Drivers of Wildfire Behaviour, Severity and Magnitude in the Limietberg Conservation Area: Understanding the Complexity of Wildfire Risk

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DECLARATION

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SUMMARY

The Western Cape Province in South Africa is home to one of the most diverse plant communities in the world, and has one of the highest concentrations of plants species in any temperate ecosystem in the world. The dominant vegetation is both fire-prone and fire-dependant (Van Wilgen & Scott 2001, Forsyth et al. 2010). The Western Cape in particular is emerging as a province that is increasingly prone to disaster events, particularly the threat of veld fires. The consequences of large wildfire disaster events are often devastating and far reaching (Van Wilgen & Scott 2001, Forsyth et al. 2010). This study was conducted in an attempt to investigate the drivers of wildfire behaviour, severity and magnitude in the Limietberg Conservation Area in order to gain a greater insight and understanding of the complexity of wildfire risk. Recognising the disaster prone character of the Western Cape and the increasing probabilities of future wildfire events in the province, this study aimed to strengthen the understanding of the drivers of wildland fire behaviour (i.e. wildland fire risk) in the Limietberg Conservation Area by analysing a number of fires to identify a range of drivers and patterns; examining the factors driving both fire danger and fire behaviour, including climate, topography, slope and fuel; examining the factors driving fire frequency and regime; and finally, determining possible ecological damage caused by the last 10 – 20 years of wildfire events in the Limietberg Conservation Area as measured by post-fire seedling ratios. This was achieved through the use of statistical techniques including multiple regression (McDonald 2009), ordination in the form of principal component analysis and non-metric multi-dimensional scaling (Clarke & Warwick 1994), and fieldwork in the form of post-fire regeneration (Proteaceae parent:seedling ratio) monitoring techniques (Bond et al. 1984; Vlok & Yeaton 2000; De Klerk et al. 2007). The results indicated that the interactions between factors driving fire danger and fire behaviour were indeed complex, being influenced mainly by meteorological variables (temperature, relative humidity, wind speed) but also quite strongly influenced by physical environmental factors (slope, topography). The use of ordination techniques in this sort of complex analysis was seen as extremely effective and its use in further fire research was strongly recommended.

KEY WORDS

Fire, Fire Danger, Fire Behaviour, Fire Frequency, Wildfire Risk, Ecological Vulnerability, Fire Ecology, Cape Floral Kingdom, Post-fire Regeneration, *Protea*, *Leucadendron*, Ordination, Principal Component Analysis, Multi-dimensional Scaling.

OPSOMMING

Die Wes-Kaap provinsie in Suid-Afrika is die tuiste van een van die mees diverse plant gemeenskappe in die wêreld, en het een van die hoogste konsentrasies van plantspesies in enige gematigde ekosisteem in die wêreld. Die dominante plantegroei is beide vuur geneig en vuur-afhanklik (Van Wilgen & Scott 2001, Forsyth et al. 2010). Die Wes-Kaap in die besonder is opkomende as 'n provinsie wat toenemend geneig is tot ramp gebeure, veral die bedreiging van veldbrande. Die gevolge van groot veldbrand rampgebeure is dikwels verwoestend en verreikend (Van Wilgen & Scott 2001, Forsyth et al. 2010). Hierdie studie is uitgevoer in 'n poging om die oorsake van veldbrande, die gedrag, erns en omvang daarvan in die Limietberg Bewaringsgebied vir groter insig en begrip van die kompleksiteit van veldbrand risiko te ondersoek. Hierdie studie erken die rampgeneigdheid van die Wes-Kaap en die toenemende waarskynlikheid van toekomstige veldbrande in die provinsie. Dit het ten doel gehad om die oorsake van veldvuur gedrag (bv. brand risiko) in die Limietberg Bewaringsgebied deur die ontleding van 'n aantal brande se oorsake en patrone te identifiseer; die ondersoek van faktore wat beide brandgevaar en vuurgedrag, bepaal insluitend klimaat, topografie, helling en brandstof; die ondersoek van faktore wat vuur frekwensie en regime; en uiteindelik die bepaling van moontlike ekologiese skade veroorsaak deur die laaste 10 - 20 jaar van veldbrand gebeure in die Limietberg Bewaringsgebied, soos gemeet deur navuur saailing verhoudings. Die doel is bereik deur die gebruik van statistiese tegnieke waaronder meervoudige regressie (McDonald 2009), ordening in die vorm van hoofkomponent analise en multi-dimensionele skaling (Clarke & Warwick 1994), en veldwerk in die vorm van navuur herlewing (Proteaceae ouer:saailing verhouding) moniteringstegnieke (Bond et al. 1984; Vlok & Yeaton 2000; De Klerk et al. 2007). Die resultate dui daarop dat die interaksies tussen faktore wat brandgevaar en vuurgedrag inderdaad kompleks aandryf is en hoofsaaklik beïnvloed word deur meteorologiese veranderlikes (temperatuur, relatiewe humiditeit, windspoed), maar ook baie sterk beïnvloed word deur fisiese omgewingsfaktore (helling, topografie). Die gebruik van ordeningstegnieke vir hierdie komplekse tipe analise is bevind as uiters effektief en die gebruik daarvan in verdere vuur navorsing word sterk aanbeveel.

