict theme was prevalent in communities in the MUA West, where the highest concentration of people are resident in the BNP, as well as integrated mixed cultural groups, whereas respondents in the MUA East, that is less populated, did not mention other groups affecting their resource base in BNP.

Most agreed that the vegetation has generally become more open (n = 20; 56 %), in comparison to the past. However, the community had observed that in some areas, the bush has become denser and that there was an increase in shrubs (n = 11; 31 %) and a decrease in trees. The observed increase in shrubs was in the Omiramba, and were referred to as thorny bushes, and were generally *Senegalia* and/or *Vachellia. spp* (pers. observation). Nineteen (52 %) of the respondents thought fires were more frequent today, than in the past, whereas thirteen (36 %) were of the view that fire was less frequent today. A number of Khwe also reported that during the South African Defence Force (SADF) occupation, the use of fire, together with their traditional activities (e.g. hunting and gathering) were restricted.

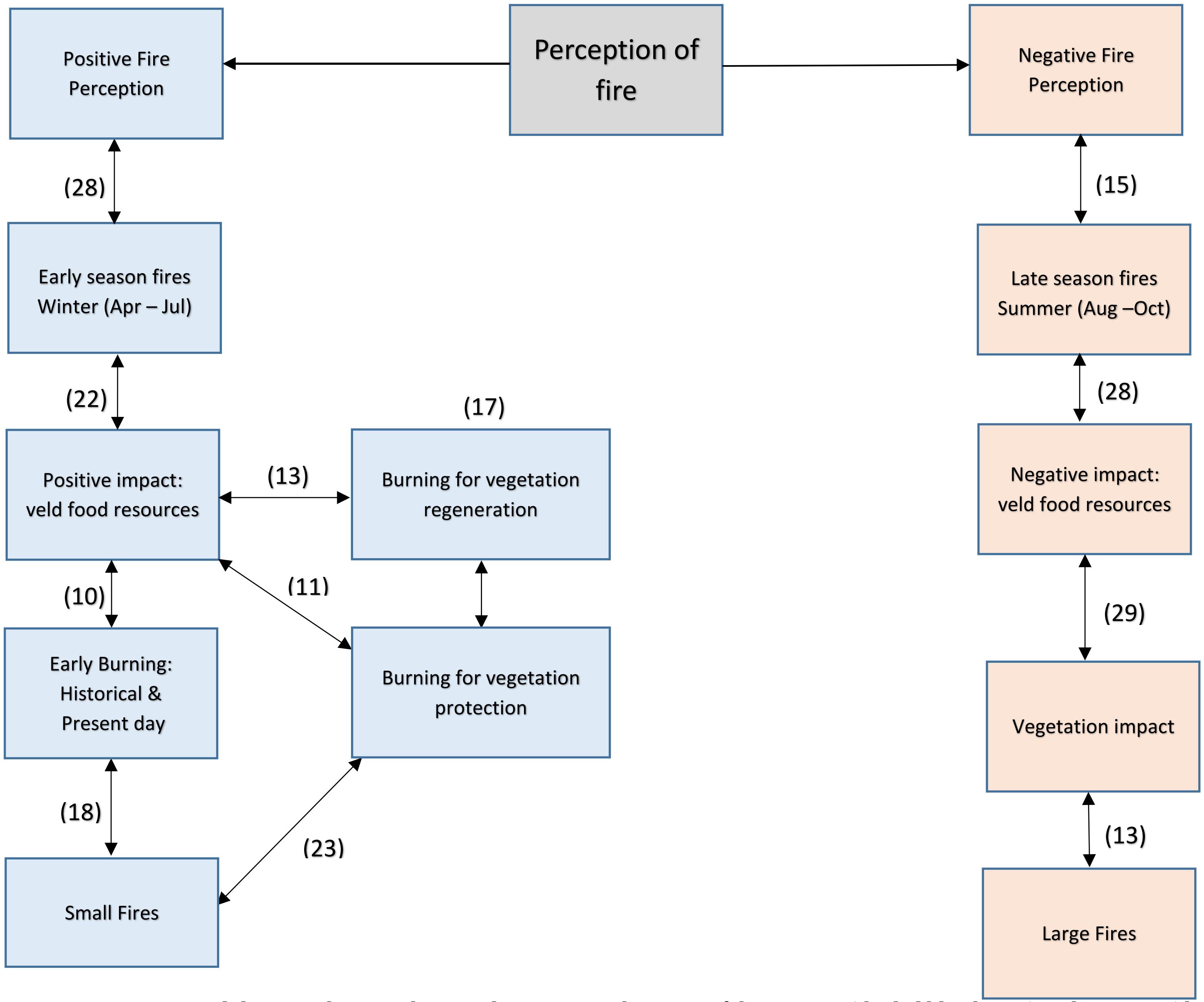


Figure 3-5: Conceptual diagram showing the causal associations between of the positive (shaded blue boxes) and negative (shaded red boxes) perceptions of fire in association with veld food resources and vegetation impact, and fire size among community stakeholders in Bwabwata National Park (2014 – 2015). *The numbers in parentheses refer to the total number of theme co-occurrences.

Resources impacted by fire

Some of the tree species that were most frequently mentioned to have decreased or disappeared from the Khwe's gathering sites on the dunes are included in Table 3-2. Many of these trees are sought after as food (i.e. fruits and leaves), medicine or wood. Although some of the older specimens are still found, people observed a lack of regeneration of the younger plants. Plants which are important particularly to the Khwe were listed as *Diospyros chamaethamnus* (*tc'inya*), *Paranari capensis* (*n/gumithara*), *Terminalia sericea* (*tcere*), however these species were described as not been negatively impacted by fire. *D. chamaethamnus* is particularly abundant after the early burns, and appears to be one of the first species to flourish following the onset of an early burn in the landscape. *Harpagophytum zeyheri* (*xam//avo*) commonly known as 'devils claw' is largely sought after for its commercial value (medicinal properties) and there is a harvesting programme in the region where by the community profits from the collection of this plant. The government and non-government as well as the community stakeholders frequently mentioned that fire is used in September and October to locate this plant by burning the vegetation in the vicinity, and reported that these harvesting activities cause more fires in the late dry season in BNP.

Table 3-2: Tree species identified by the Khwe to be impacted by fires in Bwabwata National Park.

Latin name	Khwe name (Khwé-dàm)
Acaia flekii	*//guyi* or *//ge//gam*
Baphia massiensis	*n‡were*
Bechemia discolour	*tcindjere*
Burkea africana	*xei*
Dialium engleranum	*‡ûmbé*
Dioscores sp.	*dinga*
Garcinia livingstonei	*tceuyi*
Grewia retinervis	*//quani*
Guibourtia coleosperma	*tceu*
Ochna pulcra	*kyara*
Pterocarpus angolensis	*n/gao*
Schinziophton rautanenii	*/qom*
Strychnos cocculoides	*/'x'oana*
Strychnos pungens	*‡quinya*
Terminalia prunoides	*kuu*
Vigna vexillata	*/'iya*
Ximemia americana	*kwa'‡ori*
Ximemia caffra	*//'axa‡'ori*

Government and non-government stakeholder perspectives

Perspectives on suppression versus early burning strategies

Thematic analysis of the combined government and non-government stakeholder interviews (MET; MWAF; DoF; NGOs; BNP managers; CGG; UNAM; PoN, and others) revealed 18 main themes, and 68 sub-themes (Figure B6; Appendix B). Currently, early burning strategies are preferred by these stakeholders as an ecological management approach in the BNP, and fire was described as being applied early in the dry season to reduce and prevent the intensity of the late season fires in the landscape. *"The game guards and MET burn the area and communicate with each other and maintain the fire in a patch work mosaic. They burn when the grass is wet so that the fire can't spread"* (Table B11 [Appendix B] provides a list of exemplary quotations for the government and non-government stakeholders). The emphasis on early dry season burning in the last decade was described by respondents as being in response to the prevailing perception of the decline in woodland trees, and subsequent negative impact of the late season fires on vegetation structure in the region. Consequently, twenty four (96 %) respondents held a positive perception of fire (sub-theme: *Positive- Fire*).

Moreover, the stakeholders viewed the use of early burning positively, because of the effect fire has on the improvement of grazing areas for wildlife, and the subsequent attraction of game into BNP. In particular, respondents stated the direct benefits of the use of early burning in influencing the movements of Tsessebe (*Damaliscus lunatus*), Roan antelope *(Hippotragus equinus*), Sable antelope (*H. niger*), and Common Eland (*Tragelaphus oryx*) to grazing areas in BNP. Thus, the stakeholders identified benefits associated with the positive effects of early burning on vegetation regeneration, and the resulting secondary effects of the movement and concentration of wildlife in the park. Furthermore, the climate and associated fire factors (e.g. rainfall and ensuing moist vegetation, and lower fuel loads that burn as a result of the wet grass) were positively associated with early burning strategies. Stakeholders frequently referred to the moisture laden grass, and cool and controlled burns in the earlier months of the year, which were perceived to reduce the spread of fire. However, climate, and associated adverse conditions (e.g. high winds and dry vegetation) were also perceived as being connected to the spread of the late season fires (theme: *Climate/ fire factors*). Twelve (48 %) of the respondents commented on the positive influence of the CBiFM early burning programme (Table B10; Appendix B) initiated in the *eastern Caprivi*, which they suggested has facilitated the motivation for the implementation of early burning strategies in BNP.

Even though early burning was positively viewed as a management strategy, stakeholders raised the concern about the observation of the prevalence of late season fires (n = 23; 92 %) in the BNP landscape

(Figure 3-7). The negative view of fire amongst some stakeholders was attributed to the detrimental effects of late season fires on vegetation change, and due to the mortality of the game in the area. However, not all the stakeholders held the opinion of early burning as the best strategy for fire management in the park. Seventeen (68 %) stakeholders identified an absence of knowledge and understanding concerning the use of early burning as a fire management tool. Further, it was implied that there is a need for further research (n = 12; 48 %) to understand the effects on the implementation and management of early burning on species composition, and the need to define acceptable ranges of ecological variability, as points of reference on which to base decisions. For example, the need to identify an ecological factor (e.g. rainfall) and/ or a human intervention (e.g. frequent burning) that could cause changes in vegetation state, and result in a shift in the structure and functioning of the BNP ecological systems. However, twelve (48 %) respondents acknowledged that fire is complex and there are multiple factors that need to be addressed to understand the fire regime (e.g. the combination of elephants, fire and people in the region).

The respondents described the management of early burning fires in BNP as *'ad hoc'*, meaning that there was no planning, coordination and strategic burning strategies in place based on environmental observations (e.g. rainfall, grass phenology, time since last burn etc.). Twenty one (58 %) respondents believed that the proposed early burning initiatives would improve if they were implemented and managed effectively. The main reasons identified by the respondents for the gap between fire management policy and implementation were because of the lack of communication and awareness (n = 21; 84 %) amongst all stakeholders (i.e. collaboration) (n = 16; 64 %), and with the BNP communities necessary for policy developments in the region (Figure B6; Appendix B). However, respondents held mixed views concerning the effectiveness of policy in the park, since thirteen (52 %) stated that the early burning policy was ineffective, however eleven (44 %) respondents agreed that policy was effective.

The stakeholders were asked whether they believed that it would be beneficial if the policy distinguished between uncontrolled burning, burning for productive land use and burning for fire prevention. The majority of the stakeholders believed that different approaches to the use of fire are required in different vegetation types, which in turn should be related to the specific land use type (e.g. agriculture, livestock farming, management of national parks and wildlife movements). Furthermore, the stakeholders reiterated that a designated role focussed on fire management should be established for the park. Additionally, many stakeholders mentioned the lack of sharing of research relevant to fire ecology, once researchers have collected the data in Namibia.

Fire and vegetation history: perceived changes in the fire regime

All respondents referred to the issue of people and illegal fires being the predominant source of ignition for fires in the late season versus natural causes of fires. Seventeen (68 %) of the respondents thought fires were increasing, and that there is more frequent fire, and that the fire regime is changing, and subsequently there are less trees and more shrubs (n = 18; 72 %), and the vegetation is more open. Overall, the prevailing stakeholder perception of the frequency and timing of fires were associated with a negative impact on vegetation (n = 25; 100 %) in BNP. One stakeholder suggested that the predominant change in the fire regime has involved a seasonal shift from a single late fire season to a bi-annual fire season with the recent introduction of early burning strategies. However, there was a lack of consensus amongst respondents on the timing and frequency of burning the landscape in association with early burning strategies. Concern was also expressed by the respondents that fires are occurring repeatedly in the same location on an annual basis in BNP, with the use of early burning strategies, together with the reoccurring late season fires in the absence of management. Other stakeholders reiterated that general assumptions about the occurrence of fire in BNP are based on satellite technology (n = 9; 36 %) in absence of monitoring and ground observations (n = 11; 44 %). Nine (36 %) of the stakeholders were of the impression that when it comes to fire management in northern Namibia that there is a deficiency in data, and specifically in understanding the effects of early burning on fauna and flora to further manage the fire regime.

A plethora of views emerged concerning the use of past suppression policies which held precedence for 118 years (1888 – 2005), and the ensuing effects on the vegetation (Figure 3-7). Ten (40 %) of the respondents associated the expansion of bush encroachment with the fire suppression policy, and were of the view that it had led to the occurrence of the late season fires due to the build-up of the fuel load in the absence of early burning. However, five (20 %) of the respondents stated that the notion of the suppression of fire was not feasible, and that fire occurrence was no different from the past, since fire will always be a part of a system, with the combination of people and vegetation. Reference was also made to the era of the Namibian Liberation War (1964 – 1989), and the probability of the prevalence of fires during that time due to the use of the SADF military artillery, and the ensuing ignition of vegetation during combat, and without adequate resources to suppress fires, fires would have spread in an infrequently burnt landscape. Furthermore, respondents stated that cross-border fires would have been prevalent, as Angola was at the time involved in a civil war (1975 – 2002), and Botswana has a policy of fire suppression.

Furthermore, the perceived changes in the fire regime in BNP were also associated with social-political circumstances after independence (1990). For example, after independence the government permitted the introduction of cattle to the park in cordoned areas to assist the Khwe with becoming sedentary and independent without having to move throughout the park to hunt (Taylor, 2009). Thus, a few respondents were of the view that this changed the grazing requirements, which was associated with an increase in the need for burning areas of the park for the cattle herds which belonged to the people. Secondly, respondents stated that the formation of the MUA (n = 13; 52 %; sub-theme: *Multiple Use Area*) for inhabiting communities in the park also altered the fire regime, which was attributed with an increase in fire frequencies across the park. Lastly, the impression amongst respondents (n = 8; 32 %; sub-theme: *Finnish Forest Fire Management Project*) was that the IFFM project (1996), which was funded by the Finnish government based in the eastern Caprivi woodlands, influenced the fire regime adversely. The IFFM project promoted fire suppression in the community via bill boards, which had a negative impact on fire management in the region, and particularly influenced indigenous fire activities in the region. Remarkably, the IFFM was focused on changing community attitudes, cultural values and habits in relation to fire (NFFP, 2001). It was suggested in the socio-economic technical review of the IFFM Programme that there is a need to move away from the blueprint approach focused on fire prevention towards a more people-centred approach and broader resource management perspective (Kamminga, 2001).

Views on past and present traditional fire knowledge and management

Stakeholders identified the need for increased collaboration (n = 16; 64 %), communication and awareness concerning the use of fire between the ministries (e.g. MET and MWAF), and the need to include the knowledge of communities inhabiting the park in the decision-making processes (n = 10; 40 %). In contrast, some stakeholders also referred to the need to enforce and control fire among the BNP communities, and to the effective past influence of the TA (*Induna* or chief) role (n = 10; 40 %), who had the responsibility of fining people within the communities for fires accidentally lit in the communal areas. Within the '*incorporation of traditional knowledge*' sub-theme, respondents emerged with divergent views concerning traditional fire practises. Fifty six percent (n = 14) of the respondents stated that communities are required to be educated in fire use in the MUA as the communities are generally perceived to be less informed in fire management matters, versus a few others (n = 11; 44 %) that were aware of the use of the current early burning strategy used by park management as an approach that was historically used by the Khwe in the region (main theme: *Traditional fire knowledge;* sub-theme: *Early burning practices*). Typically, government fire management initiatives discourage burning through education and awareness campaigns (1990s), firebreak networks and suppression of fires (Figure 3-6) (Beatty, 2011). The perception of some stakeholders (n = 8; 32 %) is that communities are responsible for the uncontrolled fires in the late season, that are associated with cultivation fires. Thus, the prevailing stakeholder perception was that the resident BNP communities are to blame for the increase in fires in the area, especially during the late hot season fires in the region (MET, 2016).

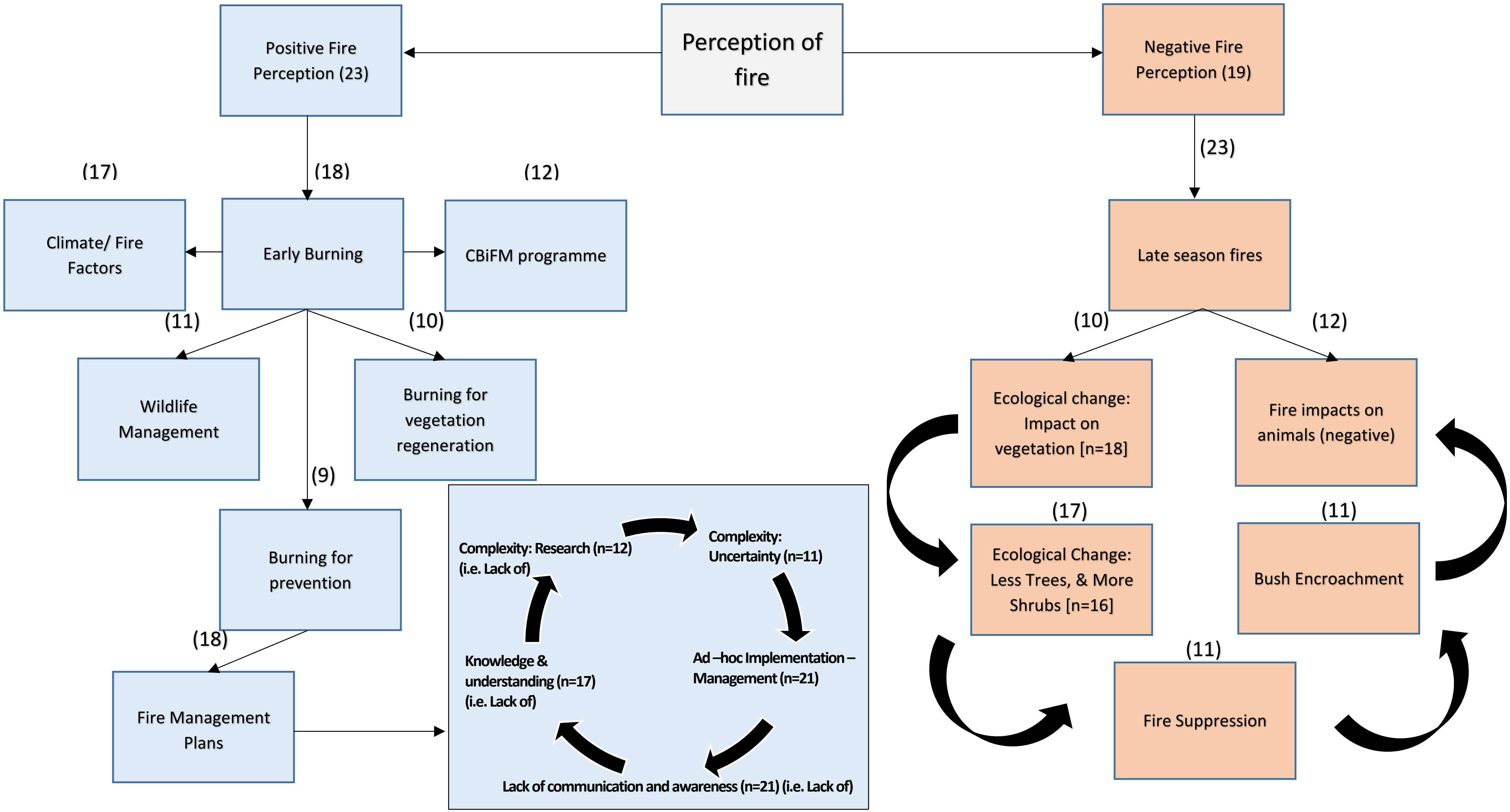
Nonetheless, there was an awareness amongst twenty (80 %) stakeholders about the use of traditional fire and cultural values of the resident communities in BNP (Figure B6; Appendix B), though there was scepticism about the use of traditional fire strategies for the management of natural resources in a sustainable way. Interview participants referred to the Khwe's method of using early burning strategies (n = 11; 44 %) and some respondents referred to their early childhood and the active use of fire by elders in the community in the early winter seasons. Thus, even though there was an awareness of the early burning strategies employed historically by the Khwe in the region, references to their practises arose from a marginal number of the stakeholders. Ten (40 %) interview participants acknowledged there was an absence of *incorporation of traditional burning strategies* (sub-theme) into the parks current fire management plans (Figure B6; Appendix B). Nevertheless, both stakeholder groups (community and government and non-government) viewed the use of fire both postively and negatively for similar reasons, however the community stakeholders perceived fire negatively for an additional factor, due to the impact on veld food resources in the park, particuraly during the late season (Figure 3-8). What is more, with the emergence of a revised fire management strategy for BNP (2016), the MET has subsequently acknowledged there is considerable knowledge of controlled burning among the resident communities and fire management implementation specifically in the east of the park (MET, 2016).

Sixteen (64 %) of the stakeholders also referred to the use of fire by the Khwe for hunting and tracking purposes. One stakeholder referred to the current fear within the communities if they are caught lighting fires by the MET. Other reasons presented by the stakeholders for the increase in fires were the integration of different cultural groups in the area e.g. competition, blame and jealousy amongst the Khwe and Mbukushu utilizing shared natural resources in the BNP. In addition, other factors mentioned for the increase in fires, included population increase within the MUA, the deterioration of traditional norms, and social cohesion among people, coupled with the loss of traditional knowledge and lack of access to financial income from local employment. Further, the stakeholders recognised that there is a shift in the younger generations towards westernized needs in the community, which detaches the youth from the elder generations in the community who have the most knowledge concerning the fire and the environment in BNP.

a) b)

c) d)

Figure 3-6: Sequence of images showing the fire prevention art used for educational fire campaigning in the communities for forest fire management at the Directorate of Forestry (DoF) in Katima Mulilo (a – c) [1996], and d) Namibia's fire management logo (2001) (Goldammer, 2001).



Feedback cycle indicating factors identified by respondents concerning early burning in BNP.

Figure 3-7: Conceptual map representing the government and non-government stakeholders' positive (shaded blue boxes) and negative (shaded red boxes) perceptions of fire and associate themes [n = 25]. *The numbers in parentheses refer to the total number of theme co-occurrences.

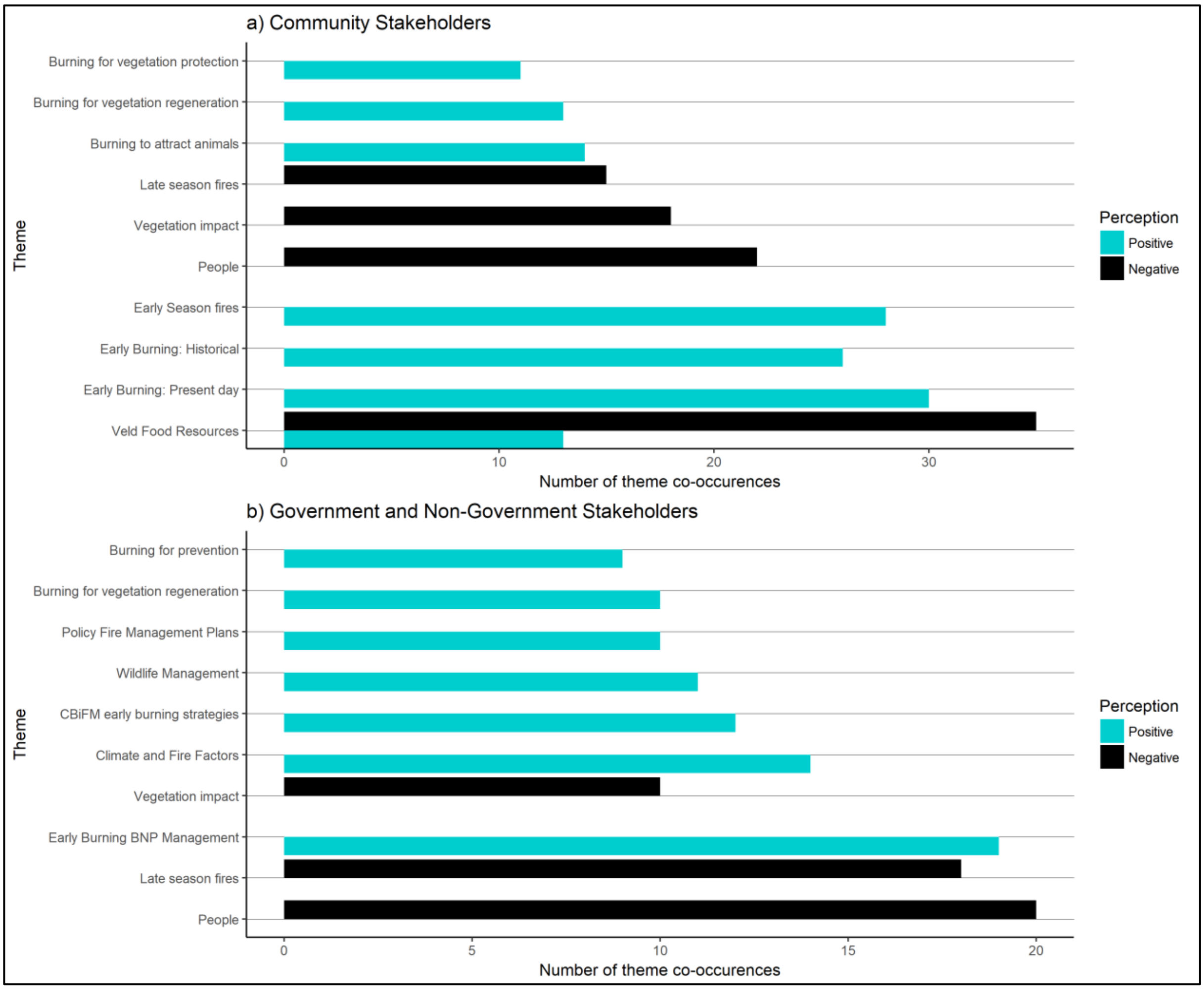


Figure 3-8: Number of theme co-occurrences associated with a positive and negative perception of fire between a) community stakeholders' and b) government and non-government stakeholders' (2014, 2015) in Bwabwata National Park.

Discussion

Community stakeholder perspectives

The importance of early season burning

This study has revealed how the Khwe and Mbukushu people historically used, and currently use, fire for both immediate and longer-term gain, manipulating fire seasonally for *interrelated* beneficial purposes. As Table 3-1, Figure 3-2,and Figure 3-5 demonstrates, the historical and current use of fire by the Khwe and Mbukushu is central to their present-day livelihoods and survival in BNP. In particular, the use of *early burning* by the Khwe emerged as central to their historical use of fire for hunting, tracking and veld food gathering, and protection from dangerous animals, which has evidently influenced their current use of fire, although their land use options and livelihood activities have fundamentally changed since the 19th century in BNP.

Specifically, the Mbukushu people had a preference for early season fires for generating grass growth for their cattle, and partially for procuring veld foods, whereas the Khwe had numerous reasons for the use of fire, which is attributed to their traditional and cultural associations with fire (Figure 3-2). Furthermore, in this study, the Mbukushu people's description of burning strategies were not as detailed or as carefully explained as by the Khwe. This is likely a result of dissimilar cultural values and livelihoods between the Khwe (former nomadic hunter-gatherers) who had more reasons to burn the landscape than the Mbukushu (fisherman/agriculturalists/pastoralists). Nevertheless, the knowledge of the Mbukushu concerning the use of fire for cultivation purposes has been transmitted to the Khwe since the 1800s, when the Mbukushu entered the Khwe's greater migration area (Suzman, 2001), and the Khwe first began cultivating crops (Taylor, 2009). Thus, fires used in the *late season* by both the Khwe and Mbukushu were useful for preparing land for cultivated crops, similar to other indigenous communities in southern Africa (Butz, 2009; Eriksen, 2007).

The BNP communities share many similarities with other aboriginal groups of people in the use of fire (Bird *et al.*, 2005; Bowman, 1998; Delcourt & Delcourt, 1997; Eriksen, 2007; Laris, 2002; Murphy & Bowman, 2007; Whitehead *et al.* 2003; Vaarzon-Morel & Gabrys, 2009; Walters, 2010; Yibarbuk *et al.*, 2001). Laris (2002; 2011) established that the Malians used an organised *annual burning regime,* which was referred to as '*seasonal or patch mosaic of burning'*, which contains unburned, burned, early burned and recently burned vegetation. This pattern of burning was linked to not only reducing the late season fires, but to increasing biodiversity in the savannas of Mali. While the Khwe seasonally burn the savanna-woodlands for a multitude of reasons early in the season, including the prevention of late season fires, their reasons for the use of fire are directly associated with their specific livelihood activities and needs, and thus these small early season burns could indirectly enhance biodiversity, and increase the variety of microhabitats in BNP. However, further research would be required to address traditional burning patterns and early season fire frequency and location, alongside biodiversity measures in BNP. Similarly, Trollope & Trollope (1999) found at the local level amongst the elder generation in the greater BNP region a well-developed traditional understanding of the role of fire in the management of herbaceous and woody vegetation in the different inhabitant communities, and found their knowledge to be practical. Nonetheless, the use of fire by disparate indigenous communities inevitably varies from location to location (Walters, 2010). As shown in this study the use of fire is deeply entrenched in the Khwe's cultural practices which were linked to elder's generations *transmission of knowledge in the use of early season burning*. Significantly, this knowledge was associated to the Khwe's former *nomadic hunting and tracking activities in the past* (including veld food collection), which indicates that cultural practices aren't static, but are flexible, and have necessarily changed and adapted over time because of the changing socio-political circumstances in the region.

The importance of historical hunter-gatherer fire histories (hunting and tracking)

Many researchers have suggested that moderate and repeated burning by Aborigines enhances hunting efficiency (Bird *et al*., 2005). Anthropological research with the !Kung and G/wi in the Kalahari in Namibia and Botswana in the 1970s provided further evidence for the link between the use of fire and attracting game to a fresh flush of grass growth (Lee & Devore, 1976; Marshall, 1976; Silberbauer, 1981). Both Schapera (1930 in Hall, 1984) and Lee & Devore (1976) reported fire use in the late winter and early spring. However, in this study in BNP, fires were used early in the onset of the dry season following the rainfall season between April and July for the specific purposes of the regeneration of vegetation and protection of veld food resources from the late season fires, as similarly documented by Silberbauer (1981) of the G/wi Bushmen (central Kalahari) to encourage the growth of cucurbitaceous ground vines. Yet, in BNP for hunting and tracking purposes, fires were lit in the middle of the winter (Aug – Oct) typically in the omiramba (i.e. the grass laden fossil drainage areas between the dune crests), similar to other San groups elsewhere (Lee & Devore, 1976; Silberbauer, 1981). Though the hunting of larger species (e.g. Kudu) has not been permitted since independence (1990), the hunting of smaller species (e.g. spring hares, tortoises etc.) is currently allowed in BNP (Rousset, 2003). Moreover, this study has shown how the use of fire was historically used to aid tracking (i.e. to detect tracks in the residue ash) with the hunting down of antelopes, similar to the Martu aboriginal's in Western Australia (Bird *et al.*, 2005). Liebenberg presented a fire and tracking related hypothesis in 2012: "Hunter-gatherers (also) use fire to burn the veld to make it easier to track… once you burn the veld, you get green shoots which attract animals…and because the veld is burnt, it is more barren and the tracks are easier to follow". Chumbo & Mmaba (2002) also established the use of fire for tracking motives by the Khwe living along the Okavango Pan-handle in Botswana. Nonetheless, a question raised during this study is why did earlier anthropological research not detect the linkages between the use of fire alongside hunting for tracking purposes? Scherjon *et al.* (2015) noted that the use of the keyword 'fire' was rarely indexed in historical anthropological hunter-gatherer studies, and thus, other areas of research for example social organisation, ethno-botany and diet were a priority. One reason as to why hunters were infrequently accompanied by researchers in earlier studies may be due to the environmental constraints of moving through the Kalahari (L. Liebenberg, pers.comm, 2014).

Africa's human history, and the *use of fire for tracking* is potentially relevant to understanding historical burning strategies, together with the use of early burning for gathering veld foods, which suggests the history of early season fires by San groups goes back a long time. However, despite understanding the biophysical drivers of fire, the invisibility of historical burning patterns, and legacy effects on vegetation alongside variable past climates make the influence of humans on past fire ecology inherently challenging to study (Archibald, 2010; Bradstock *et al.*, 2005; Trauernicht *et al.*, 2015). Nonetheless, ''hunter-gatherer fire practises have deep histories: human fire likely shaped the ecology of many global ecosystems and may be critical for understanding the economic and ecological conditions that led to the agricultural revolution'' (R. Bliege Bird & D. Bird in Scherjon *et al.*,2015: 314). However, it is a complex, and highly debated area of interdisciplinary research, and one that requires the links between paleoenvironmental change, ethnographic patterns and the attributes of past human fire use to be explicitly stated (Scherjon *et al.*, 2015).

It is evident that livelihoods in BNP have undergone considerable change (e.g. banning of hunting of large game (1990) (Jones & Dieckmann, 2014; Rousset, 2003) because of a nexus of colonial supremacies, ethnic in-migration, colonial and cross-border wars, political violence, livestock diseases, and land use changes since the early 19th century (Table A1; Appendix A).

The importance of the socio-political history

In Bwabwata National Park, people's livelihoods have undergone considerable change due to the colonial history (German and South African), internal politics and cross-border wars (Namibian War of Liberation [1966 - 1990]; Caprivi Secession [1999 - 2002], Angolan Civil War [1975 – 2002], and Namibia's independence (1990), in combination with changing land use systems (e.g. militarized area to a protected area, and later establishment of conservation and multiple use areas), and policies in BNP.

In 1888 the first fire suppression policy appeared in Namibia in the *Deutsche Kolonialgesellshaft für Südwestafrika* (German colonial society for South West Africa) banning all fires, because 'deliberate burning destroyed forests and other vegetation' (Goldammer, 1999, le Roux, 2011). However, during the German colonial period (1884 - 1914), the western Caprivi (i.e. BNP) was seen as inhospitable and hard to traverse due to the absence of water, and for a long time Germany did not take possession of the area, and there was no maintenance of law and order (Fisch, 1999). Thus, it is likely that the imposed fire suppression policy did not influence the inhabiting communities' behaviour. Moreover, prior to the arrival of the SADF (1966), the Khwe engaged in a variety of livelihood activities: hunting, veld food gathering, cultivation and fishing along the Okavango and Kwando rivers (Jones & Dieckmann, 2014). During the SADF occupation of north-east of Namibia, the South African Generals provided high salaries for the Khwe men who worked as trackers, soldiers and reconnaissance commandos, together with medical supplies, schools, food, shops and housing. However, these services collapsed as the South African military moved out of the area before independence (Suzman, 2001). Further, during the occupation, the Khwe were restricted from using fire, and moving in the area freely, since it was a war zone, and thus were inhibited from traditional fire, hunting and gathering activities, and in addition were exposed to support, labour and monetary benefits over the two-decade war (approx. 24 yrs.), which resulted in the *disruption of their indigenous resource practices* in BNP. Moreover, the SADF also relocated the Mbukushu people outside of the bounds of the park during the war, and limited in-migration (Suzman, 2001). Thus, the war also had consequences for the Mbukushu people that limited access to important subsistence resources along the rivers in the park.

In this study, the Khwe respondents emphasized that there was an absence of the sharing of fire knowledge by the elder generation to the youth, because of a shift to modernity (i.e. westernized needs), and indicated that knowledge surrounding early burning is diminishing over time. It could therefore be said that the Namibian War of Liberation resulted in ensuing costs for the Khwe, because participation with the conflicting apartheid military (SADF) in the war against Namibia led to severe ramifications associated with the socio-political situation (i.e. absence of a delegated Traditional Authority recognized by GRN), which led to harsh economic consequences (Battistoni & Taylor, 2009) and disruption of traditional livelihoods. Thus, because the Khwe had become accustomed to monetarized support that dissipated at independence, the war consequently indirectly contributed to the *deterioration of their indigenous practises*. Furthermore, the trauma of poverty and adjusting to life in the 20th century resulted in particularly the San in Namibia developing a host of social problems, the most prominent of which is alcohol abuse, and subsequent community violence (Suzman, 2001).

Further changes in their livelihood subsistence occurred after Namibia gained independence in 1990. Following independence in 1990, the former Ministry of Wildlife, Conservation and Tourism (currently the Ministry of Environment and Tourism [MET]) were permitted to return to work in the park for the first time since 1966 (Brown & Jones, 1994), and further restrictions were placed on the inhabiting populations hunting and gathering, and fire use activities, with the establishment of the MUA. However, Taylor (2012) emphasized the role of BNP in offering the Khwe a form of protection from inter-ethnic marginalisation in other areas from other tribes, and access to natural resources. Yet, the management of BNP by the MET resulted in further alteration of the communities' livelihood activities, since the two conservation areas cordoned in 2007 (Kwando and the Western core conservation areas i.e. Buffalo and Mahango as formerly recognised in BNP) encompassed both the Kwando and Okavango River systems, which were described as an important locality for veld food resources particularly by the Khwe. Under these restrictive circumstances, where access to meat through the hunting of large game is prevented, the gathering of veld foods becomes vital. Moreover, the BNP park wardens still continue to prohibit the general use of fire by communities in BNP (even after 2006 when early burning strategies were introduced), which has perpetuated that the GRN is in charge of fire management (Kamminga, 2001). Nevertheless, there is still active burning occurring in BNP (Figure 3-3), and as indicated by the community stakeholders preference for early season fires that meet their present-day livelihoods needs. Yet, due to the imposed local land use legislation (hunting [of large game] and gathering restrictions (along river systems) in the core protected areas) since independence (1990), and more rigidly in 2007 with the formation of the MUA, there has been an overall cessation of traditional livelihood activities (i.e. hunting), and subsequent loss of knowledge particularly amongst the Khwe people.

The importance of livelihoods in association with fire

Traditionally, together with hunting-gathering and pastoralism, cultivation was purportedly one of the most important livelihood strategies of the Khwe and Mbukushu in the past (Suzman, 2001, Jones & Dieckmann, 2014). The Kavango and Zambezi Regions are the two poorest regions in Namibia, and economic activity and development in BNP is scarce due to its status as a national park, and consequently opportunities for people to work and earn an income are limited (Jones & Dieckmann, 2014). Evidently, the Khwe and Mbukushu people have had to continually adapt to changing land use restrictions, and are largely reliant on the park's natural resources for sustenance in support of their livelihoods (Beatty, 2014; Taylor, 2012). However, this study has revealed that the BNP community have adapted by relying more on veld foods, together with cultivated crops (Table B6; Appendix B). However, the Khwe were generally resistant to the use of cultivation practises for various reasons, which included changes in the region (e.g. restrictive policies; land-use changes) that resulted in an adjustment from a former nomadic (i.e. hunting-gathering) to a sedentary lifestyle (Suzman, 2001). Furthermore, resistance to cultivation was because of strains associated with having to adopt to practices other than their own (e.g. practices learnt from the Mbukushu), as well as having to develop the skills associated with cultivation, which the Khwe described as difficult. The Khwe have also had a tenuous relationship since the 1800s with the in-migrating Mbukushu, who used the Khwe as slaves, and or clients, which probably also contributed to their resistance to adopt to cultivation subsistence means. Nowadays, cultivation is rarely practised among the Khwe, due to a lack of equipment and oxen, and the destruction of the crop fields by elephants (Jones & Dieckmann, 2014), particularly in the east of BNP. Furthermore, due to outbreaks of teste fly in 1945 (Hitchcock, 2012), and in the 1960s (Rousset, 2003), and the occurrence of 'lung disease' in 1996, the GRN issued a demand for the sale and/or slaughter of all the cattle in the region, thus the Khwe have not been in a position to regain their livestock herds, and have resorted to hoeing their fields by hand (Suzman 2001). Nowadays, the Khwe typically have small vegetable gardens in proximity to their homes (Jones & Dieckmann, 2014), as observed in this study.

Attila's (2013) and Jones & Dieckmann's (2014) research with the Khwe in BNP concerning livelihood strategies revealed that people mainly survive on pensions, GRN food aid, and income from piecemeal work, employment, veld food gathering, and some cultivation. However, Attila (2013) revealed that in total only 160 members of the community work as paid employees, which out of a population of 6 000, is marginal. In this study, people rarely emphasized the importance of GRN food aid, but highlighted the importance of veld food resources, in which context, fire was viewed both positively, due to the growth and the protection fire affords the vegetation, and negatively due to the impacts of fire later in the season. The GRN recognizes that fire affects the livelihood options of local inhabitants of the area that are dependent on fruit and nut bearing trees (Haliwa, 1998; MET, 2013). In this study, access to and the availability of veld food resources emerged as critical to both the Khwe, and Mbukushu livelihoods. However, how fire affects the availability of specific veld resources, and how many plant resources are used to compliment the diet of the communities is required to be quantified (K. Knott, pers. communication, 2015). Table 3-2 provides a non-exhaustive list of tree and shrub species reported by the Khwe to be affected by fire. Further work on the abundance and response of these species to fire was beyond the scope of this thesis.

Fire was viewed as positive in reference to early burning activities, however too much fire, and particularly the late season was perceived as destructive, and a threat to peoples livelihoods, and especially to veld food resources. In 2010, a study was carried out in BNP to assess the veld resource use and role on food security (Dain-Owens *et al.*, 2010), and the results indicated that the availability of food plants was not a concern at the time. Currently, the community indicates the loss of plant veld food resources due to regular fires which burn the lower and smaller, and below ground food resources, which leave little time for plant regeneration. During the last 10 years Namibia has experienced above average rainfall seasons, with the exception of 2006/7 and the 2012/13 rainfall period that was the declared the driest in 30 years (Kapolo, 2015). Fire in savanna systems is responsive to rainfall patterns and associated grass biomass production, and due to the seasonal pattern, fuel can dry out within a year (Archibald *et al.*, 2010). Thus, the increase in rainfall and associated increased grass biomass, may be the factor for the increased severity of fires, which has possibly impacted the availability and abundance of veld food resources in the region over this time period. Furthermore, through the interviews it became evident that the Khwe contested the Mbukushu burning practices, which they described as negligent as they were reported burning at any time of year. The majority of the Khwe and the Mbukushu thought there are more fires today, than there were historically due to an increase in human densities in the park. The results suggest that traditional knowledge systems are threatened by multiple stressors including shifts in population densities, demographics of traditional fire cultures, land use change, and unsupportive government policies (Mistry *et al.*,2005; Huffman, 2013).

Government and non-government stakeholder perspectives

Suppression versus early burning strategies

The BNP management plan currently specifies the objective of the use of fire as a management tool for actively maintaining and rehabilitating habitats in the park (MET, 2013; 2016). Respondents revealed that early burning is nowadays positively viewed as an ecological fire management tool in BNP. However, Namibia has been subject to a number of external fire management initiatives since the 19th century (Finland, Germany, South Africa and more recently, Australia; Table B3; Appendix B), which have influenced park management both negatively and positively. The negative influences on fire management is due to the instigation of suppression and disregard for traditional burning practises. Whereas, positive influences on fire management were because more recent collaborations (e.g. CBiFM project [2006-2011]) with the inhabiting communities and their fire knowledge resulted in a transformation in BNPs management approach to understanding fire as ecologically beneficial to the savanna-woodland system with the use of early season fires (Figure 3-8).

In BNP, the change from fire suppression to controlled fire management with emphasis on early season burning was facilitated by a pilot CBiFM policy programme in 2006 (Beatty, 2011), by a local NGO

(IRDNC) together with the DoF. The CBiFM programme hinged on devolving the responsibility of fire management to the communities, and implementation involved creating a patch mosaic pattern of burnt and unburnt areas in the landscape early in the dry season and *importantly recognised the knowledge of traditional burning practises* (Mbongo *et al.*, 2011). Thus, the CBiFM programme marked a significant yet informal transition to fire management versus the GRN Forest Act No 12 (2001), and Forest Regulations (2015) based on fire prevention, suppression, and controlled burning only under specific circumstances. The CBiFM project was completed in 2011, and subsequently, early burning was integrated into the BNP Management Plan in 2013 (MET, 2013). Further, interaction between the BNP communities and the IRDNC about fire ended as the project terminated, though the communities particularly in the east of the park continue to use early season fires (Beatty, pers.comm, 2014; MET, 2016), as they have always done. Also, early burning is apparently less prevalent in the west of the park (Beatty, pers.comm, 2014; MET, 2016), however this is likely due to differences in cultural values and livelihood practises of the Mbukushu situated mostly in the west, as well the concertation of both ethnic groups living in this area, and the Khwe in the east of the park, which is less populated (see Chapter 5 for details).

Fire regime heterogeneity in the form of early burning and/or patch mosaic burning, instead of fire suppression, is increasingly being promoted in savannas worldwide (Eriksen, 2007), as consistent with this study by the stakeholders preference for early dry season burning in BNP. However, despite the BNP officials now adhering to early burning, burning carried out by the communities in BNP is typically regarded as forbidden, yet the park officials are aware of the communities burning activities as revealed in this study. Possibly, the BNP officials turn a blind eye, considering the restrictive circumstances, and lack of infrastructure to support the communities living in the MUA. Moreover, all other Fire associated acts and policies (Table A3; Appendix A) in Namibia still regard *traditional burning practises as detrimental to the ecological system*, and burning by people in the region to this day is prohibited (Kamwi *et al.*, 2017). Equally, the DoF still largely relies upon national legislation and the threat of punishment to discourage the lighting of fires in the Zambezi Region (Beatty, 2011). However, the MET has subsequently acknowledged that insufficient and inconsistent fire management legislation and policies inadequately address the appropriate use of fire in Namibia, causing a lack of understanding that results in the uncoordinated use of fire (MET, 2016).

The implementation of fire management policies in Africa typically maintain a top-down approach (Eriksen, 2007). Butz (2009) emphasised the importance of the engagement of fire scientists, land managers, local communities and policy makers to develop regionally relevant fire management plans that maintain savanna environments, while continuing to support local livelihoods and biodiversity. Similarly, the government and non-government stakeholders identified the lack of communication and awareness between all involved in fire management (communities through to different Ministries) as to why there is a gap between policy and enactment. Further, stakeholders identified that people who write the policy, frequently have little or no involvement, or knowledge of the fire regime in the region in which policy is to be applied. Moreover, most stakeholders agreed that it would be beneficial if the policy identified different management applications for varying habitat types, and ecological conditions e.g. for preventing / controlling bush encroachment. The BNP management plan (MET, 2013; MET, 2016) currently addresses the strategy of assigning adaptive burning plans to specific habitat types, since different habitats require dissimilar fire regimes. However, most stakeholders were of the opinion that policy is not the problem, but management and implementation. Irrespective of a specific needs base policy, management is the perceived as more central to achieving fire control in the region. Nevertheless, it is particularly noteworthy that the CBiFM pilot project (2006 – 2011) in Namibia resulted in the transformation to *early burning strategies* in the BNP management plan.

Both Australia (Russel-Smith *et al.*, 1997) and South Africa (Pilanesberg National Park; Brockett *et al.*, 2001) have extensively addressed indigenous fire use in savannas, and specifically patch mosaic burning, which originated from Aboriginal fire practises in northern Australia (Trollope, 2011). Equally, in West Africa, the government in Mali devolved responsibility from the forest service to the village level for their own rules and practises on formal fire management (Laris, 2002). Further, the management in Kruger National Park (South Africa) extended their burning throughout the dry season, which was influenced by indigenous fire practise in neighbouring Mozambique because of the widespread use and perceived benefits of patch burning (Trollope 2011). Thus, the use of early dry season fires in BNP is comparable to the aforementioned studies where local fire practises have been integrated into the management plan, as well as in the recent controlled fire management programme for the park (MET, 2016).

Fire and vegetation history: perceived changes in the fire regime

In Bwabwata National Park, the government and non-government stakeholders implied that early burning strategies are applied in an '*ad hoc' (impromptu)* way with little systematic planning or monitoring (MET, 2016). Further, the stakeholders still raised concern about the prevalence of the occurrence of the late season fires. However, in the absence of organised early season burning, late season fires are likely to occur in association with high rainfall periods and associated grass growth in BNP (see Chapter 4 and Chapter 5 which address rainfall and seasonally burned area in BNP).

Moreover, fires linked to cultivation activities in savannas are inevitable in land use systems on which people are largely dependent, since burning and planting are essentially deliberate, and occur during high fire risk weather conditions in the late dry season, prior to the rainfall season (Figure 3-3; Figure 3-4). All of the stakeholders suggested fires were all started by people, and that fires are increasing in frequency and extent in BNP (see Chapter 5 for a discussion). Interestingly, very few stakeholders referred to climate and associated above average periods where rainfall increased in the last decade in the region as the precursor to an increase in fires in BNP. The overall perception is that too much burning in the landscape is taking place, with both early and late season burns, and that the same areas are being burnt repeatedly with implications for the woodland structure. Moreover, there was also a degree of uncertainty amongst stakeholders about when and where the burning was occurring in BNP. Thus, overall there was a lack of consensus amongst stakeholders concerning the frequency, timing, location and the impacts of fires in BNP. This is likely related to the absence of data, monitoring, and ground observations and knowledge of where fires occur in the park, as suggested by the stakeholders.

At an international meeting on savanna fire management in Namibia in 2014, it was stated in relation to remote sensing data, that there is a strong need to improve collection, gathering and analysis of information so that managers on the ground can better understand and quantify the temporal nature of fires, frequency, size and spatial characteristics (United Nations University [UNU], 2014). However, stakeholders acknowledged that fire is complex, and multi-faceted, which creates uncertainty in dealing with fire management. Decisions for fire managers or scientists involve high risk, as applying one strategy entails maintaining responsibility for the course of action, and the consequences for the ignitions implemented (le Roux, pers. comm, 2015). Novel adaptive fire management strategies are emerging, however making decisions about fire management is complex, uncertain and fraught with controversy (Gillson, 2015). For example, in the adaptive fire management approach pioneered in Kruger National Park (KNP) (van Wilgen *et al.,* 2004), fire knowledge is accepted as incomplete, but learning about fire is adaptive, and approaches to management are flexible in response to the observed variable fire patterns (van Wilgen *et al.,* 2014).

The effectiveness of fire suppression

The prevailing perception of the stakeholders was that more frequent fires have led to a more open landscape, devoid of trees, however with an increase in shrub cover in some areas of BNP. The consequence of repetitive burning results in a fire trap (Trollope, 1984), whereby the grasses support fire and suppress tree seedlings by fuelling frequent fires that stunt the growth of tree survivors. The process results in the occurrence of 'Gullivers', which are woody, multi stemmed shrubs that are stunted and unable to escape the flame zone (Bond & van Wilgen 1996; Bond, 2008). Reference for these observations are supported by the differences between the densely treed east of the BNP (Figure 3-9 a), where fire has been recorded in the early and late season (see Chapter 5 for details) versus the west of the park, where fire is frequent in the late season which shows a distinctly open area with few trees, and the pervasiveness of shrubs (e.g. *Baphia maaisaiensis*) (Figure 3-9 b). However, the difference in vegetation density and structure is also probably due to climatic differences, with the east being marginally wetter (classified as dry forests) (Mendelsohn *et al*,. 2010) and therefore more densely treed, versus the drier west, as well as due to differences in soil types (Tinley, 1966).

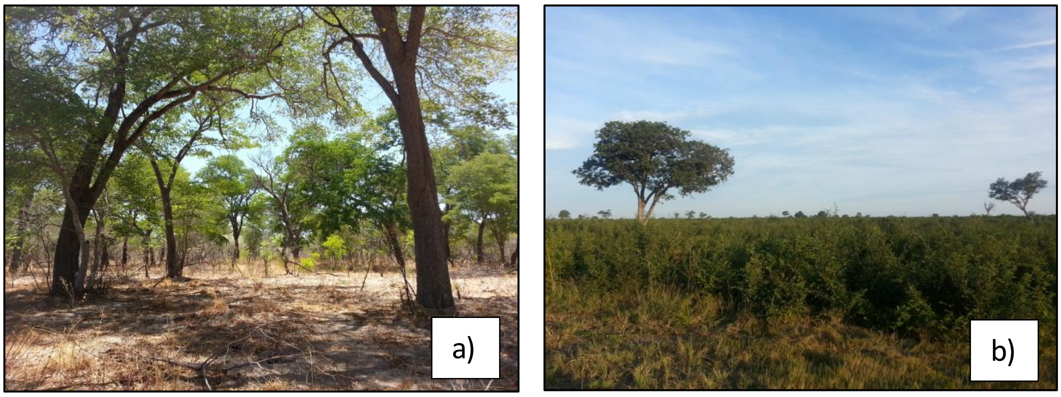


Figure 3-9: a) Vegetation in the east (Kwando Core Area, BNP) and b) vegetation in the west in the Western Core Area, BNP (Buffalo Core Area).

Even though, the vegetation was described as being more open in BNP, with fewer large trees, stakeholders also suggested that bush encroachment has occurred in some parts of the park as a result of the policy of fire suppression. Overall, the uncertainty concerning the effectiveness of fire suppression was revealed by contradictory statements by the government and non-government stakeholders. However, it is difficult to ascertain the effectiveness of fire suppression without formal quantification of the present tree species, in combination with density and structural measurements to establish changes. Nonetheless, if fire suppression was a factor, then ecologically one would expect the prevalence of late season fires associated with high fire risk weather conditions (e.g. large fires because of the fuel build-up of grass in the absence of fires), and in the absence of both early and late season fires, bush encroachment would largely be evident in BNP. But, some species commonly associated with bush encroachment in Namibia (e.g. *Acacia mellifera*; *A. reficiens, Dichrostachys cinerea*) (De Klerk, 2004) were absent in the park landscape (pers. observation), whereas others (*T. sericea)* were growing in high density on the lower slopes on the dunes at the base of the omiramba (pers. observation), probably due to their association with water seepage zones (Fanshawe & Savoury, 1963), where heavier soils have formed where water has washed down finer particles which accumulates in these fossil drainage areas (Mendelsohn & Roberts, 1997). However, it is evident that *Vachellia spp.* are partially encroaching into the typically grass laden omiramba (pers. observation), which was also observed by the BNP community stakeholders, and by Brown & Jones (2014).

The effectiveness of fire suppression remains poorly understood, as during the two decade SADF occupation, fires were also described as frequent (Burke, 2001), as expected with the use of military equipment. However, overall the general control of fires in BNP was perceived as difficult by the stakeholders, particularly the late season fires, so whether fire suppression was achieved if at all, remains questionable. Since there has an absence of general fire suppression strategies (e.g. no fire breaks etc.), as well as resources to aid fire control in the park up until 2006, when early burning was implemented. In conclusion, it seems likely that the policy of fire suppression was ineffective, but this would need to be tested using historical aerial photographs (e.g. Kruger National Park, Munyati & Sinthumule, 2016).

Views on past and present traditional fire knowledge and management

In BNP, government and non-government stakeholders were aware of the use of traditional strategies specifically for hunting and gathering, and the use of fire for cultivation purposes (Figure B6; Appendix B). However, stakeholders considered these traditional practises as regressive, and not part of an organised burning sustainable system adhered to by the locals, and unsustainable in the long term. On the contrary, more recently (2016) the MET duly recognised the BNP communities fire management knowledge in the east of the park, and therefore the perceptions of the stakeholders views of traditional burning strategies gathered during the interviews in 2014 and 2015 during this study contradicts what is currently officially perceived by the GRN. Nonetheless, the recent fire management strategy for protected areas in Namibia (MET, 2016) where the communities knowledge is recognised for the first time in history arose through consultation with a broad range of stakeholders (e.g. ministries, conservancies, NGOs, and researchers), and thus represents years of collective experience from disparate fire stakeholders, which resulted in the recent change in the GRN perceptions.

Four factors emerged in BNP that involved both groups of stakeholders (i.e. community and government and non-government), and their associations with the socio-political history of the region (Namibian Liberation War, Independence (1990) and changes in fire management policy (2006): i) the absence of recognition by the GRN of the communities knowledge about early burning strategies; ii) the continuous miscommunication of information about the use of fire in the region, which conveys 'fire suppression/prevention' and prohibits the use of fire amongst the communities; iii) refutation of entitlement of the Khwe as a TA, and thus absence of the recognition of the Khwe as a legitimate traditional community in Namibia; and lastly iv) the control of fire only by MET and park wardens. Evidence for these factors emerged within the sub-theme: '*political and ideological conflict: state and local actors'*. These four factors have resulted in a breakdown in communication, transparency and trust, and social cohesion between the GRN and BNP communities. The absence of the recognition of the communities' knowledge, and formal recognition as a TA (the Khwe), and their continual marginalisation has resulted in an absence of interest within the community about fire use and resistance to collaboration with the GRN presently. As one government stakeholder stated ''we experience difficulty as the communities are no longer interested in meetings''. Stakeholder and community collaboration was deemed a necessity if fire management issues are to be addressed in the region for the purpose of knowledge sharing and engagement. Control of people and their use of fire in a fire prone savanna landscape is a complex issue. Scott *et al.* (2014) acknowledged multiple facets which characterise societies and fire regimes: continuous turmoil, variable interaction from year to year, together with political instability; the gain and loss of knowledge, movement and the change of norms.

Until very recently, the Khwe have not been recognised by the GRN for their fire knowledge, and use of early burning strategies in the BNP landscape (see MET [2016] for details). However, the Khwe's knowledge was included in the CBiFM project (2005 – 2011), and acknowledged by the programme and responsible NGO (IRDNC) (Mbongo *et al.,* 2009), which resulted in the management conversion from suppression to early burning in BNP. The social-historical complexity is inherent, whereby the Khwe have been using early burning strategies in the landscape since time immemorial, versus the GRN who states the community needs to be taught how to use and be educated about fire. Besides, the BNP communities today observe the GRN implementing their early burning practises, yet the GRN still limits and attempts to control their use of fire in BNP. Furthermore, until recently there was continuing miscommunication of information which conveys 'fire suppression/prevention' and prohibits the use of fire amongst the communities through e.g. the community campaigns indicating the necessity of preventing all fires (Figure 3-6). Huffman (2013) emphasised that typically central governments outlaw burning or regulate the practise more tightly, and fire campaigns attempt to convince people who depend upon fire for survival to hunt, gather, herd, or cultivate to prevent fire at all costs. This results not only in conflicting perceptions, but in changes in ideas about fire (Laris, 2002). Trollope & Trollope (1999) noted that the highly visual posters (Figure 3-6) portrayed a message of fire suppression, and made the recommendation to differentiate between the harmful effects of indiscriminate fires have on the vegetation and the ecological necessity of using controlled burning when it is necessary. Furthermore, recognition of desirable versus indiscriminate burning would restore the credibility of traditional knowledge developed over millennia (Trollope & Trollope, 1999).

Consequently, recent posters displayed in the town of Katima Mulilo (2015) still exhibit the message that fire should be suppressed and/or prevented, however they also now show proactive early burning with fire teams (Figure 3-10), which shows an improvement in the communication about fire in the greater region.

Figure 3-10: Recent posters in display outside the Directorate of Forestry in the town of Katima Mulilo (2015).

Undoubtedly, the most significant factor resulting in the exclusion of the Khwe's knowledge base is related to their involvement with the SADF and the Portuguese in Angola during the Liberation War, as the Khwe fought against the Namibians for the South Africans. Thus, the Khwe were regarded as former enemies from the Liberation struggle (Gordon, 2009; Melber, 2007; Taylor, 2008). For these reasons, the GRN has refused to this day to acknowledge the Khwe as citizens of Namibia, and grant them a Traditional Authority. Thus, traditional burning practises were overshadowed by political interests on both sides (South African and Namibian) during the Namibian Liberation War (1966-1989), a time when politics was priority and not natural resource management (Kangumu, 2008). Recently, stakeholders expressed a need to re-instate the power of TAs as a means to prevent misuse of fire currently within the communities (Murphy, 2015). Furthermore, recommendations from an integrated fire management proposal for the BNP advocated the implementation of a 'Permit to Burn System' within the communities (Beatty, 2015; MET, 2016).

This study illuminates the social-political-historical and ecological complexity between primarily the Khwe and the GRN, associated with the evolution of Eurocentric fire management policy, in parallel with the restrictions and under recognition of the importance of traditional fire knowledge and livelihood activities in BNP. Figure 3-11 illustrates how complex historical factors, which disrupted traditional fire management interact with environmental uncertainty to produce a state of ecological uncertainty in BNP, where the likelihood extent and ecological consequences of fire are unpredictable. The model (Figure 3-11) summarises the associations of the exclusion of traditional knowledge embedded within the social –political context of the region, together with the ecological questions pertaining to current fire management in BNP. An understanding of this complexity highlights the need to investigate the ecological uncertainty identified during the course of this study by the government and non-government stakeholders (e.g. bush encroachment; and vegetation change due to early and late season fires) in relation to changes in the fire regime in BNP (MET, 2016). For example, scenario planning could be used to explore different future possibilities that might emerge under various combinations of environmental, social and ecological drivers using a combination of tree cover estimates, fire management practices [early/late], climate and Co_2 states. Moreover, it emerged that both groups of stakeholders have extremely similar views of the use of early burning practises (Figure 3-8). Thus, despite the BNP community and the government and non-government stakeholders' different worldviews, they demonstrated a shared common goal in the use of early burning as a strategy for similar reasons.

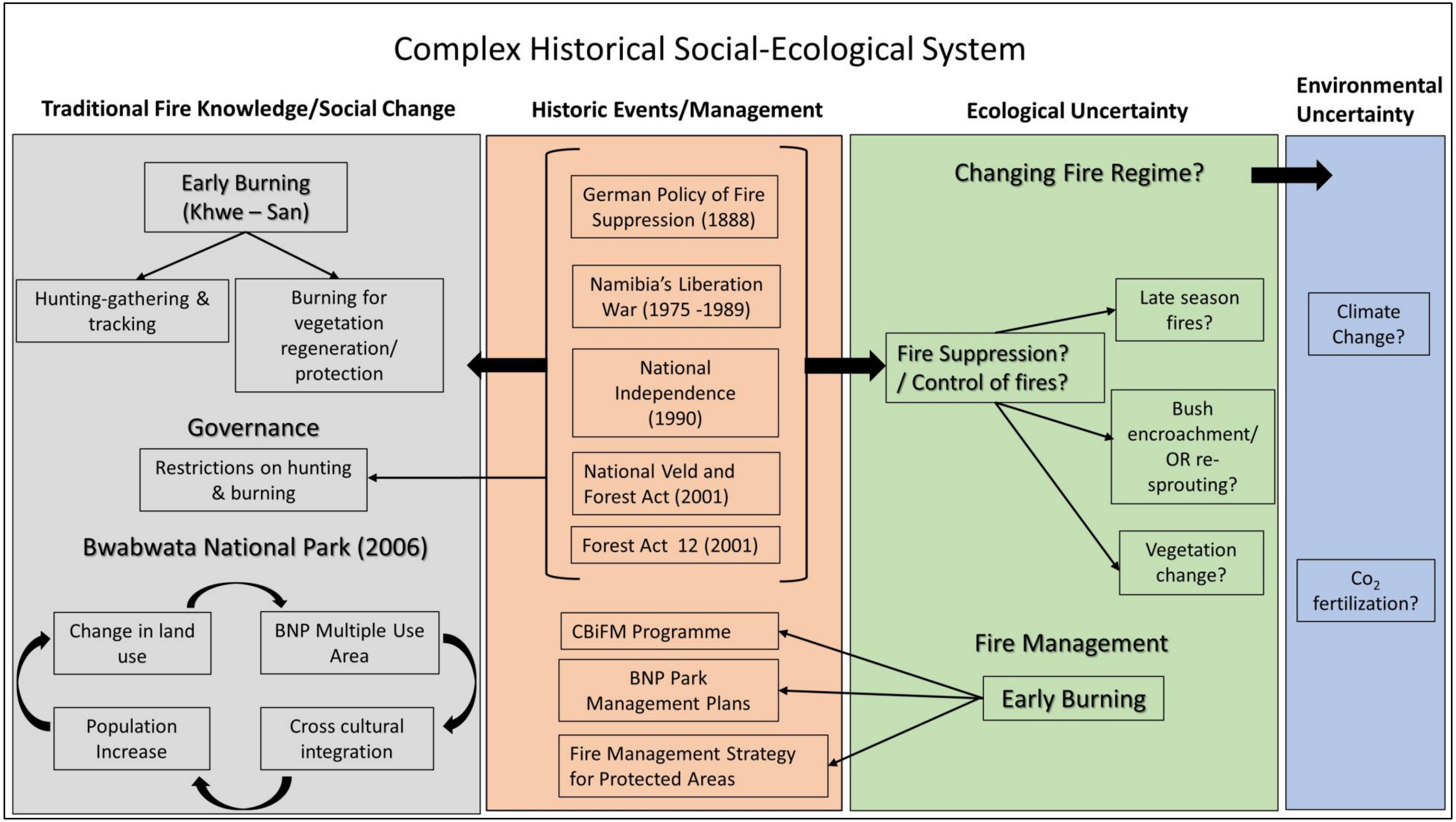


Figure 3-11: Conceptual model showing the associations of the complex social-political ecological systems in relation to the use of fire in Bwabwata National Park.

