Cape Peninsula
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AN ANALYSIS OF SELECTED INFLUENCING FACTORS OF WILDFIRE REGIMES OVER THE LAST THREE DECADES IN THE BOLAND MOUNTAIN COMPLEX, SOUTH AFRICA

by

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DECLARATION

I, Andrie-Maryna van Heerden, declare that the contents of this dissertation represent my own unaided work, and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed 　　　　　　　　　　　　 **Date** 11 September 2024

ABSTRACT

This study examined the factors influencing wildfire regimes in the Boland Mountain Complex (BMC), Western Cape Province, South Africa, for over thirty years. The fynbos region, covering the BMC, is one of the world's six floral kingdoms with high levels of endemism and is both fire-adapted and fire-dependent. Inappropriate fire regimes are a considerable concern for biodiversity loss, and as such, it is crucial to understand the influencing factors to facilitate decision-making. This study aims to identify and analyse the key anthropogenic, environmental and climatic factors contributing to wildfire frequency, size, seasonality and fire return intervals over time. A mixed-methods approach was employed to evaluate various relationships by utilising a comprehensive dataset comprising fire records, including global position information, satellite imagery, land use data, and meteorological records. The results showed an increase in fire frequency and cumulative yearly hectares burnt. The cumulative hectares have a very highly significant statistical link to the number of Very Large and Large category fires. Therefore, in order to reduce fire size, the importance of the speed and scale of the suppression response must be highlighted. Increased fuel load caused by the spread of invasive alien plants (IAPs) and changes in land use as well as climatic changes mainly an increase in temperate and drought conditions facilitate more intense fire behaviour. Additionally, urban expansion have intensified the risk of fire ignitions but could also lead to an increase in reporting biasness. From a space-time composite perspective, the fire return period had an average fire return interval of 8.63 years, which is currently not conducive to maximising biodiversity. The proximity of ignitions was examined near the closest towns and transport routes, with Grabouw and track footpaths having the highest frequency. The hectares burnt for each Very Large category fire has a very highly significant statistical link to biomass and total hectares burnt in the BMC. None of the weather-related variables showed any notable links between the dependent variable of total hectares burnt per Very Large fire category. This could be due to distance from weather stations and variations in microclimates within mountainous areas. There is, however, a notable link between antecedent annual rainfall and the fire frequency and cumulative hectares burnt in the BMC for the same year. This research shows an overall trend of increased fires, highlighting key risks and specific geographical areas as hotspots. It is recommended that results from long-term monitoring, research, and input from all stakeholders must be regularly assessed and reported back into legislation, prediction, prevention, preparedness, suppression, rehabilitation recommendations, and planning. Integrated wildfire management should also be viewed holistically, considering all stakeholders' needs and capacity, coordinating all stakeholders' management efforts, and continually practising adaptive management.

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DEDICATION

I would like to dedicate this dissertation to my two daughters, Mila (2021) and Ella (2023) van Heerden, both of whom were born during the time I've been writing it. The stretched-out completion date of this dissertation can definitely be attributed to my daughters, but they are also my driving force for self-improvement. I love both of you girls so much. Thank you for inspiring me daily.

TABLE OF CONTENTS

Declaration	**ii**
Abstract	**iii**
Acknowledgements	**iv**
Dedication	**v**
List of Figures	**ix**
List of Tables	**x**
Abbreviations and acronyms	**xi**
Glossary	**xiii**

TABLE OF CONTENTS VI

LIST OF FIGURES IX

LIST OF TABLES X

ABBREVIATIONS AND ACRONYMS XI

GLOSSARY XIII

CHAPTER 1: INTRODUCTION 1

1.1. Background 1
1.2. Statement of research problem 1
1.3. Aims and Objectives of the research 2
1.4. Research questions 3
1.5. Significance of the research 3
1.6. Location of the study area 4
1.7. Topography, geology and soils 5
1.8. Climate 6
1.9. Vegetation and fauna 7
1.10. Delineation of the research 7

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW 8

2.1. Introduction 8
2.2. Wildfires 8
2.3. Climate and weather 10

2.4. Vegetation, fynbos and IAPs as fuel 12
2.5. Fire in fynbos 14
2.6. Wildfire regime components 16
2.6.1. Wildfire size 16
2.6.2. Wildfire frequency 16
2.6.3. Wildfire return interval 17
2.6.4. Wildfire season 17
2.6.5. Wildfire intensity 18
2.7. Fire spread variables 18
2.7.1. Fire ignitions 18
2.7.2. Fire fuel 19
2.7.3. Fire weather 20
2.8. Wildfire Management Strategies 20
2.8.1. Legislation 21
2.8.2. Prediction 22
2.8.3. Prevention 23
2.8.4. Preparedness 24
2.8.5. Suppression 25
2.8.6. Rehabilitation 26
2.9. Previous studies of fire regimes in Mediterranean climatic regions 27
2.9.1. International Fire Regimes in Mediterranean Climatic Regions 27
2.9.2. Fynbos Biome fire regimes, South Africa 29

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY 30
3.1. Introduction 30
3.2. Wildfire regime Aspects 31
3.2.1. Fire size categories 31
3.2.2. Fire frequency 31
3.2.3. Fire return intervals 32
3.2.4. Fire seasonality 34
3.3. Selected influencing factors of wildfire regimes 34
3.3.1. Relative fire ignition positions 35
3.3.2. Fire fuel load 35
3.3.3. Fire weather conditions 37
3.4. Analysis and modelling of selected influencing factors of wildfire regimes 40

CHAPTER 4: RESULTS AND DISSCUSSION 42
4.1. Introduction 42
4.2. Wildfire regime components 42
4.3. Selected influencing factors of wildfire regimes 48

4.3.1. Relative fire ignition positions ... 49
4.3.2. Fire fuel load ... 52
4.3.3. Fire weather conditions ... 57

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS ... 65
5.1. Conclusion 65
5.2. Recommendations 69
5.2.1. Legislation ... 69
5.2.2. Prediction ... 69
5.2.3. Prevention ... 70
5.2.4. Preparedness ... 70
5.2.5. Suppression ... 71
5.2.6. Rehabilitation ... 71
5.2.7. Adaptive management ... 71

REFERENCES ... 73

APPENDICES ... 80
APPENDIX A: Statistical analysis using the annual total hectares burnt in the BMC between 1990 and 2019 as the dependant variable 80
APPENDIX B: Statistical analysis using the total hectares burnt per Very Large category fire in the BMC between 1990 and 2019 as the dependant variable 82
APPENDIX C: CPUT Ethical Clearance 84
APPENDIX D: CapeNature data use permission 86

LIST OF FIGURES

Figure 1.1: Location and extent of the BMC in the Western Cape Province of South Africa. 5
Figure 1.2: The typical topography of the BMC of mountainous terrain with high peaks surrounding open kloofs. 6
Figure 2.1: Wildfire triangle showing what is needed for wildfire to occur (Harrison, 2015). 9
Figure 2.2: Global fire map, showing each ecoregion as related to a fire activity index which has no associated units (Pausas & Ribeiro, 2013). 10
Figure 2.3: Snow found on the mountain peaks in Hottentots Holland Nature Reserve, within the BMC. 11
Figure 2.4: Wildfire burning in fynbos within the BMC. 13
Figure 2.5: Wildfire burning in SAFCOL marginal plantation bordering the BMC within the BMC ZOI. 14
Figure 2.6: Seeds being released from a serotinous Proteaceae species post fire. 15
Figure 2.7: Overall assessment of wildfire risk levels in South Africa (Forsyth et al., 2010). 22
Figure 2.8: A firebreak associated with a road on the boundary of the BMC commonly used to gain safer access, combat the fire from or be used as a line to back burn from. 24
Figure 2.9: Firefighters in full personal protective safety and equipped with rake hoes, a spade and a slasher. 25
Figure 2.11: Firefighter's supressing a wildfire within the BMC. 26
Figure 2.12: Five Mediterranean climatic regions found on the western sides of continents between 30-40° latitude (Keeley, 2012). 28
Figure 3.1: All merged fire polygons self-intersected to form a polygon mesh in the BMC and BMC Zone of influence (ZOI). 33
Figure 3.2: An example of pixel colour selection. In image editing software, satellite imagery for 2018 was cut to the fire extent, the year prior to a Very Large category fire (HOTT/02/2019/02) in Hottentots Holland Nature Reserve starting in 2019. A specific green pixel colour range was selected in red, indicating IAPs (no scale in image editing software; pixel measurements used IAPs pixels percentage of total pixels, which was then applied to known hectares of the fire). 37
Figure 3.3: Charts and factors to calculate the Lowveld FDI (Willis et al., 2001). 38
Figure 4.1: Fire frequency total per size category in the BMC between 1990 and 2019. 44
Figure 4.2: Total fire frequencies and hectares burnt in the BMC between 1990 and 2019 with trend lines. 44
Figure 4.3: Number of fires per size categories in each season from 1990-2005 and 2006-2019 in the BMC. 47
Figure 4.4: Distance and frequency of fire ignitions to the central hub of the nearest town or village between 1990 and 2019 in the BMC. 50
Figure 4.5: Distance from fire ignitions to the central hub of the nearest town or village between 1990 and 2019 in the BMC. 51
Figure 4.6: Ignition frequency and average distance to the closest transport route from 1990 to 2019 in the BMC. 52
Figure 4.7: Hectares of indigenous vegetation in age class and IAPs for Very Large category fires in the BMC from 1990 to 2019. 53

Figure 4.8: Scatter plots with trend lines showing the relationships between a) biomass (kg) per hectare for the Very Large category fires and b) fire frequency and total hectares burnt in the BMC from 1990 to 2019. 56
Figure 4.9: Scatter plots with trend lines showing the relationships between a) fire frequencies and total hectares burnt in the BMC from 1990 to 2019 and b) total precipitation and average temperature. 62
Figure 4.10: Annual average Standardised Precipitation Index (SPI) time series at different time scales (Botai et al. 2017). 63
Figure 4.11: Average rainfall from Very Large fires, with sufficient back data, for the year of occurrence, 12 and 24 months prior to these fires and the SPI over 12 months in the BMC from 1990 to 2019. 64

LIST OF TABLES

Table 2.1: Colour-coded FDI table providing an overview of the prevention and preparedness measures needed (Forsyth et al., 2010). 23
Table 4.1: Top five best-fit models to the dependant variable of annual total hectares burnt in the BMC. 43
Table 4.2: Fire Return Period (RP) in the BMC from 1990 to 2019. 45
Table 4.3: The fire return interval from a space-time composite perspective, including both indigenous vegetation and IAPs for fires in the BMC from 1990 to 2019. 46
Table 4.4: Top five best-fit models to the dependent variable of the total hectares burnt per Very Large fire category in the BMC between 1990 and 2019. 49
Table 4.5: The division of hectares and percentages of indigenous vegetation in various age classes and IAPs for Very Large category fires in the BMC from 1990 to 2019 54
Table 4.6: Closest weather station for each Very Large category fire in the BMC from 1990 to 2019 and the FDI (colour coded as per fire danger categories, blue 0–19 low, green 20–44 moderate, yellow 45– 59 dangerous, orange 60–74 very dangerous or red ≥ 80 extremely dangerous) individual weather variables, fire frequency, hectares burnt and seasonality. 59
Table 4.7: Annually the number of fires and hectares (Ha) burnt within the BMC and the antecedent annual rainfall (mm) and average temperature (°C) and the Standardised Precipitation Index (SPI) over 12 months for weather stations with sufficient back data in the BMC from 1990 to 2019. The drier years are highlighted in red as those with a negative SPI. 61

ABBREVIATIONS AND ACRONYMS

AIC	Akaike Information Criterion
AICc	Akaike Information Criterion corrected
AWS	Automatic Weather Station
BIC	Bayesian Information Criterion
BMC	Boland Mountain Complex
CFO	Chief Fire Officer
CFR	Cape Floristic Region
CRS	Coordinate Reference System
CSIR	Council for Scientific and Industry Research
FDI	Fire Danger Index
FPA	Fire Protection Associations
GIS	Geographic Information System
GPS	Global Positioning System
IAPs	Invasive Alien Plants
ICS	Incident Command Structure
IFM	Integrated Fire Management
IUCN	International Union for Conservation of Nature
NVFFA	National Veld and Forest Fire Act
NRM	Natural Resource Management
PAMP	Protected Areas Management Plan
QGIS	Quantum geographic information system
RS	Remote Sensing
SAFCOL	South African Forestry Company Limited
SAWS	South African Weather Services
SOP	Standard Operating Procedure
SPI	Standardized Precipitation Index
UNESCO	United Nations Educational, Scientific and Cultural Organisation

USGS	United States Geological Survey
WGS	World Geodetic System
ZOI	Zone Of Influence

GLOSSARY

Ecoregion	A terrestrial spatial unit comprising of similar biotic and physical features and processes at a regional scale (Rutherford et al., 2006).
Extended attack	The wildfire suppression phase that is moved into if a wildfire was not successfully contained within the initial attack period (Fynbos Fire Project, 2016).
Fire frequency	The number of times that fires occur within the same area within a time period (Brooks et al., 2004).
Fire return intervals	The average time between fires in the same area (Brooks et al., 2004).
Fire weather	Weather conditions including temperature, relative humidity, wind speed and precipitation that are conducive to the start and spread of wildfires (Strydom, 2014).
IAP species	Invasive alien plant species are introduced and/or spread outside of their natural distribution and regularly produce a large number of offspring with the potential to spread over a large area (Forsyth, 2012).
Initial attack	The first and most critical phase in fire suppression (Fynbos Fire Project, 2016).
Mop-up	Ensuring all wildfire embers are extinguished to prevent them crossing contained fire lines by means of surface creeping, spotting or underground creeping (Fynbos Fire Project, 2016).
Shape-files	A geospacial data format used in global information system software (Forsyth, 2012).
Vector	It is a data structure used to store spatial data (Strydom, 2014).
Wildfire regimes	The fire occurrence pattern over time in a particular area is termed a fire regime, defined as the typical frequency, seasonality, intensity, and size of fires (Kraaij & Van Wilgen, 2014).

CHAPTER 1
INTRODUCTION

1.1. Background

The rate of large, destructive wildfires is increasing, making it a growing issue of concern in many areas globally (Kraaij et al., 2018). Fire is considered a significant ecological factor, and due to the prevalent occurrence of biomass burning in Africa, the land has been historically referred to as the "Fire Continent" (Trollope & Trollope, 1997). The fynbos region in South Africa's Western and Eastern Cape provinces is one of the world's six floral kingdoms with high levels of endemism. Fynbos is both fire-adapted and fire-dependent, making it a critical component of social and ecological importance (Van Wilgen, 2009). Several factors influence the scale and impact of wildfires, including extreme weather conditions, increased fuel loads and more frequent ignitions from anthropogenic sources. These influencing factors have been attributed to global climate change, an increase in Invasive Alien Plants (IAPs), past fire suppression actions and the expansion of the urban-wildland interface (Kraaij et al., 2018). Climate change is predicted to exasperate wildfire conditions. However, human influence could be equally significant (Syphard et al. 2017). Within the Boland Mountain Complex (BMC) of the Western Cape, South Africa, both IAPs and anthropogenic ignitions were isolated, negatively impacting the fire regime and biodiversity (CapeNature, 2019). Thus, this research aims to provide recent, relevant and site-specific insight into which selected influencing factors significantly influenced the critical aspects of wildfire regimes from 1990 to 2019 to improve future IAP and fire management and the ecological state of the BMC.

1.2. Statement of research problem

The BMC falls within the CFR, which is one of the world's six floral kingdoms, and in terms of botanical diversity, is one of the most prolific regions on the planet (CapeNature, 2019; Oliver et al., 1983). Fynbos are fire-prone and well-adapted to fires, with various regeneration strategies and fire-survival mechanisms (Van Wilgen, 2013; Kraaij & Van Wilgen, 2014). Inappropriate fire regimes, however, cause biodiversity loss through seed and fauna destruction, change vegetation structure, may significantly reduce above-ground nutrients (such as Nitrogen and Sulphur) through volatilisation and, to a lesser degree, cause soil erosion and leaching from increased stream flow (Kraaij & Van Wilgen, 2014). Unplanned wildfires can also amount to additional costs for suppression actions, additional follow-up for IAP clearing, and the potential for loss of life and property (Van Wilgen & Forsyth, 2008).

The CapeNature is responsible for managing the BMC, and according to the Protected Areas Management Plan (PAMP) for the 2019 – 2029 period, the current fire regimes were highlighted as one of the main threats to their focal biodiversity values (CapeNature, 2019). While fire is required in fynbos, the shorting fire regime and its effect on slow-maturing, serotinous Proteaceae species, as a suitable indicator species for biodiversity, is a current primary concern in the BMC (Van Wilgen & Forsyth 2008). The inappropriate fire regimes are mainly attributed to anthropogenic fires and IAPs, causing a change in vegetation structure and fynbos composition, resulting in both flora and fauna species loss. Important goals set out in the 2019 – 2029 PAMP is to achieve an ecologically healthy fire regime by 2029 in Mountain, lowland and Swartland Alluvium fynbos defined as having less than 20 % of area burnt twice or more in the last 25 years, not more than two of the age classes are below 5 % or above 20 % and more than 80 % of the area burnt during December till April. This goal of rectifying the inappropriate fire regime is hoped to be achieved by improving the efficiency of their Fire Programme and Alien Vegetation Management (CapeNature, 2019).

A systematic approach to understanding the key influencing factors of wildfire regimes within the BMC has yet to be fully unpacked and analysed. This study, therefore, aims to give new insights into the influential factors of wildfire regimes in the BMC over the last three decades. Such insights could be critical for basing management decisions on improving the efficiency of Cape Nature's Fire Programme and the state of biodiversity.

1.3. Aims and Objectives of the research

The study aims to analyse selected factors influencing wildfire regimes in the BMC over the last three decades (1990 – 2019).

The project will look at the following objectives in the BMC over the last three decades:

- To analyse critical aspects of wildfire regimes, including size category, fire frequency, the fire return period and fire season.
- To investigate the relationship between the proximity of wildfire ignition points to human populations and access networks and aspects of wildfire regimes, including fire frequency and seasonality.
- To investigate the relationship between estimated above-ground biomass, and critical aspects of wildfire regimes (fire size, fire frequency, and seasonality).

- To investigate the relationship between weather conditions and critical aspects of wildfire regimes (fire size categories, fire frequency and seasonality).

This research aims to use a quantitative analysis of secondary data sets to gain insight into the major influencing factors (including relative fire ignition position, fire fuel, and fire weather conditions) of key wildfire regime aspects (including fire size, frequency, return interval, and season) in the BMC. The data sets are for the BMC over the last three decades, from 1990 to 2019. Data before 1990 has been excluded as it is considered less reliable and fragmented.

Secondary data sets were sourced from the CapeNature, the United States Geological Survey (USGS), and the South African Weather Services (SAWS). Shapefiles for wildfire perimeters, ignition points, the BMC study area, transport routes, towns and villages, and the CapeNature fire database were sourced from CapeNature. Satellite imagery was sourced from the USGS, and weather information was sourced from the SAWS from weather stations nearest to the Very Large wildfire ignition points.

1.4. Research questions

- How do the wildfire size category, frequency, return period and season compare from 1990 to 2019 in the BMC?

- What is the frequency of wildfire ignition points near human populations and access networks from 1990 to 2019 in the BMC?

- How does estimated above-ground biomass relate to the size, frequency and seasonality of Very Large category wildfires from 1990 to 2019 in the BMC?

- How do fire weather conditions relate to size, frequency and seasonality of Very Large category wildfires from 1990 to 2019 in the BMC?

1.5. Significance of the research

The current fire regimes were highlighted as one of the main threats to their focal biodiversity values (CapeNature, 2019). While fire is required in fynbos, the shorting fire regime and its effect on slow-maturing, serotinous Proteaceae species, as a suitable indicator species for biodiversity, is a current primary concern in the BMC. Several Protea species require fire return intervals of more than 12 years so as not to face population declines or local extinction (Van Wilgen 1982, Van Wilgen & Forsyth 2008). The inappropriate fire regimes are mainly attributed to anthropogenic fires and IAPs, causing a change in vegetation structure and fynbos composition, resulting in both flora and fauna species loss. Important goals set out in the 2019 – 2029 PAMP is to achieve an ecologically healthy fire regime by 2029 in Mountain, lowland and Swartland Alluvium fynbos defined as having less than 20 % of area burnt twice or more in the last 25 years, not more than two of the age classes are below 5 % or above 20 % and more than 80 % of the area burnt during December till April. Strategy three of rectifying the inappropriate fire regime of the BMC PAMP is to "Enhance the implementation efficiency of the Alien Vegetation Management and Fire Programmes in the BMC to abate the negative effect that IAPs and inappropriate fire regimes have on biodiversity and water availability" (CapeNature, 2019). This research aims to provide recent, relevant and site-specific insight into which selected influencing factors significantly influenced the critical aspects of wildfire regimes in the BMC from 1990 to 2019. This understanding can be used to base critical management decisions and enhance the implementation efficiency highlighted in Strategy 3 of the BMC PAMP.

1.6. Location of the study area

The study area consisted of the Boland Mountain Complex (BMC) and a 10 km buffering zone of influence (ZOI) totalling an area of 628 574.04 ha. The ZOI incorporates the protected areas into the landscape and allows for collaborative land and water use decision-making with the relevant stakeholders. As per the Environmental Impact Assessment Regulations Listing Notice 3 of 2014, the ZOI extends 10 km from the BMC-proclaimed cadastre as a buffer. Approximately 9 % of the ZOI is in the very high category for fire frequency due to anthropogenic causes, and as such, is included in the study area (CapeNature, 2019). The BMC is situated in the Western Cape Province, South Africa, and spans four district municipalities, as shown in Figure 1.1.

The northern section of the BMC extends to the provincial route R46 near Gouda, the R44 near Betty's Bay to the south, Stellenbosch to the west and Botriver to the east. In 2004, the World Heritage Convention, United Nations Educational, Scientific and Cultural Organisation (UNESCO) declared the BMC a World Heritage Site. In 2015, the BMC was included as part of eight protected areas within the Cape Floristic Region (CFR) as a Protected Areas World Heritage Site (CapeNature, 2019; DEAT, 2015; DEAT, 2003). The BMC comprises the following nature reserves, Kogelberg, Hottentots Holland, Jonkershoek, Limietberg and

Waterval and has an altitude ranging between 368m at its lowest peak and 1994.7m at its highest peak (Dutoitspiek). All these reserves were established to support forestry operations and to provide water to the City of Cape Town and its surroundings (CapeNature, 2019).

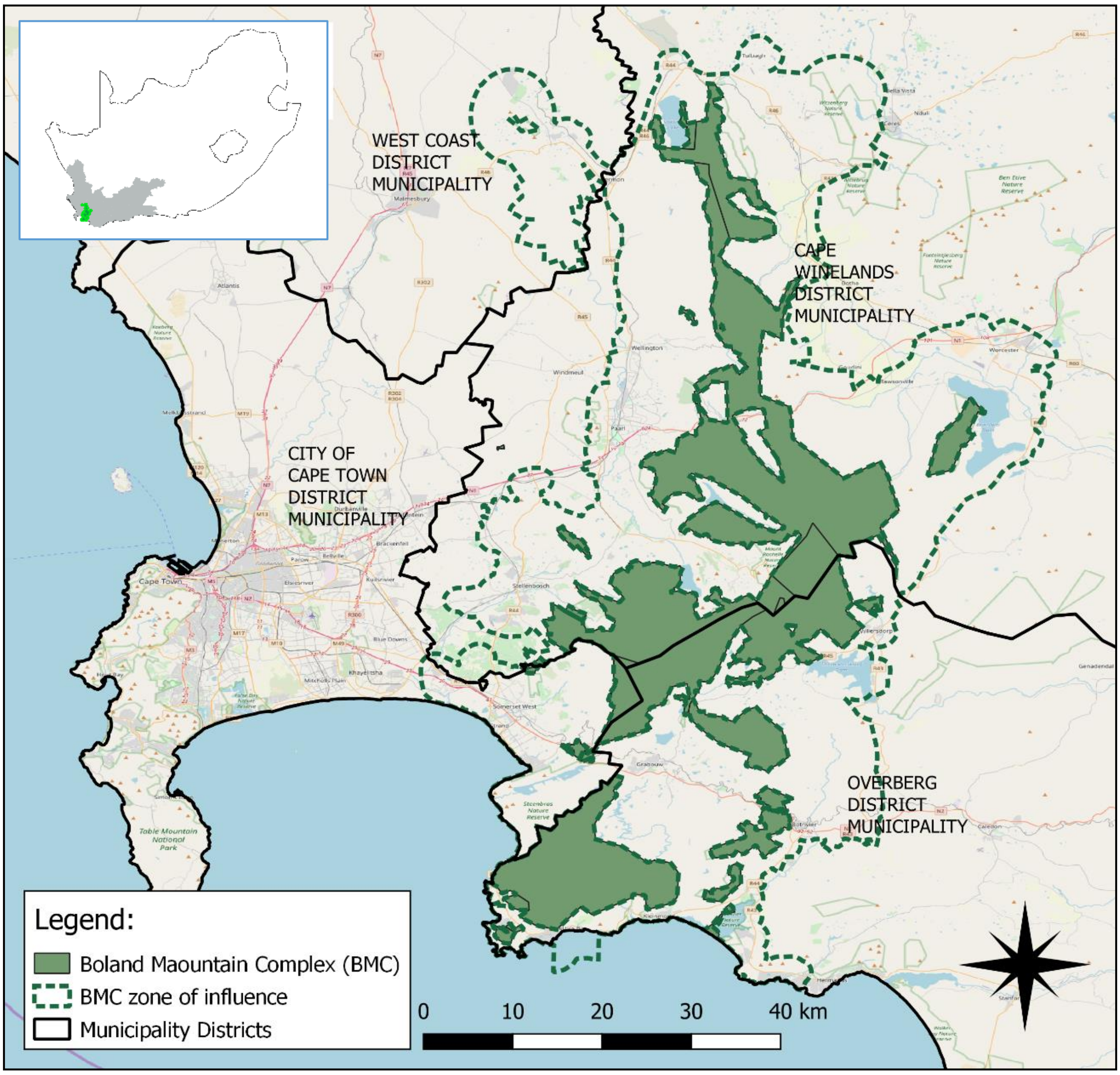


Figure 1.1: Location and extent of the BMC in the Western Cape Province of South Africa.