TREFWOORDE

Vuur, Brande, Brandgevaar, Brandgedrag, Brandgereeldheid, Veldbrand Risiko, ekologiese kwesbaarheid, vuurekologie, Kaapse Blomme Ryk, Na-brand Herlewing, *Protea*, *Leucadendron*, Ordening, hoofkomponent analise, Multi-dimensionele skaling.

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ACRONYMS AND ABBREVIATIONS

GIS	Geographic information system
GPS	Global positioning system
PCA	Principal Component Analysis
MDS	Multi-Dimensional Scaling

DEFINITIONS

Disaster	A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources. A disaster is a function of the risk process. It results from the combination of hazards, conditions of vulnerability and insufficient capacity or measures to reduce the potential negative consequences of risk. *Source: UNISDR(2004, 2007)*
Disaster Risk Management	The systematic process of using administrative decisions, organisation, operational skills and capacities to implement policies, strategies and coping capacities of the society and communities to lessen the impacts of natural hazards and related environmental and technological disasters. This comprises all forms of activities, including structural and non-structural measures to avoid (prevention) or to limit (mitigation and preparedness) adverse effects of hazards. *Source: UNISDR(2004, 2007)*
Hazard	A potentially damaging physical event, phenomenon or human activity that may cause loss of life or injury, property damage, social and economic disruption or environmental degradation. Hazards can be single, sequential or combined in their origin and effects. Each hazard is characterised by its location, intensity, frequency and probability. *Source: UNISDR(2004, 2007)*
Mitigation	Structural and non-structural measures undertaken to limit the adverse impact of natural hazards, environmental degradation and technological hazards. *Source: UNISDR(2004, 2007)*
Preparedness	Activities and measures taken in advance to ensure effective response to the impact of hazards, including the issuance of timely and effective early warnings and the temporary evacuation of people and property from threatened locations. *Source: UNISDR(2004, 2007)*

Risk	The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions. Conventionally risk is expressed by the notation Risk = Hazards x Vulnerability. Some disciplines also include the concept of exposure to refer particularly to the physical aspects of vulnerability. Beyond expressing a possibility of physical harm, it is crucial to recognize that risks are inherent or can be created or exist within social systems. It is important to consider the social contexts in which risks occur and that people, therefore, do not necessarily share the same perceptions of risk and their underlying causes. *Source: UNISDR(2004, 2007)*
Vulnerability	The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards. *Source: UNISDR(2004, 2007)*
Geographical Information System (GIS)	Analysis that combines relational databases with spatial interpretation and outputs, often in the form of maps. A more elaborate definition is that of computer programmes for capturing, storing, checking, integrating, analysing and displaying data about the Earth that is spatially referenced. Geographical information systems are increasingly being utilised for hazard and vulnerability mapping and analysis, as well as for the application of disaster risk management measures. *Source: UNISDR(2004, 2007)*
Fire Break	A natural or constructed barrier utilised to stop or slow down fires that may occur, or to provide a control line from which to work. *Source: Holloway & Roomaney (2008)*
Fuel	Flammable and combustible substances available for a fire to consume. *Source: Holloway & Roomaney (2008)*
Veld/Wild/Bush Fire	Fires in South Africa that result in the burning of grass, shrubs and trees in a single event. These can occur in national parks and rural areas as well as within the urban fringe around cities and towns. *Source: Holloway & Roomaney (2008)*

CHAPTER 1: BACKGROUND TO THE RESEARCH

1 INTRODUCTION

The Western Cape Province in South Africa is home to one of the most diverse plant communities in the world, and has one of the highest concentrations of plant species in any temperate ecosystem in the world. The dominant vegetation is both fire-prone and fire-dependant (Le Maitre & Midgley 1992; Van Wilgen & Scott 2001; Brown & Botha 2004; Forsyth et al. 2010).