Conclusion

This study has presented a historical and contemporary understanding of why, where and when people use fire in the BNP landscape. The study integrates both the stakeholder groups' (i.e. community and government and non-government) perceptions of fire management, explains the current fire management status in BNP, and its roots in the region's socio-historical and political past. Indigenous practises of preventative and regenerative burning practises have until recently received little attention in policy making circles (Butz, 2009, see Laris, 2002 for exceptions), however the BNP fire management policy is now centred on early burning as a result of the CBiFM project incorporating indigenous knowledge in north-east Namibia. Nevertheless, overall, a breakdown in social cohesion, knowledge and communication flow, combined with mixed land use (cultivation fires/national Park) and interactions with environmental factors has contributed to the misunderstanding of fire management between the two stakeholder groups in BNP.

This study has shown that it is useful to position fire ecology within the social-historical context, which allows for the contextual understanding of causal interactions between changes in policies, social systems and fire regimes. Furthermore, the comparisons of the different viewpoints of the stakeholders has shown that both groups value and understand the benefits of early burning, which indicates that there is common ground for understanding the use of fire in the future in BNP.

The implications of these findings are clear in terms of recommendations for the advancement of fire management policy: understanding the social dynamics embedded in fire management is critical for manging fires in the future. This study presents results which reveal the implications for understanding human driven fire regimes in southern Africa savannas, and how the complex social dynamics reflected in the past are affecting contemporary fire management in north-east Namibia. Thus, the implication for management is the need for scenario planning that would allow stakeholders to envision different possible ecological conditions and allow them to identify management strategies that could guide the ecosystem towards perceived desirable states.

Chapter 4 People, policy, fire and El Niño southern oscillation in Bwabwata National Park, north-east Namibia.

Abstract

People are significant sources of ignitions and are central to fire regimes in African savannas. In southern Africa, human activities have altered the relationship between climate and burned area through diverse land and fire use strategies during the dry season. Yet, the complex interplay between climate, vegetation and human factors that influence fire dynamics remains poorly understood.

Bwabwata National Park (BNP), in north-east Namibia, situated within the savanna-woodland biome, is a unique setting where people (Khwe and Mbukushu) live in a multiple use area (MUA) of the protected area, and it has two core conservation areas (CA) exclusively for wildlife management and tourism. Though fire has been traditionally used for hunting and pastoral purposes, in 1888 the colonial government initiated a policy of fire suppression. In 2006, early dry season burning management strategies were implemented throughout the park.

I analysed multiyear (2000 – 2015) MODIS fire product data to explore relationships between rainfall, seasonality, the numbers of fire, and fire size for the MUA and CAs. I tested the hypotheses that: i) land use activities would influence the rainfall-burned area relationship in BNP; and ii) a change in policy from fire suppression to early burning in 2006 would reduce the inter-annual variation in burned area, due to an anticipated increase in early dry season fires in BNP.

On average 36 % of the park burnt annually, but the inter-annual distribution of burned area amongst all land use areas was highly variable between years. Results reveal the absence of a rainfall-burned area relationship over the entire park and in the MUA East, MUA West and Kwando CA , except in the Western CA, where a positive correlation between burn area and rainfall was evident. It is likely that human activities, notably early season burning, eliminated the local rainfall and burned area relationship, and explains the persistence of the rainfall-burn area relationship in the Western CA, where early dry season fires were infrequent. Furthermore, burn area and the grass growth (i.e. available biomass) was responsive to the El Niño Southern-Oscillation (ENSO) wet season events (La Niña), which resulted in greater area burned and fire sizes in above average rainfall years in the early dry season.

This study highlights the significant interactions between people, rainfall seasonality and fuel availability, and results suggest that it is the number of fires and fire sizes, combined with variable rainfall events that are better indicators of burned area where people utilize fire in a savanna landscape.

Introduction

Fire, climate and herbivores have long been considered sculptors of southern African landscapes (Bond, 1997). The foremost factor is the prevailing climate, which has a significant influence on vegetation patterns and biomass at continental scales (Whittaker, 1975). Rainfall limits biomass availability, and fire is only possible where there is sufficient fuel to catch fire and a long enough dry season for ignitions to take place. Most of sub-Saharan Africa has the requisite climate, with distinct wet and dry periods, with the savanna vegetation becoming flammable during the dry season (Trollope & Trollope, 1999). It is the grass biomass between the trees and shrubs in savanna biomes, driven by rainfall, which provides the fuel for fires on the continent. In savanna-woodland systems with concurrent changing land use systems, large herbivores (wild and/or domesticated) alter the grass biomass and fuel connectivity (Bond & Zaloumis, 2016) and limit the spread of fire. Thus, rainfall and the ensuing grass biomass, and herbivores modify savanna fire regimes at regional – landscape scales. Added to lightning as an ignition source, people are now seen as significant causes of fire (Archibald *et al.*, 2010; Bowman *et al*., 2011; Roos *et al.,* 2014; Scott *et al.,* 2016). People are able to alter the natural vegetation, and influence fire regime patterns (i.e. repeated pattern of burning at a location in space) either in constructive or undesirable ways, through increasing ignitions, suppressing fire, and altering fuel load and connectivity (Bond & Parr, 2010; Bond & Zaloumis, 2016; Buthelezi *et al.*, 2016). The preferred fire season depends on ecological management or livelihood preferences, which determine whether early or late season burns are favoured. The interaction between people and fire is however complex (Scott *et al.,* 2016) because different factors limit fire behaviour in different places and times, and for different reasons (Syphard *et al.,* 2017). Disparate cultural values, ecological management interests, and political incentives involving the use of fire multiply this complexity (see Chapter 3). Thus, agreeing on ecological and socially desired outcomes amongst different stakeholder groups including indigenous communities, fire managers, policy-makers, and fire scientists remains a challenge.

An understanding of the complex interactions between people and fire regimes is important in the context of climate change and ecological conservation (Bowman *et al.,* 2011; Scott *et al*., 2016; Connell *et al.,* 2017; Syphard *et al.,* 2017). People's choice of when to start fire occurs at the local scale, however decisions are influenced by the stochastic dynamics of fire regimes at different spatial and temporal scales (Moritz *et al.,* 2009), rainfall patterns, and the availability of biomass to burn. Human lit fires pre-empt lightning ignitions in most parts of the globe and are generally shifted to earlier in the dry season than lightning ignitions that typically occur at the onset of the rainy season (Scholes *et al.,* 2011; Le Page *et al.,* 2010; Bond & Parr, 2010). Thus, with human induced ignitions and associated land management practices, the current fire season in African savannas spans throughout the dry season (Stott, 2000). For illustration, the period of burning extends over 8 months of the year in Bwabwata National Park (BNP) in north-east

Namibia (Figure 4-1), where this study is located. Figure 4-1 shows the inverse relationship between rainfall and the months of burning covering the early dry season (April – July), and the late dry season (August – November) where the resident communities in the park (Khwe and Mbukushu), and park management frequently use fire.

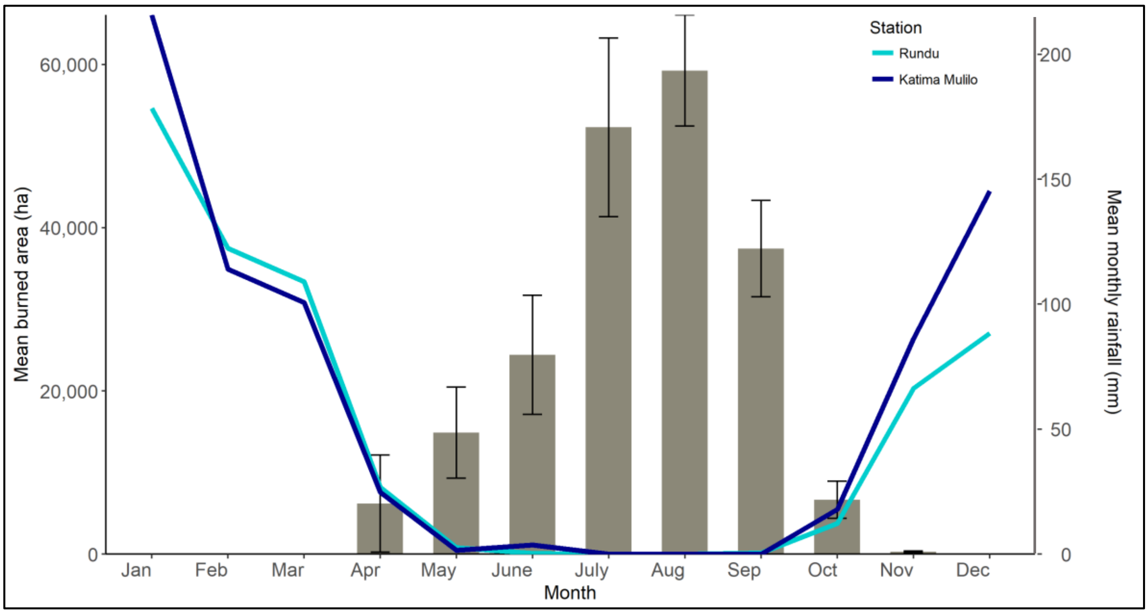


Figure 4-1: Change in average area burned from April to November in relation to mean rainfall (mm) (Namibia's meteorological data) in Bwabwata National Park, 2000 – 2015. Bars represent SE. Date derived from the MODIS MCD45A1 fire product.

Remotely sensed spatio-temporal data that reveals changes in burnt area extent and seasonality is essential in understanding fire dynamics, especially when combined with other data sets that contain climate and land-use parameters. Over the last two decades, satellites that detect fires on the earth's surface, such as the Moderate Resolution Imaging Spectrometer (MODIS) fire product data have been used to explore the spatial and temporal patterns of biomass burning on the continent (Barbosa *et al.,* 1999; Giglio *et al*., 2006; Archibald & Roy, 2009; Archibald *et al*., 2009). The main characteristics of fire regimes which include the extent of recent burn scars, fire return periods, seasonal patterns of ignition frequencies (i.e. timing and the number of fires), and the individual size of fires, together with fire intensity (i.e. energy released) can now be determined for any point on the earth (Archibald *et al.*, 2010; Murphy *et al.*, 2013). Moreover, the interactions between climate and fire characteristics can be investigated, for example with rainfall data, since it determines biomass growth; and annual rainfall has been found to explain up to 70 % of the variance in burnt area between years (Archibald, 2010). Though fires are mostly human ignited, precipitation governs when and where fires can occur (Archibald *et al.,* 2009; Andela & van der Werf, 2014).

Yet, climate does not appear to be a major determinant of fire activity on all landscapes (Keeley & Syphard, 2016). Recently, the traditional model of rainfall and burned area as a direct function of antecedent rainfall has been reconceptualised based on an understanding of human activities and land use. The human-climate-fire regime relationship is frequently investigated by using population density, land cover and/or land use tenure as variables, together with rainfall data to understand the interacting effects of humans and climate on burned area (Archibald *et al.,* 2010; Le Page *et al.* 2010; Bistinas *et al.,* 2013). These studies have focused on global (Le Page *et al.,* 2010; Bistinas *et al.,* 2013), national (Laris, 2002; Gandiwa & Kativu, 2009; Tarimo *et al.,* 2010; Magadazire, 2013), and regional coverage (Archibald *et al.,* 2010; Devineau *et al.,* 2010; Pricope & Binford, 2012; Ruffault & Mouillot, 2017), with few studies assessing the human fire dynamics at the local scale (Laris, 2011). These studies show that in areas without people, climate (rainfall) and ensuing biomass drives burned area, whereas in areas that include people, the climate, biomass and burned area relationship is dampened due to seasonal burning patterns, and reduction of fuel load across the landscape.

Rainfall-burned area interactions are not straightforward, especially in areas with high interannual rainfall variability. The El Niño Southern-Oscillation (ENSO) has been shown to play a role in influencing the patterns of burned area in southern Africa (Andela & Van der Werf, 2014; N'Datchoh *et al.,* 2012; Scholes *et al.,*2011). ENSO is the most wide-scale inter-annual natural climate variation in existence, and represents large rainfall pulses of long duration alternated with drier intervals (Holmgren *et al.,* 2006). These events have considerable impact on vegetation growth in several African regions (Dai & Wigley, 2000; Anyamba *et al.,* 2003; de Viron *et al.,* 2013; Andela & Van der Werf, 2014), and thus fire dynamics. The effect of ENSO is most profound in the rainfall months (December through to February) with lower ENSO values (La Niña) causing increasing precipitation in southern Africa. Andela & Van der Werf (2014) showed that in southern Africa the transition from El Niño (dry events) to La Niña (wet events) substantially contributed to an upward trend in burned area from 2001 to 2012.

Most global models assume strong links between fire and climate, however this appears to be less accurate in African savannas where human impacts on fire regimes are substantial and act to limit the responsiveness of fires to climatic events (Archibald *et al.,* 2010; Laris *et al.,* 2015) (Figure 4-2). Previous studies in southern Africa in strictly protected areas have revealed that grassy systems are responsive to rainfall, and the subsequent available biomass equates to greater burned area extent (Balfour & Howison, 2001; van Wilgen *et al.,* 2004; Mulqueeny, 2005; Gandiwa & Kativu, 2009). However, Archibald *et al.* (2010) revealed in a sub-continental analysis, which included areas inside and outside of protected areas in southern Africa, how human activities (e.g. agriculture, grazing livestock, and road networks) play a significant role in understanding the effect of fuel connectivity in influencing the spread of fire, affecting fuel continuity across landscapes. Archibald's *et al.* (2010) seminal work challenged the assumptions of the climate-fire relationship, and significantly showed that where there are more people, fuel connectivity is lower and consequently less area is burned, despite a greater number of ignitions, which tended to burn smaller to medium sized fires.

Research using remotely sensed imagery clearly finds that areas with the lowest inter-annual variability in burned area globally, are the savannas of Western and southern Africa (Giglio *et al.,* 2010; Archibald, *et al.,* 2010b; Le Page *et al.*, 2010). People tend to burn early in the dry season for a variety of land use reasons (e.g. for livelihood benefits such as hunting, sourcing veld-foods, and to increase productivity of livestock grazing areas), when the grass it still moist, which creates a patchy mosaic of burns. Under these conditions the relationship between fire and rainfall is less apparent because of the reduced probability of large fires since the fuel continuity has been fragmented (Archibald, 2010). An increase in the frequency of human derived smaller earlier fires has therefore been shown to reduce inter-annual variability in area burned, and as a result the characteristic burned area-antecedent rainfall relationship is less apparent. Thus, the fire regimes of the mesic savannas appear to be partially decoupled from the effects of climate (Laris *et al.*, 2015) where early season fires are common. However, if people are excluded from a savanna landscape and/or where fire management is focused on suppression, then the climate and burned area relationship represents the availability to burn (i.e. fire season [e.g. fuel moisture is low or high] and recent weather (Bradstock, 2010). Thus, without early season ignitions, large fires would prevail in a continuous grass layer at the end of the dry season. Figure 4-2, illustrates the interactions between climate, biomass and people in southern Africa. Therefore, in fire-prone savannas, people, by manipulating the number of ignitions, alter biomass connectivity (i.e. fuel load) in the early or late dry season, which influences fire size, and indirectly the area burned and variability in burned area. Moreover, Figure 4-2 shows that the choice of fire management policy (e.g. early burning or fire suppression policy) as an institutional mechanism can indirectly influence biomass amount, burned area and associated variability. An understanding of the interaction between climate and human ignitions on burned area would contribute to the implementation of effective (early burning policies) versus ineffective polices that suppress fire, which are reputed to result in large detrimental late season fires in southern Africa. Thus, because fire seasonality can have a large impact on savanna structure and function, understanding and controlling savanna fires with the appropriate policy is a priority for managers of these systems (Archibald *et al.*, 2017).

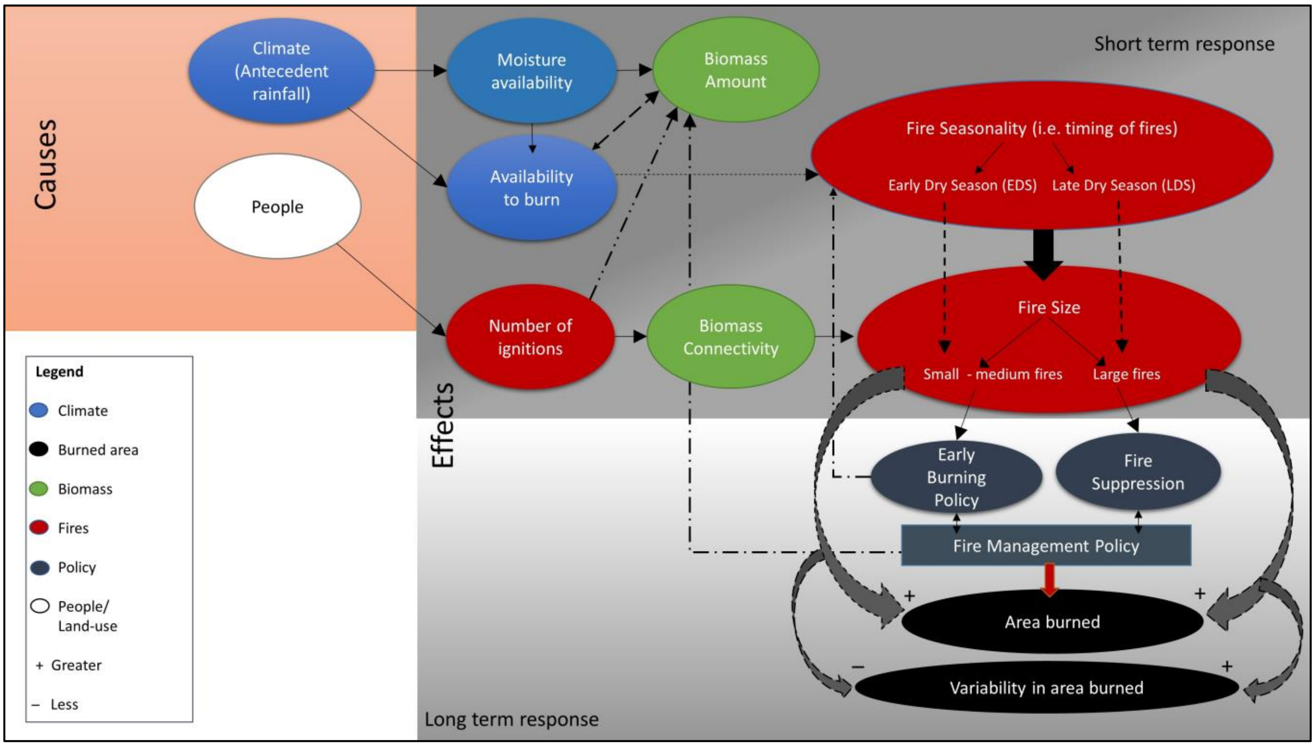


Figure 4-2: Pathways of the climate-fire regime and human dynamics in southern Africa, showing the interaction between climatic and anthropogenic influences.

In north-eastern Namibia, Bwabwata National Park (BNP) provides a unique opportunity in southern Africa to compare fire regimes in inhabited and uninhabited areas, thereby helping to elucidate the role of people on fire regimes. In BNP, inhabiting indigenous communities intensively use fire in a multiple use area (MUA) (e.g. MUA East and MUA West), and fire management is applied in two cordoned 'core conservation areas', that are uninhabited (Kwando and Western core areas [CA]) and are used for wildlife protection and tourism activities. BNP management is viewed as a cornerstone accomplishment in Namibia, as both humans and wildlife are now co-existing , offering benefits to both conservation and rural communities (Ministry of Environment and Tourism [MET], 2010). The Khwe and Mbukushu people reside in the MUA (East and West) of the park, an area which is flanked by the CAs in the west and the east, and thus presents an ideal setting to analyse fire regime characteristics, and test human-fire regime dynamics at the local scale (Figure 2-12). From 1888 up until the year 2006, officially fire was suppressed in BNP, and thus the last decade (2006 – 2015) offers an opportunity to compare potential fire regime changes from a suppression era to one where early burning management fires has been the policy.

While regional modelling of fire regimes in southern Africa has taken place (Thonicke *et al.*, 2010; Archibald *et al.*, 2010), there have been few local-scale analyses in semi-arid savannas of the seasonal burning patterns and inter-annual distribution of fire occurrences. Pricope & Binford (2012) included BNP in their regional study, and assessed fire frequencies and burned area (2000 - 2010), however they did not differentiate between early and late dry season burning during the policy transition from fire suppression to early burning. Furthermore, the probability of large infrequent fire events has been the focus of much fire research (Williams & Bradstock, 2009), with very few studies on the importance of small fires and their potential effects in savanna-woodlands in southern Africa.

The aim of this chapter is to investigate the effect of rainfall, seasonality, land-use type and fire management policy in driving variation in the fire regime during 2000 – 2015 in BNP. My main objectives are to i) investigate how fire occurrence (i.e. burned area, and seasonality of the number of fires, and fire size) vary in space and time across the BNP, and ii) to specifically determine the influence of a change in fire management policy on seasonality and fire spread in BNP. Spatially, I consider land-use areas as i) core areas (Kwando CA and the Western CA) managed by BNP park management, and ii) multiple use area (MUA East and MUA West) where communities inhabit the park, and where multiple stakeholders are involved in various land use activities. The temporal scale of interest is the whole period of 16 years, and the two fire management policy phases: 2000 to 2005, and 2006 – 2015, which includes the suppression and early burning phases respectively. For the purposes of this chapter, the different phases of policy are referred to as the suppression policy (SP: 2000 - 2005) and early burning policy (EBP: 2006 - 2015), and the fire seasons as the early dry season (EDS: April - July), and late dry season (LDS: August - November). The following hypotheses and questions were used to address the aforementioned objectives in this chapter.

Rainfall and burned area relationship

Since land use activities associated with the use of fire can decouple the rainfall and burned area relationship, I hypothesise that in areas inhabited by people in BNP, and where fire management is effective in the CAs, that the rainfall- burned area relationship would be less apparent. However, if trends in area burned are similar across different land use areas over whole period, then the underlying variability is likely to be driven by climatic factors in the park. Question 1: Is there evidence of a relationship between rainfall and burned area across the BNP landscape, and in the individual land use areas? The product used to test this hypothesis was MODIS MCD45A1 (2000 – 2015) at a 500 m spatial resolution and mean antecedent rainfall (18 months) (see Archibald *et al.* (2010) for justification of this metric).

The influence of policy on seasonality, and the spread of fires in BNP

The change in fire management policy from fire suppression (2000 – 2005) to early season burns in 2006 would have led to many small fires, rather than a few large ones because many small fires would fragment the fuel load, and prevent the spread of large runaway fires. Under these circumstances one would expect a reduction in inter-annual variability during the EBP (2006 – 2015). Question 2: Is there evidence of a reduction in inter-annual variability in burned area, associated with an increase in early dry season fires following the policy change? To test this, I used the MCD45A1 fire product and individual fire size data (Hempson *et al.*, 2017) to establish trends in inter-annual variation in burned area, seasonal burning patterns (EDS and LDS), the number of ignitions and associated fire sizes occurring across the entire BNP landscape, and in the four land use areas (i.e. MUA East, MUA West, Kwando CA, and Western CA).

Methodology

Data analysis and methods

In this study, burned area was explored with reference to rainfall, the number of fires and fire sizes in the early (EDS) and late seasons (LDS), in the two policy periods (SP [2000 -2005] and EBP [2006 – 2015]) across the BNP landscape as a whole, and in the individual land use areas. The dependent fire regime variables were burned area and timing of fire (i.e. fire seasonality), and the independent variables were rainfall, season (EDS and LDS), number of fires, fire size, land use and the two policy periods. Fires exhibit a strong seasonal cycle driven by fuel moisture and ignition sources throughout the year (Le Page *et al.*, 2010). Thus, in this chapter, I investigated patterns of seasonality, which I related to climatic, land use and policy factors. To analyse the interaction between the independent and dependent variables I used pairwise test comparisons. Thus, it was not my intention to model all the variables simultaneously, but rather to investigate the simple linear relationships. Further, planned comparisons (*a priori*) were used to reduce multiple testing and to increase the power against the familywise error (Type II error) (Kuehne, 1993). Where the data displayed normality I used parametric tests, and for non-normal data, non-parametric tests. The data was analysed as inter-annual time series (2000 – 2015), and in a summarised form for the entire BNP, and for the four land use areas. Data was organised, and illustrated at first for the BNP as whole, and secondly, at a detailed fine scale for the four land use areas for the two research questions (i) rainfall-burned area relationship, and ii) the influence of policy on seasonality, and the spread of fires. A combination of remotely sensed MODIS fire products, spatial and climatological data were used in this analysis. The spatial data was analysed in the Geographic Information Systems (GIS) software ESRI ArcGIS v 10.2, and all statistical analyses were carried out in R version 3.4.0. (R Core Team, http://www.R-project.org). The GIS shapefiles available from the (http://www.the-eis.com) were used to reclassify the land use areas for this study.

Data sources

Burned area fire product

Data obtained from Earth Observing Systems (EOS) satellites at overpass are constrained by algorithms that map the spatial extent of areas affected by fires (Roy *et al*., 2005). Deposits of ash, charcoal, and the removal of vegetation and alteration of vegetation structure on the surface of the earth are used to characterise burned areas. The MODIS algorithm detects these spectral, temporal and structural changes, and accounts for burned areas (Roy *et al*., 2005). For this study, the dependent variable of interest, burned area was derived from the MODIS fire product (MCD45A1) that represents a 500 m resolution and approximate date of burning to a precision of 8 days (Roy *et al*., 2008). The data was downloaded in Georeferenced Tagged Image File Format (GeoTIFF) format from Window 13 containing the data for southern Africa from the University of Maryland available at (http://modis-fire.umd.edu/). The GeoTIFF was derived from the standard Hierarchical Digital Format (HDF) fire product version, and was selected for ease of processing, as the files do not include any overlap between consecutive months (Boschetti, *et al*., 2015). Temporal filtering is described by Roy *et al.* (2008). MODIS fire products are however subject to satellite overpass time, obscuration through clouds, smoke and in some cases upper canopy, and more over smaller fires may not be detected in Africa (Roy *et al.*, 2005). Nonetheless, an accuracy assessment study carried out in southern Africa showed that MODIS can detect approximately 85% of the true burned area (Roy *et al.*, 2005; Boschetti & Roy, 2008). The burned area product maps the spatial extent of recent fires and is available as monthly summary products. The monthly gridded data was available from April 2000 to December 2015. Due to the prolonged sensor outage in June 2001, May and July 2001, datasets have been affected, and thus not all burned area data is representative for these periods because they were excluded.

Rainfall

The total annual and mean monthly precipitation (mm) from 2000 to 2015 for two stations located in the north-east of Namibia were obtained namely from Rundu in the west, and Katima Mulilo in the east from the Namibia Meteorological station in Windhoek (http://www.meteona.com). The multivariate ENSO index (MEI) is based on the calculation of six variables over the tropical Pacific Ocean (Wolter & Timlin, 1993), which include seal level pressure, zonal and meridional components of the surface wind, sea surface temperatures (SST), surface air temperature, and total cloudiness fraction of the sky (Hanley *et al.*, 2003). The MEI data was obtained from the National Oceanic and Atmospheric Administration (NOAA) government agency (https://www.esrl.noaa.gov/psd/enso/data.html) for the purposes of identifying El Niña and La Niña events to compare to the local rainfall patterns in BNP.

Fire size and ignition frequency

Since the burned area data provide information on the spatial extent of burning, it can be used to identify individual fires (Archibald *et al.*, 2010). Data for my study area was obtained from Hempson *et al.* (2017) in which a flood fill algorithm was used to identify individual fires derived from the MODIS burnt area (MODB45) product (Archibald & Roy, 2009). This data was used to count the number of fires (ignition frequency) and fire size distributions. The data entailed a list of points with the fire size (with a resolution of 0.25 km² [a 500 m MODIS pixel]), location of the centroid, start date, mid-date and end date of each fire in BNP.

Data analysis

Burned area

The MODIS MCD45A1 fire product was used to map, and calculate the spatial extent of annual and monthly burned area. The GeoTIFFs were reprojected from the Plate Caree projection into a Universal Transverse Mercator (UTM) WGS84, 34 South, and were processed in ArcGIS v10.2 according to methods in the MODIS Collection 5.1 Burned Area Product manual (Boschetti *et al.*, 2015). The monthly re-projected burned area subset GEOTIFF was delineated to BNP for GIS visualization and the GIS was used to eliminate the missing, cloud or no data values, and reclassify each layer according to the Julian date of burning into monthly layers. Pixels in the dataset are flagged as 'no data' when there is insufficient input data available to run the algorithm due to excessive cloud or sensor problems (Archibald *et al.*, 2010). Burned area was summarised by calendar year (April to November), as there was no fire activity detected by MODIS from January to March, and in December. Burned area is always recorded as the proportion of the total landscape (Archibald, 2010), thus the total annual area burnt was divided by the total area of each land use zone (hectares [ha]), and the percentage of area burnt for each year and /or season was reported for ease of comparison (Archibald *et al.*, 2010).

Rainfall

It has shown that the mean accumulated rainfall of the past 18 months starting in June of the year of burning can be used as an applicable index for southern Africa for estimating inter-annual variability in burned area in relation to rainfall (Archibald, 2010). Further, Archibald (2010) recommended this index be used to compare fire management approaches in different savanna systems and to test theories of the effect of climate on the fire regime. Thus for each fire year, rainfall was summed from June of the previous year and divided by 1. 5 to give the preceding 1. 5 years (i.e. 18 months) of accumulated rainfall. Rainfall from the Katima Mulilo station situated in the east was used to regress rainfall and percentage area burned for the MUA East and the Kwando CA, and data from the Rundu station in the west for the MUA West and the Western CA land use areas. Further, the Coefficient of Variation [CV: standard deviation/mean value]) of monthly rainfall for each year was calculated for the east and the west of the park to assess the dispersion of rainfall values from the mean. Further, the average MEI, representative of El Niño and El Niña phases were illustrated for the purposes of comparing these events to the local rainfall patterns in BNP during 2000 to 2015.

Because land use activities are known to be an important driver of burnt area (Archibald *et al.,* 2010), the four land use areas were used to test the burned area and antecedent rainfall relationship. I used a calendar year of area burnt (April to November), which was calculated in ha. To test whether the slopes and amount of variance of the rainfall-burnt area relationship were the same across the four land use areas (Question 1) I used Pearson Correlation tests with antecedent rainfall (1.5 years) as a single predictor, and the percentage of annual area burned (dependent variable) for each land use type. The distribution of the burned area and rainfall data was confirmed as normal using Shapiro-Wilks test (Shapiro *et al.*, 1968).

Inter-annual variability in burned area, number of fires and fire size

Inter-annual variability is a measurement commonly used in fire regime analyses to determine the extent and cause of variations in fire patterns over a period (Archibald *et al.,* 2010; N'Datchoh *et al.*, 2012). The inter-annual variability of fires mapped throughout the fire season was determined by plotting the number of fires and the area burned in each year between 2000 and 2015. The total number of fires and burned area, standard deviation and CV were calculated for each fire season across the 16 years. To assess the trends in inter-annual variation for the entire BNP, and four land use areas, I interpreted the time series data for the full 16 years using annual burned area, number of fires, and associated fire size data. Further, an interpretation of the seasonal fire history (burned area, number of ignitions and fire size), constituting inter-annual time series data of the EDS and LDS is presented. To determine if the change in policy in 2006 influenced inter-annual variability in burned area, I assessed the number of fires that occurred in the EDS and LDS, and I compared the CV for both seasonal burned area and ignition number between the land use areas (Question 2). Since these two variables are measured in different units, the CV, defined as the ratio between the standard deviation and the mean of a variable, was calculated for each season for each year to allow for the comparison in the levels of variability in number of fires and burned area. To test if there was a difference in variability in burned area between land use areas I used the 'Asymptotic test for the equality of Coefficients of Variation from k populations' (Feltz & Miller, 1996) with the use of the R package '*cvequality*'.

Further, I plotted the monthly distribution of the number of fires in BNP in relation to rainfall variability during 2000 to 2015. The CV of the annual average of monthly rainfall from 2000 to 2015 was used to identify wet and dry periods in BNP which occurred above (i.e. wet) and below (i.e. dry) the standard deviation of the mean (i.e. > 100 %) (Figure 4-4; C). Four rainfall phases were identified and included: i) above average (wet); ii) average; iii) above average (very wet); and iv) variable (dry and wet) phases (Brockett *et al.*, 2001).

The individual fire size data were used to calculate the mean fire affected area per annum and by month for the entire BNP, and the four land use areas (ha). The fire size data were binned into size classes according to Hantson *et al.* (2015), and included (≥ 25 – 100 ha; ≥ 1000 ha; ≥ 10 000 ha; and ≥ 100 000 ha). Since, large fires are known to contribute disproportionately to the total area burned, the percentage area burned by each size class was also calculated per pixel (Archibald & Roy, 2009). Further, the area burned per fire size class for fires in the EDS and LDS was calculated for the entire BNP and for each of the land use areas for the 16 years.

Spearman rank correlations (r_s) were used to examine the monotonic relationships between percentage area burned, and the number of fires to determine whether they were correlated to year in the EDS and LDS over the 16 years. Non-parametric Wilcoxon-Mann-Whitney U tests (Siegel, 1956) were used to test for differences in the annual percentage of burned area in BNP, and between the land use areas, and to detect differences in the distribution in the proportion of burned area between the EDS and LDS, and between the SP and EBP policy phases.

Results

Rainfall and burned area relationship

In southern African, the rainfall of the preceding 1. 5 years, and seasonality (the amount of time during which fuels are flammable) have been shown to be the most important predictors of the spatial and temporal distribution of burned area (Archibald, 2010; Archibald *et al.*, 2009). The area burnt during 2000 to 2015 for the entire BNP was not correlated with antecedent rainfall ($R^2 = 0.012$, d.f = 14, $p > 0.05$) (Figure C1; Appendix C). The interpreted association between burned area and antecedent mean rainfall of the previous 1. 5 years in the four land use areas is represented in Figure 4-3 and in Figures C2 & C3 (Appendix C) respectively. A correlation between the spatial extent of burning that burnt in one year and the rainfall of previous 1. 5 years was only evident in the Western CA (R^2 =0.40, d.f = 14, p = 0.009) (Figure 4-3; a). This relationship is evident in Figure C3 (Appendix C), where in the west of the BNP there was an apparent increase in rainfall over time that was evidently correlated to the percentage area burned. In contrast, in the east where people are residing in villages (MUA East), the rainfall versus burned area relationship was absent (Figure 4-3; c). Furthermore, the area burned-antecedent rainfall relationship in the Kwando CA showed a negative non-significant correlation. Thus, irrespective of above average antecedent rainfall in the east and representative of a La Niña event (wet phase) during the years 2008 and 2010 (Figure 4-4; B and C), the percentage burned area decreased (Figure C2; Appendix C). In particular, the CV of monthly rainfall of the east and west of the park revealed high variability from 2000 to 2005, and in 2008 to 2009, and in the year 2013 in BNP when the standard deviation exceeded the mean (i.e. > 100 %) (Figure 4-4; C). The mean annual rainfall for BNP ranges between 550 mm in the east, to 500 mm in the west (Mendelsohn *et al.,* 2007), however in 2008, antecedent rainfall showed an average of 840 mm, in 2009 (1051 mm) and in 2010 (926 mm) revealing that the average rainfall was twofold over this wet period. Furthermore, the 2007 – 2008 and 2010 to 2011 with the above average rainfall periods (Figure 4-4; B) were evidently correlated to the average MEI and specifically to the wet La Niña phases over this time (Figure 4-4; D).

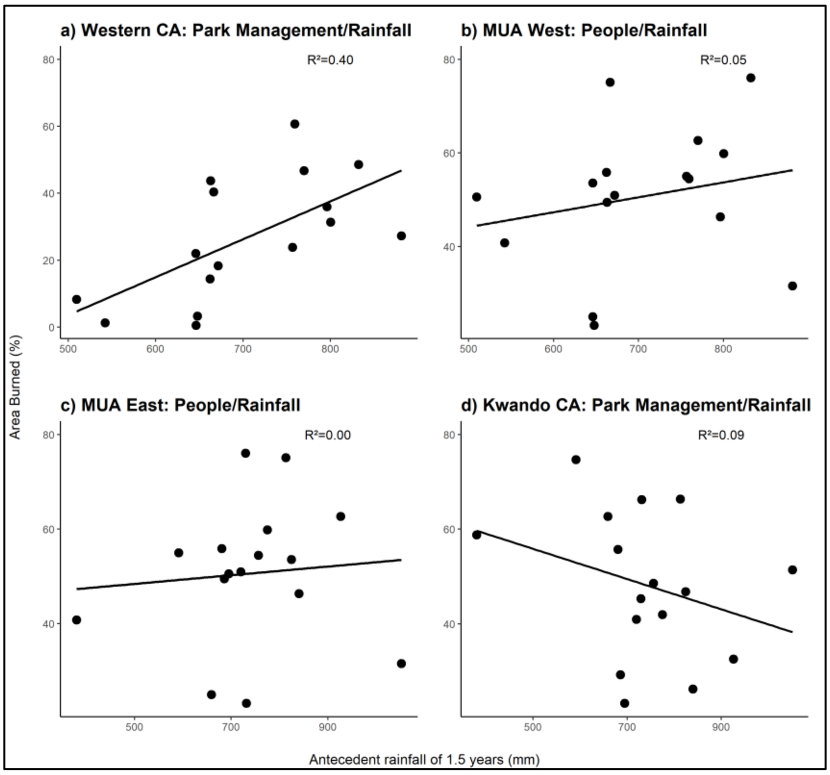


Figure 4-3: Scatterplots showing the relationship between mean annual antecedent rainfall (1. 5 years) and percentage area burned in the four land use areas in Bwabwata National Park (2000 – 2015); a) Western CA; b) MUA West; c) MUA East, and d) Kwando CA.

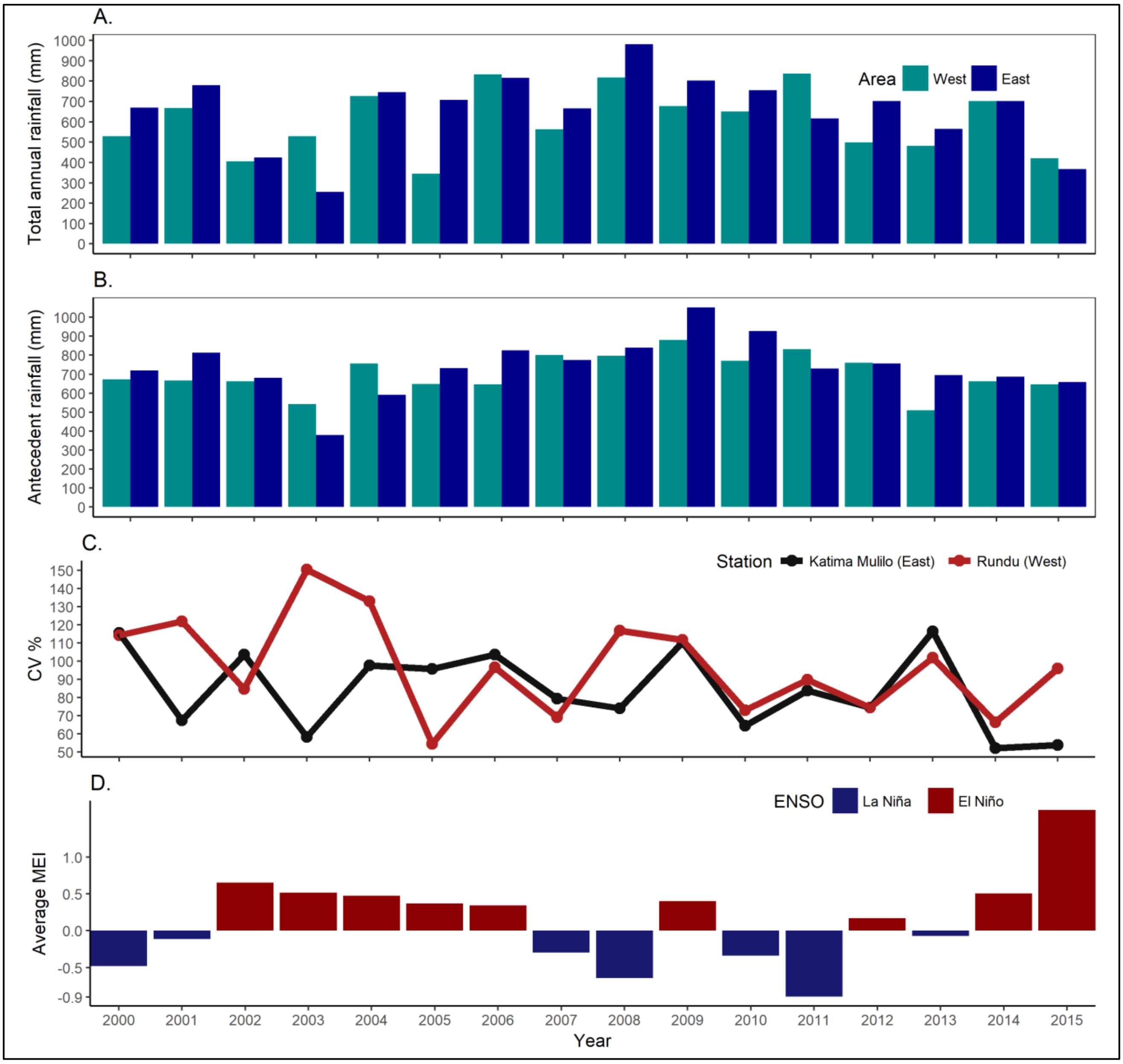


Figure 4-4: A) Total annual rainfall (mm) for the east (Katima Mulilo) and the west (Rundu) for the previous two years. Data source: Namibia metrological station, Windhoek; B) Antecedent mean annual rainfall (mm) for the east (Katima Mulilo) and the west (Rundu) for the previous 1.5 years. C) Percentage of Coefficient of Variance (CV) of monthly rainfall during 2000 to 2015 for Rundu (west) and Katima Mulilo (east) in BNP. The inter-annual variation in rainfall presented greater deviation from the mean in the west (Rundu; CV = 0.97), than in Katima Mulilo (CV = 0.85) in the east. D) The average MEI correlates to annual precipitation and standardised departures, with positive estimates indicative of the prevailing drought conditions (red) associated with dry events (El Niño), while negative departures are indicative of wet events (La Niña) (blue). The above graph shows the years oscillating between dry and wet events of interest for this study, which encompass the years 2000-2015. MEI time series (Data source: NOAA: https://www.esrl.noaa.gov/psd/enso/mei/).

The influence of policy on seasonality, and the spread of fires in BNP

Inter-annual patterns in burned area and the number of individual fires in Bwabwata National Park

The patterning of burning in BNP, as derived from MODIS imagery for the years 2000 – 2015 is given in Figure 4-5. During the 16 years the inter-annual area burned varied between 15 % and 59 %. Fires burned on average 36 % (i.e. more than a third of the park burns each year) of BNP over the study period, and an equivalent of approximately 225 335 ha per year (median = 215 587 ha ; range = 95 950 ha – 370 625 ha). Thus, every three years, the entire park has been burned. Years representative of above average percentage area burned with the largest extent were 2001, 2004 and 2011 and 2012, while 2005, 2009 and 2015 were representative of years in the park least affected by fire.

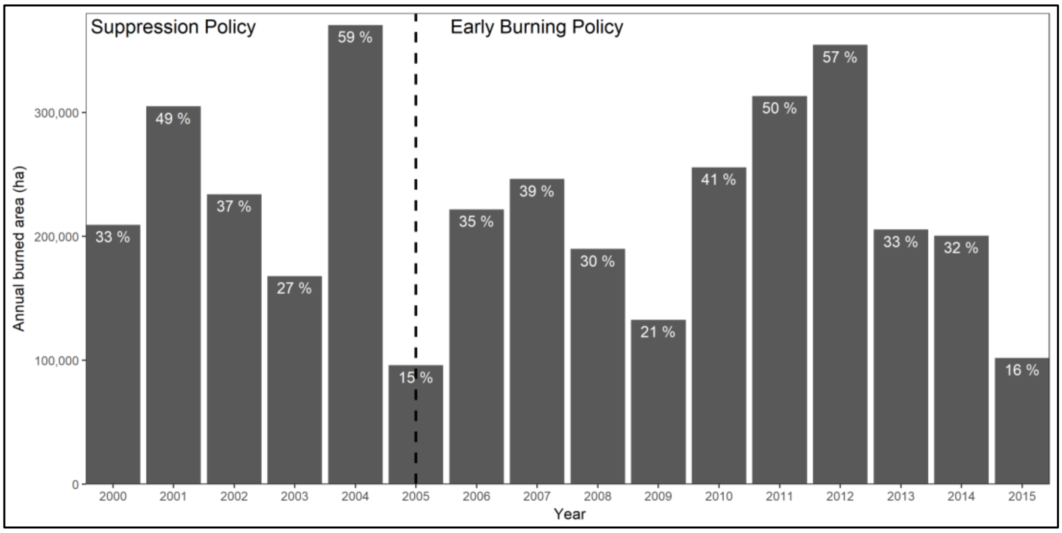


Figure 4-5: Inter-annual variation in the total annual area burned (ha) in Bwabwata National Park from 2000 to 2015 based on the MODIS (MCD45A1) fire product data. Percentage burned of the total area is indicated in each bar. The dashed vertical line indicates the division in years between the suppression and early burning policy.

The interpreted seasonal fire history of BNP for the years 2000 – 2015 is given in Figure 4-6. An above average increase in EDS burning was evident between the years 2010 and 2014 across the park. Over the entire study period 28. 73 % burnt in the EDS, and 71. 26 % in the LDS, and the proportion of burned area in the EDS was significantly different from the LDS during the 16 years (Table 4-3). While the burned area in the EDS was different, and less prevalent than LDS burning during the SP, the burned area extent in the EDS was similar to the LDS following the policy change to early burning in BNP (Table 4-3; Figure 4-6). Consequently, there was a monotonically significant positive relationship with year during the EDS (r_s = 0.622), and subsequent negative monotonic relationship with year during the LDS (r_s = - 0.544) correlated

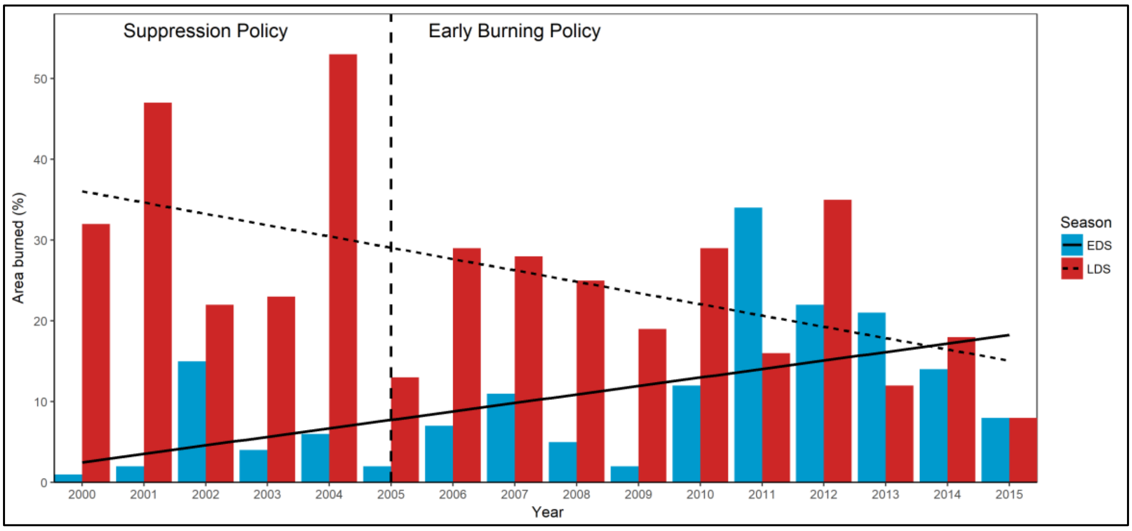


Figure 4-6: Percentage of the area burned in the early dry season (EDS), and late dry season (LDS) in Bwabwata National Park, 2000 – 2015. The dashed vertical line indicates the division in years between the suppression and early burning policy periods.

The inter-annual fire affected area (ha) by individual fires across BNP for the years 2000 – 2015, is given in Figure 4-7. The largest mean, median and maximum fire size values were in years 2002, 2004 and 2011, all of which occurred in the EDS, bar, in 2011 when the mean LDS fire size marginally exceeded the mean EDS (Figure C5; Appendix C). The inter-annual pattern of the area affected by individual fires in the BNP landscape was remarkably similar to the area burned area (Figure 4-5), and revealed that the area affected by fire in the years 2002, 2004, 2007 and between 2010 and 2012 to be above 200 000 ha per annum (> 30 %). The year 2011 was significant because a number of individual fires (n = 209) burnt over half the park (56 %) in a single year. The fire affected areas ranged from a minimum of 450 (ha) in 2000, to a maximum of 351 375 (ha) in 2011 (Table 4-1). The years least affected by individual fires were 2000, 2006, and 2015. The mean fire affected area per annum was 164 890 ha (average of 26 %), with 31 % of the area affected during the SP and 69 % in the EBP.

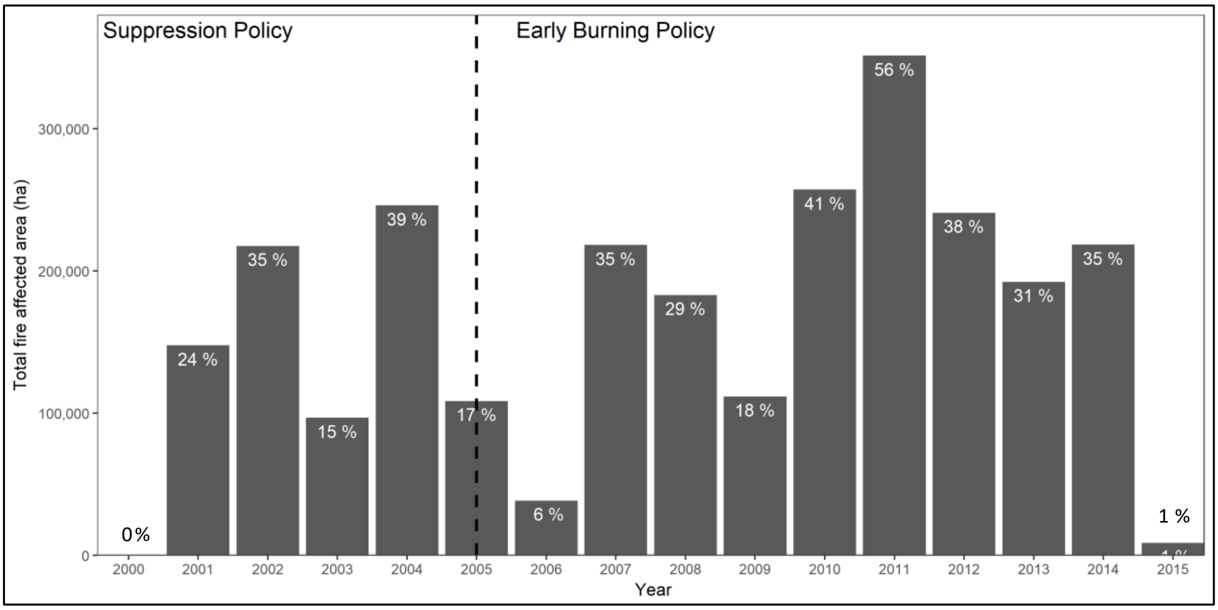


Figure 4-7: Inter-annual variation in the total area affected (ha) by individual fires in Bwabwata National Park from 2000 to 2015. Percentage burned of the total area is indicated in each bar. The dashed vertical line indicates the division in years between the suppression and early burning policy periods.

A total of 2793 individual fires were recorded of which 50.62 % were LDS fires, and 49.37 % were EDS fires in the BNP over the 16 years (Figure 4-8; Table 4-1). An average of 175 fires were mapped per annum for the entire park. There were a greater number of LDS fires during 2000 to 2005, and ignitions in both seasons were almost equivalent from 2006 to 2009, whereas EDS ignitions exceeded the LDS fires during 2010 to 2014 (Figure 4-8). In total, 1162 EDS fires were mapped in the EBP (42 %), and 217 (8 %) in the SP, whereas 889 (32 %) were LDS fires in the EBP, and 525 (19 %) in the SP. Notably, a twofold increase in mean fire size was observed in the years 2002, 2004, 2007 and 2011 to 2013, relative to other years in BNP (Table 4-1). In the years 2002 and 2011, the maximum fire size in the EDS exceeded the LDS fire size by 90 %, and 66 % respectively, and in 2004, 2007, and 2013 the maximum EDS fire sizes were comparable to the LDS sizes. Remarkably, the largest maximum fire size, which occurred in BNP during the full study period, took place in the EDS in 2011. Overall, the number of EDS were monotonically positively significant ($r_s = 0.570$) and showed an increase with year, whereas there was no change in the number of LDS fires over the entire period in BNP (Figure 4-8).

Table 4-1: Summary statistics of the annual total and mean fire affected area (ha) distribution and the number of fires, including seasonal proportions (EDS and LDS), and fire sizes in Bwabwata National Park for the period 2000 – 2015.

Year	Number of fires	Numbe r of fires (EDS)	Number of fires (LDS)	Total fire affected area (ha)	Total fire affected area (ha):EDS	Total fire affected area (ha): LDS	Mean fire size (ha)	Maximum fire size (ha): EDS	Maximum fire size (ha): LDS	Percentage of total area burned (%)
2000	3	0	3	450	0	450	150.00	N/A	225	0.07
2001	157	25	132	147700	21975	125725	940.76	8375	26575	23.54
2002	119	56	63	217550	172625	44925	1828.15	78975*	8450	34.67
2003	186	67	119	96750	35750	61000	520.16	3750	18000	15.42
2004	142	34	108	246125	104375	141750	1733.27	32600*	27125	39.22
2005	135	35	100	108550	23325	85225	804.07	3825	15675	17.30
2006	179	88	91	38612	44125	110750	215.71	2600	22950	6.15
2007	207	99	108	218275	86900	131375	1054.47	18350*	25150	34.79
2008	203	83	120	183125	50375	132750	902.09	5275	24950	29.18
2009	126	55	71	111850	15600	96250	887.70	1325	28850	17.83
2010	271	159	112	257200	89350	167850	949.08	6550	57250	40.99
2011	209	147	62	351375	232425	118950	1681.22	77075*	39400	56.00
2012	289	178	111	240875	152925	87950	1661.21	12800	10025	38.39
2013	302	193	109	192400	140150	52250	1269.97	8525*	6050	30.66
2014	244	139	105	218500	106950	111550	895.49	17775	25575	34.82
2015	21	21	N/A	8900	8900	N/A	809.09	1750	N/A	1.42

Note:* Indicates years in which maximum fire sizes in the EDS were comparable to the LDS fires, and/or where they exceeded the LDS maximum fire size. N/A indicates no fires were recorded.

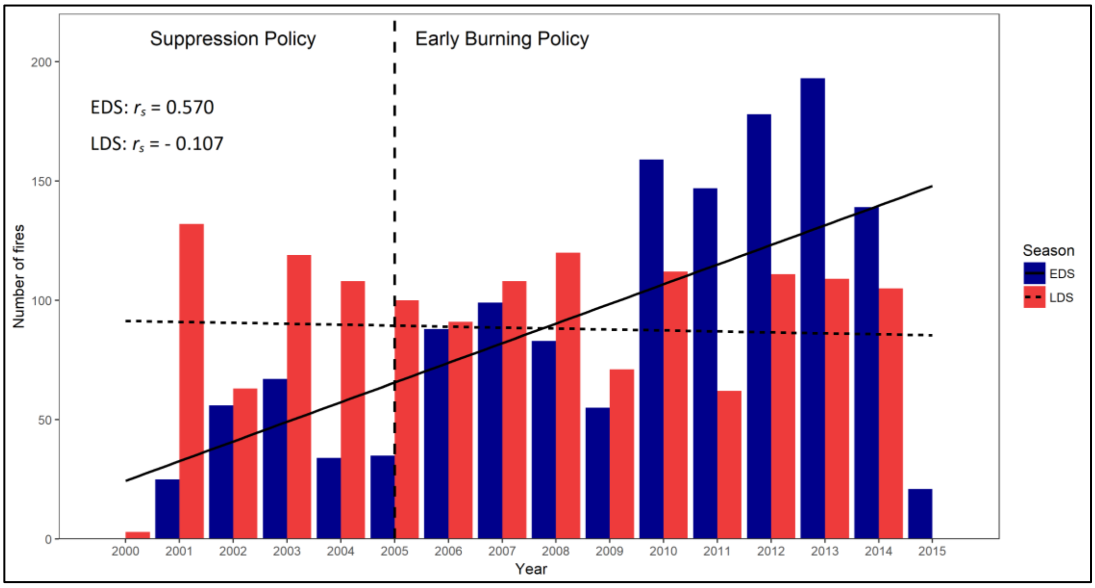


Figure 4-8.Inter-annual variation in the number of the early (EDS) and late dry season (LDS) fires in Bwabwata National Park (2000 – 2015). The dashed vertical line indicates the division in years between the suppression and early burning policy periods.

The seasonal distribution of fires between 2000 and 2015 indicates that for average and above average (e.g. 2008 – 2009) rainfall years, the distributions peaked in August, however ignitions were evident from April onwards (Figure 4-9). During wet years (2000 and 2002), and the dry years of 2003 to 2005, ignitions peaked mostly in August (n = 191), and early season fires were fewer. In 2010 to 2012 (average rainfall [very wet]) experienced the highest number of ignitions in June (n= 219), which exceeded the number of LDS ignitions for all years. Thus, during the SP, EDS fires were less prevalent, and in average and above average rainfall years they increased during the EBP phase in the park in BNP as a whole.

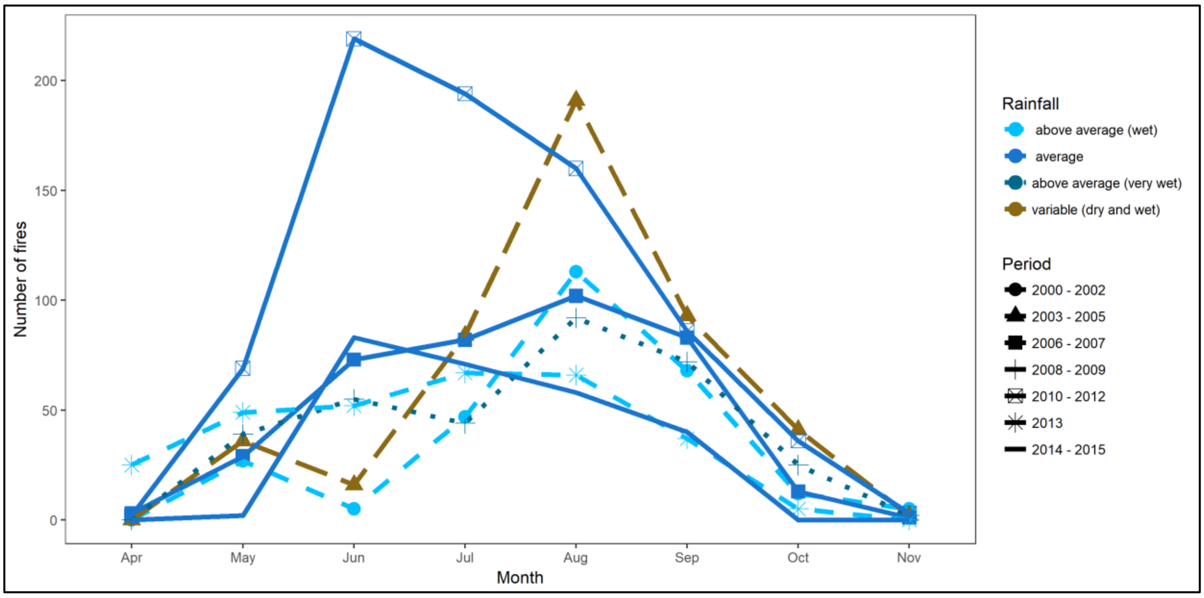


Figure 4-9. Monthly distribution of the number of fires in Bwabwata National park in relation to rainfall variability during 2000 to 2015. The CV of annual average rainfall from 2000 to 2015 was used to identify wet and dry periods in BNP which occurred above (i.e. wet) and below (i.e. dry) the standard deviation of the mean (Figure 4-4; C).

Notably, there was no difference in mean fire affected area (i.e. mean fire size) between EDS fires in July (19 %), and LDS fires in August (16 %) and September (17 %) in BNP (Figure 4-10), and mean fire sizes in July exceeded fires occurring in the LDS. Further, no significant differences were detected in the number of the fires, nor in the percentage of total area burnt (%) between the EDS and the LDS ($U = 55$; $p > 0.05$) per size class in BNP over the 16 years (Table 4-1 (above); Figure C6 a) and b); Appendix C). However, overall there were a greater number of smaller fires (EDS fires = 428; LDS fires = 527; 34 %) of ≥ 100 ha and ≥ 1000 ha (EDS fires = 696; LDS fires = 601; 46 %), than fires greater than 10 000 ha (18 %), and 100 000 ha (1. 32 %) (Figure C7 a) and b); Appendix C). Remarkably, fire sizes in both the EDS and LDS, ≥ 10 000 ha and ≥ 100 000 ha in extent contributed to 79 % to the proportion of area burnt, whereas the fire sizes between 25 and 100 ha and ≥ 1000 ha in extent contributed only 21 % to area burnt in BNP. Fire extent in the larger fire size's (≥ 10 000 ha and ≥100 000 ha) burnt a greater proportion of the area in the LDS, when compared to the EDS, however the difference was not significant. Generally, fires in the LDS burn larger areas (Yates *et al.*, 2008), however in the BNP the EDS fires (Number of fires ≥ 100 000 ha = 15; 14.26 %; mean = 26 191 ha) burnt almost as large an area as the LDS fires (Number of fires ≥ 100 000 ha = 22; 17.15 %; mean = 21 470 ha). Over the 16 years, the number of smaller fires between 25 and 100 ha and ≥ 1000 ha increased from 2006 to 2014 (the EBP period), however per annum, the proportion of area burned (%) was highest for fire patches ≥ 10 000 ha (mean = 87 197 ha), and ≥ 100 000 ha (mean = 66 556 ha) for BNP (Figure C7 a; b); Appendix C).

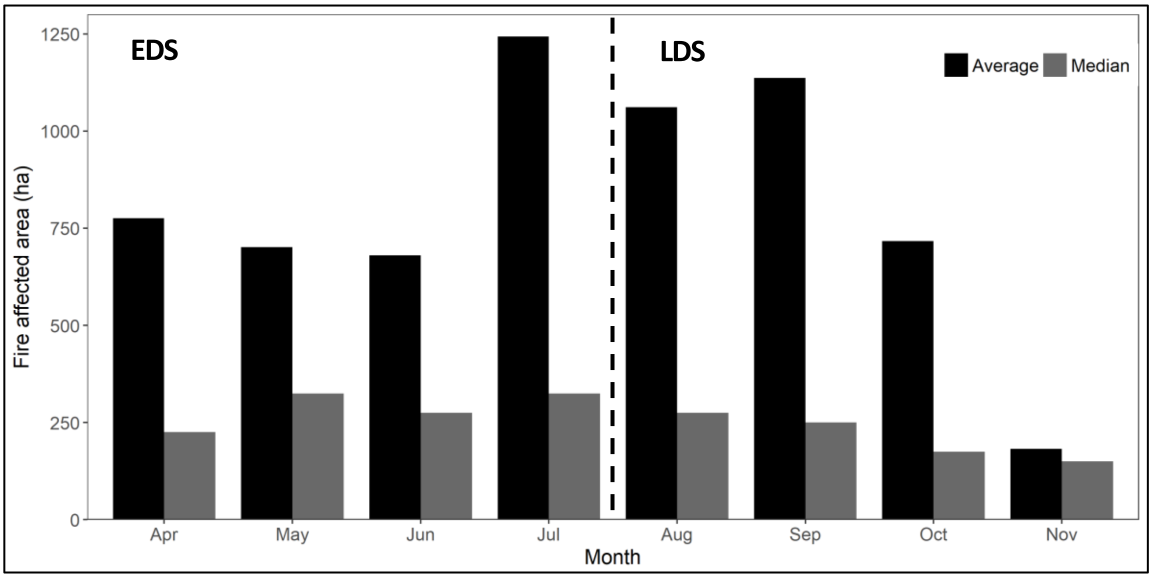


Figure 4-10. Mean and median fire affected area (ha) for Bwabwata National Park (BNP), 2000 – 2015. The dashed vertical line indicates the division between early dry season (EDS) and later dry season (LDS) months.

