FIRE ENCROACHMENT INTO THE KAROO NATIONAL PARK

by

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DECLARATION

I declare that “Fire encroachment into the Karoo National Park”, is my own work and all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

02/05/2021

(Mr. Thivhonali Jonathan Khomola)

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ABSTRACT

The impacts of fire are multifaceted and pose a threat to ecosystems not accustomed to fire. In the Karoo National Park, no study has been conducted on fire management because the park is assumed to have very little fire occurrence. This study assessed fire encroachment into the Karoo National Park utilising remote sensing and Geographic Information System (GIS). The main objective of the study was to measure the frequency and intensity of fire, and map distribution of fire hotspots over space and time. This was achieved through acquiring the aqua and terra MODIS fire data from 2002 to 2016 from The National Aeronautics and Space Administration (NASA)'s Fire Information for Resource Management System (FIRMS). The remote sensing dataset was augmented with South African Weather Services (SAWS) meteorological data like rainfall, wind speed, wind direction and temperature. The analysis of fire frequency revealed that there was a change in the fire regime in the early 21st century. Karoo escarpment grassland vegetation is associated with more fires than any other vegetation type, hence creating a fire hotspot. Furthermore, a decline in rainfall and increase in temperature was exacerbating fire intensity and frequency. For an improved fire management protocol, the study recommends the development of a fire management plan since there are high frequencies of droughts, likely to cause more fires. The results show the possibility of integrating GIS and RS to assess fire encroachment in the Karoo National Park, and perhaps other semi-arid area in Southern Africa and elsewhere.

Key words: bush encroachment; climate; fire regime; Geographic Information System; remote sensing.

DEDICATION

This dissertation is dedicated to my late mother Mrs Tsumbedzo Agnes Khomola and my late grandmother Mrs Thifhulufhelwi Khomola may your souls rest in perfect peace. Furthermore, I also dedicate it to my father Mr. Thanyani Johannes Khomola and to my wife Ndele and daughter Rikhode Khomola.

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Mushumo hoyu ndi u kumedzela mme anga musadzi wa vhane Vho-Tsumbedzo Agnes Khomola na makhulu anga musadzi wa vhane Vho-Thifhulufhelwi Khomola, mimuya yavho i edele nga mulalo. Ndi dovha hafhu nda u kumedzela khotsi nga Vho-Thanyani Johannes Khomola, ndi sa hangwi mufumakadzi wanga Ndele na nwananga Rikhode Khomola.

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ACRONYMS AND ABBREVIATION LIST

ASL: Above Sea Level

AVHRR: Advanced Very High Resolution Radiometer

DEA: Department of Environmental Affairs

EEA: European Environmental Agency

FIRMS: Fire Information for Resource Management System

FRP: Fire Radiative Power

GIS: Geographic Information System

IPCC: Intergovernmental Panel on Climate Change

KNP: Karoo National Park

LANDSAT: Land Satellite

MODIS: Moderate Resolution Imaging Spectroradiometer

NBR: Normalized Burn Ratio

NDVI: Normalized Difference Vegetation Index

NOAA: National Oceanic and Atmospheric Administration

Q-GIS: Quantum Geographic Information System

RS: Remote Sensing

SANParks: South African National Parks

SAWS: South African Weather Services

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CHAPTER 1: INTRODUCTION

Fire is an ecosystem driver in Africa and other parts of the globe (Wigley *et al*., 2010). Wildfires are usually caused by natural ignition in the form of lightning or are human-made. Fires are categorized into three types: ground, surface and crown fires. Ground fires are characterized by poor flame visibility while the production of large flames characterizes surface fires due to consumption of lichen, moss, herbaceous vegetation, shrubs, small trees and saplings (Johnson, 1996). Crown fires are surface fires that have advanced into the crown layer of the vegetation, usually > 2m (Kerby *et al*., 2007). The transition between different fire types is influenced by the content foliage moisture, length of surface flame, height to the base of tree crowns and tree crowns density (Cheney and Sullivan, 2008). Cheney and Sullivan (2008) outlined various natural elements necessary to sustain a fire, and these include fuel, oxygen, topography and weather conditions. Fire behavior is determined by the physical structure of fuel bed. The continuity of fuel bed influences the spread of fire (Cheney and Sullivan, 2008). According to Marquis *et al*. (2014), an increase in oxygen concentration in the air accelerate fire combustion. Fire burns more rapidly upslope than down slope (Kane *et al*., 2015). According to Whitlock *et al*. (2010), weather conditions influence fire behavior and regime. These elements are in turn controlled by the physiographic settings of the area as encapsulated in the concept of a biome.

A biome is a multifaceted biotic community characterized by distinct plant and animal species maintained under the abiotic conditions of the area (Botkin and Keller, 2014, Scott and Reinhardt, 2007). Biomes have a shifting distribution in response to climate, land-use change, and other ecosystem drivers like fire (Penuelas and Boada, 2003). In South Africa, there are nine biomes and fire is prevalent in three, namely, Grassland, Savanna and the Fynbos (Mucina and Rutherford, 2006). Different ecosystems respond to fire and burning in unique ways, for example, grasslands are highly flammable since grass is an excellent fuel while savannas will burn less because they have trees in addition to grass (Andreae *et al.,* 1996). The fynbos, on the other hand, lacks grasses but the vegetation is flammable due to chemical inclusions in leaves and structural adaptations such as resprouting (Bond and Midgley, 1995). Another form of adaption is the retention of old branches until they are dry and highly flammable (Schwilk, 2003). The different fire regimes in biomes are associated with particular life-history strategies that take advantage of fire or react to it. In the fynbos, for example, some plants will only germinate after a fire and the onset of seed dispersal may also be stimulated by smoke (Brown, 1993). In grasslands, plants are not killed by fire, since grasses have a specific adaptation through growth via an axillary bud, apical dominance (Clarke *et al*., 2013). Savanna trees also respond to fires by re-sprouting or more spectacularly, growing underground to escape fire (Andreae *et al*., 1996).

Remote sensing has been used worldwide as a means to detect and monitor fires in different ecosystems. According to Ahern *et al*. (2001), remote sensing plays a fundamental role in understanding before and after fire impacts on vegetation. Ahmad (2014) revealed that remote sensing reduces the costs of fire suppression methods by acting as an early warning system. Recent advances in global satellite earth observations provide an opportunity for supporting large regional analyses of ecosystem processes like fire (Kaufman *et al*., 1998). The Moderate Resolution Imaging

Spectroradiometer (MODIS) satellite in particular has orbiting satellites (Terra and Aqua) with enriched competencies for monitoring fire and characterizing land surfaces (Loboda *et al.,* 2012).

1.2 Research problem

In both local and global contexts, fires can lead to ecosystem deterioration in systems not ordinarily fire-prone (Botkin and Keller, 2014). Masubelele *et al.* (2015) found an increase in grass prevalence in the past 40 years in the Karoo, and this suggests a fundamental change in the fire regime. In addition to improvements in grass biomass, there is also some evidence that trees are becoming more common, especially along drainage lines. This phenomenon is a type of bush encroachment that may lead to additional changes to the biome (Roques *et al*., 2001). Bush encroachment can also lead to a change in fire frequencies due to change in vegetation type and fuel load. According to De Klerk (2004), bush encroachment is an invasion and thickening of aggressive and undesired woody species resulting in an imbalance of the grass to tree ratio. The Millennium Ecosystem Assessment (2005) revealed a massive decline in the world's ecosystem functionality driven by bush encroachment and alien invasive flora, which both reduce ecosystem integrity and result to fire regime change.

Mismanagement of rangelands is one of the drivers of bush encroachment (De Klerk, 2004). Van Wilgen *et al*. (2008) found that out of 9000 plant species introduced in South Africa, 198 are invasive. The majority of alien plant invasions occur in ecosystems that receive high rainfall while drier areas are characterized by limited invasion (Harper-Simmonds *et al.,* 2015). However, due to changing climate, invasion in dry areas like the Karoo is becoming prominent. Impacts of bush encroachment in terrestrial environments has long been recognized in South Africa, which directed to instituting of Working for Water (WfW) program conducted by Department of Environmental Affairs in 1995 and aimed at eradicating those species (Richardson and Van Wilgen, 2004). Remote Sensing is an ideal tool for detecting and monitoring fires in areas like Karoo National Park due to its potential to cover a large area, as compared to conventional methods which focus mostly in small areas.

1.3 Justification of the study

Karoo National Park Management Plan for the period of (2017-2027) prompts the need to conduct this study which emphasizes that no research has been done on fire management. Hence studies of this nature are encouraged. This study focuses on determining the frequency and intensity of fire in the Karoo National Park as well as identifying the fire hotspots and fire-prone areas. It is for the first time this kind of study is done in Karoo National Park. Hence it is a point of departure for future studies and will also have the potential to inform future management plans specifically for fire management.

Remote sensing techniques were employed to identify fire hotspot areas as well as fire frequency for over the past 16 years in the Karoo National Park. Remote sensing can monitor and analyze fires over large areas in a cost-effective and timely manner.

This is achieved by using satellite imagery in conjunction with spatial data from the Geographic Information System (GIS) (Sunar and Ozkan, 2001). Remote sensing is a tool used to acquire information or knowledge about a particular phenomenon devoid of being in physical contact with it (Lillesand *et al*., 2014). Remote sensing sensors like the MODIS and LANDSAT have been mainly applied both locally and globally to monitor the impacts of the environmental hazards such as fire, droughts and floods (Lillesand *et al*., 2014). The study of this nature has not been done in Karoo National Park. There are limited studies applying Remote Sensing and Geographic Information System to detect severity and extent of fire in this ecosystem. For example, Mutanga et al. (2016) applied remote sensing techniques to monitor vegetation, on the other hand Rahlao et al. (2009) applied remote sensing techniques in order to understand the effects of invasion of fire-free arid shrublands by a fire promoting invasive alien grass in the karoo.

1.4 Aim

The aim of the study was to assess the fire frequency, intensity and hotspots using Remote Sensing and GIS techniques in the Karoo National Park.