1.7. Topography, geology and soils

Topography directly influences fire spread by transporting radiant energy upslope and indirectly by creating microclimates. Microclimates influence the moisture content of fuels, the air temperature and the fuel availability via plant species distribution (Carmo et al., 2011). Sieben et al. (2004) discuss the critical role of the Fynbos Biome's mountains in influencing precipitation and evaporation. Rugged mountainous terrain with high peaks surrounding open kloofs, waterfalls or rivers best describes the topography of the BMC (Figure. 1.2). The BMC comprises various sedimentary layers. However, the most predominant geological formations are sandstones and shales from the Table Mountain Group, which are nutrient-poor, resulting in very acidic, leached, sandy soil (CapeNature, 2019; Sieben et al., 2004).

Figure 1.2: The typical topography of the BMC of mountainous terrain with high peaks surrounding open kloofs.

1.8. Climate

The climate of the CFR in the southwestern Cape is classified as Mediterranean, with hot, dry summers, with mean temperatures ranging from the high teens to lower thirties, from high-pressure systems and mild, wet winters from low-pressure systems (CapeNature, 2019; Sieben et al., 2004). Summer also brings the dominant dry, southeast winds, which can dry out vegetation and reach gale force speeds, dramatically increasing fire risk and is when most fires occur in the BMC (CapeNature, 2019). Average rainfall in the BMC ranges from 500 mm in the northern sections to 1500 mm towards the south per annum, though considerably higher rainfall is possible. The highest rainfall in South Africa was from Jonkershoek, with 3 620 mm recorded (CapeNature, 2019).

1.9. Vegetation and fauna

The BMC may be viewed as the core area of the CFR as it displays the highest levels of plant diversity and endemism within the fynbos biome (Oliver et al., 1983). There are 21 vegetation types ranging from critically endangered to least threatened, an estimated number of plant species of over 1 850 and approximately 150 locally endemic taxa occur within the BMC (CapeNature, 2019). The fynbos is fire-prone and well-adapted to fires with various regeneration strategies and fire-survival mechanisms under conducive fire regimes (Van Wilgen, 2013; Kraaij & Van Wilgen, 2014). The CapeNature (2019) reported that 81.6 % of the BMC has been burnt more than twice in the last 25 years, posing a biodiversity loss issue as this should be less than 20 %. The BMC hosts a variety of threatened amphibians, reptiles, fish, mammals, avifauna and invertebrates, and some of these groups display high levels of endemicity in this region. Some of these species can also suffer from larger and too frequent fires due to inability to escape, insufficient food availability and habitat loss (CapeNature, 2019).

1.10. Delineation of the research

The study area includes the BMC, which is approximately 125 662.05 ha and the zone of influence, which extends an additional 354 646.43 ha. The research looks at all wildfires recorded within the BMC and the zone of influence if more than 50 % of the burnt area falls within the zone of influence. The temporal delineation of this research is that from 1990 to 2019, 1 049 wildfires were recorded, which fall within the study area, 34 of which fall into the Very Large wildfire category.

Wildfire size category, frequency, mean fire return periods and seasonality as the critical aspects of wildfire regimes will be analysed for all fires within the study area and period. The selected wildfire influencing factors include the fire ignition positions from transport routes and towns and villages, estimated biomass and fire weather, which includes the Fire Danger Index (FDI), individual weather variables, antecedent rainfall and average temperature and the Standardised Precipitation Index (SPI). Estimated biomass and fire weather will be analysed only for fires within the Very Large category as an extremity sample of wildfires within the study area and period.

CHAPTER 2

Background and literature review

2.1. Introduction

Myers et al. (2000) described South Africa's Cape Floristic Province as one of the 25 biodiversity hotspots of global significance, which would need to be prioritised for conservation due to its abundance of endemic species and vulnerable habitat. The Cape Floristic Region (CFR) is documented as the smallest of the world's six floral kingdoms (Cowling et al., 2003). There are about 9 000 plant species condensed into an area of approximately 90 000 km² of which 1 435 plant species are listed on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, and 69 % of the total species are localised endemic in the CFR (Brownlie et al., 2005; Thuiller et al., 2007).

In 2004, the Boland Mountain Complex (BMC) was inscribed as a World Heritage Site World Heritage Convention by United Nations Educational, Scientific and Cultural Organisation (UNESCO), and in 2015, it was extended as part of eight protected areas within the CFR as a Protected Areas World Heritage Site (CapeNature, 2019; DEAT, 2015; DEAT, 2003). The BMC includes an additional 10 km buffer zone to increase connectivity and mitigate against climate change and other anthropogenic influences totalling an area of 628 574.04 ha. The BMC comprises Provincial Nature Reserves, Forest Act Nature Reserves, Ex-State Forests (previously declared State Forest) and unprotected state and privately owned land (CapeNature, 2019). The BMC may be viewed as the core area of the CFR as it displays the highest levels of plant diversity and endemism within the fynbos biome (Oliver et al., 1983). The current state of too frequent fires within the BMC fire regime has been highlighted in the Protected Areas Management Plan (PAMP) for the BMC 2019 – 2029 as one of the main threats to the biodiversity of the BMC (CapeNature, 2019).

2.2. Wildfires

The three essential components of wildfires are ignition sources, fuels, and favourable weather conditions, as depicted in Figure 2.1. The absence of any of these components geographically at any given time can limit the occurrence of wildfires (Harrison, 2015; Kraaij & Wilgen, 2014; Archibald et al., 2009). Climate and fuel characteristics can influence fire regimes, and either of these can be considered the most vital factors influencing fire regimes based on a specific region. It is also debated whether natural or anthropogenic factors influence fire regimes more. Anthropogenic influences account for many fire ignitions used primarily for agricultural purposes, clearing land or fuel reduction; altering fuel in the form of forestation, deforestation or changing the fuel composition such as invasive alien plants (IAPs) introduction and fire suppression (Silva et al., 2010).

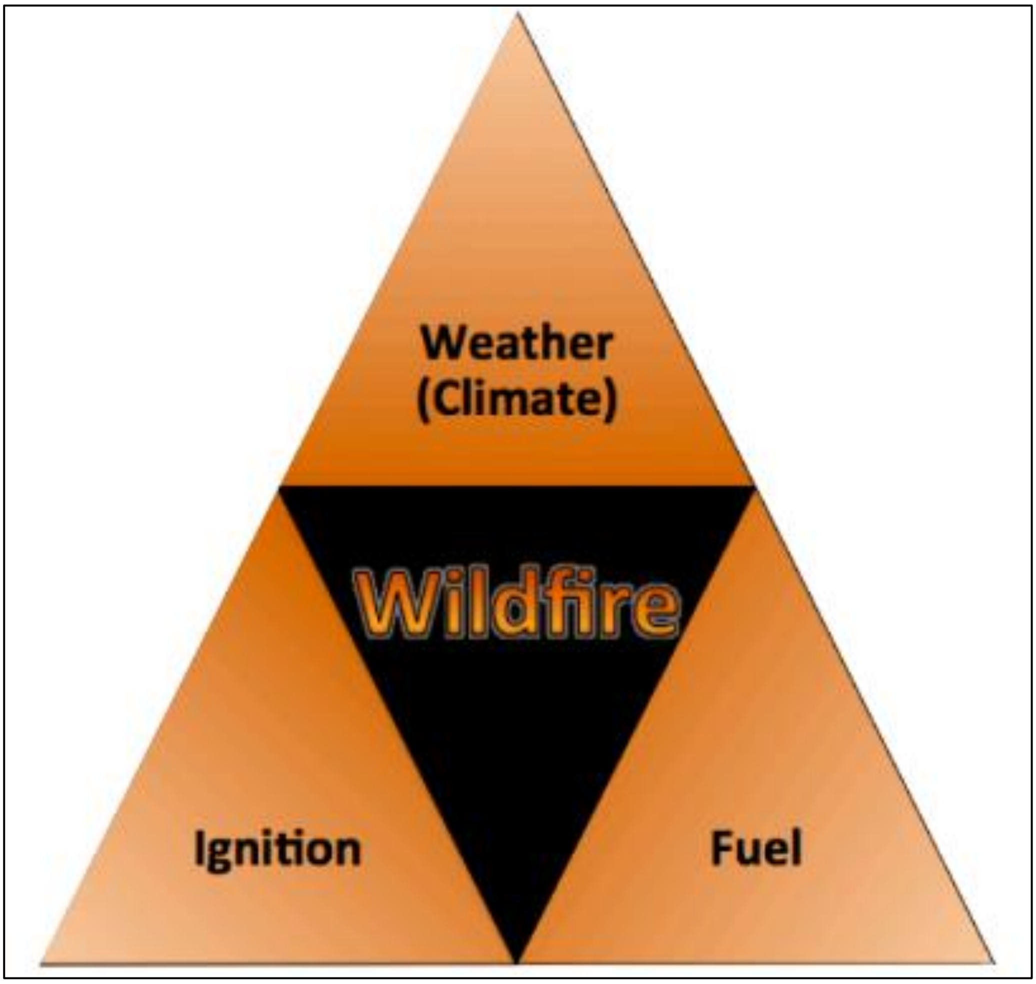


Figure 2.1: Wildfire triangle showing what is needed for wildfire to occur (Harrison, 2015).

Fire occurs in all biomes, and most ecoregions are fire-driven, but fire can also be absent in others. Figure 2.2 shows the relationship of ecoregions to fire activity on a global scale. Each bioregion has a natural fire regime characterised by frequency, the fire return interval, seasonality, and intensity (Harrison, 2015; Kraaij & Van Wilgen, 2014; Pausas & Ribeiro, 2013).

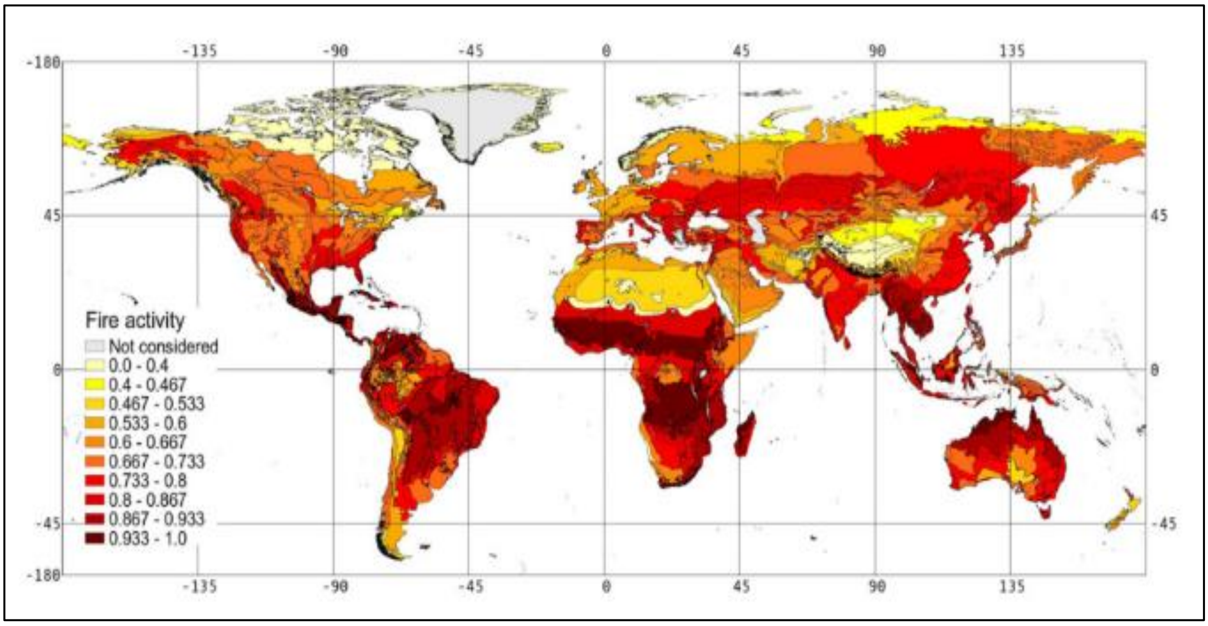


Figure 2.2: Global fire map, showing each ecoregion as related to a fire activity index which has no associated units (Pausas & Ribeiro, 2013).

2.3. Climate and weather

The climate of the CFR is classed as Mediterranean with its characteristic hot, dry summers with mean temperatures ranging from the high teens to lower thirties from high-pressure systems and mild, wet winters from low-pressure systems (CapeNature, 2019; Sieben et al., 2004). Sieben et al. (2004) stated that the mountains in the CFR significantly influence the weather, as increased altitude is strongly correlated to increased precipitation. Mist associated with the summer trade winds, also known as 'southeasters', in mountainous areas account for precipitation not recorded in rain gauges. While rain makes up the bulk of the precipitation, to a lesser degree, mist and snow (Figure 2.3), which regularly occur on mountain peaks during the winter months, also contribute.

Figure 2.3: Snow found on the mountain peaks in Hottentots Holland Nature Reserve, within the BMC.

In many ecosystems, infrequent extreme fire events account for the bulk of burned area, which only occurs when particular conditions prevail. These conditions are governed by fire weather and mediated by fuel availability and connectivity (Bedia et al., 2015; Strydom, 2014). Fire weather variables, including air temperature, humidity and wind speed, directly correlate to the rate and capability of fire spread. If these fire weather variables are incorporated to form a Fire Danger Index (FDI), it is considered more representative of the climatic conditions conducive to fires. An FDI value can respond simultaneously to more extensive trends in the different local meteorological variables and indirectly measure antecedent conditions (Bedia et al., 2015).

Harrison (2015) examined long-term records from the Global Palaeofire Working Group, which show a strong correspondence between temperature changes and fire regimes on a global and regional scale. Temperature's primary influence is vegetation productivity and the drying rate, which thus affect fuel availability and flammability.

In a study conducted by Van Wilgen et al. (2010) between 1970 and 2007 in the fynbos biome, fires were found to occur under a wide range of weather conditions. It was found, however, that more severe fires occurred in the inland zones, with three times as many days being classified as either high or very high FDI than in the coastal zones. It was also found that the Very Large category fires of over 5 000 ha was always associated with a moderate to high FDI, and fires over 10 000 ha were associated with a high to very high FDI from the McArthur Forest FDI.

The average rainfall in the BMC ranges from 500 mm in the northern sections to 1 500 mm towards the south per annum. However, considerably higher rainfall is possible, with the highest recorded rainfall in South Africa being 3 620 mm within the Jonkershoek area (CapeNature, 2019). Summer also brings the dominant dry, southeast winds, which can dry out vegetation and reach gale force speeds, dramatically increasing fire risk and is when most fires occur in the BMC (CapeNature, 2019).

2.4. Vegetation, fynbos and IAPs as fuel

Kraaij et al. (2022) discussed the ability of vegetation to burn as fuel as its flammability, which can be evaluated in terms of ignition frequency, combustion temperature and rate, burn duration and biomass consumed. Fuel traits affecting flammability include fuel moisture content, carbon compounds such as cellulose, hemicellulose, lignin, and volatile organic compounds. Fuel traits relating to structural form also bear relevance, such as fuel size and bulk density, the quantities of various fuels, and fuel bed porosity or sparseness.

Fynbos (derived from 'fijn-bosch' in Dutch) means 'fine bush', which the Dutch connected with kindling for lighting fires. Fynbos is an evergreen, fire-prone shrubland characterised by restios, ericoid shrubs, and commonly proteoid shrubs (Rebelo et al., 2006). Fire has been integral in stimulating the evolutionary diversification of fynbos, as shown in Figure 2.4 (Kraaij & Van Wilgen, 2014). Fynbos is both adapted to survive fires but also dependent on fires to propagate, either by resprouting after fire or by germinating from seeds that survive the fire but can also include non-flammable patches of Afromontane forest that seldom burn (Keeley, 2012; Van Wilgen, 2009; Van Wilgen et al., 1990). Kraaij and Van Wilgen (2014) discuss that standing dead material from ericoid and proteoid shrubs can form a vertically continuous fuel bed conducive to crown fires in mature fynbos. Seasonal drying of herbaceous vegetation and finer restioid and ericoid fuels do not affect the seasonality of burning in fynbos as in grasslands and chaparral. Fynbos's lower amount of volatile organic compounds and higher fuel moisture make it less flammable than Californian chaparral or Australian Eucalyptus woodlands (Kraaij & Van Wilgen, 2014).

Figure 2.4: Wildfire burning in fynbos within the BMC.

Pines, Australian *Acacia* species and hakea are the most prevalent IAPs within the BMC, and their spread is influenced by fire (CapeNature, 2019). The invasion of fynbos by IAPs often significantly changes the flammability and structure of the vegetation by changing the amount and the type of fuel available (Kraaij et al., 2022; Van Wilgen, 2009). Higher fire intensities are likely due to increased biomass and volatile organic compounds in IAP-invaded areas. The higher fire intensities of IAP-invaded areas can damage the soil by developing a water-repellent layer, which can, in turn, cause severe erosion during the following rainy season (Kraaij et al., 2022). Many IAPs are fire-adapted and can outcompete the indigenous fynbos due to their superior growth rates and pre-adaptation to frequent fires (Van Wilgen, 2009).

In 2000, selected South African Forestry Company Limited (SAFCOL) owned commercial plantations were phased out as they were considered marginal and, therefore, not commercially viable. Included in the marginal plantations to be phased out was 15 000 ha within the Boland area (De Beer, 2012). Van Wilgen and Richardson (2012) described this process as either abandonment or handover to resource-poor conservation agencies, resulting in the inability to rehabilitate the forest land to its natural state. The lack of, or under resourced, management has resulted in few prospects to control the IAPs in remote and mountainous areas of forestry exit land, dramatically increasing the risk of IAP spread and wildfires. Figure 2.5 illustrates this by showing a wildfire burning in the SAFCOL marginal plantation bordering the BMC within the BMC zone of influence (ZOI).

Figure 2.5: Wildfire burning in SAFCOL marginal plantation bordering the BMC within the BMC ZOI.

2.5. Fire in fynbos

Fynbos is a Mediterranean-climate, sclerophyllous shrubland that grows on nutrient-poor soil and is the dominant vegetation type within the CFR (Keeley, 2012; Forsyth & Van Wilgen, 2008; Thuiller et al., 2007). Fire has played a crucial role in shaping the evolutionary diversification of fynbos and remains an essential driving force in maintaining the functionality and diversity of the fynbos ecosystems (Kraaij & Van Wilgen, 2014). The fynbos is fire-prone and well-adapted to fires with various regeneration strategies and fire-survival mechanisms (Kraaij & Van Wilgen, 2014; Van Wilgen, 2013). Many fynbos species can propagate using both seed and resprouting after a fire. However, several obligate resprouters and obligate reseeders depend entirely on resprouting or reseeding to propagate (Kraaij & Van Wilgen, 2014; Keeley, 2012; Lamontet al., 1991). The most vulnerable species to inappropriate fire regimes are large, serotinous shrubs, typically in the family Proteaceae, as they are predominately obligate seeders and have a relatively long juvenile period (Forsyth & Van Wilgen, 2008). Kruger (1977) describes the various seed strategies that fynbos have adapted to fires, including serotiny (delayed release of its seeds as shown in Figure 2.6), hard seed coatings, abundant seed production, seed dormancy until favourable conditions and myrmecochory (the dispersal of seeds by ants).

Figure 2.6: Seeds being released from a serotinous Proteaceae species post fire.

Serotinous Proteaeae species, which take the longest to mature, are considered suitable indicator species for total ecosystem biodiversity. The shortest fire return period to maintain ecosystem biodiversity would be either all of the slowest maturing Proteaeae species should have flowered once or half of them should have flowered three times (CapeNature, 2019). The required fire frequency within the BMC is that not more than 5-10 % should burn more than twice in 25 years (CapeNature, 2019).

Inappropriate fire regimes may also result in biodiversity loss through seed and fauna destruction, change vegetation structure, and significantly reduce certain above-ground nutrients through volatilisation and, to a lesser degree, influence soil erosion and leeching from increased stream flow (Kraaij & Van Wilgen, 2014). Evidence shows that variation in fire regimes is required to satisfy numerous fire-adaptive strategies and preserve various plant species in the landscape (Thuiller et al., 2007). Brooks et al. (2004) surmised that ecosystems are partly shaped by disturbance regimes of particular frequency, intensity, extent, type, and seasonality and that fire is a type of disturbance.

2.6. Wildfire regime components

The wildfire occurrence pattern over time in a particular area is termed a fire regime, defined as the typical frequency, fire return interval, seasonality, intensity, and size of fires (Kraaij & Van Wilgen, 2014). Spatial and temporal changes in topography, climate and fuel influence fire regimes. Topography changes are relatively static as they span over geologic time, weather conditions are ever-changing, regional climate has the potential to shift within decades, and fuel conditions can change instantaneously following a significant disturbance (Brooks et al., 2004). Wildfire regimes must remain within acceptable limits to conserve biodiversity in fire-dependent ecosystems (Forsyth & Van Wilgen, 2008).

2.6.1. Wildfire size

Wildfire size affects several aspects of vegetation, such as the relative proportion of edge effects or the ability or ease to recolonise burnt sites due to the distances that must be covered by species reliant on dispersal (Kraaij & Wilgen, 2014; Forsyth & Van Wilgen, 2008). Fynbos wildfire regimes traditionally are dominated by few, extensive fires with a large number of small fires which do not contribute much to the total area burnt (Kraaij & Wilgen, 2014). However, Forsyth and Van Wilgen (2008) recommend that not more than 10 % of the area burnt from wildfires should exceed the Very Large fire category of over 5 000 ha, and more than 75 % of the area burnt should be over 1 000 ha. Large fire sizes can create homogeneity in vegetation age, can limit seed dispersal into burnt areas and thus limit food availability for faunal elements, limiting their movments (De Klerk et al. 2009). Many small fires put a lot of pressure on suppression resources and create an increased edge effect allowing for more seed predation (Van Wilgen & Forsyth 2008). De Klerk et al. (2009) stresses the importance of having a size mosaic of both young and old vegetation.

2.6.2. Wildfire frequency

Fire frequency is the number of times that fires occur within the same area within a period (Brooks et al., 2004). Richardson and Van Wilgen (1992) mention a widely accepted opinion for determining fire frequencies in fynbos that is 50 % of the population of the slowest-maturing species, generally from the family Proteaceae, in an area has flowered for at least three successive seasons before burning should be considered. Globally and within the CFR, however, a current upward trend is noted in fire frequency, mainly attributed to an increase in the regularity of weather conditions favourable for fires (Kraaij & Van Wilgen, 2014).

2.6.3. Wildfire return interval

The fire return interval is the average time between fires in the same area (Brooks et al., 2004). Like with fire frequency estimates of the ecologically ideal fire return interval is based on the juvenile periods of the slowest-maturing obligatory reseeding species dictating the shortest viable period between fires and on the longevity of short-lived reseeding species that do not maintain long-lived seedbanks defining the longest viable period between fires (Kraaij & Van Wilgen, 2014). If fire return intervals are shorter than juvenile periods of slowest-maturing obligatory reseeding species, certain species can become eliminated from the vegetation. Species loss can also occur if fire return intervals are longer than the longevity of short-lived reseeding species that do not maintain long-lived seedbanks (Forsyth & Van Wilgen, 2008; Lamont et al., 1991). In fynbos, Proteaceae species indicate both extremes, generally rely on canopy-stored seed for regeneration, and have a comparatively long juvenile period. If Proteaceae species were to become eliminated from the vegetation, substantial structural changes would be caused, as well as a loss of biodiversity (Forsyth & Van Wilgen, 2008). Treurnicht *et al.* (2016) noted that the wildfire return interval consistently affects the fecundity of Proteaceae species. If a wildfire occurs before Proteaceae species can build a fertile canopy seed bank, local extinction is possible for the species that cannot resprout. Shorter fire return intervals are beneficial for sprouting species, leading to their populations increasing and overall biodiversity decreasing (CapeNature, 2019). A decrease in fecundity was also observed in the rare event that wildfire return intervals were too long due to age-induced decline in seed production (Treurnicht *et al.*, 2016).

2.6.4. Wildfire season

In the BMC fire regime, fynbos burns mainly in the dry summer and autumn. Late summer and early autumn fires are optimal for most flora and fauna species within fynbos, as most flowering activity and breeding habits are associated with non-fire season month strategies (CapeNature, 2019; Van Wilgen & Forsyth, 1992). In the fynbos biome, recruitment of Proteaceae species was generally highest after autumn burns, lower after summer burns, and poor to zero after winter and spring burns (Heelemann et al., 2008). This Proteaceae species recruitment performance is attributed to the seeds released from serotinous cones after cool-season burns being exposed to increased predation or heat exposure (seed loss) and for more extended periods (Heelemann *et al.*, 2008; Lamont *et al.*, 1991). After autumn burns, the exposure period is shortest (less seed loss) because germination occurs in the early winter months, after the first rain-bearing cold fronts; as such, higher recruitment is recorded after fires in this season (Heelemann *et al.*, 2008). Similarly, the breeding habits of some fynbos faunal species are also seasonally adapted to fires by breeding in non-fire season months and giving live birth or eggs hatching towards the end of fire season, allowing young to grow and become mobile before the following year's fires (CapeNature, 2019; Branch 1998; Fraser, 1990; Frandsen, 1982). Burning in different seasons could limit seedling regeneration and food availability or interfere with various breeding strategies (CapeNature, 2019; Van Wilgen & Forsyth, 1992). Forsyth and Van Wilgen (2008) recommend that for fynbos ecosystems, the majority (> 80–90 %) of fires occur in summer or autumn to avoid negative impacts.