Inter-annual variability in area burned and in the number of fires in the land use areas

The inter-annual burned area in each of the land use areas was highly variable over the 16-year period (Figure 4-11). On average the Kwando CA (52.38 %) and the MUA East (36. 22 %) experienced the greatest extent of burned area, and the MUA West (31. 30 %) and the Western CA (27. 89 %) the lowest between 2000 and 2015. Unequivocally, burned area was predominant in the east of the park during the SP, whereas the western areas showed less burned area during these years. Furthermore, burned area during the suppression period revealed larger inter-annual variability, whereas from instigation of the EBP, variability declined within all land use areas in BNP. A comparison of CV over the 16 years showed greater deviance from the mean in burned area during the SP and less deviation during the EBP for all land use areas bar the Western CA in BNP (Figure 4-12; Table 4-2). Following the transition to EBP, the variability in the eastern land use areas declined, whereas there was little change in the west (Table 4-2). The year 2003 showed a high CV specifically in the Kwando CA, and in the MUA West, whereas in the year 2011 it was the highest in the MUA East in comparison to all other years. However, an asymptotic test for the equality of CVs showed that there was no significant difference in the variability in burned area between the four land use areas (t statistic = 5.57; $p > 0.05$). Nonetheless, due to the overall decline in variation in burned area post the policy change, I anticipated an increase in EDS fires, smaller sized fires, and an increase EDS burning, where people inhabited the landscape in the MUA East and MUA West, and where early burning had been applied in the CAs. Thus, I assessed the number of fires and the distribution of fire sizes across land use areas in the EDS and LDS to explore whether these variables explained the change in variation post 2006.

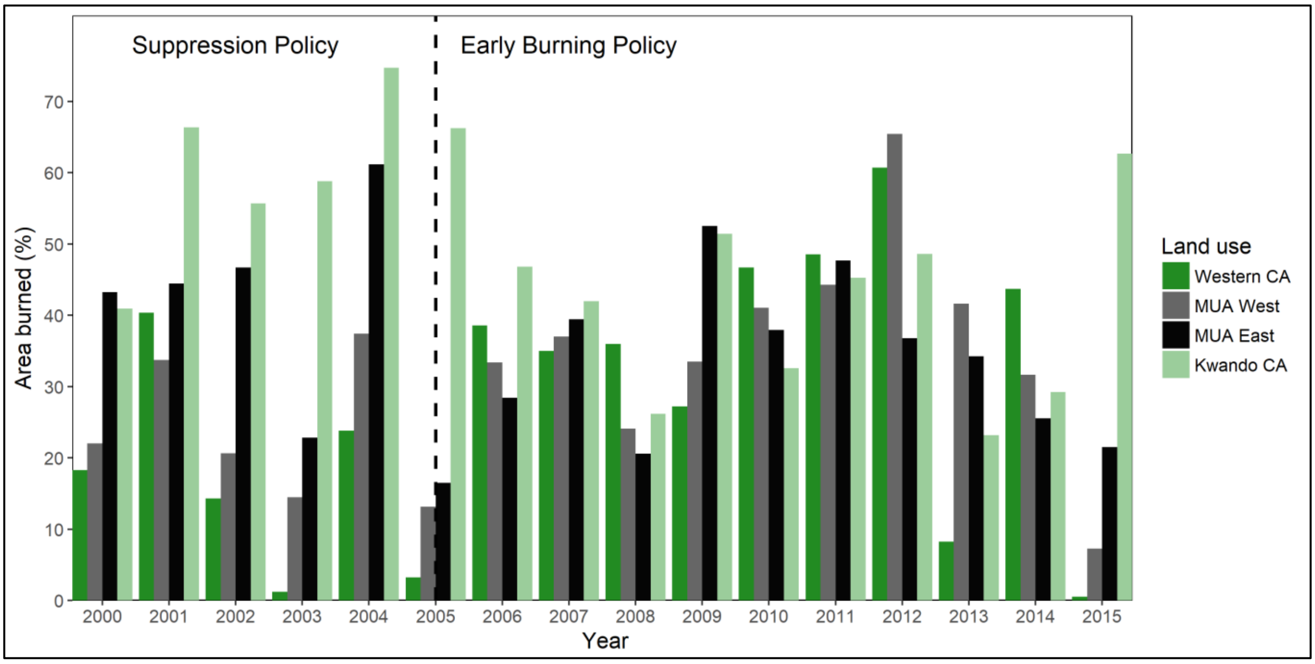


Figure 4-11: Frequency distribution in the percentage of area burned in the land use areas in Bwabwata National Park, 2000 – 2015. Data derived from MCD45A1 fire product. The dashed vertical line indicates the division in years between the suppression and early burning policy periods.

Table 4-2: Comparison of the mean percentage of the Coefficient of Variation (CV) of burned area between the suppression policy (SP: 2000 - 2006) and the early burning policy (EBP: 2006 - 2015) for the four land use areas in Bwabwata national park.

Land use	SP	EBP
Western CA	91,51	115,87
MUA West	129,81	112,61
MUA East	118,12	98,41
Kwando CA	160,67	97,69

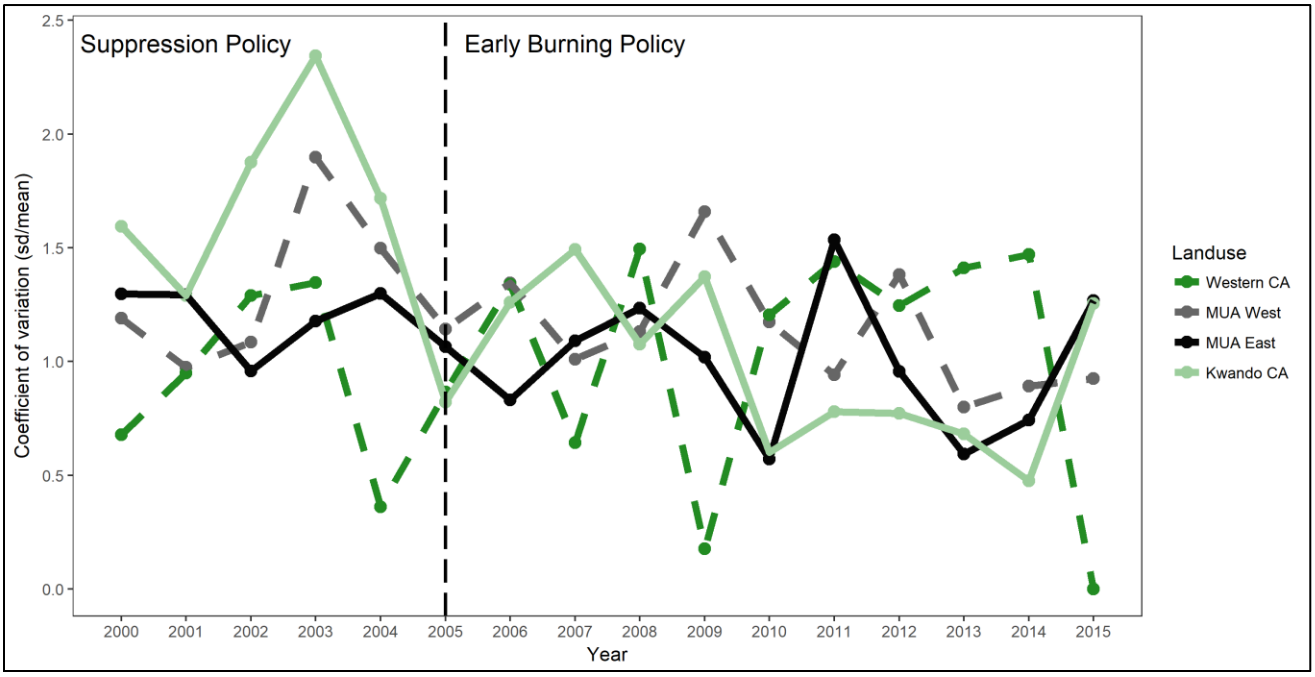


Figure 4-12: Inter-annual variability in burned area showing the Coefficient of Variation (CV) over 16 years for the respective land use areas in Bwabwata National Park. The dashed vertical line indicates the division in years between the suppression and early burning policy.

A comparison between the east and the west land use areas revealed opposite seasonally burned area extents throughout the 16 years (Figure 4-13). The extent of burning increased significantly in the Western CA and MUA West post 2006, however the majority of burning took place in the LDS (Figure 4-13; Figure 4-14; Table 4-3). MUA East and the Kwando CA showed a similar seasonal pattern of burning in the LDS in the SP period (2000 – 2005), however with an increase in EDS burned area particularly between 2010 and 2015. Similarly, the MUA West showed an increase in EDS burning over this time. EDS burning was evidently more consistent in the MUA East, and was not significantly different between the two policy periods (Table 4-3). Yet, EDS and LDS were significantly different between the MUA East and Kwando for both policy periods. Unpaired Wilcoxon-Mann-Whitney U Tests revealed that were significant differences in median percentage burned areas between the MUA East and MUA West, and between Kwando, the Western CAs, as well as the MUA West (Table 4-3) between policy periods. EDS burning was more prominent in the MUA East, Kwando and MUA West, than in the Western CA, whereas LDS burning was imminent in the Western CA. Largely, burning in the MUA East and the Kwando CA showed similar seasonal burning trends, and the MUA West and the Western CA were similar.

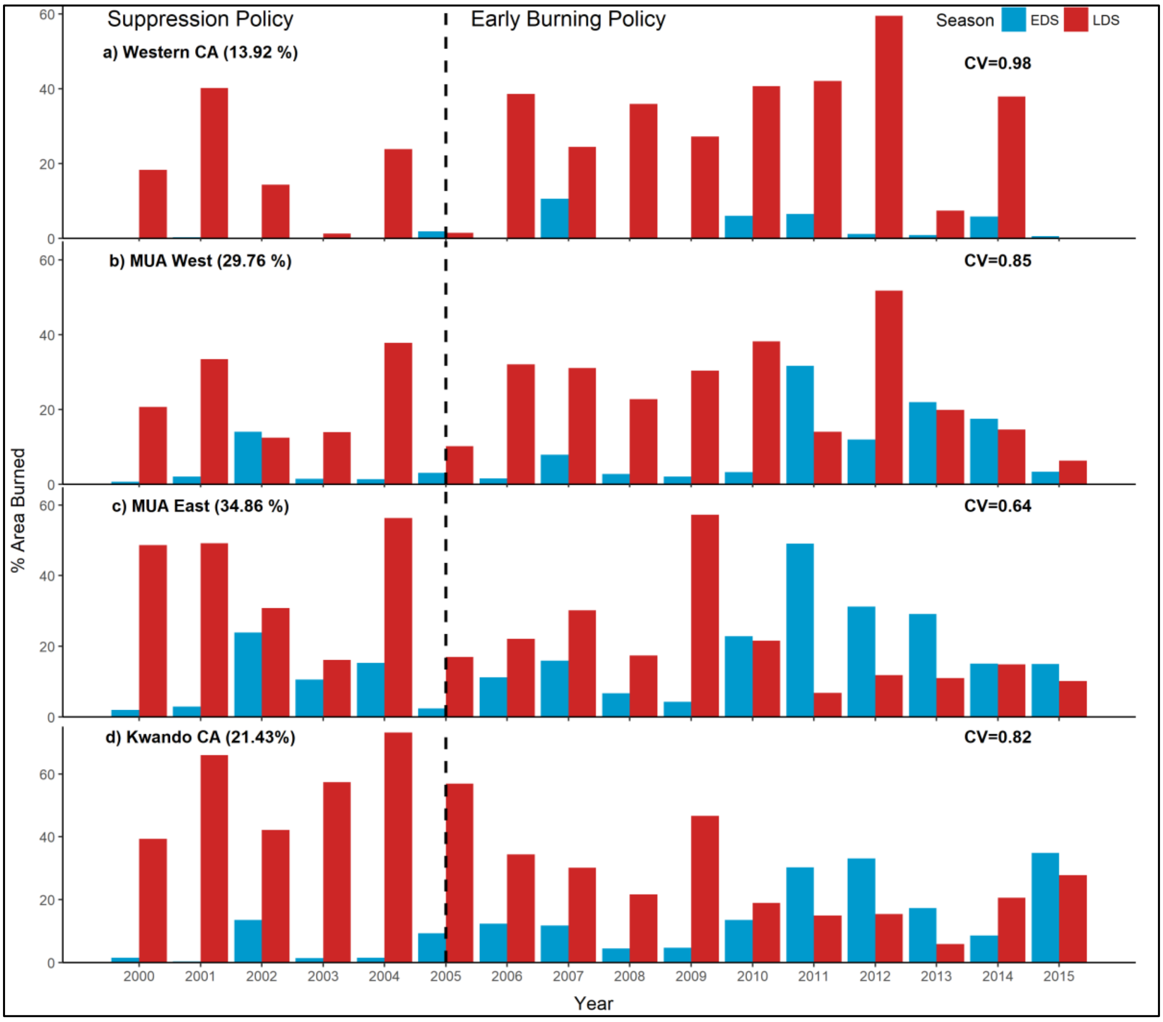


Figure 4-13: Frequency distribution of percentage burned areas in the early (EDS) and late dry (LDS) seasons in the land use areas in Bwabwata National Park (2000 – 2015). The percentage of area covered and the average Coefficient of Variation (CV) is presented for each land use area. The dashed vertical line indicates the division in years between the suppression and early burning policy.

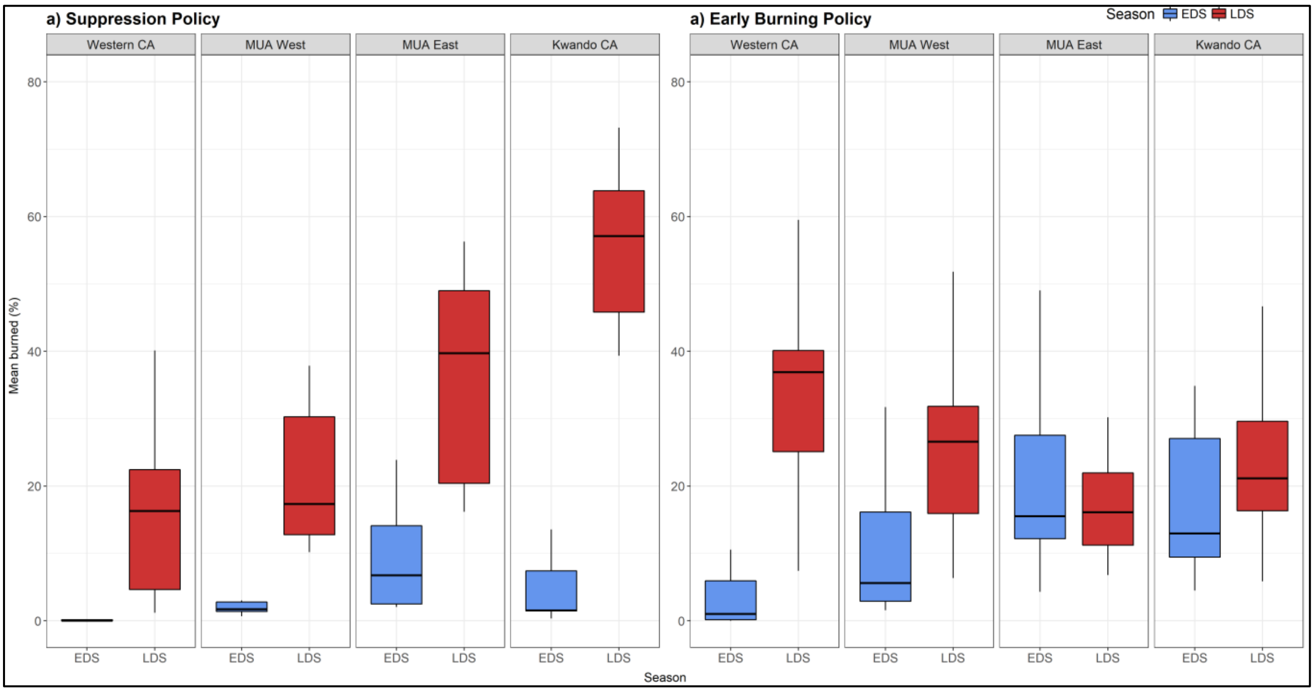


Figure 4-14: Box and whisker plots of median percentage burned area in the land use areas in the early dry season (EDS) and late dry season (LDS) in the a) Suppression Policy (SP: 2000 - 2005), and b) Early Burning Policy (EBP: 2006 - 2015) in Bwabwata National Park.

Table 4-3: Comparison of (two sample unpaired Wilcoxon Mann Whitney U Tests) of the extent of burning in the early dry season (EDS) and late dry season (LDS) between the suppression (SP) and early burning policies (EBP) for Bwabwata National Park, and land use areas. For each comparison, median 1 and 2, and IQR 1 and IQR 2(Interquartile range) refer to the respective proportion of burned area for each policy period (SP and EBP).

Area	Season	Policy/years	*U*	*p*	Median 1	Median 2	IQR 1	IQR 2
BNP	EDS vs LDS	2000 - 2015	34	0.0001*	0.08	0.24	0.10	0.12
	EDS	SP vs. EBP	11	0.0420*	0.03	0.12	0.04	0.12
	LDS	SP vs. EBP	41	0.2635	0.27	0.22	0.21	0.12
Kwando CA	EDS vs LDS	2000 - 2015	790	0.0889	0.03	0.05	0.08	0.17
	EDS	SP vs. EBP	70	0.0077*	0.01	0.05	0.01	0.08
	LDS	SP vs. EBP	319	0.7907	0.04	0.06	0.27	0.10
Western CA	EDS vs LDS	2000 - 2015	116	0.0003*	0.01	0.06	0.05	0.13
	EDS	SP vs. EBP	14	0.9405	0.01	0.01	0.01	0.05
	LDS	SP vs. EBP	93	0.0400*	0.05	0.07	0.08	0.22
MUA EAST	EDS vs LDS	2000 - 2015	71	0.0318*	0.15	0.26	0.17	0.35
	EDS	SP vs. EBP	14	0.0934	0.07	0.16	0.12	0.15
	LDS	SP vs. EBP	71	0.0825	0.43	0.16	0.17	0.17
MUA WEST	EDS vs LDS	2000 - 2015	28	0.0000*	0.02	0.19	0.07	0.16
	EDS	SP vs. EBP	30	0.1813	0.02	0.07	0.04	0.13
	LDS	SP vs. EBP	23	0.4923	0.15	0.22	0.17	0.13
Land use areas								
MUA East vs. Kwando CA	EDS	SP	180	0.0003*	0.15	0.01	0.17	0.01
	EDS	EBP	229	0.0023*	0.16	0.04	0.15	0.09
	LDS	SP	104	0.0018*	0.43	0.04	0.17	0.27
	LDS	EBP	239	0.0017*	0.16	0.06	0.17	0.10
MUA West vs. Kwando CA	EDS	SP	38	0.8820	0.01	0.01	0.02	0.01
	EDS	EBP	130	0.7567	0.04	0.04	0.11	0.09
	LDS	SP	70	0.2686	0.12	0.04	0.20	0.27
	LDS	EBP	267	0.0000*	0.19	0.06	0.12	0.10
MUA East vs. MUA West	EDS	SP	19	0.0184*	0.07	0.01	0.12	0.02
	EDS	EBP	55	0.0019*	0.16	0.04	0.15	0.11

	LDS	SP	27	0.0303*	0.43	0.12	0.17	0.20
	LDS	EBP	48	0.6539	0.16	0.19	0.17	0.12
MUA East vs. Western CA	EDS	SP	32	0.0131*	0.15	0.01	0.17	0.01
	EDS	EBP	145	0.0001*	0.16	0.01	0.15	0.05
	LDS	SP	89	0.0007*	0.43	0.05	0.17	0.08
	LDS	EBP	142	0.1244	0.16	0.07	0.17	0.22
Kwando CA vs. Western CA	EDS	SP	11	0.9272	0.74	1.03	1.09	0.80
	EDS	EBP	317	0.0066*	4.33	0.51	8.63	5.06
	LDS	SP	182	0.4412	3.79	5.01	26.91	8.44
	LDS	EBP	221	0.1032	5.94	7.38	9.89	22.25
MUA West vs. Western CA	EDS	SP	8	0.6429	0.01	0.01	0.02	0.01
	EDS	EBP	122	0.0099*	0.04	0.01	0.11	0.05
	LDS	SP	61	0.0446*	0.12	0.05	0.20	0.08
	LDS	EBP	157	0.1045	0.19	0.07	0.12	0.22

Note:*denotes significance at the 0.05 level.

Seasonal distribution of the number of fires and fire sizes in the land use areas

The seasonal distribution of the number of EDS and LDS fires in the four land use areas is illustrated in Figure 4-15. A higher number of EDS fires were evident in the MUA East and MUA West, and in the Kwando CA, and far fewer in the Western CA. The number of EDS fires substantially increased in the years 2010 to 2014 in the MUA East, and MUA West and in the Kwando CA. The Western CA experienced mostly LDS fires throughout the 16 years, however they were far fewer in number when compared to the other land use areas. The Unpaired Mann-Whitney-Wilcox U tests revealed significant differences in the number of EDS fires between the SP and EBP in the MUA East, the Kwando CA, and the Western CA, and between the land use areas between the east and the west (Table C1; Appendix C). However, the MUA West showed a similar trend in the EDS fires to the eastern land use areas. A comparison of the CV in the number of EDS and LDS fires over the full period revealed that the MUA East showed the least variability, when compared to all other land use areas. This is probably because the MUA East experienced a similar number of EDS and LDS fires per annum, which reduced the variance. I assessed the difference in variability between seasonal inter-annual percentage burned area and the number of fires between land use areas using the CV. An average of the CV revealed that variability was higher for area burned than in the number of fires across all land use areas. This confirms that there is a greater deviance from the mean in area burned, and therefore greater variability in the area affected by fire than in the number of seasonal fires in the land use areas in BNP (Figure 4-13; Figure 4-15).

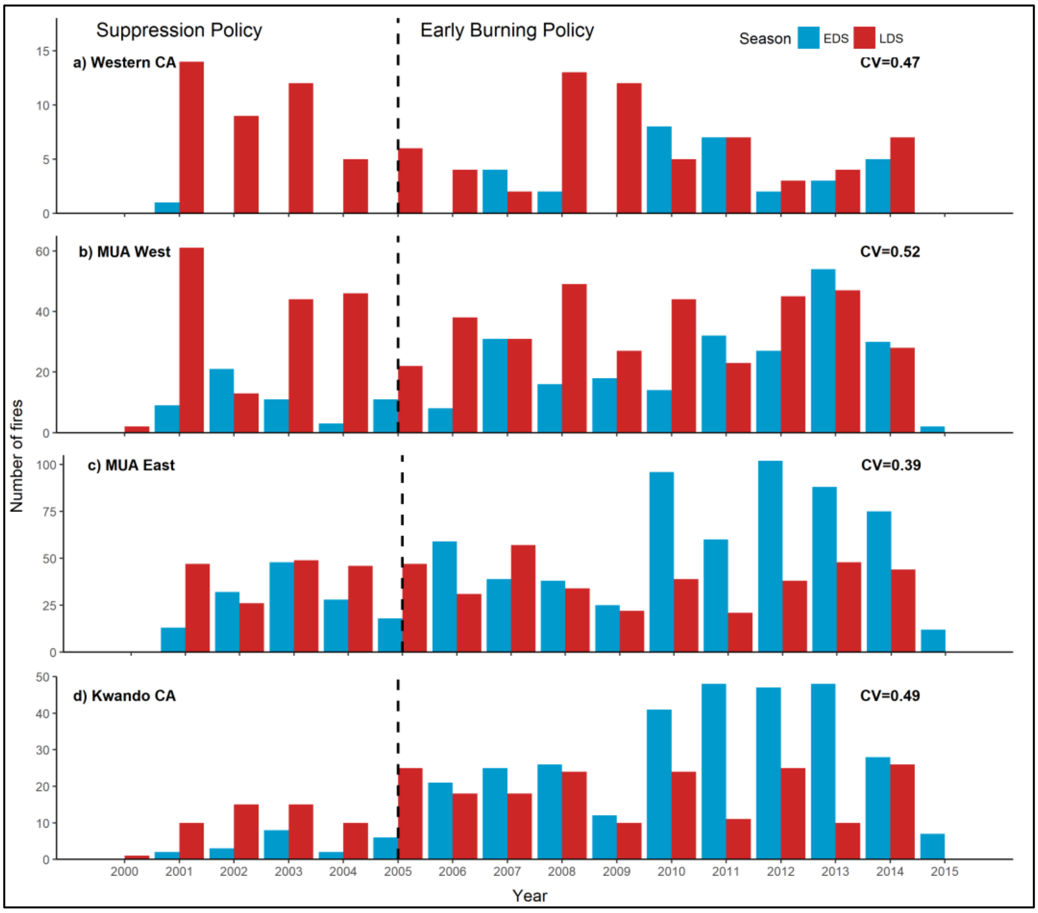


Figure 4-15: Frequency distribution of the number of fires in EDS and LDS in the land use areas, a) Western CA; b) MUA West, c) MUA East and d) Kwando CA in BNP, 2000 – 2015. The average Coefficient of Variation (CV) is presented for each land use area. The dashed vertical line indicates the division in years between the suppression and early burning policy.

Mean fire size in the MUA East peaked in July (1613 ha), and thereafter decreased in average size through to November, whereas mean fire size was highest in the Western CA in the months of August (3037 ha), September (2792 ha) and October (2090 ha) relative to the other land use areas (Figure 4-16). MUA East and the Kwando CA experienced the lowest mean fire sizes, relative to the MUA West and the Western CA in BNP. Notably, Kwando had higher average fire sizes in September (1 500 ha), and in October, relative to the MUA East and MUA West land use areas.

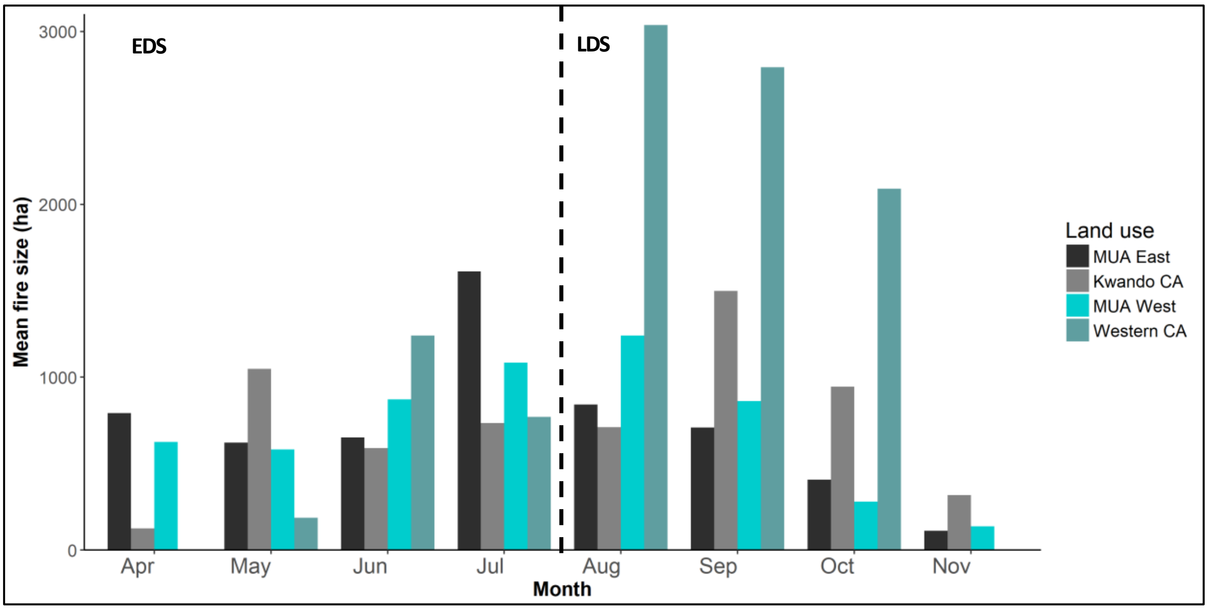


Figure 4-16: Mean fire size per month per land use area in Bwabwata National Park (2000 – 2015). The dashed vertical line indicates the division between early dry season (EDS) and later dry season (LDS) months.

There were substantial differences in the number of EDS and LDS fires, and the percentage of area burned (i.e. fire affected area per size class) evident in the aggregated data (16 years) in the respective land use areas in BNP (Figure C8; Appendix C). The number of EDS fires in the MUA East and Kwando CA outnumbered the LDS fires, and burnt a greater proportion of area, bar in the Kwando CA for fires greater than ≥ 10 000 ha, where the area burnt was larger in the LDS. In the MUA East 10 fires between ≥ 10 000 and ≥ 100 000 ha in the EDS were recorded, however these fires burnt 28 % (mean = 53 887 ha) out of the total proportion of area burnt. The number of EDS fires ≥ 1000 ha were most frequent in the MUA East (n = 362) and in Kwando CA (n = 171). The opposite pattern was observed in the MUA West and Western CA, where the LDS fires exceeded the number of EDS fires, including the proportion of area burnt. The MUA West experienced a greater number of small (≥ 100 ha; n = 209) and ≥ 1 000 ha (n = 199) LDS fires, however a greater proportion of area was burnt when fires occurred between ≥ 10 000 ha (32 %) and ≥ 100 000 ha (21 %) in size. In the Western CA, far less fires in the smaller size classes were evident, however fires in the ≥ 100 000 ha class burnt a greater proportion of area. In total six large LDS fires occurred between ≥ 10 000 ha and ≥ 100 000 ha in the Western CA, of which burnt (59 %) of the total area. A more detailed analysis of the annual percentage of area burned in the EDS and LDS in the fire size classes per land use area is illustrated in Figure 4-17. Interestingly, fire sizes in the EDS in the larger classes (e.g. ≥ 10 000 ha and ≥ 100 000 ha) were evident in all land use areas particularly in the years 2010 to 2014 during the EBP. Furthermore, in the absence of a greater area burnt in the EDS, particularly between the years of 2005 to 2010, LDS fires in various size classes were evident, and a greater percentage of area burnt for all land use areas. Moreover, irrespective of the EDS burning in the Western CA, LDS large fire size classes still burnt a greater area in the years when EDS fires increased.

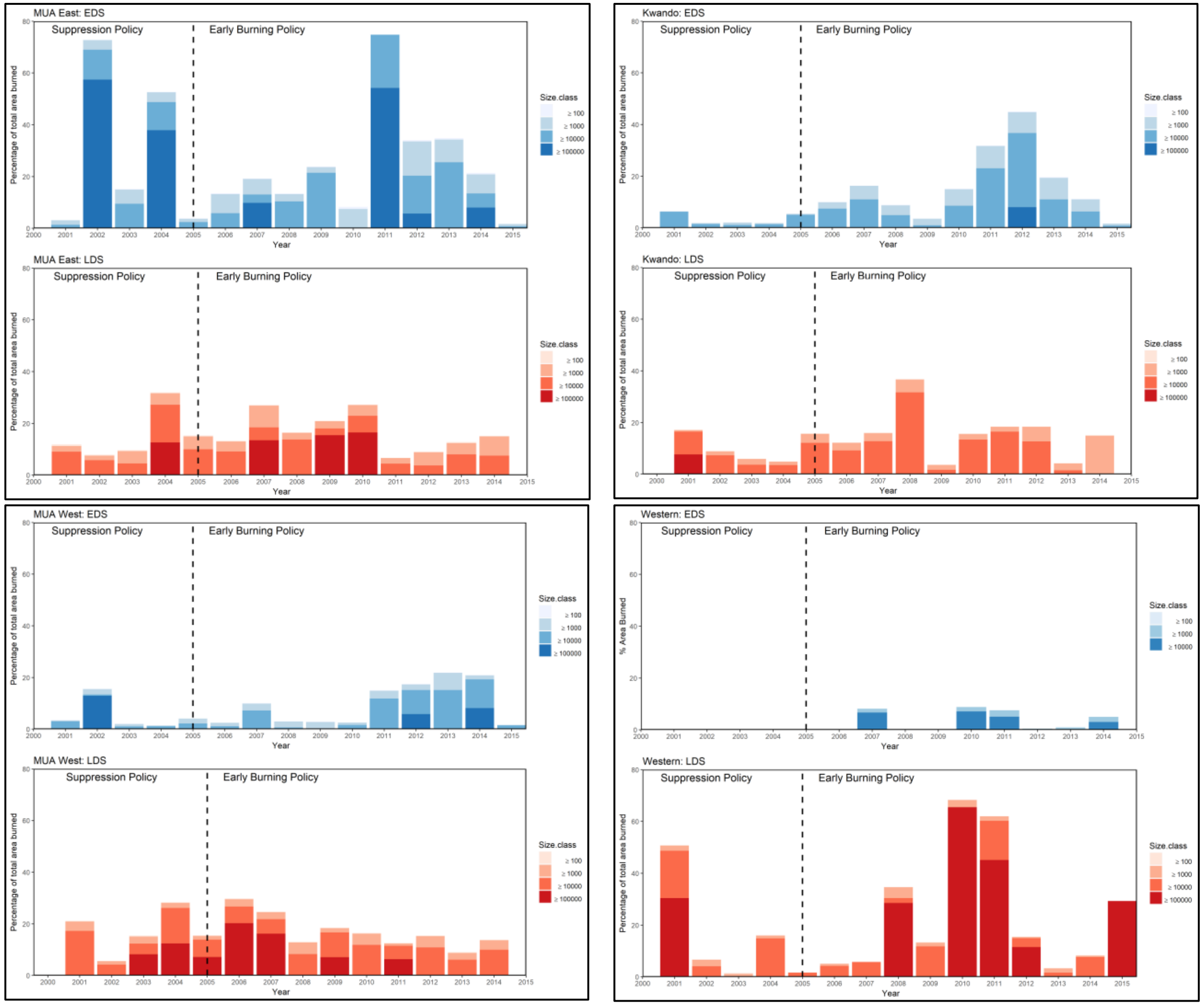


Figure 4-17: Frequency distribution of annual fire size classes in the four land use areas during the early dry season (EDS) AND late dry season (LDS) in Bwabwata National Park, 2000 – 2015.

Discussion

Burned area and rainfall dynamics

Fire frequency in southern Africa follows a productivity gradient, which is determined by a rainfall gradient (Bond, 1997; van Wilgen & Scholes, 1997). Changes in burned area regimes are therefore best analysed in concurrence with climatic data (Carcaillet *et al.*, 2001). However, there is no evidence in any parts of southern Africa that fires are a result of a lightning regime; thus, people are the main cause of fire in the region and must also be considered when analysing fire frequency (Archibald, 2010). Significantly, recent research by Archibald *et al.* (2009, 2010) in southern Africa revealed, how the presence of humans fragments, and alters the fuel load through various land use activities (e.g. road networks, cultivation, agriculture), and decouple fire from the regional climate signal. A key aspect of this chapter was to assess burned area in relation to rainfall variability and seasonality in the different land use areas in two opposing policy periods in BNP. I hypothesised that areas inhabited by people in BNP, and where fire management is effective in the CAs, that the rainfall-burned area relationship would be less evident. However, if trends in area burned were similar across different land use areas over whole period, then the underlying variability is likely to be driven by climatic factors in the park.

Effects at the local-scale of the four land use areas presented in this study reveal a more nuanced relationship between rainfall patterns, and the people inhabited areas, together with park management areas in BNP. At the scale of the entire park, burned area was not responsive to the local rainfall gradient. Similarly, Verlinden & Laamanen (2005) found no relationship between rainfall and burned area, nor a significant decrease in burned area for West Caprivi (i.e. BNP), which was under a policy of fire suppression at the time of writing (1989 – 2001). However, in BNP in the Western CA where fires were infrequent, burned area showed a positive relationship to rainfall, whereas no relationship was evident in the other land use areas (MUA East, MUA West and Kwando CA), albeit where fires were frequent. However, Pricope & Binford (2012) concluded that changes in yearly burned area, and the increasing fire frequencies they detected were attributed to climatic changes and variability, with an increase in dry years and warm ENSO phases in the overall region in which BNP is the nexus. The lack of correlation between rainfall and burned area in BNP in the land use areas where fires were frequent (MUA East, MUA West and Kwando CA) suggests that human use of fire swamped the climate-burned area association. In contrast, in the park management area (Western CA) where fires were infrequent, rainfall was the driver of burned area. Nonetheless, a detailed analysis of inter-annual and seasonal burning trends in area burned, and in the number of fires and fire sizes revealed surprising patterns in years with above and below rainfall periods in BNP.

The influence of policy on seasonality, and the spread of fires in BNP

In 2006, with the transition to an early burning policy, I expected a reduction in inter-annual variability, since the accumulation of many of small fires is known to reduce overall area burned, and variability between years (Archibald *et al.,* 2010). For example, the presence of large fires in the late dry season would be associated with an average rainfall gradient in the absence of people to ignite fires, and rainfall would be a function of burned area, and inter-annual variability would be evident. Conversely, where there are many more fires throughout the year, the fuel load would be reduced, and would eliminate the rainfall signal, and one would expect a reduction in variability between years. In BNP, an average of 36 % burnt annually, with an inter-annual variation of 15 % and 59 %, while only 7 % was unburnt in proximity to the villages, and along the Kwando and Okavango River systems. Verlinden & Laamanen (2005) presented burned area results from 1989 to 2001 for the greater region (eastern Caprivi and Kavango, covering 63 000 km²), and Pricope & Binford (2012) from 2000 to 2010 for the Kavango/Upper Zambezi Transboundary Conservation Area (KAZA-TFCA) encompassing 440 000 km². Both these studies show remarkably similar results to the present study in terms of the fire affected area. Verlinden & Laamanen (2005) showed that 27 % and 51 % burned annually between 1989 and 2001, while only 10 % did not burn, which included settlements and permanent wetlands. Pricope & Binford's (2012) estimates of burned area for 2000 – 2010 for BNP were equivalent to my findings. Even though their studies covered broader spatial scales, BNP falls within the nexus of their respective study regions. Interpretation of their analyses, together with my results has revealed that burned area in BNP has remained fairly consistent for the past 26 years (1989 – 2015).

Unexpectedly, post 2006 (i.e. during the EBP), inter-annual variability in BNP, and in the land use areas was still apparent, however in the MUA East, where ignitions were most frequent, variability was markedly less than the other land use areas with a fewer number of ignitions. Wildland fires are generally characterised by burned area extent, however many more factors describe a fire regime (e.g. intensity, size, number of fires, return interval), and determine the resulting impact of fire on the environment (Archibald *et al.,* 2010; Murphy *et al.,* 2013). Subsequently, it is the number and size of fires in combination which are better indicators of area burned in locations which are populated by people (Archibald *et al.,* 2010). Fire size is a function of seasonality and human preferences, for e.g. large fires typically burn late in the year and are influenced by the climate (e.g. high winds, evaporation rates, and temperatures), and small fires, ignited by people early in the season are limited by fuel moisture after the rainfall season (Figure 4-2). To elucidate the reason for the inter-annual variability following the implementation of the EBP, I assessed the inter-annual seasonal patterns (EDS and LDS) of burned area, the number of fires, and fire sizes together with the variation of rainfall.

In this study, I found that annual burned area, the number of fires and fire sizes in BNP showed a response to both wet (La Niña) and dry (El Niño) periods associated with ENSO variations in southern Africa. Notably, the years 1999 – 2000 in southern Africa were associated with a wet season (Wessels *et al.* (2004), and the years 2004 to 2006 were reportedly dry years in the KAZA-TFCA region (Pricope & Binford, 2012), whereas 2008 to 2009 were associated with an extreme wet event and flooding in the region (Ringrose *et al.*, 2007). Subsequently, an above average percentage area burnt in 2001 (49 %), 2004 (59 %), and 2012 (57 %) reflecting the consumed accumulated fuel load following the high rainfall in the region (Figure 4-4; B). Despite a higher average of antecedent rainfall in the east (Kwando CA and MUA East) between 2009 and 2010 (Figure C2; Appendix C), an overall decrease in burned area was evident, which was attributed to the increase in EDS burning (Figure 4-6). Conversely, in the year 2012, the western land use areas (MUA West and Western CA) both experienced the highest percentage of burned area (Figure C3; Appendix C). Thus, the eastern land use areas showed the opposite to the west, and thus a decline in burned area irrespective of the accumulated rainfall of the previous 1.5 years. Grass fuel regrows very quickly after burning (Archibald *et al.*, 2009), and fire spread in Africa is therefore limited by the amount of fuel, rather than the dryness of the fuel (Scholes *et al.*, 2011). Fires are however limited by the moisture content of the grass sward because of seasonal curing (Govender *et al.*, 2006), and it is for this reason that fires in the EDS tend to be patchy and limited in extent (Andersen, 2003). However, the greatest extent of burned area in the MUA East occurred in the years 2004 and 2009, where two independent fires of 32 600 ha, and 77 076 ha burnt respectively in the early dry season. Interestingly, the maximum fire size in the EDS in 2004 was almost equivalent in size to the maximum LDS fire, and in the year 2011 the EDS fire size exceeded the LDS fire by 90 % in the MUA East in a single season, however the fuel was available due to the exceptionally high rainfall in the region in the preceding years (2008 – 2009). This shows that grass growth, positively related to the previous 18 months rainfall (2009: 948 mm; 2010: 888 mm) was burnt in the year 2011, by the inhabitants, and/or the BNP park wardens. It highlights, that when there is grass available to burn, people will burn it. Typically, it is a single or a few LDS fires which burn a greater area (Yates *et al.*, 2008), due to the high fuel load, and continuity of grass available to burn, however this example in MUA East of these two large EDS fires shows contrary to what would be expected. Furthermore, the greatest number of EDS fires were observed in the years 2010 – 2012 (an average rainfall period), and it is likely the high number of fires that occurred was in response to the above average antecedent rainfall of 2008 and 2009 in BNP (Figure 4-4; B). Moreover, the greatest number of LDS fires were observed during 2003 – 2005 in the late season month of August

(Figure 4-9), during a distinguished dry El Niño phase in the region. Further, the number of EDS fires and area burned also increased substantially after the implementation of the EBP (Figure 4-6; Figure 4-8), and therefore the coincidental ENSO wet phases (La Niña) and the EBP policy influenced the fire regime in BNP. These data suggest that the seasonal burned area and the number of fires were in response to both wet (La Niña) and dry (El Niño) periods associated with ENSO in southern Africa for the entire BNP, and in the land use areas. Similarly, in Australia Bird *et al.* (2016) revealed how ENSO influenced the anthropogenic regime and the area burned by the aboriginal Martu community that was correlated with high antecedent rainfall, and an increase in the number of fires.

The extent of the EDS burning (Figure 4-6 & Figure 4-13), and the high number of EDS fires and specifically in the ≥ 25 – 100 ha, ≥ 1000 ha and ≥ 10 000 ha fire size classes, and the respective proportion of area burned (%) in the eastern land use areas resulted in the elimination of the rainfall-burned relationship. However, periods of above rainfall periods (La Niña wet periods), and the below rainfall (El Niño dry phase of 2002 - 2005) influenced the seasonal occurrence of fires and fire sizes (Figure 4-4 D; Figure 4-9; Figure 4-17). Thus, even though the rainfall was above average in 2009 to 2010, the subsequent biomass was reduced by the extensive EDS burning that occurred from 2011 to 2013 in the east, and is likely the reason for the absence of the rainfall and burned area association. Accordingly, frequent burning in the EDS diminished the rainfall relationship. Interestingly, the Kwando CA showed a weak negative insignificant relationship with antecedent rainfall, even though EDS burning is applied in an ad-hoc way by the park game wardens, and remains unplanned (Stakeholder interviews, BNP, 2014 -2015). As rainfall increased, burned area decreased in the Kwando CA, and thus shows the effect of a greater number of smaller fires, and more extensive EDS burning. The MUA West, and the Western CA experienced a higher number of LDS fires, which was evident in the proportion of areas burnt with representative larger extents burnt, than the EDS, in all size classes (Figure C8; Appendix C).

A skewed fire size distribution is well known in several diverse ecosystems from boreal forests (Strauss *et al.,* 1989) to the Australian savannas (Yates *et al.,* 2008), in that single large fires are rare, but burn a greater extent, whereas small fires are many, but contribute insignificantly to the overall burned area. An alternative pattern occurred in BNP, with the majority of smaller fires contributing significantly to the area burned in the Kwando CA (52 %) and the MUA East (36 %) (with the contribution of a few large EDS fires related to the availability of accumulated fuel from the previous 1. 5 years), versus the few large fires that occurred in the western land use areas of BNP. As Archibald *et al.* (2010) distinguished, the diversity of fire sizes in southern Africa break the rules, as there are many smaller to medium sized fires due to the presence of human ignitions, than single large fire events, which affect the annual area burned. Thus, it is the number of fires, and the season in which they occur, rather than single fire events, that is a better indication of annual burned area. The analyses of the seasonal number of fires, and maximum fire sizes, and the variation in rainfall periods has revealed the interaction between people, rainfall seasonality and fuel availability at the local scale in BNP. My results are consistent with the greater number of smaller to medium range of fire size patterns, and burned area estimates for southern Africa (Archibald *et al.,* 2010), and are in accord with observations from Australia (Yates *et al.,* 2008) where it was noted, that even though large fires burn a greater extent on occasion, these fires are not only limited to the LDS, but also occur in the EDS, as in the human occupied areas of the MUA East, and park management area of the Kwando CA in the BNP.

The MUA East and MUA West, and the Kwando CA are representative of areas where the local people, and park management have overridden the climate influence at the local scale, through the frequent use of fire in the EDS. Archibald *et al.* (2010) found a similar scenario and a noticeable reduction in climatically driven variability of fire outside protected areas in southern Africa where people frequently use fire in the landscape. However, it was noted in their study, that fire was not entirely decoupled from climatic factors in southern Africa, and the regional data provided evidence that accumulated rainfall, seasonality, and Fire Danger Index (FDI) were correlated with variation in burnt area between years. Increasing precipitation can increase annual burned area by increasing productivity and thus fuel availability, or limit burned area by shortening the dry season (van der Werf *et al.,* 2008), and this changes in southern Africa as one moves from drier to wetter regions (Archibald, 2010). In BNP, it is people living in the park and their use of fire, and the transition in fire management policy to early burning that have altered the fire dynamics inside the protected area. It was shown that inter-annual variability is associated with the occurrence of large fires, and large fires are only found in areas with low human presence (Archibald, 2010). The Western CA with limited park management focus (Ministry of Environment and Tourism [MET], 2016), and thus infrequent EDS burning, is the only land use area where rainfall was correlated to burned area, and is representative of an area in the BNP that shows natural variability in burned area that is responsive to the rainfall regime. However, differences in the vegetation structure could also have influenced the fire dynamics observed. The west even though marginally drier has a different vegetation structure to the east of the park. The eastern area of the park, and particularly the Kwando CA overall has a greater density of tall trees than the west, which is characterised by sentinel trees, open grasslands and predominant shrub layers. The absence of EDS burning, and the subsequent higher frequency of LDS fires in the west of the park has likely resulted in the removal of large trees, and more open savanna with resultant greater fuel build up, associated grass continuity and more grass available to burn in the absence of tree-grass competition. However, there are also areas in the Western

CA where low-lying shrubs have increased in density (e.g. *Bauhinia petersiana*) (pers. observation), and it is likely the proliferation of shrubs may inevitably limit the growth of grass available to burn in the EDS and the LDS in this area. The widespread bush fires that occur frequently have had a major impact on the structure of the woodlands in north-east Namibia (Mendelsohn & el Obeid, 2005). However, a concurrent vegetation analysis and discussion is beyond the scope of this chapter. Nonetheless, this data suggests that both the dry and wet ENSO phases have influenced the fire regime in BNP. Other remote sensing studies have found relationships with fire and ENSO, where increased fire incidences were associated with above average rainfall periods (Anyamba *et al.*, 2003; Van Der Werf *et al.,* 2008; Andela & Van Der Werf, 2014; Bird *et al.,* 2016). Moreover, Andela & Van der Werf (2014) specifically noted in their analysis that burned area trends showed high inter-annual variation particularly in Namibia.

Van Wilgen *et al.* (2004) found that irrespective of the fire management policy applied in Kruger National Park (KNP), the area burned was responsive to the amount of preceding 2 years rainfall, indicating that rainfall (and consequently the available grass biomass) had an overriding influence on area burned in any given year. However, in KNP, the burning regimes are exclusively managed by park management, but the majority of fires are the result of human ignitions (e.g. tourists, poachers, or cross-border migrants) (Archibald *et al.,* 2010), as local indigenous burning practises are excluded from the KNP park system. Archibald *et al.* (2010) identified that the KNP is different to other parks, with a limited road network, no cultivation, and a lower biomass of grazing mammals, than outside the park, which accounted for differences in area burnt and fire size. In BNP, beyond the Golden Highway (B8), the main thoroughfare through the park, there is a limited road network that is remnant from the South African Border War (1966 – 1989), nevertheless, people living in the MUA generally move through the landscape on BNP on foot (pers. observation). Moreover, the inhabitant Khwe and Mbukushu populations in BNP and their extensive use of fire in the EDS in the MUA East and MUA West, together with the change to an EBP policy have influenced the fire regime and burned area, however the burning is in response to the *availability of fuel* following *above average rainfall events*. This availability of fuel also influences when people (i.e. season) of burn, since following the dry period, fires were most frequent in August in BNP, however this period coincided with the SP, and thus the variability in rainfall was confounded with the two policy periods in BNP. The dry period in BNP coincided with the SP, and the EBP with the average and above average rainfall events. This research agrees with Archibald's *et al.* (2010) findings, whereby they found the amount of fuel available and fuel continuity appear to be more important than the ignition regime. Though BNP is a protected area, people are resident within the bounds of the park, and have altered the fuel load and overridden the characteristic climate and burned area relationship, but their burning practises have been in response to the rainfall patterns. Nonetheless, the change in policy from suppression to early burning is significant as a high number of small fires in the early dry season, prevents the spread of late season fires. Thus, it makes sense for people to continue lighting fires in the early season (Archibald, 2010), and to integrate the local early burning practise knowledge within the park management plans in the future. This study has emphasised the importance of global (ENSO) and local rainfall in influencing burned area, however further highlights the importance of the extent of burned area, and number of fires in the EDS and the LDS, and thus the influence of people on fire seasonality in understanding fire regimes.

Conclusion

Analysis of the fire history of BNP derived from remotely sensed data is shown here to afford insights concerning the burned area and rainfall relationship, seasonal extent, and fire size in the different land use areas. The evidence using MODIS instrument data has shown that as hypothesised, the relationship between rainfall and area burned becomes weaker depending on the extent of human fire management. Where people are resident in the MUA and BNP management are controlling the fire regime through early season burning at the local level in the park, there is no significant relationship between burned area and rainfall, whereas in the Western CA the opposite was apparent, and the rainfall explained the variability of the area burned in the absence of frequent fires. The frequency of fire increased after the implementation of the EBP (MUA East, MUA West and the Kwando CA), however inter-annual variability in burned area was still evident, which was found to be owing to increased variability in the ENSO phases, with increasing and decreasing rainfall phases. Thus, during wet La Niña events, burned area increased, whereas during the dry events (El Niño), burned area was not prominent in the land use areas in BNP.

This research highlights some of the complexities between human land use and fire regimes. Integrating both global (ENSO) and local rainfall patterns, together with different fire use strategies in varying land use systems has demonstrated that human management through early season burning can dampen the relationship between rainfall and burned area. The data presented here provide evidence for the contrast between land use areas where people actively use fire for either management purposes (Kwando CA), and or for livelihoods (MUA East and West), versus a wildlife protected area with limited fire management protocols in place (Western CA), and clearly shows how people through purposeful burning override the climate at the local scale, yet burn greater fuel loads when grass increases following high rainfall events. Thus, the data suggests that ENSO events superimposed on the local climate regime are driving the variability in the number of fires and fire sizes, and people are removing the fuel load in such events. Further, that it is the number of fires and fire sizes, combined with variable rainfall events that are better indicators of burned area where people are living in a savanna landscape.

Further, this study has shown, that people can influence the spatial extent of burning by increasing the number of fires, and thereby influence the range of fire sizes that could occur in the landscape. Thus, the season of fire and associated ignition frequencies, and possibly fire sizes are constituted elements of the fire regime that could be influenced by BNP management in the future. For example, in years of high rainfall, managers can increase the numbers of EDS fires in the landscape to reduce the fuel loads to prevent the LDS intense fires (Archibald, 2010), which are currently part of the fire regime in the Western CA. This management approach would allow managers to respond to changing environmental conditions, as has been implemented in KNP as an adaptive management approach to fire management (van Wilgen *et al.*, 2004). In summary, managers of African savannas can manipulate the fire regime by choosing the season of fire, and further by burning in years with higher fuel loads (Govender *et al.*, 2006). Shifting the focus from discussions of *how much burns* to *how and when it burns* (Laris, 2013, Mistry & Bizerril, 2011) should enable management plans that are feasible, and create more common ground for decision-making (Archibald, 2016).

In BNP it is clear that the presence of people who actively use fire, both the local community and the park management, has resulted in an effective policy of early burning, whereby the increase in the number of small and medium sized fires have reduced the occurrence of later larger dry season fires. Thus, the inhabitant people together with park management have influenced the fire spread and fuel continuity through increasing ignitions alongside the EBP in fluctuating rainfall events. These results have consequences for understanding and appreciating people's fire use strategies as well as emphasising the need to consider both climatic and anthropogenic factors. The direct impact of the number and seasonal timing of fires have been shown to have a substantial impact on the fuel amount, and reduce the size of fires and influence the total area burned particularly in the community areas. Therefore, recognition of the community burning patterns and their knowledge of early burning practises has implications for the parks biodiversity objectives, and future fire management policies in BNP. Results of less burning in the LDS in human inhabited settlement areas, versus the park areas show how anthropogenic fire regimes in Africa and other grassy systems reduce, rather than increase, fire-related carbon emissions (Archibald, 2016). Furthermore, such results are important for modelling the human influence of fire and carbon emissions in Africa (Archibald, 2010, 2016).

Chapter 5 Who is burning where? Associations between fire frequency, fire seasonality, fire intensity, land use and policy.

Abstract

Fire frequency and fire intensity are two significant fire regime components that influence African tree demographics. Typically, is it these components that fire managers and people living in African savannas try to control for conservation purposes, and for livelihood benefits. Fire radiative power (FRP) measurements from satellites play an important role in quantifying the energy released by fires, and in distinguishing fires of different intensities. FRP has a linear relationship with the total amount of vegetation biomass consumed, and biomass availability varies in response to climate, and people's use of fire in the dry season months. I analysed multi-year (2000 – 2015) MODIS derived FRP, and MODIS MCD45A1 burned area data to describe relationships between fire frequency, burned area, seasonality, and fire intensity, for different vegetation types in strictly protected areas, and areas inhabited by people (Multiple Use Area [MUA]) in north-east of Namibia in Bwabwata National Park (BNP), before and after a change in fire management policy from fire suppression to early burning in 2006.

Analysis of seasonal fire frequencies and burn areas in both the MUA and conservation areas (CAs) showed that under a policy of early burning, a greater area was burned at a lower frequency than under a policy of fire suppression. As a consequence, the extent, frequency and spatial distribution of late dry season fires decreased across the BNP landscape following the policy shift. Fire frequencies and burned areas were highest in the early dry season in the omiramba grasslands and savanna-woodland vegetation types in the east of the park during the early burning policy. In contrast, burning in the Burkea shrublands was frequent in the late dry season over the entire 16 years. Results revealed that fire intensity was significantly lower in the people inhabited area of the MUA East, and Kwando CA, and omiramba grasslands and savanna-woodland vegetation types under the early burning policy where early season fires were prevalent. In contrast, in the west of the park highly variable intensities occurred in the Burkea shrublands in the absence of infrequent early season fires under both policy phases. Accordingly, high fire risk weather conditions (i.e. strong winds, low humidity and high temperatures), and years of high rainfall influenced the intensities of fires later in the season in the west of the park, and partially in the MUA.

Results show the important role of local burning practises, in combination with policy in influencing fire intensity, through increasing ignitions in the early season to reduce the spread of the damaging late season fires. These findings have implications for the management of the savanna vegetation structure, because reduced late season fires may allow more tree recruitment. Furthermore, local fire regime management strategies and fire use for livelihood needs, should be integrated into fire management policy within BNP.

Introduction

Fire in Africa is characterised by persistent seasonal variability with most vegetation fires occurring in the dry season (Cahoon *et al.*,1992; Giglio *et al.,* 2006; Page *et al.*, 2010). In southern Africa, it is the arrangement of savanna vegetation and seasonal rainfall (Osborne, 2008) with an extended dry season (3 – 6 months), which produces the environment where fuel is both available and flammable (Bradstock, 2010; Archibald *et al.*, 2017). Further, there is little evidence that fires are caused by a lightning regime in southern Africa, and most ignitions are explicitly human derived (Archibald *et al.,* 2010) in the early dry season (EDS: Apr - July) and late dry seasons (LDS: Aug – Nov). People burn the landscape for a multitude of reasons, which include livelihood subsistence (e.g. crop cultivation, regeneration of plant foods, improve grazing value of grass for cattle) and for conservation purposes (e.g. prevent the damaging late hot season fires). Furthermore, in many fire-prone ecosystems, diverse vegetation types occur with different flammabilities, and co-exist on landscapes (e.g. 'open' tree canopy, high grass biomass and flammable, versus 'closed' tree canopy, low grass biomass and non-flammable) (Bond & Midgely, 1995; Pausas & Schwilk, 2012). Thus, the combination of rainfall seasonality, structure and composition of the vegetation, and land management practices have a significant influence on the frequency of fires (Scholes & Archer, 1997; Archibald *et al.*, 2009; Le Page *et al.,* 2010). Consequently, fire regimes representing patterns in time and space of the frequency, type, extent and intensity (i.e. heat energy released during the course of a fire) of fires vary in response to multiple interacting environmental and human factors (Archibald *et al.,* 2017). The human preference for igniting cool small EDS fires when the grass is moisture laden and green, versus the large hot intense LDS fires (Aug – Nov) when climatic conditions and dry vegetation yield highly flammable settings, is at the centre of fire management approaches in Africa, and other fire prone ecosystems (Anderson, 2003).

Decisions for all fire managers on where, when, and how to burn, or not burn or suppress fires in a certain landscape are largely related to fuel load, which is dependent on seasonal rainfall (Bonta *et al.,* 2017). Other important motives for *why* people ignite fires are related to their livelihood needs and management objectives, which influences *when* they burn (season and/or time of day), which in turn effects the heat and spread of fire, and governs how *often* and *where* people use fire in a landscape. It is also essential to know *where* low and high intensity fires occur, and how *frequent* these fires are for managers to understand their impact in grassy savannas (Anderson, 2003) and the consequences for policy development and people's livelihoods. The combination of the intensity and frequency of fire are important, because together they can substantially impact savanna structure and associated ecosystem services (Archibald *et al.,* 2017). Therefore, people, through increasing or decreasing ignitions (fire frequency) alter the fuel load, and indirectly the intensity of fires in savannas, with important implications for tree-grass dynamics (Andela *et al.*, 2017; Archibald *et al*., 2010; Archibald, 2016; Archibald *et al*., 2017), and their livelihoods. The use of fire for a diverse array of land use management practices and livelihood needs is entrenched in southern Africa, however *how* the frequency of these fires influences fire intensity in savannas is unclear. Accordingly, peoples' regular burning practises are important for understanding variation in vegetation structure and composition, and for setting objectives for national fire management plans, and policy.

Quantifying the impact of fires on the environment requires information from multiple scales (Vadrevu *et al.,* 2013), disciplines (Coughlan & Petty, 2012; Bowman *et al.,* 2011), and methods (Laris, 2011). Traditionally fire intensity was calculated using Byram's (1959) fireline intensity, which measures the rate of energy released from a fire per unit of length along the fire front. Satellites from the Moderate Resolution Imaging Spectrometer (MODIS) can now measure the heat energy released from active fires at overpass (revisit of 1 to 2 days). These satellite observations have been used to investigate significant spatio-temporal differences in fire radiative intensity (Wooster & Zhang, 2004; Smith & Wooster, 2005; Scholes *et al.,* 2011), and fire frequency (Siljander *et al.,* 2009; Archibald *et al.,* 2010). The MODIS Fire Radiative Power (FRP) is a measure of the radiant energy liberated per unit of time of burning vegetation in megawatts (MW), and has been used as a correlate to the amount of biomass available to combust (Shea *et al.,* 1996; Wooster *et al.,* 2003; Roberts *et al.,* 2005). Thus, FRP is theoretically used as a spatially and temporally continuous measure of fireline intensity (Smith & Wooster, 2005). Differences in fire intensity have also been related to unique vegetation characteristics (e.g. fine grassy fuels versus densely wooded vegetation) and land use systems (Archibald *et al.,* 2010; Roberts *et al.,* 2005; Oliveria *et al.,* 2015).

Fire intensity can be manipulated for different conservation management or livelihood objectives. For example, where bush has thickened and/or encroached in the absence of fire, managers would prefer hot intense fires to remove the density of trees to allow the grasses to grow (Lohmann *et al.*, 2014), and/or for maintaining high grass-ratios for herbivores in conservation areas (Smit & Prins, 2015). People living within savannas typically burn earlier in the dry season for a number of livelihood reasons, other than for biodiversity purposes, including hunting purposes to attract game to fresh grass growth, regenerate herbaceous vegetation for livestock feed quality (Sheuyange, 2002; Sheuyange 2005). Laris (2011) described a seasonal mosaic as a landscape pattern that is annually re-created by people, which contains patches of unburned, early-burned, and recently burned vegetation which he referred to as '*humanized*' savannas. This term is used to portray a fire regime mainly driven by human practises rather than by natural factors, such as weather and fuel (Laris *et al.,* 2015). For example, research in southern Africa (Archibald *et al.,* 2010) and Australia (Bird *et al.,* 2012) has revealed how people and their use of fire can diminish the traditional climate and burned area association, whereby rainfall determines grass biomass which determines area burned. Specifically, people alter fire regimes through increasing ignitions and by limiting the spread of fire through fire suppression and fuel fragmentation (Loepfe *et al.*, 2011). Laris's *et al.* (2015) intention of the use of the term '*humanized*' was to emphasize the role of people in fire dynamics. This is because frequently indigenous knowledge concerning the use of fire, and reasons why people light fires (le Roux, 2011; Laris, 2011; Archibald, 2016) are relegated to the background in fire regime analyses (Darques, 2015).

Ignoring the numerous direct impacts of people on fire can lead to ineffective fire management and perverse outcomes (Laris & Wardell, 2006; Moritz *et al.,* 2014). For example, when indigenous practises have been altered and/or suppressed, invariably large conflagrations ensue (Pyne, 1997; Laris, 2002). Furthermore, local-scale impacts of people on fire are often perceived as disruptive (Laris, 2002; Laris & Wardell, 2006), yet concurrently diversifying (Bowman *et al.,* 2011). The intent to create small patchy fires is thought to enhance biodiversity by increasing the variety of microhabitats (Laris, 2002; Parr & Andersen, 2006; Beale *et al.,* 2018). Besides, these frequent, small and cool fires help protect cultivated fields, homes, and forest patches (Laris *et al.,* 2015; Bond & Zaloumis, 2016), and prevent the spread of late season fires (Russell-smith *et al*., 1997; Laris, 2002). The view that Aboriginal burning patterns benefit the savanna ecosystem has recently gained acceptance among managers, and has clear policy, and management implications (Laris, 2002).

There is now widespread research suggesting that anthropogenic practices have resulted in mosaic burning patterns that have positive effects on the ecological system (Russell-smith *et al.,* 1997; Mbow *et al.,* 2000; Yiburak *et al.,* 2001; Laris, 2002; Bowman *et al.,* 2004; Mistry *et al.,* 2005; Welch *et al.,* 2013; Walters *et al.,* 2015). In southern Africa, however, local indigenous burning practises have rarely been integrated into fire management policy (Frost, 1999; Eriksen, 2007) or acknowledged, though fire managers have included early dry season burns into conservation plans in some protected areas. (Parr & Brockett, 1999; Brockett *et al*., 2001; van Wilgen *et al.,* 2004; Parr & Anderson, 2006; Govender *et al.,* 2006; MET, 2013; 2016). Most studies concerning fire intensity in southern Africa have focused on understanding intensity in ecological management settings where indigenous people are excluded from protected areas (Pilanesberg National Park: Brockett *et al.,* 2001; Kruger National Park: Trollope & Tainton, 1984; Shea *et al.,*1996 [including Kasanka National Park, Zambia]; Govender *et al.,* 2006). Further, research using FRP have been at global (Ichoku *et al.,* 2008), national (Tarimo *et al.,* 2015), regional (Oliveria *et al.*, 2015), and/ or sub-regional (Archibald *et al.*, 2010) scales with none at the local scale with indigenous communities as part of the ignition regime.