1.5 Objectives

The objectives of the study were to:

- Determine and map the distribution of fire hotspot area in the Karoo National Park
- Investigate change in the fire regime in the Karoo National Park between 2002 and 2016
- Provide management recommendations for an improved fire management protocol or plan

CHAPTER 2: LITERATURE REVIEW

2.1 Factors influencing fire occurrence

For a fire to start, the following elements are required, conducive weather conditions, favourable topography and enough fuel (Dean and Milton, 1999). Meteorological variables such as wind, humidity and temperature are also critical levers on fire spread and persistence (Cheney *et al*., 1993). Wind supplies fire with oxygen and makes it travel and burn faster. High temperatures, low humidity and high winds increase chances of a fire event to kick-start. Topography determines wildfire activity since fire spreads much faster up a slope than down a slope (Maingi and Henry, 2007; Keeley, 2009). The moisture content of fuel or biomass is also essential because dry fuel ignites quicker and burns much more efficiently than moist fuel (Cheney *et al*., 1993). According to Boonman *et al.,* (2014), fire generally occurs during the dry season when vegetation is dry.

2.2 Impacts of fire

In the African landscape, millions of square kilometres are burned annually, and fire in Africa is characterized by strong diurnal and seasonal variability. According to Sandberg *et al.* (2001), estimates of fire effects are based on the type of vegetation. The rationale for using vegetation characteristics to classify fuel load is that fuels are ultimately derived from vegetation; this entails how much fuel a particular vegetation type produces (Scott and Reinhardt, 2007). In South Africa, fires are prevalent in the Grassland biomes of the Free State, Gauteng, KwaZulu-Natal, Mpumalanga and the Western Cape's Fynbos biome. Procter (2011) found out that Free State is deteriorated by fires annually leading to the destruction of more than 240 000 hectares of Grassland. Forest fires occur regularly both locally and globally and their economic losses are well documented. The invasion of perennial grass promotes combustion efficiency of arid shrublands in the Karoo (Rahlao *et al*., 2009).

2.3 Components of a fire regime

According to Pechony and Shindell (2010), the fire regime is a critical component to understand before relating the effects of climate change on fire patterns. It characterizes the spatial and temporal patterns, and the impacts of fire in the landscape (Keelay *et al*., 2009). The fire regime is conditioned by the type of fire, fire ignition sources, season, frequency, size and intensity of fire.

2.3.1 Types of fire

There is variation in fire types, head fires usually burns in favor of wind or upslope, back fires burn against wind or down slope Bond and Van Wilgen (1996); Trollope, (2009); Forsyth *et al*., 2010). Ground fires burn the organic layer, surface fires burn above ground and crown fire burn tree canopies. Crown fires are normally sustained by surface fires beneath. However, under extreme conditions, independent crown fires occur and they race ahead of surface fires (Trollope, 2009; Forsyth *et al*., 2010).

2.3.2 Fire ignition sources

According to Forsyth *et al.* (2010), fire will only occur if there is an ignition source. The ignition sources do not have any ecological significance but a change in the primary ignition source can alter the entire fire regime. Lightning events have been the prime cause of fires in natural vegetation (Pyne *et al*. 2004). In the Cape Mountains, more than half of the fires recorded in Fynbos shrublands are ignited by lightning. Very rarely, sparks from hardened quartzite rocks have also been recorded as a cause of fires in the Cape.

Humans remain the main cause of contemporary fires (Bond and Van Wilgen, 1996), as they can alter fire by subduing fires and shifting vegetation by presenting new plants and land-use activity (McWethy *et al*., 2013). Furthermore, human activities such as arson, accidental or prescribed burns can result in wildfires from a diversity of heat sources like cigarette butts, matches and sparks from power lines. Prescribed burning for the removal of moribund material, unwanted plant material, control and/or prevent the encroachment of undesirable plants in appropriate biomes are recommended (Trollope, 2004). In recent times, it is rare to find fire regimes which are unaffected by humans whether intentionally for land management or arson or by accident (Bond and Van Wilgen, 1996).

2.3.3 Fire frequency

Fire frequency is a number of fires experienced by a particular community within a given space of time (Morrison *et al.*, 1995). Fire frequency is influenced by event-dependent and interval-dependent effects and must be borne in mind when reporting on fire. The event dependent effects transpire at the time of the fire and are encouraged by the type and intensity of burn and physiological state of vegetation at the time of the fire, whereas the interval dependent effects are influenced by treatment and growing conditions that occur during the interval between the burns (Bond and Van Wilgen, 1996). Fire deteriorating consequence on vegetation depends upon the susceptibility of different species to burns.

2.4 Heterogeneity in fire impact

Parisien and Moritz (2009) outlined that biotic, abiotic, and human factors drive a heterogeneous distribution of fire. According to Chia *et al.* (2015), fire influences the spatial and temporal patterns of landscape heterogeneity. Fire induced heterogeneity in biota is highlighted by the probable impacts of climate change on fire frequency and intensity. Fire has potential to create spatial heterogeneity in forest landscapes over time (Lindenmayer *et al.*, 2013).

Spatial heterogeneity of fire stems from the spatial arrangement of factors that affect fire ignition, behavior and effects (Baker, 1989). At course scales, regional variation in climate creates variation in fire regimes, however, at fine-scale, site factors such as topography, aspect, and fuel continuity may result in differences between adjacent areas. The fire regime is defined for a specific spatial domain which depends upon the spatial scale of the area and type of landscape elements (Baker, 1989). Large fires exhibit substantial internal heterogeneity in the severity with which they burn. Fires of different severity or areas within a single fire that burnt with different severity leave different types of evidence. Internal heterogeneity has significant influences on patterns of recovery in the post-fire plant community (Baker, 1989). According to Turner *et al.* (1994), most biotic variables such as the density and species richness of plants respond significantly to variability in burn severity.

2.5 Factors contributing to change in fire regime

Factors affecting fire regimes are spatially and temporally correlated (Keane, 2013). According to Heyerdahl *et al*. (2001), the interaction between bottom-up and top-down controls create a natural fire regime. Examples of bottom-up controls include vegetation, fuels, and topography, which dictates fire spread. Swetnam (1990) emphasized that top-down controls include climate and weather, which dictate fire frequency, duration, and synchrony. According to Agee (1998), humans start fire when the fuel is driest and has a potential to control the number and types of ignition. Agee (1998) argued that frequency and intensity of fire are the best criteria to define a fire regime. Fig. 1 shows a schematic representation of factors contributing to a change in fire regime.

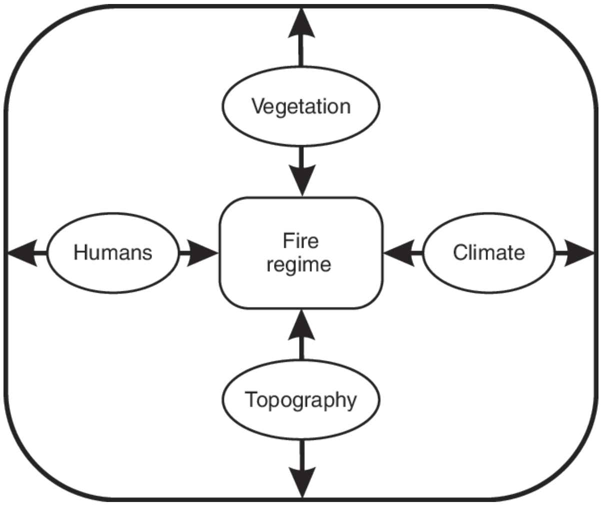

Figure 1: Factors affecting fire regimes and their interactions (Keane, 2013)

2.6 Bush encroachment

Bush encroachment is common in many arid environments, especially where there is insufficient fuel (Ward, 2005). Bush encroachment has been primarily documented since the late nineteenth century in South Africa. Encroachment is common in most world's arid and semi-arid biomes and change in vegetation structure has proliferated since 1900s due to overgrazing (O'Connor *et al.*, 2014).

2.6.1 Causes of bush encroachment

According to Angasa and Oba (2007), bush encroachment is associated with inter-annual rainfall variability. Rapid woody plant encroachment was experienced in the mid-

1970s, which was a high rainfall decade. Recent studies suggest that increasing CO_2 and climate change lead to increased bush encroachment (O'Connor *et al*., 2014). More grazing herbivores has led to the suppression of the competitive effect of grasses which curtails trees (O'Connor *et al*., 2014). The global consensus suggests that bush encroachment results multiple interacting factors and recovery from anthropogenic disturbances. Bush encroachment affects the functionality and processes of the ecosystem and as such, it ultimately leads to change in fire frequency and intensity. Encroaching bushes in grasslands leads to an increase in fuel load, hence change in the fire regime.

2.7 Using satellite imagery and remote sensing to study fire

According to Lillesand *et al*. (2007), remote sensing is a science and art of attaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object under scrutiny. Researchers have used RS and GIS to better understand fire and its effects on the environment. According to Zhang *et al.* (2011), detection and monitoring of forest fires have been accomplished using a variation of space-borne systems or sensors in the past three decades in China. National Oceanic and Atmospheric Administration (NOAA) and Advance Very High Resolution Radiometer (AVHRR) satellite images were used to detect the fire hotspots by thresholding three infrared channels in the early 1980s. Remote sensing has a potential to measure the components of fire such as frequency, severity, intensity and hotspots using multi scale remote sensing from Landsat to MODIS.

2.7.1 Land Satellite (LANDSAT)

In the past, meteorological sensors had limited capabilities for land resources observation. The first LANDSAT was designed in 1960 and launched in 1972 for broad-scale observation of earth resources (Cambell and Wyne, 2011). It recorded energy in visible and near infrared (NIR) spectra. LANDSAT system comprises of airborne spacecraft sensors that detect the Earth and transmit data by microwave radiation to ground stations that collect and process the data (Cambell and Wynne, 2011). Each LANDSAT satellite passes over an area on the Earth's surface during daylight approximately 20 times yearly. Some critical factors that affect LANDSAT images include cloud cover, sun angle and whether or not the satellite was in operational during the specific pass. This ultimately provides for many areas to have LANDSAT images for several dates annually (Lillesand *et al*., 2007). The study conducted by Oliveira *et al*. (2012) outlined the application of LANDSAT to assess fire frequency. According to Kato *et al*. (2020), the analysis multi-temporal LANDSAT image has a capacity to track contemporary fire frequency and burned area in a spatially unequivocal manner. The pre and post-fire difference of the Normalized Burn Ratio has been applied widely for Burn Area Reflectance classification (Meddens *et al.,* 2018). According to Justice *et al*. (2002), the inherent limitation of Landsat temporal resolution is that it may not be effective for mapping active fires.