2.6.5. Wildfire intensity

Fire intensity refers to the rate at which energy is released during combustion, and it varies with the amount of fuel and the time it takes to burn (Kraaij & Van Wilgen, 2014). If the intensity or heat generated is high enough, fire will stimulate the release of mature seeds in fynbos, but if it is too intense, it poses the risk of destroying the seeds (Lamont et al., 1991).

2.7. Fire spread variables

Harrison (2015), Kraaij and Van Wilgen (2014) and Archibald et al. (2009) stated that three components must be present for any wildfire to start. These include sufficient and continuous fuel to allow fires to spread, weather conditions conducive to fire and a source of ignition. Recently, ecological and anthropogenic factors have played significant roles in the occurrence and spread of wildfires (Brosofske et al., 2007). Pausas and Ribeiro (2013) found that fire activity in low plant productivity ecosystems was not driven by warm periods and was limited by low biomass, while in high plant productivity ecosystems, fire was more sensitive to high temperatures, and a large amount of biomass was available for fires.

2.7.1. Fire ignitions

Fire ignitions come from two causes, namely, natural and anthropogenic causes. Lightning and, less commonly, falling rocks or earth tremors are natural causes of wildfire in fynbos within the CFR. Lightning, however, is by far the most common natural cause of wildfires in the CFR and, in some fynbos areas, remains the dominant ignition source. Anthropogenic ignition causes are the foremost cause of wildfires in most places, and this is set to grow as human populations grow (Kraaij & Van Wilgen, 2014; Forsyth & Van Wilgen, 2008). Human ignitions have the potential to negatively affect fynbos ecosystems by changing the seasonality and increasing the frequency of wildfires (Kraaij & Van Wilgen, 2014). Increased levels of human population densities and access networks generally lead to increased wildfire ignitions, either accidentally or deliberately (Brosofske et al., 2007). Proximity to human populations and access networks increases the potential for increased anthropogenic ignitions, the probability of reported fires, and better access to fire suppression (Cardille et al., 2001). Land use also plays a crucial role in conjunction with urbanisation regarding increased fire activity. Price and Bradstock (2014) noted considerable high fire activity where some urbanisation had occurred, but still a large amount of vegetation remained. In an African context, many rural communities have a history of living with fire and use it not just for cooking but as a tool for grazing, hunting or clearing land, which can contribute to greater ignitions. The urban wildlands interface is the most likely to experience anthropogenic causes of ignition. It comprises a variety of stakeholders, including poor rural communities, structured communities, agriculture, forestry, and conservation land (Fynbos Fire Project, 2016).

2.7.2. Fire fuel

The essential elements regarding fuel are the fuel type, continuity, structure, moisture, and amount (Flannigan et al., 2009). The majority of these key fuel elements are primarily influenced by veld age. Fynbos generally need to be about four years post-fire age to accumulate enough above-ground biomass (6 700 kg/ ha) to burn, but it will most commonly burn around 12 to 20 years post-fire. If fynbos reaches over 30 years post-fire age, it can become moribund and only burn under extremely rare circumstances (Van Wilgen, 1982).

Fire-prone fynbos as a fuel has less crude fat and a higher foliar moisture content than Californian chaparral or Australian Eucalyptus woodlands and, thus, is less flammable in comparison (Kraaij & Van Wilgen, 2014). The IAPs is more flammable, increasing fynbos' above-ground biomass and propagating faster than fynbos. The IAPs propagate faster by its seedlings germinating after fires, which usually increases the density and extent of infestation (Van Wilgen, 2009). Plant invasions are widely recognised as significant threats to biodiversity; invasions can affect Indigenous ecosystems by changing fuel properties, which can affect fire behaviour (Brooks et al., 2004). The IAPs can increase the above-ground biomass, resulting in higher fuel loads leading to increased fire intensity under certain conditions, which can have consequences such as killing small soil-stored seeds, mainly when shallowly buried, soil damage, erosion and increased difficulty of fire control (Kraaij & Van Wilgen, 2014).

2.7.3. Fire weather

A strong link exists between meteorological conditions conducive to fires and subsequent wildfire disasters (Strydom, 2014). Temperature and relative humidity are prominent factors influencing fuel moisture content, thus greatly determining ignitability and fire behaviour. Precipitation also plays a role in fuel moisture content to a lesser degree, while wind speeds and direction play a substantial role in the spread of fire (Kraaij & Van Wilgen, 2014). Weather variables, including temperature, relative humidity, wind speed and precipitation, influence fire behaviour, ignitions, and the success of suppression operations and are used to calculate the fire FDI, a system to rate wildfire danger based on weather (Strydom, 2014).

In addition to climate during the fire season, the antecedent climate (i.e., weather conditions that occur months or years before the fire season) also plays an important role due to its influence on fuel load and flammability of live and dead fuels (Urbieta et al., 2015). Climate change is also predicted to have a marked influence on many weather factors and thus significantly influence fire regimes (Treurnicht et al., 2016; Flannigan et al., 2009).

2.8. Wildfire management strategies

In the past, wildfire management was predominately reactive and focused on suppression, resulting in negative ecological and social results. Both globally and within the Western Cape Province of South Africa, a paradigm shift has occurred to be more proactive and to focus on an integrated fire management (IFM) approach. The IFM incorporates different fire management activities from different stakeholders, such as early warning (prediction), fire awareness (prevention), fuel reduction, firebreaks and resources (preparedness), fire suppression (extinguishing wildland fires) and rehabilitation in a strategic framework to maximise resource sharing and coordination for effective adaptive wildfire management (Fynbos Fire Project, 2016; Harrison, 2015; Silva et al., 2010).

2.8.1. Legislation

The IFM in South Africa is governed by various pieces of legislation, which set out mandates and clarity for stakeholders from different government departments, spheres of government, and the private sector, as listed below (Fynbos Fire Project, 2016).

- The Constitution of the Republic of South Africa, 1996
- Local Government: Municipal Systems Act (Act 32 of 2000)
- Local Government: Municipal Structures Act (Act 117 of 1998)
- Disaster Management Act (Act 57 of 2002)
- Fire Brigade Services Act (Act 99 of 1987)
- National Veld and Forest Fire Act (NVFFA) (Act 101 of 1998)
- Conservation of Agricultural Resources Act (Act 43 of 1983)
- Environment Conservation Act (Act 73 of 1989)
- National Environmental Management Act (Act 107 of 1998)
- National Environmental Management: Air Quality Management Act (Act 39 of 2004)
- National Environmental Management: Biodiversity Act (Act 10 of 2004)
- National Environmental Management: Protected Areas Act (Act 57 of 2003)
- National Environmental Management: Protected Areas Amendment Act (Act 15 of 2009)
- Pollution Prevention Act (Act 45 of 1965)
- National Forests Act (Act 84 of 1998)
- National Heritage Resources Act (Act 25 of 1999)
- National Parks Act (Act 57 of 1976)
- National Water Act (Act 36 of 1998)
- Western Cape Environmental Implementation Plan – November 2002
- Western Cape Planning and Development Act (Act 7 of 1999)

Key pieces of legislation regarding IFM are the Fire Brigade Services Act, Act 99 of 1987, which provides for the establishment, maintenance, employment, coordination and standardisation of fire brigade services and matters connected therewith and the National Veld and Forest Fire Act (NVFFA), Act101 of 1998, the purpose of which is to reform the law on veld and forest fires; to repeal specific provisions of the Forest Act, 1984; and to provide for related matters. The NVFFA provides particulars for establishing Fire Protection Associations (FPAs), a fire danger rating system, specific duties and requirements for fire prevention and suppression and penalties with associated admissions of gilt fines list (Fynbos Fire Project, 2016).

2.8.2. Prediction

Risk assessments are critical in predicting risks from wildfire and thus prioritise preventative actions. Risk management can best be explained as potential risks from either a social, environmental or economic perspective, together with the likelihood of them occurring and the potential consequences if they do occur. Figure 2.7 shows the fire risk map developed using a combination of the influencing factors (Fynbos Fire Project, 2016; Forsyth et al., 2010). The Fynbos Fire Project (2016) outlines the factors that influence wildfire risks, including:

- Fire weather, including climate change
- Fire fuel, including combustibility, continuous availability, vegetation type and age
- Fire history, including historic fire paths and burn scars
- Urban edge activities which could increase the social, environmental or economic risk, likelihood or potential consequence

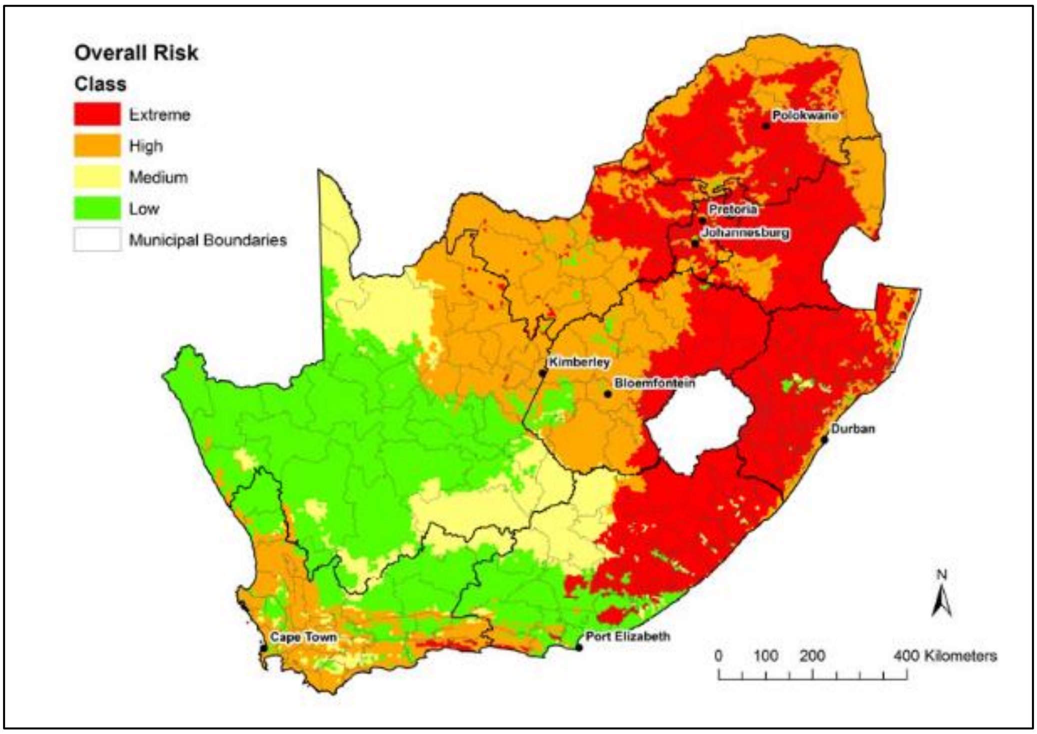


Figure 2.7: Overall assessment of wildfire risk levels in South Africa (Forsyth et al., 2010).

The South African Weather Services (SAWS) prepares and maintains a fire danger rating system or FDI based on weather variables, which the FPA distributes to its members to help prevent wildfires. Figure 2.8 shows the FDI classified into five categories and an overview of the relevant prevention and preparedness measures.

Table 2.1: Colour-coded FDI table providing an overview of the prevention and preparedness measures needed (Forsyth et al., 2010).

FDI Description	Colour		Lowveld FDI Precaution
SAFE	BLUE	0 - 20	Low fire hazard. Controlled burn operations can normally be executed with a reasonable degree of safety.
MODERATE	GREEN	21 - 45	Although controlled burning operations can be executed without creating a fire hazard, care must be taken when burning on exposed, dry slopes. Keep constant watch for unexpected wind speed and direction changes.
DANGEROUS	YELLOW	46 - 60	Controlled burning not recommended when fire danger index exceeds 45. Aircraft should be called in at early stages of a fire.
VERY DANGEROUS	ORANGE	61 - 75	No controlled burning of any nature should take place. Careful note should be taken of any sign of smoke anywhere, especially on the upwind side of any plantation. Any fire should be attacked with maximum force at hand, including all aircraft at the time.
EXTREMELY DANGEROUS	RED	75<	All personnel and equipment should be removed from the field. Fire teams, labour and equipment placed on full standby. At first sign of smoke, every possible measure should be taken to bring the fire under control in the shortest possible time. All available aircraft should be called for without delay.

The Council for Scientific Industrial Research (CSIR) have developed a real-time fire information tool based on satellite observations called Advanced Fire Information System (AFIS), which is also used in the detection of wildfires (Fynbos Fire Project, 2016; Forsyth et al., 2010).

2.8.3. Prevention

Fire awareness campaigns aim to reduce wildfire risks by creating behavioural changes in target audiences. It has been found that an integrated approach of combining educational programmes, engineering or environmental changes (risk mitigation such as removing a fuel load or installing a smoke detector), and enforcement of legislation have collectively the best chance of reducing community risk from fire. South African fire awareness campaigns pay special attention to at-risk communities and areas of poverty to reduce ignitions and implement risk mitigations. Legally, this is supported by the NVFFA, which prohibits starting wildfires and only starting a fire, including a cooking or braai fire, in a designated area (Fynbos Fire Project, 2016). South African fire awareness campaigns over the years include:

- 2000 UKUVUKA Operation Firestop campaign
- 2005 FireWise Communities programme
- 2015 Fire & Rescue Service's "Fire is Everyone's Fight" campaign

Fuel load reduction is another great preventative measure to reduce the number or severity of wildfires. Fire hazards identified or high-risk areas are generally prioritised for fuel load reduction, which can be done by prescribed burning or mechanical means. This is also legally supported by the NVFFA, which tasks landowners with managing fuel load on their property by removing IAPs as well as other unwanted fuel loads (Fynbos Fire Project, 2016).

According to the NVFFA, landowners are legally required to create firebreaks deemed wide and long enough to have a reasonable chance of preventing the spread of wildfire to or from adjoining properties unless given an exemption. It is also legally stipulated that prescribed burning for firebreaks or fuel load reduction may not occur if the FDI is high or the FPA has any objection against such a burn. Fires within the Fynbos Biome can spot up to a kilometre ahead of a fire line if wind-driven, and as such, firebreaks play a slightly different role. Firebreaks serve as an area of reduced fuel and thus will carry a reduced fire intensity where firefighters can more effectively combat the fire or be used as a line to backburn from, as shown in Figure 2.9 (Fynbos Fire Project, 2016).

Figure 2.8: A firebreak associated with a road on the boundary of the BMC commonly used to gain safer access, combat the fire from or be used as a line to back burn from.

2.8.4. Preparedness

The NVFFA makes provisions for landowners' preparedness by saying that they must have access to equipment and trained personnel to fight fires on their behalf. It is mandatory for state landowners and municipalities to be part of FPAs and legally beneficial for private landowners. The main benefit of FPA membership is due to the exemption of compliant FPA members from the presumption of negligence clause in the NVFFA against civil claims regarding fire damage. As such, membership is favourable for many insurance companies. The FPAs provide several services, including advising landowners on the minimum standards of wildfire fighting equipment, training and PPE per their property size (Figure 2.10) and risk to comply with readiness for wildfire fighting and play a coordination role with the various stakeholders concerning strategies, call-out procedures and mutual aid agreements for wildlands firefighting (Fynbos Fire Project, 2016; Harrison, 2015). The fire department is mandated to manage fires and will generally assume the role of Incident Commander. However, landowners on which a wildfire could start must have firefighters, crew leaders and occasionally fire bosses or managers, who must have the basic training, safety equipment and firefighting equipment (Fynbos Fire Project, 2016).

Figure 2.9: Firefighters in full personal protective safety and equipped with rake hoes, a spade and a slasher.

2.8.5. Suppression

The initial attack period is the first and most critical phase in fire suppression when wildfires have not had prolonged time to spread, and thus, firefighting effects can be most effective and have the best chance of containing fires. Suppose a wildfire is not contained within the initial attack period. In that case, firefighting goes into the extended attack period, which could continue for several days to around a month until a wildfire is contained. Figure 2.11 shows firefighters suppressing a wildfire within the BMC. As divisions of the fire line are contained, they can be mopped up to ensure all wildfire embers are extinguished to prevent them from crossing contained fire lines by surface creeping, spotting or underground creeping (Fynbos Fire Project, 2016).

Wildfires are managed in accordance with the Incident Command Structure (ICS), a modular structure that is expandable should the scale or complexity of a wildfire incidence expand. The ICS creates a complete structure for command, communication, planning, and responding to disasters regardless of jurisdiction or agencies involved and provides common terminology and a manageable span of control. The ICS structure also creates a framework for managing multiple incidents simultaneously (Chang, 2017; Fynbos Fire Project, 2016).

Figure 2.10: Firefighter's supressing a wildfire within the BMC.

2.8.6. Rehabilitation

After a fire has been put out, it is best practice to map its extent and assess the damage to quantify the rehabilitation work needed. Environmental rehabilitation can include soil protection against erosion or IAP removal should an infestation occur. Economic rehabilitation may be to replant lost commercial crops, trees, or infrastructure. Rehabilitation can also have social implications by affecting livelihoods and living conditions. Rehabilitation is the responsibility of the landowners and can be done by their own personnel or by trained contractors (Fynbos Fire Project, 2016).

2.9. Previous studies of fire regimes in Mediterranean climatic regions

The Mediterranean ecosystems are frequently characterised by the prevalence of wildfires and summer droughts (Gumbi, 2011). The degree, severity and impact of these fires are influenced by several factors, including weather conditions, fuel accumulation, increased sources of ignition linked to human population growth and IAP invasions (Kraaij et al., 2018). Montenegro et al. (2004) highlight the growth of human populations in Mediterranean regions and, thus, the increase of anthropogenic causes of fire that impact on natural ecosystems. The driving factors and subsequent changes in fire regimes have been studied in detail in Mediterranean ecosystems, including the Americas, Europe, Australia and Africa (Gumbi, 2011).

2.9.1. International fire regimes in Mediterranean climatic regions

The Mediterranean regions globally share a similar climate and structurally similar plant communities, which are dominated by evergreen sclerophyllous-leaved shrublands, semi-deciduous scrub, and woodlands (Figure 2.12). The mild, rainy winters result in sufficient plant growth to provide a continuous fuel load that is highly flammable and fire-prone in dry, hot summers (Keeley, 2012).

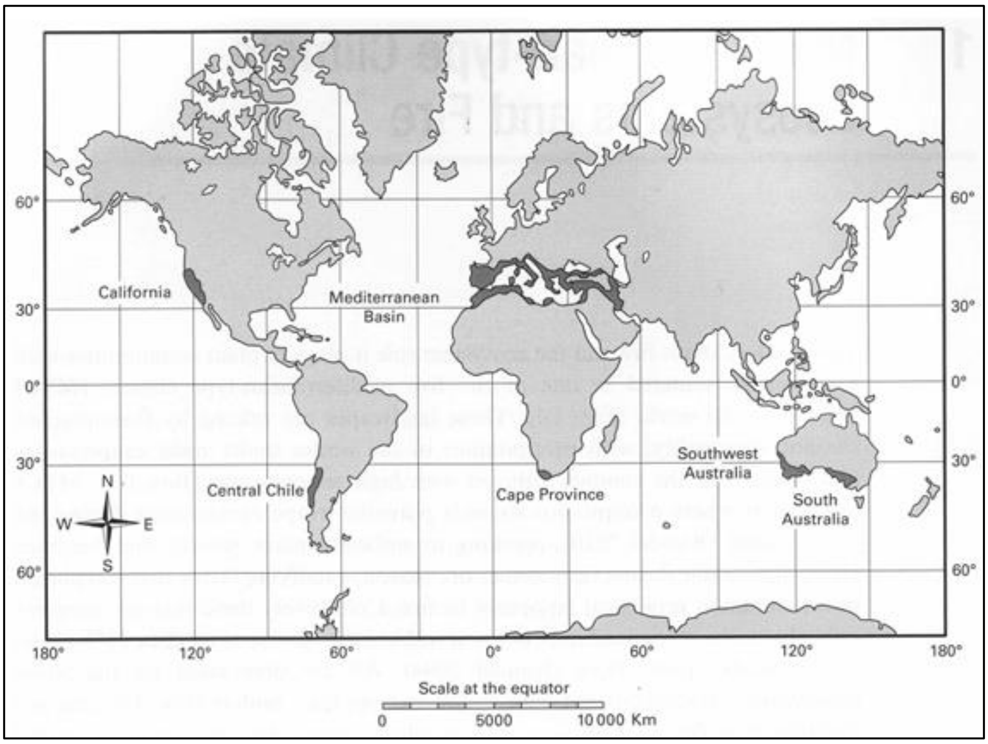


Figure 2.11: Five Mediterranean climatic regions found on the western sides of continents between 30-40° latitude (Keeley, 2012).

Montenegro et al. (2004) compared the fire regimes and vegetation responses of the central zone of Chile (matorral) and the southern area of California in the United States (chaparral), two Mediterranean-climate regions. In Chile, most fires result from anthropogenic activities, whereas lightning fires as an ignition are more frequent in California. In both regions, fires are more prevalent in summer and have a strong correlation between human activity and ignition frequency. However, the size remains mainly unchanged, assumedly due to fire suppression actions and landscape fragmentation (Montenegro et al., 2004).

In the Mediterranean region of Europe, De Luís et al. (2001) researched fire as one of the major disturbances affecting ecosystems and closely related to climate. There is evidence, for the region of Valencia (East Spain), of decreasing precipitation and increased variability in the rainfall distribution conditions being more favourable for wildfires (De Luís et al., 2001).

Bradstock (2010) compared fire regime patterns across Australia to biomass growth, availability to burn, fire weather, and ignition. Current and future trends include an increase in dryness and elevated CO_2 over much of Australia, which suggests an uncertain future for fire regimes (Bradstock, 2010).

2.9.2. Fynbos Biome fire regimes, South Africa

Archibald et al. (2009) examined the factors controlling the extent of fire in Southern Africa. The most significant factors were tree cover, rainfall in the previous two years, and rainfall seasonality. Human activities, including grazing, roads per unit area, population density, and cultivation fraction, were also shown to affect fires, but only in particular climatic regions and often, counterintuitively, linked to a reduction in fire (Archibald et al. (2009).

Gumbi (2011) looked at the impact of changes in climate, human demography, and other social factors on the Kogelberg Nature Reserve fire regime, which falls within BMC. The results show an increase in younger veld burning (under six years old), fire frequency and total burnt area. The increased fire behaviour could be attributed to more favourable fire weather conditions and a dramatic increase in the population size of surrounding towns and villages (Gumbi, 2011). The CSIR Natural Resources and the Environment prepared a report to determine the wildfire regime trends in geographic regions of the Western Cape Province, reviewing the ecological impacts of historic wildfire regimes and making wildfire management, policy and future data collection recommendations (Van Wilgen & Forsyth, 2008). The BMC falls within the study area of this research as the western inland zone, based on climate, and characterised by seasonally increased fire potential variations predominately in summer (CapeNature, 2019; Van Wilgen & Forsyth, 2008). Van Wilgen and Forsyth (2008) found that in the wildfire regime of the western inland zone, a small number of fires were responsible for burning the majority of the burnt area, and an upward trend of Very Large category fires was noted. There was also a decrease in wildfire return intervals and an increase in the percentage of short-interval fires (> 6 years), most of which were found in summer and autumn. An influencing factor in the wildfire regime Wilgen and Forsyth (2008) also looked at was ignitions, which they found between 1.2 % and 54.1 % of ignitions were natural and caused by lighting. This study is an excellent review of the ecological impacts of historic wildfire regimes but does not look at the proximity of ignition points to human populations and access networks or above-ground biomass.

CHAPTER 3
Research design and methodology

3.1. Introduction

This research aimed to follow a quantitative analysis of secondary data sets to gain insight into the critical influencing factors (including relative fire ignition position, fire fuel and fire weather conditions) of key wildfire regime aspects (including fire size, frequency, return interval and season) in the Boland Mountain Complex (BMC). The data sets are for the BMC over the last three decades, from 1990 to 2019. Data before 1990 has been excluded as it is considered less reliable and fragmented.

The secondary data sets used for this research have been sourced from the CapeNature, Landsat imagery courtesy of the United States Geological Survey (USGS) and the South African Weather Services (SAWS). Shapefiles for wildfire perimeters, ignition points, transport routes, towns and villages, the study area, and the CapeNature fire database were sourced from the CapeNature. Satellite imagery from Landsat 4-5 TM C2 L2 and Landsat 7 ETM+C2 L2 at a 30-meter spatial resolution ranging from 1990 to 2019 were used for the year before Very Large category wildfires (see Section 3.2.1 below for fire size class categories). This satellite imagery was accessed via the Earth Explorer site (http://earthexplorer.usgs.gov/). Lastly, historical climate data was sourced from the SAWS.

All shapefiles were projected to World Geodetic System (WGS) 84, and GIS projects were projected in South African Coordinate Reference System (CRS) Hartebeesthoek no. 19 in Quantum Geographic Information System (QGIS), a freeware Geographic Information System (GIS) programme.

The major influencing factors were broken down into relative fire ignition position (including proximity of wildfire ignition points to human populations and access networks), fire fuel (including estimated above-ground biomass), and fire climatic conditions (including FDI categories, individual weather variables, the Standardized Precipitation Index (SPI) and antecedent annual rainfall and average temperature)

Within this research's temporal delineation, 1049 wildfires were recorded within the BMC, 34 of which fell into the Very Large wildfire category (see Section 3.2.1 below for fire size class categories). The Very Large wildfire category has been used as a representative sample of wildfires when calculating fire fuel and fire weather condition variables. Very Large wildfires have strongly influenced the aggregate annual burnt area correlations (Stavros et al., 2014).