In the context of South Africa as a whole, the Western Cape in particular is emerging as a province that is increasingly prone to disaster events, and it faces a wide variety of threats, particularly in the form of environmental risks. The Western Cape is characterised by a mosaic of urban and natural areas with substantial urban infringement, and is often badly invaded by alien plant species. The consequences of large wildfire disaster events are often devastating and far reaching (Le Maitre & Midgley 1992; Van Wilgen & Scott 2001; Brown & Botha 2004; Forsyth et al. 2010). It is essential therefore that past wildfire events are analysed and evaluated in order to inform the planning for future wildfire events. This thesis will use a disaster risk framework approach to examine the major driving factors of wildfires in the Western Cape.

1.1 Background to Wildfire Risk in the Western Cape

Most regions in Western Cape are situated in naturally fire-prone ecosystems. Wildfires are a frequent occurrence during the dry summer months, and the inherent fire hazard is exacerbated by many factors including an increase in the extent of the urban development interface with naturally fire-prone systems, the escalating occurrence of extensive infestations of invading alien plants, fire risks associated with forestry and agriculture, and the build-up of excessive fuel loads (natural, commercial and invasive) (Le Maitre & Brown 1992; Cowling & Richardson 1995; Van Wilgen & Scott 2001; Forsyth et al. 2010).

Fire is a global phenomenon and can play a role in maintaining or threatening natural habitats and human societies (Shlisky et al. 2008; Forsyth et al. 2010). Over half of the world’s terrestrial ecosystems are dependent on fire to maintain ecological structure and function (Shlisky et al. 2007, Forsyth et al. 2010). Wildfire is a frequently occurring, natural phenomenon in the

Western Cape of South Africa with large environmental and social consequences (Cowling 1987; Keeley & Bond 1997; Cowling & Richardson 1995; Wilson et al. 2010). The Western Cape Province in South Africa is home to one of the most diverse plant communities in the world, and has one of the highest concentrations of plant species in any temperate ecosystem in the world. The dominant vegetation is both fire-prone and fire-dependant with many species requiring fire to reproduce, as their seeds need fire stimulation, through the smoke, heating or clearing of vegetation cover, in order to germinate (Le Maitre & Brown 1992; Cowling & Richardson 1995; Van Wilgen & Scott 2001).

By far the most dominant vegetation of the South-Western Cape is fynbos, which occurs in several bands along the west and southern Cape coasts, from north of Clanwilliam in the west to Port Elizabeth in the east. The greatest proportion of fynbos vegetation occurs within the boundaries of the Cape Floristic Region (Cowling 1987; Cowling & Richardson 1995; Keeley & Bond 1997; Wilson et al. 2010).

The Cape Floristic Region is considered one of the most species-rich floristic regions in the world and is identified as a hotspot for biodiversity conservation by Conservation International, containing the greatest non-tropical concentration of higher plant species in the world, despite its small geographical extent (Goldblatt & Manning 2002; Wilson et al. 2010). The dominant vegetation type within this region is fynbos. One of the characteristic features of fynbos vegetation is its ecological dependence on fire. Fynbos is in fact a fire-adapted vegetation type and evidence suggests that, in the absence of regular fires, all but the driest fynbos types would become dominated by trees (Goldblatt & Manning 2002; Wilson et al. 2010). Fire is an integral part of the functioning of the fynbos ecosystem, and has played a significant role in the development of the patterns of botanical diversity in this region (Cowling 1987; Cowling & Richardson 1995; Keeley & Bond 1997; Wilson et al. 2010).

Fynbos plants and animals have therefore become adapted to periodic fires, and have indeed become dependent on fire to complete their life cycles (Le Maitre & Midgley 1992; De Klerk 2008; Keeley 2009). Consequently fire is critical for maintaining the ecological functioning of fynbos vegetation and fires at appropriate intervals is not only integral, but also an essential part of fynbos ecology. Such fires would usually ignite under natural circumstances, and exercise the role of maintaining the ecological functioning of fynbos vegetation (Goldblatt & Manning 2002; Wilson et al. 2010). Fire is thus a key aspect for managers of fynbos areas to understand, so that they can make appropriate management decisions in this very important biodiversity hotspot ((Le Maitre & Midgley 1992; De Klerk 2008; Keeley 2009).

The consequences of large wildfire disaster events are often devastating and far reaching. The commercial sectors of Forestry and Agriculture suffer extensive financial loss every year as uncontrolled fires destroy crops, plantations, buildings and equipment. Both sectors invest substantially in fire protection measures, through the development of firebreaks, deployment of fire-fighting teams and purchase of fire-fighting equipment (Forsyth et al. 2010). There is also substantial investment on the part of the regional Municipalities.