In Bwabwata National Park (BNP) in the north-eastern savanna-woodlands of Namibia, the Mbukushu (agropastoralists), and Khwe (former hunter-gatherers) people, the latter being the most marginalised community in southern Africa (Suzman, 2017), have used fire for thousands of years, yet how their ignitions influence fire frequency, and fire intensity in BNP remains undocumented to date. The current study incorporates a remote sensing view of indigenous burning regimes of the Mbukushu and Khwe at a scale of 624, 700 ha.

The Mbukushu and Khwe people inhabit villages in the savanna-woodlands of the protected area of BNP, which are flanked by two core conservation areas exclusively used for wildlife and tourism activities, namely the Kwando Core Area (CA), and Western CA. In BNP, fire is commonly used to support the inhabitant communities' livelihoods. This study therefore presents an ideal opportunity to assess how fire intensity changes in response to fire frequency in different vegetation types in the park with two different land use practises, and types in place: i) multiple use area (MUA); and ii) core conservation areas (CAs). Furthermore, BNP altered their fire management policy from an earlier period of fire suppression (suppression policy: 2000 to 2005) to an early burning policy (EBP) in 2006, and herein lies the opportunity to assess changes in fire intensity concerning before and after a change to a more frequent burning regime. The aim of this chapter is to investigate the interaction between fire occurrence, seasonality and fire intensity, as represented by fire radiative power (FRP), in different land use areas and vegetation types, during the years 2000 to 2015, before and after a change in fire management policy in BNP.

My main objectives are to explore fire frequency and intensity in four vegetation types, namely in the omiramba grasslands, savanna-woodlands, Burkea shrublands and riparian coverages, within four land use areas explicitly in the Western CA, MUA West, MUA East and the Kwando CA before and after the policy transition from fire suppression to early burning. Specifically: i) to determine how *fire frequency* varies in space and time across the BNP, and within the four land use areas and aforementioned vegetation types, and secondly (ii) to determine how *fire intensity* responds to changes in the fire regime, in terms of seasonality, fire frequency and burned area in the four vegetation types and land use areas before and after the transition from a fire suppression to early season burn policy.

Burned area data and FRP derived from MODIS satellite imagery are used to test hypotheses on the fire regime. The results from this study are aimed at providing evidence on where, and how frequently fires occur, together with the fire intensity and vegetation characteristics for the park. The spatial dynamics of the fire intensity data is useful for addressing fire management and mitigation options in the land use areas in BNP. The following hypotheses and questions were used to address the objectives in this chapter.

Fire frequency

Influence of fire policy and land use on seasonal fire frequency and spatial distribution

People use fire for a variety of reasons, thus I expected where people inhabit BNP, that they would frequently use fire. Further, after the enactment of the Early Burning Policy (2006), I expected the frequency of fire would increase across all land use areas in BNP. The frequency of fire affects savanna structure and functioning (Frost & Robertson, 1997), and can affect people's livelihoods and access to natural resources, thus it is important to locate *where* in the landscape fires are most frequent.

Question 1: How was the frequency of fire distributed in the BNP landscape, and within the four land use areas a) over the entire 16 years, and under b) the Suppression Policy (SP) and Early Burning Policy (EBP) eras? Over the 16 years, I hypothesised that fires would be i) most frequent close to villages in the MUA, and in the CAs, since I expected a combination of early and late season fires, and ii) less frequent on the neighbouring park boundaries, alongside protected areas in Botswana and Angola where fire management is reportedly unregulated, and along the Okavango and Kwando River systems bordering the east and west of the park. iii) I hypothesised that there would be less EDS burned area, and more LDS burning in proximity to villages in the SP, and in contrast, there would a greater area burned in the EDS in proximity to villages, and a reduction in LDS burning during the EBP. Moreover, the effect of early dry season burning has always been to prevent the spread of late dry season fires in a landscape. Therefore, with a change in policy, I hypothesized that iv) an increase in EDS burning would reduce the spatial distribution of LDS burning in the landscape.

Influence of fire policy, land use and vegetation type on frequency of fire and seasonal burned area

In savannas, the grass provides the fuel for fires, and people frequently ignite the grass. Therefore, I expected a higher fire frequency in vegetation types with more grass biomass and more people. Furthermore, because grass can cure within a few weeks of no rain, I expected fires to occur earlier in the dry season in grassy vegetation types.

Question 2: How did fire frequency and burn area vary between vegetation types in the whole of BNP, and within the land use areas before and after the policy change? I hypothesised i) that burning would be more frequent and over a wider burn area in the omiramba grasslands, and in the intervening grass within the savanna-woodlands, and riparian areas (i.e. floodplains with grass cover), than in the Burkea shrubland vegetation type with less grass. Furthermore, I hypothesized ii) that burning would occur earlier in the dry season in in the omiramba grasslands, savanna-woodlands and riparian floodplain areas during the EBP.

Fire intensity

Influence of fire policy and land-use on seasonal fire intensity (FRP)

FRP has a linear relationship with biomass consumed, and intensities vary in relation to season and variations in climate. For example, intensities are typically higher during the late fire season with increasing ambient temperatures, lower humidity, and fuel moisture content, and stronger winds. In contrast, intensities are typically lower in the early fire season following rainfall due to the moisture content of the grass. Thus, fire intensity is expected to be higher in the late dry season (LDS), and lower in the early dry season (EDS). Secondly, fire intensities typically decrease with an increase in burning as the fuel available to burn is removed. In BNP, I anticipated an increase in burning close to human settlements, and in areas where early season fires are applied for management purposes.

Question 3: How was fire intensity distributed in the BNP landscape, and within the land use areas a) over the entire 16 years, and under b) the SP and EBP eras? I hypothesized i) that fire intensity (FRP values) would be lower in the land use areas where people frequently use fire, and higher in areas where fire is less frequent; and ii) that FRP would differ between the EDS and LDS, and policy periods (SP and EBP), with FRP being higher in the LDS and SP due to less frequent burning and high fire risk weather conditions, and lower in the EDS, and EBP due to more frequent burning and a higher moisture content of the grass sward; and iii) FRP would increase in above average rainfall periods with an associated increase in biomass availability. Thus, I expected FRP would generally be lower in land use areas more frequently burned irrespective of an increase in rainfall.

Influence of fire policy, land use and vegetation type on fire intensity

Fire intensity also depends on the type, amount, arrangement, and moisture content of the biomass available to burn (Byram, 1959). For example, an uninterrupted layer of fine grasses generally burn a significant amount of fuel than shrublands, and a densely wooded vegetation type, with less grass between the trees (Roberts *et al*., 2009). Furthermore, woodlands and shrublands which generally have a lower biomass and uneven distribution of fuel, tend to have less intense fires when compared to grasslands (Frost & Robertson ,1997).

Question 4: Is there evidence of a change in fire intensities in the different vegetation types associated with an anticipated increase in burning within the land use areas after the transition in policy? I hypothesized i) that FRP would be lower in the vegetation types with grassland cover due to frequent fires, and higher in the densely wooded Burkea shrublands with less grass, and less fire. Furthermore, I hypothesized ii) that the variation in intensities in the vegetation types would be associated with an increase in EDS burning in the land use areas after the policy change.

Methodology

In this study, data concerning fire frequency, burned area extent, FRP and seasonality were analysed with respect to digital coverages for the park as a whole as well as for the four vegetation types and land use areas in the two different policy periods (SP and EBP) in BNP from 2000 to 2015. Data were analysed in a summarised form, and in detail using inter-annual variation time series illustrations, particularly since the purpose of this study was to assess changes under the policy transition in fire frequency, burned area and fire intensity. The dependent variables were burned area, fire frequency and timing (seasonality), and the independent variables comprised the two policy phases (SP and EBP), seasons (EDS and LDS), four vegetation types (omiramba grasslands, savanna-woodlands, Burkea shrublands and riparian) and land use areas (Western CA, MUA West, MUA East and the Kwando CA). Data were arranged, at first for BNP as a whole, and thereafter at a detailed scale for the four land use areas. I used planned (*a priori*) pairwise test comparisons to investigate the simple linear relationships between the dependent and independent factors to avoid multiple testing, and inflation of the Type II error (Kuehne, 1993). Overall, my approach has been to compare and test similarities and differences among subsets of the data representing appropriate factor combinations (e.g. policy, land use and season) to answer my research questions. Thus, statistical testing of the interactions has not been performed since some factor combinations can't be tested because there is too little data or no data available for all the factors of interest. Therefore, I have focused on the explanatory variables, with the intention of understanding the ecological causes of the emergent patterns in BNP. Where the data displayed normality I used parametric tests, and for non-normal data, non-parametric tests. The MODIS MCD45A1 spatial data (raster-based) was analysed in the GIS software ESRI ArcGIS v 10.2, and the Fire Information for Resource Management System (FIRMS) MODIS FRP data in combination with ArcGIS v 10.2 and GeoDa v1.8. 16.4 (Anselin *et al.*, 2011). All statistical analyses were carried out in R version 3.4.0. (R Core Team, http://www.R-project.org.).

Data sources

Satellite fire data 1 : Burned area

Satellite data have been used to monitor biomass burning at regional to global levels over the last two decades and detect the location of actively burning fires at the time of overpass (Roy *et al.*, 2005). Several algorithms have been developed to identify and map these burned areas (Barbosa *et al.*, 1999; Roy *et al.*, 2005; Giglio *et al.*, 2009). For this study, burned area data was derived from the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectrometer (MODIS) fire product (MCD45A1) that represents a 500 m location and approximate date of burning to a precision of 8 days (Roy *et al.*, 2008). The monthly burned area data available from April 2000 to December 2015 were downloaded in GeoTIFF format from the University of Maryland (http://modis-fire.umd.edu/). During the months of June 2001, May and July 2001 there was a prolonged sensor outage, which affected these datasets, and hence not all burned area data will be representative of these periods. Overall, several studies have validated the MODIS fire product (Roy *et al.*, 2005; Roy & Boschetti, 2009), and determined that this product can accurately detect ~ 85 % of the true burned area in southern Africa (Archibald *et al.*, 2009).

Satellite fire data 2 : Fire intensity / Fire radiative power (FRP)

The global MODIS active fire data non-standard Near Real-Time (NRT) MCD14ML contains 1 km fire pixel locations that are most appropriate for determining the spatial distribution and seasonality of fires (Davies *et al.*, 2009). The MODIS Collection 5 Active Fire product MCD14ML shapefiles from the FIRMS were downloaded from November 2000 to December 2015 from the archive data tool (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/active-fire-data). The data files consist of spatially explicit and georeferenced (WGS 84, UTM 34 South) point layers for each year. The two sun-synchronous, polar-orbiting satellites pass over the equator at approximately 10:30am/pm (Terra) and 1:30 am/pm (Aqua) with a revisit of 1 to 2 days (Vadrevu *et al.*, 2013). These data contain the acquisition date and time, latitude and longitude, satellite name, a detection confidence (0 – 100%), brightness temperature (Kelvin), and the fire radiative power measurements (FRP) measured in megawatts (MW) per pixel (Giglio *et al.*, 2003). FRP is an extension of the active fire data, and is subject to the same limitations, which is satellite overpass time, obscuration through clouds, smoke and in some cases upper canopy, however under ideal conditions flaming fires as small as 50 m² can be detected (Vadrevu *et al.*, 2013). FRP is estimated as the whole pixel area (1 x 1 km), as it cannot distinguish between a very small intense fire with a small extent and a larger fire with a lower intensity (Williams *et al.*, 2008), thus some uncertainty in the data is introduced (Archibald *et al.*, 2010). However, in extensive and remote locations such as BNP, FRP is the only feasible way of estimating fire intensity data (Ichoku *et al.*, 2008; Oliveria *et al*., 2015). The confidence level is based on detection reliability that indicates the degree of missing data with clouds, heavy smoke and sun glint (Davies *et al.*, 2009). The detection confidence is used to assign the classes of low confidence (< 30 %), nominal confidence (30 – 80 %), or high confidence (> 80 %) to each observation in the dataset. For the purpose of this study the low confidence active fires were excluded, since higher confidence levels can be applied to reduce the number of false alarms (errors of commission) at the expense of a lower detection rate (Giglio, 2010). The acquisition time was converted from Coordinated Universal Time (UTC) to West African Standard Time (WAST) for Namibia, which is two hours ahead of UTC. Data is missing from the end of June to the beginning of July in 2001, 2002 is missing some data throughout the data set, including mid-August 2007, and on the dates 21 – 22 April 2009 (Justice *et al.*, 2002; Davies *et al.*, 2009). Thus, during these times, the FRP values will not be completely representative.

Vegetation data

In this study, GIS layers resulting from analyses of satellite imagery and ground surveys by Mendelsohn & Roberts (1997) were used to delineate the main vegetation types and landscape features in the BNP. Spatial data from the Environmental profile of the Caprivi (Mendelsohn & Roberts, 1997) was obtained from (http://www.the-eis.com/). The 13 vegetation classes in the vegetation map of Mendelsohn & Robert's (1997) were reclassified into four major broad types, namely: (1) savanna-woodlands (82. 35 %), (2) omiramba grasslands (9. 40 %) (3) riparian (4. 39 %), and (4) Burkea shrublands (3. 86 %) (Figure 5-1). The savanna-woodlands were reclassified based on grouping the following woodland types characterised in Mendelsohn & Roberts (1997): open-camelthorn woodland, teak savanna, teak woodland, Burkea-teak woodland, Burkea-Combretum woodlands and omirmaba fringe woodlands, which constitute mixed open woodland vegetation in BNP. The omiramba grasslands (plural; singular: 'omuramba') fall within a distinct palaeodune feature in BNP and are fossil drainage lines covered in grassland that lie between each remnant dune crest, which form part of the savanna-woodlands coverage in the park. The riparian vegetation was characterised by grouping the okavango-kwando valley woodland, okavango-kwando grassland, and rivers and open water vegetation types. The Burkea shrublands represent a degraded form of teak woodland (trees over 4 metres are rare), and are characterised by a shrub layer that can cover up to 50 % of the extent of this vegetation type (Mendelsohn & Roberts, 1997). Since the omiramba grasslands and Burkea shrublands are characterised as distinctive, as they differ from the other aforementioned types in BNP, they were not grouped with any other vegetation types occurring in the park.

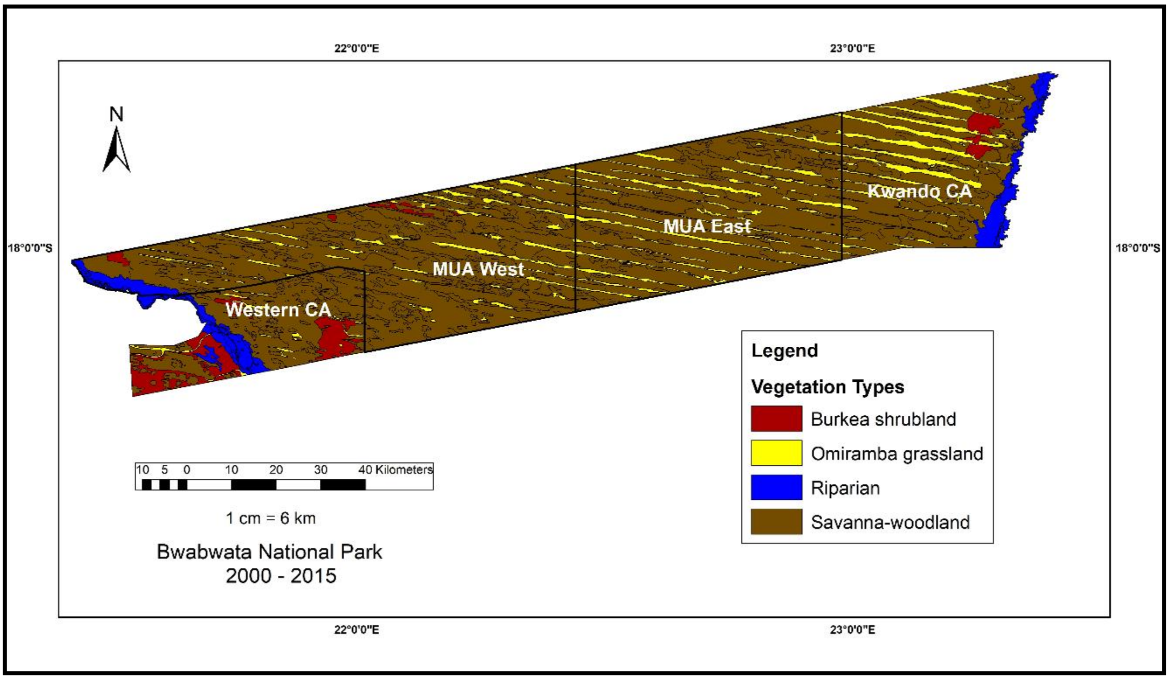


Figure 5-1: Vegetation map showing the four vegetation types within the four land use areas in Bwabwata National Park. Refer to text for details.

Data analysis and methods

Fire frequency

Influence of fire policy and land use on seasonal fire frequency and spatial distribution

Fire frequency for a given area represents the number of fires during a certain unit of time (Bond & Keely, 2005; Hely & Alleaume, 2006). The MODIS MCD45A1 monthly burned area data were summarised by calendar year (April to November), as no fire activity was detected from January to March, and in December by MODIS. The data were combined to produce a burnt and unburnt layer for each fire year, and merged from 2000 to 2015 to calculate fire frequency, expressed as the number of times a pixel burned in a 16 year period (Archibald *et al.*, 2010). The proportion of the area that burned within each frequency class (0 – 16) was calculated in hectares (ha), and expressed as a percentage for ease of comparison. The result was a single GIS raster fire frequency map at a 500 m resolution for the entire BNP (0 = unburned and 16 = burned annually). Further, the percentage frequency of individual 25 ha pixels affected by fire within each of the land use area were quantified and illustrated. A Spearman rank correlation (r_S) was used to measure the monotonic relationship between fire frequency and burned area for the entire BNP.

To test the area burned in relation to distance from village, the GIS was used to define non-overlapping kilometre wide zones of increasing distance (500 m to 15 km) from villages in the MUA East and MUA

West independently. The core conservation areas (Kwando and Western CAs) were excluded from this analysis because no villages were present in these areas. The fire frequency data set was converted to a vector format (shapefile) to integrate with the village data points to investigate the influence of distance from village on the seasonal percentage of area burned. The percentage of burning in the EDS and LDS for the respective policy phases (SP and EBP) were calculated for each distance zone. To determine similarities or differences between burning in the EDS and LDS for each village area in the two policy phases an analysis of covariance (ANCOVA) was performed with distance from village (km) as a covariate. The studentized Breusch-Pagan algorithmic test was used to test for homogeneity of the regression slopes (Breusch & Pagan, 1937), and the assumptions were met for each model tested. Further, independence of the distance covariate and the treatment effects (policy and season [EDS and LDS]) assumptions (Field *et al.*, 2012) were satisfied.

To determine the seasonal burning patterns in relation to the policy phases the fire frequency dataset was separated into the two policy period data sets: a) SP (2000-2005), and b) EBP (2006 – 2015) during the EDS and LDS for each of the four land use areas. Four raster-based fire frequency maps were produced at a 500 m resolution representing the number of burns a pixel experienced in 6 years (2000 – 2005) during the SP, and associated EDS and LDS fire frequencies, and for 10 years (2006- 2015) during the EBP, and the EDS and LDS burning extents were illustrated. The SP and the EBP seasonal maps were illustrated independently for a visual comparison of the extent and spread of the fire frequency within each land use area. To determine the variation in burned area, the percentage change (increase and /or decrease) was calculated and compared between each the two policy phases, and seasons (EDS and LDS) for the entire BNP, and for each land use area (Question 1).

Influence of fire policy, land use and vegetation type on frequency of fire and seasonal burned area

The seasonal extent of burned area (EDS and LDS) was summarised for the entire BNP, and within the four land use areas, and vegetation types under the two policy periods (SP and EBP). Burned area is typically recorded as a proportion of the total landscape (Archibald, 2010), thus the total area burnt was divided by the entire area of each land use boundary and vegetation type, and the percentage for each year and /or season was reported for ease of comparison.

Herberich *et al.* (2010) proposed a new statistical multiple comparison procedure for assessing multiple means between groups where the data reveals unequal sample sizes and variances. Because the data was heteroscedastic, the *multcomp* and *lsmean*s packages (R core team, 2013) were used to assess multiple comparisons of the group means and obtain simultaneous confidence intervals using the percentage area burned of vegetation types in the total dry season (TDS), EDS and LDS for the entire BNP and for the four land use areas. Non-parametric unpaired Wilcoxon-sign rank tests were used to test for significant differences in the EDS and LDS in the four vegetation types since the data were not normally distributed.

Spearman rank correlations (r_s) were used to examine the relationship between percentage area burned and year in the EDS and LDS over the 16 years specifically in the omiramba grasslands and savanna woodlands vegetation types because they constitute the grass coverage (this is what typically burns), and together cover approx. 91 % of the BNP. Non-parametric Kruskal-Wallis tests were used to establish if there were differences in the means of percentage area burned in the EDS and LDS under the SP and EBP periods for each level of land use and vegetation type. Bartlett's tests (Bartlett, 1937) were used to examine the null hypothesis that the variances of the groups were the same, and the assumptions were met. Post-hoc analyses were performed to determine which levels of season and policy phase differ for each of the vegetation types, and land use areas. The post-hoc Dunn test (Zar, 2010) was used since there were unequal number of observations for each level, and was implemented with the *dunntest* function in the *FSA* package in R. Furthermore, the percentage frequency of individual 25 ha pixels affected by fire, and the proportion of total area burnt for each land use area in the four vegetation types within each of the land use areas was quantified and illustrated (Question 2).

Fire intensity

Influence of fire policy and land-use on seasonal fire intensity (FRP)

The MODIS active fire dataset (MCD14ML) was clipped to the BNP boundary and land use areas. Active fire detections for the BNP were extracted from the global dataset and were separated by land use area (MUA East, MUA West, Kwando and Western CAs) and for each of the four vegetation types for each month and year. A spatial join analysis was performed in the GIS to spatially locate all FRP values within the land use areas. Furthermore, summarised distributional statistics (mean, median, maximum and 90th-percentile) of the MODIS FRP values were derived for all fires in the land use areas in BNP.
Exploratory spatial data analysis (ESDA) of autocorrelation patterns was performed on the MODIS MDC14ML collection 5 active fire data set using FRP values for the period 2000 – 2015. Spatial autocorrelation quantifies the clustering of similar values and is tested against a null hypothesis for random location. Thus, the rejection of the null hypothesis is indicative of spatial patterning in the data, providing useful information concerning the process under study (Anselin, 1995). The ESDA approach is ideal for the MODIS FRP data as values indicate the release of heat energy at NADIR (point on the ground directly in line with the remote sensing system and the centre of the earth) at a point in time. Spatial statistics were performed on the FRP (1 x 1 km) pixel data and included the use of Getis-ord Gi*

statistic, Global Moran's I spatial autocorrelation, and Anselin Local Moran's I Cluster and Outlier analysis.

A geographically weighted matrix (i.e. using FRP as the weight attribute/variable) was used to identify hot [i.e. red: high values] and cold [i.e. blue: low values] spots (Getis-ord Gi* statistic) (Mitchell, 2005). Investigation of these spatial patterns of FRP were analysed with a Hotspot Analysis (ArcGIS, v 10. 2) based on the Getis-Ord Gi* algorithm (Getis and Ord, 1994). Spatial autocorrelation was measured with Moran's index [I]. If the index (average nearest neighbour ratio) is less than 1, the pattern exhibits clustering. If the index is greater than 1, the trend is toward dispersion (Moran, 1950). Thus, Moran's I was used to characterise the spatial patterns of active fire hotspots and produce a Moran scatterplot of FRP values (Anselin *et al.,* 2010). It gives a measure of overall clustering and does not reveal the location of clusters or outliers nor the type of spatial association that may exist in the data (Oom & Pereira, 2012). To overcome these limitations, Anselin Local Moran's I statistic (Local indicators of spatial autocorrelation; LISA) was used to assess the significance of local spatial patterns, and classify the data values into four types of association, with a distinction to local clusters (high-high [HH] or low-low [LL]) or local spatial outliers (high-low [HL] or low-high [LH]) (Mitchell, 2005). A false discovery rate (FDR) detection correction was applied to the data to account for multiple testing and spatial dependency (Mitchell, 2005). A total of 8576 (> 80 % high confidence FRP values) MODIS active fire points in the landscape were used for this analysis. A threshold distance of 1.3 km to each fire point in the landscape was determined with the use of the 'calculate distance band from Neighbour count' in the GIS. Two maps (500 m resolution) were produced showing the active fire hotspot locations in BNP landscape and associated FRP values in the land use areas of the Getis-Ord Gi* statistics (i.e. hotspot map of hot and cool values), and Anselin Local Moran's I (i.e. cluster and outlier map).

Time series analysis (2000 – 2015) using the mean FRP for each of the land use types were plotted to inspect whether there were changes over the 16 years during the policy transition. Spearman's rank correlations (r_s) were used to analyse the time series data to determine whether there was a correlation between (timing) year and mean FRP during the SP (2000 – 2005) and EBP (2006 – 2015) policy periods for all land use areas. Further, the Coefficient of variation (CV: standard deviation/mean value) was used to test for variation in the annual mean FRP during both the EDS and LDS under both policy periods. The data were non-normal, and showed the same distribution and location; and the values were largely skewed to the left, thus non-parametric Wilcoxon-Mann-Whitney U tests for unpaired samples were used to test for differences in the medians in the EDS vs. LDS FRP for the entire park, and in the four landuse areas during both policy periods. The medians and interquartile ranges (IQR) for each land use and respective season, and policy period were presented.

Influence of fire policy, land use and vegetation type on fire intensity

Aggregated distributional statistics (mean, median, maximum and 90th-percentile) of the MODIS FRP values were derived for all active fire hotspots in the four vegetation types in BNP. The maximum MODIS FRP is of interest to researchers as the maximum fire intensity affects vegetation processes like grass and tree response to fire (Trollope & Tainton, 2007; Archibald *et al.*, 2010). The FRP data had an unequal distribution, and unequal sample sizes and variances were apparent in the land use area, and vegetation type data. Thus, non-parametric unpaired Wilcoxon-sign rank tests were used to test for similarities and differences in FRP between the EDS and LDS among the four vegetation types, land use areas, and policy phases (Question 4).

Results

Fire frequency

Influence of fire policy and land use on seasonal fire frequency and spatial distribution

The reconstruction of the BNP fire history using the fire frequency data revealed that in total 93 % (580 725 ha) of the area burned over the 16 years (Figure 5-2). Fifty five percent of all burned areas were burned between one and six times, 33 % between seven and eleven times, and 5 % of the area was burned 16 times. Considering the entire park, the percentage burned area was monotonically negatively correlated to the frequency of burning (r_s = - 0.85) (Figure 5-3). A greater proportion of area burned at a lower frequency (i.e. 2 and 4 times), and as the frequency of fire increased, burned area decreased. Areas which burned frequently (16 times) were located on the borders of BNP, whereas there was an absence of fire on the Okavango and Kwando River systems, and in the area surrounding Omega 1 village in the MUA West. Areas burned less frequently (between 2 and 6 times) were in proximity to the BNP settlements in the MUA East and MUA West. A pattern was identified that indicated a lower fire frequency in the southern section of the MUA West, and in proximity to the edges of permanent wetlands and rivers (Kwando and Okavango Rivers), respectively in the east and the west of the park. In total 7 % (46 675 ha) of the area did not experience fire during the study period. Over the 16 year period a total 203 875 (ha) of burned area (93 %) occurred within the MUA West, and 182 875 ha (98 %) in the MUA East, and 126 00 ha (94 %) occurred in the Kwando CA, and 70 925 ha (81 %) in the Western CA. Overall, a greater frequency of burning was evident in the MUA West, MUA East and in the Kwando CA when compared to the Western CA (Figure 5-4). The Kwando CA distinctly showed a burning regime at a lower frequency (1 – 5 times), and a greater frequency between 6 and 10 times over the 16 years.

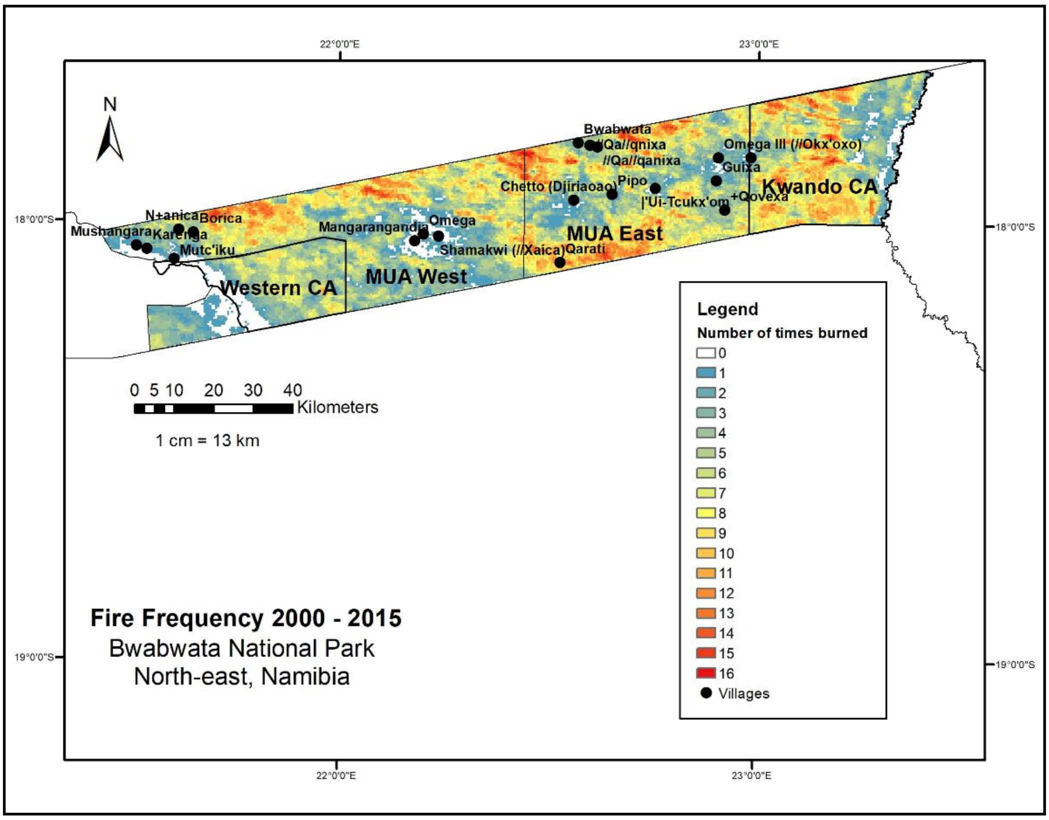


Figure 5-2. The fire affected area (fire frequency) determined for a period of 16 years in Bwabwata National Park derived from MCD45A1 burnt area product (2000 – 2015).

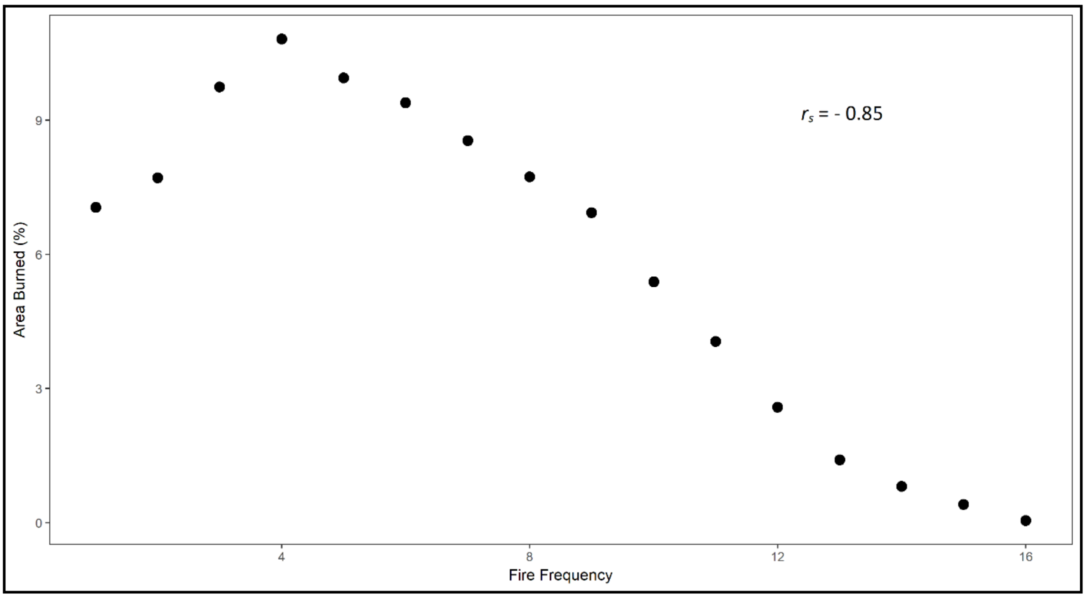


Figure 5-3: A scatter plot showing the negative monotonic relationship between fire frequency (i.e. number of times pixel is burnt) and the percentage of area burned for the entire Bwabwata National Park, 2000 – 2015.

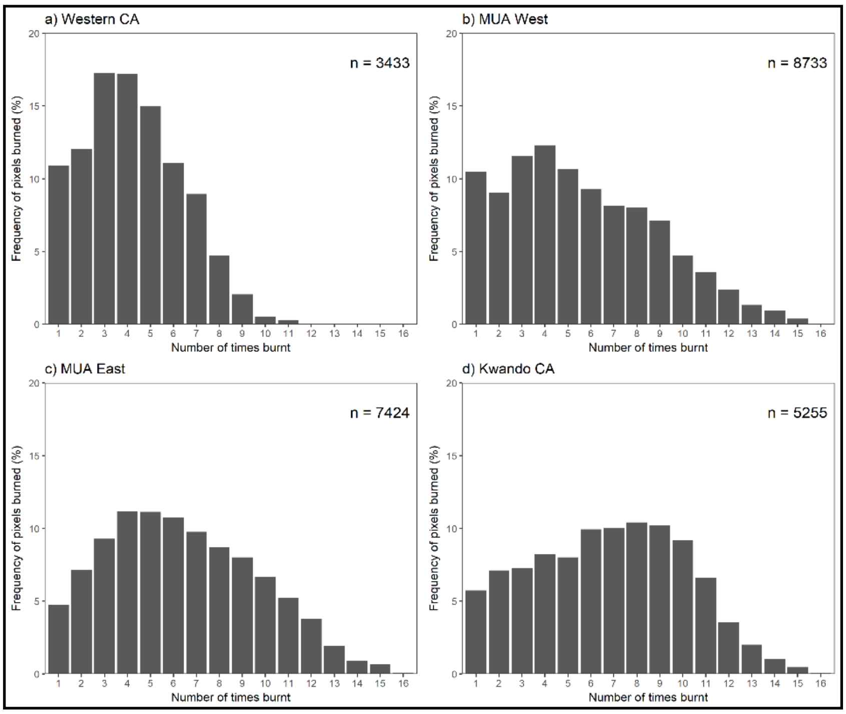


Figure 5-4: Frequency distribution (%) with which individual 25 ha pixels have been classified as burnt over 16 years (2000 – 2015) for a) Western CA; b) MUA West; c) MUA East , and d) Kwando CA in Bwabwata National Park. Data derived from the MD45A1 fire product. Sample size n refers to the number of pixels affected by fire.

Throughout the SP and EBP periods in the BNP the overall burned area over the entire period increased by 20. 4 % (Figure 5-1). Notably, under the SP the MUA East showed the greatest percentage of burned area, however it was the only land use area which showed a decline in total area burned (- 31.7 %) (Table 4-1), and a subsequent decrease in LDS burning, together with the Kwando CA under the two policy periods (Table 5-3).

Table 5-1: Summary of percentage area burned (ha) in Bwabwata National Park, and in each of the land use areas under the suppression policy (SP) and early burning policy (EBP) transition.

	Suppression policy (SP)		Early Burning policy (EBP)		
Land use	Burned area (ha) (2000 - 2005)	%	Burned area (ha) (2006 - 2015)	%	% change
BNP	503 700	80.2	606 825	96.7	20.4
MUA East	178 875	95.7	120 150	64.3	-31.7
MUA West	152 575	69.7	196 000	89.6	28.4
Kwando CA	71 940	53.4	118 725	88.3	65.0
Western CA	50 175	57.4	70 200	80.3	39.9

Overall burned area increased significantly with increasing distance from the villages in BNP ($p < 0.001$). The ANCOVA analysis revealed that both fire policy and distance from village had a significant effect on the seasonal percentage of area burned from villages in the MUA East and MUA West (Table 5-2; Figure 5-5).

Table 5-2: ANCOVA results showing the effect of distance on area burned in the early dry season (EDS) and late dry season (LDS) in the MUA East and MUA West under the suppression policy (SP) and early burning policy (EBP) in Bwabwata National Park.

Treatment	*F value*	d.f	*p*	R^2	Policy: *p value*	Distance: *p value*
MUA East: EDS	11.52	(2,27)	0.0002	0.46	0.0002	0.0396
MUA East: LDS	134.4	(2,27)	0.0000	0.90	0.0000	0.0000
MUA West: EDS	43.13	(2,27)	0.0000	0.76	0.0000	0.0000
MUA West: LDS	42.25	(2,27)	0.0000	0.75	0.0616	0.0000

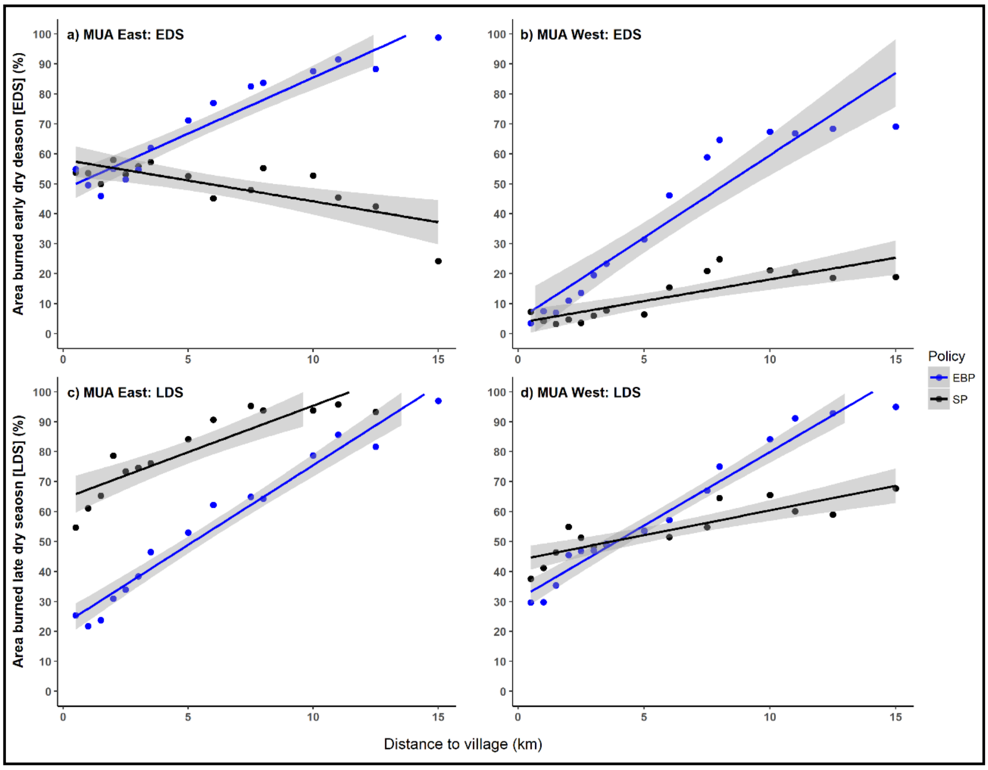


Figure 5-5. The relationship between seasonal burned area (EDS and LDS) and distance from village in the a) MUA East: EDS; b) MUA West: EDS; c) MUA East: LDS, and d) MUA West: LDS and the effect of fire management policy under the suppression policy (SP) and early burning policy (EBP) on the percentage of area burned in the Bwabwata National Park. The grey band around each regression line represents the 95 % confidence interval (CI).

Seasonal distribution of fire during the suppression policy (SP)

A strong spatial and temporal variation in fire occurrence in both the EDS and LDS, in the SP was observed in BNP (Figure 5-6 a, b; Table 5-1; Table 5-3). In the absence of extensive EDS burning (26 %) in the SP, LDS burning was prevalent, and affected 78 % of the BNP landscape. EDS burning under the SP primarily occurred in the MUA East, in the western part of the Kwando CA, and partially in the MUA West in proximity to the settlement areas. The western section of the Kwando CA experienced EDS fires predominantly only once (16 %), whereas in the MUA West (18 %), and in the Western CA only 1 025 ha (1 %) was affected by EDS burning. However, 45 % of the MUA East burnt between one and two times during the EDS. Late dry season burning was prevalent at a higher frequency in the Kwando CA (91 %), and in the absence of EDS burning in the Western CA, half the area was affected by LDS (51 %) (Table 5-3). Overall, the Kwando CA experienced the highest frequency of LDS burning (86 %; 116 025 ha; burnt 1 – 5 times) during the SP when compared to the other land use areas (Figure 5-6; b). Notably, areas in MUA East and Kwando CA were affected by a high incidence of fires in the LDS in the absence of EDS burning in these areas.

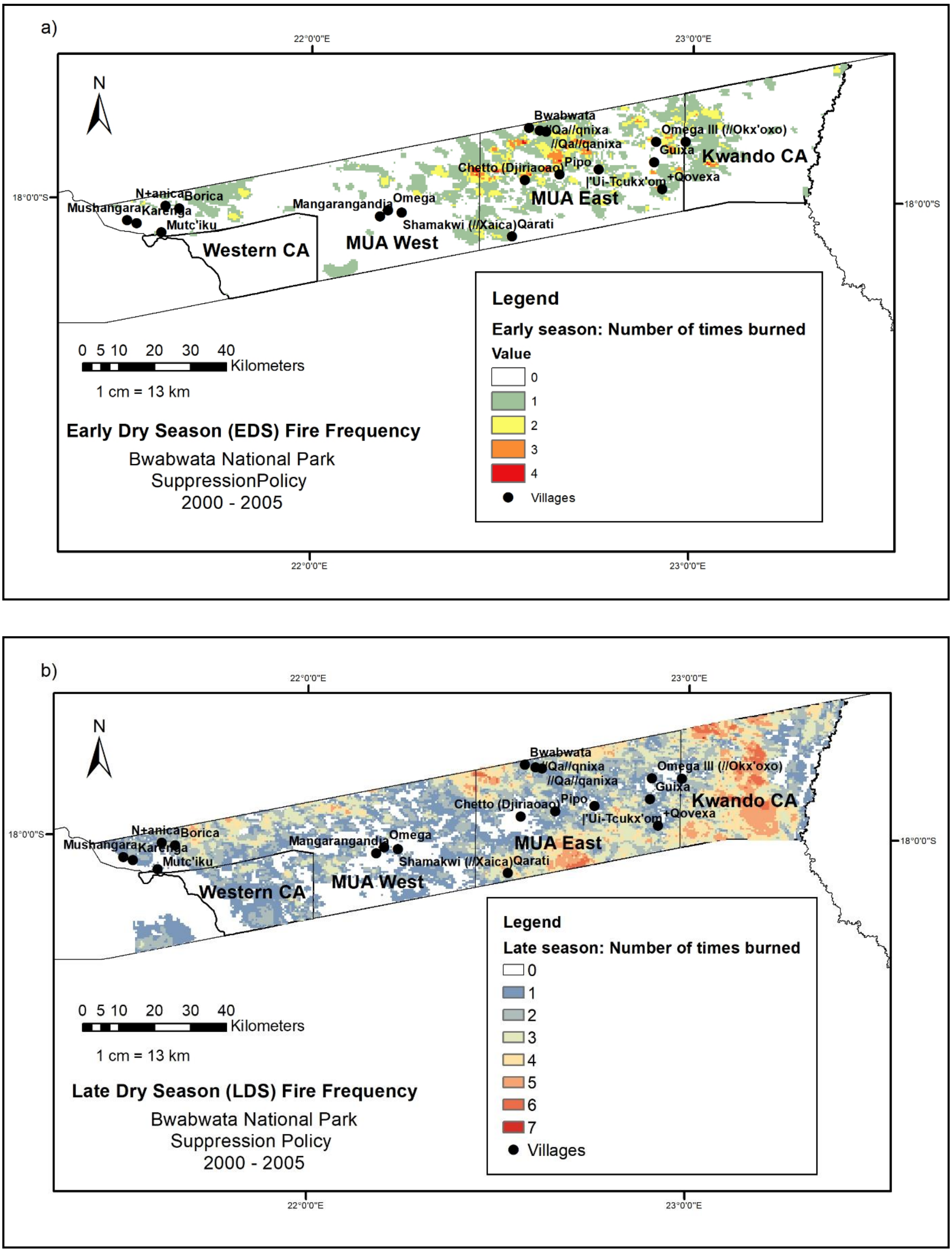
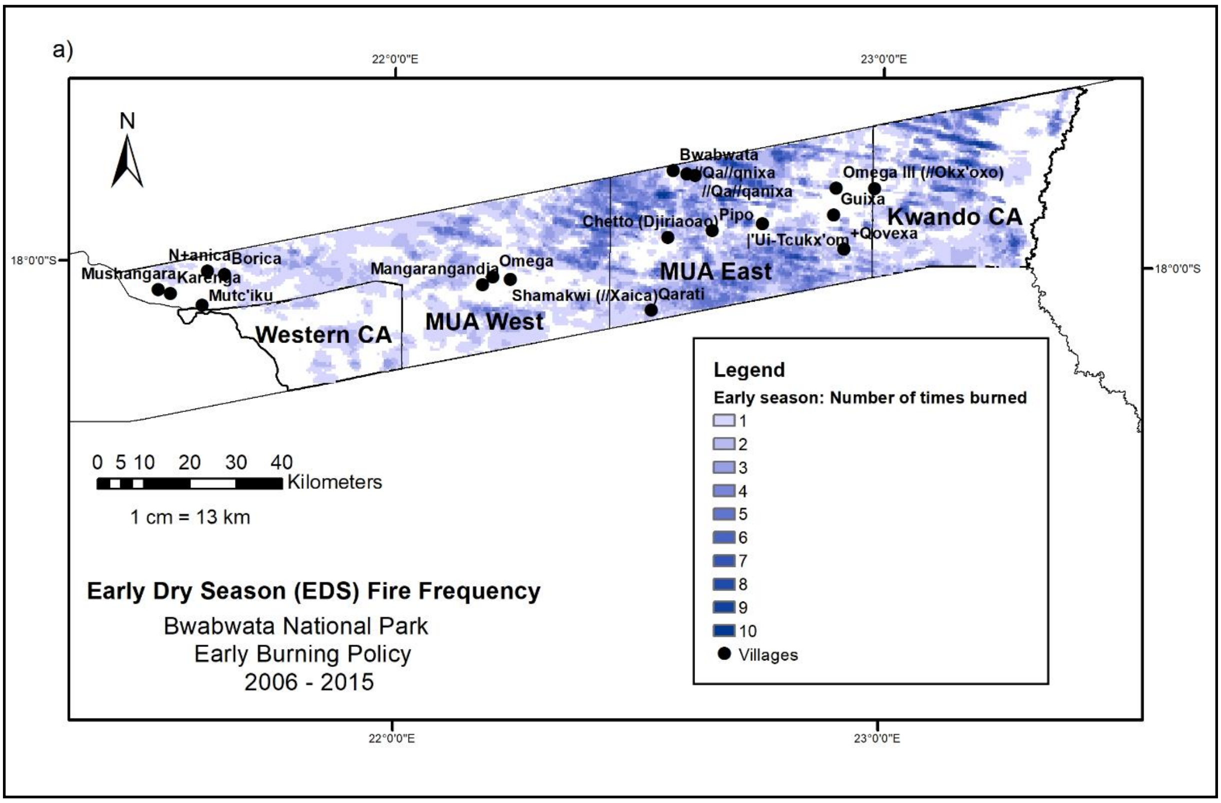


Figure 5-6: Map showing the frequency distribution of a) early dry season (EDS) and b) late dry season (LDS) fires under the suppression policy (SP: 2000 - 2005) in the four land use areas in Bwabwata National Park. Data derived from MCD45A1 burnt area product.

Seasonal distribution of fire during the early burning policy (EBP)

The frequency distribution of the area burnt in the EDS and LDS during the EBP is illustrated in Figure 5-7 (a, b). Conspicuously, the distribution of the LDS fire frequency in the EBP was less in areas which had a higher frequency of burning in the EDS. Explicitly, areas on the border of the eastern land use extents in BNP, in the MUA East and the Kwando CA which showed a higher frequency of EDS burning (5 – 6 times) over the 10 year period, showed a lower frequency of LDS. Specifically, a frequency of EDS (burnt > 4 times) fires reduced the occurrence and distribution of the LDS fires in the MUA East and Kwando CA. Correspondingly, in areas that only burned once in the EDS, the frequency of fire was higher in the LDS. Overall, EDS burning was far more evident in the east of the park, in the MUA East and in Kwando CA, when compared to the MUA West and Western CA. Subsequently, the western areas of the park were subject to higher fire frequencies in the LDS during the EBP. The MUA East village areas rarely experienced LDS burning during the EBP (64 %) relative to the other land use areas (Table 5-3). Conspicuously, frequently burned areas in the EBP occurred during the EDS in the omiramba grasslands in the MUA East and Kwando CA, as evident by the ESE-WNW striations on the map (Figure 5-7 a).

The instigation of the EBP in the BNP management plan coincided with an increase in EDS burning across the landscape in all land use areas (Table 5-3). Analysis of the EDS and LDS fire frequency in the SP and EBP revealed an overall increase in the frequency of EDS burning, and subsequent shift in the distribution of LDS burnt areas in relation to the land use areas in the BNP (Figure 5-7). Thus, while there was a marginal difference in burned area extent between the SP and EBP in the LDS, there was a significant transformation in *where* late season fires occurred in the landuse areas in BNP attributed to the *spread* of EDS burning post the EBP in BNP. Overall, the Kwando CA, the Western CA, and the MUA West showed the greatest increase in the frequency of EDS burning in the park corresponding to the policy change. However, out of all land use areas, LDS burning was most extensive in the Kwando CA throughout both policy periods (SP: 91 %; EBP: 77 %), but when compared to the Western CA, it burnt at a lower frequency.



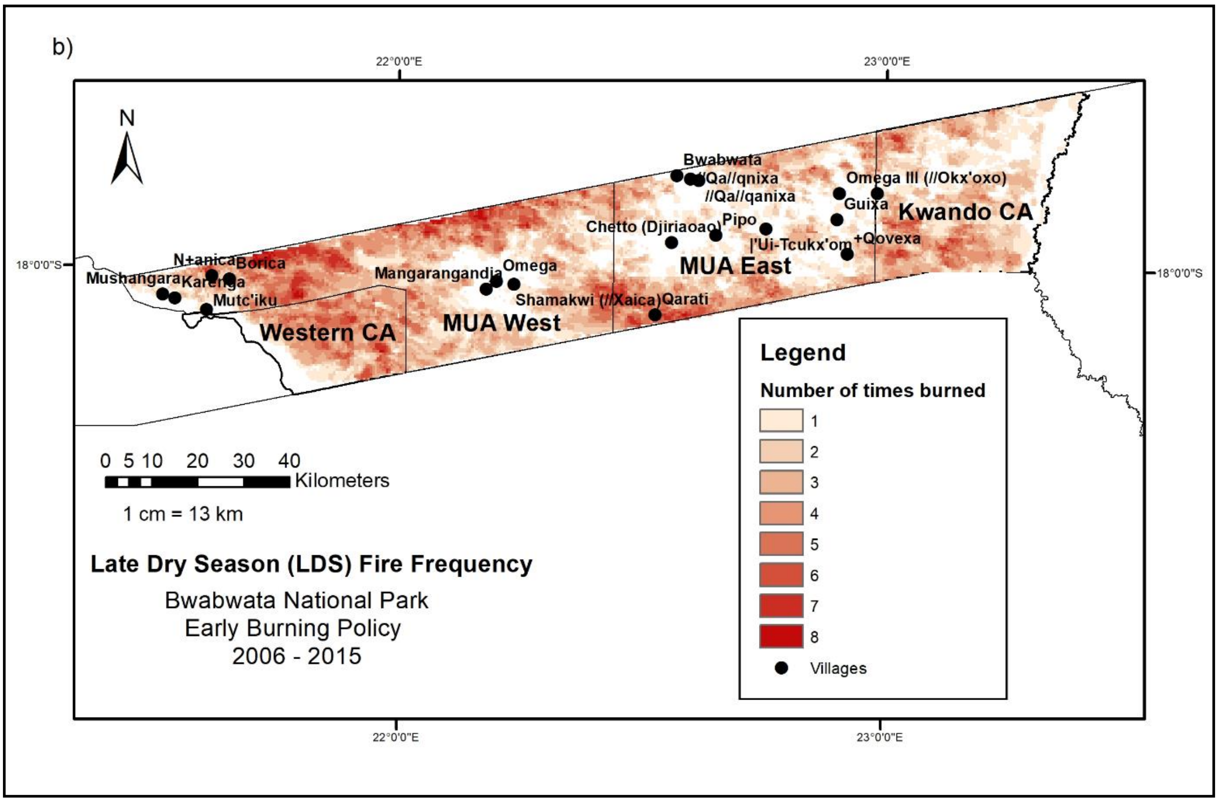


Figure 5-7: Map showing the frequency distribution of a) early dry season (EDS) and b) late dry season (LDS) fires under the early burning policy (EBP: 2006 - 2015) in the four land use areas in Bwabwata National Park determined for 10 years. Data derived from MCD45A1 burnt area product.

Table 5-3: Summary of percentage area burned in the early (EDS) and late dry seasons (LDS) during the suppression (SP) and early burning (EBP) policy transition in Bwabwata National Park (2000 – 2015).

Suppression Policy (SP): 2000 - 2005					Early Burning Policy (EBP): 2006 - 2015					
	Burned area (ha)				Burned area (ha)					
Landuse	Early Season	%	Late Season	%	Early Season	%	Late Season	%	% change: EDS	% change: LDS
BNP	161 050	25.6	484 200	77.1	417 525	66.5	516 150	82.2	159.3	6.6
MUA East	89 200	47.7	166 475	89.1	145 775	78.0	120 150	64.3	64.1	-27.8
MUA West	44 725	20.9	143 350	65.5	131 975	60.3	178 450	81.5	188.5	24.4
Kwando CA	26 000	19.3	122 475	91.0	84 500	62.8	103 000	76.5	225.0	-15.9
Western CA	1 025	1.17	49 975	51. 1	19 725	22.5	65 850	75.3	1 828.2	47.2

Influence of fire policy, land use and vegetation type on frequency of fire and seasonal burned area

The interpreted aggregated average area burnt during 2000 - 2015 in the four vegetation types is presented in Figure 5-8 . Overall the omiramba grasslands (TDS: mean: 47.2; standard deviation [SD] ± 14. 3), and the savanna woodlands (TDS: 36.2; ± 13.0) showed a greater percentage of area burnt in comparison to the Burkea shrublands (TDS: 23.0; ± 15.8) and riparian (TDS: 10.0; ± 5.4) vegetation types for the entire BNP from 2000 to 2015 (Table D1; Appendix D). A multiple comparison of means test revealed that the riparian and Burkea shrublands burned area for the TDS were significantly different from the omiramba grasslands, and savanna woodlands, whereas there was no difference between the latter two (Table D2; Appendix D). Burning in the EDS were similar between the savanna-woodlands and omiramba grasslands, and between the Burkea shrublands and the riparian areas. However, the omiramba grasslands significantly differed from the Burkea shrublands and riparian in percentage area burned in the EDS, whereas the savanna-woodlands showed a similarity to these two vegetation types (Table D3; Appendix D). Notably, the omiramba grasslands showed the largest mean percentage area burnt in the EDS (18.4 ± 14.0). The percentage of area burnt in the LDS were similar for omiramba grasslands, savanna woodlands, and Burkea shrublands, however these respective vegetation types significantly differed from the riparian vegetation type in the LDS (Table D4; Appendix D). Unpaired Wilcoxon rank sum tests revealed statistically significant differences between the EDS and LDS for omiramba grasslands (W = 75; $p < 0.05$), savanna-woodlands (W =33; $p < 0.001$), and the Burkea shrublands (W = 22; $p < 0.001$), but there were no seasonal differences in the riparian (W = 77; $p > 0.05$) vegetation type.

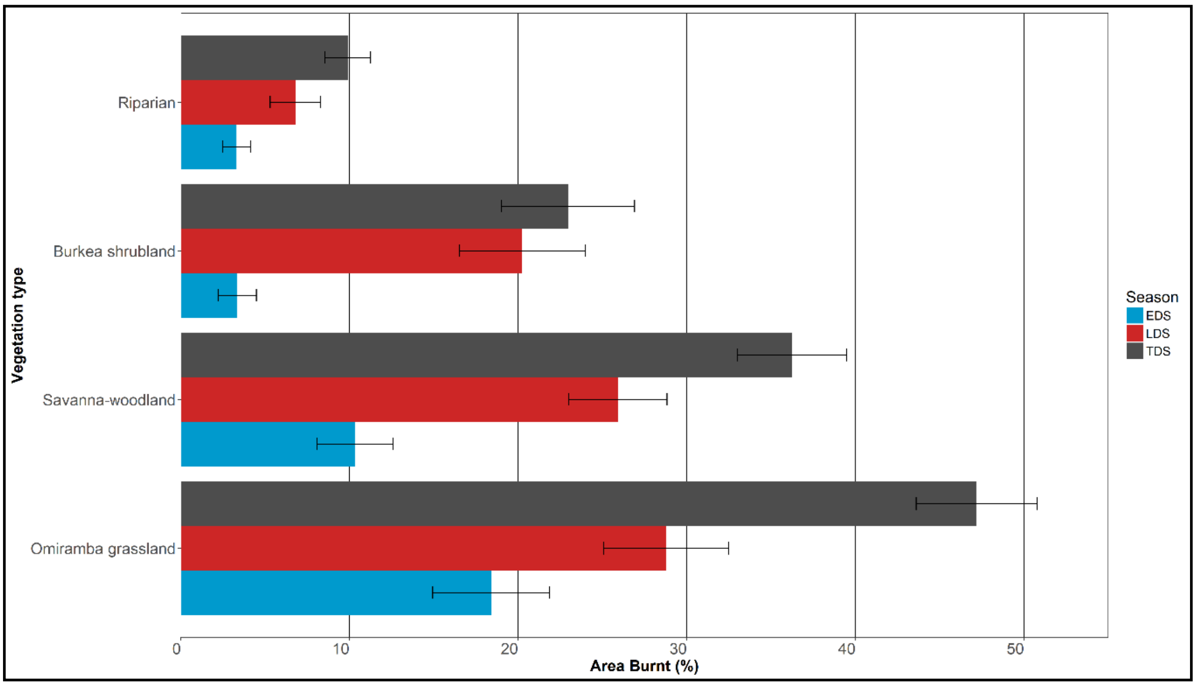


Figure 5-8: Interpreted early dry season (EDS), late dry season (LDS) and total dry season (TDS) fire histories for the four vegetation types in the Bwabwata National Park, 2000 – 2015. (Error bars = SEM).

The seasonal extent of area burned in the four vegetation types, namely, the savanna-woodland, omiramba grassland, Burkea shrubland and riparian is explored in more detail in Figure 5-9 (a – b, respectively). LDS burning was prevalent across all vegetation types during the SP, however decreased post 2006 in BNP. A Spearman's rank correlation showed a significant positive relationship burning in the savanna-woodlands, which was moderately correlated to year (r_s = 0.618), and in the omiramba grasslands (r_s = 0.691) during the EDS (Figure D1; Appendix D). Consequently, burning in the LDS in the omiramba grasslands significantly decreased over time (r_s = - 0.844), and in the savanna woodlands (r_s = - 0.523) over the entire study period. Notably, the rank correlations show a positive relationship with year in the EDS, and a negative relationship in the LDS for both the omiramba grasslands and savanna-woodlands. Markedly, EDS burning in the omiramba grasslands, savanna-woodlands and riparian vegetation types began primarily in 2006 following the implementation of the EBP in BNP. The majority of burning in the riparian area occurred in the LDS, prior to 2006, with an increase in EDS burning thereafter. Burning in the Burkea shrublands occurred mostly in the LDS, with peaks in 2001, 2004, 2008, 2010 and 2012.

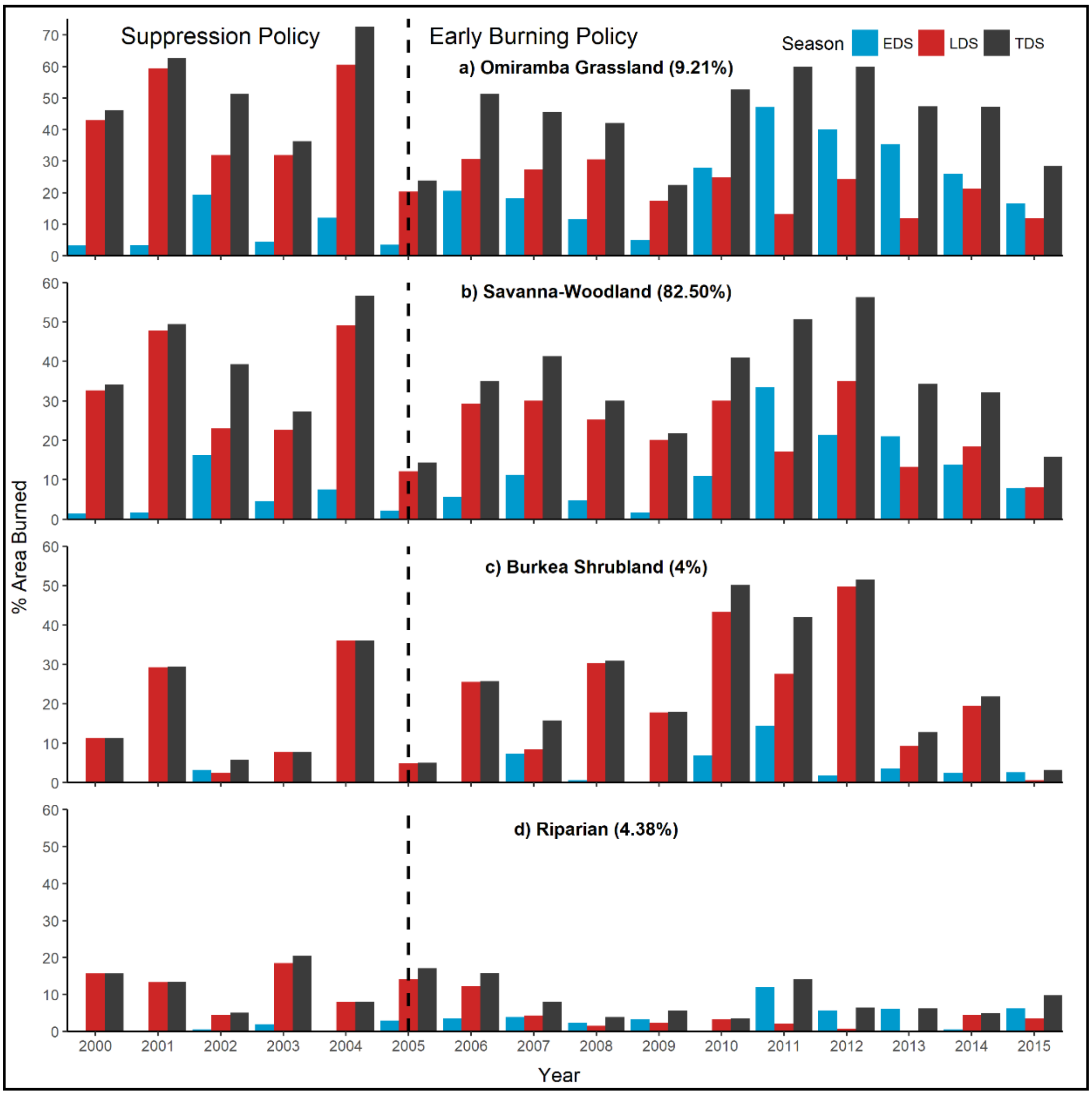


Figure 5-9: Inter-annual variation in the percentage area burnt in the early dry season (EDS), late dry season (LDS) and total dry seasons (TDS) for a) savanna woodland; b) omiramba grassland, c) Burkea shrubland, and d) riparian vegetation types in Bwabwata National Park, 2000 – 2015. Number in parentheses represent the percentage of the park occupied by the respective vegetation types. The dashed vertical line distinguishes the divide between the suppression and early burning policy.