Furthermore, Forsyth and Van Wilgen (2008) observed a tendency for the Very Large fire category to increase within the BMC.

3.2. Wildfire regime aspects

Based on data availability, the study used selected wildfire regime aspects, size, frequency, return intervals, and seasonality.

3.2.1. Fire size categories

The CapeNature fire database was used to determine fire sizes in the BMC over the last three decades, from 1990 to 2019. The CapeNature fire database uses Global Positioning System (GPS) coordinates around the fires' perimeter to digitise the fire shapefiles in QGIS from which the area can be extrapolated. Wildfire sizes over the last three decades in the BMC were categorised using the Forsyth and Van Wilgen, 2008 classification as the following:

- Small (0 - 100 ha)
- Medium (> 100 – 2 000 ha)
- Large (> 2000 – 5 000 ha) and
- Very Large (> 5 000 ha)

The wildfire size categories were then analysed with other wildfire regime aspects, including fire frequency and seasonality, and selected influencing factors, including fire fuel and fire weather conditions.

3.2.2. Fire frequency

The CapeNature fire database was used to determine the fire frequency and total hectares burnt in the BMC over the last three decades, from 1990 to 2019. The frequency and total hectares burnt were looked at annually with other wildfire regime aspects, including wildfire size categories and seasonality, and selected influencing factors, including fire ignition position, fire fuel, and fire weather conditions.

3.2.3. Fire return intervals

The CapeNature fire database and wildfire perimeter shapefiles were used to determine the fire return intervals over the last three decades from 1990 to 2019 in the BMC. Two methods were used to determine the fire return intervals: the first method, described by Forsyth and Van Wilgen (2008), gives a single summary statistic, and the second method, described by Wittkuhn and Hamilton (2010), in which polygons for each year are intersected with one another to form a polygon mesh to create a space-time composite data model. These two methods were then analysed.

The Forsyth and Van Wilgen (2008) method used Equation 1 to calculate the mean fire return interval in years (RP) by dividing the extent of all wildfires (b) by the area over which fires were recorded (a) and dividing this by the number of years (y). The mean fire return interval was then analysed for all wildfires with other wildfire regime aspects and the selected influencing factors over the last three decades from 1990 to 2019 in the BMC.

Equation 1: $$\boldsymbol{RP} = \boldsymbol{y} / (\boldsymbol{b}/\boldsymbol{a})$$

Where:

RP: fire return interval in years

y: number of years

a: area over which fires were recorded

b: extent of all wildfires

In the method described by Wittkuhn and Hamilton (2010), the wildfire vector polygon shapefiles for the period 1990 to 2019 in the BMC were loaded onto QGIS and intersected with one another to form a polygon mesh while retaining both the spacial integrity and attributes of the original data as shown in Figure 3.1. In the attributes of the original vector polygon shapefiles, new columns were created for individual identification once intersected, and a second unique identifier was used for overlapping polygons. New columns were also created for the wildfire size category, each year with a record under the appropriate year if a fire event occurred to derive frequency, successive interval columns for the maximum number of fire frequencies to derive fire return interval and seasonality. The polygons were then intersected to form a polygon mesh, and the attribute table was converted to an MS Excel 2003 format (extension .xls) from a database file (extension .dbf).

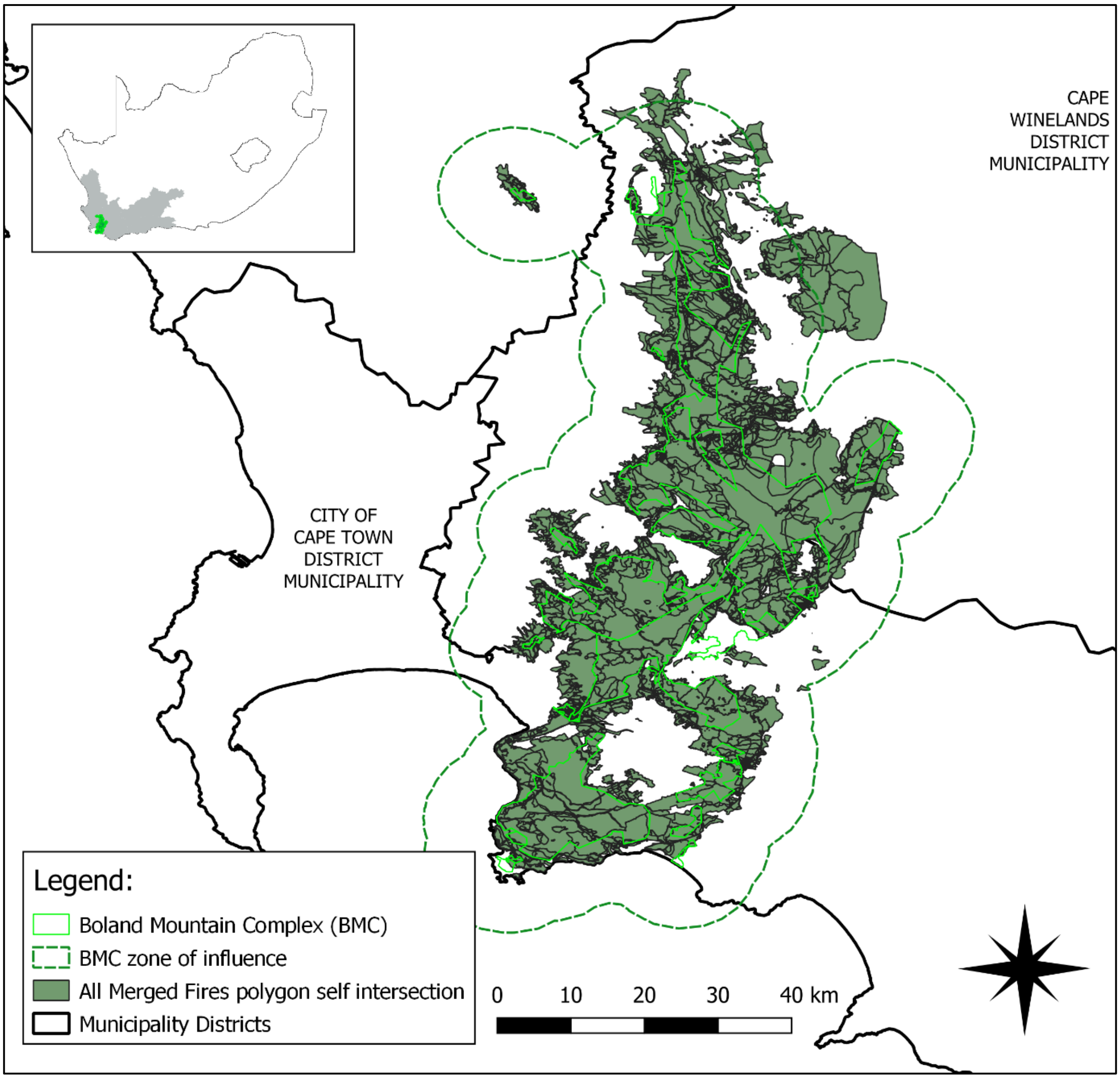


Figure 3.1: All merged fire polygons self-intersected to form a polygon mesh in the BMC and BMC Zone of influence (ZOI).

The fire return intervals were then calculated based on the years between fire occurrences and divided into seven return interval classifications as defined by CapeNature (2019).

- 0 - 2 years
- 2 - 4 years
- 4 – 6 years
- 6 – 10 years
- 10 – 15 years
- 15 – 25 years
- > 25 years

The data was then imported back into QGIS and analysed for all wildfires, other wildfire regime aspects, and selected influencing factors over the last three decades from 1990 to 2019 in the BMC from a space-time composite perspective.

The mean fire return interval was calculated for the method described by Wittkuhn and Hamilton (2010) in Equation 2; the total sum of weighted burnt area (b) is divided by the total burnt area (a) so it could be comparable to the first method described by Forsyth and Van Wilgen (2008) in Equation 1. The mean fire return interval was then analysed for all wildfires in the BMC from 1990 to 2019.

Equation 2: $$\boldsymbol{RP = b / a}$$

Where:

RP: fire return interval in years

a: total burnt area

b: the total sum of the weighted burnt area

3.2.4. Fire seasonality

Wildfire seasonality over the last three decades, from 1990 to 2019, in the BMC was sourced from the CapeNature fire database. Based on the start date of wildfires, they were grouped as the following using Van Wilgen & Forsyth, 2008 classification:

- Summer (November – February inclusive)
- Autumn (March – April inclusive)
- Winter (May – August inclusive)
- Spring (September – October inclusive)

The frequency of wildfire seasonality was then analysed with other wildfire regime aspects, including wildfire size categories and frequency, and selected influencing factors, including fire ignition positions, fire fuel, and fire weather conditions from 1990 to 2019 in the BMC.

3.3. Selected influencing factors of wildfire regimes

Influencing factors of wildfires were selected based on data availability. The selected influencing factors are:

- Fire ignition positions (including distance from transport routes and towns and villages),
- Fire fuel load from an estimate of above-ground biomass the year prior (for the Very Large category as an extremity sample of wildfires) and
- Fire weather conditions (including FDI, individual weather variables and antecedent annual rainfall and average temperature and SPI) for the Very Large category as an extremity sample of wildfires.

3.3.1. Relative fire ignition positions

The shapefiles for wildfire ignition points over the last three decades from 1990 to 2019, transport routes (including major roads, secondary roads for forestry and farming, footpaths and railway lines), as well as towns and villages in the BMC were sourced from the CapeNature. Using QGIS, the linear infrastructure was converted to points, and the central point was taken from polygon shapes. The distance from the wildfire ignition points was then measured to the nearest transport route and town or village (Brosofske et al., 2007).

The distance from wildfire ignition points to human populations and access networks increases the potential for increased anthropogenic ignitions, the probability of reported fires, and better access to fire suppression (Cardille et al., 2001). The distance of wildfire ignition points from the nearest transport route and town or village was then analysed in the BMC against the frequency of wildfires over the last three decades, from 1990 to 2019.

3.3.2. Fire fuel load

The above-ground biomass is made up of both Indigenous vegetation and Invasive Alien Plants (IAPs) post-fire. The above-ground biomass was calculated only for the Very Large category fires as an extremity sample of wildfires strongly influencing the aggregate annual burnt area correlations (Stavros et al., 2014).

The post-fire vegetation age was sourced from the CapeNature fire database. Equation 3 will calculate the above-ground biomass for tall alien trees (Pine species) and growth curves based on post-fire age. In equation 3, above-ground biomass (b) and growth curves for tall alien trees based on post-fire age (a) in years (Le Maitre et al., 2000).

Equation 3: $$\boldsymbol{b} = \mathbf{20\ 000}\ \boldsymbol{log}\mathbf{10}(\boldsymbol{a}) - \mathbf{7060}$$

Where:

a: post-fire age in years

b: above-ground biomass for tall alien trees

Equation 4 calculated the above-ground biomass for indigenous vegetation classed as predominantly tall moist fynbos and growth curves based on post-fire age. In equation 4, above-ground biomass (b) and growth curves for tall moist fynbos based on post-fire age (a) in years (Le Maitre et al., 1996).

Equation 4: $$\boldsymbol{b} = \mathbf{9\ 540}\ \boldsymbol{log}\mathbf{10}(\boldsymbol{a}) - \mathbf{636}$$

Where:

a: post-fire age in years

b: above-ground biomass for tall, moist fynbos

The estimated percentage of IAPs was worked out using satellite remote sensing (RS) and GIS techniques, and the coverage was measured by colour-selected pixels and manual sense checking (Brundrett et al., 2019). Brundrett et al. (2019) found that colour-selected pixels and manual sense checking were accurate enough to use as their control method for canopy cover but were considered too time-consuming for general usage. However, the colour-selected pixels and manual sense-checking method were selected due to the lack of spectral band data availability for the study area over the selected time frame.

Satellite imagery from both Landsat 4-5 TM C2 L2 and Landsat 7 ETM+C2 L2, as the only satellite imagery that could be sourced spanning the temporal delineation of the research, at a 30-meter spatial resolution was sourced from the Earth Explorer site (http://earthexplorer.usgs.gov/) courtesy of the USGS. The satellite imagery was used for years before Very Large category wildfires over the last three decades from 1990 to 2019 in the BMC. In QGIS, the satellite imagery was imported as image layers per year, and the Very Large category fire vector shapefiles were overlaid. The satellite imagery was then cut to the shape of the corresponding Very Large category fire for the following year. Using image editing software (Adobe Photoshop CCTM), the "Select by Colour Range" tool was used, at a set tolerance of 20, to isolate specific green pixels indicative of Pine species, the major invasive alien species within BMC (Brundrett et al., 2019). The automatic selections were then visually sense-checked and manually edited accordingly, as shown in Figure 3.2. The result was then recorded as a percentage of pixels representing the estimated percentage of IAPs of the total area within the Very Large category fire per Very Large category fire.

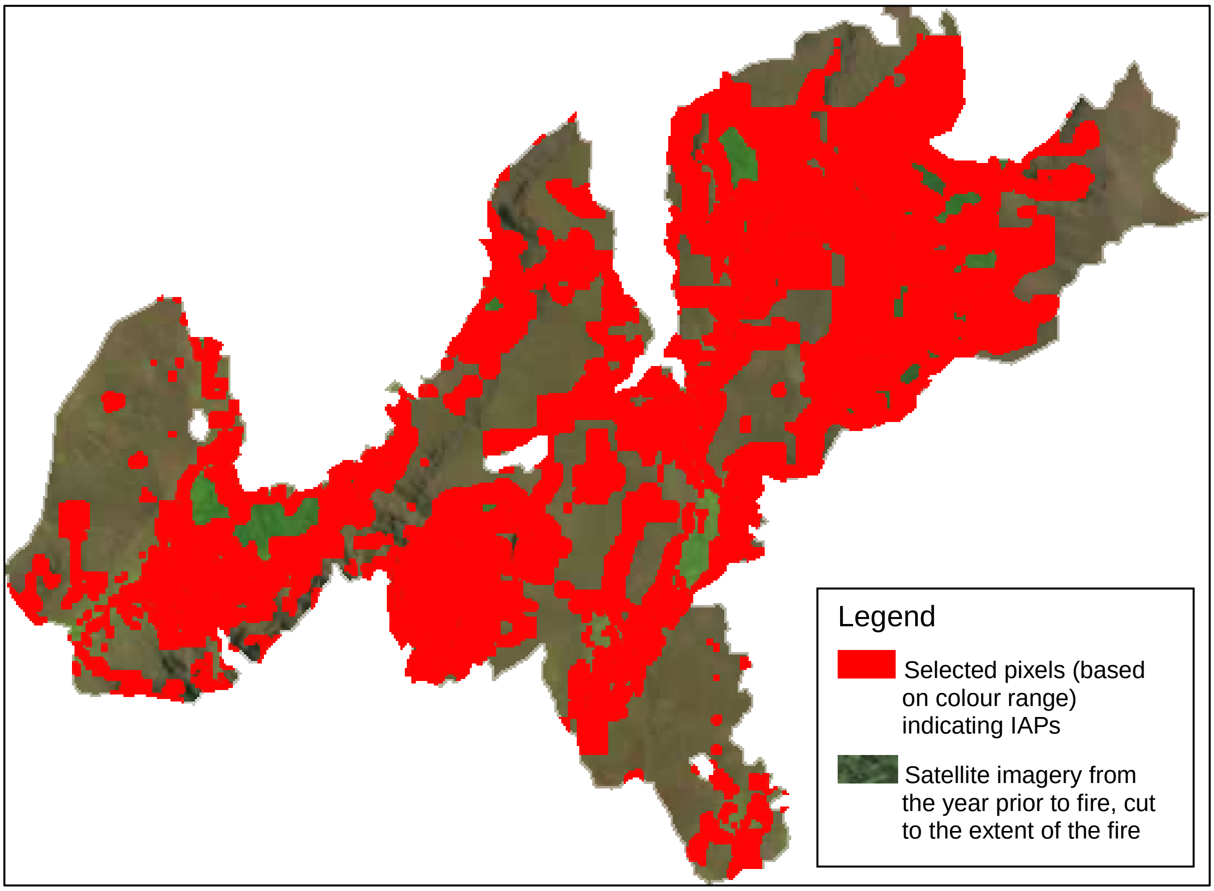


Figure 3.2: An example of pixel colour selection. In image editing software, satellite imagery for 2018 was cut to the fire extent, the year prior to a Very Large category fire (HOTT/02/2019/02) in Hottentots Holland Nature Reserve starting in 2019. A specific green pixel colour range was selected in red, indicating IAPs (no scale in image editing software; pixel measurements used IAPs pixels percentage of total pixels, which was then applied to known hectares of the fire).

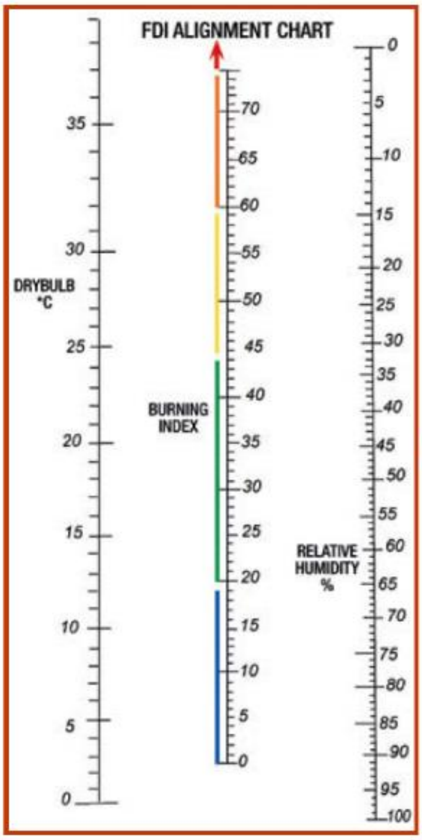
The total above-ground biomass was then estimated per Very Large category fire by adding the percentage of indigenous vegetation (tall moist fynbos) and IAPs (tall alien trees Pine species) above-ground biomass together prior to Very Large category fires occurring. The total above-ground biomass was then analysed against wildfire frequency and seasonality over the last three decades, from 1990 to 2019, in the BMC.

3.3.3. Fire weather conditions

The Lowveld FDI, distributed by SAWS, is the official system weather danger index used in South Africa. The FDI and individual weather variables were only considered for the Very Large category fires as an extremity sample of wildfires as they have been shown to strongly influence the aggregate annual burnt area correlations (Stavros et al., 2014). Data from eight weather stations surrounding the BMC was provided by SAWS, of which four were considered based on their proximity to ignition points and data availability; the weather stations selected are:

- Hermanus
- Paarl
- Strand
- Worcester and Worcester - Automatic Weather Station (AWS)

If sufficient back data was available, the average days burnt and the start date FDIs were calculated for Very Large category fires within the BMC from 1990 to 2019. The FDI is calculated as shown in Figure 3.3 using a nomogram, the relationship between the dry bulb air temperature in degrees Celsius and the percentage of relative humidity, deriving a burning index.



FDI RAINFALL CORRECTION FACTOR

RAINFALL mm	NUMBER OF DAYS SINCE LAST RAINFALL 1	2	3	4	5	6	7-8	9-10	11-12	13-15	16-20
0.1-2.6	0.7	0.9									
2.7-5.2	0.6	0.8	0.9								
5.3-7.6	0.5	0.7	0.9	0.9							
7.7-10.2	0.4	0.6	0.8	0.9	0.9						
10.312.8	0.4	0.6	0.7	0.8	0.9	0.9					
12.9-15.3	0.3	0.5	0.7	0.8	0.8	0.9	1.0				
15.4-20.5	0.2	0.5	0.6	0.7	0.8	0.8	0.9				
20.6-25.5	0.2	0.4	0.5	0.7	0.7	0.8	0.9	1.0			
25.6-38.4	0.1	0.3	0.4	0.6	0.6	0.7	0.8	0.9	1.9		
38.5-51.1	0.1	0.2	0.4	0.5	0.5	0.6	0.7	0.8	0.9		
51.2-63.8	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	
63.9-76.5	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.9
76.6+	0.1	0.1	0.1	0.2	0.4	0.5	0.6	0.6	0.7	0.8	0.9

WIND FACTOR Add the correction factor to the BI to calculate the FDI

Wind Speed	Correction Factor	Wind Speed	Correction Factor	Wind Speed	Correction Factor	Wind Speed	Correction Factor
0	0	12	10	24	15	36	26
1	0	13	10	25	16	37	29
2	4	14	10	26	19	38	30
3	5	15	10	27	20	39	30
4	5	16	11	28	20	40	30
5	6	17	14	29	20	41	31
6	9	18	15	30	20	42	34
7	10	19	15	31	20	43	35
8	10	20	15	32	21	44	35
9	10	21	15	33	24	45	36
10	10	22	15	34	25	46	40
11	10	23	15	35	25	47	40

Figure 3.3: Charts and factors to calculate the Lowveld FDI (Willis et al., 2001).

Equation 5 shows the Burning Index (BI) from Lowveld FDI Temperature (T) in degrees Celsius and Relative humidity (RH) in percentage. The burning index is then adjusted upwards to account for wind speeds and downwards to correct for short-term historical rainfall, as shown in Figure 3.3 (Strydom, 2014; Willis et al., 2001).

Equation 5: $$\boldsymbol{FDI} = \{(\boldsymbol{T} - \mathbf{35}) - ((\mathbf{35} - \boldsymbol{T})/\mathbf{30}) + ((\mathbf{100} - \boldsymbol{RH}) * \mathbf{0.37}) + \mathbf{30}\}$$

Where:

FDI: Fire Danger Index

T: Temperature in degrees Celsius

RH: Relative humidity in percentage

The weather variables used were from one of the four SAWS weather stations closest to the ignition points with available data for the timeframe. The time recording for the weather variables was at 14:00 daily for the days each Very Large category wildfire burned.

FDI values can be allocated into the following categories (Forsyth & Van Wilgen, 2008; Willis et al., 2001):

- **BLUE:** 0–19 (low)
- **GREEN:** 20–44 (moderate)
- **YELLOW:** 45– 59 (dangerous)
- **ORANGE:** 60–74 very (dangerous)
- **RED:** ≥ 80 (extremely dangerous)

The various FDI categories and individual weather variables (including temperature, relative humidity, precipitation, and wind speed and direction) for the Very Large category wildfires were analysed against the hectares burnt, frequency and seasonality over the last three decades from 1990 to 2019 in the BMC. The antecedent annual total rainfall, average temperature, and annual SPI for the BMC were then analysed with fire frequency and total hectares burnt.

Equation 6 shows the SPI with total precipitation for a chosen period (P), the long-term average precipitation (P avg) and the standard deviation of precipitation over the same long-term period given in millimetres. A drought event has been defined as an SPI of lower than 0, and the more negative pertains to the severity (Botai et al., 2017). The SPI was used to define drought years within the BMC with available data between 1990 and 2019, and it was compared to SPIs for the Western Cape Province for 12-month periods (Botai et al., 2017).

Equation 6: $$SPI = (P - P\,avg) / \sigma\ SPI = (P - P\,avg) / \sigma$$

Where:

SPI: Standardised Precipitation Index

P: Total precipitation for a chosen period (mm)

P avg: Average precipitation for the same period over a long-term record (mm)

σ: Standard deviation of precipitation for the same period over a long-term record (mm)

The antecedent annual rainfall and average temperature was considered for 12 and 24 months before the year of Very Large fires from the weather station closest to the ignition point of such fire. This was then compared to the average precipitation of the year, which was that a Very Large category fire occurred from the same weather station data from SAWS. Botai et al. (2017) explain that the Standardised Precipitation Index (SPI) can be looked at on different timescales for different purposes. However, 12 and 24 months are the most relevant to hydrological and socio-economic impacts, respectively.

3.4. Analysis and modelling of selected influencing factors of wildfire regimes

Large wildfires are considered relatively rare events, and therefore, statistical models for wildfires must consider fire occurrence over space and time to have enough input data. Logistic regressions provide the means to model wildfire occurrence at fine spatial and temporal resolutions (limited only by the available data) while statistically aggregating across locations with similar characteristics (Westerling et al., 2011).

The data was sorted into two Excel spreadsheets, one organised by years from 1990 to 2019; the annual total hectares burnt in the BMC was the dependent variable against all other variables annually in the BMC, including the fire frequency, age class, season, closest transport route, closest town, average rain days and average rain amount. The Very Large fire category organised the second Excel spreadsheet. The hectares of burnt area for each Very Large wildfire was the dependent variable against all other variables, including the total frequency, size and season in the BMC for the same year as the Very Large fire; the biomass, percentage of IAPs, indigenous vegetation and age class, start date and average FDI, individual weather variables, total days burnt for each Very Large fire and the antecedent annual rainfall for the year each Very Large fire occurred and 12 and 24 months prior. The median of each column was used to fill in missing values, a common practice for handling missing data in statistical analyses.

The coefficient of variation was worked out independently for each variable to assess the degree of variability within each group and linear regression models was fitted in R, a free statistical computing software program. Akaike Information Criterion (AIC), the corrected Akaike Information Criterion (AICc) used in particular with smaller sample sizes, and the Bayesian Information Criterion (BIC) were then used to evaluate and compare the goodness of fit of different statistical models. The P-value, R-squared, and Percent Variance Explained were used to gauge the significance of model selection.

CHAPTER 4
Results and Discussion

4.1. Introduction

This chapter discusses results from analysing thirty years of wildfire data for the Boland Mountain Complex (BMC) and the zone of influence (ZOI), totalling 628 574.04 ha. The temporal delineation of this research is from 1990 to 2019, totalling 1049 recorded wildfires that fall within the study area. It also looks at the Very Large category of wildfires as a subset comprising 34 fires.