2.7.2 Moderate Resolution Imaging Spectro-radiometer (MODIS)

Moderate Resolution Imaging Spectro-radiometer (MODIS) is widely used to study fires (Justice *et al*., 2002). MODIS provides comprehensive data about land, ocean and atmospheric processes**.** MODIS also offers observations in moderate spatial (from 250 m –1 km) and temporal (1 – 2 day) resolutions in diverse spectral regions of the electromagnetic spectrum and collects data in 36 spectral bands. MODIS has been found to be an effective estimator of biomass consumed by fire (Ellicot *et al*., 2009). Although MODIS has a high revisit period of 1-2 days beneficial for mapping fires, some fires remain undetected (Justice *et al*., 2002). According to Hendel and Ross (2020), thermal infrared remote sensing technologies can be applied to detect early fire.

2.7.3 Normalized Difference Vegetation Index (NDVI)

The normalized difference vegetation index (NDVI) has been utilized for understanding changes in land cover types such as woodlands, cropland, water and urban area. This index is computed using the red and infrared (IR) spectral reflectance measuring the characteristics of green plants, and it is simple and effective to monitor vegetation cover and its growth conditions over time (Wang *et al*., 2014). Chuvieco *et al*. (2004) found out that the application of NDVI provides a consistent estimation of fuel moisture content. It was found that the Karoo biome has had a significant increase in NDVI compared to other biomes due to increases in vegetation cover (Hoffman *et al*., 2018).

2.8 Fire and climate change

Over the years, fire mitigation has gained attention due to the effects of socio-economic changes and ultimately, fire suppression expenditure and prevention has increased globally particularly in countries that are fire-prone (Stephens *et al.*, 2014). A worse fire danger scenario has been projected in future due to extreme weather conditions which threaten environmental aspects (Alcasena *et al.*, 2019; Badia *et al.*, 2011). According to DaCamara *et al*. (2014), climate change scenarios based on General Circulation Models (GCM) has been applied to understand future fire projections. Liang *et al*. (2008) argued that the difference in surface temperature and precipitation between the present and future climates show that the current climate preconceptions are systematically propagated into future-climate projections at regional scale. According to Flannigan *et al*. (2005) and Balshi *et al*. (2009), current and future climate change drives fire regime changes. According to the EEA Report (2012), the distribution and variability of fire regime is influenced by current and future changes in spatial patterns of temperature and precipitation, and more droughts are expected and less precipitation. Climate affects the fuel characteristics such as vegetation type, fuel moisture, continuity and abundance. Drier summers and severe droughts increases the frequency of fires and plant mortality worsen the fire hazard (McWethy *et al.*, 2013).

2.9 Fire in Europe

According to San-Miguel-Ayanz *et al*. (2013), in the European Mediterranean, large fires are accountable for economic, human and environmental loses. Study conducted by Turco *et al*. (2017) and Ruffault *et al*. (2018) revealed that largest fires occur due to extremely hot and dry weather conditions. Future predictions show a substantial increase in fire activity in Europe (Kovats *et al*., 2014; Turco *et al*., 2018), however, Dupuy *et al*. (2019) postulated that future fires can be affected by a host uncertainty which relates to biophysical and human factors apart from climate-driven uncertainty.

2.10 Fire in Africa

In the tropical savannahs and forests, fires have been taking place for millennia (Goldammer, 1990; Levine, 1991; Crutzen and Goldammer, 1993). Fires are regarded as a landscape disruption subsequent to partial or complete devastation of vegetation cover (Guerra *et al*., 1998). In Senegal, prescribed burning is practised as part of rangeland management to diminish disturbing run-away fires (Hough, 1993). In Central Africa, pastoralists prefer to burn grasses early in the season and is regarded a safest way to burn (Mbow *et al*., 2002). According to Laris (2002), in Mali earliest burning is practiced on soils that support short annual grasses that are not palatable. Uys *et al.* (2004) found that forb species endure a wide range of season and frequency of fire than the dominant grasses. According to Solofondranohatra *et al*. (2020), over an ecological and evolutionary timescales fire and grazing shape tropical grasslands.

2.11 Fire in South Africa

In savannas and grasslands ecosystems, fire and grazing are competitive processes due to their ability to consume above-ground biomass (Archibald and Hempson, 2016; Bond and Keeley, 2005). In conservation areas, the interaction between herbivore and fire management is infrequently considered in herbivore or fire management plans. A study conducted in Hluhluwe showed that the removal of white rhino leads to an alarming increase in the burnt area and individual fires (Waldram, 2008). Cattle grazing reduces the burn area (Alvarado *et al*., 2018; Archibald *et al*., 2009).

According to Smit and Archibald (2019), in their study on the spatio-temporal patterns of fire in semiarid savannas due to herbivore culling, found that fires were more predominant during the culling period than thereafter and the fire suppression effects of increasing grazing were more noticeable in areas adjacent to rivers. Furthermore, Smit and Archibald (2019) recommended that herbivory and fire management actions should be incorporated because occasions that influence herbivore density, subsequently influence fire occurrence.

2.12 Fire in arid and semi-arid areas

It was argued that in arid and semi-arid areas, fire is significant in managing forage production (Everson, 1999; Pe'rez *et al*., 2008). Fire is used as a management tool for diminishing the buildup of unacceptable dead plant materials (Trollope, 2009), however, these conditions seldom occur in arid and semi-arid rangelands, hence burning is reckoned to be unnecessary (Snyman, 2003a). Fire likelihood is promoted by a plenty of undesirable shrub and tree encroachment in arid and semi-arid environments (Zimmerman *et al*., 2010; Joubert *et al*., 2012). According to Killgore *et al*. (2009) and Liang *et al*. (2009), fire impacts in arid environments is dependent upon the adaptability and sustainability of the vegetation. In the arid and semi-arid areas, fire cannot be disassociated with grazing (Dalgleish and Harnett, 2009). The impacts of post-fire grazing on the recovery of plants are poorly documented in arid and semi-arid areas (Snyman, 2004b; Vermeire *et al*., 2011).

CHAPTER 3: MATERIALS AND METHODS

3.1Study area

The Karoo National Park (KNP) is located in the Western Cape Province near Beaufort West, South Africa (Figure2). The park was proclaimed in 1979 and is currently 90535 ha. The KNP has five physiographic units, the Southern and Central Plateau of less than 1000 m above sea level (ASL), the South Eastern Plateau of less than 1000 m ASL, the Middle Plateau of 1100-1200 m ASL, the Northern Upper Plateau of 1600-1900 m ASL, and the flat-topped Korannasfontein Mountain in the west, which lies 1400 to 1550 m ASL. The park is characterised by five vegetation types, the Eastern Upper Karoo, Gamka Karoo, Karoo Escarpment Grassland, Upper Karoo Hardeveld and Western Upper Karoo. These plant communities have distinct flora with unique fuel loads and flammability.

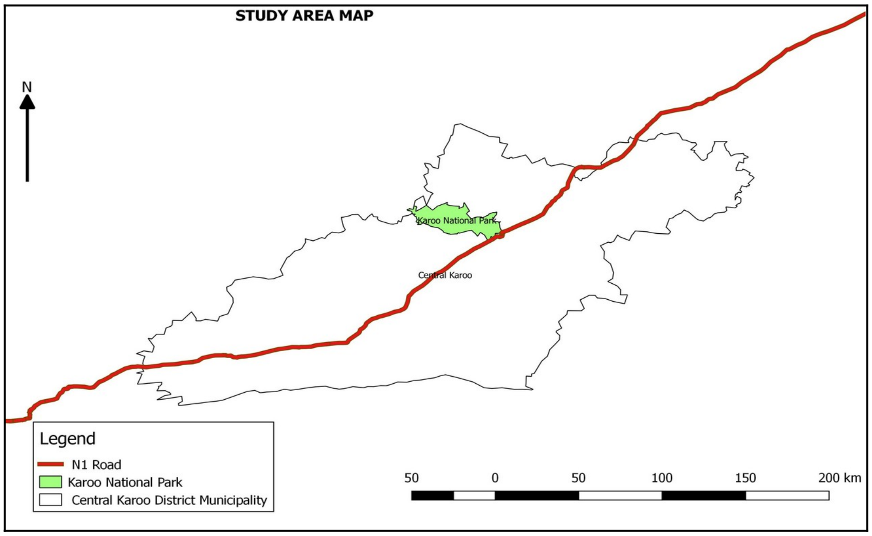

Figure 2: Location of the Karoo National Park in the Western Cape along the N1 highway

The KNP is part of the Great Karoo, which is South Africa's largest ecosystem, covering 35% of its land area. It is situated in the semi-arid Nama-Karoo Biome against the Nuweveld Mountain range. Thus the park straddles two biomes, the Nama-Karoo, which covers the largest portion, and a relatively small section of the Grassland Biome. The Grassland Biome is represented by the Karoo Escarpment Grassland vegetation type, which forms part of the Dry Highveld Grassland Bioregion of the country. The plant functional groups that occur in the park include grassy shrublands, grassy dwarf shrublands, succulent dwarf shrublands and riparian vegetation.

The mean annual rainfall in the park ranges from 175 to 406 mm. It experiences cold winters and hot summers, with mild to heavy frost and episodic snow on the Nuweveld Mountains. The vegetation growth season persists for seven to eight months. The Westerly and North Westerly winds prevails and have a scorching effect on soil and vegetation.

According to DEA (2013) and Driver *et al*. (2012), the average temperature in the Karoo National Park is expected to increase by between 1.5^0C and 2.5^0C by the year 2050. Although the increase seems to be minimal, there would be 16-31 days in a year where Karoo National Park would exceed 35^0C, such extreme temperatures negatively impact fauna and flora. Furthermore, rainfall is expected to decrease by between 20 to 80 mm annually (DEA, 2013; Driver *et al*., 2012).

3.2 Data collection

3.2.1 Fire data

The mean annual rainfall in the park ranges from 175 to 406 mm (Driver et al., 2012). It experiences cold winters and hot summers, with mild to heavy frost and episodic snow on the Nuweveld Mountains. The vegetation growth season persists for seven to eight months. The Westerly and North Westerly winds prevail and have a scorching effect on soil and vegetation. The Fire Information for Resource Management System (FIRMS) product has a capacity to detect fires in 1 km pixel size. FIRMS was developed by the University of Maryland. It distributes Near Real Time (NRT) active fire data within three hours of satellite observation from MODIS aboard the Aqua and Tera satellites. FIRMS provide active fire information in vector format and gives user an ability to download a customized fire data sets (https://firms.modaps.eosdis.nasa.gov/download/create.php)

To understand fire encroachment into the KNP, the dataset within 5 km radius from the park boundary was considered. The fire dates ranged from 2000 to 2018. The data were used to identify the spatial distribution of fires over time to map fire hotspots. The fire data were imported into the Quantum Geographic Information System (QGIS), to produce maps demonstrating the spatial and temporal distribution of fires over the study period. The data include location, month of occurrence, fire temperature, power and time of the day at which the fire event took place. All fires which took place on the same day at the same time in the same pixel were group together and counted as one.