The average percentage of area burnt in the four vegetation types in the respective seasons and land-use areas is presented in Figure D2 and Figure D3 (Appendix D). These data illustrate, that over the 16 year period, the omiramba grasslands and savanna-woodlands had the highest percentage burned area in both the east and the west of the park. Markedly, the omiramba grasslands and savanna-woodlands were more frequently burnt during the SP in the LDS in the east of the park, however during the EBP, burning occurred in the EDS, particularly in the years 2011 to 2014. The MUA West and the Western CA showed the opposite trend with burning occurring in the aforementioned vegetation types during the LDS under the EBP. The riparian areas showed the least area burned, and that burning occurred predominantly in the Kwando CA during the EDS in the EBP, and during the LDS in the MUA West during both policy periods.

The Burkea shrublands were predominantly burnt in the MUA West and Western CA in the LDS over both policy periods, together with the omiramba grasslands and savanna-woodlands. Kruskal-Wallis tests confirmed there were significant differences among the land use areas between the EDS and LDS during the two policy periods in the omiramba grasslands and savanna-woodlands, as well as between the MUA West and the Kwando CA in the SP in the riparian vegetation type (Table D5; Appendix D).

The percentage frequency with which 25 ha pixels have been burnt over the 16 years is presented for the major vegetation types in Figure 5-10. Persistent fires occurred regularly in the omiramba grasslands and savanna woodlands, and recurring fires were less prevalent in the riparian and Burkea shrublands in BNP. The cumulated fire affected area in each of the vegetation types in the respective land use areas is illustrated in Figure 5-11. Most fire activity occurred in the omiramba grasslands and the savanna-woodlands across all land use types, however these two vegetation types were less frequently burnt in the Western CA and in MUA West, than the east of the park. The riparian area is most frequently burnt in the Kwando CA, and the Burkea shrublands in the west of the park, and in particular in the MUA West.

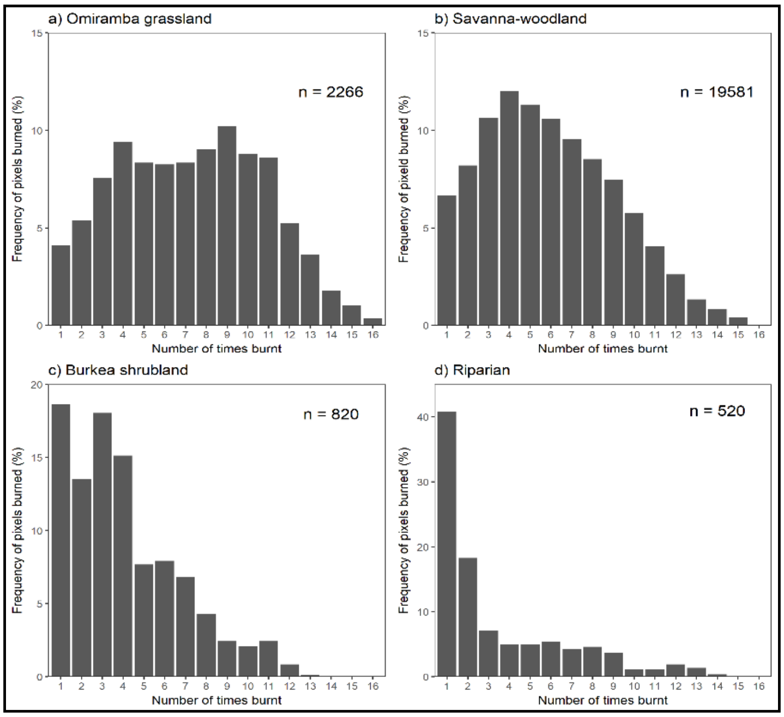


Figure 5-10: Frequency with which individual 25 ha pixels have been classified as burnt in the four major vegetation types a) omiramba grassland; b) savanna-woodland, c) Burkea shrubland, and c) riparian in Bwabwata National Park (2000 – 2015). Sample size n refers to the number of pixels affected by fire.

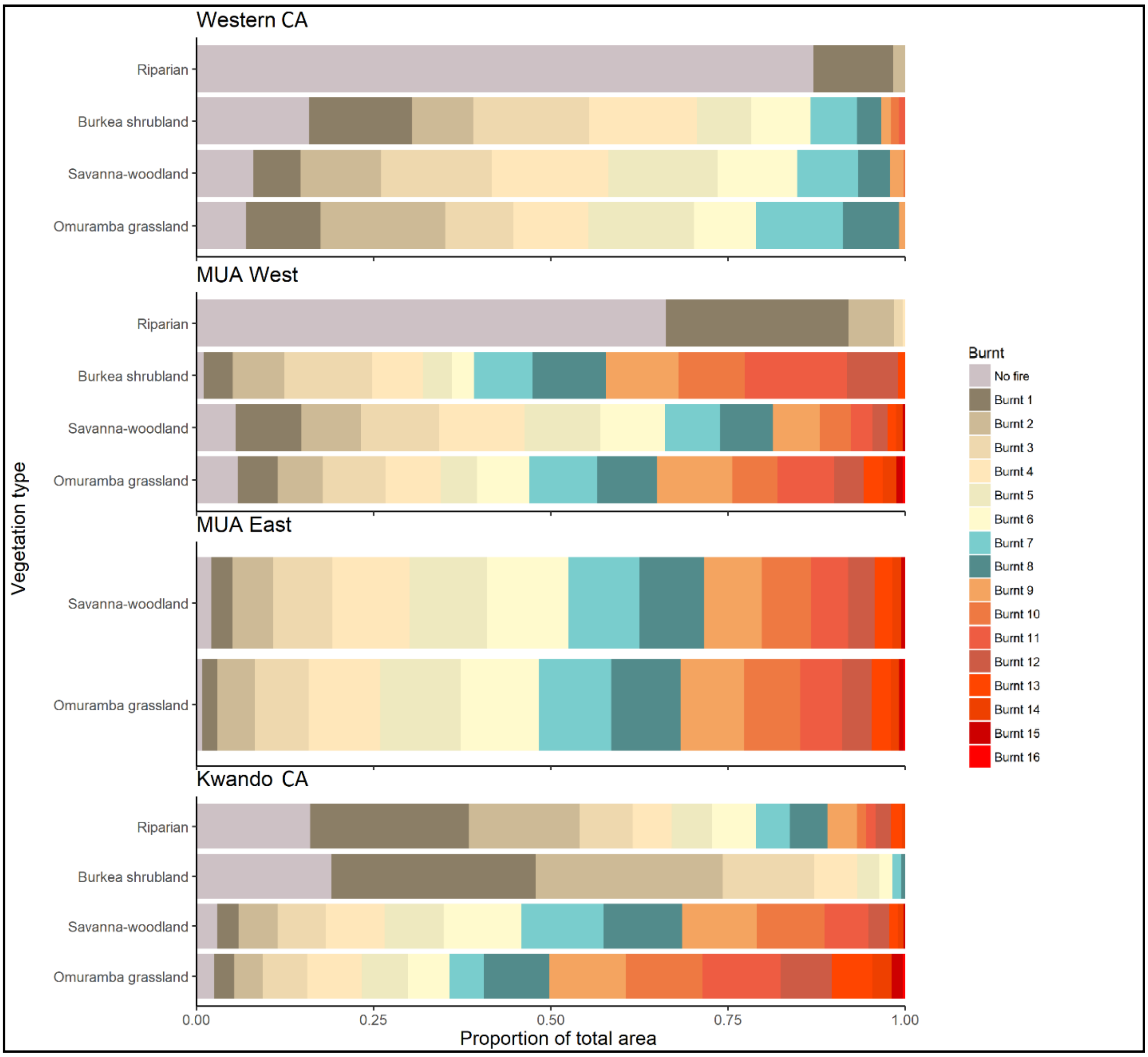


Figure 5-11: The frequency of fire (expressed as the proportion of the total area which burned 0 – 16 times over the 16 years) per vegetation type in the four land use areas in Bwabwata National Park (2000 – 2015). Data derived from the MODIS MCD45A1 product.

Fire intensity

Influence of fire policy and land-use on seasonal fire intensity (FRP)

Based on 1 km resolution data acquired by MODIS Aqua and Terra polar orbiting satellites the annual mean FRP values in BNP ranged between 25. 18 MW (minimum) and 197. 60 MW (maximum), with an overall median of 73.24 MW, and mean of 77.21 MW. The overall minimum and maximum values of FRP per pixel were found to be 3.7 MW and 1445.50 MW respectively for the study period 2000 – 2015. Overall the mean, median and maximum FRP were highest in the Western CA and MUA West, and lowest in the Kwando CA and MUA East (Figure D4; Table D6; Appendix D).

Global Moran's I statistic (0.063) with FRP as a weight field revealed distinct clustering of high and low fire intensity (FRP values) in relation to the land use types in BNP (Figure D5; Appendix D). A z-score of 47.32 indicates that there is less than 1% likelihood that this clustered pattern could be the result of random chance (Figure D6; Appendix D). Figure 5-12 illustrates hot spots (i.e. high values) and cold spots (i.e. low values) in FRP values along a continuum in the BNP landscape, and clearly shows that there is a strong relationship between FRP and land use. The hotspot and cluster analyses maps (Figure 5-13) show a distinct gradient of high to low FRP was evident across the landscape from west to east in BNP. High FRP values were located in the west (Western CA and partially in the MUA West), and lowest were located in the MUA East, and the MUA West, however only in proximity to the villages, and on the western boundary of the Kwando CA. The cluster outlier analysis results showed high-high clusters in the Western CA, MUA West and in Kwando CA, and low-low clusters within the MUA East (Figure 5-13). High-low clusters were identified within the MUA East and MUA West. The cluster outlier analysis results are in direct correlation with Getis Ord Gi* hot spot analysis, confirming hot spots as clusters of high and low values of FRP.

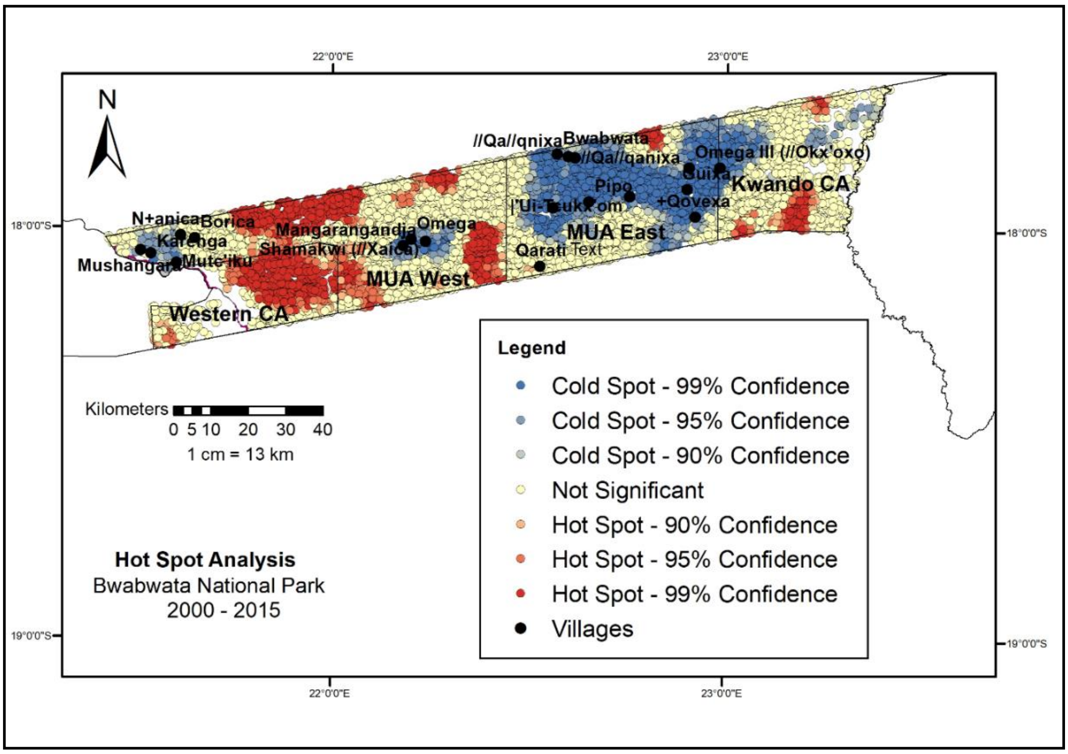


Figure 5-12: Hot spot analysis (Getis-Ord Gi* statistic) showing clustering of hot (red spots) and cold spots (blue spots) based on FRP per 1 km x 1 km pixel (MW) values within the four land use areas in Bwabwata National Park, 2000 – 2015. Data derived from MODIS FIRMS MCD14ML product.

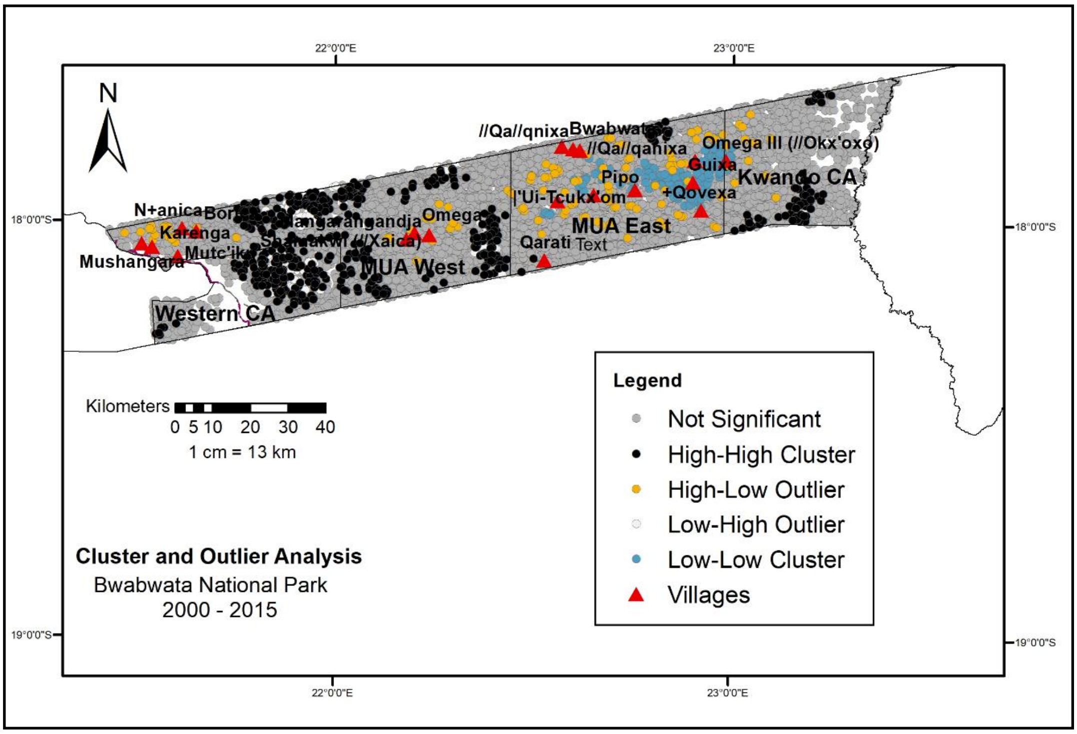


Figure 5-13: Anselin Local Moran's I Cluster and Outlier analysis indicating high-high [HH], low-low [LL], high-low [HL], low-high [LH] clusters of FRP per 1 km x 1 km pixel (MW) values within the four major land use areas in Bwabwata National Park, 2000 – 2015. Data derived from MODIS FIRMS MCD14ML product.

The comparison of multiple means revealed significant differences in seasonal FRP values between the EDS (mean: 47.62 ± [standard deviation] 56.42; median: 29.70; maximum: 869.30 MW) and LDS (mean: 86.60 ± 106. 60; median; 52.20 MW; maximum: 1445.50 MW) in BNP (t = 26.33; $p < 0.001$) (Figure D7; Appendix D).

Annual mean FRP during the EDS and LDS in the east of the BNP (MUA East and Kwando CA) during the 16 year period decreased from 2007 to 2015, whereas the western BNP areas (MUA West, Western CA) showed far greater variation (Figure 5-14). However, the MUA West in comparison to the Western CA showed less variation during both the EDS and LDS in the BNP. Notably, mean FRP significantly monotonically declined in the east of the park from 2009 to 2015 ($r_s = - 0. 42$), however variance in the west of the park could not be explained by year. The Western CA revealed far greater variation between years and the highest values across all land use values with peaks in the years 2005, 2008 and 2011. The MUA East and Kwando CA experienced two peaks in the years 2002 and 2007, where the mean FRP values irrespective of season showed the same trend. A comparison of the average CV amongst season and policy phases within land use areas showed that variance was greatest in the Western CA, and lowest in the MUA East during the LDS under the SP (Table 5-4). In addition, the CV in the MUA East under the SP showed the least variability during both seasons of all land use areas (Table D7; Appendix D). Moreover, and explicitly in the MUA East and MUA West land use areas the average variance exceeded the mean (i.e. > 100 %) in both the EDS and LDS under the EBP indicating there is greater variability in FRP in the inhabited areas of the park versus the CAs (Table D8; Appendix D). Though, the average CV in the EDS was always generally lower in the MUA East than in the MUA West due to frequent burning.

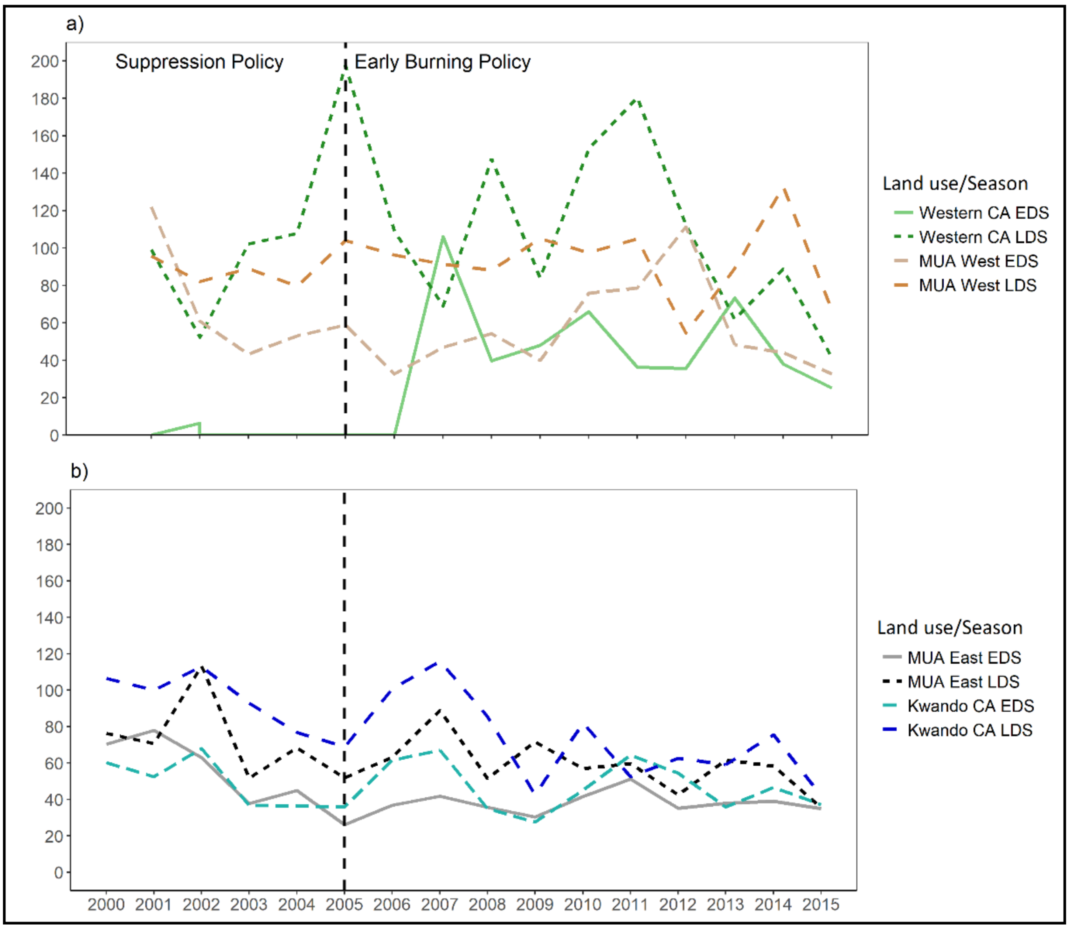


Figure 5-14: Mean FRP (1 x 1 km pixel) in the western a) MUA West and Western CA, and eastern land use areas b) MUA East and Kwando CA during the early dry season (EDS) and late dry season (LDS) in Bwabwata National Park, 2000 - 2015. The vertical dotted line indicates the division between the suppression policy (SP) and the early burning policy (EBP). Note: there was absence of fires in the Western CA during a) EDS (2002 – 2006).

Table 5-4: Comparison of the average percentage of the coefficient of variation (CV) of FRP between the suppression policy (SP: 2000 - 2006) and the early burning policy (EBP: 2006 - 2015) in the early dry season (EDS) and late dry season (LDS) for the four land use areas in Bwabwata national park.

Land use	**SP**	**EBP**
Early Dry Season		
MUA East	42,06	101,23
MUA West	56,45	107,58
Kwando CA	44,32	94,62
Western CA	N/A	81,43
Late Dry Season		
MUA East	77,60	106,93
MUA West	81,46	117,29
Kwando CA	91,90	84,73
Western CA	111,76	82,34

Note: N/A = insufficient values.

The difference in median FRP values in the two policy phases (SP and EBP) during the EDS and LDS for all land use types is illustrated in Figure 5-15, and summarised in Table 5-5 and Table 5-6. For the entire BNP study period there was a significant difference between the EDS and LDS median FRP values, except in the LDS for both policy periods. While the median FRP in the EDS was significantly different from LDS in the MUA East during both policy periods, no differences were detected in the SP or EBP during the EDS in the Kwando CA and the MUA West. The Kwando CA, MUA West, and the Western CA showed similar median FRP in the LDS during the SP, however the Kwando CA FRP significantly decreased in the EDS and LDS during the EBP. The median FRP in the MUA East in the EDS and LDS were significantly different, and lower than all other land use areas, however during the SP the Kwando CA and the MUA East shared similar values in both seasons. Even though EDS FRP values increased significantly in the Western CA following the policy change to early burning, the LDS median FRP values increased irrespective. In addition, LDS FRP values increased in the MUA West during both policy phases. Conversely, values significantly decreased in the LDS in the east of the park. Overall, medians in the LDS declined in the east of park (MUA East and Kwando CA) following the implementation of the EBP, however in contrast the MUA West and the Western CA showed an increase in FRP. Notably, the MUA East showed the lowest FRP values in the LDS in BNP.

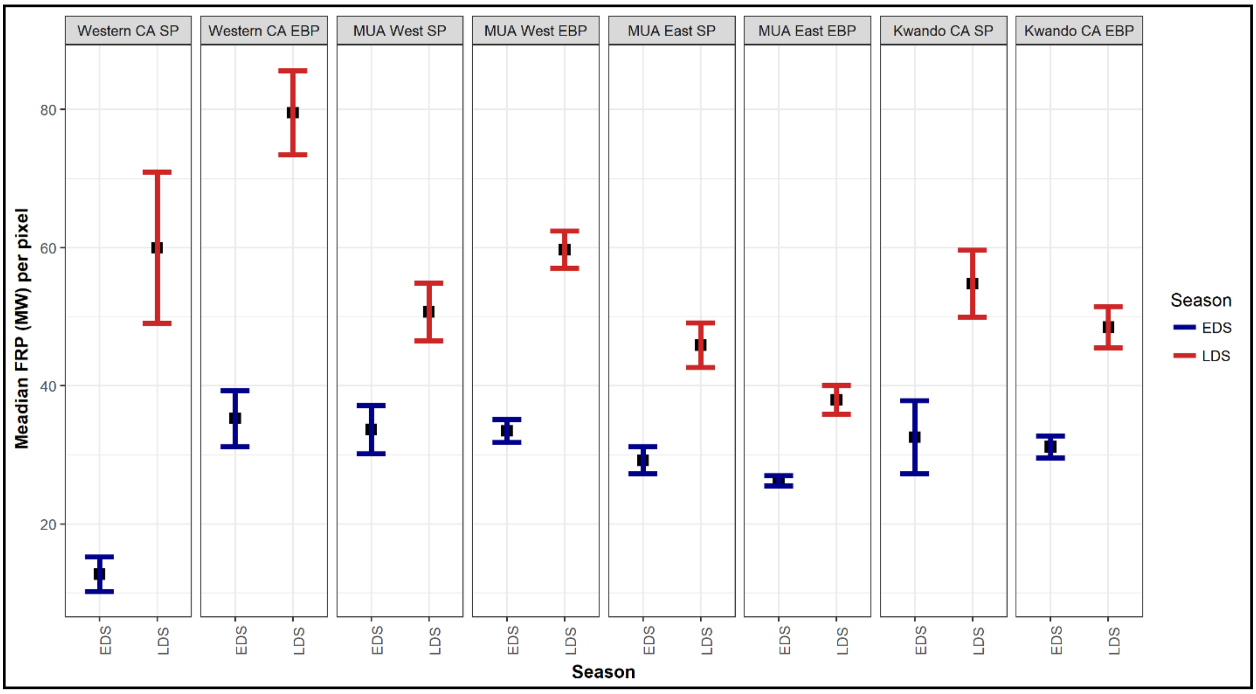


Figure 5-15: Comparison of median FRP (MW) per 1 km x 1 km pixel in the EDS and LDS in the four land use areas during the Suppression Policy (SP: 2005 - 2005) and Early Burning Policy (EBP: 2006 - 2015) in Bwabwata National Park.

Table 5-5: Comparison (Wilcoxon-Mann Whitney U tests - unpaired) of median FRP per 1 km x 1 km pixel in the early dry season (EDS) and late dry season (LDS) for the entire period in Bwabwata National Park, and for each land use area and between SP (2000 – 2005) and EBP (2006 – 2015). Median 1 and 2, and IQR 1 and 2 presented refer to the respective land use areas, and associated fire treatment.

Landuse	**Season**	**Years/Policy**	***U***	**P**	**Median 1**	**Median 2**	**IQR 1**	**IQR 2**
BNP	EDS vs LDS	2000 - 2015	15789000	0.0000*	30.6	52.0	40.4	74.3
	EDS	SP vs EBP	4608300	0.0021*	33.2	30.1	42.5	39.9
	LDS	SP vs EBP	3404600	0.6465	51.1	52.2	73.9	74.8
Kwando CA	EDS vs LDS	2000 - 2015	544810	0.0000*	31.2	50.8	40.5	69.1
	EDS	SP vs EBP	87608	0.5966	33.0	31.0	41.0	40.0
	LDS	SP vs EBP	151840	0.0220*	54.7	48.1	81.5	61.3
Western CA	EDS vs LDS	2000 - 2015	23349	0.0000*	37.0	77.8	48.5	116.8
	EDS	SP vs EBP	N/A	N/A	N/A	N/A	N/A	N/A
	LDS	SP vs EBP	20890	0.0005*	55.3	83.5	77.9	128.0
MUA East	EDS vs LDS	2000 - 2015	2743500	0.0000*	26.8	41.1	33.7	53.1
	EDS	SP vs EBP	976620	0.0321*	29.3	26.3	37.0	32.9
	LDS	SP vs EBP	151840	0.0226*	46.0	38.0	53.0	50.1
MUA West	EDS vs LDS	2000 - 2015	2132300	0.0000*	35.0	56.6	50.9	83.8
	EDS	SP vs EBP	355180	0.4621	33.7	35.3	46.0	52.7
	LDS	SP vs EBP	611300	0.0060*	50.6	59.0	75.5	87.0

Note: N/A = insufficient values; the symbol * indicates significance at the 0.05 level.

Table 5-6: Comparison (Wilcoxon-Mann Whitney *U* tests - unpaired) of median FRP per 1 km x 1 km pixel within land use areas in the early dry season (EDS) and late dry season (LDS) for the entire period in Bwabwata National Park, and for each land use area under the SP (2000 – 2005) and EBP (2006 – 2015) periods. Median 1 and 2, and IQR 1 and 2 presented refer to the respective land use areas, and associated fire season and policy period association.

Land use comparisons	**Season**	**Years/Policy**	***U***	**P**	**Median 1**	**Median 2**	**IQR 1**	**IQR 2**
MUA East vs. MUA West	EDS	SP	95172	0.0032*	29.3	33.7	37.0	46.0
	EDS	EBP	2626000	0.0000*	26.3	34.9	32.9	52.0
	LDS	SP	211630	0.0235*	45.9	50.7	53.0	75.5
	LDS	EBP	869220	0.0000*	38.0	59.0	50.2	87.0
MUA East vs. Kwando CA	EDS	SP	33811	0.2218	29.3	32.9	37.0	41.0
	EDS	EBP	1954600	0.0000*	26.3	30.9	32.9	40.0
	LDS	SP	115550	0.0031*	45.9	54.7	53.1	81.5
	LDS	EBP	372810	0.0000*	38.0	48.5	50.2	61.3
MUA West vs. Kwando CA	EDS	SP	25586	0.4847	33.7	32.9	46.0	41.0
	EDS	EBP	1400100	0.0000*	34.9	30.9	26.7	40.0
	LDS	SP	152400	0.3006	50.7	54.8	75.5	81.6
	LDS	EBP	651530	0.0000*	59.0	48.1	46.6	61.3
MUA East vs. Western CA	EDS	SP	N/A	N/A	N/A	N/A	N/A	N/A
	EDS	EBP	208660	0.0000*	26.3	36.6	32.9	48.4
	LDS	SP	41340	0.0018*	45.9	55.3	53.0	77.9
	LDS	EBP	114720	0.0000*	38.0	83.5	50.1	127.9
Kwando CA vs. Western CA	EDS	SP	N/A	N/A	N/A	N/A	N/A	N/A
	EDS	EBP	94176	0.0127*	30.9	36.6	40.0	48.4
	LDS	SP	32420	0.3486	54.8	55.3	81.5	77.9
	LDS	EBP	70649	0.0000*	48.2	83.5	61.3	127.9
MUA West vs. Western CA	EDS	SP	N/A	N/A	N/A	N/A	N/A	N/A
	EDS	EBP	151000	0.6041	35.53	36.55	52.70	48.35
	LDS	SP	54772	0.0799	50.65	55.30	75.48	77.90
	LDS	EBP	222640	0.0000*	59.00	83.50	87.00	127.93

Note: N/A = insufficient values; the symbol * indicates significance at the 0.05 level.

Influence of fire policy, land use and vegetation type on fire intensity

Overall, the mean and median FRP values were highest for the Burkea shrublands (mean:108.70 ± [SD] 97.94; median: 57.70 MW; (Quartile (Q)1: 30.70 MW; Q3: 111.60 MW, maximum: 741 MW), and savanna-woodlands (66.17 ± 87.10; 66.17 MW; Q1: 21 MW; Q3: 75.50 ; maximum: 1445.50 MW), and lowest in the omiramba grasslands (55.82 ± 70.24, 55.82 MW; Q1: 18.60 MW; Q3: 67.60 MW; maximum: 1064.70 MW) and riparian (46.83 ± 38.17; 46.83 MW; Q1: 20.80 MW; Q3: 58.60 MW; maximum: 228 MW) vegetation types in BNP. There were also significant differences in the means of FRP among all four vegetation types (Figure D8; Table D9; Appendix D).

The difference in median FRP between the two policy phases in the four major vegetation types, and land use areas is illustrated in Figure 5-16, and summarised in Table 5-7 and Table 5-8. Overall, in BNP there were significant differences in median FRP values between the two policy phases in the savanna-woodlands, the omiramba grasslands and riparian vegetation types. The Kwando CA was the only land use type that showed differences within vegetation types (savanna-woodland, omiramba grasslands, and riparian) between policies, whereas no differences were detected between the MUA East, Western CA, nor MUA West in any of the vegetation types. However, there were significant differences in FRP between land use areas under both policy phases evident between MUA East and MUA West; and MUA East and Kwando CA for all vegetation types. Notably, the MUA East revealed the lowest median values in the omiramba grasslands and in the savanna-woodlands across all land use types in both policy periods.

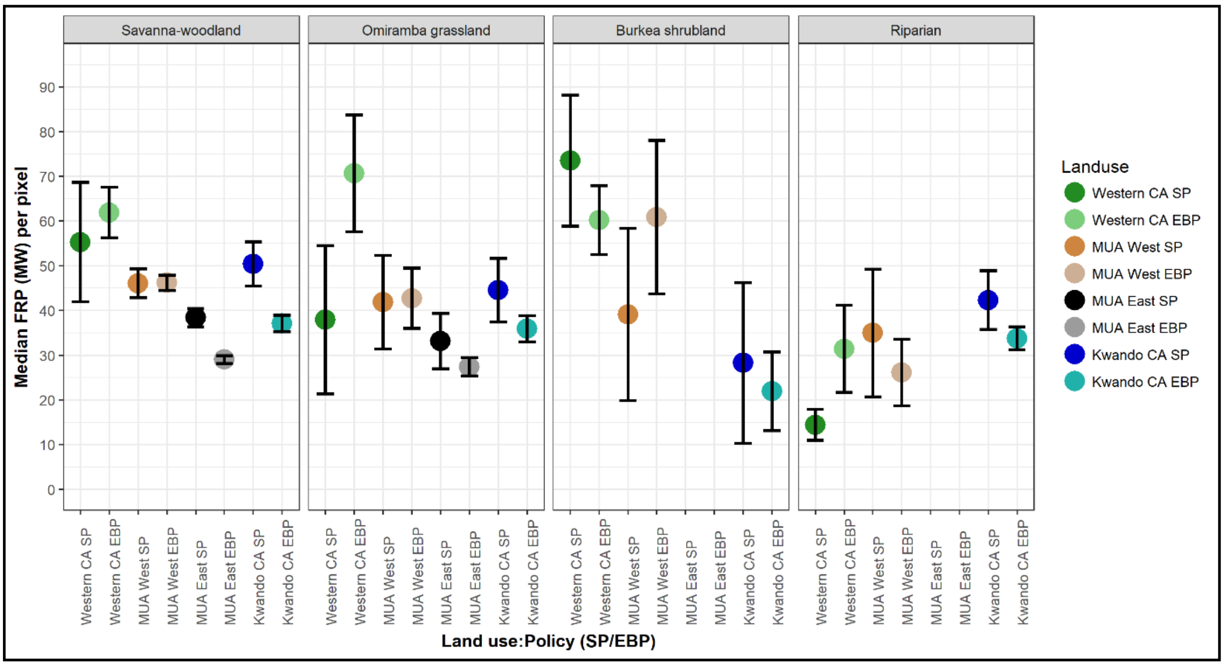


Figure 5-16. Interaction plot showing the median FRP confidence intervals (CI) for each respective land use type under both the suppression Policy (SP) and early burning policy (EBP) periods in the four vegetation types in Bwabwata National Park, 2000 – 2015.

Table 5-7: Comparison of (Wilcoxon-Mann Whitney U test – unpaired) FRP between land use in the four major vegetation types during the policy transition from the suppression policy (SP) to the early burning policy (EBP) in Bwabwata National Park (2000 – 2015). For each comparison, median 1 and 2, and IQR 1 and IQR 2(Interquartile range) refer to the respective proportion of burned area for each vegetation type under each policy period (SP and EBP).

Landuse	Vegetation type	Policy	U	*p*	median 1	median 2	IQR 1	IQR 2
BNP	Savanna-woodland	SP vs EBP	13563000	0.0000*	43.7	36.8	62.9	53.0
	Omuramba grassland	SP vs EBP	189480	0.0148*	37.8	33.6	55.8	46.8
	Burkea shrubland	SP vs EBP	3372,5	0.2271	62.8	52.0	115.8	76.2
	Riparian	SP vs EBP	7282	0.0183*	40.4	33.2	63.5	32.6
Kwando	Savanna-woodland	SP vs. EBP	360020	0.0000*	50.3	37.0	80.0	49.5
	Omuramba grassland	SP vs. EBP	15459	0.0279*	44.6	35.9	64.1	49.6
	Burkea shrubland	SP vs. EBP	42	0.7846	28.2	21.9	29.1	25.4
	Riparian	SP vs. EBP	5208,5	0.0229*	40.4	33.7	65.0	34.3
Western CA	Savanna-woodland	SP vs. EBP	35214	0.4142	55.3	64.9	82.0	105.4
	Omuramba grassland	SP vs. EBP	63	0.7517	37.9	60.8	64.9	50.6
	Burkea shrubland	SP vs. EBP	246,5	0.2677	104.9	56.6	137.3	75.5
MUA East	Savanna-woodland	SP vs. EBP	1747300	0.9238	38.4	29.0	49.3	37.9
	Omuramba grassland	SP vs. EBP	9636,5	0.5904	33.1	27.4	43.6	40.0
MUA West	Savanna-woodland	SP vs. EBP	1747300	0.9238	46.0	46.2	69.8	70.6
	Omuramba grassland	SP vs. EBP	9636,5	0.5904	41.9	42.7	51.4	61.9
	Burkea shrubland	SP vs. EBP	246,5	0.2677	39.1	72.8	88.6	92.3
	Riparian	SP vs. EBP	91,5	0.8610	35.0	26.1	26.7	23.4

Table 5-8: Comparison of (Wilcoxon-Mann Whitney U test – unpaired) within land use areas of FRP in the four major vegetation types under the policy transition from the suppression policy (SP) to the early burning policy (EBP) in Bwabwata National Park (2000 – 2015).

Land use comparison	Vegetation type	Policy	U	*p*	median 1	median 2	IQR 1	IQR 2
MUA East vs. MUA West	Savanna-woodland	SP	474580	0.0000*	38.4	46.1	49.3	69.8
	Savanna-woodland	EBP	5063500	0.0000*	29.0	46.2	37.9	70.6
	Omuramba grassland	SP	3971,5	0.0253*	33.1	41.9	43.6	51.6
	Omuramba grassland	EBP	59376	0.0000*	27.4	42.7	40.0	61.9
MUA East vs. Kwando CA	Savanna-woodland	SP	181190	0.0000*	38.4	50.3	49.3	79.9
	Savanna-woodland	EBP	2512300	0.0000*	29.0	37.0	37.9	49.5
	Omuramba grassland	SP	3836	0.0103*	33.1	44.6	43.6	64.1
	Omuramba grassland	EBP	92632	0.0010*	27.4	35.9	40.0	49.6
MUA West vs. Kwando CA	Savanna-woodland	SP	205770	0.0883	46.0	50.3	69.8	80.0
	Savanna-woodland	EBP	2733700	0.0000*	46.2	37.0	70.6	49.5
	Omuramba grassland	SP	2495,5	0.7013	41.8	44.5	51.5	64.1
	Omuramba grassland	EBP	51176	0.0912	42.7	35.9	61.9	49.6
	Burkea shrubland	SP	38	0.3275	39.1	28.2	88.6	29.1
	Burkea shrubland	EBP	645,5	0.0006*	72.8	21.9	92.3	25.4
	Riparian	SP	123	0.3149	34.9	40.4	26.6	65.0
	Riparian	EBP	1942	0.2099	26.1	33.7	23.4	34.3
MUA East vs. Western CA	Savanna-woodland	SP	59016	0.0000*	38.4	55.3	49.3	82.4
	Savanna-woodland	EBP	522570	0.0000*	29.0	64.9	37.9	105.4
	Omuramba grassland	SP	230	0.2222	33.1	37.9	43.5	64.9
	Omuramba grassland	EBP	3240	0.0436*	27.4	60.7	40.0	50.6
Kwando CA vs. Western CA	Savanna-woodland	SP	29786	0.0619	50.3	55.3	79.9	82.4
	Savanna-woodland	EBP	226380	0.0000	37.0	64.9	49.5	105.4
	Omuramba grassland	SP	171	0.8605	44.5	37.9	49.6	50.6
	Omuramba grassland	EBP	2401,5	0.2069	35.9	60.	49.6	50.6
	Burkea shrubland	SP	9	0.0194*	28.2	105.0	29.1	137.3

	Burkea shrubland	EBP	500	0.0008*	21.9	56.0	25.4	75.5
	Riparian	SP	147	0.0246*	40.4	14.4	65.0	5.5
	Riparian	EBP	1929	0.5982	33.7	31.4	34.3	25.4
MUA West vs. Western CA	Savanna-woodland	SP	76138	0.0017*	46.05	55.30	69.77	77.70
	Savanna-woodland	EBP	743440	0.0000*	46.20	61.90	70.60	95.50
	Omuramba grassland	SP	163	0.7330	41.85	37.90	51.40	64.90
	Omuramba grassland	EBP	2386.50	0.0661	42.70	70.65	61.90	73.90
	Burkea shrubland	SP	194	0.1156	39.10	73.50	88.63	113.45
	Burkea shrubland	EBP	3993.50	0.6507	60.90	60.20	88.10	76.75
	Riparian	SP	223.50	0.0852	34.95	55.25	26.75	78.65
	Riparian	EBP	305	0.6059	26.10	31.40	23.40	25.54

Note: The symbol * indicates significance at the 0.05 level.

Discussion

Influence of fire policy and land use on seasonal fire frequency and spatial distribution

High fire frequency and intensity have consequences for vegetation structure, composition and function (le Roux, 2011), as well as for people's livelihoods, and fire frequency is therefore an important management focus (Gill, 1975). Intense fires usually occur in the late dry season and are more damaging than low intensity fires in the early season, which allow a greater variation of fire-resistant and fire-sensitive to occupy a savanna (Bond & Zaloumis, 2016). In BNP, over the entire 16 years, a total of 93 % of the area burned, with the highest burn areas and the lowest burn frequencies in the EDS near villages. Thus, contrary to my hypothesis i) lower burn frequencies were detected near villages, with corresponding higher burn areas. This amount of burned area decreased as the frequency of fire increased. Thus unexpectedly, low fire frequencies occurred in proximity to villages in the MUA during the 16 years, where a conspicuously greater area was burned during the EDS, which resulted in the removal of biomass that reduced the frequency of LDS fires. Mbongo *et al.* (2011) similarly reported low fire frequencies around settlements in the greater Caprivi region. These EDS fires were purposefully set by the Khwe and Mbukushu people in support of their livelihood needs (e.g. protection of veld food resources from the LDS fires, and pasture fires to stimulate the growth of grass for wildlife and livestock, and included park management fires (Stakeholder interviews, BNP, Namibia, 2014 & 2015).

Contrary to my hypothesis where I expected fewer fires on the neighbouring Angolan and Botswana borders due to unregulated fire management, the BNP border areas were frequently burnt ($\geq$ 16 times) with reoccurring LDS fires ensuing likely due to fuel accrual over time in the absence of any extensive EDS burning (Figure 5-2; Figure 5-6; Figure 5-7). The high fire frequencies alongside the borders are indicative of probable transboundary fires in the protected areas in Angola (Luiana Partial Reserve) and in Botswana (Okavango Delta and Linyanti Game Reserve) flanking the BNP. Botswana still holds a policy of fire suppression which has been in place for the last 20 years (Pricope & Binford, 2012; Southworth *et al.,* 2016). Moreover, research in Angola established there has been an increase in the extent of uncontrolled burning for subsistence agriculture and hunting, as well as to increase mid-dry season fires both within and outside protected areas (United States Department of Agriculture [USDA], 2006). The incidence of fires along international borders signals the need for collaboration and cooperation between neighbouring countries and fire stakeholders (Kazapua *et al.,* 2009), as there are likely to be structural changes to the vegetation with repetitive LDS fires. Thus, integrated management efforts on EDS burning ought to be addressed by trans-border fire management alliances between the KAZA TFCA and MET, together with the local communities to reduce the occurrence of these repetitive LDS fires (Beatty, 2014).

Nevertheless, as hypothesized, low fire frequencies (burned ≥ 2 times out of 16 years) were also detected along the Kwando and Okavango Rivers, and adjacent floodplain areas, which are likely due to the drying out of the grasses located on the edges of the floodplain areas that are infrequently burnt by park management during the EDS. Fire was absent along the Okavango River, and the connected floodplains situated in the Western CA, and the Kwando River in the Kwando CA, which is attributed to the high frequency of flooding, presence of permanent swamps, and seasonal marshes (Mendelsohn *et al.*, 2010) that would limit the occurrence of fire. Similarly, Omega 1 village (a former SADF military base) located in the MUA West did not experience any fire, since there is no vegetation to burn (pers. observation), and any growth is likely cleared by the residents to prevent fire from entering the village in the LDS. Further, a few people in this area keep cattle (Brown & Dieckmann, 2014), which would further reduce the fuel load, and occurrence of fire.

With regard to the change from fire suppression to EBP, results confirmed my hypothesis that EDS burning would increase, and spread through the BNP landscape after the policy change, reducing the extent of area burned in the LDS. The ANCOVA analysis revealed that both policy and distance from village had a highly significant effect ($p < 0.001$) effect on the seasonal frequency of fire in BNP. The effect of EDS burning on the area affected by LDS was more distinct in the MUA East, than in the MUA West (Figure 5 a – d). The dissimilar seasonal burning patterns observed between the MUA East and West is attributed to the differences in cultural livelihood practices. Since in the east the inhabitant Khwe people are 'gatherers', whilst in the west, the Mbukushu are predominantly crop farmers who regularly burn prior to the onset of the rainy season (Oct – March), during the late dry season and some fires are known to burn out of control (Stakeholder interviews, BNP, Namibia, 2014 & 2015). Furthermore, this result could also be partially attributed to the fear of people in the villages to use fire during the suppression policy, whereas after the EBP, the Khwe and Mbukushu people may have been more inclined to use fires in the EDS. Moreover, the BNP game guards are similarly likely to have contributed to the extent of EDS burning after the EBP policy, as it is their responsibility to burn in the MUA, alongside the CAs. Thus, overall the spread of EDS burning is a result of both the park's EDS burning strategies in combination with the communities use of early season fires following the enactment of the EBP in the park.

Furthermore, the comparisons of the extent of area affected by EDS and LDS fire frequency, together with spatial distribution maps of seasonal burning patterns revealed that the frequency of fire in the MUA East, and Kwando CA, created a fine scale mosaic of burnt areas in the EDS, which affected the distribution and frequency of burning in the LDS (Figure 5-6 a; Figure 5-7 a). Conversely, the LDS fire frequency was still persistent in the Western CA and MUA West during the EBP due to the absence of EDS burning. These results suggest that the shift in policy had most effect in the MUA East, and in the Kwando CA, suggesting a shift in behaviour, as well as in management, and indicates that the EBP has been successfully implemented in these areas. However, this shift was not observed in the MUA West nor in the Western CA. This observation could be attributed to the remoteness of the park station, and possibly less of a presence of park management, and subsequent attention to EDS fires, versus the Kwando CA, which is situated in close proximity to the park headquarters (Suswe) and the town Katima Mulilo, where the MET head office is based.

Nevertheless, due to the high frequency of fires (especially EDS fires), in the aforementioned land use areas, there are relatively few areas that have remained unburnt, or burnt on a few occasions only, over the study period. The high frequency of burning in the MUA East and Kwando CA in the EDS, may affect the fire intolerant tree species in the area, such as Burkea (*Burkea africana*) and Kiaat (*Pterocarpus angolensis*), as they are threatened at the seedling recruitment stage (Curtis & Mannheimer, 2005). However, a positive aspect of the EDS burning concerns the re-distribution of the LDS fires in the east of the park. Long-term experiments have shown that EDS burns allow a much broader range of fire-resistant and fire-sensitive species to occupy a savanna (Bond *et al.*, 2005; Higgins *et al.*, 2007; Bond & Zaloumis, 2016). Though, important woodland tree species, such as Zambezi Teak (*Baikiaea plurijuga*) are fire sensitive, and frequent intense LDS fires may change a mature teak woodland into a shrub dominated landscape (Burke, 2001; le Roux, 2011). As evident in the Western CA where repetitive LDS burning has resulted in the removal of large trees over time, and the proliferation of low multistemmed shrubs (Figure 5-17). There are important issues concerning the response of the ecological system to fire, however a detailed analysis of the impacts of fire frequency on vegetation species composition and structure were beyond the scope of this chapter. Archibald (2016) emphasized that the impacts of changes in fire season on fauna and flora have not been adequately addressed in Africa.

Figure 5-17: A site in the Western CA showing a large *Burkea africana* (Wild syringa) tree in the foreground surrounded by a dense cover of *Bauhinia pertersiana* (Kalahari white bauhinia) shrubs indicating that this area has been exposed to a high frequency of LDS fires.

Laris's (2002) study in Mali revealed similar results, whereby EDS burning by Malian's resulted in a patch mosaic effect, of burnt, and unburnt patches, and recently burned areas that reduced the effect of the larger late season burns. Extensive research in the northern territories of Australia in Aboriginal land management practises and the use of early dry seasonal burning patterns (Russell-Smith *et al*., 1997; Bowman, 1998; Bowman *et al.,* 2004; Yibarbuk *et al.,* 2001; Russell-Smith *et al*., 2013) show comparable findings, with the ensuing reduction of late season fires. Further, my results are analogous with those of Pricope & Binford (2012), where they determined an increase in ignitions after the introduction of EDS burning program, and a subsequent shift in fire seasonality in BNP. Overall, the current stance of 'cool' fire regimes in densely settled parts of Africa is that they would be the least damaging to ecological structure and function (Bond & Zaloumis, 2016).

Influence of fire policy, land use and vegetation type on frequency of fire and seasonal burned area

In savanna systems, it is the grass that provides the majority of fuel for fires, and is an important determinant of fire frequency (Bond, 1997). As hypothesised, the omiramba grasslands and savanna woodlands were the most frequently burned in both dry seasons out of all the vegetation types due to the presence of flammable fine grasses in the low-lying fossil drainage omiramba features, and between the savanna-woodland trees in all land use areas in BNP. However, in contrast to my hypothesis, the riparian areas were the vegetation type least affected by fire in the park. However, burning was concentrated in the EDS after the EBP in the Kwando CA in the riparian area, and was likely due to burns applied by the game park wardens. Furthermore, the Kwando River flows are held up by extensive reed beds in Angola a further 300 km north of where it flows into Namibia, and peak flows only reach BNP in July (Mendelsohn & Weber, 2011), which explains why these areas were least affected by fires, and why the moist grasses on the fringes of the floodplains were infrequently burnt in the EDS. The riparian areas in BNP are also characterised by tall riparian trees along the river banks, which shade out the grass layer, and further explains the absence of fire. The Burkea shrublands were largely burned in the LDS, and were shown to be more frequently burned in the MUA West and Western CA than in the Kwando CA where burning was generally infrequent for this vegetation type. Some areas of the Burkea shrublands are characterised by 50 % shrub cover, however typically comprise dense stands of trees (< 4 m in height) (Mendelsohn & Roberts, 1997), which would result in an intermittent grass layer (due to the trees shading out the grass) and less fire. Frost & Robertson (1997) emphasised that in woodlands and shrublands, where there is generally a lower biomass and more uneven distribution of fuel, fires tend to be less intense.

During the SP in BNP, the grasslands and savanna-woodlands were largely burnt in the LDS. However, as hypothesized, this changed during the EBP, where the burning of these vegetation types mostly occurred in the EDS, and subsequently LDS burning decreased, which is attributed to the removal of the fuel load earlier in the season. The evident increase in EDS burning in the MUA East, MUA West and the Kwando CA particularly between the years 2011 and 2014 is possibly attributed to the above average antecedent rainfall identified between the years 2009 and 2011 (Figure 4-4 B; Chapter 4) associated with the ENSO La Niña event (refer to Chapter 4 for details). People frequently set fire to the grasses when they burn, and it is likely the reason for the extensive burning in grasslands and woodlands in the MUA East because of EDS burning carried out by the inhabiting communities and/or the game park wardens, and within the Kwando CA after the policy changed to early season burning. Fine vegetation fuels or dead fuels desiccate rapidly after the dry season starts, and are thus predisposed to early season fires, as in the case of grasslands and savannas (Le Page *et al.,* 2010). Further, in agreement with my hypothesis, the shrublands were shown to be frequently burnt in the LDS in both policy periods, which as suggested may be attributed to the absence of grass and EDS burning. Thus, the area burnt in the grasslands and in the more densely wooded vegetation types, such as the Burkea shrublands in BNP, were a result of the seasonal vegetation burning patterns observed in relation to the use of fire in the land use areas, together with the vegetation type susceptibility to fire and the associated availability of grass to burn. The EDS burning practises in the MUA East and Kwando CA have implications for understanding land-atmosphere exchanges of carbon. Since, at the landscape level the combustion efficiency of grassland fires increases as the fuel becomes drier towards the end of the dry season (Korontzi, 2005). Thus, early season fires generally emit less oxidized products such as carbon dioxide into the atmosphere (Korontzi *et al.*, 2003).

Archibald (*et al.*, 2010; 2016) highlighted that the majority of tropical grassy ecosystems (savannas) burn far more than any other vegetation type, and Robert's (*et al.,* 2009) highlighted that grasses burn a significant amount of fuel than shrublands (Frost & Robertson, 1987; Archibald *et al.,* 2010). Further evidence for this is provided by the fire frequency data in the respective vegetation types, where fires were frequent in the omiramba grasslands and savanna-woodlands, for all land use areas, although there was gradient of increasing fire frequency, with lowest in the west, to highest in the east of the park. These findings are in agreement with Archibald *et al.* (2010), who showed similar evidence, although across the whole of the southern African sub-region.

Fire intensity

Influence of fire policy and land-use on seasonal fire intensity (FRP)

In this study, FRP was used to test for differences and similarities between areas where people reside (MUAs) and within cordoned off protected areas that exclude people (core conservation areas). The results confirmed the hypotheses that fire intensity (FRP values) are lower in the land use areas where people frequently use fire, and higher in areas where fire is less frequent in BNP. These results suggest that there is a strong relationship between FRP, the seasonal use of fire, fire density, fire frequency and land use practises. Thus, land use and associated seasonal burning patterns are correlated to FRP, showing that an increase in fire frequency, reduces overall fire intensity over time, and conversely less fire, increases intensity. FRP generally decreases as human land use increases, except in areas under cultivation in arid shrublands (Archibald *et al.*, 2010). The hotspot and cluster analyses highlighted a distinct gradient of high to low FRP across the BNP landscape from west to east, which follows a gradient of people density and frequently burned areas in relation to different livelihood practices.

Further, the results partially confirmed my hypotheses that FRP would be higher in the LDS and SP due to less frequent burning and high fire risk weather conditions, and lower in the EDS, and EBP due to more frequent burning, and greater moisture content of the grass sward. Results suggest that early season burning practises in the BNP which subsequently increased post-2006, reduced the amount of biomass availability, and decreased FRP specifically in the MUA East and Kwando CA areas. Thus, people, when they are enabled to light fires can manipulate fire intensity by altering the time of burning, and therefore the seasonality of fire occurrence (Archibald, 2016). This was specifically evident in the variation in mean FRP values between the west and east of the park during the two policy periods in the EDS and LDS. Notably, FRP values in the EDS were significantly lower than values in the LDS for all land use areas, and during both policy stages. However, FRP in the LDS where fire was used extensively in the EDS in the MUA East and in the Kwando CA showed significantly different and lower values than the land use areas in the west of the park, where burning was less frequent. Thus, even though FRP was lower in areas where fire was used most extensively in the EDS, there was still a seasonal, and thus a climatic influence on FRP. Increased fire intensity is generally associated with high fire risk weather conditions (e.g. increasing temperature, lower humidity, and fuel moisture conditions, and strong winds) in the dry season (Oliveria *et al.,* 2015), and thus seasonal changes in ignitions alter fire intensity (Archibald, 2016).

However, remarkably and in contrast to hypothesized, the analysis of the CV during both seasons and policy periods across land use areas revealed greater variation in FRP in the inhabited areas versus the CAs. In the years 2002, and 2009 to 2012 in both the MUA East and MUA West, and only in 2010 in the CAs (Table D7; Table D8; Appendix D), the variance exceeded the mean FRP in the LDS. However, this could be an effect of the increase in rainfall, and ensuing available fuel load, which resulted in an increase in the variability of FRP in the inhabited land use areas, and in the CAs (2010) under the respective policies in the LDS, since FRP is correlated to biomass availability (Wooster *et al.,* 2005). Specifically, the antecedent rainfall in 2009 and 2010 showed above average rainfall of 948 mm and 888 mm respectively in BNP (Figure 4-4 B; Chapter

4). Govender *et al.* (2006) reported in Kruger National Park (KNP) that mean fire intensities were positively correlated with mean annual rainfall, which reveals the relationship between rainfall, associated accruing biomass and increasing fire intensity. Thus, although frequent early burning in the east of the park (MUA East; Kwando CA) decreased overall intensities, differences in seasonal fire frequencies, burned area, and fire intensities were attributed to the availability of seasonal fuel moisture, and grass laden fuel after above average rainfall periods in BNP.

My findings were similar to Edwards *et al.* (2008), Williams *et al.* (2009), and Oliveria *et al.* (2015) in northern Australia where they showed that fires lit in the EDS are smaller and less intense than fires in the LDS. In contrast, the findings of Archibald *et al.* (2010) research in the southern African sub-region, revealed no obvious increase in fire intensity from the early to late season. The reason for the disparity between Archibald's *et al.* (2010) and this study's findings, where distinctive seasonal, frequency and policy differences in FRP values were evident in the CAs, and people-inhabited areas, could be related to the difference in scale and temporal aspects of the two studies. Archibald's *et al.* (2010) study incorporating FRP pixel values which covered the sub-regional scale over a single year, whereas this study presents a fine scale analysis over 16 years. Further, the sub-regional scale analysis could have resulted in the saturation of FRP values as a result of the mosaic of land use areas in southern Africa integrated amongst the vegetation types analysed, resulting in a loss of resolution between the EDS and LDS. In BNP, areas less frequently burned (Western CA and MUA West) showed a higher fire intensity when compared to the frequently burned areas of the east of the park. Similarly, Palumbo *et al.* (2011) showed that protected areas in sub-Sharan Africa revealed higher intensities than buffer areas surrounding parks, and that the mid- or late-season fires had higher intensities than the early fires. Correspondingly, research in KNP showed higher fire intensities in the dry season related to lower moisture content of the vegetation, though a 50 % increase in mean annual rainfall corresponded to an increase in intensity (Govender *et al.,* 2006). Moreover, Govender's *et al.* (2006) study found no significant differences in mean fire intensities between annual burns, and burns in biennial, triennial and quadrennial categories, despite lower fuel loads, and it was suggested that seasonal fuel moisture overrode those of fuel load. Notably, the study in KNP excludes indigenous people living in the bounds of the protected area, and intensities were thus related to climatic influences, specifically rainfall and the seasonal availability of moisture in the vegetation, as partially demonstrated in this study, but where people are inhabiting the park.

Influence of fire policy, land use and vegetation type on fire intensity

Overall, in the whole of BNP, the Burkea shrublands showed the highest fire intensity, and the omiramba grasslands, savanna-woodlands and riparian vegetation types the lowest, in accordance with my hypothesis that FRP values would be lower in the vegetation types with high grassland cover due to frequent fires, and higher in the densely wooded Burkea shrublands with less grass, and less frequent fire. Figure 5-18 presents a summary of the aspects of the fire regime showing the mean percentage of area burned (ha) and median FRP per pixel for each of the four land use areas, and vegetation types in BNP (2000 – 2015). The data in the Figure 5-18 shows that as burnt area increases, FRP values decrease, and where there is less burning, FRP values are typically higher in the respective land use and vegetation types in BNP.

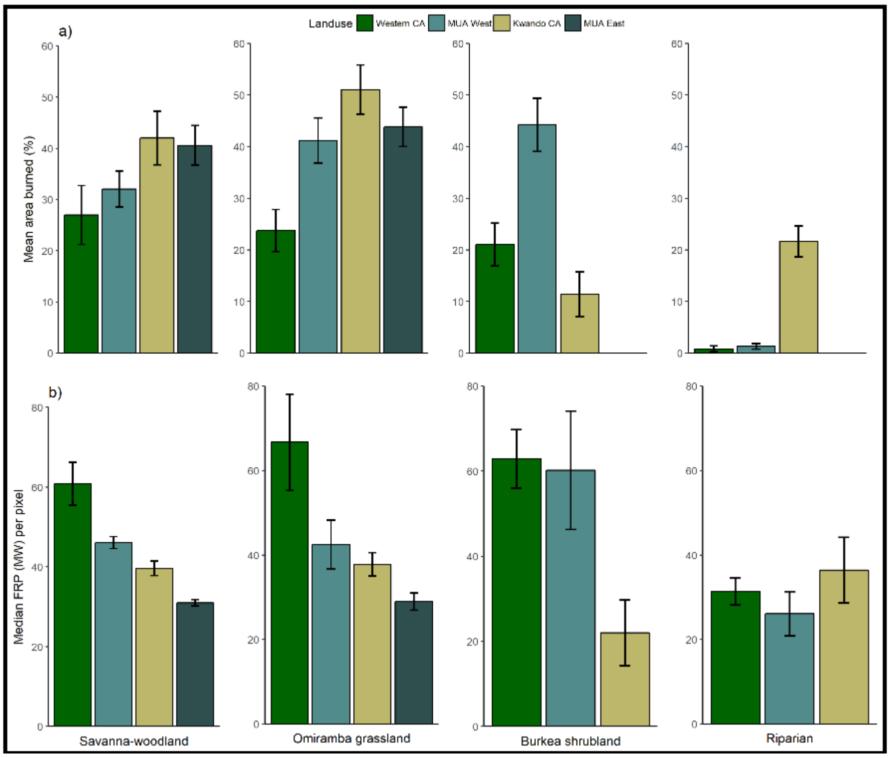


Figure 5-18: Aspects of the interpreted fire regime parameters summarised by land use and vegetation type by a) mean percentage area burned, and b) median fire intensity (FRP; MW) per pixel in Bwabwata National Park, 2000 to 2015; (Error bars = ± SEM).

Further, results confirmed my hypothesis that FRP would differ seasonally in the vegetation types, and be influenced by the frequency of burning associated with different land uses in the SP and EBP periods. In the MUA East and in the Kwando CA, both the omiramba grasslands and savanna-woodlands showed the greatest percentage of burned area in the EDS during the EBP, whereas these respective vegetation types were mostly burnt in the LDS in the SP. Conversely, the Burkea shrublands were primarily burnt in the LDS in the Western CA and MUA West during the EBP, and this is likely the reason for the high FRP values, of which might be further explained by the low density of grass to high density of trees (< 4 m) ratio.

These results suggest that the low FRP values evident in the MUA East and the Kwando CA in the grasslands and savanna-woodlands are a result of the frequent burning in the EDS, which reduced the fuel load, and subsequent fire intensity. In contrast, the high values in the Burkea shrublands in the west of the park are a result of the absence of burning in the EDS, and are in response to seasonal changes attributed to high temperatures, and windy conditions together with the availability of more dry fuel at the end of the dry season (Frost, 1999; Roy *et al.,* 2005). Thus, FRP values in BNP, although influenced by people and fire frequency in the east, were also affected by seasonal climatic factors (e.g. windy conditions, low humidity, and high temperatures late in the season), which affected fire intensity in the omiramba grasslands, savanna-woodlands, and Burkea shrublands, although explicitly in the west of the park. Interestingly, the riparian vegetation type experienced similar FRP values to the omiramba grasslands and savanna-woodlands in all land use areas where it occurred, and in both policy periods, and might be explained by the high water moisture content in the floodplain areas, and consequent lower rates of combustion completion. This is probably because forested habitats are typically characterised by higher moisture content, and are less combustible than drier senescent grasses (Roberts *et al.,* 2009).

Similarly, Giglio *et al.* (2005) found that low FRP tended to be associated with cropland burning, whilst higher FRP were located in areas of grassland burning. Archibald *et al.* (2010) similarly found that the grasslands had the highest and most uniform FRP throughout most of the fire season. However, the grassland FRP were far lower in the settlement and cultivated areas versus the protected areas in southern Africa (Archibald *et al.,* 2010), and thus are similar to my results, though in the CA in BNP where EDS burning was extensive in the EBP, FRP decreased. Nevertheless, vegetation fires have essentially similar general combustion and energy release characteristics, though the specific characteristics of biomass fuel (density, dryness) and weather conditions (rainfall, wind speed and relative humidity) at a particular site significantly influence the fire size, rate of combustion, and thus FRP measures (Ichoku *et al.,* 2008). Moreover, this study has shown that it is the frequency of fire, together with the seasonal timing and policy changes in different vegetation and land use types, which have influenced overall FRP values in BNP, although years of above average rainfall as demonstrated are important in influencing biomass availability and FRP, even when people are burning extensively.

Conclusion

Analysis of the fire regime characteristics of interest (fire frequency and intensity, area burnt, and seasonality) derived from interpretation of the MODIS MCD45A1 and the MCD14ML active fire data revealed how the intensity of land use in the different vegetation types, and during the policy changes have altered the distribution of fire frequency and intensity in BNP. Human land use fire activities, and associated seasonal fire frequencies were shown to have increased fire frequency and reduced overall fire intensity in the grasslands and savanna-woodlands following a change from fire suppression to early dry season burning. However, simultaneously, rainfall variability (specifically above average rainfall years), and the absence of burning specifically in the Burkea shrubland vegetation type have increased fire intensities in BNP throughout the whole time period.