1.2 Background and Context to the Research: Introduction to the Limietberg Conservation Area

The Limietberg Conservation Area is located in the Cape Winelands, a region of the Western Cape Province of South Africa. Limietberg is in the Du Toitskloof Mountains near Paarl, forming a part of the greater Boland mountain range. It lies between latitudes 33^0 45' S and 34^0 23' S and longitudes 18^0 50' and 19^0 12' E and falls within the 3319 quarter degrees (Figure 1-1). The Limietberg Conservation Area is covered by the Worcester, Paarl, Wellington and Wolsely magisterial districts and falls within the Boland District Council (Cape Nature IRMP 2011).

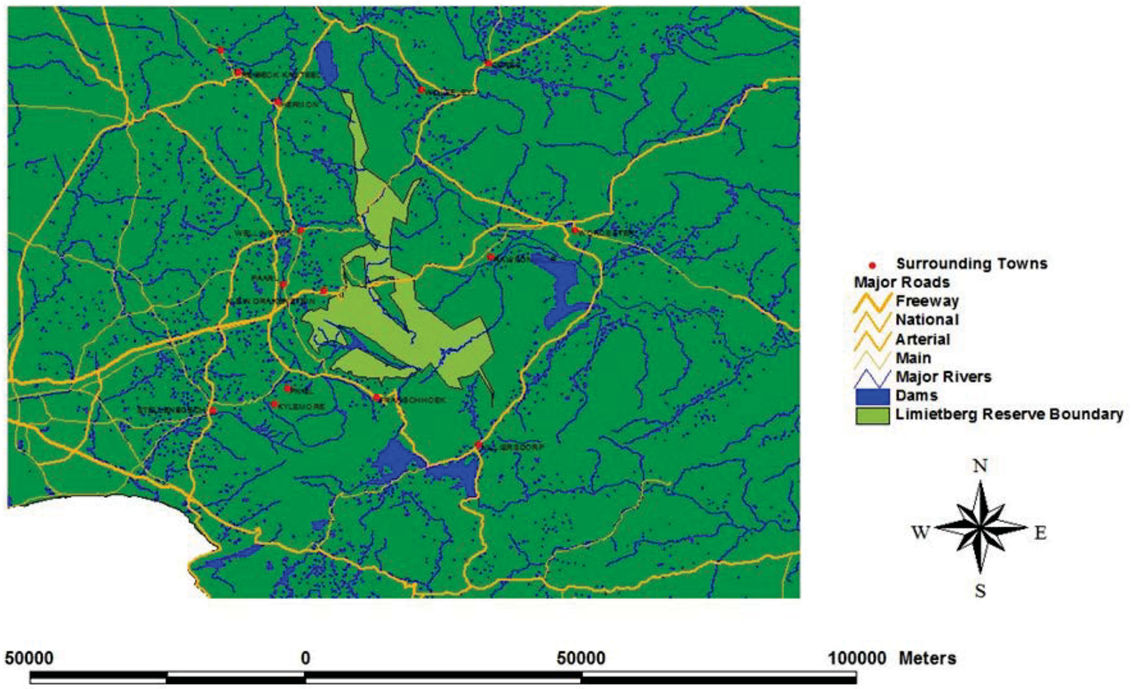

Figure 1-1: Study area, the Limietberg Conservation Area located in the Western Cape Province of South Africa.

The reserve stretches from Franschhoek in the south, eastwards towards Groot Drakenstein, and northwards as far as Voëlvlei dam, covering an area of some 117 000ha. The terrain is rugged, with steep kloofs and deep valleys (Figure 1-2). Du Toits Peak at 1996m is the highest point within the reserve. Limietberg is an important water catchment for the Breede and Berg Rivers which flow through the reserve, and feed the Wemmershoek, Stettynskloof, Theewaterskloof and Voëlvlei dams (Cape Nature IRMP 2011).