3.2.2 Fire angles calculation from the centroid

The angles of fire location were calculated using haversine formular to ascertain angles at which fires take place from the centroid. Centroid is the point considered as the centre of one or two-dimensional figure or the displacements of all points in the figure (Chopde and Nichat, 2013). The equation was used to understand angles at which most fires emanate from,

$$\theta = atan2(\sin \Delta\lambda . \cos \varphi_2 . \cos \varphi_1 . \sin \varphi_2 - \sin \varphi_1 . \cos \varphi_2 . \cos\Delta\lambda) .... (1)$$

φ_1,λ_1 *is the start point,*

φ_2,λ_2 *he end point (*$\Delta\lambda$ *is the difference in longitude)*

3.2.3 Distance calculation from the centroid to fires

Distance from the centroid to the respective fire points was calculated using haversine formula. The haversine formula calculates the great circle between two points, which is the shortest distance over the earth surface (Chopde and Nichat, 2013).

$$a = sin^2\ (\Delta\varphi/2) + cos\varphi_1 \cdot cos\varphi_2\ .\ sin^2(\Delta\lambda/2) \qquad (2)$$

$$c = 2.atan2(\sqrt{a}\ .\ \sqrt{(1-a)}\ )$$

$$d = R.c$$

Where: φ *is latitude* λ *is longitude, R is earth's radius (mean radius = 6,371km)*

3.2.4 Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) was calculated using Raster Calculator in QGIS. NDVI calculates vegetation by measuring the difference between near-infrared (NIR) and red (R) bands. In near-infrared vegetation reflects strongly and the red light is absorbed by vegetation.

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \tag{3}$$

3.2.5 Normalized Burn Ratio (NBR)

The Normalized Burn Ratio (NBR) was calculated from Landsat imagery using Raster Calculator in QGIS. NBR highlights burn areas and also estimate fire severity. NBR uses near-infrared (NIR) and shortwave infrared (SWIR) bands.

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{4}$$

3.2.6 Meteorological data

Meteorological data were obtained from the South African Weather Services (SAWS) for the weather station situated in Beaufort West Town in the Western Cape Province of South Africa. The data was in an annual format from the period of 2000 to 2018. The meteorological variables requested include; rainfall, temperature, wind speed and wind direction. The meteorological aspects were considered due to their profound role in fire events. The seasonal temperature and rainfall graphs were drawn using excel in order to understand how fire is affected by climatic factors. Wind roses were drawn in order to understand the prevailing wind directions in the KNP in association with fire hotspot.

3.2.7 Karoo National Park Management Plan

The Karoo National Park Management Plan for 2017-2027 was thoroughly reviewed to ascertain whether plans were in place to protect the park from fire events which may have detrimental effects to the biodiversity within the park. Furthermore, the plan was reviewed to determine whether the most critical aspects of fire management were captured.

3.2.8 Karoo National Park Fire Hotspot map

The KNP fire hotspot was created using Q-GIS all the fire events which took place from the year 2000 to 2018 were captured and spatially represented in the form of map and the fire hotspots of the park were indicated on the map.

3.2.9. Statistical analysis

A statistical correlation between fire frequency, NDVI, NBR, rainfall and temperature was conducted using excel to understand relationship between variables with $p<0.05$ which resembles a statistical significant at 95% confidence level. The strength of relationship between variables was depicted by the size of correlation coefficient. A correlation of +1 resembles positive correlation, 0 resembles no correlation and -1 resembles negative correlation. A negative correlation means that knowing the value of one variable allows prediction of the other variable, but with less accuracy. A positive correlation revealed that when one variable is known it is possible to predict the other with a considerable accuracy (Leedy and Ormrod, 2010).

CHAPTER 4: RESULTS

4.1 Fire frequency

There were 201 individual fires between January 2001 and December 2016 of which 75% were in the day while the rest were at night. Almost half (57%) were inside the park boundary while 43% were outside the boundary but within the 5 km buffer. Most fires burnt on Saturday (26%), followed by Wednesday (23%), Friday (8%), Sunday (10%) and Thursday (10%) experienced the least fire events (Appendix A; Table 1). There were no fires recorded in May and June during the 15 year study period. Most fires took place in October (43%), followed by March (29%), all other months experienced less than 10% of the total fires. November had just a single fire while April and July had 4 each. Curiously, there were no fires on the second day of every month, also on the 16th to 19th, 22nd, 30th and 31st, no fires occurred in the 15 years. Twenty percent of the fires took place on the 12th while 16% burnt on the 9th, the rest of the days all had less than 10% of the fires. Day 1 and the 3rd had particularly low fire occurrences, one fire in each out of the 201 over the 15 years (Appendix Table 1). Yearly, most fires occurred in 2013 (34%) and 2016 (28%), 2002 and 2010 were almost fire-free with a single burn in each year. The rest of the years had less than five fires annually, noteworthy highs were in 2004 with 17 fires (8.5%) and 2003 with 16 fires (8%) (Appendix A; Table 1).

Year	Fire frequency (n)	Fires (%)
2002	1	0.5%
2003	16	8%
2004	17	8.5%
2005	4	2%
2006	3	1.5%
2007	4	2%
2009	4	2%
2010	1	0.5%
2013	86	43%
2014	5	2.5%
2015	3	1.5%
2016	57	28%
Total	***201***	***100%***

Table 1: Annual fires in the KNP

There were 43 aggregated fires between January 2001 to December 2016 including fires outside the study area boundary but within 5km buffer. The total aggregated fires which took place within the KNP boundary constituted (56%). Most fires burnt in an area characterized by Karoo Escarpment Grassland (37%), followed by Upper Karoo Hardeveld (12%), Easter Upper Karoo (5%), Gamka Karoo (2%), and Western Upper Karoo experienced no fire. About 44% of aggregated fires took place outside the boundary but within a 5km buffer (Appendix A; Table 2).

Vegetation class	Fire frequency (n)	Fires (%)
Eastern Upper Karoo	2	5%
Gamka Karoo	1	2%
Karoo Escarpment Grassland	16	37%
Upper Karoo Hardeveld	5	12%
Western Upper Karoo	0	0%
Fires outside KNP Boundary	19	44%
Total	***43***	***100%***

Table 2: Vegetation class, fire frequency and percentage

The Karoo Escarpment Grassland experienced the most fires with about 37% of the total fires. Although the park is dominated by Gamka Karoo and Upper Karoo Hardeveld vegetation, few fires were experienced with about 2% and 12% respectively. The Eastern Upper Karoo experienced 5% of the fires while 44% of the fires were outside the park in the 5 km buffer (Fig.3). Finally, the western upper Karoo did not experience any fire during the period of assessment.

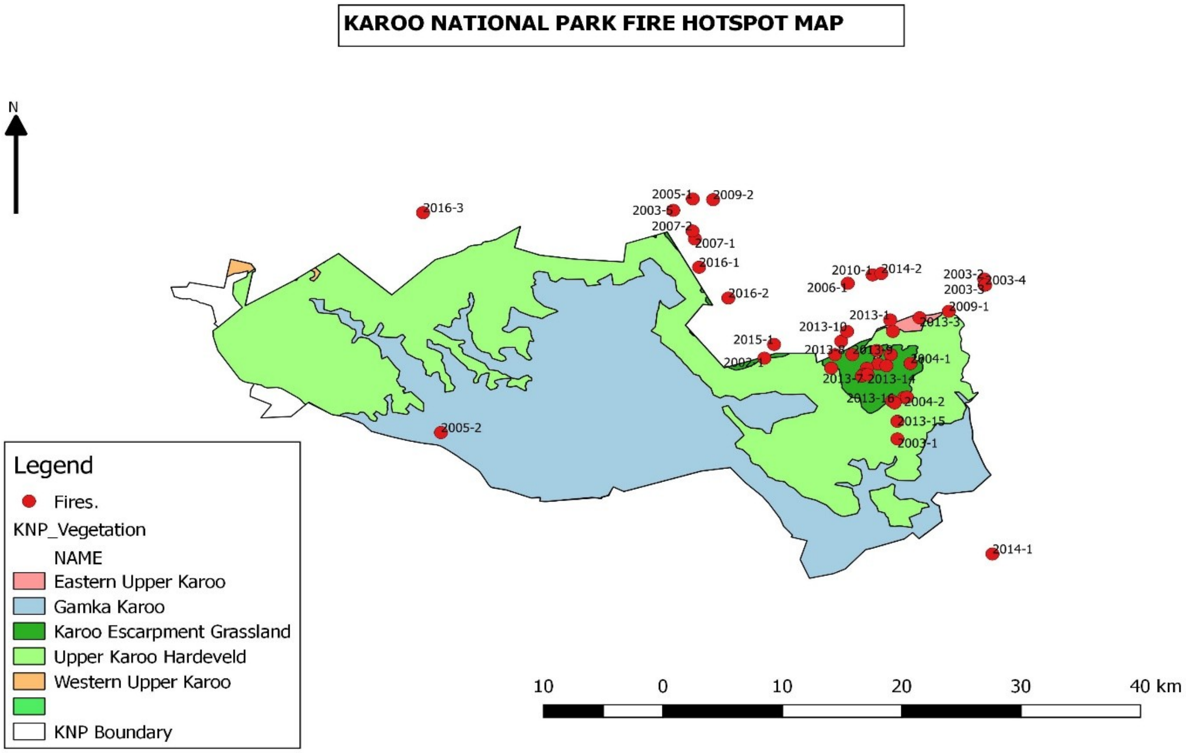

Figure 3: Fires in the KNP in different vegetation types between 2001 and 2016

Table 3 shows correlations between fire frequency, NDVI, NBR, rainfall and temperature. There was a positive correlation between NDVI and fires with a correlation coefficient of 0.17. Fires and temperature had a positive correlation with a correlation coefficient of 0.12. NDVI and NBR had a negative correlation with a correlation coefficient of -0.26. Fire and rainfall had a negative correlation with a correlation coefficient of -0.09. NBR and fires have a moderately strong positive correlation with a correlation coefficient of 0.67.