Specifically, I have shown that people inhabiting the MUA, and park management have altered the fire regime, by increasing the extent of EDS burning after the change in policy from fire suppression to early season burning. This study highlights that information regarding, season, area and fire intensity are pivotal to fully capture the seasonal dynamics of biomass burning, especially where local people are inhabiting fire prone savanna-woodlands, such as in BNP. Thus, people can manipulate fire intensity through their seasonal burning patterns, which has consequences for managing the vegetation structure and function, and understanding this at the local scale is critical in predicting fire frequency and intensity and in planning fire management. Humans alter the season when fires occur, with important implications for fire intensity, green-house gases (GHG) emissions, as well as tree-grass dynamics (Archibald, 2016) – all factors that need to be considered in the development of fire management policy. For example, these local findings are relevant to global concerns about CO_2, since EDS fires tend to exhibit more incomplete combustion due to higher fuel moisture content and consequently emit a greater proportion of less oxidized products such as CO than do later fire season events (Korontzi *et al.,* 2003; Roberts *et al.,* 2009). Further, the use of EDS fires in the east of the park were shown to have significantly lower fire intensities, and these cool fires are known to be the least damaging to savanna ecological structure and function, because EDS burning promotes heterogeneity in landscapes (Laris, 2002), and is generally less damaging to tall fire sensitive trees (Bond & Zaloumis, 2016). These findings highlight the importance of integrating local realities into fire management plans, particularly in understanding *how*, and *when people burn* which is integral for addressing fire management at the national level (Mistry & Bizerril, 2011) for policy development. In the case of Bwabwata National Park, the EDS burning practises by the Khwe and Mbukushu people in the MUA, *together* with the park management in the Kwando CA are reducing the impact of the intense LDS fires, which indicates there is common ground between BNP management and community burning strategies. Therefore, the inclusion and recognition of the communities burning strategies would largely benefit fire policy in BNP in the future.

Chapter 6 Synthesis and Conclusion: ‘Local pyrogeography – a social-ecological-historical synthesis’.

Introduction

Global narratives concerning fire use, have changed over the last century (Wardell *et al.,* 2004) with a vastly enriched understanding of humans and their relationship with fire (e.g. fire suppression, fuel fragmentation, vegetation-fire feedbacks and biome switches) and the consequences of this for ecological function and ecosystem services. An understanding of social-ecological fire systems has been enhanced due to accessible state of the art remote sensing products (e.g. MODIS; Landsat) that can be integrated with social and land use data concerning the use of fire among indigenous communities and fire managers. However, specifically in Africa, most savanna fire studies come from reserves such as Kruger National Park in South Africa where indigenous people have been removed (Laris, 2011) and the focus has been distinctly on fire ecology. The majority of interdisciplinary studies concerning fire and people's land use regimes in relation to fire have stemmed from West Africa (Laris, 2002; Laris, 2011 [Mali], Mbow *et al.*, 2000 [Senegal], Walters, 2010 [Gabon]), and from Madagascar (Kull, 2004). Further instrumental Australian studies have revealed how investigating where, why, when, and how dissimilar indigenous groups of people use fire contributes to a location-specific understanding of climate-fire-people-vegetation interactions (Bird *et al.*, 2016; Bowman *et al.,* 2004; Russell-Smith *et al.,* 2013). Thus, these integrative studies have aided in understanding the interactions between climate-fire controls and human factors in the landscape among fire scientists globally (Laris *et al.*, 2015), a function of the discipline of pyrogeography (Bowman *et al.,* 2013). Surprisingly, there is little literature and research in southern Africa concerning indigenous knowledge and fire (Butz, 2009). This study has revealed that there is much to be learnt about former hunter-gatherer and agro-pastoralism fire regimes in combination with climate variation, which has consequences for the preservation of biological diversity, and the sustainability of livelihoods.

Pyrogeography provides the framework to understand fire in the Anthropocene, and acknowledges the importance of the global carbon cycle, alongside the protection of human life, biodiversity conservation, and provision of ecosystem services (Bowman *et al.,* 2013). Thus, it supports the cross-examination of both positive and negative, social, economic and ecological reasons for burning in different cultural landscapes. In this study, I used an interdisciplinary pyrogeographic approach to bridge the disciplinary boundaries (social-ecological fire systems) and produce a richer narrative and understanding of human-fire-climate-vegetation interactions. The mixed method approach of social qualitative and remote sensing data highlights the value of integrating different disciplinary perspectives to gain insight of human-fire feedbacks in southern Africa, similar to previous research in other areas (Laris, 2006, 2011; Laris & Wardell, 2006; Russel-smith *et al.,* 1997). The pyrogeographic framework was particularly useful in that it provided a platform to cross-reference the social data (i.e. locality, time of day, and seasonality) with the GIS vegetation, climate and spatial–temporal MODIS data. This approach enabled my conceptual understanding of the historical and present day anthropogenic burning patterns in juxtaposition with the climate, in parallel with Namibia's complex social-political history.

This thesis has explored the fire dynamics in Bwabwata National Park in north-east Namibia through analyses of the MODIS satellite data, alongside interviews with the community and policy stakeholder groups. The results highlighted the feedbacks between the social-political history (18^{th}- 21^{st} century), and contemporary fire regime patterns (2000 – 2015) within the savanna-woodlands, and importantly early season burning was identified as a focus of agreement amongst stakeholder groups. A central task of this chapter is to synthesize the relations between the reasons for burning and the patterns of fire detectable in the MODIS dataset, and identify the social and ecological implications important for fire management in BNP. Here I synthesize my findings using a sequence of pyrogeographic frameworks, which illustrate the local pyrogeographic settings, associations and feedbacks between the social and remote sensing data (2000 – 2015) analysed in BNP (objective 3 defined below), draw conclusions, and discuss the management and policy implications of this research.

This thesis had three main objectives:

1. To identify spatial and temporal fire trends in relation to land use and transformation and vegetation and fire, through the use of remote sensing fire products and local ecological knowledge surveys.

2. To explore the relationships between livelihoods, land-use, policy, biodiversity conservation and the fire regime through stakeholder interviews.

3. To explore and identify factors influencing the current fire regime through the conceptual synthesis of the remote sensing and local ecological knowledge surveys using a pyrogeographic framework.

Fire is multifaceted and pyrogeography is therefore complex, as it involves space-time relationships, evolutionary adaptation (e.g. human and biological), fire-vegetation-herbivory feedbacks, climatic variation, human control and intervention, and disparate management perspectives from people with varying social and cultural backgrounds. Many fire-prone ecosystems have adapted over millennia to deliberate landscape burning by indigenous people to maintain plant and animal resources (Trauernicht *et al.,* 2015). In recent times (21^{st} century), western approaches to fire management have been changing in response to indigenous burning practises, and have begun moving away from suppressive Eurocentric policies in Africa (Laris, 2002; Wardell *et al.,* 2004), Australia (Whitehead *et al.,* 2003), South America (Rodríguez *et al.,* 2013) and North America (Ryan *et al.* 2013). Furthermore, the integration of anthropogenic burning with ecological theory is considered challenging and intricate, because of the diversity of historical, economic, and cultural contexts intrinsic to fire management (Fowler, 2013), which makes generalizations difficult. Thus, the study of fire, which requires a combination of disparate disciplines (Pyne, 2017), can be viewed as an ideal social-ecological conundrum, because an understanding of fire dynamics includes the debated aspect of human derived ignitions in parallel with climate-fire-vegetation relations. Previously, research on fire rarely incorporated the social – ecological complex circumstances that create conditions for ignitions in Africa (Laris, 2002; Archibald, 2010, Coughlan & Petty, 2012). In southern Africa, since the 20th century, fire science has mostly maintained ecological boundaries (Trollope, 2011), and interdisciplinary research investigating human-ecological interactions in savannas is relatively new in the region (Shaffer, 2009).

The discipline of pyrogeography (Bowman *et al.,* 2013) offers a stimulating platform from which to study people, climate, vegetation and complex fire regimes. It provides a holistic framework for understanding the variation of landscape fire activity in space and time, and to extricate human burning patterns from background climate driven fire activity (Bowman, in Scherjon *et al.*, 2015). Thus, the field of pyrogeography presents the opportunity for the synthesis of culture, history, ecology, and climate, and in combination with remote sensing data, allows one to explore how people manipulate fire regimes by altering the patterns of landscape burning. Equally, this interdisciplinary approach presents a platform for the cross-examination of variability in the processes, and feedbacks involved that have significant social and environmental impacts (Bird & Bird, in Scherjon *et al.,* 2015). Thus, pyrogeography provides the nexus between climate driven, and anthropogenic fire, alongside human well-being and livelihoods (Bowman *et al.,* 2013).

Bwabwata National Park presents a unique setting where the communities have been inhabiting the savanna-woodland systems for millennia, and as this study has demonstrated, have continued using fire within a protected area for the last half century (1963 – 2015). An understanding of the historical and current burning practises (Chapter 3), in combination with the political history, and subsequent socio-economic status particularly of the Khwe (Chapter 2) were integral for illustrating how, and why the communities, as well as the park managements' burning policies and practises (historic and current) were influencing the observed contemporary fire regime patterns in the park (Chapters 4 & 5). Furthermore, during the study period, the fire legislation changed in BNP from a policy of suppression to early burning, which reflects renewed GoN attitudes towards fire and the recognition of the traditional burning practises by the inhabiting communities, and the subsequent revision of early burning management strategies in the park (MET, 2016). Thus, the synthesis of the observed pyrogeographic factors, and associated feedbacks within the complex social dynamics led to a more nuanced understanding of current fire management in BNP, as I aim to reveal in this concluding chapter.

Bwabwata National Park is characterised by an extremely complex historical political background dating from the earliest known record of modern human inhabitation in southern Africa (approx. 200 000 yrs. ago) (Scott *et al.*, 2014) to the 21st century (Figure 6-1). Historically, the former nomadic hunter-gatherer Khwe people used fire for millennia in the BNP landscape. Furthermore, the Mbukushu people who reportedly arrived in the region in the late 1700s (Tinley, 1966), also used fire for iron smelting, and as pastoralists and agriculturalists. The complexity in BNP involved the colonial and internal war history, together with suppressive fire policies that restricted subsistence and altered land-use strategies and fire use over time from the 19th to the 21st century. Thus, the political-historical circumstances of BNP featured the emergence of various power regimes (colonials and later national governance), which implemented their authority through Eurocentric and national policies on the local inhabiting communities (Table A3; Chapter 2; Appendix A). Moreover, as the political situation stabilised, and Namibia became Independent (1990), conservation became a priority, which subsequently led to further changes in land use plans (e.g. formation of the MUA), park management plans, fire perspectives and legislation (MET, 2013; 2016).

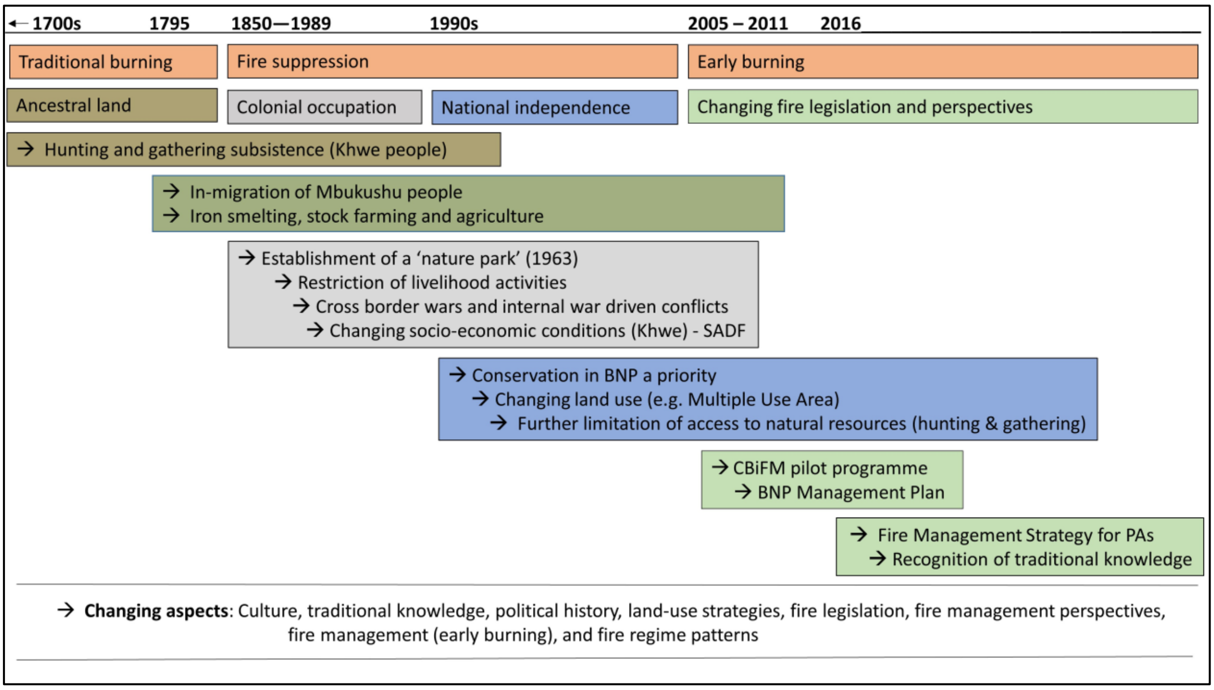


Figure 6-1. Chronological time line showing the progression of changing aspects from prior to the 18th century to the 21st century in Bwabwata National Park.

Pyrogeography in Bwabwata National Park

Bowman *et al.*, (2013) defined pyrogeography as the study of fire on Earth that unites biological, atmospheric, and social perspectives, and therefore diverse disciplines of fire. In this study, significant *'pyrogeographic factors'* were identified based on the empirical results from both the social and MODIS datasets that were founded in the context of BNP, which were associated with each discipline (e.g. biological, geophysical and social). Unequivocally, the interpretation of climate variation (e.g. ENSO events; antecedent rainfall), human influences (e.g. land-use, policy) and the fire regime parameters (e.g. fire size, intensity and seasonality), in combination with the social data (e.g. socio-political context, fire use and perspectives) led to a theoretical understanding of the interactions and feedbacks between people, climate, vegetation, topography and the fire regime in BNP (Figure 6-2). Fire research has established that it is impossible to reduce fire to a single variable (Murphy *et al.,* 2011), because fires exhibit complex varying patterns at different scales of space and time (Moritz *et al.,* 2005). Hence, inevitably the contextual setting of social-ecological landscapes vary across time and space, and each provide a unique pyrogeographical setting, and thus many different local and regional pyrogeographies result (Huffman, 2013). Figure 6-2 illustrates the identified pyrogeographic factors, associated scales and feedbacks representing a holistic framework of pyrogeography in BNP.

In Bwabwata National Park, pyrogeography encompassed distinctive 'society, culture and fire' factors that were interconnected to the 'climate, biology and fire' factors (e.g. spatial fire regime parameters, fire management, and subsequent ecological changes), and the 'topographical environment and fire' factors (e.g. Kalahari palaeo-landforms) as depicted in Figure 6-2. In addition, temporal and spatial scales relevant to each pyrogeographic factor were identified that included a 'social-historical scale', 'global-landscape scale', and a 'landscape scale'. This interdisciplinary approach evolved with an understanding of the people dynamics (e.g. political-history, burning practises, changing perspectives) in combination with the ecological findings (e.g. climate, vegetation and fire occurrence) in BNP. Consequently, distinct feedbacks connecting each pyrogeographic factor to the social dynamics in the park emerged. For example, in this study, the social-historical scale was associated with the ecological aspects (e.g. livelihood subsistence and ecosystem services), and was therefore labelled as a 'social-ecological-subsistence feedback'. The 'climate, biology and fire' factors in BNP occurred at the global-landscape scale that involved feedbacks between the social-ecological-management circumstances in BNP (e.g. ENSO events and emergent spatial-temporal fire regime patterns). Lastly, the 'topographical environment and fire' factors incorporated social-landscape feature feedbacks involving the characteristic palaeo-landforms in BNP, which influenced where people choose to light fires in BNP (e.g. to regenerate ecosystem services [i.e. veld foods in the omiramba's and/ or on the dune crests]), and or limited ignitions (e.g. seasonally inundated floodplain areas of the major river systems in the park). In conclusion, it is apparent that the social dynamics and feedbacks (past and present) are central to understanding fire dynamics across all the pyrogeographic factors from the local to the global scale in BNP.

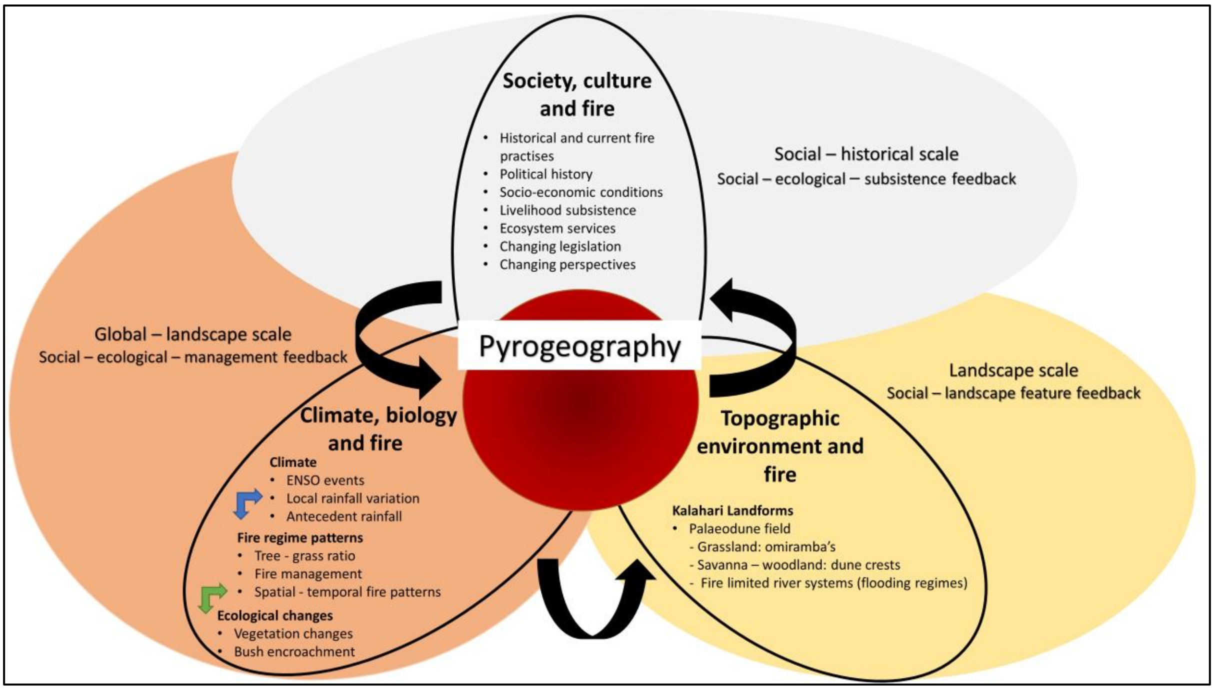


Figure 6-2: A conceptual model illustrating the associations between three key pyrogeographic factors (e.g. 'society, culture and fire'; 'climate, biology and fire'; and the 'topographic environment and fire'), the applicable scales (e.g. social-historical; global-landscape; and landscape), and the interacting feedbacks connected with the social dynamics in Bwabwata National Park (adapted from Bowman *et al.*, 2013). The key aspects that define each pyrogeographic factor in BNP are listed within each black oval circle. The precursory influence of each of the three pyrogeographic factors is illustrated by the overlapping display of the coloured ovals/circles (e.g. the 'society, culture and fire' factors overlay the 'climate, biology and fire' factors), and the black arrows indicate the cyclical feedbacks between the factors in the park. The scale applicable to each pyrogeographic factor, and the identified feedbacks connected to the social dynamics are labelled within each coloured oval.

Spatial-social-historical-ecological synthesis

Further analyses and interpretation of the social data (i.e. fire perceptions and reasoning for the use of fire amongst all stakeholders), in combination with the climate and the MODIS fire product data (i.e. spatial-temporal fire regime patterns, 2000 - 2015) resulted in the identification of interrelated sub-factors, and coupling dynamics unique to BNP (Figure 6-3). Within the 'society, fire and culture' pyrogeographic factor, three distinctive interrelated sub-factors were identified from Chapters 2 and 3, which included 'political-historical, 'historical and current traditional fire practise, and 'recent policy'. The interaction of these aforementioned factors resulted in significant influential feedbacks that were recognised as a social-historical-ecological coupling in BNP. For example, the political history (i.e. governance, wars, inter-ethic integration), influenced land use, and livelihood subsistence strategies (i.e. restriction of hunting-gathering activities), however the BNP communities historical, and current early burning strategies were recently (2006; 2016) integrated into the revised park fire management policies.

Under the 'climate, biology and fire' and 'topographic environment and fire' factors, the 'fire regime' and the 'ecological and topographic' aspects were identified as sub-factors (from Chapters 4 & 5) that formed a spatial-social-ecological coupling in BNP. For example, fire frequencies in BNP were associated with specific vegetation types, for instance the grasslands were burned more frequently than the densely treed Burkea shrublands, which differed according to the land-use and the policy in place, and were therefore related to the social dynamics ('society, fire and culture' factors). Equally, fire sizes and intensities, and the seasonal number of ignitions, differed between the land-use areas (i.e. MUA and conservation core areas), vegetation types, and under the two policy periods (i.e. suppression and early burning) in BNP. Furthermore, it was shown in Chapters 3 and 5 that traditional early burning strategies were extensively used in the community inhabited areas (e.g. MUA East), which influenced the frequency and occurrence of the late season fires in the park. In combination, both of the coupling scenarios described above (i.e. 'social-historical-ecological' and 'spatial-social-ecological') resulted in a spatial-historical-ecological synthesis within a pyrogeographic framework for BNP.

The assimilation of the findings from Chapters 2, 3, 4 and 5 provided an understanding of how the social dynamics (past and present) influenced the timing of fire (i.e. seasonality), the location of fire (i.e. MUA vs. CAs), and current fire regime patterns (e.g. fire size, number of ignitions, intensity and frequency) in BNP. Figure 3 illustrates the relationship between the pyrogeographic factors, and aforementioned sub-factors, and coupling dynamics, in parallel with the supporting climate and MODIS data within a spatial-historical-ecological synthesis model in BNP. Therefore, the synthesis of the human-fire-climate-vegetation interactions within this illustrative framework (Figure 6-3) provided a platform for the understanding of the coupling dynamics in BNP.

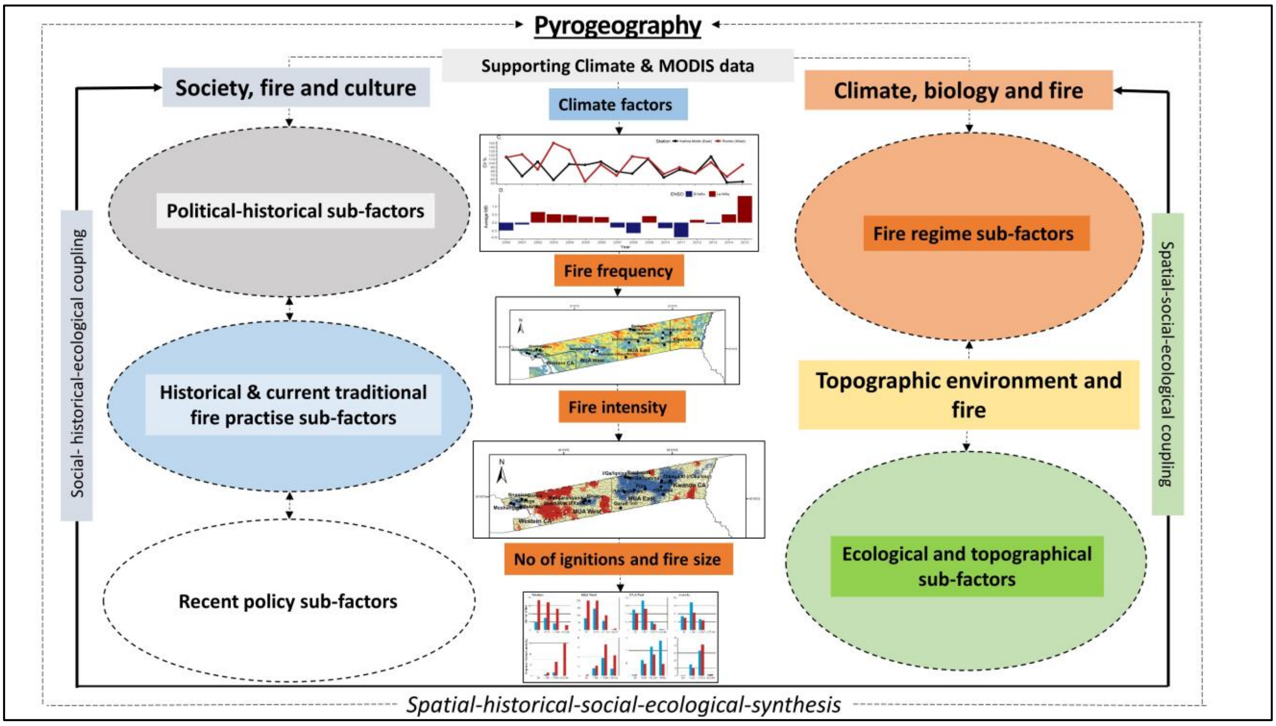


Figure 6-3. A conceptual model illustrating a spatial-historical-ecological synthesis of the interrelated sub-factors (e.g. political-historical; historical and current traditional fire practises; recent policy; fire regime, and ecological and topographical), and the associated coupling (e.g. social-historical-ecological and spatial-social-ecological) between the sub-factors in Bwabwata National Park. The black solid line and arrows indicate the connection between the two coupling scenarios, and represent a spatial-historical-ecological synthesis (dashed lines) within a pyrogeographic framework for BNP.

Fine-scale pyrogeographic dynamics

Narratives that characterize factors and interactions about cultural knowledge and societal systems (i.e. policy), in combination with observed ecological dynamics add much to our understanding, however are inherently complex systems. In this study, the analysis of the community interviews deepened my understanding of how the past regional suppressive policies, wars, and changes in land use with respect to conservation areas impacted on their livelihoods, through restrictive means, and contributed to an overall loss of cultural fire knowledge. Thus, in-depth fine scale analyses and interpretation of the complex interrelated sub-factors unique to BNP (Figure 6-3) led to an understanding of the precursory sub-factors, interrelating associations within the context of the social-historical dynamics, and the consequent emergent spatial-temporal fire regime patterns (Figure 6-4). The management of the vegetation and fire by people in the park for various reasons (Chapter 3), in combination with analyses of the climatic variation (ENSO events; local rainfall variability; antecedent rainfall), revealed changes in the spatial-temporal fire regime dynamics (Chapters 4 & 5) that have consequences for the biological, topographical and ecological vegetation status of the park (green oval E in Figure 6-4).

Figure 6-4 shows that BNPs complex political-history was the mainstay factor that had an influence on the communities historical fire use patterns. However, the documentation of the historic early burning practises, still evidently in use today, in parallel with all stakeholders' fire perspectives (Chapter 3), in combination with the political history of the region (Chapter 2), resulted in a more nuanced understanding of the current fire regime patterns observed in BNP (2000 – 2015) (Figure 6-4). In this study, the Khwe specifically reported a deterioration of fire knowledge concerning early burning (e.g. due to suppressive fire policies, changing livelihoods, land-use, and subsequent restrictions on the use of natural resources). Nevertheless, it was evident based on the analyses of seasonally burned area, number of fires and associated fire sizes, and fire intensity in the different land use areas and vegetation types from 2000 - 2015 (Chapters 4 & 5), that the use of fire in the early dry season was still prevalent within the communities especially in the east of the park. Moreover, these findings emphasize how early burning activities, in particular by the Khwe people, are essentially culturally and traditionally entrenched in their livelihood practices, even though the political-historical factors had a suppressive influence on their indigenous fire practises (e.g. prohibition of hunting-gathering activities) since the late 19th century (Figure 6-1).

Thus, it is unequivocal that the political-historical factors (Figure 6-1; Figure 6-4) had a predominant influence on the current use of fire by the Khwe and Mbukushu people, the GRN, and the local management of the park, which has influenced the contemporary spatial-temporal fire patterns, and subsequent fire management approaches in the 21st century. Figure 6-4 depicts a complex array of the fine-scale interrelated factors, and precursory sub-factor influences, and subsequent feedbacks of these factors in BNP.

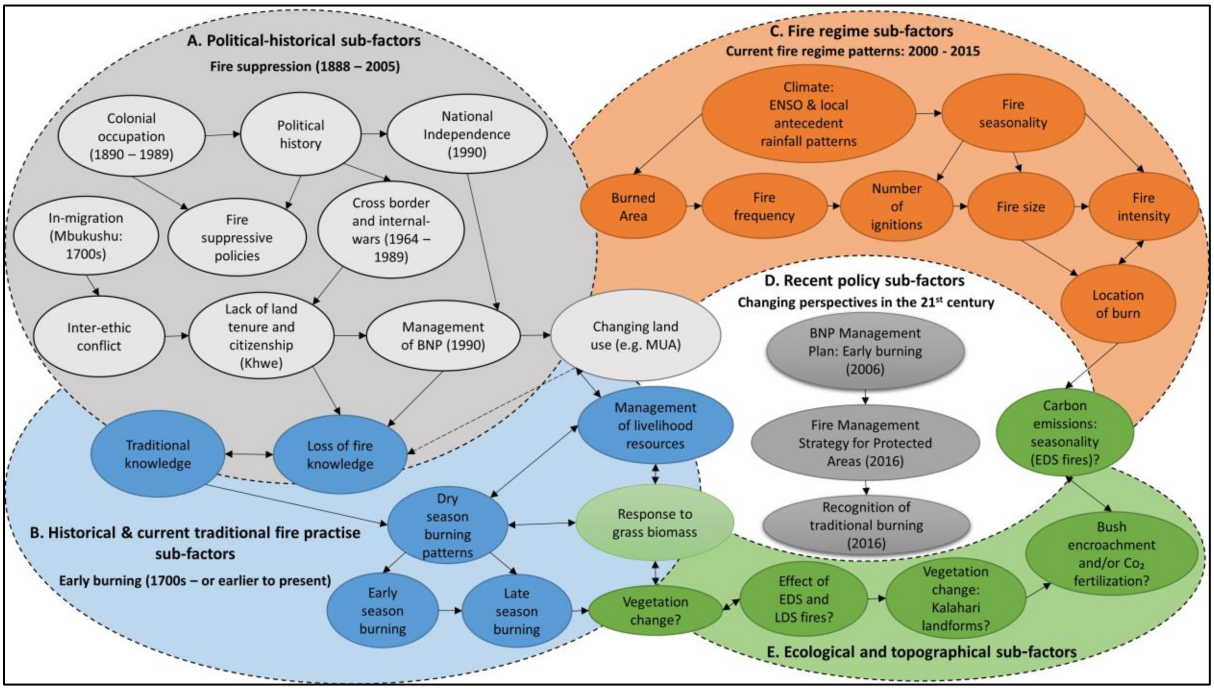


Figure 6-4. A complex conceptual model showing the precursory factors as A. political-historical, B. historical and current traditional burning practises, C. fire regime, D. recent policy, and E. the ecological and topographical sub-factors, and the interaction between these sub-factors representing local pyrogeographic dynamics at a fine scale in Bwabwata National Park (18th – 21st century). The sequential overlapping boundaries of the circles in Figure 4 designates the precursory influential sub-factors (A; B) on the current fire regime (2000 – 2015) (C), as well as on the recent policy sub-factors (D), which in turn resulted in emergent questions pertaining to the current ecological vegetation status of the park (E).

Past and present drivers of the fire regime

Analyses of the MODIS data clearly showed a defined trend where people reside in the landscape (MUA East; MUA West), and where *ad-hoc* burning was implemented in the core conservation areas of the park (Kwando and Western CAs) (Chapters 4 & 5). Explicitly, Figure 6-5 illustrates the association between climate (e.g. ENSO events and antecedent rainfall) and the *past* complex interrelated factors (A and B), in combination with the explicit land use areas (e.g. community areas versus conservation core areas), and the observed fire regime patterns (2000 – 2015), representing the current fire regime: spatial-temporal social-ecological coupling in BNP. Unequivocally, the seasonal burning patterns associated with the number of ignitions, fire size and intensity specifically in the MUA East, and partially in the Kwando CA showed how frequent early season burning influenced the fire regime, reducing the frequency of late season fires, in frequency, size and intensity. Conversely, the fire regime patterns in the western part of the park (Western CA; MUA West) reflected higher frequencies of the late season fires that were larger and more intense than in the east. Furthermore, burning particularly in the east was in response to an increase in grass following above average rainfall events, which were correlated to ENSO La Niña events, which highlighted the association between variation in climate and people living remotely in savanna-woodlands.

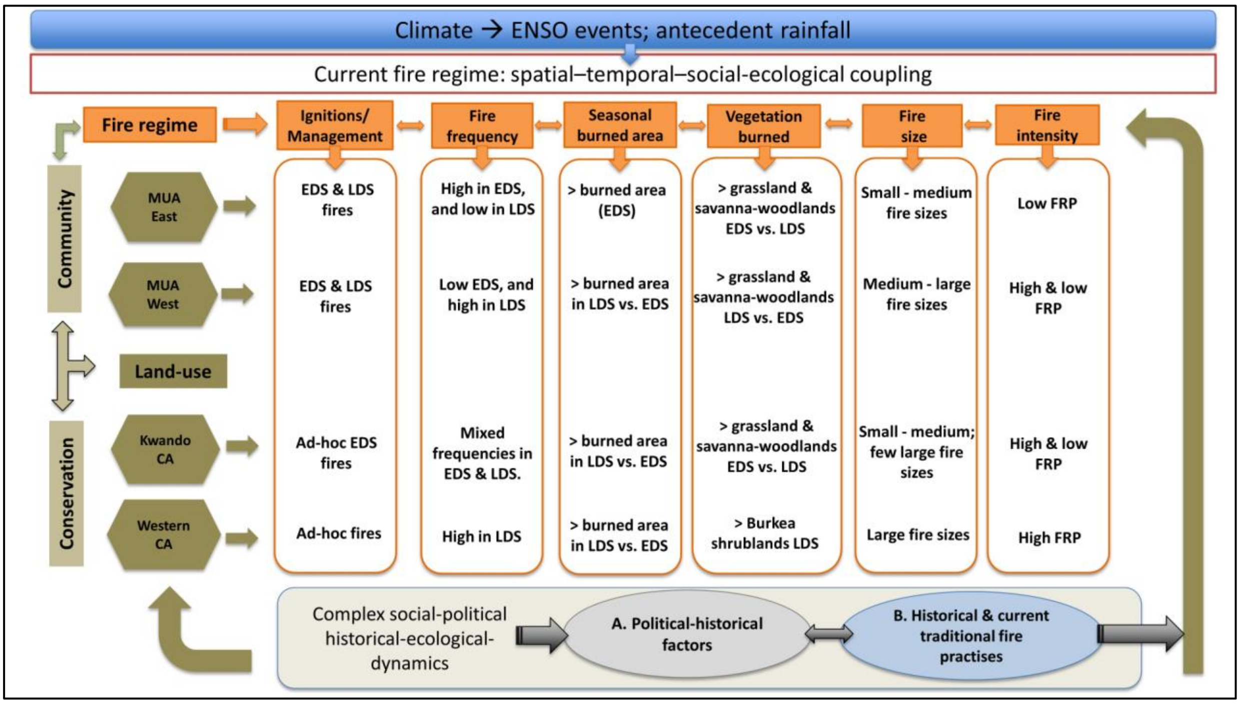


Figure 6-5. Conceptual model showing the linkages between climate (ENSO; antecedent rainfall) and the past complex social-historical ecological dynamics in relation to land use (community vs. conservation core areas), and the current patterns (2000 – 2015) of the fire regime in a spatial-temporal- social-ecological coupling in Bwabwata National Park. The complex social-historical ecological dynamics underpin the present day dynamics in the park, and this is shown in this diagram by the direction of the brown arrows pointing towards the four land-use areas and current fire regime spatio-temporal-social-ecological coupling patterns in the BNP landscape. The climate (ENSO; antecedent rainfall) are shown as superimposed on the current fire regime dynamics and land use areas.

The east-west fire regime trend clearly distinguished where disparate livelihood interests and burning activities were active in the park, with the Khwe located in the east where early burning was prolific, versus the more densely culturally integrated populated area in the west of the park, where late season fires were more frequent. Similarly, the east-west trend in fire regime patterns were also evident in the core areas of the park, whereby the use of fire (i.e. early burning) in the Kwando CA was clearly more consistent and organised, when compared to the western CA where far less controlled fires were ignited over the 16 years of interest. The aforementioned burning regimes were reflected in the emergent spatial-temporal fire patterns in the respective land use areas (Figure 6-5; Figure 6-6). Figure 6-6 illustrates the linkages between the present data drivers, with emphasis on the specific outcome of the respective land use fire regimes patterns (2000 – 2015), underpinned by the complex social-political-historical-ecological dynamics in BNP.

In consideration of the changing perspectives evident in the 21st century in Namibia represented in the recent policy factors (D; Figure 6-4), the CBiFM pilot programme centred on community involvement in fire management resulted in the integration of early burning into the BNP Management Plan (2006) (Chapter 3). However, the more recent developments in fire management policy in Namibia, subsequently occurred during this study in 2016, whereby the Fire Management Strategy for Protected Areas detailed the recognition of the historical traditional burning practises of people inhabiting BNP (MET, 2016). The recent GRN, and MET recognition of traditional burning patterns, represents the first time in history in Namibia, and shows a positive shift towards acknowledging local fire practises. This acknowledgement represents an outstanding opportunity for mutual ground between the communities and BNP park management, where new relationships concerning fire use could be built.

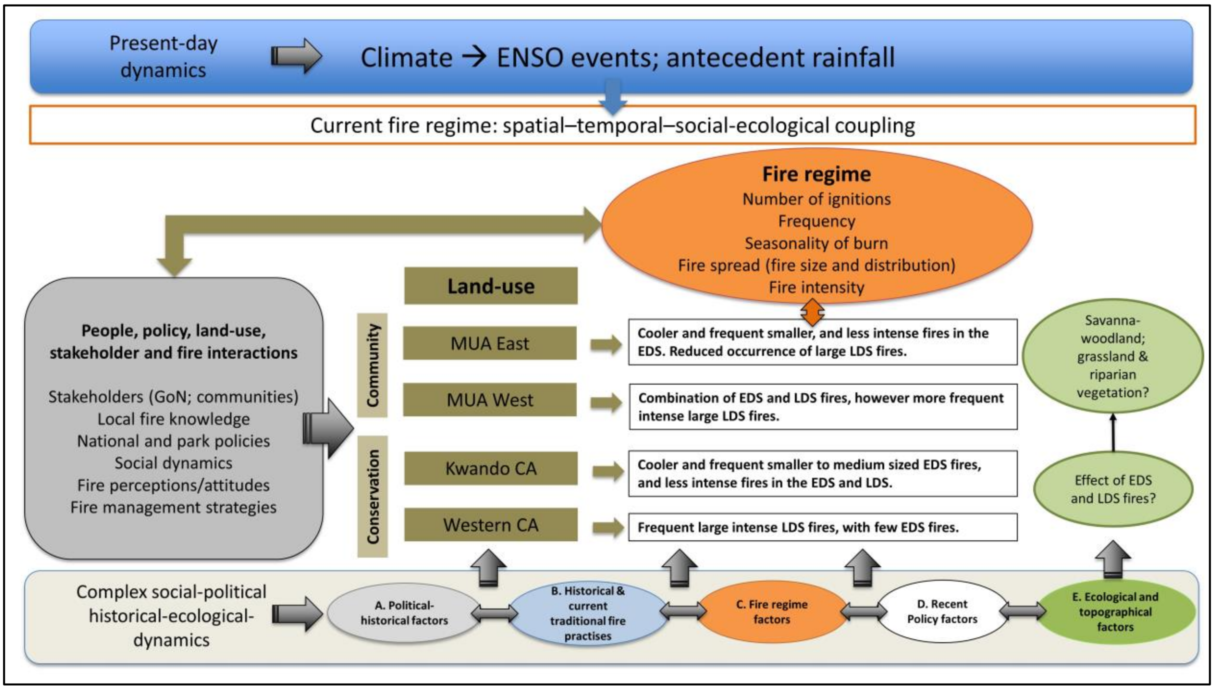


Figure 6-6. A conceptual model showing the linkages between the present-day dynamics, and the emergent land use fire regime patterns (2000 – 2015), underpinned by the complex social-political-historical-ecological dynamics in Bwabwata National Park.

Scott *et al.* (2014) prominently highlighted, that the study of fire in interdisciplinary contexts has implications for existing pressing conservation and human well-being decisions or (indecisions) because of the need to address sustainable fire management, human-health, livelihoods at risk, property, ecosystems and accelerating global environmental change. Thus, Figure 6-4, Figure 6-5 and Figure 6-6, provide fine scale and broad-scale frameworks of the apparent social-ecological dynamics and feedbacks in the park for identifying critical areas for future fire management plans, people's well-being and livelihoods in BNP.

Social and environmental implications

This study has shown that the all-encompassing social-historical-political circumstances (Figure 6-1) fundamentally influenced present-day land-use strategies, peoples' livelihoods, fire regime patterns, peoples' perspectives on fire, and subsequent fire policies. Furthermore, it was revealed how and why the Khwe and Mbukushu people used fire historically, and how these traditional practises (specifically early burning) are embedded in the current context of park fire management, developing policies and associated changing perceptions (both within the communities and park management). Certainly, understanding the importance of community burning patterns for local livelihoods, and its importance to savanna-woodlands, in combination with the regions social-political and fire history is crucial for the implementation of informed management and conservation practises in BNP.

It is important to recognise that the goals of fire management used by people to manipulate burn seasons and therefore fire size, among other fire related characteristics for livelihood purposes may differ from the goals of contemporary management for conservation (Huffman, 2013). For example, the Khwe burning strategies were linked to specific livelihood activities and needs, and although described as organised directed by the elders of the community, fires were most likely randomly set in the EDS, whereas the park management with the more recent planned burning strategies may follow a more organised planned burning schedule based on a mapping approach (MET, 2016). However, both the community and the government and non-government stakeholders have a preference for the early dry season fires for similar reasons, which is an important area of agreement that can be integrated into future fire management plans, and conservation objectives. Furthermore, since the community are using early burning that benefits the park (e.g. reduced fire frequency in the late dry season, with less area being burnt in the more damaging fire season, lower fire intensities, and smaller fire sizes), it suggests that the BNP management staff would largely benefit from collaboration with the communities concerning the location and frequency of ignitions in the EDS. Therefore, the GoN and MET should further engage with the BNP community concerning their fire knowledge, and employ it as an essential complement to their western scientific knowledge (Whitehead *et al.,* 2003). These findings indicate that an exchange of knowledge, and an improvement in communication between people who use fire in BNP, alongside a share in the governance of fire (e.g. BNP community and MET) would be central to improving livelihoods and fire management strategies in the long term in BNP.

The use of early burning demonstrated by the BNP communities for livelihood subsistence, irrespective of the land use changes imposed, highlights the resilience of the cultural use of fire under extreme social-political marginalisation. However, the use of multiple fire strategies by both the Khwe and Mbukushu in support of their livelihoods are considered imperative given the continuing dire socio-economic conditions (e.g. absence of employment opportunities, and thus the money to purchase basic everyday necessities, such as food), and because of the status of BNP as a remote conservation area. Moreover, given the uncertainty surrounding global environmental change (e.g. flooding regimes; increased fires; droughts; plagues etc.) (Polasky *et al.*., 2011), peoples' livelihoods are at stake in BNP. This is because the BNP communities are dependent on ecosystem services (i.e. veld foods) that are affected by global systems (i.e. ENSO events), and local rainfall patterns, and frequent fires (as portrayed in this study). Thus, the BNP community are inherently socially-ecologically vulnerable because of their dependence on rainfall and fire to sustain their livelihoods. Moreover, this vulnerability is accentuated in the absence of traditional governance structures (e.g. Khwe Traditional Authority [TA]) that would grant them support within their respective individual communities (i.e. Khwe and Mbukushu) under extreme environmental change. Landres *et al.* (1999) emphasised that natural variability in ecosystems provides the opportunity, as well as a challenge for ecologists to provide relevant information, and to collaborate with managers to improve the management of ecological systems.

In Chapter 3 of this study, community burning in the park was generally perceived as negative in the eyes of the officials, however probably a blind eye is turned on fire use, likely because of the absence of community support structures in BNP. In addition, the communities iterated that they viewed the MET in control of fire (i.e. early burning) in the park. Wardell & Lund (2004) emphasized that the contradiction between one 'official system' and the other as 'unofficial' has the potential to lead to periodic tensions between the main and local actors. Thus, it is recommended that the GRN, and MET in BNP convey their recent acknowledgement of the communities early burning practises. Nonetheless, the use of local fire knowledge must always be used with regard to the effects on the ecosystem (Walters, 2010) since not all seasonal burning patterns (e.g. late season fires) lead to better resource use (e.g. impact on veld foods), and ecological productivity. Thus, the 'blanket' combination of early and late burning can contribute to reducing the biodiversity of ecosystems (Wardell *et al.,* 2004). Although currently in southern Africa, the cooler, smaller EDS patchy fires are recognized as the most beneficial for ecological structure, composition and function (Bond & Zaloumis, 2016). Therefore, the bi-seasonal burning requirements for livelihood ecosystem services (e.g. cultivation and veld foods) are likely to present a challenge for park management control measures concerning the communities fire use. However, acknowledgement by the GRN concerning traditional practises, as well as communication and co-operation in favour of early burning strategies may lead to rewards for the both the GRN and the BNP community in the future in BNP. Moreover, as recognized by the government and non-government stakeholders', further research is required to understand the ecological effects of both early and late seasoning burning on the ecological status of the park (Figure 6-4, Figure 6-5 and Figure 6-6).

Thus, I would suggest that both BNP park management, as well as Namibian students participate and instigate fire research, thus increasing the capacity within Namibia to manage fire. However, it would be beneficial to include the social-ecological aspects of the region, as this study has revealed, it is an appropriate approach to conserving the savanna-woodlands important to Namibia's human and vegetation history. This study has provided information concerning the vulnerability of the BNP community in response to environmental variability that would threaten their well-being and livelihoods (e.g. ENSO events). Furthermore, given that the communities traditional burning strategies have been recognised by MET (MET, 2016), it would aid in improved communication structures and collaboration concerning fire use in the park if TAs were representative of each individual community in BNP. This collaboration would help in the search for a fire management policy that is ecologically appropriate, as well as fair and just. The GRN should consider the acknowledgement of the Khwe as national citizens and grant them TA status (Hitchcock & Vinding, 2004) given the environmental and social circumstances described above.

Policy implications

Whether the results of this research will translate into effective management recommendations and policies arrangements is challenging to answer. This is because of the complexity of the political history as previously described (Chapter 3). A number of factors are likely to influence future science-policy debates on fire issues in BNP. The following recommendations could be considered by the GRN and MET in BNP:

1. A better understanding of the various fire management strategies at the local scale of both the positive as well as negative, may lead to locally adapted and acceptable policies, thereby allowing the BNP communities to use fire in a more controlled and rational manner for livelihood purposes together with park management. For example, the reduction of fire intensity and the frequency of late dry season in response to the communities use of early fires for their livelihoods in the MUA has implications for acknowledging peoples burning patterns.

2. The stakeholders raised concern about the extent of early and late dry season burning in the BNP landscape. Therefore, I suggest that a fire monitoring programme in parallel with fire research be implemented that would document change in vegetation structure and species composition, as well as wildlife movement in the park.

3. The distinction of official and unofficial polices in BNP might help clarify any misunderstanding between the MET and the BNP communities concerning the use of fire during the early and late dry seasons. In addition, it would be important to acknowledge traditional burning practises within the intended future fire management campaigns (MET, 2016).

4. To burn a higher number of early dry season fires specifically in years when there has been above rainfall periods (e.g. during ENSO La Niña events) to reduce the occurrence of the later dry season fires in BNP. However, it is still important to develop more precise and locale-specific applications to ensure the effective use of early dry season fires in the MUA and the CAs.

5. The GRN acknowledge that the community may be socially-ecologically vulnerable to changes in climate variation (e.g. during ENSO events within both the drier El Niño and wetter La Niña phases) in the future, and provide support during these times.

6. To grant the Khwe community in BNP a Traditional Authority (TA), which would facilitate improved communication and allow for opportunities for an exchange of knowledge between the community and people who manage fire in the park.

7. In consideration of the fact that a great proportion of the community have not had the opportunity to obtain a formal education and are non-English speaking, it would be valuable in the future to translate the campaign signage concerning fire management on display into the dominant local languages (e.g. Khwé-dàm; Thimbukushu; Ma-Yea-yi) in the region.

An enlightening outcome following analyses of the social data is how the responses gathered from the interviewees assisted in the identification of relevant ecological questions applicable to understanding the past and present ecological changes. For instance, the impacts of fire suppression and associated proliferation of bush encroachment, and the effect of the early burning, and associated impact of increased fire frequencies, alongside late season fires (e.g. thresholds) on the vegetation in the BNP. For example, the need to identify ecological and /or human factors that could cause major changes, and result in the shift of in the structure and functioning of the BNP ecological systems. In addition, a further question was raised concerning the investigation of the impact of the frequent early and late dry season fires on the veld food resources in relation to the communities' needs. Thus, while the analysis of the vegetation structure, composition, diversity, and impact of fire on important veld food resources was beyond the scope of this thesis, important questions were raised by the BNP stakeholders, and during the course of this study, which could be addressed in the future.

Future research

As with many research endeavours more questions emerged than could be answered by this thesis. In order to contribute to enhancing our understanding of savanna-woodland fires, the following future research agenda may include a number of components.

1. An investigation of land cover and vegetation change (e.g. woody density in the savanna-woodlands) using ground-based vegetation transects in parallel with modern and historical aerial photography would be important, since for this study only 5 years were representative of the fire suppression policy (2000 – 2005) and 10 years for the early burning policy (2006 – 2016). This would help in understanding whether the past policy of fire suppression influenced woody density over time in the park, and assist in the identification of possibly more recent vegetation changes in response to the early burning park strategies recently implemented (2006) in the Kwando CA. Furthermore, it would assist in distinguishing whether changes in the fire regime were driven by changes in the past policy, and the impact of the Namibian War of Liberation, and the subsequent influence of these on the human burning patterns in the savanna-woodlands of BNP.

2. The timescale could be further extended using palaeoecological research using pollen and charcoal analyses to investigate long term change in relation to fire events and vegetation change over time in the BNP landscape. This would allow assessments to be made of whether twentieth century changes in woody vegetation cover and fire were within the historical range of variability or represent unprecedented ecological states, associated with unique social and environmental conditions.

3. Local, historical knowledge is disappearing in the savanna-woodlands in the north-east of Namibia. Research relevant to BNP would entail the impact of fire on important veld food resources, and would require the quantification of how many (i.e. species), and how much do veld foods contribute to the Khwe people's diets. Furthermore, studies among different San groups in southern Africa would be beneficial to ascertain the use of fire in the landscape in relation to using fire for tracking and hunting, as well as to record to the impact of fires on veld food resources in other regions.

4. In this study, the Khwe were shown to be particularly vulnerable, however resilient in adapting to adverse conditions and managing fires for various livelihood activities. Thus, further research could address how to build resilience, and increase food security in the occurrence of semi-predictable events during drought and flooding events in the north-east of Namibia.

5. Research based on quantifying the impact of a change in seasonal burning patterns on carbon emissions. For example the shift to early dry season burning in BNP has implications for understanding land-atmosphere exchanges of carbon. This is because early season fires tend to exhibit more incomplete combustion due to higher fuel moisture content and consequently emit a greater proportion of less oxidized products such as CO_2 than do later fire season events. This research would be relevant to the southern African context, as has been shown in northern Australia (Russell-Smith *et al.,* 2013).

6. Lastly, it would valuable for stakeholders to explore different future scenarios of the social and ecological drivers of fire regimes in the park with a combination of variables, for example using tree cover estimates, seasonal burning patterns, climate and CO_2 conditions in BNP.

Conclusions

In this thesis I have provided a social-historical and ecological account, and a conceptual understanding of fire dynamics in a savanna-woodland fire-prone inhabited area. This study has investigated the complexity and inter-relations between fire and people's livelihoods. Further, its highlighted the emerging changing government perspectives towards people's knowledge, which are reflected in the recent policy changes, and approaches to fire management. This research has revealed that by viewing the land-use practises integrated within the different vegetation types in any savanna landscape oversimplifies the social-ecological interactions that produce the knowledge to address dynamics concerning fire management on the ground. Therefore, the cross-examination of the social-political historical dynamics in BNP provided a vital narrative, and enriched my understanding of the contemporary fire patterns across the park landscape.

The issue of savanna fires has been controversial in Namibia since colonial rule and continues to be so. However, current fire management policies in the region need to be understood in the context of political and historical background, as well as within changing scientific and political discourses (e.g. the recent shifts to early burning strategies). The integration of the social data with the remote sensing data led to a more complete synthesis of the dynamics in BNP through the use of a pyrogeographic framework approach, which bridged the fire science data, social-political history and current burning patterns, and led to a more nuanced understanding of fire management in the landscape.

Namibia has only recently acknowledged the traditional burning practises in the east of BNP, although there is ground to cover in consideration in improving relations between the communities and the fire managers in the park, as well as from a GRN institutional perspective. Nonetheless, it marks a turning point in the complex political history of north-east Namibia. Colonial forestry discourse and the perceived negative effects of fires on vegetation in Namibia, have been supplanted by ecologically recent concerns that consider seasonal burning patterns by the indigenous communities. The BNP community knowledge set down the foundation for the understanding of early burning in the park, and subsequently, these early burning practises are essentially being integrated into developing policies, and are viewed as influencing western approaches to fire management. Yet, the BNP community still remain social-ecologically vulnerable to environmental change because of their dependency on ecosystem services. Therefore, respect for diverse knowledge, cultural understanding, communication and shared governance are central to improving BNP communities livelihoods and adapting fire management strategies in the BNP. The human savanna-woodlands of BNP is a complex social-ecological system, and this study has explicitly revealed the importance of the historical social-ecological dynamics in understanding the spatial-temporal fire patterns. The BNP landscape has evolved and has been conserved through the human-environment fire interactions since human moderns arrived (100, 000 - 200, 000 yrs. ago), and has this study has highlighted, from the 19th to the 21st century that has consequences for current conservation practises.

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APPENDIX

Appendix A: Chapter 2

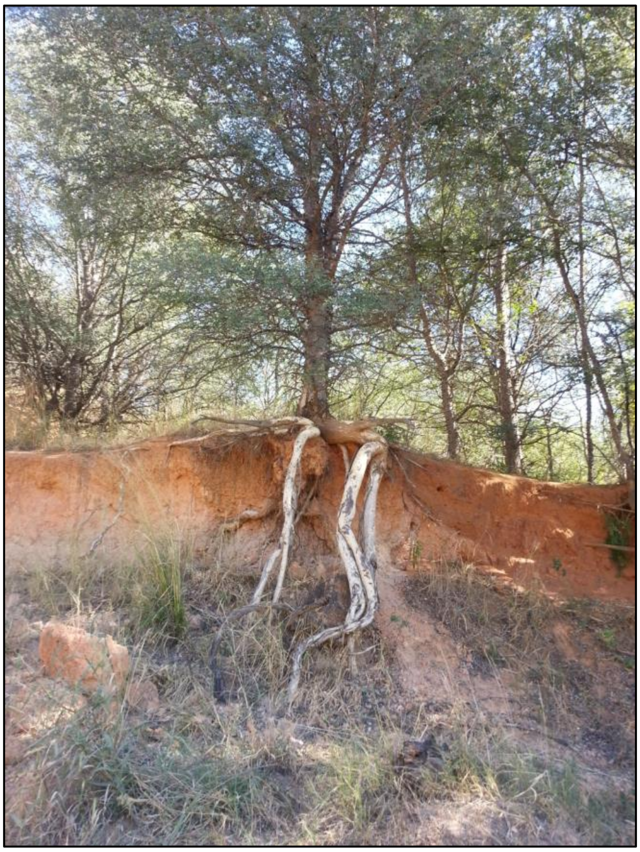

Figure A1: Exposed root system of a knob thorn tree (*Senegalia nigrescens*) on the crest of a palaeo-dune crest in the Kwando core area in Bwabwata National Park.

Table A1: Timeline of historical events affecting the Khwe, Mbukushu and the Government of the Republic of Namibia (GRN) in Bwabwata National Park (1795 – 2016).

Year/s	Historical event
Prehistoric period	Presence of hunter-gatherer cultures in the region
1795 -1800	Arrival of Bantu-speaking tribes in the region
1830	Khwe were subject to slave raids that extended from the Angolan coast to northern Namibia
1840 -1850s	First recorded encounters of the Khwe with Europeans
1852	First map produced of north-east Namibia by the Swedish hunter and explorer, Sir Charles John Andersson
1850s	Settlement of Mbukushu along the Kwando and Okavango Rivers in West Caprivi
1884	Establishment of Namibia as a German Protectorate (Deutsch Sudwestafrika) as German South West Africa
1900s	Hunter-gather societies were exposed to Bantu tribes and introduced to stock farming and agriculture
1886	Delineation of Germany's northern boundaries in an agreement called the Portuguese-German Convention drawn up between Portugal (Angolan colony) and Germany
1888	Banning of all fires by law under the German Colony of South West Africa (Deutsche Kolonialgesellshaft für Südwestafrika)
1890	West Caprivi under the jurisdiction of German administration through an agreement, the Anglo-German signed between Britain and Germany
1896-97	Rinderpest epidemic affects wildlife and livestock in the northern Kalahari and Namibia, killing between 80 to 90 % of cattle, and together with drought, leg to great hardship
1908	Caprivi strip was referred to as 'German Barotseland' or the 'German Zambezi region'
1900 -30	The period 1900-30, in particular, brought considerable displacement, migration, and resettlement of both Khwe and Mbukushu in what are now Angola, Namibia, Botswana, and Zambia
1911-1915	Bushman Plague in northern Namibia: included attacks by German troops, police and settlers on San communities (San genocide) and forcing of San men into labour
1914	Beginning of First World War: German colonial period ended when South African army troops invaded Namibia
1915	Germany surrenders territory of South West Africa to South Africa
1919	After 1919 Versailles Peace Treaty, the League of Nations declared South West Africa (SWA) a South African protectorate
1915 - 1921	Caprivi came under SADF military administration
1929	Administration of the west Caprivi was handed to the South West African Administration (SWAA) by the Bechuanaland Protectorate
1929	Correspondence refers to the prohibition of Mbukushu migration from Angola, as well as cattle into West Caprivi
1930	Rife cattle epidemics in the Kavango area resulted in the administration ordering that natives and cattle be cleared from West Caprivi. People were wither moved to the west bank of the Kavango River or the east bank of the Kwando River
1940	West Caprivi was made a livestock free territory
1940s-1960s	Khwe were used a contract labourers on the Gold Mines on the Witwatersrand in South Africa
1945	Tsetse fly invasion, and resident Mbukushu, Mafwe and Mayeye tribes move out of low lying areas of the park

1947	SWAA commenced a scheme to bring the 'bush people' under greater protection
1949	The SWAA established a Commission for the Preservation of the Bushmen.
1949	Khwe men were considered part of the labour pool and sent to work on the Witwatersrand mines in South Africa
1949	Rundu Native Commissioner employed 'pure Bushmen' policies, of which the official policies were to 'tame' the wild bushmen and bring them under administrative control and into the settler economy
1949	Economic exchanges of food, goods and labour were in place in West Caprivi between the Khwe and Mbukushu
1960s	Mass slaughter of indigenous wildlife by the SADF in the region
1960	Formation of South West African Peoples Organisation (SWAPO) under the majority of the Ovambo people
1961 -1975	Angolan War of Independence
1963	South West African Administration declared the 'Odendaal Commission' for the purpose of creating 'native reserves' for non-white people; Process of apartheid planning for Namibia, however BNP was excluded (West Caprivi), thus a Homeland for the Khwe for traditional hunting and gathering purposes was dismissed
1963	Formation of West Caprivi Nature Park (BNP) between the Okavango and Kwando Rivers (Proclamation No. 67 of 1963, Schedule Caprivi nature Park, in the official Gazette of South West Africa No. 2513 of 15th October 1963), and as a result, the hunting of wild animals in the region was declared illegal
1966	Ecological Assessment of the Caprivi Nature Park by Ken Tinley to determine whether any valuable resources would be lost to South West Africa (SWA)
1966	Caprivi Nature Park was administrated by the Bantu Affairs Department
1966-1989	Namibian War of Independence/ War of Liberation / South African Border War: Namibian Government restricted from area; Khwe were banned from using fires; removal of the responsibility of Fire management from the Traditional Authorities; further implementation of fire prevention
1966-1990	Khwe were restricted from using fire, and collecting veld food resources in BNP, and were settled in South African army bases
1968	Caprivi Nature Game Park renamed to Caprivi Game Reserve
1966-1989	Khwe used as trackers and soldiers for the SADF during the War of Liberation
1974	SADF Battalions established in central western Caprivi (provision of wages, supplies, food, clinics, and housing for the Khwe), and included 7 major camps
1975	Independence of Angola
1975	Mbukushu were removed from the western Caprivi (BNP) by the SADF
1975 - 2002	Angolan Civil War
1978	!Xun and Khwe relocated by SADF from Caprivi (BNP) to West Bushmanland to work as soldiers
1920s -1980s	Mbukushu were dominant and disparaging of the Khwe
1980s	Fires were intensively used for strategic purposes during war-times particularly in the north-eastern part of Namibia
1980s	Omega formed the largest SADF base, home to 4500 Khwe and !Xu
1989	End of the War of Liberation
1989	Proclamation of Mahango Game Reserve on the border of Botswana (Mohembo)
1990	Emergence of Community Based Natural Resource Management (CBNRM) programmes in Namibia

1990	Occupation of Caprivi Game Park for conservation purposes / Ministry of Environment and Tourism (MET) resumes management
1990	Namibian, NGO, Integrated Rural Development and Nature Conservation (IRDNC) assisted Ministry of Wildlife, Conservation and Tourism (Later MET) to involve local people in conservation efforts in West Caprivi
1990	The Namibian government settled the Khwe in agricultural schemes in the western part of the caprivi strip
1990	Namibian independence declared on 21 March; relocation of !Xun and Khwe soldiers and their families to Schmidtsdrift, South Africa by the SADF
1990	After SADF left the Mbukushu (approx. 1 000 people) move back into the area and settle along the Kavango and Kwando River courses following the 1945 Tsetse fly outbreak
1994	Namibia's Secessionist movement occurred within the Caprivi Strip; formation of the Caprivi Liberation Army (CLA; rebel group); a number of Khwe fled to Botswana as they were viewed as perpetrators supporting the movement
1994	Social-ecological survey of the Caprivi Game Park which recommended that the people living in the park should be allowed to remain there. In terms of the CBNRM principles, it was recommended that any conservation plans for the area should involve and benefit the people
1995	Outbreak of lung plague among cattle across the border in Botswana, resulting in the government's destruction of 320,000 head in Namibia
1995	The GRN made a decision to build a prison farm on the banks of the Okavango River with permission form the Mbukushu TA. The Khwe strongly objected these plans as it was officially on a tourism site, which provided employment to the Khwe community
1995	Traditional Authorities Act No 17 of 1995: 'act to provide for the establishment of traditional authorities, the designation and recognition of traditional leaders; to define their functions, duties and powers; and to provide for matters incidental thereto'
1996	The Working Group of Indigenous Minorities (WIMSA) founded, a San advocacy group
1996	An application from the West Caprivi community (i.e. Khwe) for a conservancy to be established was denied by the MET due to the status of the area as a Game Park
1998 - 2000	A number of Khwe people were harassed by the Namibian Defence Force (NDF) soldiers, and fled the West Caprivi because of the alleged involvement with Angola and UNITA
1998	The Ministry of Local Governments and Housing in a policy statement (not formally decided by the Cabinet) would take over the responsibility for rural fire control
1998	The Directorate of Environmental Affairs, Ministry for Environment and Tourism (MET) clearly indicated that it would support future intersectoral policies in fire management
1998	Namibia's Ministry of Environment and Tourism (MET) introduced a conservation and development plan for the West Caprivi Game Park, called the MET Vision for Caprivi/Bwabwata National Park Plan
1998	Formation of Multiple Use area (MUA) and zonation of two core wildlife areas (Kwando and Buffalo core areas)
1998	Khwe restricted from hunting, and collecting veld food resources in core areas
1998	1000 Khwe fled to Botswana due to the expansion of the Angolan conflict (War)
1999	The GRN permitted Angolan government armed forces to use the West Caprivi to launch a counter-attack on UNITA rebels on southern Angola

1999	Technically no cattle are allowed in BNP as per a Namibian cabinet decision in 1999 for conservation and veterinary reasons. Today there are cattle in the villages of Bagani and Omega 1. Mutc'iku, Bagani and Omega 1 were meant to be deproclaimed form the park, but this never occurred
2000	Cabinet approved the change in status from a Game Park to a National park
2000	Mass exodus of people form West Caprivi due to the Caprivi Secessionists
2000	Traditional Authorities Act No 25 of 2000
2001	National Resettlement Policy: Historically disadvantaged groups such as the San be granted access to land
2001	Directorate of Forestry (DoF) regulates fire management
2004	Kyaramacan Residents Association (KA) established for all resident people in the bounds of the park; involves the collaborative wildlife and natural resource management involving the resident communities and the neighbouring communal area conservancies
2006	Community Based Integrated Fire Management (CBiFM) pilot project was adapted into the Bwabwata National Park Plan
2006	Inclusion of BNP and the eastern Zambezi Region into the Kavango Zambezi Transfrontier Conservation Area (KAZA -TFCA)
2006	MET follows a controlled burning management policy, with the aim of burning 1/3 of the parks surface each year, with emphasis on early cool burns
2007	Re-proclamation of Bwabwata National Park (BNP), which included Mahango Game Reserve, and the Kwando Triangle an area of the river previously excluded from the park
2013- 2014 to 2017/18	BNP Management Plan (control or suppression of fires will only take place under certain circumstances
2012	Development of the Kyaramacan Association (KA) for the representation of all people living in Bwabwata National Park
2013	Official publication of the GRN document of the National Policy on Community Based Natural Resource Management (CBNRM)
2016	MET recognises traditional burning practises in BNP for the first time in history

Table A2: Population survey of each Khwe village in Bwabwata National Park (Brenzinger, 2010)

Khwe Village	**No. of Khwe**	**%**	**No. of !Xũ**
Mǘtc'ìkù	1020	28,95	!Xũ 182
N‖áné-Cà	35	0,99	
Bórí-Cà	27	0,77	!Xũ 10
Nova	23	0,65	
Omega I	630	17,88	!Xũ 100
Màngárángàndjà	54	1,53	
Chetto	590	16,75	
Bwàbwátà	39	1,11	
‖'Á-‖'Ánì-xà	63	1,79	
N‖ám-‖Xòm	103	2,92	
ǀÙí-Tcùkx'òm	16	0,45	
Omega 3	638	18,11	
Gùíxà	62	1,76	
ǂQòwɛ́xà	78	2,21	
ǀ'Íyó-‖'Ánà (Mashambo)	119	3,38	
Doppies	10	0,28	
Susuwe	16	0,45	

*****(Adapted from Brenzinger 2010). Population of Khwe recorded in BNP in 1996 : 3,523.).

Table A3: Timeline of the evolution of policy in relation to fire management in Namibia (1800 – 2016).