4.2. Wildfire regime components

The wildfire regime components analysed in this project were size, frequency, return intervals and seasonality. The annual total hectares burnt in the BMC was analysed as the dependent variable against all other variables annually in the BMC, including the fire frequency, age class, season, closest transport route, the closest town, average rain days and average rain amount (Table 4.1). Table 4.1 shows the top five best-fit models with the frequency of Very Large and Large category fires being the best fit, both with comparably low AIC, AICc and BIC values; highly significant p values with less than 0.001 and high R-squared value and percentage variance explained with 0.711, 17.088 % and 0.413, 41.298 %, respectively. Also considered statistically significant is the number of ignitions closest to Ceres and Gouda, with p values less than 0.05; however, they do not have very high R-squared values and percentage variance explained. The number of ignitions closest to Lanquedoc got a p-value of over 0.5, so not considered statistically significant. The number of Very Large and Large category fires per year best explains the number of hectares burnt in the same year. This places great importance on preventative measures and the initial attack period to keep fire sizes as small as possible. In the BMC over the time frame Very Large category fires made up 59 % of the total area burnt, Large category fires made up 17 %, Medium category fires made up 22 % and Small category fires made up 2 %. Van Wilgen et al. (2010) found that prescribed burning was fundamentally not required in addition to wildfires for fynbos regeneration and ineffective in reducing the incidence of wildfires but recommends that prescribed burns be conducted to assist in the control of Invasive Alien Plants (IAPs). However, looking at the fire scars, prescribed burning should be considered strategically to provide areas of younger vegetation and thus help prevent the spread of wildfire in the Large and Very Large category fires.

Table 4.1: Top five best-fit models to the dependant variable of annual total hectares burnt in the BMC.

Variable	CV Decimal	AIC	AICc	BIC	P-Value	R-Squared	Percent Variance Explained
BMC_very_large	1.003	647.523	647.968	650.326	<0.001	0.711	71.088
BMC_large	1.105	668.775	669.219	671.577	<0.001	0.413	41.289
Ceres	1.515	679.375	679.819	682.177	0.026	0.164	16.407
Gouda	1.383	679.924	680.369	682.726	0.035	0.149	14.862
Lanquedoc	5.477	681.360	681.804	684.162	0.078	0.107	10.689

Where: CV is the Coefficient of variance; AIC, the Akaike Information Criterion; AICc, the Akaike Information Criterion corrected; BIC, Bayesian Information Criterion; P-value, the Probability value and R-squared, the Coefficient of determination.
p < 0. 05 – Significant
p < 0. 01 - Very significant
p < 0. 001 - Highly significant

Figure 4.1 shows the total number of fires annually from 1990 to 2019 in each size category. There has been a sharp rise in the number of fires in the Small category fires in the second half of the temporal delineation from 2005, with an average increase from 8.73 to 37.67 per year. Fires in the Very Large, Large and Medium categories also increased from an average of 0.73, 1.27 and 8.87 fires recorded before to 2005 and to an average of 1.53, 1.07 and 10.07 fires respectively recorded after that.

The recorded increase in ignition frequencies post-2005 could be due to increased reporting. Following the establishment of the National Veld and Forest Fire Act (NVFFA), 1998 (Act No. 101 of 1998), the 2000 UKUVUKA Operation Firestop campaign, the establishment of the Cape Peninsula Fire Protection Association (CPFPA) in 2002, and later other Fire Protection Association and the FireWise Communities Programme initiated in 2005, there was more encouragement for landowners and the general public to report fires. Hence, this could account for increased recorded fire frequencies (Fynbos Fire Project, 2016). The increase in ignitions could be entirely or partly due to urban expansion. There is a history of using fire as a tool for cooking, improving grazing, hunting, or clearing land in many poorer communities and as such, urban expansion coupled with changes in land use or management, the spread of IAPs and climate change can play a role in increased fire ignitions (Fynbos Fire Project, 2016).

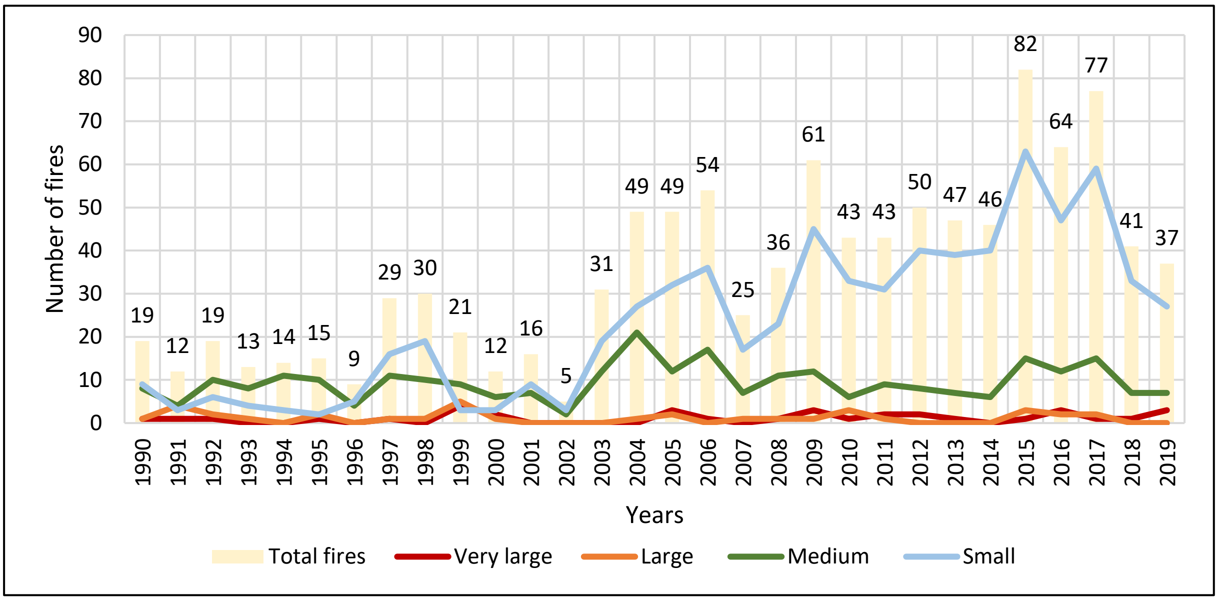


Figure 4.1: Fire frequency total per size category in the BMC between 1990 and 2019.

Figure 4.2 shows fire frequency and cumulative hectares burnt yearly in the BMC from 1990 to 2019 with trend lines. The trend lines seem to show an increase in both fire frequency and hectares burnt over the study period. The frequency increased from 294 fires recorded prior to 2005 to 755 fire records after that, and the cumulative hectares burnt per year also increased from 302 586.59 ha prior to 2005 to 379 452.11 ha after that.

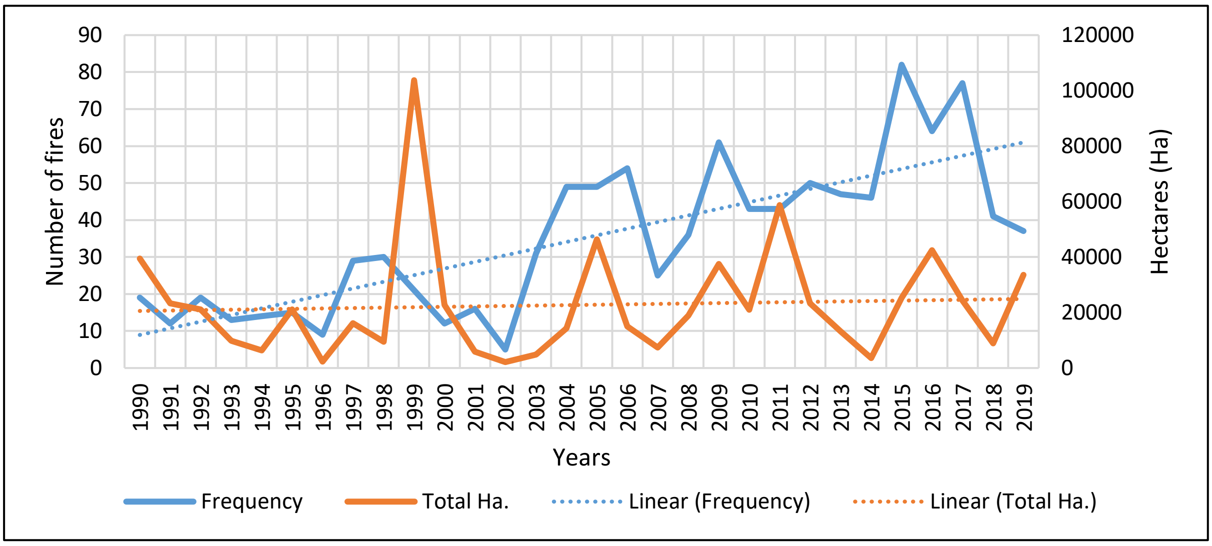


Figure 4.2: Total fire frequencies and hectares burnt in the BMC between 1990 and 2019 with trend lines.

While fire frequency indicates the regularity and likelihood of fires, the cumulative hectares burnt per year give a better understanding of the scale of impact (Lutz et al., 2011). A potential increase in reporting would account for more Small or Medium-category fires that might not have been reported if landowners had been able to suppress them without statutory assistance. Instating relevant legislation, associations, and awareness campaigns likely explains the increase in reported ignition frequencies. Increased reporting, however, is less likely to explain the increase in total hectares burnt, as statistically, Very Large and Large category fires were the best-fit models for total annual hectares burnt in the BMC. Very Large and Large fires are also more likely to have been consistently reported. In 1999, there were four Very Large category fires within the study area, totalling 82 283.02 ha burnt area, the most recorded in the temporal scope of this research, accounting for the spike in hectares burnt for this particular year.

The mean fire return interval, as determined by the same method used by Forsyth and Van Wilgen (2008), is 12.8 years, including both indigenous vegetation and IAPs, as detailed in Table 4.2. The required fire return interval within the BMC should be less than 5-10 % of the area, which should burn more than twice in 25 years (CapeNature, 2019). For the majority of the area to have a fire return period of more than 12.5 years (twice in 25 years) while still allowing up to 10 % of the area to burn in this period, the average fire return period should be approximately 15 to 20 years or more. Based on this, the fire return period is too frequent to maximise ecological biodiversity. The limitations of this method used by Forsyth and Van Wilgen (2008) for fire return intervals are that it assumes that fires are randomly distributed over time and only gives an average interval between fires, not looking at it holistically from a spatio-temporal perspective.

Table 4.2: Fire Return Period (RP) in the BMC from 1990 to 2019.

Fire return period (RP) calculation steps	**Study specific input**	**Study data**
a = area over which fires were recorded	Total burnt area of BMC in hectares	290 969.74
b = extent of all wildfires recorded over time	Total hectares burnt in the BMC from 1990-2019	682 038.70
y = years	30 years, from 1990-2019	30
RP = y / (b/a)	RP in the BMC from 1990-2019	12.80

Table 4.3. shows the fire return interval for the BMC from 1990 to 2019 in cumulative hectares and the percentages of fires per veld age category (including indigenous vegetation and IAPs) from a space-time composite perspective, a method described by Wittkuhn and Hamilton

(2010). This method shows the most extensive area burnt between 6–10 years old, with 10 559 512.55 ha burning in this age category from 1990 to 2019, equating to 37 %. The smallest age category burnt was 25 years or older, with 213 155.54 ha burning from 1990 to 2019, equating to 1%. The method described by Wittkuhn and Hamilton (2010) gives an average fire return interval of 8.63 years, with only 28.89 % of the area having a fire return interval of over 12.5 years (twice in 25 years) as recommended to maximise ecological biodiversity. The historically used fire return method by Forsyth and Van Wilgen (2008) of 12.8 years is 4.17 years more than the Wittkuhn and Hamilton (2010) average fire return interval of 8.63 years. This highlights that the current fire return period is more frequent than previously anticipated, making the potential biodiversity loss higher.

Table 4.3: The fire return interval from a space-time composite perspective, including both indigenous vegetation and IAPs for fires in the BMC from 1990 to 2019.

Category	**Hectares**	**Percentage**
0-2-years-old vegetation	1 108 773	4
2-4-years-old vegetation	4 545 788	16
4–6-years-old vegetation	4 203 509	15
6–10-years-old vegetation	10 559 513	37
10–15-years-old vegetation	5 393 948	19
15–25-years-old vegetation	2 689 998	9
≤ 25-year-old vegetation	213 156	1

Seasonal wildfire frequency within the BMC between 1990 and 2019 was as follows: summer 670 fires, autumn 214 fires, spring 85 fires and winter 80 fires. The seasonal percentage of total area burnt in in BMC over the study time frame was summer fires 72 % of the total area burnt, autumn fires made up 23 %, winter fires made up 3 % and spring fires made up 2 %. The seasonality of wildfire occurrence is in line with what is considered the best time ecologically to burn: late summer to early autumn. The number of fires seasonally for each size category between 1990 to 2005 and 2006 to 2019 for the BMC is shown in Figure 4.4. Summer fires equate to the bulk of all fires, with 64 %, showing a steep increase of 187 % before 2005. Autumn has the second highest percentage of fires, with 20 %, but with the smallest increase, pre- and post-2005, at 85 %. Lastly, both spring and winter had 8 % fires, but spring had a slightly higher frequency and a more significant increase of 225 % prior to 2005, while Winter only had an increase of 108 %. The number of fires increased after 2005 with a few exceptions, including the following:

- Very Large, Large and Medium category fires in autumn decreased by an average of 36 %.
- Large category fires in summer decreased by 36 %.
- Medium category fires in winter decreased by 23 %.

These decreases could be due to suppression efforts, fluctuations in climatic conditions, fuel load availability, or ignitions. Spring shows the smallest increase in fire frequency, and with no Large and Very Large category fires, this can be attributed to the Small and, to a lesser degree, the Medium fire category (Figure 4.3). The increase in spring fires and a decrease in autumn fires could suggest a slight shift to an earlier fire season with more fires starting in spring, or this again could be attributed to reporting bias. Again, the increased frequency increase across all season's post-2005 could be due to increased reporting. The one unexpected result is that the most significant increase in frequency was from spring; this could be attributed to the increase in reporting from the Small and Medium category fires, as shown in Figure 4.3. The overall increase in fire frequency could also be attributed to urban expansion coupled with changes in land use or management; the spread of IAPs and climate change can play a role.

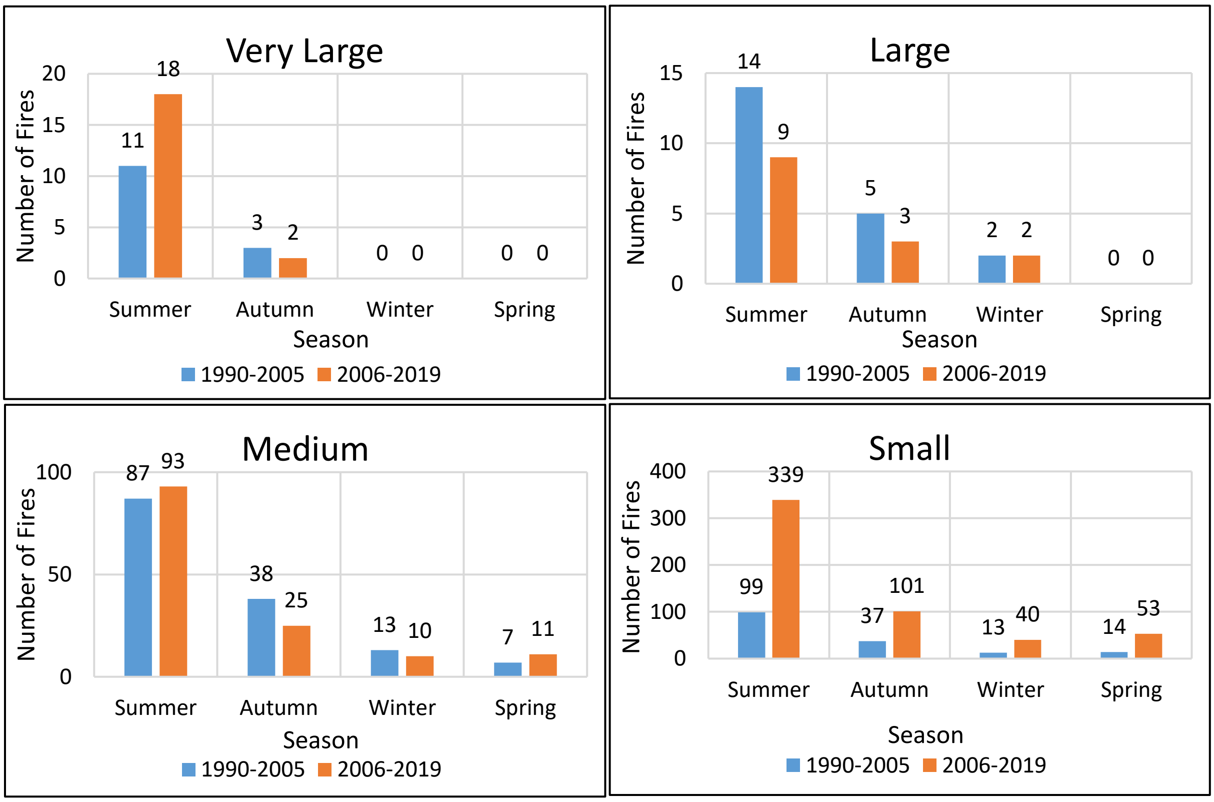


Figure 4.3: Number of fires per size categories in each season from 1990-2005 and 2006-2019 in the BMC.

4.3. Selected influencing factors of wildfire regimes

The selected influencing factors are fire ignition positions for all fires and the Very Large category as an extremity sample of wildfires, fire fuel load and fire weather conditions. The hectares of burnt area for each Very Large wildfire was the dependent variable against all other variables, including the total frequency, size and season in the BMC for the same year as the Very Large fire; the biomass, percentage IAPs, indigenous vegetation and age class, FDI, individual weather variables, total days burnt for each Very Large fire and the antecedent annual rainfall for the year each Very Large fire occurred and 12 and 24 months prior. Table 4.4 shows the top five best-fit models with the biomass and total hectares burnt in the BMC for the same year as the Very Large fire being the best fit both with comparably low AIC, AICc and BIC values; highly significant p values with less than 0. 001 and high R-squared value and percentage variance explained with 0.428, 42.795 % and 0.296, 29.580 % respectively. None of the other variables were considered statistically significant.

It is relatively predictable that the total hectares burnt in the BMC would be a best-fit model to explain the total hectares burnt of Very Large category fires for the same year as they would experience the same influencing factors such as urban expansion, changes in land use or management, the spread of IAPs and climatic changes. Very Large category fires take place only when particular conditions prevail. These conditions are governed by fire weather and mediated by fuel availability and connectivity (Bedia et al., 2015; Strydom, 2014). It is interesting, however, that the best-fit model was the biomass of Very Large category fires for the same year, suggesting that fuel load plays the most significant role in facilitating the occurrence of Very Large category fires.

Table 4.4: Top five best-fit models to the dependent variable of the total hectares burnt per Very Large fire category in the BMC between 1990 and 2019.

Variable	CV Decimal	AIC	AICc	BIC	P-Value	R-Squared	Percent Variance Explained
FIRE_CODE_Biomass_kg	0.702	593.794	593.919	595.321	<0.001	0.428	42.795
Hectares	0.672	600.860	600.985	602.387	0.001	0.296	29.580
BMC_Small	0.657	609.921	610.046	611.447	0.103	0.081	8.076
BMC_Summer	0.492	609.991	610.116	611.518	0.107	0.079	7.886
BMC_Large	0.919	610.063	610.188	611.589	0.112	0.077	7.691

Where: CV is the Coefficient of variance; AIC, the Akaike Information Criterion; AICc, the Akaike Information Criterion corrected; BIC, Bayesian Information Criterion; P-value, the Probability value and R-squared, the Coefficient of determination.
p < 0. 05 – Significant
p < 0. 01 - Very significant
p < 0. 001 - Highly significant

4.3.1. Relative fire ignition positions

The proximity of wildfire ignition points to human populations and access networks with wildfire frequency were analysed. Figure 4.4 shows the fire ignition frequency and the average distance from the closest town within the BMC from 1990 to 2019; this is more spatially represented on the map shown in Figure 4.5. The town with the most ignitions closest to it is Grabouw, with 75 ignitions an average of 6.6 km away from the central hub of the town, and Hermanus had the fewest ignitions, with only one ignition an average of 9.4 km away. Land use has also been found to influence fire activity. Price and Bradstock (2014) noted considerably higher fire activity where some urbanisation had occurred but still a large amount of vegetation remained. In an African context, many rural communities have a history of living with fire and use it not just for cooking but as a tool for grazing, hunting or clearing land, which can contribute to greater ignitions (Fynbos Fire Project, 2016). Many of the towns and villages surrounding BMC have land use practices like farming, which mostly requires a seasonal labour force or forestry, large portions of which have been phased out since 2000. This has resulted in growing improvised communities in many of these towns and villages, which illegally utilise conservation or forestry exit land to meet their needs. The increased illegal access in these areas is the likely cause of an increase of ignitions for activities including recreational use (such as cooking on open fire and smoking), arson (due to criminal, political or work circumstances) and cultural rituals (which involve fire). Other illegal activities also influence ignitions, including wood collection, which can cause sparks from using machinery for cutting and result in an increase in finer fuel, which is easily ignited (remaining smaller branches after harvesting firewood) and grazing (which is sometimes illegally burnt to create more grazing land).

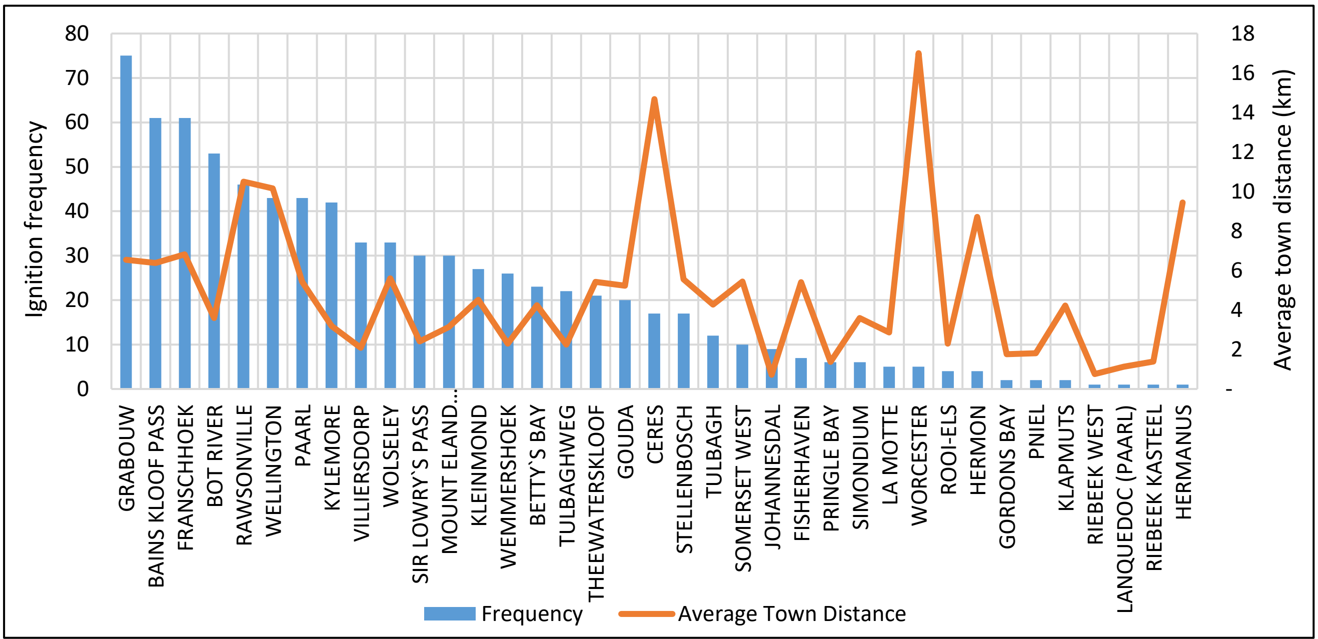


Figure 4.4: Distance and frequency of fire ignitions to the central hub of the nearest town or village between 1990 and 2019 in the BMC.

Figure 4.5 shows the distance from fire ignitions to the central hub of the nearest town or village on a map. Thus, the phasing out of selected South African Forestry Company Limited (SAFCOL) owned commercial plantations and a large amount of agricultural land could play a role in most of the ignitions being recorded closest to Grabouw due to its proximity. The town of Hermanus had the fewest ignitions, likely due partly to its proximity extending outside the study area, as shown in Figure 4.5. Regardless of these findings from a BMC management perspective, Hermanus would have the least relevance regarding ignitions based on proximity.