Table 3: Correlation between fire frequency, NDVI, NBR and climatic variables

	Fires	NDVI_Min	NDVI_Max	NDVI_Average	NBR_Min	NBR_Max	NBR_Average	Temperature	Rainfall(mm)
Fires	1.00	0.10	0.17	0.17	0.15	**0.70**	**0.67**	0.12	-0.09
NDVI_Min	0.10	1.00	**0.52**	**0.65**	0.19	0.08	0.12	-0.03	0.03
NDVI_Max	0.17	**0.52**	1.00	**0.99**	-0.38	-0.26	-0.32	-0.45	-0.07
NDVI_Average	0.17	**0.65**	**0.99**	1.00	-0.31	-0.21	-0.26	-0.41	-0.06
NBR_Min	0.15	0.19	-0.38	-0.31	1.00	0.31	0.51	0.36	-0.13
NBR_Max	**0.70**	0.08	-0.26	-0.21	0.31	1.00	**0.98**	0.41	-0.06
NBR_Average	**0.67**	0.12	-0.32	-0.26	0.51	**0.98**	1.00	0.46	-0.08
Temperature	0.12	-0.03	-0.45	-0.41	0.36	0.41	0.46	1.00	-0.36
Rainfall(mm)	-0.09	0.03	-0.07	-0.06	-0.13	-0.06	-0.08	-0.36	1.00

Fig. 4 shows the correlation between NDVI and fires. There was a positive relationship between NDVI and fires, when the NDVI was high more fires took place and when the NDVI was low fewer fires took place. It can thus be surmised that the vegetation influences the intensity of fire in the KNP.

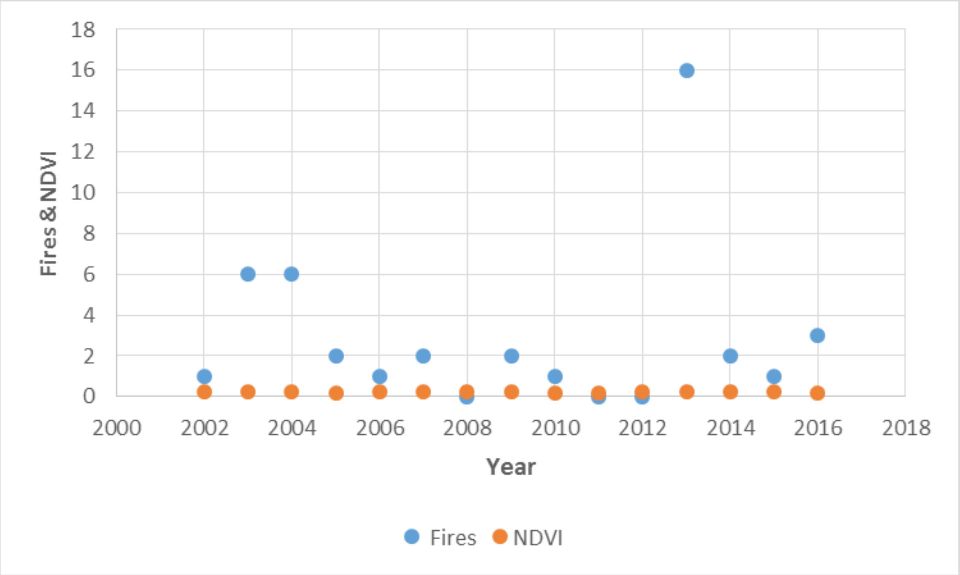

Figure 4: Correlation between NDVI and fires

Fig. 5 shows the correlation between fires and temperature. There was a positive relationship between the two high temperatures led to more fires occurrence in the KNP.

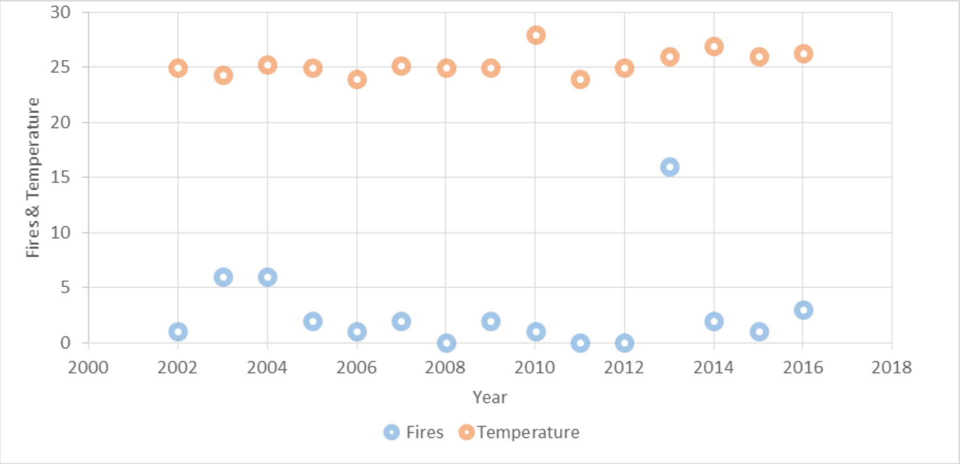

Figure 5: The relationship between fires and air temperature over time

Fig. 6 depicts the correlation between NDVI and NBR. There two variables show a positive relationship, when the NDVI was high, the NBR was high as well.

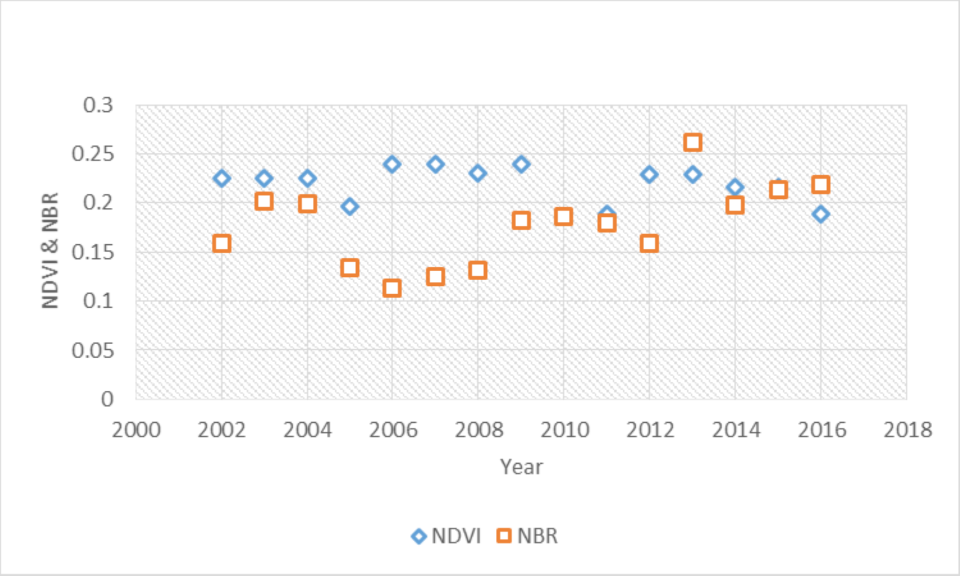

Figure 6: The relationship between NDVI and NBR

Fig. 7 shows the correlation between fires and rainfall. The graph shows a negative relationship between fire and rainfall in the KNP.

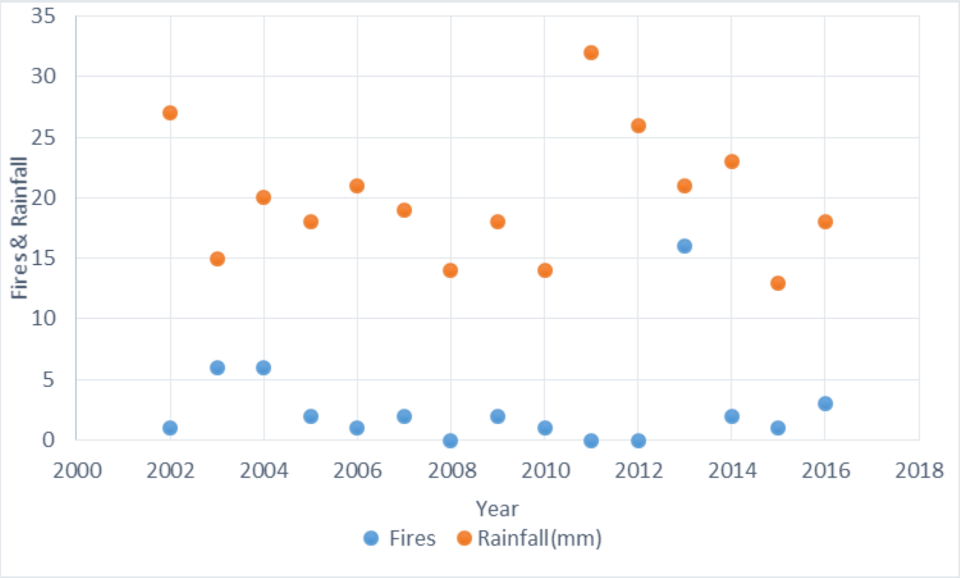

Figure 7: The relationship between fires and rainfall

The NDVI was mapped using QGIS shows plant density in the eastern region of the park where more fires were experienced. The light colour in the maps represent dense vegetation and dark colour represents less vegetation. The NDVI revealed that the western region of the park has highly stressed vegetation as compared to the eastern region. The Karoo grassland escarpment vegetation dominates the eastern area where more fires were experienced. Grasslands played a large role in vegetation and increased fire susceptibility (Figure 8).