Year	Event/Policy	Description	Institution	Reference
1884	Removal of power from Traditional Authorities (TA) to control fire	The supervision and control of burning was transferred from the Traditional Authorities to Government. Daily supervision ceased and uncontrolled shifting cultivation and hunting with the use of fires began in Northern Namibia.		NFVFMM policy document
1888	*Deutsche Kolonialgesellshaft Für Südwestafrika*	First official Fire policy in Namibia banning all fires in the late 19th century.	German South West Africa	Le roux, 2011
1952	Preservation of Trees and Forest Ordinance	Regulates the use of fire in construction of fire belts and assistance in fire suppression. Included the special protection of 23 tree species.	GRN	GRN, 1952
1960 - 1989	Namibian War of Liberation (SADF occupation of NE Namibia)	Namibian Government restricted from area; Khwe-San were banned from using fires by the South African Military (SADF): removal of the responsibility of Fire management from the Traditional Authorities by south African administration.	SADF	(MWAF, 2002; Kamminga, 2001)
1968	Forest Act No 72	Procedural regulations on clearing of fire belts and rules of fire control. Provided for the establishment of protected forest areas in 1968.	DoF	IFFN, 2001
1995	Namibia is a signatory to the United Nations Convention on Climate Change (UNFCC) and the International Decade on Natural Disaster Reduction	Concern at the international level that large scale burning is contributing to the anthropogenic greenhouse effect and influencing global climate change. These concerns provided the justification for the Integrated Forest Fire Management Programme (IFFM) component of the Namibian Finland Forestry Pilot project (NFFP).	GoN	(Goldammer, 1998; Trollope& Trollope, 1999)
1996	Namibia Forestry Strategic Plan (NFSP)	Provided the foundation for fire policy and management planning; the NFSP was based on ecological, environmental, cultural and socio-economic considerations. "Production, Protection, and Participation " were considered the three imperatives of forest policy. The plan was underscored by reducing the negative effects of fires. Section 3.2.1. "The occurrence and severity of uncontrolled and accidental forest fires has to be reduced*, and the policy of burning off patches of woodlands to improve hunting grounds, should be changed to one of using fire only as a controlled tool under specific circumstances". The importance of community participation in fire management was recognised. One objective was to increase rural income and employment.* Recognised that different ecosystems require different policies, and thus diverse vegetation types have disparate fire regimes.	DoF	(DoF; IFFN, 2001; Goldhammer, 2001)

1998	The Ministry of Local Governments and Housing	The Ministry of Local Governments and Housing in a policy statement (not formally decided by the Cabinet) *has taken over the responsibility for rural fire control.*	GRN	IFFN, 2001
1998	National Gender Policy in 1998	In Section "Gender and the Management of the Environment" emphasis has been given on the role of women in protecting the environment. Although fire management has not yet been mentioned explicitly in that section it is expected that more detailed activity programmes will include a fire component.	GRN	IFFN, 2002
1997 - 2001	Namibian -Finland Forestry Program (pilot project) (NFFP): Integrated Fire Management Programme (IFFP)	Objective: increase the role of forestry in the socio-economic development of Namibia through continuous development and implementation of sustainable forest management practises. Finnish project assisted the Directorate of Forestry (DoF) in ‘’reducing the fires in the East Caprivi in order to improve living standards and the environment for the local people’’; Diminish negative impacts of the indiscriminate use of fire on forest regeneration, agricultural and pastoral lands and to improve the environment and living standards of local people;; communities were mobilised , and trained to create fire breaks to prevent the spread of fire in important forest reserves; fire campaign awareness programmes. Assistance in National fire policy development and the collaboration of a regional fire management plan for East Caprivi.	IRDNC, GoN	NFFP; Beatty (2007); IFFN (2001); Trigg & le Roux (2001); Kamminga, 2001)
1999 (1998 - 2001)	National Fire Policy and Guidelines on Fire Management	Namibia Round Table on Fire : Namibia-Finland Forestry Programme was supported by the Fire Ecology Research Group of the Global Fire Monitoring Centre (GFMC) to develop a "*National Fire Policy and Guidelines on Fire Management in Namibia*’’ in collaboration with the DoF. *Major emphasis was on fire prevention, particularly on a community-based approach. Major focus on fire prevention and suppression, and implementation consists of discouraging burning through public awareness campaigns, firebreak networks and community wildfire suppression.*	Global Fire Monitoring Centre (GFMC)	IFFN (2001); Goldhammer (1998)
1999	Technical Review of the Integrated Forest Fire Management Component of the Namibia-Finland Forestry Programme	Technical Review of the Integrated Forest Fire Management (IFFM) component of the Namibian Finland Forestry programme (NFFP): assessed the positive and negative attributes of controlling forest fires; provided recommendations for prescribed burning based on different land use categories in East Caprivi. This study formed the basis for fire management that was adapted to and specifically focussed on the maintenance of land for specific uses.	University of Fort Hare	Trollope & Trollope (1999)

1999	Technical Review of the Integrated Forest Fire Management *Socio-economic* Component of the Namibia-Finland Forestry Programme	Assess strengths and weaknesses of the IFFM's implementation strategy (the "model") were assessed in terms of their effectiveness, socio-economic impact and long-term sustainability, thus qualitative analysis was undertaken, drawing on recent experiences with so called "livelihoods approaches"; to the enhancement of local livelihoods and to identify opportunities for improvement. *The IFFM component was identified as lacking experience in community development and participatory approaches, and showed no regard for exiting fire management systems and practise.*	IFFN	(Kamminga, 1999; Kamminga, 2001)
2001	Forest Act 12 of 2001	Custodian for veld and forests fires in Namibia. One of the main objectives is '*to provide control and management of forest fires..'; Emphasis on fire suppression and prevention*	DoF	GRN, 2001
2001	National Guidelines on Forest Fire Management	*Focused on forest fire prevention, suppression, prescribed (controlled) burning, post fire evaluation and community education campaigns in the East Caprivi forests.* Development of an early warning system and to encourage forestry departments, Government institutions, farmers networks and communities to develop a database of forest fire occurrence.	IFFN	IFFN, 2001
2001	A local operational tool for fire monitoring and management for the Kavango and Caprivi regions	Mapping and GIS for the support of Regional Fire Management in Namibia: to provide data to revise the fire management practises and in preparation of a fire management policy (*National Forest and Veld Management Policy (2004)*	National Remote Sensing Unit (MWAF/DoF)	MWAF, 2002
2004	*Draft* National Forest Veld Fire Management Policy	Forest fire prevention, suppression, and prescribed (controlled) burning.	DoF	DoF, 2005
2005	Forest Act No 12 2001; Transfer of line Ministry	Transferred from the Ministry of Environment and Tourism to that the Ministry of Agriculture, Water and Forestry.	MET/MWAF	Dentlinger, 2005
2009	Mapped Burned area reports	Initiation of fire scar maps of which are disseminated.	National Remote Sensing Unit (MWAF/DoF)	Le roux, 2011
2010	Southern African Development Community (SADC) Protocol on Forestry	Adherence to cross-border co-operation in fire management	SADC	(MWAF, 2011; SADC ,2010)

2006-2011	Caprivi Region: Draft Integrated Fire Management Programme	Implemented to support community, national parks and forestry in the East Caprivi region. A pilot CBiFM policy was established for fire management that complements the environment, land use, resources and capacity of communities. It is implemented through a fire management strategy based on controlled burning, decentralized community fire management decision-making and integrating CBiFM into regional fire management. Resulted in the formation of the pilot Community Based integrated Fire Management Policy (CBiFM) in the Caprivi. *Based on holistic management principles, the strategy integrates traditional burning practices, contemporary land use and environmental requirements. It was the first policy to describe the instigation of patch mosaic burning, and focused on the benefits to managing resources. The timing, intensity and frequency of burning was prescribed to specific land-use objectives in specific areas. The programmes enabled communities to acquire the rights and responsibilities of fire management in their areas of authority. Controlled burning is implemented in the early dry season when weather conditions and fuel characteristics lead to low intensity fires of limited extent.*	IRDNC, DoF	(Mbongo *et al.*,2011; Beatty, 2011)
2011-2015	Forest Research Strategy for Namibia	Identified focus area to monitor fires, including seasonal variation, timing, severity and extent to understand the dominant regional fire regime; and to understand the communities' interaction with fire, including attitudes towards fire	MWAF	MWAF, 2011
2013-2018	Bwabwata National Park Management Plan	This management plan sets out the objectives and guidelines for the management and development of BNP. Thus, it represents the policies and intentions of the MET. Objective to is use fire as a management tool for actively maintaining and rehabilitating all habitats in the Park. Implemented early burning as a strategy to reduce the impact of the late hot season fires. Active involvement of communities and other stakeholders in the greater KAZA region.	MET	MET, 2013
2013	Can savanna burning projects deliver measurable greenhouse emissions reductions and sustainable livelihood opportunities in fire-prone settings?	Scientific journal article: Assessment of the inclusion of CBiFM in global carbon budgets research	Journal article	Russell-Smith *et al.*,2013

2014	International Savanna Fire Management Initiative Southern African Regional Workshop	Learning exchange between southern Africa and Australia; objective was to explore how sustainable livelihoods can be reinforced through integrated fire management drawing from traditional fire management and the application of emissions abatement burning methodologies; biodiversity protection and sustainable livelihood opportunities.	UNU-IAS/IRDNC	Jacobsohn *et al.*,2014
2014	Community-Based Fire Management: An integrated Trans-frontier Fire Management approach for Luiana National Park in Angola and Bwabwata National Park in Namibia	Instigation of an integrated transboundary fire management project to achieve i) Protected Area Management objectives; ii) improve community livelihoods and reduce greenhouse gas emissions (GHG); iii) provide recommendations for Integrated Transfrontier Fire Management Approach	GIZ/IRDNC/Fire 321/ACADIR	Beatty, 2014
2015	Integrated Regional Land use Plan for Kavango East and West, and the Zambezi Regions	Identified that large areas of the Kavango East & Zambezi Regions burn every year; The fires have a number of negative impacts on people and the natural environment: grazing area is lost, timber resources are lost from trees being killed, bush encroachment often follows, and soil fertility declines.	Ministry of Lands and Resettlement	Ministry of Lands and Resettlement, 2015
2015	Regional Fire Co-ordination committee Meeting - Zambezi Region	Development of a regional fire management committee in the Zambezi Region to address fire management through stakeholder collaboration in the conservancies and community forests.	MWAF & MET	DoF, 2015
2015	Forest Regulations: Forest Act, 2001	Measures to be taken for forest protection, prevention of fires and protection of soil and water resources; permit system for controlled burning and stipulation of a rehabilitation agreement for any person who uses fire for resource utilization.	MWAF	MWAF, 2015
2016	Fire Management Workshop and Strategy Development	The Ministry of Agriculture, Water and Forestry (MWAF) in partnership with the Ministry of Environment and Tourism (MET) has been working on approaches to manage veld fire. The conference was attended by practitioners and researchers and the conference served to discuss issues and share experiences around fire management, including: identification of the key causes of veld and forest fires, assessment of current fire management practices, and identification of key research gaps on the causes and management of fires. A draft policy statement was the main outcome of the workshop serving to inform the forest management policy and strategy that is currently in draft.	MWAF	NAFOLA, 2016

2016	**Fire Management Strategy for Namibia's Protected Areas**	**Sets the overall framework for fire management in Namibia's Protected Areas for the future. The framework includes a controlled fire management programme specific to each Protected Area that has been developed through a structured planning, implementation and monitoring process. Formulated to balance the beneficial an harmful effects of fire, and to manipulate ecosystems and enhance land use.**	**MET**	**MET, 2016**

*Note: Italicised sentences are my emphasis.

Appendix B: Chapter 3

Table B1: List of semi-structured interviews and focus group meeting and their locality in Namibia, and elsewhere (2014, 2015).

No	Type	Location (city/village)
25	Government and non-government stakeholder Interviews (23 males; 2 females)	Windhoek, BNP, Katima Mulilo, Cape Town
26	Khwe stakeholder interviews	Mut'ijuku, Pipo, Chetto, Mashambo, Tokoloshi, Omega III
10	Mbukushu stakeholder interviews	Mut'ijuku, Diye, Mashshane
3	Focus Group Meetings	Chetto

Figure B1: Example of using topographical maps to question the locality of large and small fires amongst the community stakeholders in Bwabwata National Park (2014, 2015).

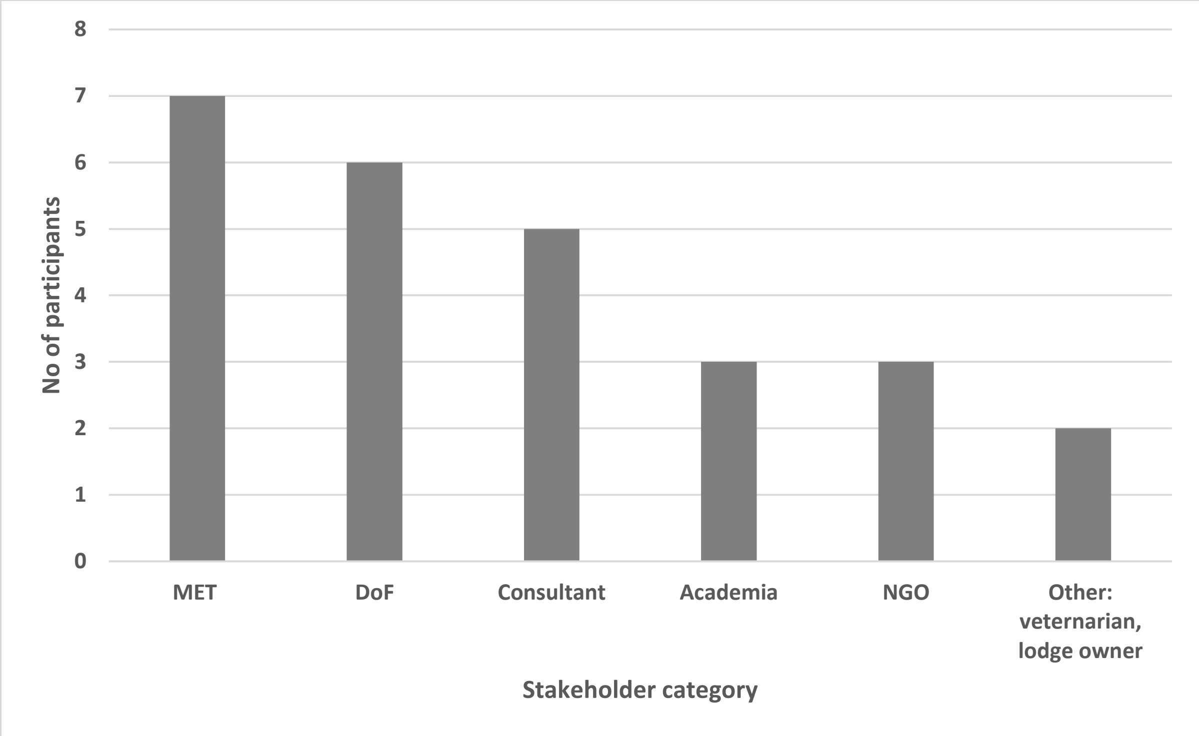

Figure B2: Number of interview participants within each stakeholder category [n=24]. *Ministry of Environment and Tourism (MET): BNP park managers (i.e. east and west chief wardens, community game guards (CGG), and field rangers); Ministry of Agriculture, Water and Agriculture (MWAF); Directorate of Forestry (DoF); non - governmental Organisations (NGO) staff members; academic staff from the University of Namibia (UNAM), and Polytechnic of Namibia (PoN), the state veterinarian, independent ecological consultants, and regional local stakeholders (e.g. tourism operators).

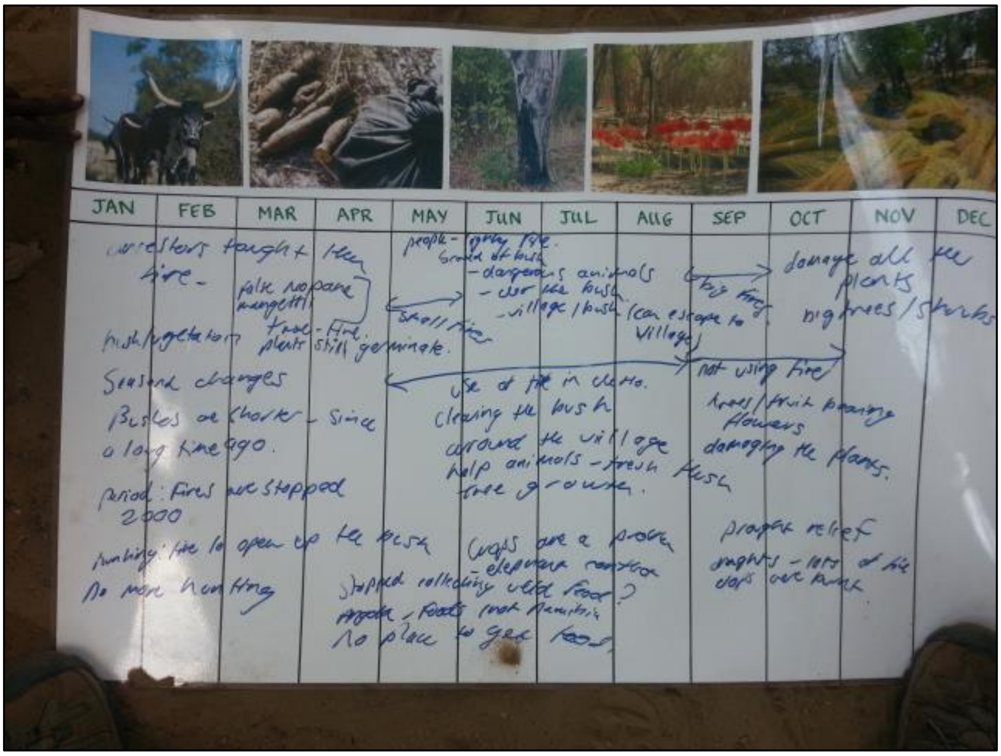

Figure B3: Example of a seasonal calendar following an individual interview with the Community stakeholders' within Bwabwata National Park (2014, 2015).

Figure B4: Focus group meeting in Chetto village involving the discussion on the use of veld food resources in the BNP (2014).

Table B2: Semi-structured questions: Community stakeholder (Khwe and Mbukushu) interviews.

i) Cultural practises

1. Do you use fire as a traditional practise in your culture? How?
2. What are your cultural beliefs about fire?

ii) Fire management: How, where, when and how often fire is used

3. Do you have a problem with fire in your area?
4. How do the fires start? Natural fires (lightning), by accident, or started by humans?
5. Why are the fires started? Is it important to burn?
6. Are there small or large fires in your area? Where are the small and large fires in the Park?
7. In what months are the fires are there big fires and small fires?
8. What is/are your primary land use practise/s?
9. Do you use fire to manage your land (How)? What months of the year do you use fire? What time of day?
10. What is/are your primary land use practise/s?
11. Do you use fire to manage your land (How)? What months of the year do you use fire? What time of day?
12. Why do you burn? How do you use fire to manage your land? / What type of activities do you use fire for?
13. Why do you burn early in dry season? Reasons?
14. Why do you burn late in dry season? Reasons?
15. How often do you burn in a season? What are your burning (grasses / trees / scrub)? How long do the fires burn?
16. How do you know when to burn? How do people decide which areas to burn?
17. Do you think it is better for the vegetation to burn early or late in the season? Why?
18. How do you view fire? Is it good or bad for the land, or should it be stopped?

iii) Vegetation and fire history

19. Is burning different now than it was in the past? If so, how and why?
20. Do you think fires occur more or less than in the past / fire pattern in the area over the last 10 / 20 / 50 years?
21. Has the vegetation changed over time in your area over the last 50 years?
22. Do the big trees burn? How about the shrubs? Is there more or less trees / shrubs because of burning?

iv) Livelihood resources: Impact of fire on plant and livelihood resources

23. Are resources that you depend on affected by fire (species name)? What are the resource attributes that makes it valuable (e.g. for charcoal, edible fruits, poles, Medicinal plants).
24. What does fire do to the plants? Is it good or bad?
25. Do you know of plants that fire is good or bad for? Have you noticed certain plants have disappeared or become more because of fire? Which plants are they? (Local name).

Table B3: Semi-structured questions: Government and non-government stakeholder interviews.

1. What is your view of the increased incidence in fires that occur in the Zambezi region (BNP)?
2. How do you think the fires start? Natural fires (lightning), by accident, or started by humans?
3. Management of fires in the BNP has been dominated by fire exclusion, protection, and suppression policies dating back several decades. What is your view on current fire management practise of prescribed early season burns (May - July) in the Zambezi region/BNP? Reference: Controlled Fire Management Programme (Robin Beatty).
4. Do you think it would be beneficial if fire policy distinguished between uncontrolled burning, burning for productive land use, and burning for fire prevention?
5. Do you think the policy of fire suppression in the past has had an effect on fire patterns in the Zambezi?
6. How do you think the policy of fire suppression/prevention has affected vegetation in the Zambezi region?
7. Do you think the community in the Zambezi region is informed about the fire policy?
8. Do you know about the use of any current traditional fire management practises in the Zambezi region?
9. Do you think the controlled burning instigated in 2007 in the eastern Caprivi has made an impact on the occurrence of fire in the region?
10. Do you think the fire regime is changing? How? Why? If so, what is causing the changes?
11. Do you think there is a difference between fires 20/50 years ago versus the last 10 years? Why?
12. How do you think fire has affected habitats in the BNP?
13. Do you think the small and or big fires can be controlled if there were resources to put out the fires? What do you think about that?
14. Do you think the high fire frequency in the Zambezi region has affected tourism?

Table B4: Socio-demographic characteristics of the Khwe and Mbukushu stakeholders [n=36].

Participant	Locality in BNP	Village	Cultural Group	Gender	Age	Interview year
Khwe 1	MUA West	Mut'ijuku	Khwe	Male	65	2014
Khwe 2	MUA West	Mut'ijuku	Khwe	Male	70	2014
Mbukushu 1	MUA West	Mut'ijuku	Mbukushu	Female	65	2014
Khwe 3	MUA West	Mut'ijuku	Khwe	Male	65	2014
Khwe 4	MUA West	Mut'ijuku	Khwe	Male	65	2014
Khwe 5	MUA West	Mut'ijuku	Khwe	Female	60	2014
Khwe 6	MUA West	Mut'ijuku	Khwe	Male	67	2014
Khwe 7	MUA West	Mut'ijuku	Khwe	Male	65	2014
Khwe 8	MUA West	Mut'ijuku	Khwe	Male	71	2014
Khwe 9	MUA West	Mut'ijuku	Khwe	Male	60	2014
Mbukushu 2	MUA West	Mut'ijuku	Mbukushu	Male	65	2014
Mbukushu 3	MUA West	Diye	Mbukushu	Male	40	2014
Khwe 10	MUA West	Diye	Khwe	Male	65	2014
Khwe 11	MUA East	Chetto	Khwe	Male	60	2014
Khwe 12	MUA East	Chetto	Khwe	Male	73	2014
Khwe 13	MUA East	Chetto	Khwe	Male	65	2014
Khwe 14	MUA East	Pipo	Khwe	Female	70	2014
Khwe 15	MUA East	Pipo	Khwe	Female	70	2014
Khwe 16	MUA East	Chetto	Khwe	Male	50	2014
Khwe 17	MUA East	Chetto	Khwe	Male	43	2014
Khwe 18	MUA East	Mashambo	Khwe	Male	60	2015
Khwe 19	MUA East	Mashambo	Khwe	Female	60	2015
Khwe 20	MUA East	Mashambo	Khwe	Female	64	2015
Khwe 21	MUA East	Mashambo	Khwe	Male	65	2015
Khwe 22	MUA East	Tokoloshi	Khwe	Male	60	2015
Khwe 23	MUA East	Tokoloshi	Khwe	Male	60	2015
Khwe 24	MUA East	Poca	Khwe	Male	60	2015
Khwe 25	MUA East	Omega III	Khwe	Male	68	2015
Khwe 26	MUA East	Mashambo	Khwe	Male	60	2015
Mbukushu 4	MUA West	Mut'ijuku	Mbukushu	Male	60	2015
Mbukushu 5	MUA West	Mut'ijuku	Mbukushu	Female	60	2015
Mbukushu 6	MUA West	Mut'ijuku	Mbukushu	Male	60	2015
Mbukushu 7	MUA West	Mut'ijuku	Mbukushu	Male	68	2015
Mbukushu 8	MUA West	Mut'ijuku	Mbukushu	Male	60	2015
Mbukushu 9	MUA East	Mashashane	Mbukushu	Male	60	2015
Mbukushu 10	MUA East	Mashashane	Mbukushu	Male	80	2015

Table B5: Institutional and non-institutional characteristics of the government and non-government stakeholder participants interviewed (n=25), 2014 - 2015.

Participant	Institution affiliation & other	Interview year
Stakeholder 1	MET	2014
Stakeholder 2	Consultant	2014
Stakeholder 3	DoF	2014
Stakeholder 4	DoF	2014
Stakeholder 5	MET	2014
Stakeholder 6	DoF	2014
Stakeholder 7	DoF	2014
Stakeholder 8	Consultant	2014
Stakeholder 9	MET	2014
Stakeholder 10	Consultant	2015
Stakeholder 11	Lodge owner	2015
Stakeholder 12	IRDNC	2015
Stakeholder 13	IRDNC	2015
Stakeholder 14	IRDNC	2015
Stakeholder 15	DoF	2015
Stakeholder 16	UNAM/Academic	2015
Stakeholder 17	State Veterinarian	2015
Stakeholder 18	DoF	2015
Stakeholder 19	MET	2015
Stakeholder 20	MET	2015
Stakeholder 21	MET	2015
Stakeholder 22	MET	2015
Stakeholder 23	MET/Academic	2015
Stakeholder 24	Consultant/Academic	2015
Stakeholder 25	Consultant/Academic	2015

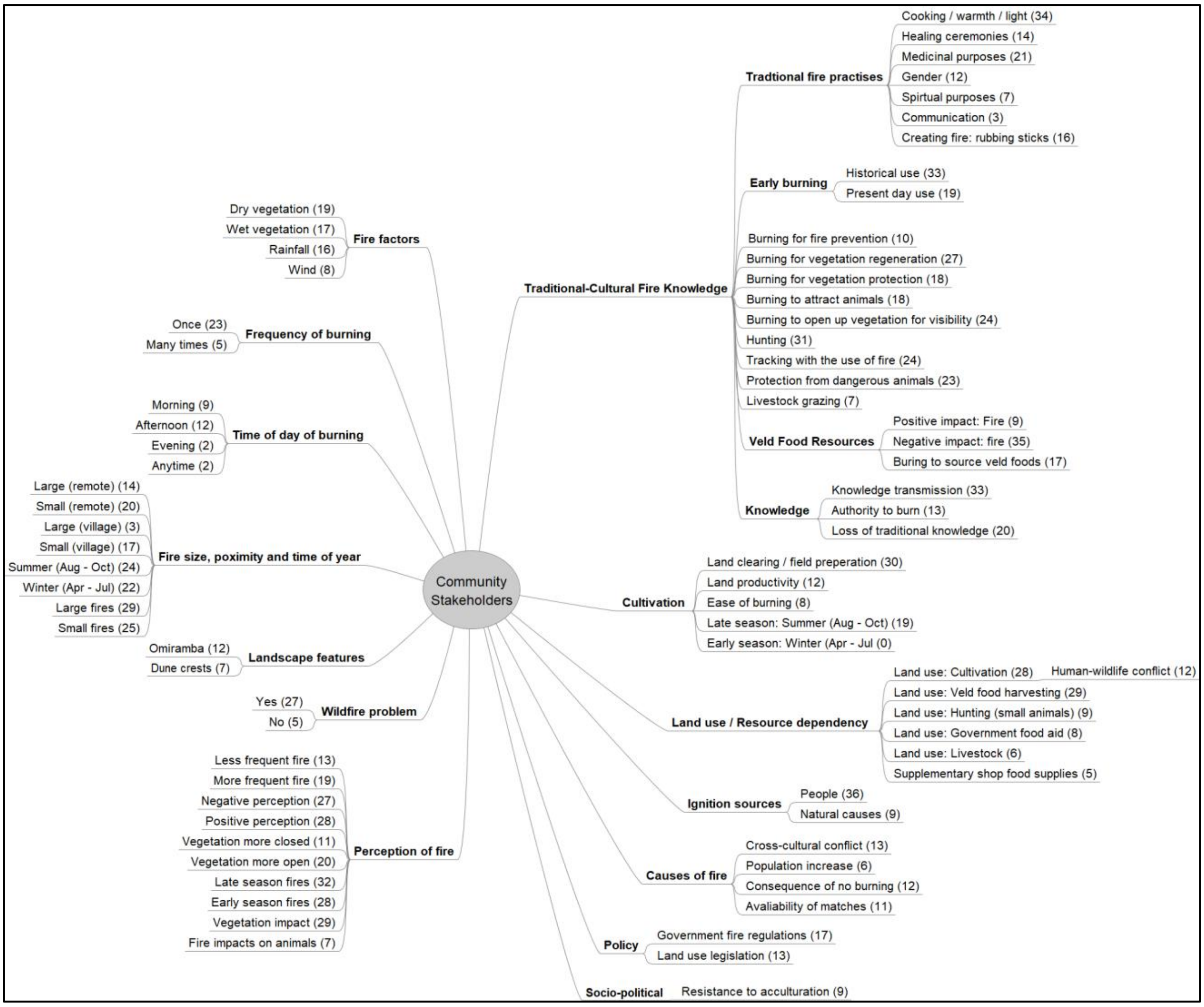

Figure B5: Map showing the main themes (n = 18) and sub-themes (n= 75) based on thematic content analysis of interview data (n = 36) with the Khwe and Mbukushu people in Bwabwata National Park (2014 - 2015). *The numbers in parentheses refer to the number of participants who provided a response for each sub-theme within the context of the sub-theme.

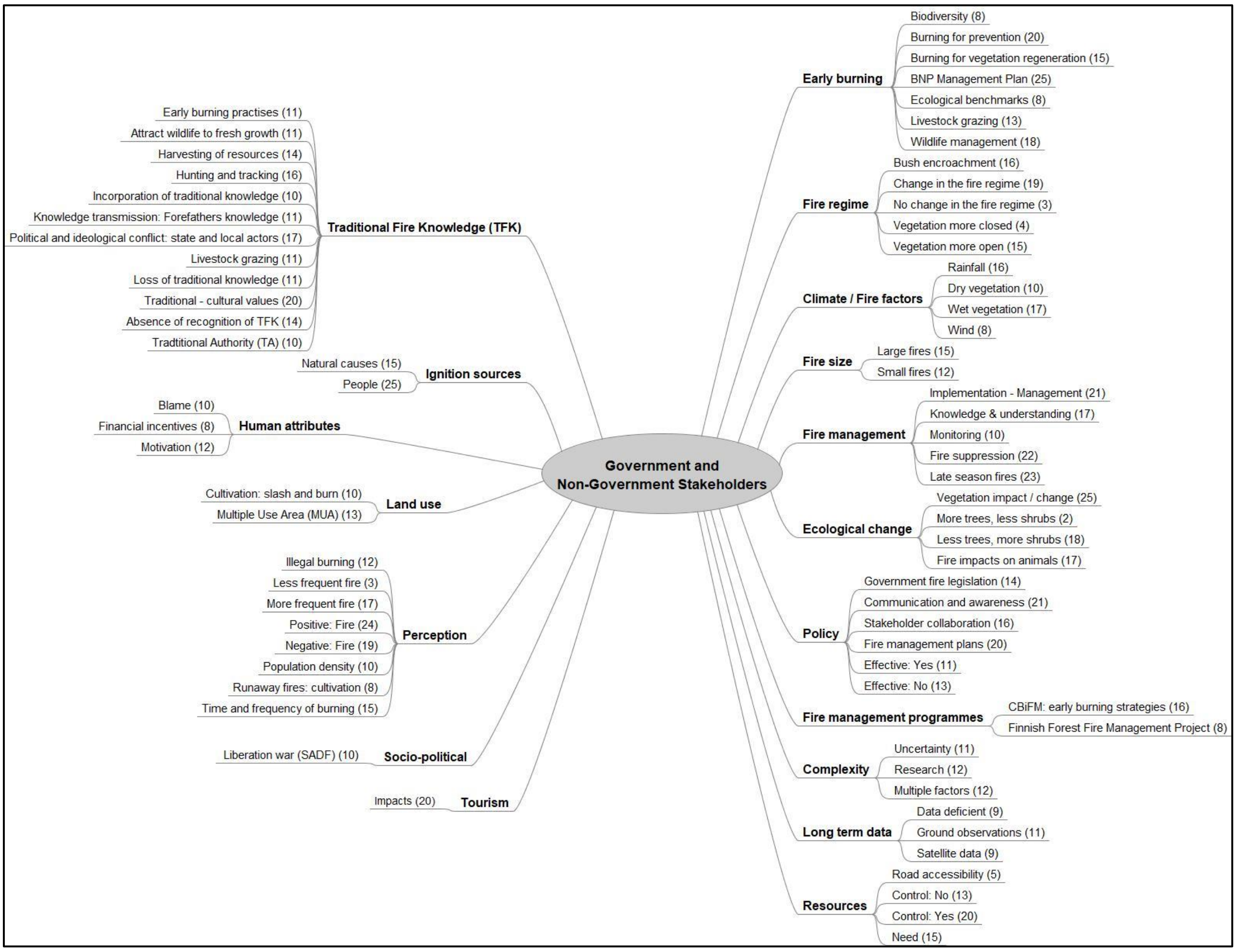

Figure B6: Map showing the main themes (n = 18) and sub-themes (n= 68) categories based on thematic content analysis of interview data for the Stakeholder data [n=25]. The numbers in parentheses refer to the number of participants who provided a response for each sub-theme.

Table B6: List of themes and sub-themes associated with the community stakeholder thematic analysis in Bwabwata National Park (2014, 2015).

Traditional-Cultural Fire Knowledge	
Traditional Fire Practises	Fire related knowledge and practises that have been developed and applied for specific purposes by inhabitants of the area, inclusive of the use of fire in association with cooking and warmth, medicinal plants, healing ceremonies/rituals, gender associations and spiritual practises within the community.
Early Burning: Historical	Reference made to the use of fire in the early season winter months (April – July) in the past.
Early Burning: Present day	Reference made to the current use of fire in the early season winter months (April – July) by the community inhabitants in the park.
Burning for fire prevention	Reference made to the use of fire for the prevention of late season fires in the landscape and in proximity to the homestead.
Burning for vegetation regeneration	Burning of vegetation for the purpose of regenerating plants and/or vegetation
Burning for vegetation protection	Burning of vegetation for the purpose of protecting the plants.
Burning to attract animals /game	Burning of vegetation to attract wildlife to a fresh flush of growth.
Burning to open up vegetation for visibility	Use of fire to reduce dense vegetation and to increase visibility in the landscape.
Hunting	Reference to the practise of hunting.
Tracking with the use of fire	The use of fire to facilitate the visibility of tracks/spoor on the ground to aid tracking.
Protection	Reference made to the use of fire for the protection from dangerous animals (elephant, lions etc.); provision of light at night, and for chasing snakes away in the veld and away from the homestead.
Livestock grazing	Reference made to the use of fire in association with the management of grazing areas for cattle.
Veld Food Resources	
Burning to source veld foods	Reference made to the use of fire to source veld food resources.
Negative impact: Fire	Negative statements made concerning the impact of fire on veld food resources.
Positive impact: Fire	Positive statements made concerning the impact of fire on veld food resources.
Knowledge	
Knowledge Transmission	General references to the transfer of knowledge concerning the use of fire between the older and younger generations, including reference to the exchange of knowledge concerning fire management in BNP.
Loss of knowledge	Reference made to the loss of knowledge among inhabitant park communities, including the absence of knowledge concerning the mismanagement of fire in the landscape.
Authority to burn	Reference made to the elders' knowledge in association with the instruction of past burning strategies of who, when and where and how to use fire in the landscape.
Socio-political	
Resistance to acculturation	Results when groups of individuals having different cultures come into first-hand contact, with subsequent changes in the original cultural patterns of either or both groups. In this study acculturation is defined as the resistance to a change in livelihood strategies between the Khwe and Mbukushu people in BNP.
Land Use/Resource dependency	
Land Use: Cultivation	Reference made to the dependence on cultivation as a form of land use in the BNP.
Land Use: Livestock	Reference made to the dependence on livestock.
Land Use: Veld Food Harvesting	Reference made to the dependence on veld food resources.

Land Use: Hunting (small animals)	Reference made to the dependence on hunting for small animals.
Land Use: Government Food Aid	Reference made to the dependence on government food aid.
Land Use: Shop supplements	Reference made to the dependence on foods purchased at stores to supplement livelihoods in BNP.
Landscape features: Omiramba & Dunes	Reference made to fire in association with landscape features in the BNP.
Human -wildlife conflict	Reference made to human-wildlife conflict in proximity to cultivated fields.
Land use for cultivation	
Land clearing/ field preparation	Reference made to the use of fire for clearing land and for preparing fields for cultivation purposes.
Easy to burn vegetation	Statements made in reference to the ease of burning brush piles in preparation for the cultivation of crops.
Land Productivity (e.g. nutrient enrichment from ash)	Reference made to the use of fire to aid land productivity in association with the cultivation of crops.
Summer (Aug - Oct)_Cultivation	Fires set in the late dry season months in preparation for cultivation.
Winter (Apr – Jul)	Fires set in the early dry season months in preparation for cultivation.
Frequency of burning	
Once	Respondent reports burning once for cultivation purposes.
Many times	Respondent reports burning on several times in one season for cultivation purposes.
Time of day of burning	
Morning	Fires set before noon.
Afternoon	Fires set between noon and 18h00.
Evening	Fires set after 18h00.
Anytime	Fires set any time of day.
Policy	
Government fire regulations	Reference made to the change in the government fire regulations.
Land use legislation	Reference made to a change in land use regulations.
Ignition sources	
Natural Causes	Reference made to the origin of fires in the BNP as a natural occurrence (i.e. associated with climate, and or lightning events).
People	Reference made to people being responsible for the occurrence of fire.
Perception of fire in the landscape	
Less Frequent Fire	Statements that address the perception of less frequent fire in relation to the past.
More Frequent Fire	Statements that address the perception of an increase in fire in relation to the past.
Negative perception	Statements that address the perception of fire as negative.
Positive perception	Statements that address the perception of fire as positive.
Vegetation more closed	Reference to the vegetation being visually denser in comparison to the past.
Vegetation more open	Reference made to the vegetation being visually more open in comparison to the past.
Late season fires	Reference made to late season fires in the landscape.
Early season fires	Reference made to early season fires in the landscape.
Vegetation impact	Reference made to fire and vegetation change/impact.
Fire impacts on animals	Reference made to fire negatively impacting animals in the park.
Causes of fire	
Cross Cultural Conflict	Statements made that address the concentration and mixed settlements, and conflict over different uses of fire between the Khwe and Mbukushu people in BNP.
Availability of matches	Reference made to the availability of matches.
Population Increase	Reference made to an increase in population density.

Consequence of no burning	Statements made that address fire suppression and the observation of the absence of burning in the landscape.
Wildfire problem	
Yes	Respondent reports that fires are a problem.
No	Respondent reports there is no problem with fire.
Fire Size, proximity and time of year	
Large (Remote)	Statements emphasising the observation/ and or experience of large fires occurring in remote locations far from the villages.
Large (Village)	Statements emphasising the observation/ and or experience of large fires occurring in proximity to the villages.
Small (Remote)	Statements emphasising the observation/ and or experience of small fires occurring in remote locations from the villages.
Small (Village)	Statements emphasising the observation/ and or experience of small fires occurring in proximity to the villages.
Summer (Aug - Oct)_Fire Size	Reference made to the fire size in the summer months (Aug – Oct).
Winter (Apr- Jul)_Fire Size	Reference made to the fire size in the winter months (Apr - Jul).
Large fires	Reference made to large fires in the landscape.
Small fires	Reference made to large fires in the landscape.
Fire factors	
Rainfall	Reference made to rainfall and fire.
Wind	Statements emphasising the observation of wind conditions in association to the use of fire and fire size.
Dry vegetation	Statements emphasising dry vegetation and the awareness of dry fuel loads and the implications of applying fire.
Wet vegetation	Statements emphasising moist or wet vegetation and the time of occurrence in association to the application of fire.
Landscape features	
Omiramba	Reference made to the use of fire in the omiramba grasslands.
Dunes	Reference made to the use of fire on the dune crests.

Table B7: List of themes and sub-themes associated with the Government and Non-government stakeholders' thematic analysis (2014, 2015).

Early Burning	
Biodiversity	Reference made to early burning strategies for the management of biodiversity in BNP.
Burning for prevention	Reference made to early burning strategies for decreasing the later hot season fires.
Burning for vegetation regeneration	Reference made to early burning strategies for the purpose of increasing vegetation regeneration.
BNP: Management plan	Reference made specifically to the Bwabwata National Park Management Plan (2013 – 2018).
Ecological benchmarks	Reference made to early burning strategies and the effects on species composition, plant phenology and the need for ecological benchmarks.
Livestock grazing	Reference made to early burning strategies for livestock grazing purposes.
Wildlife Management	Reference made to early burning strategies for wildlife management purposes.
Fire regime	

Bush Encroachment	Statements emphasising the invasion and/or thickening of aggressive undesired woody species resulting in an imbalance of the grass: bush ratio, a decrease in biodiversity, and a decrease in carrying capacity and concomitant economic losses (De Klerk, 2002)
Change in the fire regime	Reference made to a change in the fire regime.
No change in fire regime	Reference made to no change in the fire regime.
Vegetation more open	Reference made to the vegetation being more open today when compare to the past.
Vegetation more closed	Reference made to the vegetation being more closed today when compare to the past.
Climate/Fire factors	
Rainfall	Reference to climatic factors in relation to the occurrence of fire (e.g. wind, rainfall, climate change, dry and wet vegetation)
Dry vegetation	Reference made to dry vegetation.
Wet vegetation	Reference made to wet vegetation.
Wind	Reference made to the wind in relation to fires in BNP.
Fire size	
Large fires	Statements emphasising the observation/ and or experience of large fires.
Small fires	Statements emphasising the observation/ and or experience of small fires.
Fire management	
Implementation - Management	Reference made to the implications of the implementation of fire management.
Knowledge and understanding	Statements emphasising that knowledge and understanding are required to manage fires in the BNP.
Monitoring	
Fire Suppression	General references made to all activities concerned with controlling and extinguishing fire following its detection.
Late season fires	Reference made to late season fires in the BNP landscape.
Ecological change	
Vegetation impact/change	Reference made to ecological change in the context of vegetation structure, and a negative impact of fire on fire on vegetation.
Less Trees , more Shrubs	Reference made to the perception of less trees and the prevalence of more shrubs in the landscape.
More trees, less shrubs	Reference made to more trees, and less shrubs in the BNP landscape.
Fire impacts on animals	Reference made to the negative effects of fire on animals.
Policy	
Government fire legislation	Statements referencing the Namibian government fire regulations.
Communication and Awareness	Statements emphasising the need for increased communication and awareness concerning fire management amongst stakeholders and communities.
Stakeholder collaboration	Statements emphasising the need for increased stakeholder collaboration (e.g. MET, MWAF, grass roots community).
Fire management plans	Reference made to the Namibian fire management plans and the need to define management objectives for different habitat and land use types.
Information conflict: Fire use	Reference made to the misinformation concerning fire management between communities and fire stakeholders.
Effective: Yes	Respondent reports that the fire management policy is effective.
Effective: No	Respondent reports that the fire management policy is ineffective.

Fire management programmes	
CBiFM: early burning strategies	Reference made to the Community Based Integrated Fire Management (CBiFM) initiative developed in 2006, where early burning strategies were implemented together with the community.
Finnish Forest Fire Management Project	Reference made to the Finnish World Bank program in the eastern caprivi for the fire management of the forest woodlands.
Complexity	
Uncertainty	Reference made to the uncertainty concerning appropriate measures required for fire management.
Research	Reference made to research in relation to early burning strategies.
Multiple factors	Reference made to multiple factors in relation to early burning strategies.
Long term data	
Data deficient	Reference made to limited data availability in conjunction with fire management.
Satellite data	Reference made to the use of remotely sensed satellite data for the use of fire management.
Ground Observations	Reference made to ground observations of fire use in the landscape.
Resources	
Road accessibility	Reference made to road accessibility in association with controlling fires in the BNP.
Control: No	Reference made to the inability to control fires with immediate resources.
Control: Yes	Reference made to being able to control fires with immediate resources.
Need	Reference made to the need for resources (funding etc.)
Traditional Fire Knowledge (TFK)	
Traditional - cultural values	Reference made to fire and traditional-cultural values.
Early burning practises	Reference made to the use of early burning practises in the landscape
Attraction of wildlife to fresh growth	Reference made to the use of early burning strategies by the BNP communities to attract game to a fresh flush of growth
Harvesting of resources	Reference made to the use of fire for the harvesting of resources
Hunting and tracking	Reference made to the use of fire for use by the BNP communities for hunting and tracking purposes
Livestock grazing	Reference made to the use of fire to generate vegetation growth for livestock grazing purposes
Loss of traditional knowledge	Reference made to a loss of traditional knowledge amongst the BNP communities
Incorporation of traditional knowledge	Reference made to the need to incorporate/and or inclusion of local traditional knowledge in decision making in relation to fire management
Knowledge transmission: Forefathers knowledge	Reference made to knowledge being communicated by traditional forefathers
Political and ideological conflict: state and local actors	Reference made to power relations between local and state members, and associated conflict.
Absence of recognition of TFK	General statements made that revealed scepticism about the use of traditional fire management practises.
Traditional Authority	Reference made to Traditional authority (TA) and the control of fires in the BNP community
Ignition sources	
Natural causes	Reference made to natural causes of fire (e.g. lightning)
People	Reference made to people as the main cause of fires in the BNP landscape.
Human attributes	

Blame	General statements that place blame on others for the reason for fires in the landscape.
Motivation	Reference made to the motivation to control and or ignite fires
Financial incentives	Reference made to the motivation to the control of fires in relation to financial incentives
Land use	
Cultivation: slash and burn	Reference made to the use of fire for cultivation purposes in the MUA.
Multiple-Use Area (MUA)	Reference made to land use and the Multiple-Use Area (MUA).
Perception	
Illegal burning	Reference made to illegal fires from cross border immigrants e.g. poachers.
Less Frequent Fire	Reference made to less frequent fire when compared to the past.
More Frequent Fire	Reference made to more frequent fire when compared to the past.
Positive: Fire	Statements that reflect a positive perception of fire as an ecological tool in the landscape.
Negative: Fire	Statements that reflect a negative perception of fire as an ecological tool in the landscape.
Population Density	Reference made to an increase in human population density
Runaway fires: cultivation	Reference made to cultivation fires in the late season and the potential for these fires to escape out of control
Time and Frequency of burning	Reference made to the timing and frequency of fires in the landscape
Socio-political	
Namibian Liberation War	Statements emphasising the combination of the social and political dynamics including the Liberation War between the SADF and SWAPO, the Secessionist Movement, and present political influence (dominance by MET & DoF) and exclusion of community participation (century) in fire management.
Tourism	
Impacts on tourism	General references to the negative impacts of fire on tourism in the BNP.

Table B8. List of representative oral accounts: Community stakeholders

Traditional Fire Practises

“Medicinal purposes to burn plants are still in use today; fires are used for different purposes e.g. Fires used for treating illnesses is different to cooking and fires for warmth and sitting around; learnt from elders - up till now we use this same way” (Khwe).

Early burning

"Knowledge passed on from father and grandfather,..during winter, burn dry grass (small fire); you must burn the grass when is not too dry, so that you can have a small fire" (Khwe).

"Past, the fire was small because people were using patch burning, these days people are not using that system, they are burning anytime". Patch burning is when you get small dry grasses and you put the fire, and if you see the fire, then you have to stop it. The part you burnt earlier the area it germinates earlier, then animals come closer to graze (Khwe).

‘’No late season fires as you will ruin the grass for the cattle; if there is burning it is because people don't know how to use fire; burn early season for the grass for cattle; if you burn early the grass starts to germinate’’ (Mbukushu)

Veld food resources

‘’In the past they were using fire in May and June months- told by grandparents and his parents; but today people burnt nearby still today; fires should burn early to get wild fruits - burning is good for the vegetation; reason for burning is looking for food, put fire and walk’’ (Khwe).

‘”Sometimes burning has a negative side as the fires kill of veld foods; when the fire comes to the food plants - it will kill the food plants itself and you won't find that type of plants anymore” (Khwe).

’’Using fire when they go hunting - old grasses and thick bushes are burnt on his way he finds Mangetti tree; then they come back and discuss and then go burn the next day; collect seeds (food resources)’’ (Khwe)

Government Fire Regulations

‘’Different, today and long time ago people were burning freely, but were burning in the months that they know, and burning with the purpose of collecting false mopane, but today were are controlled by the Ministry on burning - really quite different - long ago we were free" (Khwe).

Vegetation change: Fire Suppression/ Consequence of no burning

“Yes, vegetation has changed; completely different now; policy of no burning destructive to regular burning” (Khwe).

Hunting & Tracking with the use of fire

‘’Use fire for clearing thick bush and to find footprints of animals such as tortoises, monitor lizards, and duikers’’ (Khwe).

Table B9: Summary of theme co-occurrences for the community stakeholders [n= 36] responses in Bwabwata National Park, 2014 - 2015.

Sub-theme 1	**Sub-theme 2**	**No. of theme co-occurrences**	**%**
Veld Food Resources	Early Burning: Present day	35	97
Negative impact: veld food resources	Veld Food Resources	35	97
Early Burning: Present day	Late season fires	34	94
Hunting	Tracking with the use of fire	31	86
Early burning: Historical	Late season fires	31	86
Positive Fire: perception	Early Burning: Present day	30	83
Vegetation impact	Late season fires	29	81
Burning to open up vegetation for visibility	Knowledge Transmission	28	78
Hunting	Burning to open up vegetation for visibility	28	78
Negative impact: Fire (veld food resources)	Late season fires	28	78
Early season fires	Positive Fire: perception	28	78
Early Burning: Historical	Burning for vegetation regeneration	27	75
Veld Food Resources	Late season fires	27	75
Burning to open up vegetation for visibility	Tracking with the use of fire	24	67
Knowledge Transmission	Early Burning: Historical	24	67
Summer (Aug - Oct): Fire Size	Late season fires	24	67
Winter (Apr- Jul)_Fire Size	Small fires	23	64
Early season fires	Positive impact: Fire	22	61
People	Negative Fire: perception	22	61
Land Use: Cultivation	Land Use: Veld Food Harvesting	20	56
Negative Fire: perception	Vegetation impact	18	50
Hunting	Early Burning: Historical	18	50
Traditional Fire Practises	Knowledge Transmission	18	50
Early season fires	Small fires	18	50
Veld Food Resources	Burning for vegetation regeneration	17	47
Decision Hierarchy	Knowledge Transmission	17	47

Burning for vegetation regeneration	Burning to attract animals /game	16	44
Early burning: Historical	Burning for vegetation protection	15	42
Burning to attract animals /game	Early Burning: Historical	15	42
Consequence of no burning	Late season fires	15	42
Ease of burn	Land clearing/ field preparation	15	42
Hunting	Veld Food Resources	15	42
Negative fire: Perception	Late season fires	15	42
Burning for vegetation regeneration	Burning for vegetation protection	14	39
Burning to attract animals /game	Positive Fire: perception	14	39
Government fire regulations	Early Burning: Present day	14	39
Large fires	Late season fires	14	39
Positive fire: perception	Burning for vegetation regeneration	13	36
Veld Food Resources	Cross Cultural Conflict	13	36
Vegetation impact	Large fires	13	36
Positive impact: Fire	Veld Food Resources	13	36
Veld Food Resources	Burning for vegetation protection	12	33
Dry vegetation	Late season fires	12	33
Early season fires	Veld Food Resources	12	33
Government fire regulations	Land use legislation	12	33
Positive fire: perception	Burning for vegetation protection	11	31
Hunting	Knowledge Transmission	11	31
Loss of traditional knowledge	Early Burning: Historical	11	31
Burning to attract animals /game	Veld Food Resources	10	28
Veld Food Resources	Tracking with the use of fire	10	28
Cross Cultural Conflict	People	10	28
Positive impact: Fire (veld food resources)	Early Burning: Present day	10	28
Fire problem: Yes	Veld Food Resources	10	28
Fire problem: Yes	Negative impact: Fire (veld food resources)	10	28
Land clearing/ field preparation	Cultivation: Summer (Aug - Oct)	10	28
Land Use: Livestock	Land Use: Cultivation	10	28

Vegetation impact	People	10	28
Protection	Traditional Fire practises	10	28
Early burning: Historical	Burning to open up vegetation for visibility	9	25
Burning to attract animals /game	Burning for vegetation protection	8	22
Burning to open up vegetation for visibility	Protection	8	22
Fire problem: Yes	People	8	22
Government fire regulations	Veld Food Resources	8	22
Knowledge Transmission	Loss of traditional knowledge	8	22
Landscape features: Omuramba & Dunes	Early Burning	8	22
Early Burning: Present day	Burning for fire prevention	7	19
Burning for fire prevention	Early Burning: Present day	7	19
Livestock grazing	Early Burning: Present day	7	19
Burning to open up vegetation for visibility	Burning to source veld foods	6	17
Land Use: Hunting (small animals)	Land Use: Veld Food Harvesting	6	17
Livestock grazing	Burning for vegetation regeneration	6	17
Land Use: Hunting (small animals)	Land Use: Cultivation	5	14
Land clearing/ field preparation	Late season fires	4	11

Table B10: Summary list of theme co-occurrences for the government and non-government stakeholders (n=25) responses (2014 – 2015).

Sub theme 1	**Sub theme 2**	**No of theme co-occurrences**	**%**
Ignitions source: People	Late Season Fires	23	92
Perception: Negative: Fire	People	20	80
Early Burning: Early Burning: BNP Management	Late Season Fires	19	76
Early Burning: Early Burning: BNP Management	Perception: Positive: Fire	19	76
Early Burning: Burning for prevention	Early Burning: Early Burning: BNP Management	18	72
Late Season Fires	Ecological Change: Vegetation impact/change	18	72
Climate/Fire Factors	Early Burning: Early Burning: BNP Management	17	68
Early Burning: Burning for prevention	Late Season Fires	17	68
Perception: More Frequent Fire	Ecological Change: Less Trees, & More Shrubs	16	64
Fire Management: Fire Suppression	Ecological Change: Vegetation impact/change	16	64
Early Burning: Early Burning: BNP Management	Fire Management: Implementation - Management	14	56
Perception: More Frequent Fire	Fire Regime: Vegetation more open	16	64
Ecological Change: Vegetation impact/change	Ecological Change: Less Trees, & More Shrubs	14	56
Fire Management: Implementation - Management	Policy: Fire Management Plans	14	56
Policy: Stakeholder Collaboration	Policy: Communication & Awareness	14	56
Early Burning: Early Burning: BNP Management	Policy: Fire Management Plans	14	56
Perception: Positive: Fire	Climate/Fire Factors	14	56
Late Season Fires	Climate factors/Fire factors	13	52
TFK: Incorporation of traditional knowledge	Policy: Fire Management Plans	13	52
Early Burning: Early Burning: BNP Management	Ecological Change: Vegetation impact/change	12	48
Perception: Time & Frequency of Burning	Ecological Change: Vegetation impact/change	12	48
Ecological Change: Fire impacts on animals	Late Season Fires	12	48
Early Burning: Early Burning: BNP Management	Policy: Communication & Awareness	12	48
TFK: Traditional - cultural values	TFK: Hunting and Tracking	12	48

Fire Management: Implementation - Management	Policy: Communication & Awareness	12	48
Perception: Positive: Fire	FMP: CBiFM: early burning strategies	12	48
Fire Management: Implementation - Management	Late Season Fires	11	44
Early Burning: Early Burning: BNP Management	Fire Management: Knowledge & Understanding	11	44
Fire Regime: Bush Encroachment	Ecological Change: Vegetation impact/change	11	44
Ecological Change: Vegetation impact/change	Fire Management: Fire Suppression	11	44
Perception: Positive: Fire	Early Burning: Wildlife Management	11	44
Early Burning: Early Burning: BNP Management	Early Burning: Wildlife Management	10	40
TFK: Incorporation of traditional knowledge	Policy: Fire Management Plans	10	40
Early Burning: Early Burning: BNP Management	Fire Management: Fire Suppression	10	40
Early Burning: Early Burning: BNP Management	Perception: Time & Frequency of Burning	10	40
Ecological Change: Fire impacts on animals	Ecological Change: Vegetation impact/change	10	40
Perception: Negative: Fire	Ecological Change: Vegetation impact/change	10	40
Fire Management: Fire Suppression	Fire Regime: Bush Encroachment	10	40
Perception: Positive: Fire	Policy: Fire Management Plans	10	40
Policy: Fire Management Plans	Fire Management: Knowledge & Understanding	10	40
Perception: Positive: Fire	Early Burning: Burning for vegetation regeneration	10	40
Fire Management: Implementation - Management	Fire Management: Knowledge & Understanding	9	36
Complexity: Uncertainty	Early Burning: Early Burning: BNP Management	9	36
Early Burning Strategy: Burning for vegetation regeneration	Early Burning Strategy: Early Burning: BNP Management	9	36
Early Burning: Burning for prevention	Perception: Positive: Fire	9	36
Early Burning: Early Burning: BNP Management	Complexity: Research	9	36
Early Burning: Early Burning: BNP Management	TFK: Positivism approach to TEK	9	36
Early Burning: Burning for prevention	Fire Management: Implementation - Management	8	32

Table B11. List of representative oral accounts: Government and non-government stakeholders

Early burning

‘’Early burning; how organised is that, who does it, where is it done, is it super monitored that burning or is just to say it is early burning; Yes, when it is done; partly successful, I am still sceptical about the effect of early burning during that period about the species which burn; until we know the impact on certain species; there are a lot of hypothetical questions about endemic species, or the species which depends on the species which burns - that could be a problem; conservation biology the significance of the micro environment; I am not in favour of early burning; what I favour is controlled burning, block burning to give each species a chance; during that time not all species burn; the frequency of burning will have an effect’’ (12).

‘’What I do believe it that it has shifted the season of burn; early burning has not reduced the frequency; I don’t know if it has been successful - it depends on how you measure success; if the aim is to shift the burning to earlier in the year the to some extent that has been achieved - whether it has been monitored I am uncertain’’ (23).

‘’Early burning helps in some way; if its implemented properly and managed – preventing future and larger fires - over larger areas to prevent the spread of fire’’ (17).

Fire Management

’Yes, it would make a difference if land management was distinguished and instilled according to different habitat and land use types. Policy is ineffective currently, and has not changed the system; although the government has instilled early burning practises. We need more stakeholder collaboration’’ (9).

Perceived changes in the fire regime

’From 1990 the landscape has changed; forest to open savanna grasslands’’ (16).

‘’A long time we have been looking at the late dry season fires over much of the area which was a consequence of fire suppression’’ (23).

’Suppression of fire is a mistake - fires are natural - detrimental to vegetation ; managed systems now; during the military days fire was suppressed and after Independence the accumulation in fuel resulted in a change from forests to savannahs; there were densely vegetated areas in BNP; in the military there were conservationists, although with not much training in conservation; reported to authorities - people weren’t consulted; people did not have a say; 60 - 80's anti-fire - military in control - 1990 independence; uncontrolled fire’’ (16).

Perception of traditional fire knowledge

“No, they did not manage the veld; it was less populated then, so did not have a disastrous effect on vegetation at that time; they did not practice sustainable management; people were mobile so less damaging effect; indigenous tribes did not manage natural resources; they moved so that could not see the disastrous effects on vegetation’’ (10).

‘”Early burning was there all along, we copied it from the bushmen, and include it by now” (6).

“These communal areas - the policy is only effective if your headman or Khuta/chief controlling it” (11).

Figure B7: Research ethic clearance approval from the University of Cape Town (UCT), 2013.

Faculty of Science
University of Cape Town
RONDEBOSCH 7701
South Africa

E-mail: richard.hill@uct.ac.za
Telephone: + 27 21 650 2786
Fax: + 27 21 650 3456

26 November 2013

Ms Glynis Humphrey
Department of Biological Sciences

Dear Ms Humphrey

THE ROLE OF HUMANS IN THE FIRE, CLIMATE AND VEGETATION SYSTEM OF NORTH-EAST NAMIBIA

I am pleased to inform you that the Faculty of Science Research Ethics Committee has approved the above-named application for research ethics clearance, subject to the conditions listed below. You are required to:

- implement the measures described in your application to ensure that the process of your research is ethically sound, and
- uphold ethical principles throughout all stages of the research, responding appropriately to unanticipated issues: please contact me if you need advice on ethical issues that arise.

Your approval code is: FSREC 038– 2013

I wish you success in your research.

Yours sincerely

Dr Richard C Hill
Chair: Faculty of Science Research Ethics Committee

Figure B8: Ministry of Environment and Tourism (MET) Research permit for Bwabwata National Park, 2014 -2015.

MINISTRY OF ENVIRONMENT AND TOURISM

RESEARCH/COLLECTING PERMIT

Permit Number 1880/2014
Valid from 7 March 2014 to 28 February 2015

Permission is hereby granted in terms of the Nature Conservation Ordinance 1975 (Ord. 4 of 1975) to:

Name: **G.J. Humphrey**
Address: **Plant Conservation Unit, Department of Biological Science**
University of Cape Town
Private Bag X3
Rhondebosch
7701
South Africa
Coworkers: **B. Kandjimi, J. Mahingi, P. Muyambango, J. Kamiyo, W. Geria, J. Mushavanga, A. Shipungu, L. Mpoko, H. Ndara, Hl. Rosa, Hl. Mavis, S. Geria, R. Mbomba, B. Weshu, W. MajunduW. Katimba, M. Mackey, A. Chedau, B. Kupinga, B. Bishu, E. Tjiteere, P. Masilisu, T. Chedau and S. Ngungwe**
To conduct a study on the role of humans in the fire, climate and vegetation svstem of North-east Namibia including Bwabwata NP, subject to attached conditions.