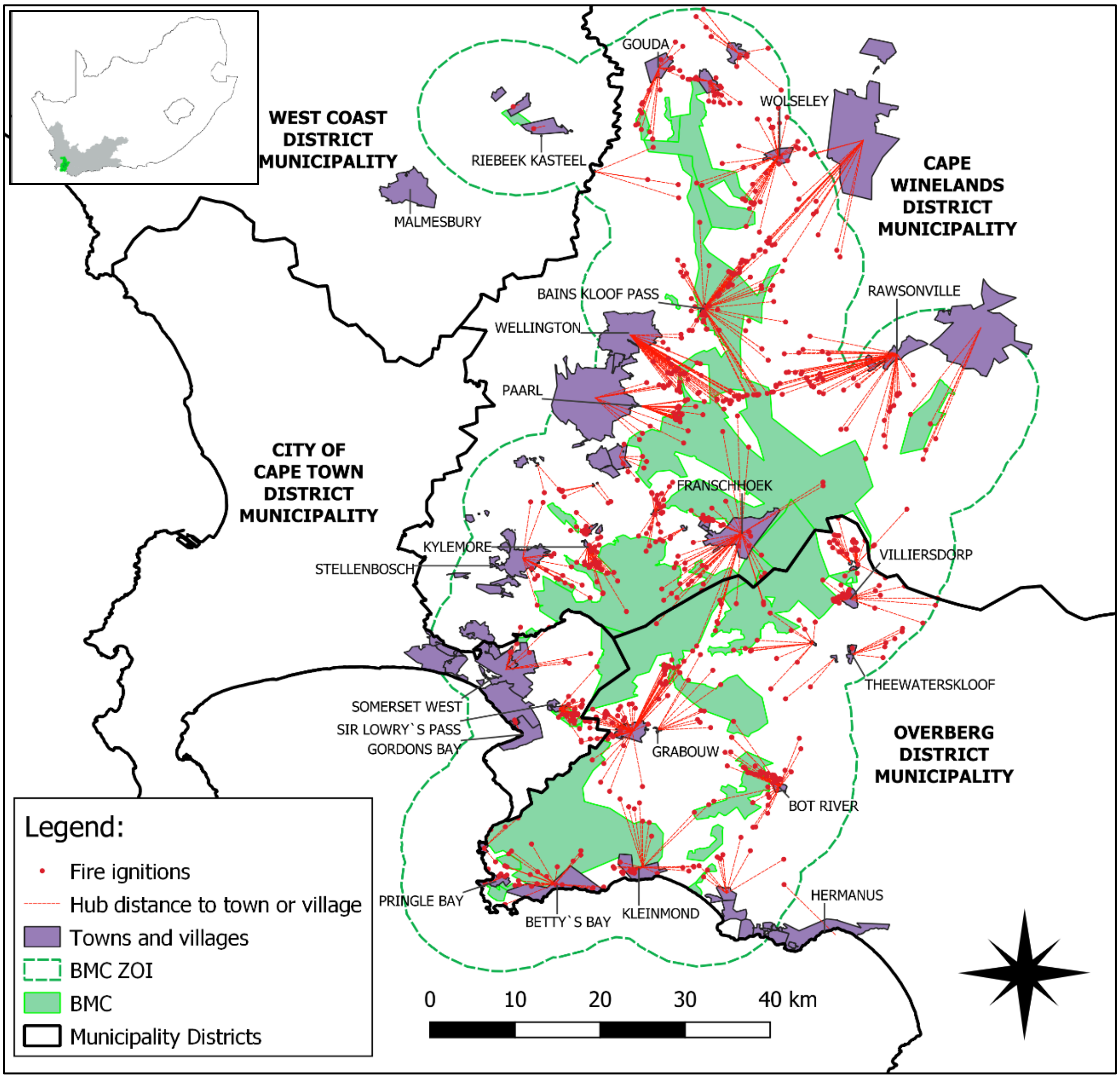


Figure 4.5: Distance from fire ignitions to the central hub of the nearest town or village between 1990 and 2019 in the BMC.

The ignition frequency and average distance to the closest transport route in the BMC from 1990 to 2019 are shown in Figure 4.6. Ignitions are recorded most frequently near track footpaths, with 340 ignitions an average distance of 0.20 km away, then secondary roads (including forestry and farm roads) with 249 ignitions an average of 0.25 km away, major roads with 184 ignitions an average of 0.14 km away and lastly railways with 29 ignitions an average of 0.28 km away. Most ignitions near track footpaths could be accounted for by illegal access from growing impoverished communities in many of these towns and villages that illegally utilise conservation or forestry exit land to meet their needs. Footpaths are also used for tourism and management access, but in such cases, users are more likely to be educated on the dangers of starting fires and, thus, a less likely ignition source. Secondary roads (including forestry and farm roads) could be linked to management activities or unauthorised access;

major roads give general public access and have the ignition possibility from vehicle accidents, as do railway lines with an added risk from potential embers and sparks from steam trains and or breaking.

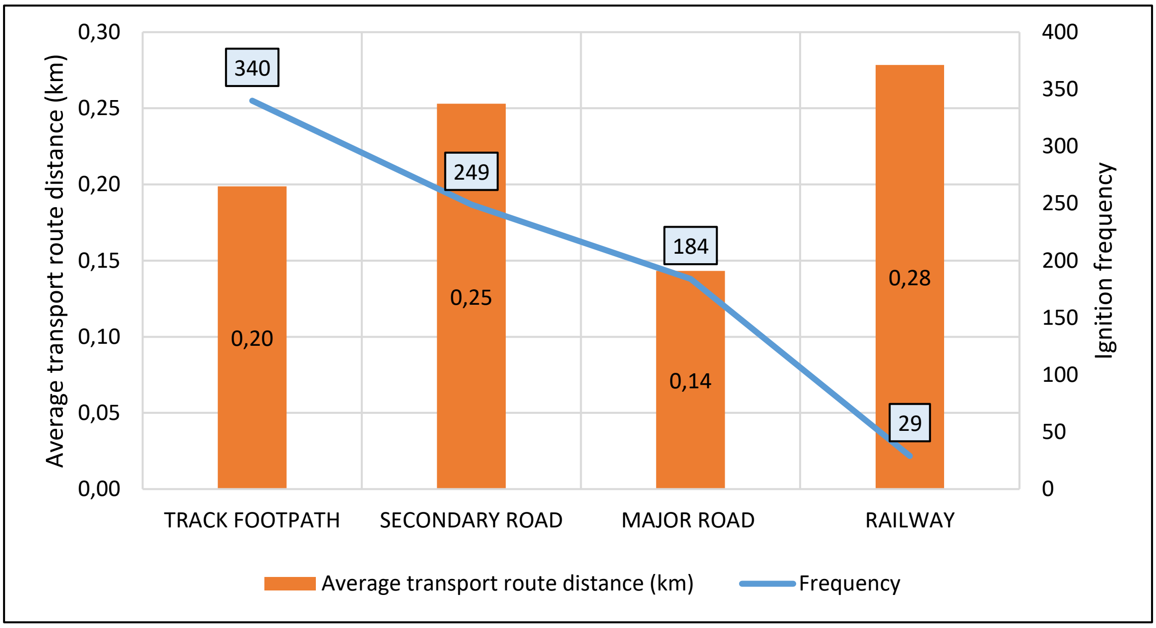


Figure 4.6: Ignition frequency and average distance to the closest transport route from 1990 to 2019 in the BMC.

4.3.2. Fire fuel load

The above-ground biomass was estimated and analysed for the Very Large category fires as a sample (if insufficient data was unavailable for individual fires, they were excluded) against critical aspects of wildfire regimes (fire size, frequency and seasonality). Figure 4.7 shows the division of hectares of indigenous vegetation in various age classes and IAPs for Very Large category fires in the BMC from 1990 to 2019. The IAPs equate to the largest burnt area for the Very Large category fires in the BMC within the study time frame, with 136 369.05 ha burnt. The 6-to-10-year-old category equates to the largest area of Indigenous veld burnt with 90 313.07 ha, closely followed by the 10-to-15-year-old category with 88 241.53 ha. The 25-years and older veld burnt the least, with 2 462.14 ha burnt within the Very Large category fires in the BMC in the study time frame.

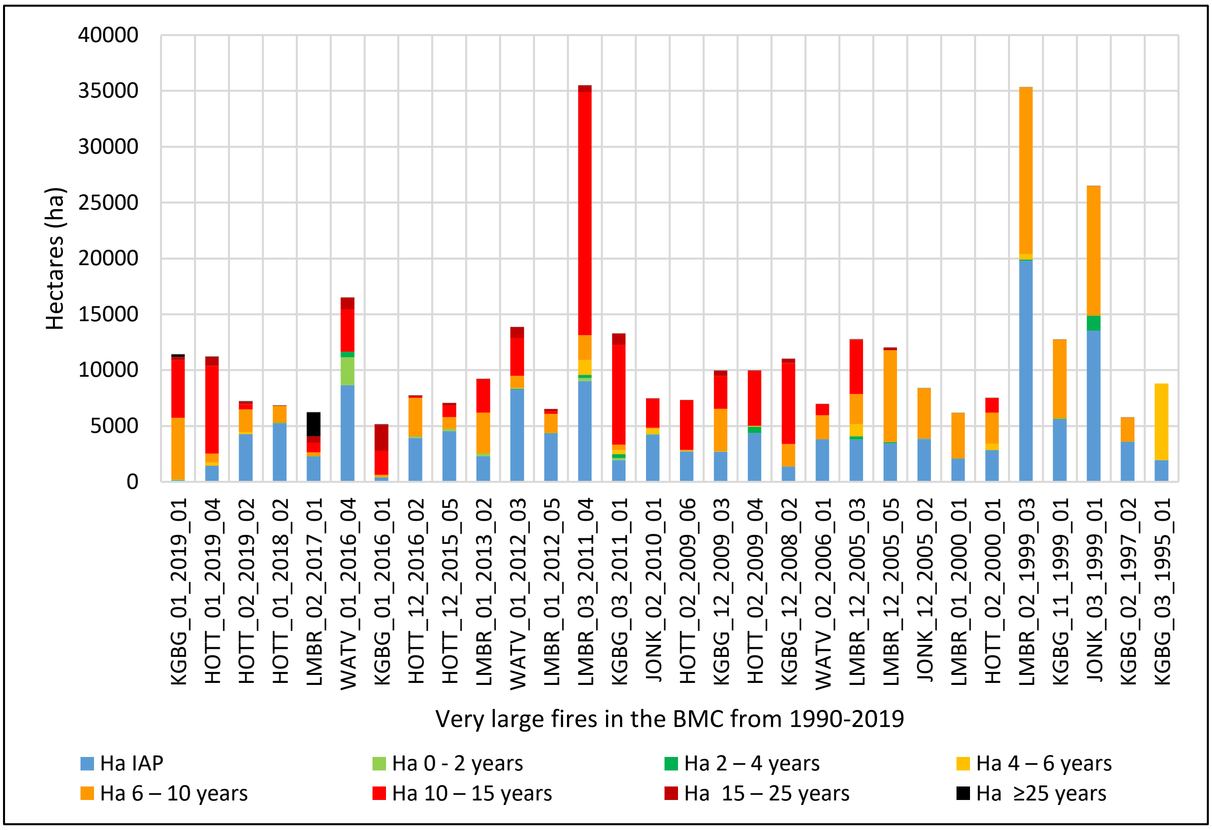


Figure 4.7: Hectares of indigenous vegetation in age class and IAPs for Very Large category fires in the BMC from 1990 to 2019.

It is interesting to note that the 6-to-10-year-old category equates to the largest area of indigenous veld burnt, which aligns with the average and majority of fire return intervals from the method described by Wittkuhn and Hamilton (2010) of 8.63 years and 37 %, respectively. According to Van Wilgen (1982) fynbos generally need to be about four years post-fire age to accumulate enough above-ground biomass to burn, but it will most commonly burn around 12 to 20 years post-fire. It is interesting to note that in this study the majority of fires are occurring just after they have accumulated enough above-ground biomass to burn which could be due to biomass accumulation, increased flammability of biomass or increased ignitions as discussed by Kraaij et al. (2022). This is however in line with more recent findings of Van Wilgen and Forsyth (2008) which found that in the wildfire regime of the western inland zone there was a decrease in wildfire return intervals and an increase in the percentage of short-interval fires (> 6 years). The second largest area of indigenous veld burnt in this study was from the 10-to-15-year-old category, which aligns with the average fire return interval from the method described by Forsyth and Van Wilgen (2008) of 12.8 years, and the second largest area burnt within this fire return interval from the method described by Wittkuhn and Hamilton (2010) of 19 %. This is also in line with the findings from Van Wilgen (1982) that above-ground biomass of fynbos most commonly burns around 12 to 20 years post-fire. It is also important to remember that the method used to extrapolate the IAPs was an estimate by colour-selected pixels and manual sense checking, but the method was consistently applied. More quantitative methods are currently being used to extrapolate the IAP percentage. However, they still allow a large margin for human error and inconsistency bias, and they have not consistently been done over the years this research examines.

In the statistical analysis, biomass was the best fit explanatory model for the dependent variable of total hectares burnt per Very Large category fire in the BMC between 1990 and 2019. It is important to remember that this was not biomass per hectare but the total biomass, which speaks to the biomass composition and the area's size. The division of hectares and percentage of burnt area for indigenous vegetation in various age classes and the IAPs for Very Large category fires in BMC from 1990 to 2019 is shown in Table 4.5. The IAPs make up the most significant average percentage of burnt area for Very Large category fires with 39 %, followed jointly with 26 % by the 6-10- and 10-15-year-old categories, then the 15- 25-year-old category with 3 %, and lastly, a three-way tie with 2-4-, 0-2- and 25 year and older categories.

The results are not too dissimilar from the fire return period method described by Wittkuhn and Hamilton (2010), considering that this method did not discern between IAP and indigenous vegetation. The Wittkuhn and Hamilton (2010) technique shows that from 1990 to 2019, the greatest amount of area burnt in the 6–10-year-old category at 37 % and the second largest area burnt fell into the 10-15-year-old category at 19 % and the smallest area burnt in the 25 year or older category with 1 % burning.

Table 4.5: The division of hectares and percentages of indigenous vegetation in various age classes and IAPs for Very Large category fires in the BMC from 1990 to 2019

Category	**Hectares**	**Percentage**
invasive alien vegetation	136 369,05	39
0–2-year-old indigenous vegetation	3 960,50	1
2–4-year-old indigenous vegetation	3 960,50	1
4–6-year-old indigenous vegetation	11 964,03	6
6–10-year-old indigenous vegetation	90 313,07	26
10–15-year-old indigenous vegetation	88 241,53	26
15–25-year-old indigenous vegetation	9 492,12	3
≥25-year-old indigenous vegetation	2 462,14	1

Figure 4.8 shows scatter plots with trend lines showing the relationships between the biomass (kg) per hectare for the Very Large category fires in BMC from 1990 to 2019 and the same year fire frequency and hectares burnt for the BMC. The biomass per hectare has an average of 95.63 kg, a maximum of 137.71 kg and a minimum of 62.30 kg per hectare. The year with the highest frequency of fires recorded within the BMC was 2015, with 82 fires, followed by 2017, with 77 fires; the biomass of the Very Large category fires for both of these years was above average, with 101.92 kg and 137.71 kg per hectare, respectively. The year with the largest area burnt recorded within the BMC was 1999, with 103 747.33 ha burnt; four Very Large category fires were recorded that year, but due to data gaps, the biomass for only three of these was calculated. The biomass of the 1999 Very Large category fires were 98.66 kg, 95.79 kg and 83.56 kg per hectare, two of which were above average. The year with the second highest recorded area burnt was 2011, with 58 781.00 ha; two Very Large category fires were recorded that year with biomasses of 100.68 kg and 99.23 kg per hectare, both of which are above average. Figure 4.8 seems to indicate a positive relationship between the biomass per hectare and the frequency of fires and hectares burnt within the BMC from 1990 to 2019. This supports the premise that higher amounts of biomass per area increase the likelihood of ignitions and the potential for larger areas to burn if continuous fuel is available. Frequent burns reduce fynbos biomass due to the loss of seed-reproducing shrubs, however, this is not the case with many IAPs which are fire-adapted and can outcompete the indigenous fynbos due to their superior growth rates and pre-adaptation to frequent fires (Van Wilgen, 1982; Van Wilgen, 2009). Van Wilgen (1982) found fynbos biomass was 6 700 kg per hectare four years after burning, 51 000 kg per hectare 21 years after burning and 76 000 kg per hectare 37 years after burning however a different equation was used to calculate biomass so these results are not comparable. Van Wilgen (1982) discussed that the fires burning under different weather conditions effects the amount of biomass is burnt, the hotter and drier the more biomass would be burnt. Vegetation recovery after longer fire return intervals, 20-25 years, was observed to be better than those areas burnt at shorter intervals, approximately 12 years (Van Wilgen, 1982)

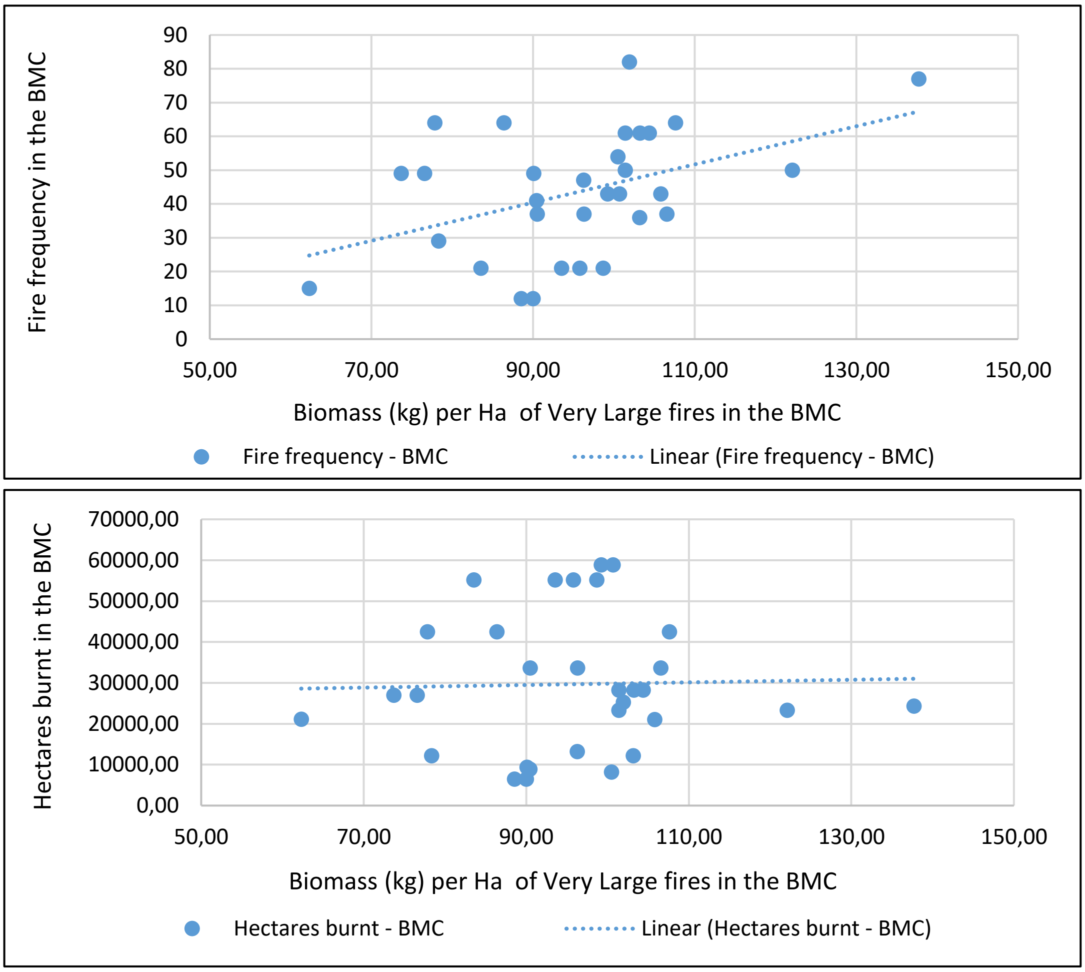


Figure 4.8: Scatter plots with trend lines showing the relationships between a) biomass (kg) per hectare for the Very Large category fires and b) fire frequency and total hectares burnt in the BMC from 1990 to 2019.

Of all the Very Large category fires in the BMC from 1990 to 2019 that occurred in summer and autumn, four Very Large fires were excluded as there was not enough available data to work out the biomass, two of which fell in summer and two in autumn. There does not seem to be any noticeable link between biomass and season. From the remaining 30 Very Large category fires 28 occurred in summer and had an average biomass of 95.39 kg of biomass per hectare and two occurred in autumn and had an average biomass of 99.95 kg of biomass per hectare.

4.3.3. Fire weather conditions

The average and start date FDIs and individual weather variables (temperature, relative humidity, precipitation and wind speed and direction) for the Very Large category fires as a sample were analysed against the frequency, hectares burnt and seasonality over the last three decades from 1990 to 2019 in the BMC. The antecedent annual rainfall, average temperature, and the Standardised Precipitation Index (SPI) over 12 months for weather stations with sufficient back data in the BMC were also examined regarding fire frequency, hectares burnt, and size category.

Weather variables were sourced from the closest weather stations, and the average and start date FDI were calculated and analysed against the critical aspects of wildfire regimes, including fire frequency and hectares burnt for relevant reserves and the BMC and seasonality for the Very Large category of fires from 1990 to 2019 in the BMC detailed in Table 4.6. Weather stations ranged from 8 km to 36 km from the Very Large category fire ignitions, averaging 22 km from the fire ignition. The FDI averages of all Very Large category fires between 1990 and 2019 in the BMC on the start date were 59 and 58 as the average FDI over all days burnt, both of which fall into the Yellow category. The highest start date and average FDI of a Very Large fire was in Limietberg Nature Reserve in the year 2000, with a start date FDI of 86 and an average FDI throughout the time it burnt of 77, both falling in the Red category. The frequency of fires for 2000 was two on reserve and 12 throughout the BMC, significantly lower than the average over the study period of 10 and 35, respectively. The total hectares burnt for 2000 were 6 465.47 ha on reserve and 22 711.29 ha throughout the BMC, lower than the average over the study period of 9 317.68 ha and 22 734.62 ha, respectively. These results could have been limited due to the availability of continuous fuel as the year 1999 showed the largest area burnt with 103 747.33 ha and suppression efforts.

In a study conducted by Van Wilgen et al. (2010) between 1970 and 2007 in the fynbos biome, fires were found to occur under a wide range of weather conditions. It was found, however, that more severe fires occurred in the inland zones, with three times as many days being classified as either high or very high FDI than in the coastal zones. It was also found that the Very Large category fires of over 5 000 ha was always associated with a moderate to high FDI, and fires over 10 000 ha were associated with a high to very high FDI from the McArthur Forest FDI.

No significant correlation exists between the start date or average FDI and the frequency of ignitions or hectares burnt on reserve and within the BMC between 1990 and 2019. There does, however, seem to be a significant relationship between the individual weather variables and the FDI values that were calculated from them. However, no positive relationship was found between the weather data and other aspects of the fire regime. It is important to note that the distance from ignition to weather stations averaged 22 km and ranged from 8 km to 36 km further than this was excluded. Weather can change dramatically in mountainous regions, even from one side to another of a Very Large category fire, due to complex interactions between altitude, topography and atmospheric conditions and fires can create their microclimate, so it is most likely that the weather data from the weather stations is not fully representative of that at the fires.

Table 4.6: Closest weather station for each Very Large category fire in the BMC from 1990 to 2019 and the FDI (colour coded as per fire danger categories, blue 0–19 low, green 20–44 moderate, yellow 45– 59 dangerous, orange 60–74 very dangerous or red ≥ 80 extremely dangerous) individual weather variables, fire frequency, hectares burnt and seasonality.

Fire Code	Year	Closest weather station	Weather station distance	Days burnt	Hectares burnt	Start date FDI	Average FDI	Max Temp (°C)	Min Temp (°C)	Avg. Temp (°C)	Avg. Wind Speed (km/h)	Avg. Wind direction	Avg. Rain (mm)	Avg. Humidity	Fire frequency BMC same	Ha burnt BMC same year	Season
HOTT/01/2019/04	2019	Hermanus	29,45	11	11211,82	45	42	26,40	18,40	22,15	18,69	S	0	68,33	37	33596,04	Summer
HOTT/02/2019/02	2019	Paarl	35,86	7	7212,12	62	59	35,10	29,60	32,54	7,65	SW	0	33,75	37	33596,04	Summer
KGBG/01/2019/01	2019	Strand	23,63	19	11423,77	46	52	32,10	17,50	24,47	24,52	WSW	0,01	55,50	37	33596,04	Summer
HOTT/01/2018/02	2018	Worcester-AWS	30,13	8	6831,07	84	64	41,50	28,40	33,10	15,00	SSW	0	32,11	41	8868,71	Summer
LMBR/02/2017/01	2017	Paarl	11,59	6	6234,79	56	57	34,00	24,30	29,76	9,98	S	0	34,43	77	24320,59	Summer
HOTT/12/2016/02	2016	Strand	10,09	21	7715,61	52	56	35,40	20,70	26,72	22,53	S	0	49,50	64	42440,36	Summer
KGBG/01/2016/01	2016	Hermanus	23,46	7	5141,71	53	42	26,00	18,20	22,40	18,32	SE	0	65,50	64	42440,36	Summer
WATV/01/2016/04	2016	Worcester-AWS	19,26	18	16497,38	61	65	39,30	26,00	31,62	19,10	SSW	0	34,21	64	42440,36	Summer
HOTT/12/2015/05	2015	Paarl	35,71	9	7062,70	64	62	41,90	23,90	31,88	11,75	SW	0	31,38	82	25250,53	Summer
LMBR/01/2013/02	2013	Paarl	22,12	6	9208,70	64	65	37,70	30,00	33,63	11,37	SSE	0	26,00	47	13172,44	Summer
LMBR/01/2012/05	2012	Worcester-AWS	22,82	7	6508,90	63	62	36,50	25,60	30,29	18,05	S	0	35,38	50	23273,37	Summer
WATV/01/2012/03	2012	Worcester-AWS	26,31	5	13839,61	67	71	34,70	29,50	33,22	20,34	SSW	0	28,00	50	23273,37	Summer
KGBG/03/2011/01	2011	Hermanus	16,48	14	13290,45	44	39	26,60	18,60	22,16	14,09	SSW	0,08	63,47	43	58781,00	Autumn
LMBR/03/2011/04	2011	Worcester	17,43	16	35499,75	49	61	35,80	23,50	29,72	15,52	S	0	33,65	43	58781,00	Autumn
JONK/02/2010/01	2010	Paarl	29,29	6	7470,23	58	61	39,60	30,90	33,71	9,41	WSW	0	33,00	43	21001,60	Summer
HOTT/02/2009/06	2009	Strand	22,36	7	7317,54	52	43	31,00	22,80	26,49	21,29	SW	0	53,75	61	28217,78	Summer
KGBG/12/2009/03	2009	Hermanus	24,13	4	9940,13	40	41	24,40	21,50	22,64	19,87	S	0	72,40	61	28217,78	Summer
KGBG/12/2008/02	2008	Strand	18,93	6	11005,61	57	56	34,10	25,00	28,49	18,98	S	0	45,29	36	12134,64	Summer
WATV/02/2006/01	2006	Worcester-AWS	24,93	7	6979,40	69	63	40,20	26,20	31,45	18,54	SSE	0	37,13	54	8154,80	Summer
JONK/12/2005/02	2005	Paarl	25,10	5	8362,90	64	66	36,90	32,00	34,73	8,82	SSE	0	21,17	49	9287,38	Summer
LMBR/12/2005/03	2005	Paarl	22,83	6	12775,20	58	60	32,50	23,10	28,04	10,39	SSE	0	25,14	49	26940,25	Summer
LMBR/12/2005/05	2005	Paarl	19,97	10	12011,51	68	66	36,90	31,60	33,69	9,46	SSE	0	21,27	49	26940,25	Summer
LMBR/01/2000/01	2000	Worcester	9,81	2	6179,91	86	77	38,50	32,50	35,47	22,68	W	0	22,00	12	6465,47	Summer
LMBR/02/1999/01	1999	Paarl	15,73	3	7713,30	69	65	36,60	32,60	35,33	8,91	SSE	0	27,25	21	55124,90	Summer
KGBG/02/1997/02	1997	Strand	8,11	5	5764,57	44	53	27,10	21,90	24,03	23,64	S	0	53,83	29	12180,87	Summer

Table 4.7 shows the fire frequency, hectares burnt, the antecedent annual rainfall, average temperature, and the SPI over 12 months for weather stations with sufficient back data in the BMC. The drier years are highlighted in red as those with a negative SPI based on the average rainfall across the four nearest weather stations with sufficient data. Weather rainfall data was unavailable for the relevant weather stations from 1990 to 1995; thus, the SPI was only worked out from 1996 to 2019. Drought years in the BMC included 2019, 2017, 2016, 2015, 2011, 2010, 2006, 2005, 2000, 1998 and 1997. Of the 24 years considered 11 had a negative SPI, equating to just under half of the years looked at in this study were drought years. The drought years account for 54.34 % of the fire frequencies, 56.16 % of the total hectares burnt and 70.83 % of the Very Large category fires (Table 4.7).