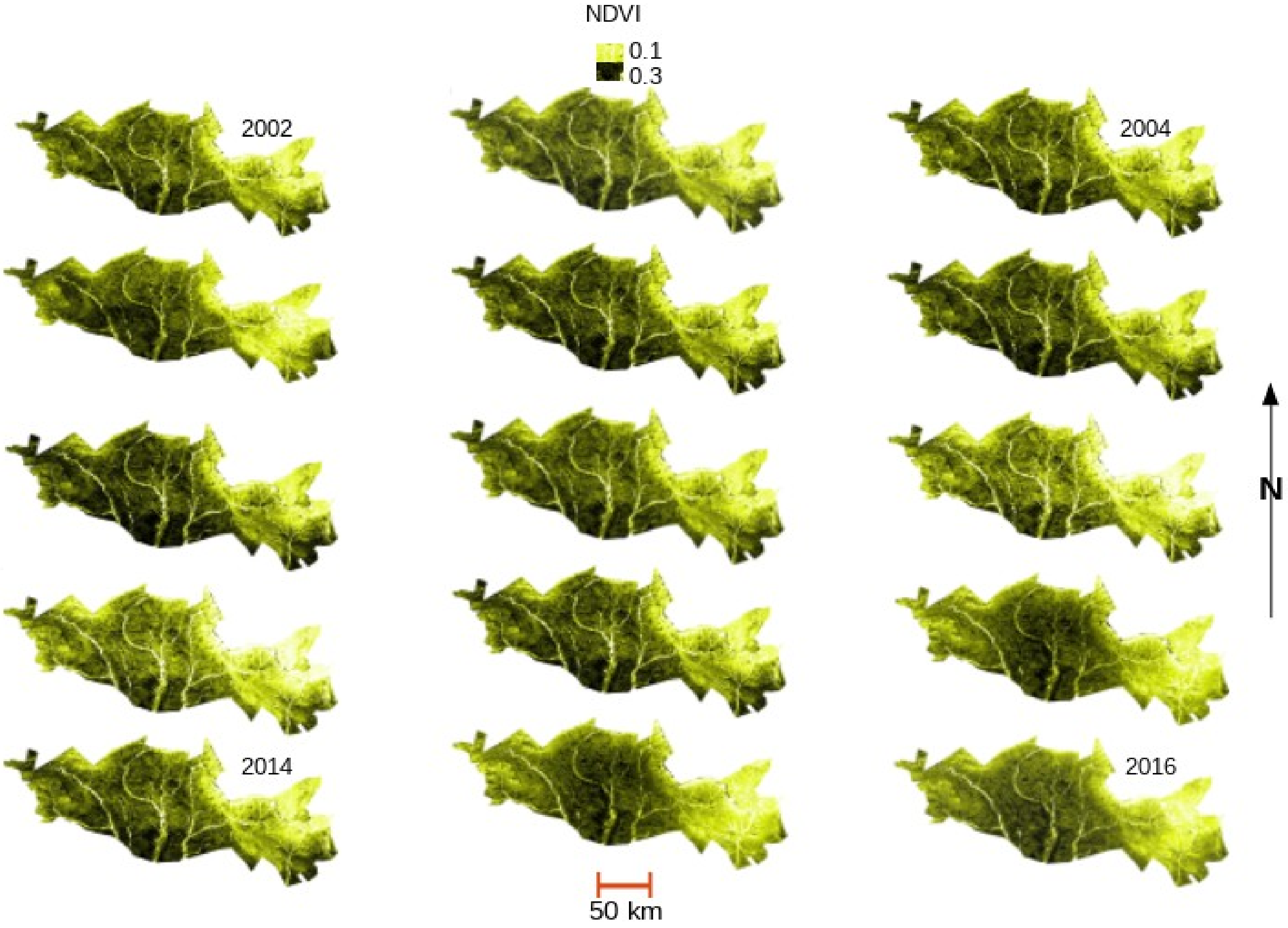

Figure 8: KNP NDVI from 2002 to 2016

The NBR was mapped using QGIS shows fire severity in four classes (unburned, low burn, moderate and high burn) in the KNP from 2002 to 2016 (Figure 9). Fires in the east were more severe where grassland is located as shown in figure 3 and 4 above.

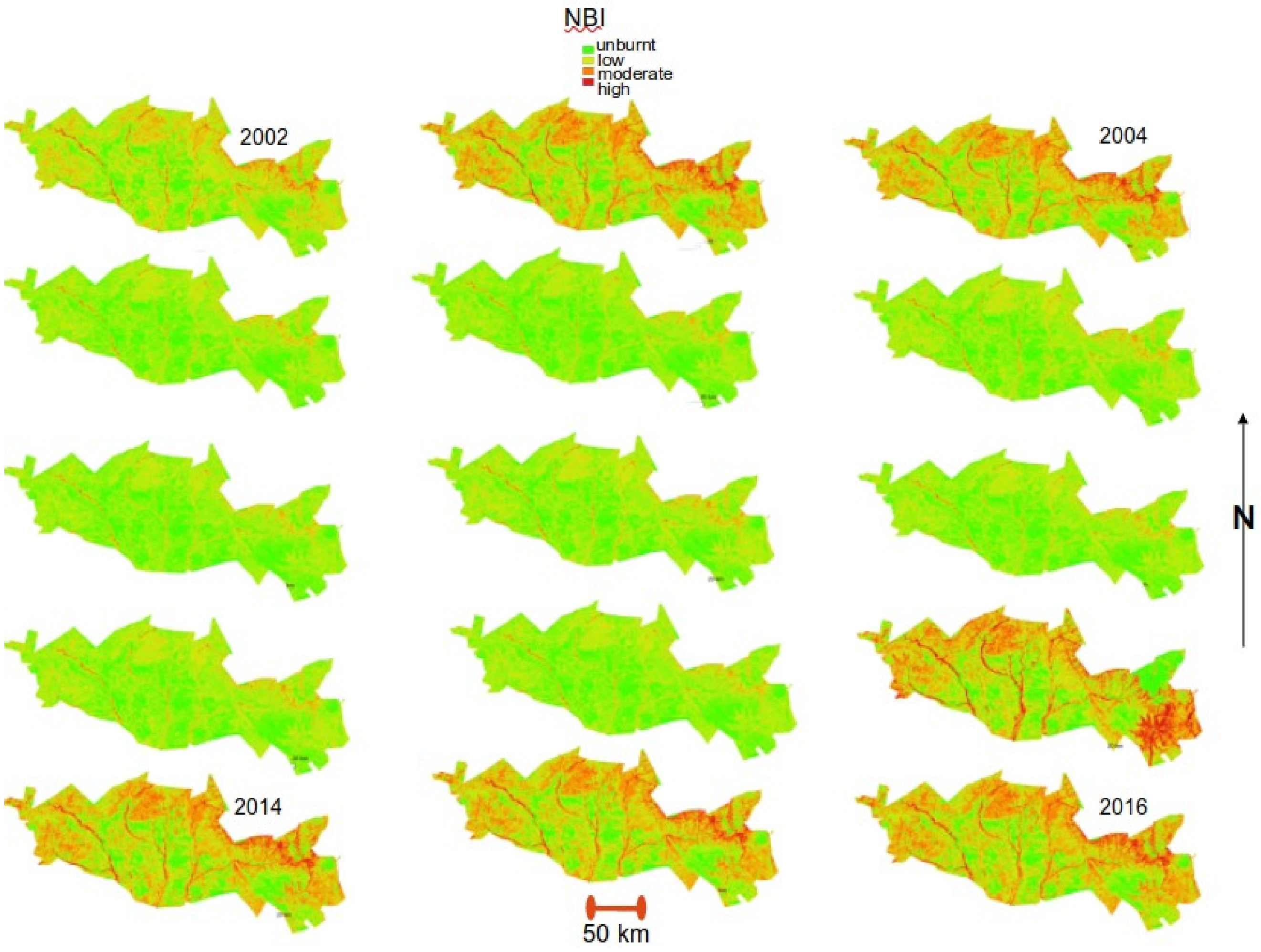

Figure 9: KNP NBR 2002 to 2016

Most KNP fires were less than 30 km from the centroid between zero and 100^0 from the north, and the furthest angle at which fire occurred in the KNP was 327^0. The FIRMS data provide Fire Radiative Power (FRP) and the highest FRP was 312 MW in 2016 as shown in Fig. 10.

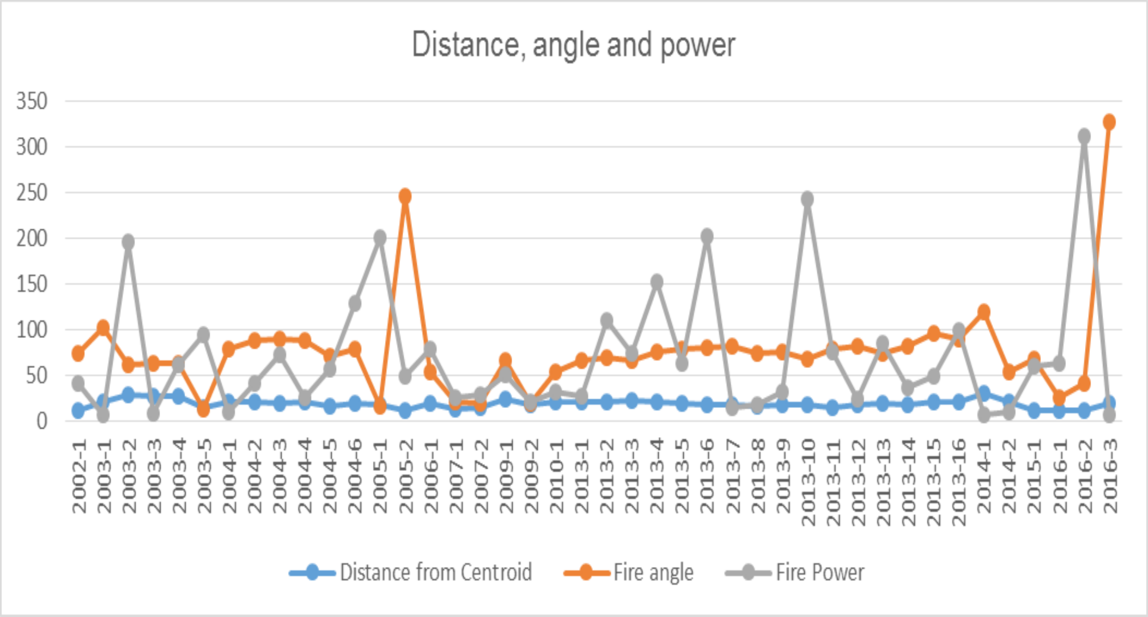

Figure 10: Fire distance from the centroid, fire angles and fire radiative power

Fig. 11 shows the areas burnt by individual fires in the park. There was a significant increase in the size of area burnt in the KNP. The largest area burnt in the park during the study period was in 2016 and the fire burnt 3.125 km^2.