IMPORTANT: This permit is not valid if altered in any way.

MINISTRY OF ENVIRONMENT AND TOURISM
REPUBLIC OF NAMIBIA
10 MAR 2014
WINDHOEK
Private Bag 13306, Windhoek
Tel: 2842111 • Fax: 258861

Authorising Officer

IMPORTANT
This permit is subject to the provisions of the Nature Conservation Ordinance, 1975 (Ordinance 4 of 1975) and the regulations promulgated thereunder, and the holder is subject to all such conditions and regulations.

Enquiries: Conservation Scientist, email imatheus@met.na
Private Bag 13306, Windhoek, Namibia

Figure B9: Ministry of Environment and Tourism (MET) Research permit for Bwabwata National Park, 2015 - 2016.

MINISTRY OF ENVIRONMENT AND TOURISM

RESEARCH/COLLECTING PERMIT

Permit Number 2008/2015
Valid from 1 March 2015 to 29 February 2016

Permission is hereby granted in terms of the Nature Conservation Ordinance 1975 (Ord. 4 of 1975) to:

Name: **G.J. Humphrey**
Address: **Plant Conservation Unit, Department of Biological Science**
University of Cape Town
Private Bag X3
Rhondebosch
7701
South Africa

Coworkers: **None**

The role of humans in the complex fire, climate and vegetation regimes of north-easet Namibia including Bwabwata National Park, subject to attached conditions.

IMPORTANT: This permit is not valid if altered in any way.

MINISTRY OF ENVIRONMENT
AND TOURISM
REPUBLIC OF NAMIBIA

2015 -02- 13

WINDHOEK
Private Bag 13306, Windhoek
Tel: 2842111 • Fax: 258861

Authorizing Officer

IMPORTANT
This permit is subject to the provisions of the Nature Conservation Ordinance, 1975 (Ordinance 4 of 1975) and the regulations promulgated thereunder, and the holder is subject to all such conditions and regulations.

Enquiries: Warden, email clouw@met.na
Private Bag 13306, Windhoek, Namibia

Appendix C: Chapter 4

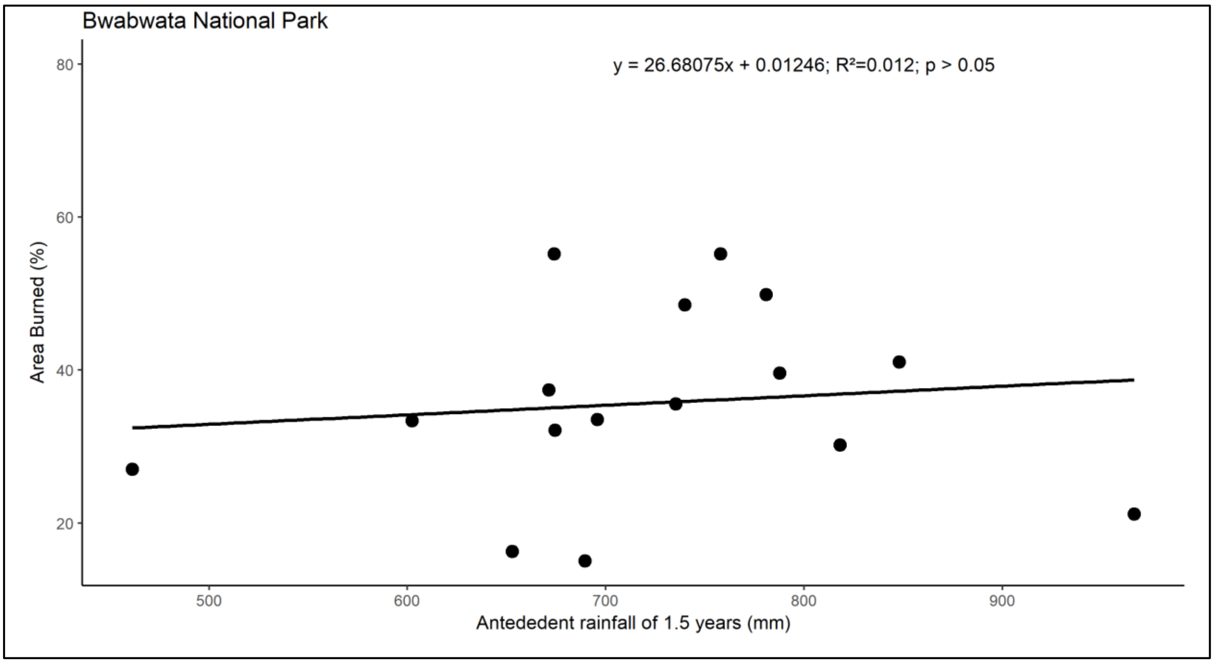

Figure C1: Scatterplot showing the absence of a relationship between mean annual antecedent rainfall over the preceding 1. 5 years (mm) and area burned (%) in Bwabwata National Park (2000 – 2015).

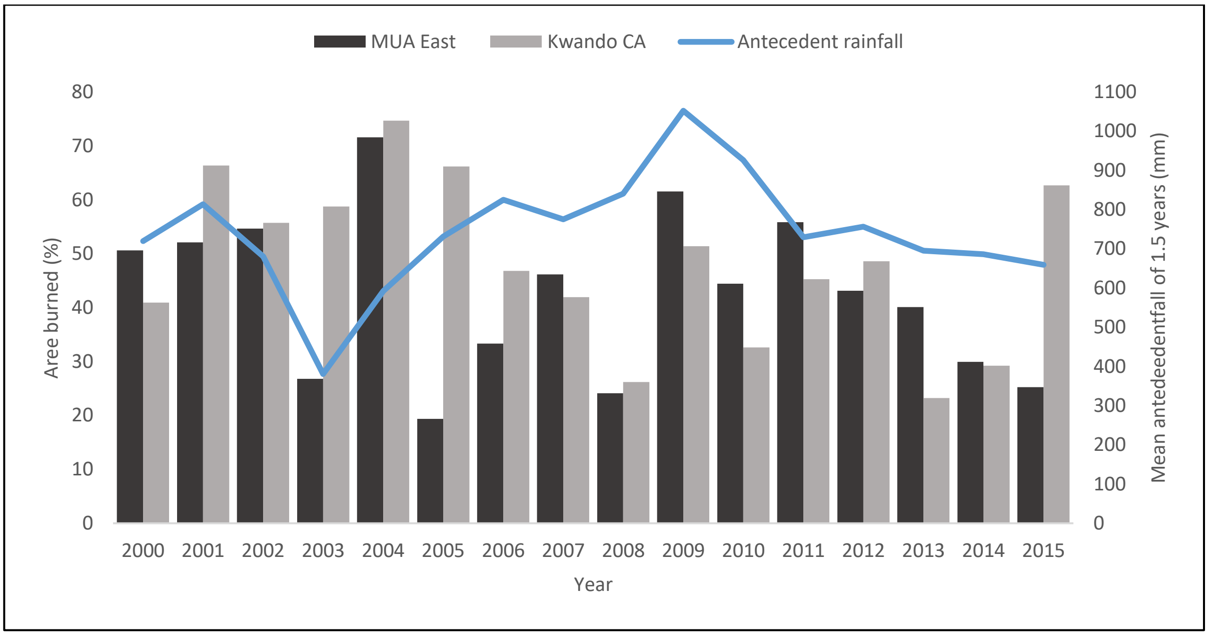

Figure C2: Percentage burned area and mean 1. 5 year antecedent rainfall for a) MUA East ($R^2 = 0.007$, $p > 0.05$) and Kwando CA ($R^2 = 0.09$; $p < 0.05$) for the period 2000 to 2015 in Bwabwata National Park.

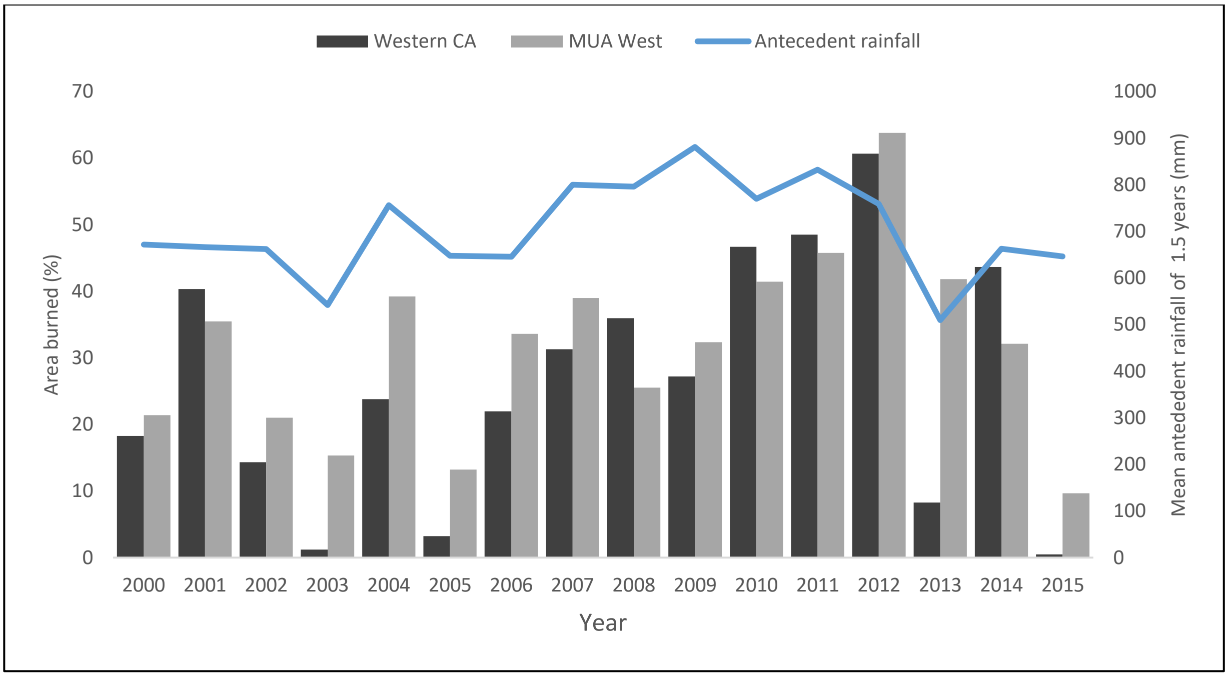

Figure C3: Percentage burned area and mean 1. 5 year antecedent rainfall for the Western core area (CA) ($R^2 = 0.40$; $p < 0.05$), and MUA West ($R^2 = 0.05$; $p > 0.05$) for the period 2000 to 2015 in Bwabwata National Park.

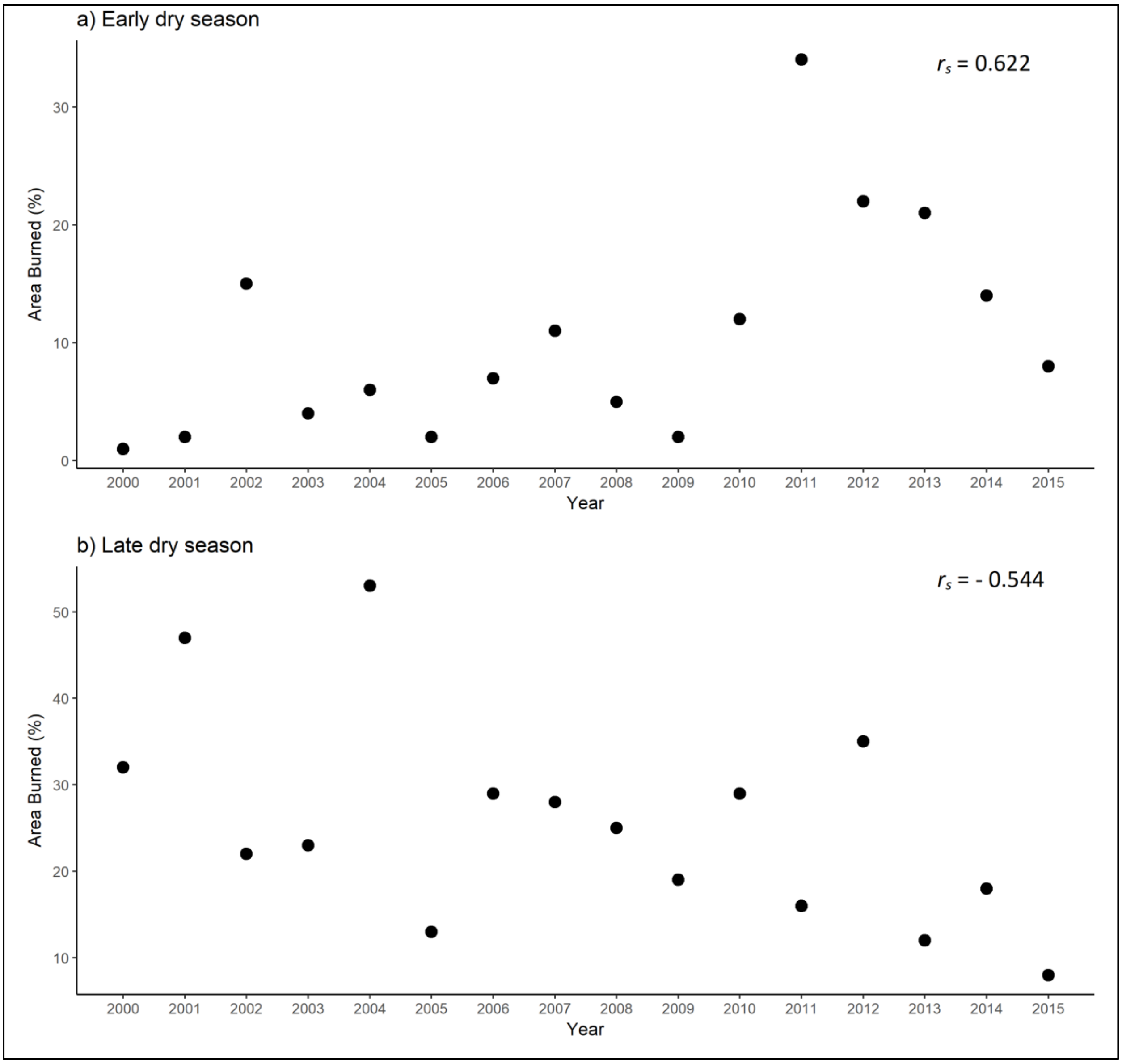

Figure C4: Scatterplots showing the positive and negative monotonic relationship between year and percentage area burned in a) early dry season (EDS), and b) late dry season (LDS) in Bwabwata National Park (2000 – 2015).

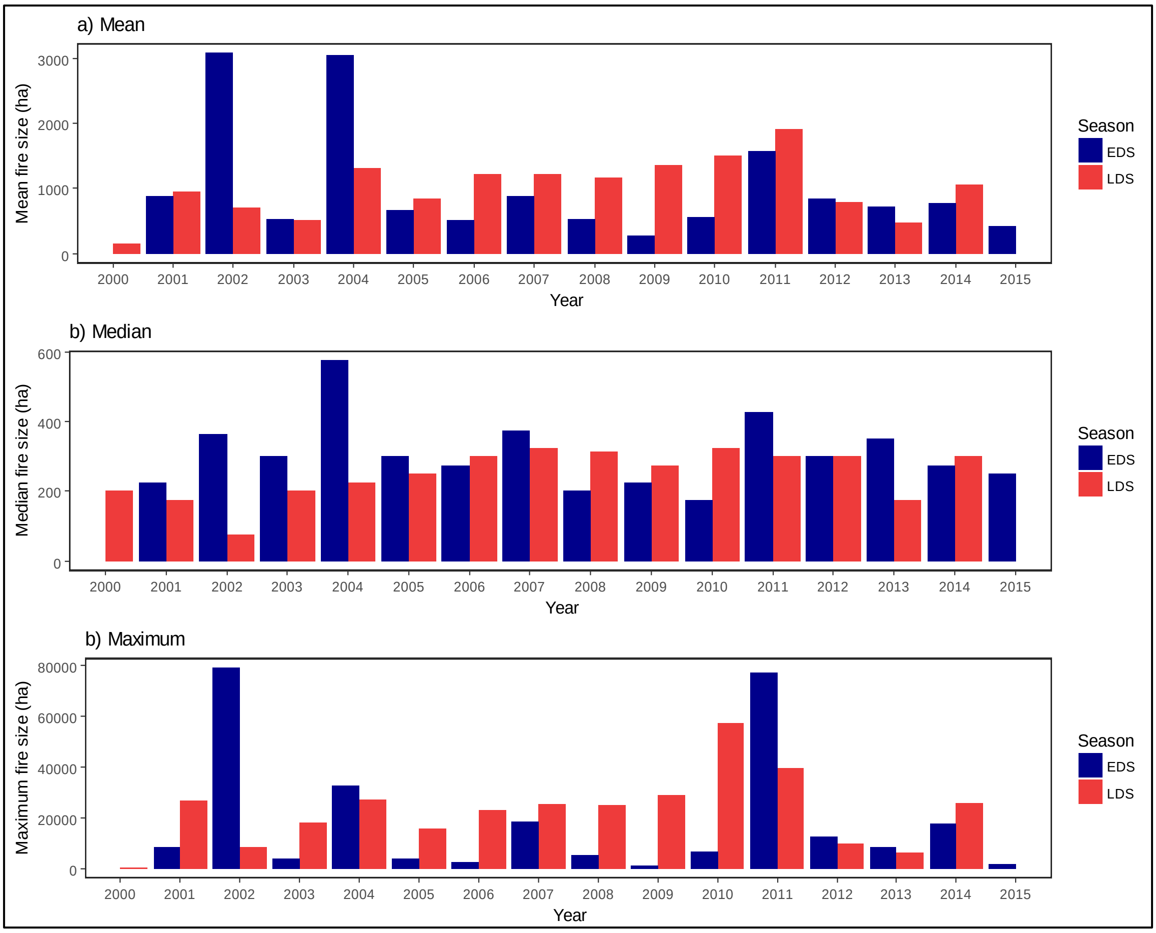

Figure C5: Interpretation of the a) mean, b) median and c) maximum fire size during the EDS and LDS over the full time period in Bwabwata National Park (2000 – 2015).

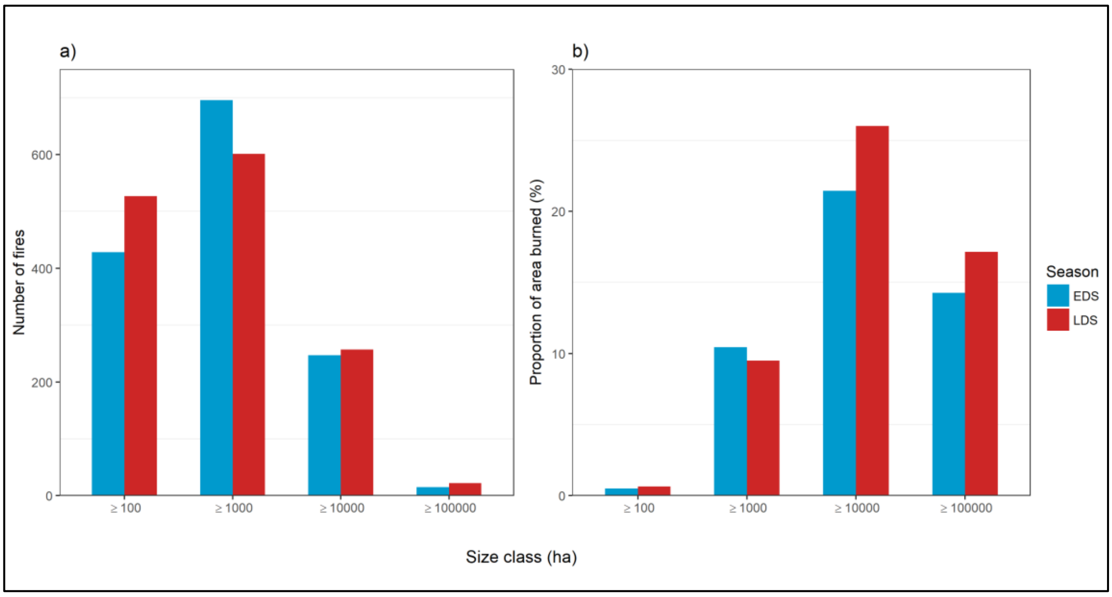

Figure C6. Frequency distribution of the number of fires and proportion of area burnt (%) in the four fire size classes during the period 2000 – 2015 in Bwabwata National Park; a) Number of fires; and b) Proportion of area burned (%).

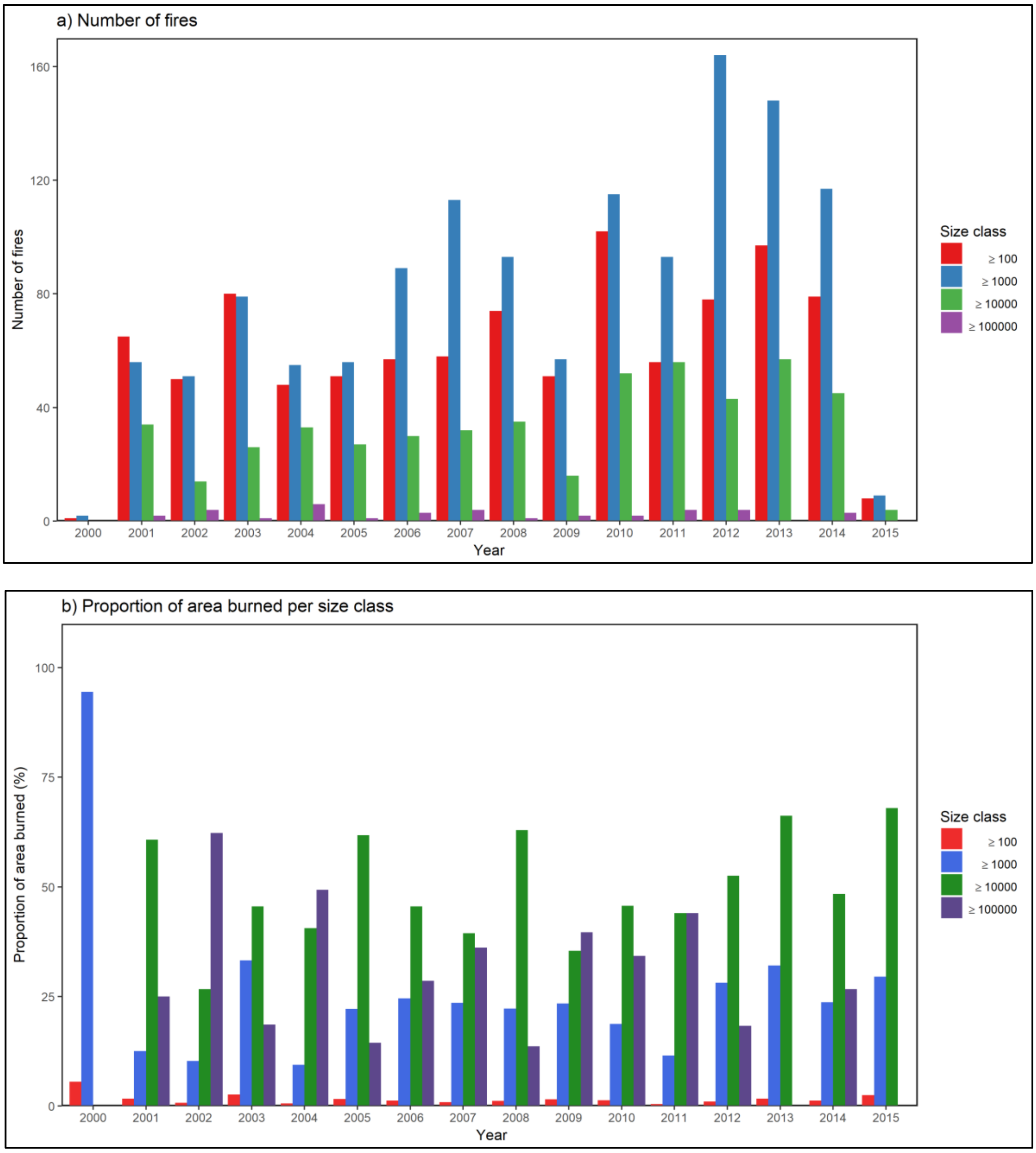

Figure C7: The frequency distribution of a) number of fires, and b) percentage burned area per fire size class in in Bwabwata National Park, 2000 – 2015.

Table C1: Comparison of (two sample unpaired Wilcoxon Mann Whitney U Tests) of the number of fires in the early dry season (EDS) and late dry season (LDS) between the suppression (SP) and early burning policies (EBP) for the four land use areas. For each comparison, median 1 and 2, and IQR 1 and IQR 2 (Interquartile range) refer to the respective number of fires for each fire treatment.

Land use	**Fire treatment**	**Period**	**W**	***p***	**Median 1**	**Median 2**	**IQR 1**	**IQR 2**
MUA East	EDS	SP vs. EBP	10.00	< 0.05*	23.00	59.50	16.75	46.50
	LDS	SP vs. EBP	36.50	> 0.05	46.50	36.00	16.00	18.50
Kwando CA	EDS	SP vs. EBP	1	> 0.001*	2.50	27.00	0.25	23.50
	LDS	SP vs. EBP	21.5	> 0.05	12.50	18.00	5.00	13.75
Western CA	EDS	SP vs. EBP	10.5	< 0.05*	0.00	2.50	1.00	4.25
	LDS	SP vs. EBP	38.5	> 0.05	7.5	4.5	6	3.95
MUA West	EDS	SP vs. EBP	12	> 0.05	10.00	22.50	6.50	16.25
	LDS	SP vs. EBP	27.5	> 0.05	33.00	34.50	45.75	17.50
Land use comparisons								
MUA East vs. Kwando CA	EDS	SP	30.50	> 0.05	23.00	2.50	16.75	3.25
	EDS	EBP	38.50	> 0.05	59.50	27.00	46.50	23.50
	LDS	SP	38.50	> 0.05	46.50	12.50	16.00	5.00
	LDS	EBP	38.50	> 0.05	36.00	18.00	18.50	13.75
MUA West vs. Kwando CA	EDS	SP	28.00	> 0.05	10.00	2.50	6.50	3.25
	EDS	EBP	40.00	> 0.05	22.50	27.00	16.25	23.50
	LDS	SP	27.00	> 0.05	45.50	15.00	30.25	5.00
	LDS	EBP	86.50	< 0.05*	34.50	18.00	17.50	13.75
MUA East vs. MUA West	EDS	SP	28.50	> 0.05	23.00	10.00	16.75	6.50
	EDS	EBP	85.00	< 0.05*	59.50	22.50	46.50	16.25
	LDS	SP	22.50	> 0.05	46.50	33.00	16.00	30.25
	LDS	EBP	49.00	> 0.05	36.00	34.50	18.50	17.50
Kwando CA vs. Western CA	EDS	SP	32.50	< 0.05*	2.50	0.00	3.35	N/A
	EDS	EBP	98.50	< 0.05*	27.00	2.50	23.50	4.25
	LDS	SP	27.00	> 0.05	12.50	7.50	5.00	6.00

	LDS	EBP	84.50	< 0.05*	18.00	4,50	13,75	3,75
MUA East vs. Western CA	EDS	SP	32.50	< 0.05*	23.00	0,00	16,75	N/A
	EDS	EBP	100.00	> 0.001*	59.50	2,50	46,60	4,25
	LDS	SP	30.50	> 0.05	46.50	7.50	16.00	6.00
	LDS	EBP	90.50	< 0.05*	36.00	4.50	18.50	3.75
MUA West vs Western CA	EDS	SP	32.50	< 0.05*	10.00	0.00	6.50	N/A
	EDS	EBP	93.50	< 0.05*	22.50	2.50	16.25	4.25
	LDS	SP	30.00	> 0.05	33.00	7.50	30.25	6.00
	LDS	EBP	90.5	< 0.05*	34.5	4.5	17.5	3.75

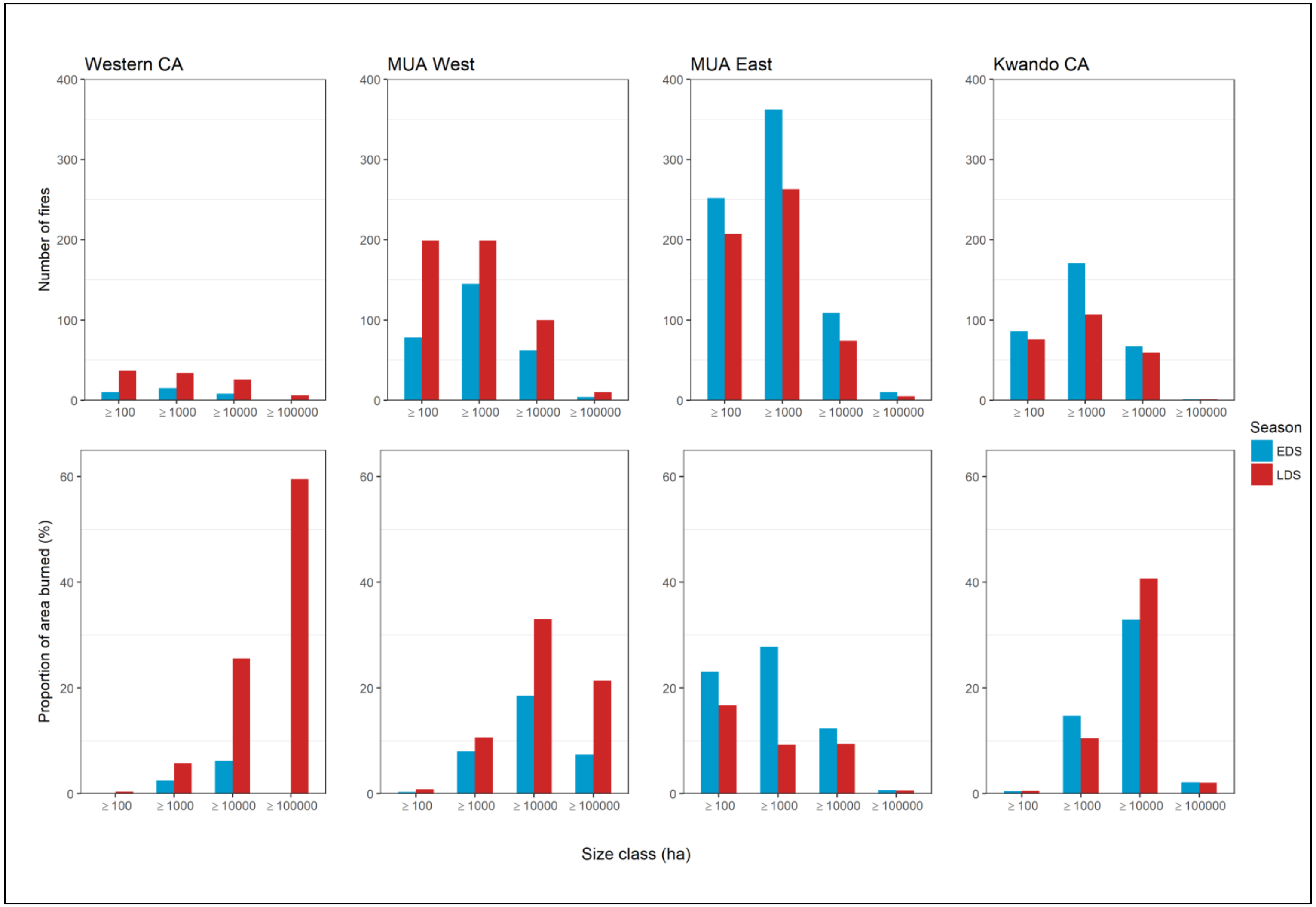

Figure C8: Frequency distribution of the number of fires, and the proportion of area (%) burned in the respective fire size classes within the four land use areas in Bwabwata National Park, 2000 - 2015.

Appendix D: Chapter 5

Fire frequency

Influence of fire policy, land use and vegetation type on frequency of fire and seasonal burned area

Table D1: Summary statistics for the percentage of burned area within the four main vegetation types during the early dry season (EDS), late dry season (LDS) and total dry season (TDS) in Bwabwata National Park (2000 – 2015).

Vegetation type	Season	Mean	SD	n	SE
Omiramba grassland	EDS	18.4	14.0	16	3.5
Savanna-woodland	EDS	10.3	9.0	16	2.3
Burkea shrubland	EDS	3.3	4.1	13	1.2
Riparian	EDS	3.3	3.2	15	0.8
Omiramba grassland	LDS	28.8	14.8	16	3.7
Savanna-woodland	LDS	26.0	11.7	16	2.9
Burkea shrubland	LDS	20.2	15.0	16	3.7
Riparian	LDS	6.8	6.0	16	1.5
Omiramba grassland	TDS	47.2	14.3	16	3.6
Savanna-woodland	TDS	36.2	13.0	16	3.2
Burkea shrubland	TDS	23.0	15.8	16	3.9
Riparian	TDS	10.0	5.4	16	1.3

Note: *indicates significance at the 0.05 level.

Table D2: Multiple comparison of means of area burned between the four vegetation types during the total dry season (TDS) in Bwabwata National Park, 2000 – 2015.

Vegetation type comparisons	Estimate	Std. Error	t value	*p*
Omiramba grassland - Burkea shrubland	24.2	4.5	5.4	0.0010*
Riparian - Burkea shrubland	-13.0	4.5	-3.0	0.0266*
Savanna-woodland - Burkea shrubland	13.3	4.5	3.0	0.0231*
Riparian - Omiramba grassland	-37.3	4.5	-8.3	0.0010*
Savanna-woodland - Omiramba grassland	-11.0	4.5	-2.4	0.0840
Savanna-woodland - Riparian	26.3	4.5	5.8	0.0010*

Note: *indicates significance at the 0.05 level.

Table D3: Multiple comparison of means of area burned between the four vegetation types during the early dry season (EDS) in Bwabwata National Park (BNP), 2000 – 2015.

Vegetation type comparisons	Estimate	Std. Error	t value	*p*
Omiramba grassland - Burkea shrubland	15.0	3.3	5.0	0.001*
Riparian - Burkea shrubland	-0.0	3.3	-0.0	1.000
Savanna-woodland - Burkea shrubland	7.0	3.3	2.0	0.166
Riparian - Omiramba grassland	-15.0	3.2	-4.7	0.001*
Savanna-woodland - Omiramba grassland	-8.0	3.1	-2.6	0.062
Savanna-woodland - Riparian	7.0	3.2	2.1	0.138

Note: *indicates significance at the 0.05 level.

Table D4: Multiple comparison of means of area burned between the four vegetation types during the late dry season (LDS) in Bwabwata National Park (BNP), 2000 – 2015.

Vegetation type comparisons	Estimate	Std. Error	t value	*p*
Omiramba grassland - Burkea shrubland	9.0	4.4	2.0	0.2189
Riparian - Burkea shrubland	-13.4	4.4	-3.0	0.0164*
Savanna-woodland - Burkea shrubland	5.6	4.4	1.2	0.5703
Riparian - Omiramba grassland	-22.0	4.4	-5.0	0.0010*
Savanna-woodland - Omiramba grassland	-3.0	4.4	-0.6	0.9133
Savanna-woodland - Riparian	19.1	4.4	4.3	0.0010*

Note: *indicates significance at the 0.05 level.

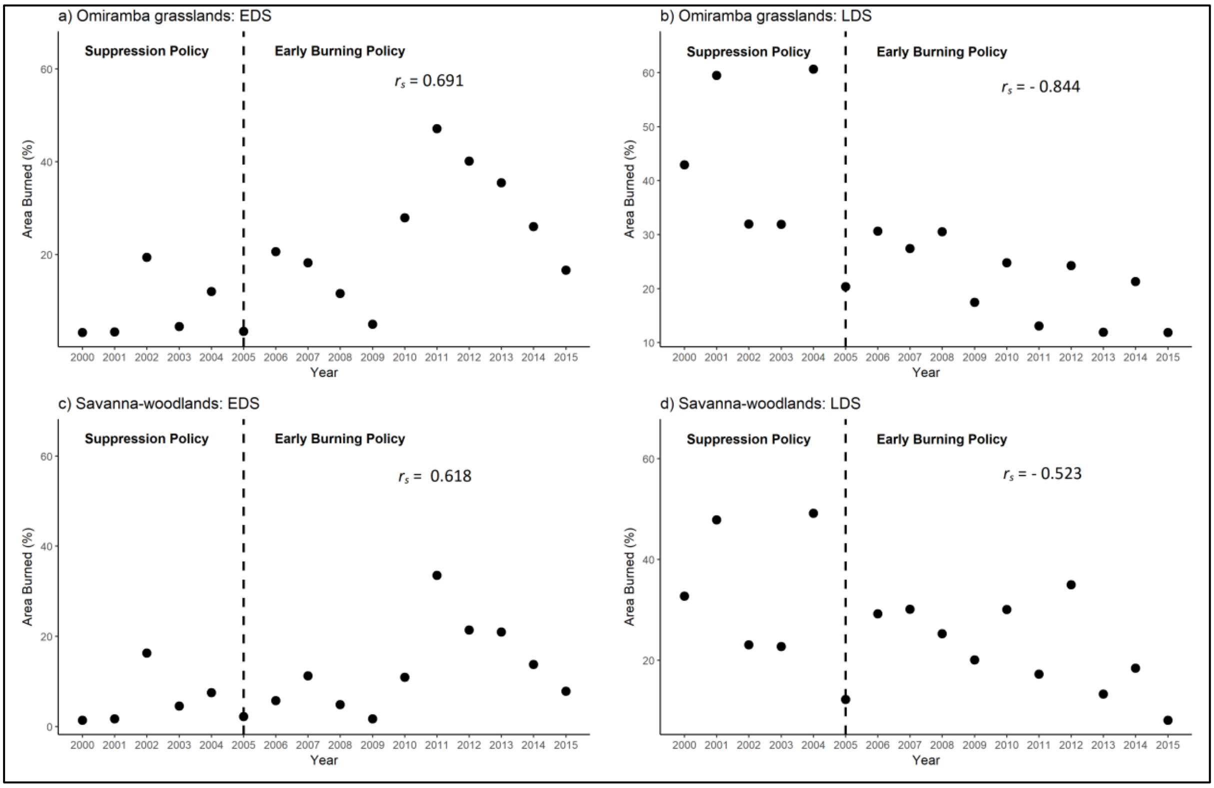

Figure D1: The relationship between year and percentage area burned in a) early dry season (EDS), and b) late dry season (LDS) in the omiramba grasslands (a; EDS; b; LDS), and in the savanna-woodlands (c; EDS; d; LDS) in Bwabwata National Park (2000 – 2015) The dashed vertical line distinguishes the divide between the suppression and early burning policy.

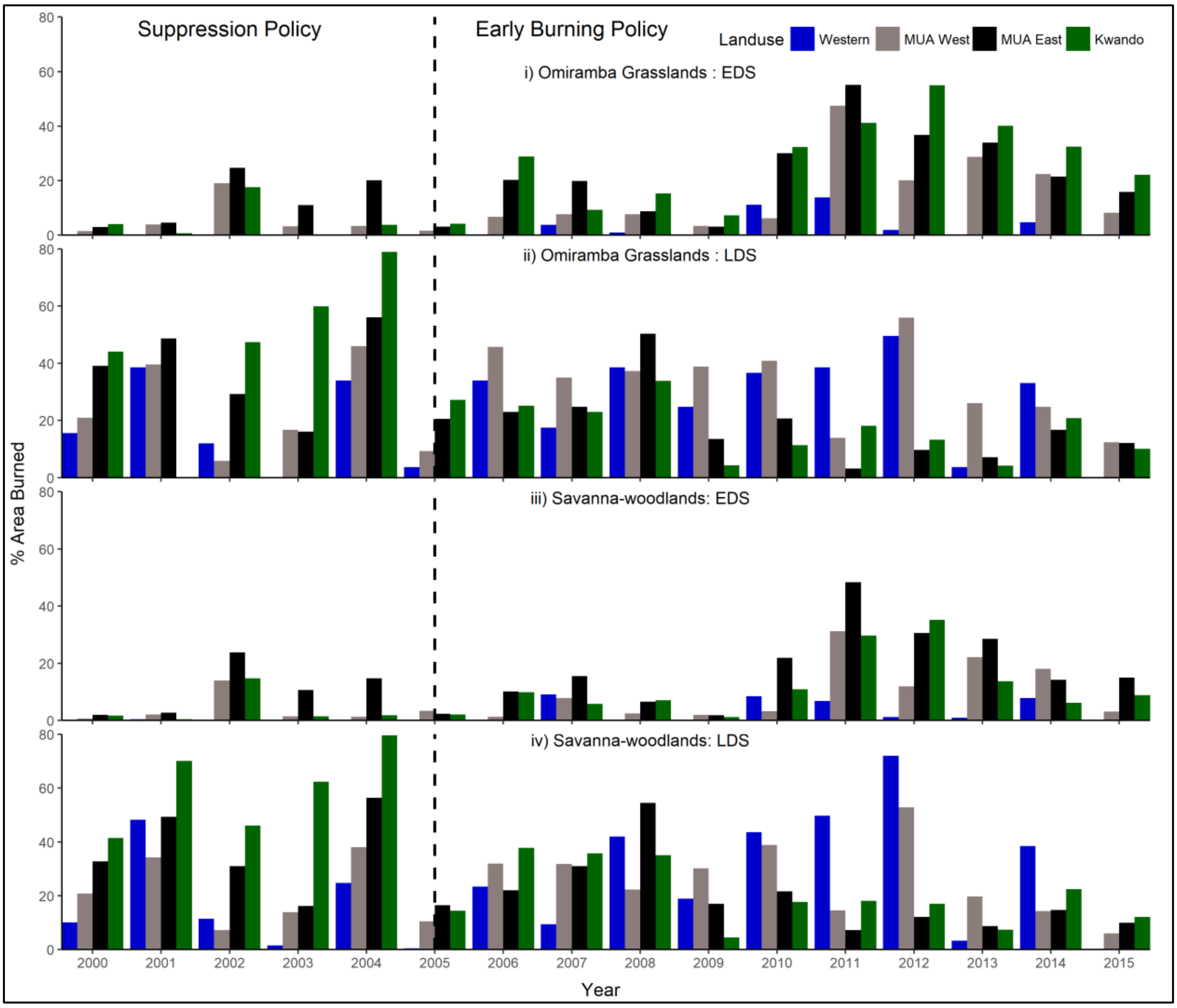

Figure D2: Inter-annual variation in the frequency distribution of the average percentage area burnt in the omiramba grasslands and savanna-woodlands vegetation types for each of the land use areas in the early dry season (EDS) and late dry season (LDS) in Bwabwata National Park (2000 – 2015). The dashed vertical line indicates the division between the suppression and early burning policy.

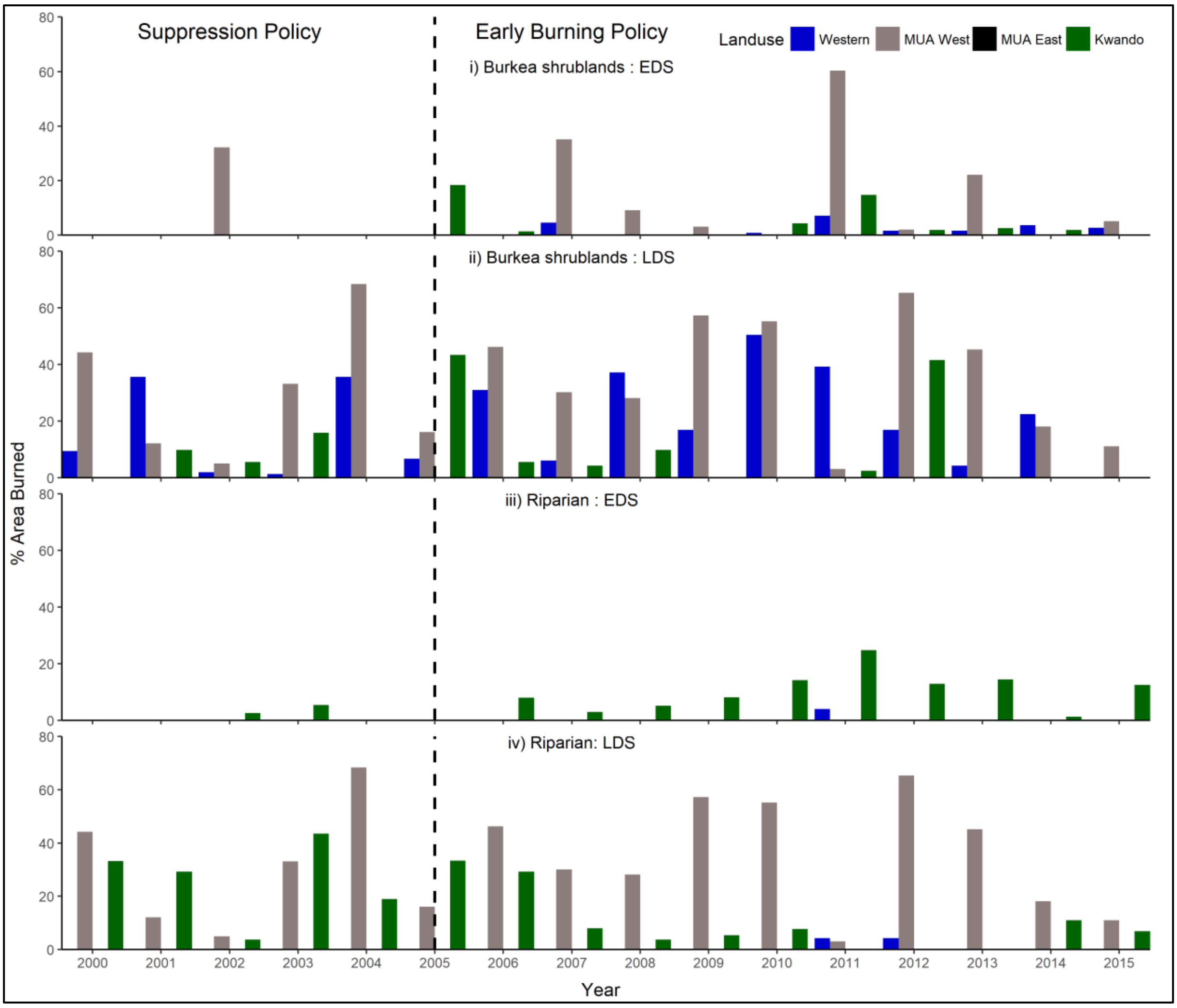

Figure D3: Inter-annual variation in the frequency distribution of the average percentage area burnt in the Burkea shrublands and riparian vegetation types for each of the land use areas in the early dry season (EDS) and late dry season (LDS) BNP (2000 – 2015). The dashed vertical indicated the division between the suppression and early burning policy.

Table D5: Kruskal - Wallis results of the comparison of mean percentage burned area for each of the four vegetation types within each land use area during the early dry season (EDS) and late dry season (LDS) in combination with both policy periods (suppression policy [SP: 2000 - 2005] and early burning policy [EBP: 2006 - 2015]) in Bwabwata National Park.

Land use	Vegetation type	Policy	Season	d.f	*H*	*p value*
Kwando CA, MUA East, MUA West	Omuramba grassland	SP	EDS	2	2.2	0.3235
Kwando CA[a], MUA East[ab], MUA West[b]; Western Ca[b]		SP	LDS	3	9.4	0.0245*
Kwando CA[a], MUA East[a], MUA West[ab]; Western CA[b]		EBP	EDS	3	11.8	0.0080*
Kwando CA[a], MUA East[a], MUA West[b]; Western CA[ab]		EBP	LDS	3	11.4	0.0095*
Kwando CA, MUA East, MUA West; Western CA	Savanna-woodland	SP	EDS	3	6.0	0.1081
Kwando CA[a], MUA East[ab], MUA West[ab]; Western CA[b]		SP	LDS	3	9.3	0.0252*
Kwando CA[ab], MUA East[a], MUA West[ab]; Western CA[b]		EBP	EDS	3	8.0	0.0469*
Kwando CA, MUA East, MUA West; Western CA		EBP	LDS	3	3.7	0.2996
Kwando CA, MUA West, Western CA	Burkea shrubland	SP	EDS	N/A	N/A	N/A
Kwando CA, MUA West, Western CA		SP	LDS	2	2.1	0.3463
Kwando CA[a], MUA West[a], Western CA		EBP	EDS	2	6.6	0.0368*
Kwando CA, MUA West, Western CA		EBP	LDS	2	5.2	0.0724
Kwando CA, MUA West, Western CA	Riparian	SP	EDS	N/A	N/A	N/A
Kwando CA[a], MUA West[b], Western CA[ab]		SP	LDS	2	9.3	0.0095*
Kwando CA, MUA West, Western CA		EBP	EDS	N/A	N/A	N/A
Kwando CA, MUA West, Western CA		EBP	LDS	2	4.4	0.1096

Note:* indicates significance at the level of 0.05 amongst groups; superscripts [a] and [b] indicate the post-hoc Dunn tests significance between land use areas with vegetation type percentage area burned in the respective policy periods and seasons; N/A indicates insifficent values avaliable for comparison.

Fire intensity

Influence of fire policy and land-use on seasonal fire intensity (FRP)

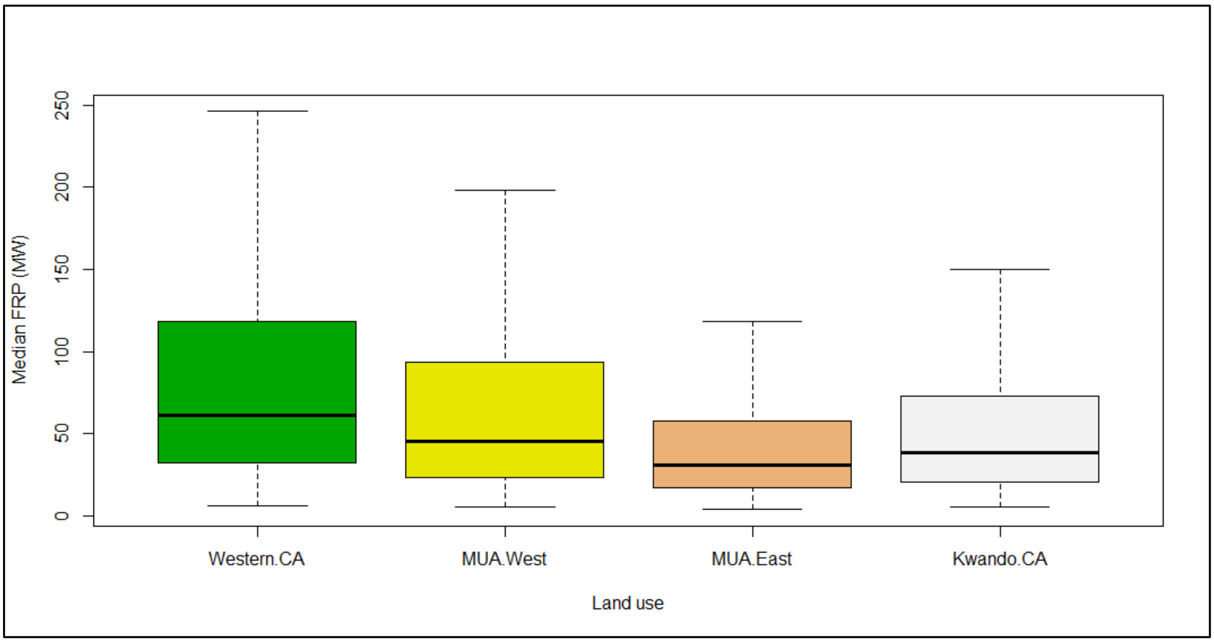

Figure D4: Box plot of the median fire radiative power (FRP) by land use type (2000 – 2015); error bars = 10-quantile and 90-quantile Western CA [n = 780]; MUA West [n = 4839]; Kwando CA [n = 2536], and MUA East [n = 5788] in Bwabwata National Park, 2000 - 2015; total n = 14180; Kruskal-Wallis test (p < 0.0001).

Table D6: Summary statistics for Fire Radiative Power (FRP) for the four land use are in Bwabwata National park (BNP), 2000 – 2015.

Land use	**Mean (MW)**	**Median (MW)**	**Maximum (MW)**
Western CA	105.0	61.5	1445.5
MUA West	78.4	45.6	1332.0
MUA East	48.9	30.9	1068.8
Kwando CA	62.2	38.6	990.5

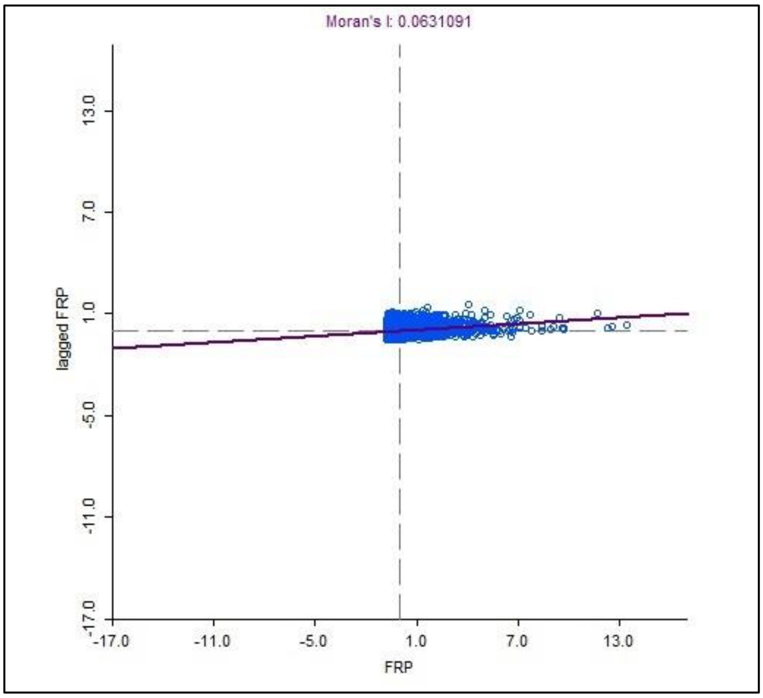

Figure D5: Scatterplot of the Global Moran's I Spatial autocorrelation. Data derived from MODIS MCD14ML product.

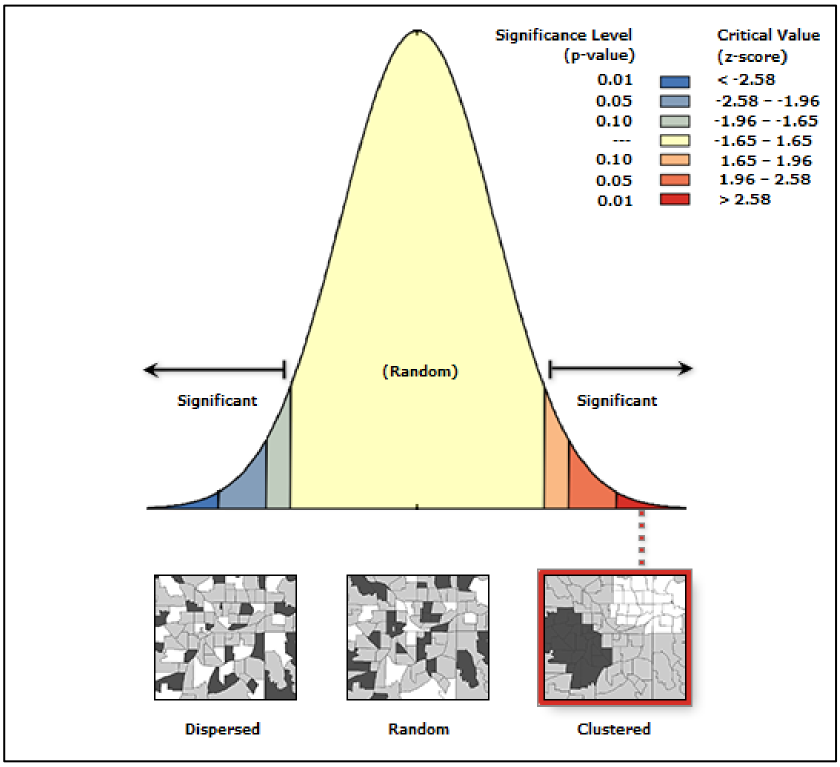

Figure D6: Summary of Global Moran's I Spatial autocorrelation outcomes showing the significance of dispersion and clustering patterns (source: ArcGIS v.10.2).

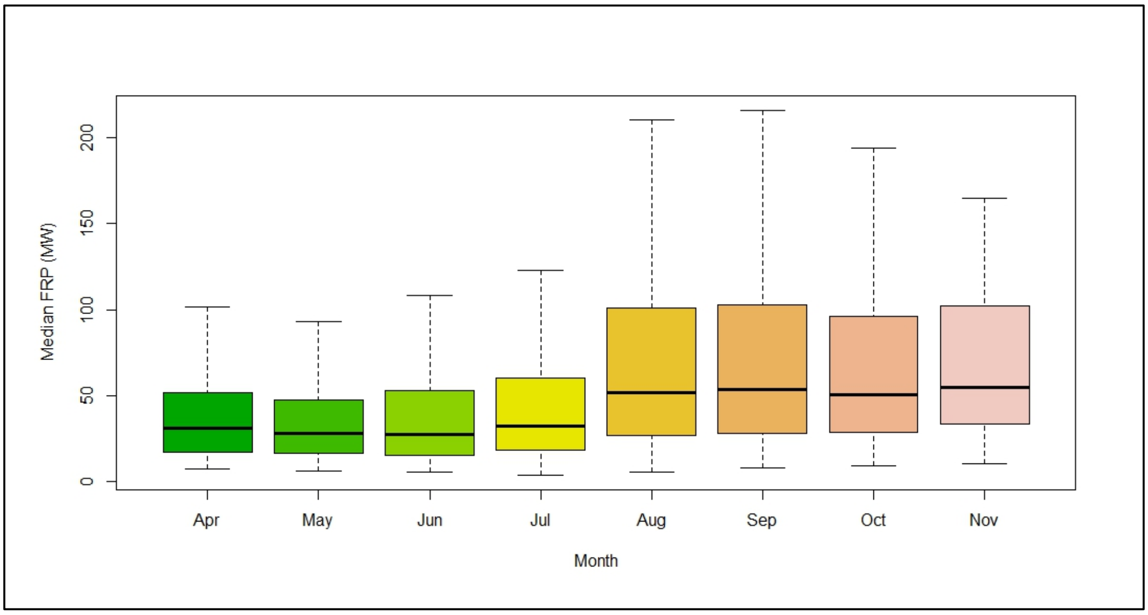

Figure D7: Box plot of monthly mean fire radiative power (FRP) in Bwabwata National Park (2000 – 2015); error bars = 10-quantile and 90-quantile.

Table D7: Comparison of the average percentage of the Coefficient of Variation (CV) of FRP during the early dry season (EDS) and late dry season (LDS) within the four land use areas under the suppression policy (SP: 2000 - 2006) in Bwabwata national park.

Early Dry Season (EDS)

Land use	2000	2001	2002	2003	2004	2005	% CV
MUA East	N/A	36.42	62.90	38.34	46.94	25.68	42.06
MUA West	N/A	77.76	62.72	42.58	37.86	61.33	56.45
Kwando CA	N/A	N/A	68.06	36.86	36.49	35.87	44.32
Western CA	N/A	6.30	N/A	N/A	N/A	N/A	N/A

Note: N/A indicates insufficient values.

Late Dry Season (LDS)

Land use	2000	2001	2002	2003	2004	2005	% CV
MUA East	93.86	81.63	109.78	56.20	67.77	56.39	77.60
MUA West	23.69	106.70	86.20	88.65	80.12	103.42	81.46
Kwando CA	99.96	99.96	112.98	92.80	76.86	68.81	91.90
Western CA	N/A	99.19	52.22	102.11	107.68	197.60	111.76

*Note N/A indicates insufficient values.

Table D8. Comparison of the average percentage of the Coefficient of Variation (CV) of FRP during the early dry season (EDS) and late dry season (LDS) within the four land use areas under the early burning policy (EBP: 2006 - 2015) in Bwabwata National Park.

Early Dry Season (EDS)

Land use	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	% CV
MUA East	99.05	117.80	99.97	98.49	124.59	99.94	86.49	104.06	88.64	91.44	101.05
MUA West	95.33	103.36	144.28	91.54	142.38	123.72	112.36	103.72	84.39	74.76	107.58
Kwando CA	97.42	122.58	70.66	63.78	97.43	136.24	106.15	77.31	82.62	91.97	94.62
Western CA	N/A	106.22	98.55	83.42	93.62	61.58	58.46	79.39	67.59	84.00	81.43

Note: N/A indicates insufficient values.

Late Dry Season (LDS)

Land use	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	% CV
MUA East	114.60	148.50	97.48	110.01	115.87	91.65	103.17	81.11	104.10	100.03	106.65
MUA West	100.97	89.17	135.17	105.15	113.74	104.74	108.23	94.44	117.42	203.89	117.29
Kwando CA	83.35	101.97	93.89	67.62	101.91	66.66	92.99	68.81	91.53	78.53	84.73
Western CA	66.74	52.89	109.02	70.96	107.68	97.36	97.81	88.98	89.65	42.36	82.34

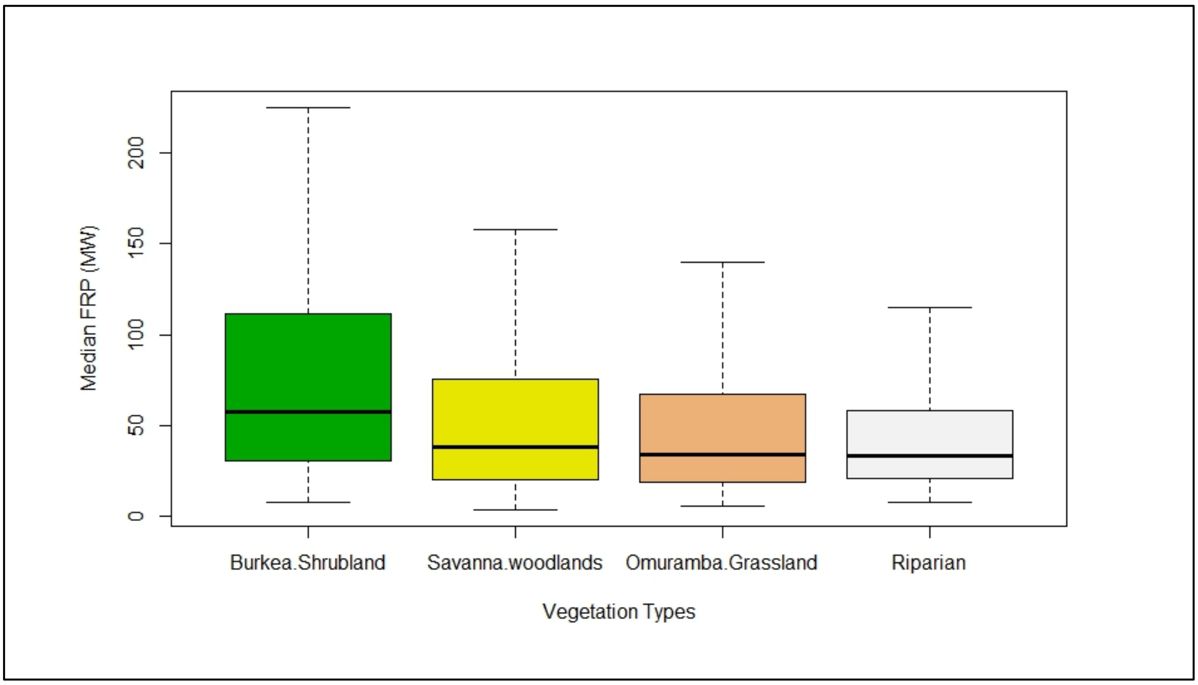

Figure D8: Box plot of the median fire radiative power (FRP) by vegetation type (2000 – 2015); Burkea shrubland [n = 289]; Savanna-woodlands [n=12 058]; Omiramba grassland [n =1513]; Riparian [n = 261]. Error bars = 10-quantile and 90-quantile.

Table D9: Results of the multiple pairwise comparison analysis (Tukey–Kramer test) using the R *multcomp* package for unbalanced designs showing differences in mean FRP among vegetation types in Bwabwata National Park, 2000 - 2015.

Vegetation Type comparisons	**Estimate**	**Std. Error**	**t value**	***p***
Omiramba grassland - Burkea shrubland	-36.8	6.0	-6.0	0.001*
Riparian - Burkea shrubland	-45.9	6.2	-7.3	0.001*
Savanna-woodlands - Burkea shrubland	-26.5	5.8	-4.5	0.001*
Riparian - Omiramba grassland	-9.2	2.9	-3.0	0.008*
Savanna-woodlands - Omiramba grassland	10.3	1.9	5.2	0.001*
Savanna-woodlands - Riparian	19.5	2.5	7.8	0.001*

Note: *indicates significance at the 0.05 level.