Keeley (2004) found a statistically significance relationship between drought years and fire occurrence in coastal California with a lag effect of one year; however, it was found to have little predictive power. However, Keeley (2004) speculated that rainfall might have some predictive benefit in indicating to managers whether the upcoming fire season would be abnormally high or low. Increased rainfall affects vegetation growth and, thus, biomass accumulation and slows down vegetation curing, leaving it with a higher moisture content, which is less flammable. Decreased rainfall can kill off some biomass, facilitate curing and prepare it as fuel.

This study considered a lag effect of one year preceding years with a negative PSI from 1995 to 2020 to accommodate the lag. The lag accounted for 45.08 % of the fire frequencies, 54.42 % of the total hectares burnt and 60 % of the Very Large category fires. For the same time frame, the years with a negative PSI without the lag effect accounted for 53.28 % of the fire frequencies, 54.85 % of the total hectares burnt and 68 % of the Very Large category fires. Considering the results from this study, it would be more accurate to look at years with a negative PSI without the lag effect as an indication of how extreme a fire season will be. Years with a negative PSI in the BMC are likelier to have higher fire frequencies, more total hectares burnt, and more Very Large category fires.

Table 4.7: Annually the number of fires and hectares (Ha) burnt within the BMC and the antecedent annual rainfall (mm) and average temperature (°C) and the Standardised Precipitation Index (SPI) over 12 months for weather stations with sufficient back data in the BMC from 1990 to 2019. The drier years are highlighted in red as those with a negative SPI.

Year	BMC		Hermanus		Paarl		Strand		Worcester		Total		
	Fires	Ha burnt	Avg Temp	Total Rain	Avg Temp	Total Rain	Avg Temp	Total Rain	Avg Temp	Total Rain	Avg Temp	Total Rain	SPI-12
1990	19	39497,3							19,1		19,1		
1991	12	23321,6							20,9		20,9		
1992	19	21117,3	19,4						19,7		19,6		
1993	13	9779,3	19,6	129,4	22,5	69,8			20,7	63	20,9	87,4	
1994	14	6360,8	18,8	83,6	22,1	153,8			20,9	50,2	20,6	95,9	
1995	15	21067,3	18,4	126,8	21,6	226			20,5	50,8	20,2	134,5	
1996	9	2295,4	18	69,4	20,9	232,8	16,7	100,8	20,1	54	18,9	114,3	0,43
1997	29	16134,4	18,8	64,4	21,7	143,2	19,3	115,6	21	32,6	20,2	89	-0,73
1998	30	9449,1	18,6	105,6	22	162,4	19,3	103,6	20,9	8,4	20,2	95	-0,45
1999	21	103747,3	19	80	22,8	301,8	20	107,4	22	49,4	21	134,7	1,37
2000	12	22711,3	18,8	37,2	22,2	144,6	19,4	87,2	22,2	35	20,7	76	-1,33
2001	16	5865,2	18,9	83,6	21,6	274,4	19,2	121,8	22,2	36,4	20,5	129,1	1,11
2002	5	2140,1	18,8	113,8	20,9	193,4	19,4	93,8	21,9	61,4	20,3	115,6	0,49
2003	31	4827,6	19,2	128	21,4	136,2	20	131,6	21,9	36,2	20,6	108	0,14
2004	49	14272,4	18,9	101,4	22,3	189	20,5	116,6	22,1	25,8	21	108,2	0,15
2005	49	46334,9	19,4	89,8	21,6	146,6	20	60	21,4	38,6	20,6	83,8	-0,97
2006	54	14992,4	18,7	71,6	22	123,2	19,6	105,2	21,1	34,4	20,3	83,6	-0,98
2007	25	7411,4	19,4	109,8	21,8	127,6	19,9	121,4	21,2	67,6	20,6	106,6	0,08
2008	36	18981,6	18,8	115,4	21,9	231,8	20	178	21	86,2	20,4	152,9	2,20
2009	61	37453	19,2	109,4	22,7	149	19,4	127	21	77,4	20,6	115,7	0,50
2010	43	21001,6	18,9	83	22,9	120,4	19,5	126	21	36	20,6	91,4	-0,62
2011	43	58781	18,6	87,2	22	105,6	20,1	115	20,8	72,2	20,4	95	-0,45
2012	50	23273,4	19	93,8	21,5	177	19,6	134,2	20,7	57,2	20,2	115,6	0,49
2013	47	13172,4	19,1	121,6	21,5	186	19,5	192,4	20,6	85	20,2	146,3	1,90
2014	46	3574,1	19,5	116,4	22,1	166,2	20,7	150	20,9	63,6	20,8	124,1	0,88
2015	82	25250,5	18,6	93,6	22,4	105,4	20,2	53,8	21,3	38	20,6	72,7	-1,48
2016	64	42440,4	19,3	81,4	22,8	106,8	20,4	103	22,2	29	21,2	80,1	-1,14
2017	77	24320,6	19,1	62,8	22,4	115,4	20,3	79,2	22,1	33,4	21	72,7	-1,48
2018	41	8868,7	19,5	94	22,3	172	20,3	96,6	21,9	63,4	21	106,5	0,07
2019	37	33596	19	135,6	22,1	107,6	20,6	105	22	55	20,9	100,8	-0,19

Figure 4.9 shows scatter plots with trend lines showing the relationships between fire frequencies, total hectares burnt in the BMC from 1990 to 2019, total precipitation, and average temperature. This seems to indicate a positive relationship between years with higher temperatures, resulting in a tendency for more frequent fires and more hectares burned. It also seems to show a negative relationship between years with higher rainfall, suggesting more fires and more hectares burnt in years with less rainfall.

Long-term weather forecasts of lower rainfall and higher temperatures can indicate a fire season with more frequent ignitions and larger amounts of burnt hectares. Fire frequency seems to have a stronger relationship with temperature and rainfall. This could also relate to fuel availability. Suppose lower rainfall and higher temperature conditions occur sequentially. In that case, it might not allow enough biomass to build up, thus accounting for more frequent ignitions but insufficient fuel to burn large amounts of hectares.

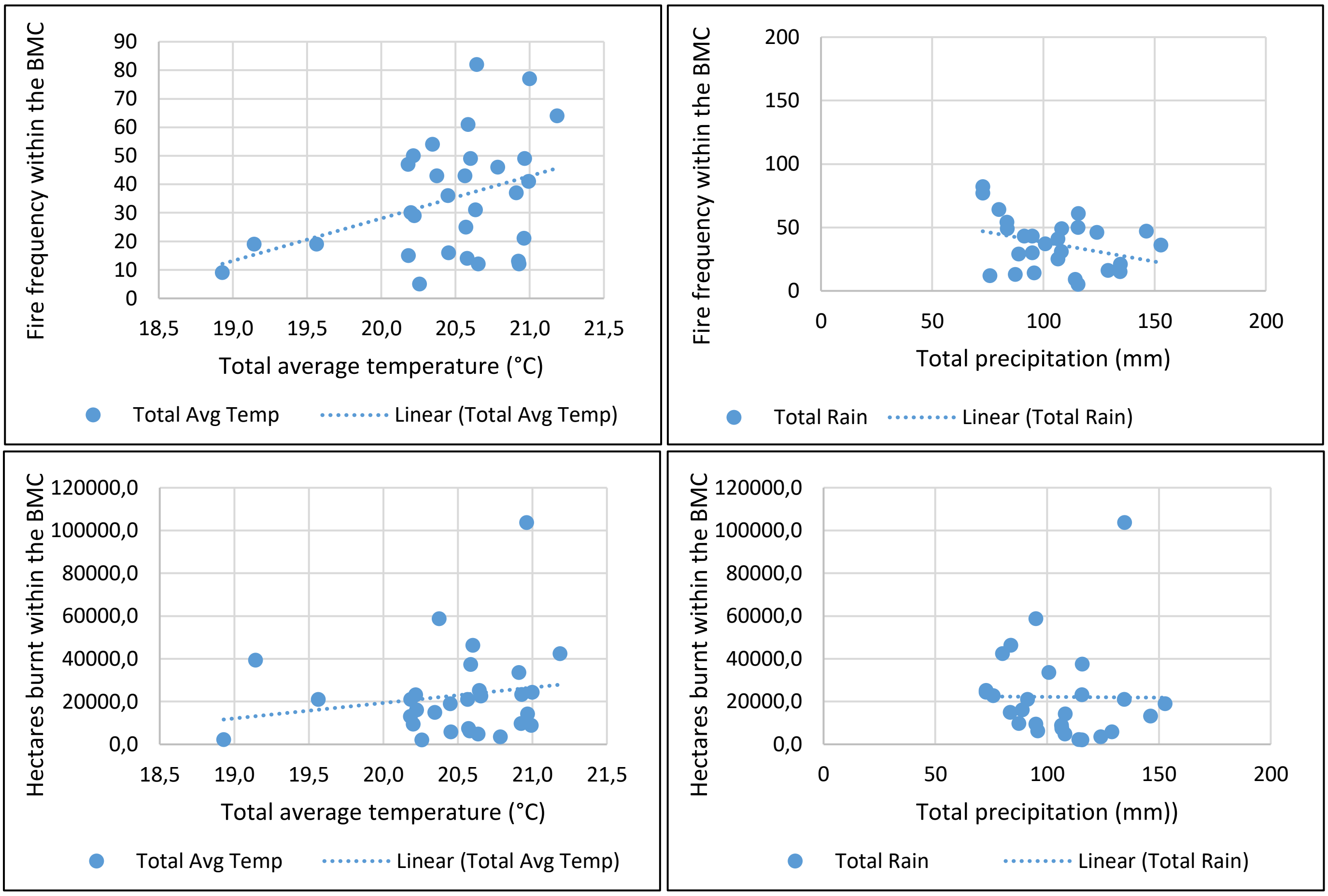


Figure 4.9: Scatter plots with trend lines showing the relationships between a) fire frequencies and total hectares burnt in the BMC from 1990 to 2019 and b) total precipitation and average temperature.

Botai et al. (2017) looked at the SPI for the Western Cape Province from 1985 to 2016; the averages for these time series can be seen in Figure 4.12 for three (SPI-3), six (SPI-6) and 12 (SPI-12) months. A drought event has been defined as an SPI lower than zero, and the more negative pertains to the severity. Botai et al. (2017) explain that SPI can be looked at on different timescales for different purposes, but 12 and 24 months are the most relevant to hydrological and socio-economic impacts, respectively. Interestingly, the drought years noted for the BMC mostly fall within the Western Cape Province drought years. If the years after 2015 are excluded to align the timeframes, then 2005 and 2006 are the only two that are not drought years for the Western Cape Province. Table 4.7 shows the following years as years with less precipitation: 2015, 2011, 2010, 2006, 2005, 2000, 1998 and 1997 within the BMC and Botai et al. (2017) findings show 2015, 2014, 2011, 2010, 2009, 2000, 1999, 1998 and 1997 as drought events for the Western Cape Province over the same time frame (Figure 4.10). The Western Cape Province drought prediction would be most effectively utilised as an exclusionary tool; if no drought is predicted, there is likely to be fewer frequent fires and fewer total hectares burnt within the BMC. If a drought is predicted from the Western Cape Province, it does not necessarily translate to the BMC but does not exclude it.

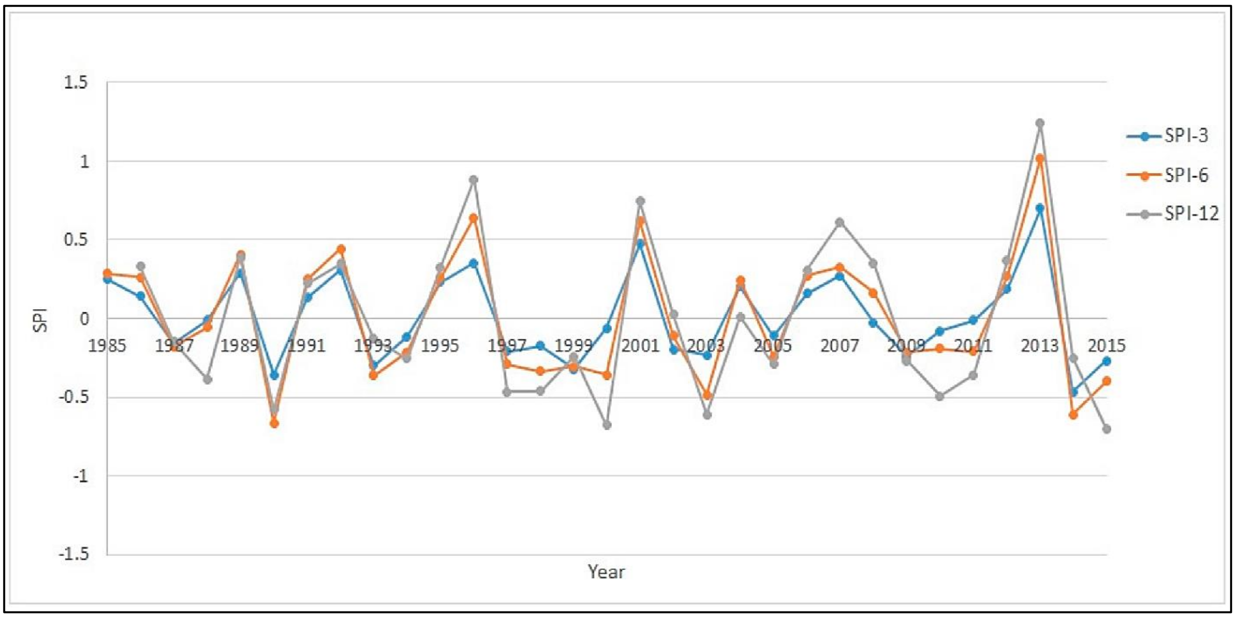


Figure 4.10: Annual average Standardised Precipitation Index (SPI) time series at different time scales (Botai et al. 2017).

Figure 4.11 shows the average rainfall for the same year, 12 months, and 24 months prior to Very Large fires from weather stations closest to the ignitions and the SPI over 12 months for the BMC from 1990 to 2019, where data was available. Based on the average annual rainfall on the year that Very Large category fires occurred within the BMC, 40 % of Very Large category fires received less rainfall 12 months prior to the year the fire occurred, and 60 % of Very Large category fires received less rainfall 24 months prior than the year the fire occurred. This seems to show a link between drier years preceding years with fires from the Very Large category. Unfortunately, this has very little predictive value related to PSI, which is worked out from the annual precipitation for the same year that the Very Large category fires occurred. However, 18 out of 30 Very Large category fires from 1996 to 2019 occurred in negative PSI years, accounting for 60 %. As a predictor for management, it must be noted that a lower average annual rainfall seems to dramatically increase the chances of a Very Large category fire.

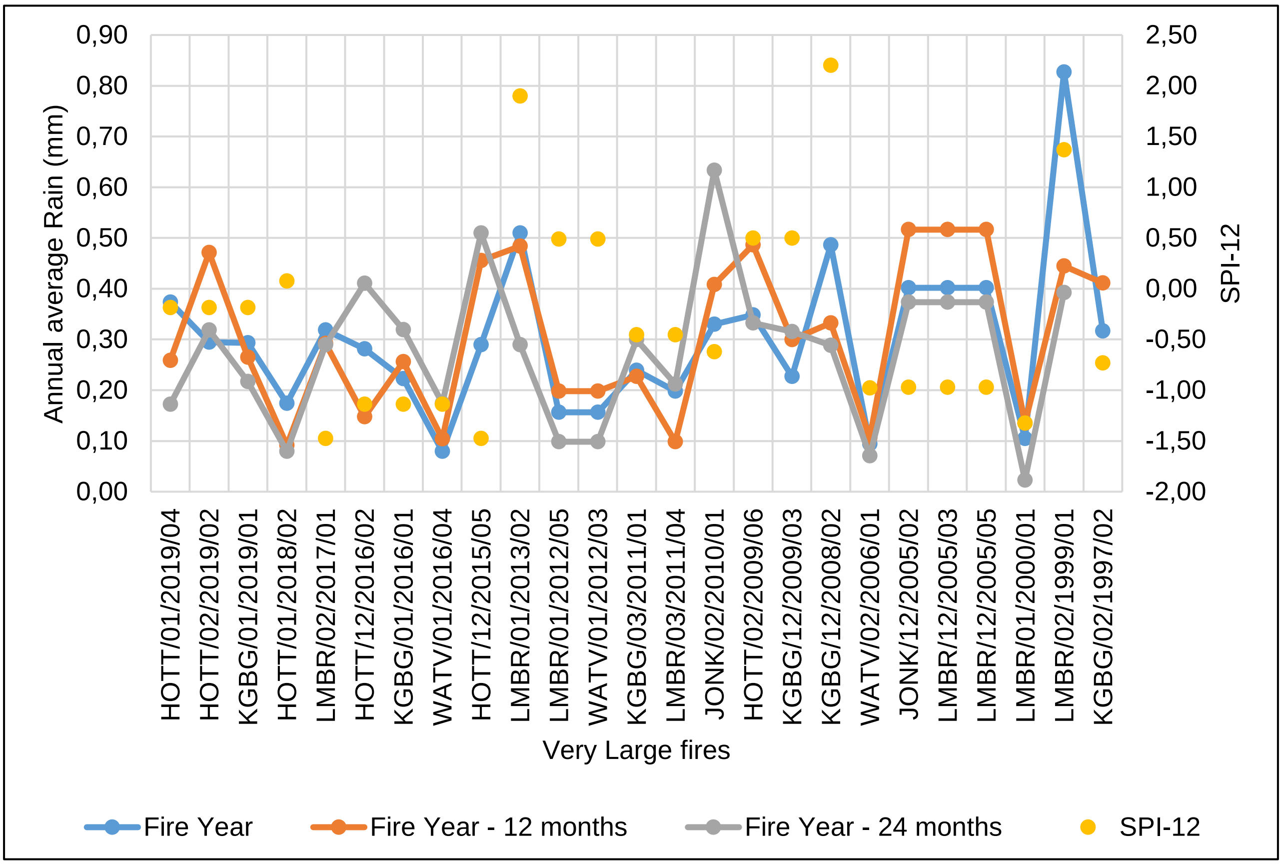


Figure 4.11: Average rainfall from Very Large fires, with sufficient back data, for the year of occurrence, 12 and 24 months prior to these fires and the SPI over 12 months in the BMC from 1990 to 2019.

CHAPTER 5
Conclusion and Recommendations

5.1. Conclusion

This thesis has provided an in-depth examination of influencing factors that shape the fire regime, explicitly focusing on the roles of fire ignitions, fuel load and weather conditions in the Boland Mountain Complex (BMC) from 1990 to 2019. The research highlights the detailed relationships between these factors and the fire regime and discusses the potential causes and impact on biodiversity.

The key findings of wildfire regimes in the BMC from 1990 to 2019, including the size category, fire frequency, the fire return period, and the fire season, are as follows. While fire frequency was a good indication of regularity and likelihood of fires, as confirmed by Lutz *et al.* (2011), due to potential bias, cumulative hectares burnt per year gave a more reliable indication of the scale of impact on ecosystem health, with too frequent fires leading to potential degradation of habitats and loss of biodiversity. The fire frequency increased from 294 fires recorded prior to 2005 to 755 fire records after that, and the cumulative hectares burnt per year also increased from 302 586.59 ha prior to 2005 to 379 452.11 ha after that. It is important to note that the recorded increase in ignition frequencies and subsequently measured hectares post-2005 could be due to increased reporting, particularly in the Small fire category. It could also be attributed to urban expansion coupled with changes in land use or management, the spread of invasive alien plants (IAPs) and climate change can play a role in increased fire ignitions.

Conversely, many fynbos plant species require fire for germination. Thus, too infrequent fires may result in biodiversity loss and the accumulation of combustible materials, increasing the likelihood of catastrophic fires. The study emphasised the need for maintaining a fire regime that maintains biodiversity and ecological resilience while reducing the risk of extreme fire events. The concept of the fire return period provided valuable insights into the natural recurrence of fires and subsequent potential impact on biodiversity. By analysing historical data, the research gave a more accurate insight into the fire return period within the BMC and compared it to current standards for maintaining biological diversity. The mean fire return interval, as determined by the same method used by Forsyth and Van Wilgen (2008), is 12.8 years, including both indigenous vegetation and IAPs. The fire return interval from a space-time composite perspective, as determined by the same method used by Wittkuhn and Hamilton (2010), including both indigenous vegetation and IAPs, shows the 6–10-years-old vegetation category with the highest percentage of 37 % and only 1 % in the 25-year or older vegetation category. The method described by Wittkuhn and Hamilton (2010) gives a comparable average fire return interval of 8.63 years, with only 28.89 % of the area has a fire return interval of over 12.5 years (twice in 25 years), as recommended to maximise ecological biodiversity. While fire is required in fynbos, the shorting fire regime and its effect on slow-maturing, serotinous Proteaceae species, as a suitable indicator species for biodiversity, is a current primary concern in the BMC. Several Protea species require fire return intervals of more than 12 years so as not to face population declines or local extinction (Van Wilgen 1982, Van Wilgen & Forsyth 2008). The findings suggest that the current fire return period is shorter than previous estimations, which could result in biodiversity loss through seed and fauna destruction, change vegetation structure, and significantly reduce certain above-ground nutrients through volatilisation and, to a lesser degree, influence soil erosion and leaching from increased stream flow (Kraaij & Van Wilgen, 2014).

For the statistical analysis, the annual total hectares burnt in the BMC between 1990 and 2019 was used as the dependent variable, and the frequency of Very Large and Large category fires were the best-fit models. This highlights the importance of speed and scale of suppression response to keep wildfires in the Small or Medium fire categories. According to Van Wilgen and Forsyth (2008), no fires should exceed 5 000 ha, putting them in the Very Large category of fires; however, fires over 1 000 ha in size should make up more than 75% of the total burnt area. Large fire sizes create homogeneity in vegetation age, can limit seed dispersal into burnt areas, and thus limit habitat and food availability for faunal elements (De Klerk et al. 2009). An increase in Small and Medium category fires would create a buffering effect by creating sections of younger, less flammable vegetation, helping to limit fire spread and facilitate suppression efforts. However, too many small fires put increased pressure on suppression resources and create an increased edge effect, allowing for more seed predation (Van Wilgen & Forsyth 2008).

Seasonality was also identified as a critical factor in fire regimes. Late summer and early autumn fires are optimal for most flora and fauna species within fynbos, as most flowering activity and breeding habits are associated with non-fire season month strategies (CapeNature, 2019; Van Wilgen & Forsyth, 1992). Out-of-season burns can impact the potential ecological benefit of burns and are critical for wildfire management in planning resource availability. The seasonal frequency breakdown of wildfires with the BMC from 1990 to 2019 was as follows: summer 63.9 %, autumn 20.4 %, spring 8.1 % and winter 7.6 % and the seasonal percentage of total area burnt were summer fires 72 %, autumn fires 23 %, winter fires 3 % and spring fires 2 %, which is in line with what is considered the best time ecologically to burn, late summer to early autumn. The number of fires seasonally for each size category mainly increased between 1990 to 2005 and 2006 to 2019 in the BMC, with a few exceptions. Fires in autumn for Very Large, Large and Medium categories decreased by an average of 36 %, fires in Summer for the Large category decreased by 36 %, and fires in winter for the Medium category decreased by 23 %, which is lightly due to suppression efforts. Spring showed a slight increase in wildfires and a notable decrease in autumn fires, which could suggest a slight shift to an earlier fire season with more fires starting in late spring. This seasonal shift could be attributed to reporting bias or climate change, land use or management changes, and the spread of IAPs. Effective wildfire planning and preparedness must be in place to account for seasonal variations in weather conditions and buffer against potential long-term effects of climate change to minimise adverse ecological outcomes.