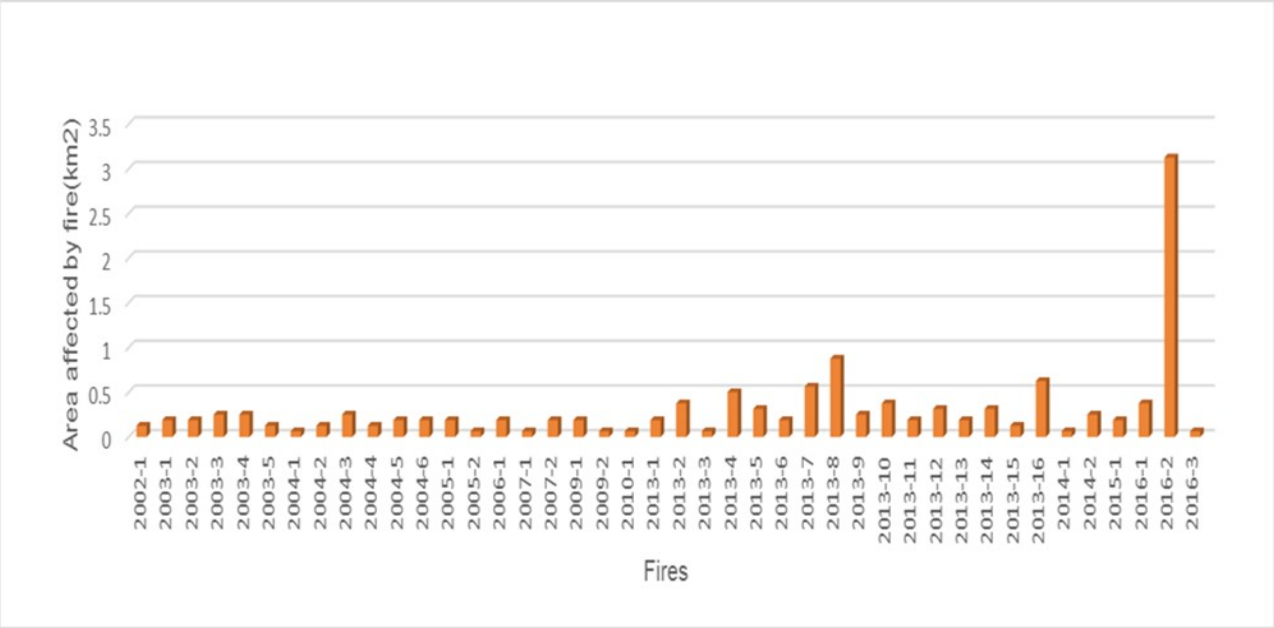

Figure 11: Area affected by fire

4.2 Fire regime

Fig. 12 shows annual aggregated fires which took place in different years. While the KNP experiences few fires, there might be a recent increase in fire occurrence in the park.

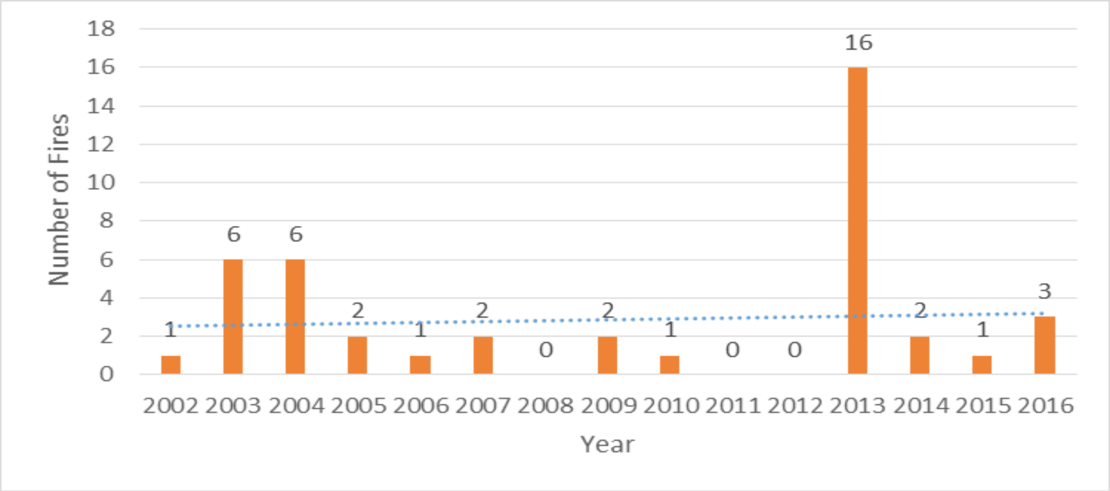

Figure 12: KNP annual aggregated fires (2002-2016)

Fig. 13 shows that 51% of fires in the KNP took place in spring, summer (21%), autumn (12%) and winter (16%). These results show that the fire management plan of the KNP should mostly focus its attention on spring high fire prevalence.

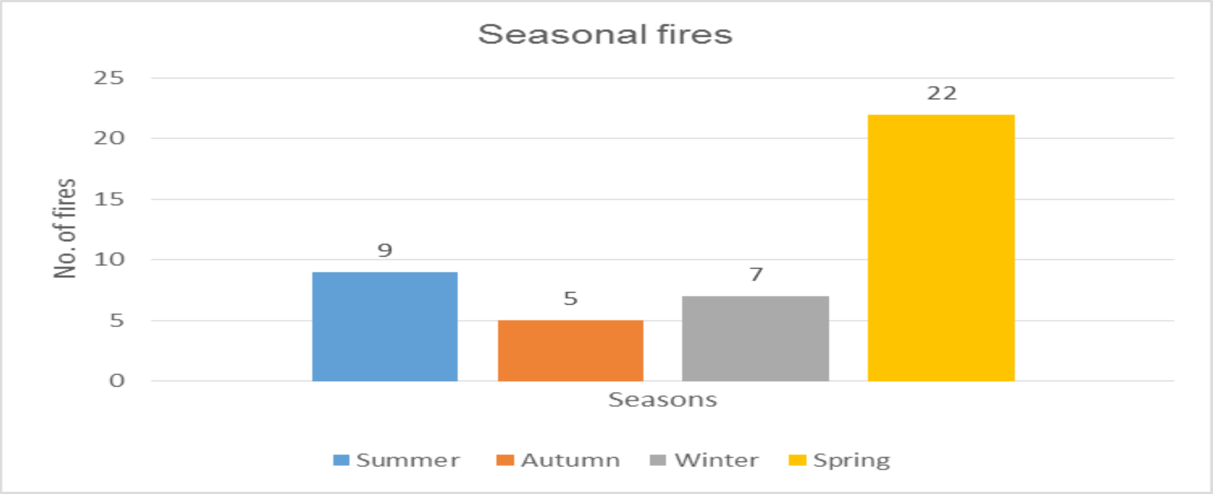

Figure 13: Seasonal fires

4.2.1 Rainfall

The Western Cape is characterised by three climatic zones induced by the Cape Fold Belt, namely; the Mediterranean, South Coast and Karoo zone. The Mediterranean zone predominantly receives winter rainfall and South Coast receives all year rainfall with a peak in winter while the Karoo zone receives all-year rainfall that peaks in summer. Fig. 14 shows the rainfall annual average from 2000 to 2018 in the KNP. The historic mean annual rainfall of the Park ranges from 175 mm – 406 mm with 60 to 75% falling in summer. The seasonal analysis of rainfall during the study period revealed that rainfall is mostly received in summer followed by autumn, winter, and spring in decreasing order. The highest amount of rainfall received in summer was 115 mm in

December 2002, peak autumn rain was 16 mm in March 2010, winter peak was 55 mm in August 2002 while the spring peak rain was 62 mm in November 2005 (Figure 14).

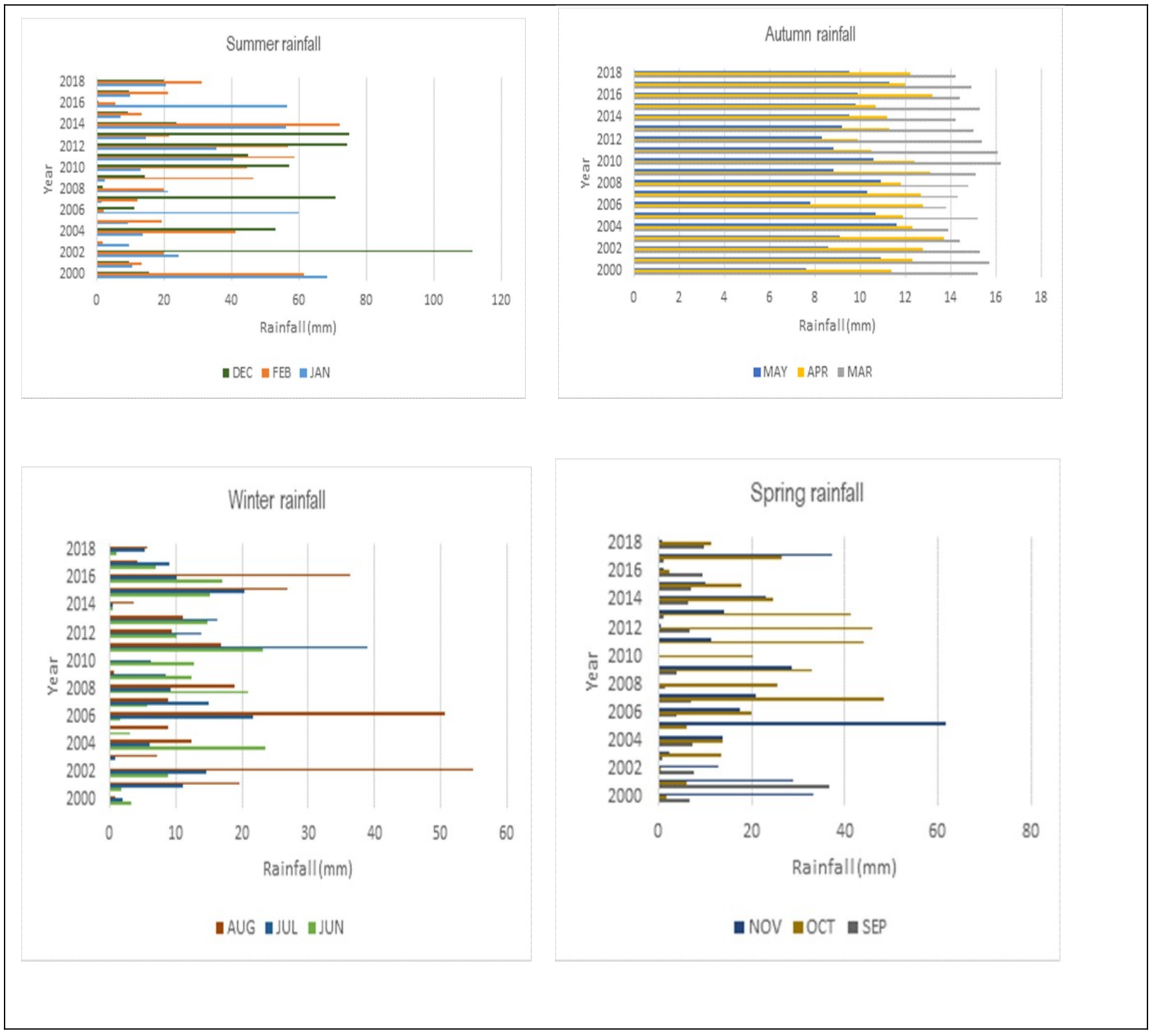

Figure 14: KNP seasonal rainfall from 2000-2018

4.2.2 Temperature

Temperature is one of the factors affecting fire occurrence. Fig. 15 shows seasonal temperature in the KNP. The KNP experienced a high temperature in the summer of over 30^{0}C. In autumn has reached 30^{0}C especially in March. In winter, temperatures were below 20^{0}C and towards the end of the season, there was a rise in temperature reaching over 20^0C. At the beginning of spring, temperatures were over 20^0C, but towards the end of the season, a temperature rise was recorded of approximately 30^0C (Figure 15). High temperatures increase the flammability of fuel.