The key findings of selected influencing factors comprising fire ignition positions, fire fuel load, and weather are as follows.

Fire ignition frequency and the average distance from the closest town within the BMC from 1990 to 2019 were calculated, with the most significant number of ignitions being closest to Grabouw, with 75 ignitions at an average distance of 6.6 km. The ignition frequency and average distance to the closest transport route were recorded most frequently near Track Footpaths, with 340 ignitions an average distance of 0.20 km away, then Secondary Roads (including forestry and farm roads) with 249 ignitions an average distance of 0.25 km away, Major Roads with 184 ignitions an average distance of 0.14 km away and lastly Railways with 29 ignitions an average distance of 0.28 km away. Cardille *et al.* (2001) found that proximity to access networks brings a higher potential for increased anthropogenic ignitions and the probability of reported fires and better access to fire suppression, which could account for Major Roads having the highest percentage of ignitions from the Small fire category. It should be considered to use proximity to access networks and their various user groups as the cause of anthropogenic ignition sources, as this method can be consistently applied if the ignition cause is unknown.

In the statistical analysis, biomass followed by hectares burnt within the BMC each year was the top two best-fit explanatory models for the dependent variable of total hectares burnt per Very Large category fire in the BMC between 1990 and 2019. Biomass was calculated from IAPs and indigenous vegetation per age class. The method used to extrapolate the IAPs was an estimate based on colour-selected pixels and then manual sense-checking, but the method was consistently applied. More quantitative methods are currently being used to extrapolate the IAP percentage. However, they still allow a large margin for human error and inconsistency bias, and they have not consistently been done over the years this research examines.

None of the weather-related models were statistically significant against the dependent variable of total hectares burnt per Very Large category fires in the BMC between 1990 and 2019. There is, however, a notable correlation between annual rainfall and average temperature against fire frequency and cumulative hectares burnt in the BMC for the same year. It is important to note a few things from the weather data: weather stations further than 36 km from the ignition point were excluded, and the average weather conditions were taken from the duration of the time the fire burnt. Weather can change dramatically in mountainous regions, even from one side of a Very Large fire category fire to another. These weather changes are due to the complex interactions between altitude, topography, and atmospheric conditions, and additionally, fires can create a microclimate. Considering this, the weather station data may not fully represent the weather variables influencing Very Large fires.

Important goals set out in the CapeNature 2019 – 2029 PAMP is to achieve an ecologically healthy fire regime by 2029 in Mountain, lowland and Swartland Alluvium fynbos defined as having less than 20 % of area burnt twice or more in the last 25 years, not more than two of the age classes are below 5 % or above 20 % and more than 80 % of the area burnt during December till April (CapeNature, 2019). The results show in the temporal time frame of this research that if the 10-15-year-old category were divided equally into half, 81.5 % of the area would have burned more than twice in 25 years, falling short of the goal by 61.5 %. Not more than two age classes were below or above the given thresholds, with the 0-2-years-old and ≤ 25-year-old vegetation categories area being below 5 % with 4 and 1 %, respectively, and the 6–10-years-old vegetation category is over 20 % with 37 %, so this is in line with the healthy fire regime goal. Seasonally, 95 % of burns occurred in summer and autumn from November till April inclusive, which also seems to align with the healthy fire regime goal. Strategy three of rectifying the inappropriate fire regime of the BMC PAMP is to "Enhance the implementation efficiency of the Alien Vegetation Management and Fire Programmes in the BMC to abate the negative effect that IAPs and inappropriate fire regimes have on biodiversity and water availability" (CapeNature, 2019). This research confirms that IAP management and Fire Programmes must be prioritised to significantly decrease the fire return period.

Overall, this study contributes to a more significant understanding of the wildfire regime, notably wildfire size category, frequency, return period, and seasonality within the BMC necessary for its management. The insights gained from this study underscore the importance of a comprehensive and holistic knowledge base from a spatio-temporal perspective. Such an approach is essential in practising integrated wildfire management to protect against negative social, ecological and economic impacts from wildfires.

5.2. Recommendations

Based on this study's findings, the following recommendations are proposed to enhance integrated wildfire management strategies, focusing on size category, fire frequency, fire return period, and fire seasonality.

5.2.1. Legislation

Legislation regarding wildfire management creates structure and provides guidelines for effective management. While an adequate legislative framework is thought to exist, many government spheres at various levels and other entities mandated to uphold the legislation do not have the capacity in terms of personnel and operating budget to do so effectively. It is recommended that a specific in-depth review of legislation pertaining to wildfires be conducted to identify any shortcomings.

5.2.2. Prediction

Prediction measures can help reduce wildfire size, optimise fire return periods over time, and buffer against changes in seasonality. Risk assessments can help plan and schedule preventative measures and prioritise resources for preparedness. Early detection can help the speed and scale of resource deployment for the initial attack.

- **Risk assessments:** Risk assessments must be updated annually, including hazards, such as areas with high fuel loads and historically high ignition frequency and vulnerable areas where life safety is at risk or ecological or economic assets are exposed. It also ranks hazardous and vulnerable areas to prioritise risk mitigation efforts. It is also recommended not to just consider the special aspects of risk but also temporal aspects to see if any patterns emerge, such as seasonally or particular days of the week when more wildfires or ignitions are likely to occur.
- **Early detection:** It is recommended to make use of satellite fire detection tools to assist with detection in remote areas or when staff are not on-site and using the Fire Danger Index (FDI) and Standardized Precipitation Index (SPI) to provide short and long-term insight to the likelihood and potential scale of wildfire occurrence.

5.2.3. Prevention

Prevention measures can help reduce fire frequencies and wildfire size and, over time, optimise fire return periods. Fire awareness efforts could also help reduce ignitions, while fuel load reduction methods such as firebreaks, rotational block burning, or IAP clearing could reduce fuel load and aid in suppression efforts.

- **Fire Awareness:** It is recommended to plan for fire awareness activities to inform various user groups on fire safety and what to do in the event of fire to improve reporting and thus response time. It is further recommended to prioritise fire awareness efforts by using the proximity of ignitions to both towns and villages and transport routes. It is important to understand the various user groups for transport routes to focus on within towns and villages associated with high ignition rates.
- **Fuel load reduction:** It is recommended that firebreaks are planned and regularly maintained to protect vulnerable areas identified from risk assessments and strategically aid with fire suppression efforts. The IAP removal is integral for reducing biomass, and such hazards should be prioritised near vulnerable areas. Rotational block burning should be considered in high-risk areas to form a buffer for vulnerable areas, especially as a cut-off if they have a history of burning in a particular fire scar.

5.2.4. Preparedness

Preparedness measures can help reduce wildfire size, optimise fire return periods over time, and buffer against changes in seasonality. Ensuring suitably trained and equipped personnel are available can also help speed and effectively deploy resources for suppression efforts.

- **Resources:** It is important for all landowners at risk of wildfires to have enough firefighting equipment and trained personnel with appropriate personal protective equipment (PPE) to respond to wildfires. It is recommended that they coordinate with other stakeholders to plan shared resource allocation based on risk assessments, review response protocols, practice training scenarios, and coordinate stand-by rosters. It is recommended that time is allocated to maintaining fire preparedness throughout the year and not just as a precursor to fire season, to ensure readiness in any season and maintain protocol familiarity.

5.2.5. Suppression

Suppression efforts can help reduce wildfire size, buffer against changes in seasonality, and, over time, optimise fire return periods. The speed and scale of the initial attack have a massive impact on stopping wildfire size increases, and continued support of extended attack can help limit further size increases. Vulnerable and hazardous areas identified during risk assessments should have priority responses from multiple stakeholders, as previously coordinated in preparedness to reduce major risks from social, ecological, and economic perspectives.

5.2.6. Rehabilitation

After a fire has been put out, it is recommended to map its extent and assess the damage to quantify the rehabilitation work needed such as soil stabilisation, IAP control, replacing signage or infrastructure repairs. If areas containing IAPs were burnt, it is recommended to prioritise such areas for follow-up IAP treatments to assist in reducing biomass. Fires can also impact soil stability, leading to erosion. Transport routes for fire suppression damaged by erosion should also be prioritised to ensure further response speed.

5.2.7. Adaptive management

Long-term monitoring of fire regime aspects is necessary to view trends and adapt management requirements accordingly. Monitoring the major factors influencing wildfires, including ignitions, biomass, and weather conditions, is also recommended. Using high-resolution imagery could assist in fire mapping and gain more accurate results for fire size and fire return periods. It is also recommended to only include formally protected land and use a space-time composite method fire for return periods to increase the accuracy of results. Ignition proximity to towns and villages and transport routes is recommended as this can be consistently applied if the ignition source is unknown. It is recommended that high-resolution imagery be used for biomass calculations to be more accurate and eliminate human error and inconsistency bias. Weather data varies so much in mountainous areas that it is recommended to capture on-site weather readings by means of a Kestrel weather station on active fire lines where possible.

It is recommended that results from long-term monitoring, research, and input from all stakeholders be regularly assessed and fed back into legislation, prediction, prevention, preparedness, suppression, rehabilitation recommendations, and planning. Integrated wildfire management must be viewed holistically, considering all stakeholders' needs and capacity, coordinating all stakeholders' management efforts, and continually practising adaptive management.

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APPENDICES

APPENDIX A: Statistical analysis using the annual total hectares burnt in the BMC between 1990 and 2019 as the dependant variable

Variable	CV Decimal	AIC	AICc	BIC	P-value	R-squared	Percent Variance Explained
BMC_frequency	0.584	683.809	684.254	686.612	0.353	0.031	3.090
BMC_very_large	1.003	647.523	647.968	650.326	0.000	0.711	71.088
BMC_large	1.105	668.775	669.219	671.577	0.000	0.413	41.289
BMC_medium	0.427	684.285	684.730	687.088	0.514	0.015	1.540
BMC_small	0.770	684.591	685.035	687.393	0.702	0.005	0.533
BMC_summer	0.650	683.723	684.167	686.525	0.332	0.034	3.370
BMC_autumn	0.663	683.891	684.336	686.694	0.375	0.028	2.825
BMC_winter	0.986	684.180	684.624	686.982	0.469	0.019	1.887
BMC_spring	1.032	684.569	685.013	687.371	0.683	0.006	0.606
Footpath	0.864	684.008	684.453	686.811	0.409	0.024	2.445
Secondary_road	0.796	684.241	684.685	687.043	0.494	0.017	1.687
Major_road	1.032	684.541	684.986	687.344	0.661	0.007	0.696
Railway	1.316	684.748	685.193	687.551	0.961	0.000	0.009
Grabouw	1.340	683.896	684.340	686.698	0.376	0.028	2.811
Bainskloof_pass	0.996	684.723	685.167	687.525	0.873	0.001	0.093
Franshhoek	0.962	684.733	685.178	687.536	0.899	0.001	0.059
Botriver	1.293	684.632	685.076	687.434	0.741	0.004	0.396
Rawsonville	1.389	682.594	683.038	685.396	0.160	0.069	6.938
Wellington	1.304	684.086	684.530	686.888	0.435	0.022	2.193
Paarl	1.342	684.590	685.034	687.392	0.701	0.005	0.536
Kylemore	2.026	684.735	685.179	687.537	0.903	0.001	0.054
Villiersdorp	1.419	684.351	684.795	687.153	0.545	0.013	1.326
Wolseley	1.399	684.404	684.848	687.206	0.573	0.012	1.151
SLP	1.576	684.739	685.183	687.541	0.916	0.000	0.041
Mount_eland_township	1.509	684.609	685.053	687.411	0.718	0.005	0.472
Kleinmond	1.660	684.637	685.081	687.439	0.746	0.004	0.380
Wemmershoek	0.993	683.176	683.620	685.978	0.229	0.051	5.116
Bettys_bay	1.595	684.748	685.192	687.550	0.957	0.000	0.011
Tulbaghweg	1.337	684.716	685.161	687.519	0.858	0.001	0.116
Gouda	1.383	679.924	680.369	682.726	0.035	0.149	14.862
Ceres	1.515	679.375	679.819	682.177	0.026	0.164	16.407
Stellenbosch	1.835	684.627	685.072	687.430	0.736	0.004	0.412
Tulbagh	2.236	684.169	684.613	686.971	0.465	0.019	1.922
Somerset_west	2.133	684.736	685.181	687.539	0.907	0.000	0.049
Johannesdal	2.171	684.539	684.984	687.342	0.660	0.007	0.703

Fisherhaven	1.953	684.376	684.821	687.179	0.558	0.012	1.241
Pringle_bay	2.034	684.620	685.065	687.423	0.729	0.004	0.435
Simondium	2.034	684.162	684.606	686.964	0.462	0.019	1.946
La_motte	2.274	681.428	681.873	684.231	0.081	0.105	10.484
Worcester	2.767	684.353	684.798	687.156	0.546	0.013	1.318
Rooi_els	2.593	684.109	684.553	686.911	0.443	0.021	2.117
Hermon	3.256	684.641	685.086	687.444	0.751	0.004	0.365
Gordons_bay	5.477	684.525	684.969	687.327	0.649	0.008	0.752
Pniel	3.806	684.335	684.780	687.138	0.537	0.014	1.376
Klapmuts	3.806	683.678	684.122	686.480	0.321	0.035	3.514
Riebeek_west	5.477	684.458	684.903	687.261	0.605	0.010	0.970
Lanquedoc	5.477	681.360	681.804	684.162	0.078	0.107	10.689
Riebeek_kasteel	5.477	684.040	684.485	686.843	0.420	0.023	2.341
Hermanus	5.477	684.603	685.047	687.405	0.712	0.005	0.493
Rain_days	0.180	618.525	619.025	621.117	0.568	0.013	1.319
Rain_mm	0.210	618.883	619.383	621.474	0.972	0.000	0.005

APPENDIX B: Statistical analysis using the total hectares burnt per Very Large category fire in the BMC between 1990 and 2019 as the dependant variable

Variable	CV Decimal	AIC	AICc	BIC	P-Value	R-Squared	Percent Variance Explained
Hectares	0.672	600.860	600.985	602.387	0.001	0.296	29.580
BMC_Frequency	0.469	610.571	610.696	612.097	0.152	0.063	6.303
BMC_Very_large	0.481	610.587	610.712	612.113	0.153	0.063	6.259
BMC_Large	0.919	610.063	610.188	611.589	0.112	0.077	7.691
BMC_Medium	0.299	612.087	612.212	613.613	0.421	0.020	2.030
BMC_Small	0.657	609.921	610.046	611.447	0.103	0.081	8.076
BMC_Summer	0.492	609.991	610.116	611.518	0.107	0.079	7.886
BMC_Autumn	0.599	612.735	612.860	614.262	0.832	0.001	0.143
BMC_Winter	1.009	611.245	611.370	612.772	0.232	0.044	4.425
BMC_Spring	0.940	611.407	611.532	612.933	0.258	0.040	3.970
FIRE_CODE	0.569	610.443	610.568	611.970	0.141	0.067	6.653
FIRE_CODE_Month	1.050	612.654	612.779	614.180	0.729	0.004	0.381
FIRE_CODE_Year	0.004	610.664	610.789	612.190	0.161	0.060	6.045
FIRE_CODE_Biomass_kg	0.702	593.794	593.919	595.321	0.000	0.428	42.795
FIRE_CODE_Biomass_kg_ha	0.143	612.710	612.835	614.236	0.793	0.002	0.218
FIRE_CODE_IAP_percentage	0.457	612.747	612.872	614.273	0.853	0.001	0.109
FIRE_CODE_natural_percentage	0.305	612.747	612.872	614.273	0.853	0.001	0.109
FIRE_CODE_percentage_0_2_years	3.820	612.574	612.699	614.100	0.659	0.006	0.616
FIRE_CODE_percentage_2_4_years	1.857	610.489	610.614	612.015	0.144	0.065	6.528
FIRE_CODE_percentage_4_6_years	3.417	612.668	612.793	614.194	0.743	0.003	0.340
FIRE_CODE_percentage_6_10_years	0.755	612.777	612.902	614.303	0.935	0.000	0.021
FIRE_CODE_percentage_10_15_years	0.856	612.681	612.806	614.208	0.758	0.003	0.301
FIRE_CODE_percentage_15_25_years	1.892	611.864	611.989	613.391	0.356	0.027	2.668
FIRE_CODE_percentage_25_years_plus	5.516	612.256	612.381	613.782	0.484	0.015	1.542
FIRE_CODE_Avg._FDI_rain_wind_corrected	0.144	612.588	612.713	614.114	0.670	0.006	0.575
FIRE_CODE_Start_date_FDI_rain_wind_corrected	0.167	611.947	612.072	613.473	0.378	0.024	2.432
FIRE_CODE_Days_burnt	0.144	612.611	612.736	614.137	0.689	0.005	0.507
FIRE_CODE_Max_Temp	0.125	612.744	612.869	614.271	0.848	0.001	0.117
FIRE_CODE_Min_Temp	0.163	612.495	612.620	614.021	0.605	0.008	0.847
FIRE_CODE_Avg_Temp	0.129	612.782	612.907	614.309	0.967	0.000	0.005

FIRE_CODE_Avg_Wind_Speed	0.129	612.782	612.907	614.309	0.967	0.000	0.005
FIRE_CODE_Avg_Wind_Degree_Direction	0.240	611.907	612.032	613.434	0.367	0.025	2.545
FIRE_CODE_Avg_Rain	5.204	612.752	612.877	614.279	0.864	0.001	0.093
FIRE_CODE_Avg_Humidity	0.354	612.347	612.472	613.873	0.524	0.013	1.278
FIRE_CODE_nearest_WS_Rain_Fire_Year	0.454	612.462	612.587	613.989	0.585	0.009	0.942
FIRE_CODE_nearest_WS_Rain_Fire_Year_12_months	0.424	611.343	611.468	612.869	0.248	0.042	4.151
FIRE_CODE_nearest_WS_Rain_Fire_Year_24_months	0.431	612.648	612.773	614.174	0.722	0.004	0.399

APPENDIX C: CPUT Ethical Clearance

Cape Peninsula
University of Technology

Statement of Permission

Data/Sample collection permission is required for this study.

Reference no.	207003831/06/2020
Surname & name	Sommers, A.M.
Student Number	207003831
Degree	Master of Environmental Management
Title	A meta-analysis of selected factors influencing wildfire regimes over the last three decades in the Boland Mountain Complex, South Africa
Supervisor(s)	DR NTOKOZO MFANUFIKILE MALAZA
FRC Signature	
Date	2020 July 02

Cape Peninsula
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P.O. Box 1906 · Bellville 7535 South Africa ·Tel: +27 21 953 8677 (Bellville), +27 21 460 4213 (Cape Town)

Provisional Ethics Approval Letter **Reference no:** 207003831/06/2020

Office of the Chairperson **Research Ethics Committee**	**Faculty of Applied Sciences**

On 29 June 2020, the Faculty Research Ethics Committee of the Faculty of Applied Sciences granted provisional ethics approval to Sommers, A.M. for research activities related to a project to be undertaken for a degree (Master of Environmental Management) at the Cape Peninsula University of Technology. The study can begin once the wording in the data acquisition permit from CapeNature is revised. The permit should clearly authorise the student to conduct the research and should have a permit number.

Title of project:	A meta-analysis of selected factors influencing wildfire regimes over the last three decades in the Boland Mountain Complex, South Africa

Comments (Add any further comments deemed necessary, e.g. permission required)

1. Human subjects are not included in the proposed study.
2. This permission is granted for the duration of the study.
3. Research activities are restricted to those detailed in the research proposal.
4. The research team must comply with conditions outlined in AppSci/ASFREC/2015/1.1 v1, CODE OF ETHICS, ETHICAL VALUES AND GUIDELINES FOR RESEARCHERS.

Signed: Chairperson: Research Ethics Committee	**29/06/2020** **Date**

APPENDIX D: CapeNature data use permission

CapeNature

BIODIVERSITY CAPABILITIES

postal	Private Bag X29, Gatesville, 7766
physical	cnr Bosduif and Volstruis Streets, Bridgetown
website	www.capenature.co.za
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email	crampartab@capenature.co.za
reference	DataSharingAgreement_CPUT_2021_A Sommers (van Heerden)

Request for Dataset(s)

A. Applicant details			
Organisation/Institution	CapeNature / Cape Peninsula University of Technology		
Name	Andrie-Maryna		
Surname	van Heerden		
Position/Student no	Conservation Officer (On Reserve) / Student No. 207003831		
Email address	asommers@capenature.co.za/ andrie.sommers@gmail.com		
Tel no	084 799 7229		
Postal address	36 Prospect Ave, Somerset West		
Third parties who will also access the data	Name	Surname	Organisation

B. Purpose			
Project or study	✓	Private use	
If project or study, complete the rest of section B. If private use, leave blank.			
Project name	Fire analysis		
Project description	An analysis of selected influencing factors of wildfire regimes over the last three decades in the Boland Mountain Complex, South Africa		
Project completion date	[DD/MM/YYYY] 2022		
Supervisor details	Name	Surname	Email address
	Dr Ntokozo	Malaza	malazan@cput.ac.za
	Co-supervisor: Dr Antoinette Veldtman		aveldtman@capenature.co.za

C. Datasets requested	
Dataset 1	CapeNature Fire Data base
Dataset 2	Fire perimeter and ignition shape-files for HOTT, JONK, KGBG, LMBR and WATV
Dataset 3	BMC and study area shape-file
Dataset 4	Towns and village's shape-file
Dataset 5	Roads shape-file

Applicant signature

06/07/2021
Date

D. FOR OFFICE USE					
Name	Cher-Lynn	Surname	Petersen	Date	07/07/2021

[Comments]
Roads can be sourced from the National Geospatial Portal via http://www.cdngiportal.co.za/cdngiportal/ filed under: 'Browse ERDAS\TOPO_DATA\geoPackage\WC_NGI_TOPODATA_202006.gdb\TRAN_ROADS' also available to CapeNature staff members under the 2_Geographic\Infrastructure\General_Infrastructure_NGI_TOPO_Vector_Geodatabase\

E. APPROVAL			
Datasets requested		Approved	Not approved
Dataset 1	HOTT, JONK, KGBG, LMBR & WATV Firedbases (Non-spatial & spatial data)	x	
Dataset 2	All_Fires_Ignitions_19_20_gw_Boland_StudyArea10km.shp	x	
Dataset 3	Boland_Complex_boundaries.shp Boland_StudyArea_10kmBuffer.shp	x	
Dataset 4	Allotment_Townships_Boland_StudyArea10km.shp Suburbs_Boland_StudyArea10km.shp	x	
Dataset 5	Roads: Download via http://www.cdngiportal.co.za/cdngiportal/	x	

Ms Chanel Rampartab, duly authorised
on behalf of CapeNature

13-07-21
Date

TERMS & CONDITIONS

1. I understand that the data provided by the Western Cape Nature Conservation Board t/a CapeNature ("CapeNature") is issued to those named above and shall be protected due to privacy concerns.

2. I understand that data may not be passed to any third party without written consent from CapeNature, which consent shall not be unreasonably withheld. This includes clients, agents and colleagues unless they are named above and have received a copy of this form.

3. I understand that I may not copy, sell, distribute, disseminate, publish or broadcast the data in any form, including the internet, without written consent from CapeNature, which consent shall not be unreasonably withheld.

4. I undertake to inform CapeNature of any publications and reports emanating from the use of the data provided by CapeNature.

5. I will acknowledge CapeNature in accordance with generally accepted academic referencing guidelines and principles in all parts of any series of publications or reports arising from the project in which the dataset, or information derived from, it was used.

6. I confirm that all data provided by CapeNature shall be used for legitimate and legal purposes.

7. I confirm that to the best of my knowledge neither I, nor any of my colleagues who may have access to the data obtained from CapeNature have been investigated or convicted of any crime against nature conservation.

8. I confirm that to the best of my knowledge neither I, nor any of my colleagues have been responsible for the misuse of data.

9. I acknowledge that I cannot use the data provided by CapeNature for any purpose other than for which it was requested.

10. I acknowledge that the data provided by the CapeNature is deemed to have been accurate at the time of collection and further that CapeNature cannot guarantee the accuracy of the data supplied, although all data has been validated as far as is reasonably possible.

11. I will not hold CapeNature and its employees liable for any errors, damages and or financial loss which might arise from the inaccuracy and incompleteness of any data supplied by CapeNature.

12. I understand that this data may only be utilised for the specific project for which the data was requested. Where I require this data for future projects I am required to submit a new request in order for CapeNature to supply me with the most up-to-date data available.

13. I understand that CapeNature has the right to withhold any data from any person or body in accordance with the provisions of the Promotion of Access to Information Act, 2000.

14. I acknowledge that CapeNature reserves the right to demand that the data user returns the data to CapeNature, for whatever reason, and destroy all other copies of the data.

15. Both Parties agree that they will comply with the provisions of the Protection of Personal Information Act No. 4 of 2013 and its regulations and process all personal data, to the extent that it is applicable, in accordance with the provisions of the aforesaid Act and Regulations.

16. If the data is applicable to a project or study, a copy of any project write-up (both a digital and paper copy) and all digital data collected and enhanced as part of the study (with completed metadata documents) must be supplied to CapeNature to support its work to conserve the environment and to make informed decisions.

17. I acknowledge that there is a turn-around time period of at least 2 (two) weeks from date of receipt of a duly completed application form.

I, Andrie van Heerden (the applicant),

accept the terms and conditions outlined herein on the 06 of July 2021.

Applicant signature