Figure 15: KNP Seasonal Temperatures

CHAPTER 5: DISCUSSION AND CONCLUSIONS

5.1 Discussion

Although KNP has a park management plan which is considerate of the impacts of fire in the park, there is a need to develop a fire management plan. Hotspot areas are characterised by a concentration of fire incidents within a limited geographical area over time. Identification of hotspot allows for better resource allocation for combating the problem.

To understand fire occurrence, climate change has to also be taken into consideration. According to Driver *et al*. (2012), the average temperatures in the KNP are anticipated to increase by between 1.5^0C and 2.5^0C by the year 2050. Temperature is one of the critical ingredient controlling fire (Sundin *et al*., 2009), however, the plan did not outline how the projected increase in temperature can affect or alter change in the fire regime of the KNP. The Karoo escarpment grassland dominates the eastern part of the park influencing fire behaviour due to its high flammability. Fire mushroomed in areas characterised by grassland creating a major fire hotspot. The noticeable decline in seasonal rainfall has been recognized in the KNP which has a direct impact on fire occurrence (Smit and Archibald, 2019). A decline in rainfall promotes fuel dryness and increases the susceptibility of vegetation to fire (Williams *et al*., 2019). The study recommends that a fire management plan should be developed due to projected high frequencies of droughts which will likely cause more fires.

5.2 Conclusions

The main focus of the study was to assess fire encroachment into the KNP using GIS and RS. The study put more emphasis on the employment of GIS and RS to understand fire behaviours. Q-GIS was used to map fire hotspot, vegetation distribution and burn severity.

Fire is encroaching into the KNP more especially in areas characterised by Karoo Escarpment Grassland vegetation type. These fires are encroaching from the eastern direction of the park towards the west, the prevalent wind direction thereof is easterly. GIS and RS techniques are therefore recommended to be utilised for a better fire management plan.

The results of the study revealed that the KNP Management plan for 2017-2027 was considerate of the likelihood of fire in the park, however there is a need to develop a fire management plan which takes into consideration how herbivory affects fire and fire threat assessment. The climatic data from 2000 to 2018 indicated that KNP is an all-year-round rainfall region, however, maximum rainfall is experienced in summer (December-February). This study has therefore achieved its objectives.

5.3 Recommendations

Concerning the research findings outlined in the previous chapter, the study recommends the following management strategies for an improved fire management protocol in the KNP.

For a better fire management protocol in the KNP, the study recommends that a thorough analysis unravel the rate of flammability of different types of vegetation. The focus should be on potential hotspots. Different vegetation types have distinct flammability rate. Rahlao *et al.* (2009) suggested that the presence of grass in the Karoo ecosystem makes fires more prevalent. Furthermore, grass would have to widespread to support continuous fire in Karoo. Figure 4 revealed that most fires occur in the Karoo Escarpment Grassland vegetation as compared to other vegetation types in Karoo National Park.

KNP accommodates both plants and animals, in line with the study conducted by Dalgleish and Harnett (2009), a better fire management plan cannot be disassociated from grazing especially in arid and semi-arid environments like KNP. Grazers play a key role in influencing fire behaviour. The study conducted by Smit and Archibald (2019) in the Kruger National Park revealed that the effects of grazers on years with higher grazer, biomass burnt less than areas during the years with lower grazer. By contrast, fires were more predominant during the culling period as compared to post culling period. It is therefore recommended that the KNP should develop a fire management plan which incorporate a herbivory management plan for better fire management. Fire management plan should be developed due to the high frequencies of droughts with a likelihood of causing more fires.

The study also recommends that a threat assessment study should form part of the park management plan taking cognisance of climate change, the study should outline how future fires might affect planning in the park. This will also allow park management to reserve more funds for fire management.

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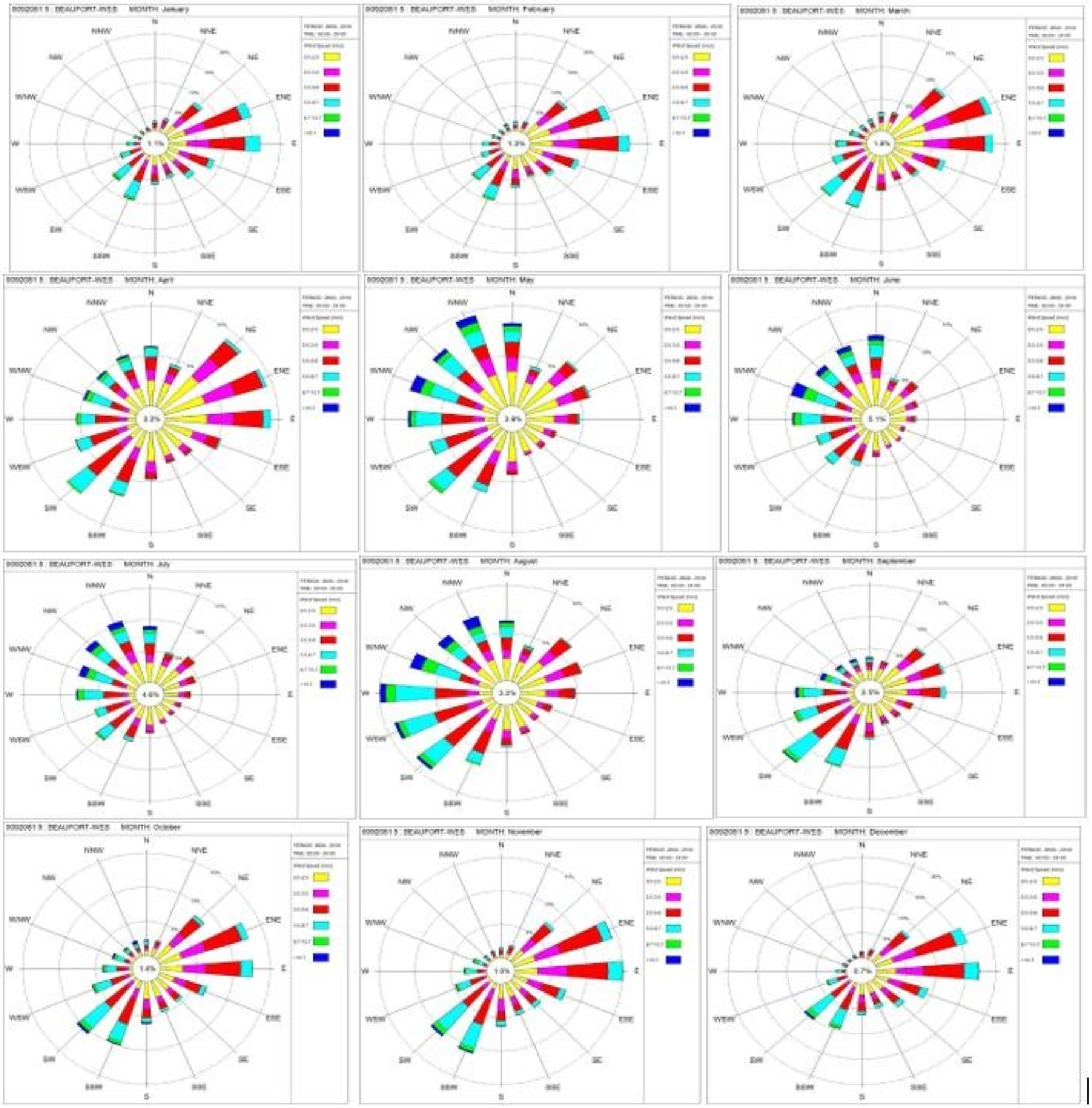
APPENDICES

Appendix A: Summary of Monthly wind direction (2000-2018)



Appendix B: Number of annual fires and coordinates in the Karoo National Park (2002-2016)

name	x	y
2002-1	22.4102	-32.2308
2003-1	22.5103	-32.296
2003-2	22.5756	-32.1669
2003-3	22.57603	-32.1719
2003-4	22.5764	-32.1718
2003-5	22.3416	-32.1115
2004-1	22.52015	-32.2352
2004-2	22.5154	-32.2625
2004-3	22.5062	-32.2653
2004-4	22.5175	-32.2623
2004-5	22.468	-32.2172
2004-6	22.4959	-32.2355
2005-1	22.35633	-32.1023
2005-2	22.1668	-32.2908
2006-1	22.47297	-32.1704
2007-1	22.3579	-32.1346
2007-2	22.3561	-32.1282
2009-1	22.549	-32.193
2009-2	22.3716	-32.1029
2010-1	22.4916	-32.1636
2013-1	22.50483	-32.1999
2013-2	22.5069	-32.2092
2013-3	22.527	-32.1982
2013-4	22.5053	-32.2279
2013-5	22.5021	-32.2369
2013-6	22.48725	-32.239
2013-7	22.48472	-32.2439
2013-8	22.46337	-32.2279
2013-9	22.4764	-32.2279
2013-10	22.47244	-32.2092
2013-11	22.46048	-32.2388
2013-12	22.48355	-32.2452
2013-13	22.49473	-32.2246
2013-14	22.48788	-32.2441
2013-15	22.51025	-32.2817
2013-16	22.50819	-32.2669
2014-1	22.5818	-32.3888
2014-2	22.4982	-32.1625
2015-1	22.4175	-32.2197
2016-1	22.36105	-32.1574
2016-2	22.38305	-32.1823
2016-3	22.1533	-32.1134