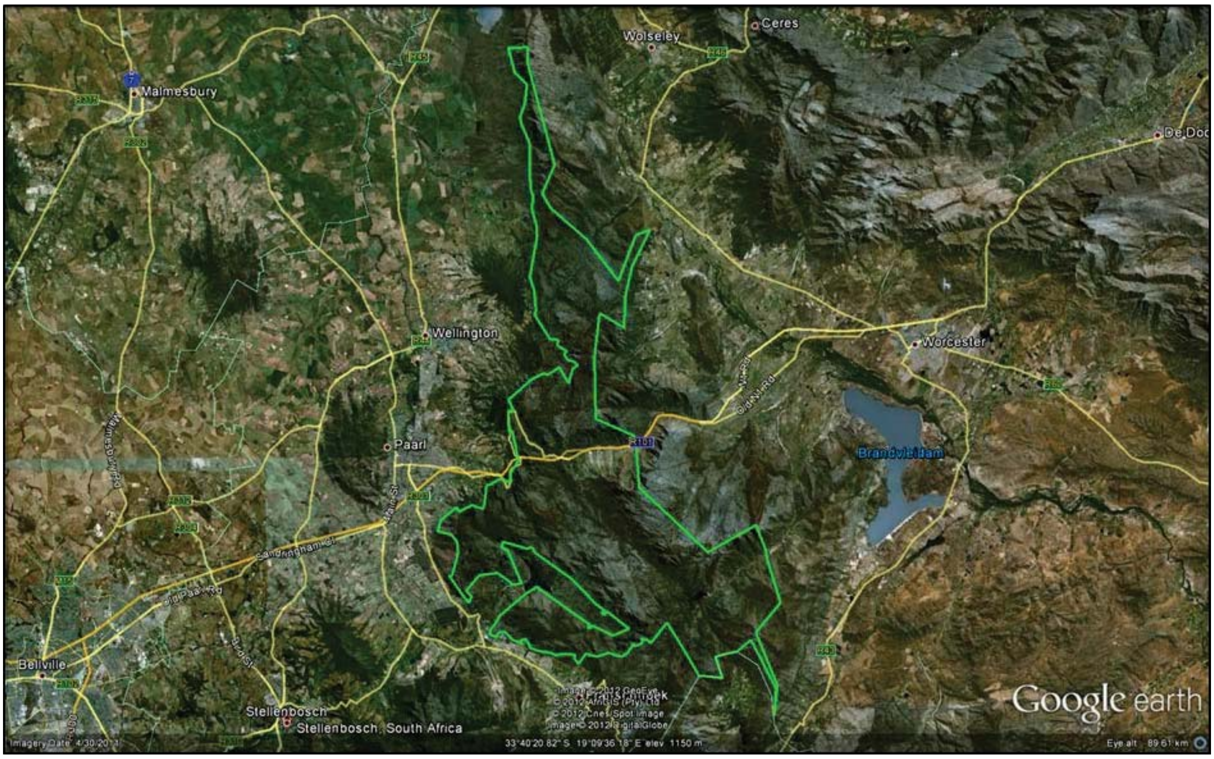

Figure 1-2: Aerial photograph indicating the study area, the Limietberg Conservation Area located in the Western Cape Province of South Africa. (Courtesy of Google Earth 4/5/2011)

1.2.1 Climate

The weather conditions within the Limietberg Conservation Area vary from very hot and dry in the summer months, to extremely cold and wet during winter, with snow on the higher peaks. It is characterised by a Mediterranean climate that has hot, dry summers and cool, wet winters. The type of rainfall occurring is mostly cyclonic (from cold fronts) and the high rainfall is a result of the topography of the mountains. Thunderstorms are known to occur in the mountains in summer, which can result in the ignition of fires. Other forms of precipitation such as hail and snow also occur within the Limietberg Conservation Area. Snow typically occurs on the high peaks, but may also occur low down, even for example on the Du Toitskloof Pass (Cape Nature IRMP 2011).

The driest months are December, January, February and March and are thought to have the highest fire danger. Temperatures can reach over 40^0 C in the summer months and below freezing in the winter months. In the summer months, wind can be problematic by exercising the role of elevating fire danger conditions, especially when there is an existing fire, and a south-easterly wind blows. Bergwinds can increase the temperature by up to 10^0 C (Cape Nature IRMP 2011).

1.2.2 Topography

Situated in the Cape Fold Mountains, the height varies from about 200 m above sea level to 1993 m above sea level (Cape Nature IRMP, 2011). Limietberg has characteristic high krantz's, deep ravines and inaccessible terrains.

1.2.3 Geology

The analysis of soils in the study area have shown the soils to be acid and the pH ranges from 4 to 6 (H_2O paste) and 3 to 5 (KCl) (Cape Nature IRMP, 2011). In this area, soils are mainly derived from quartzite of the Table Mountain Group, with the exception of below and on the shale band. Clay content in most of the area is less than 8%. The soil has low water retention and is oligotrophic because of the high rainfall and sandy texture (Van Wilgen, Le Maitre & Kruger, 1985).

1.2.4 Vegetation

The Protected Area falls within the Cape Floristic Region (CFR). The area is dominated largely by Mountain Fynbos.

1.3 Research Aims and Objectives

Recognising the disaster prone character of the Western Cape and the increasing probabilities of future wildfire events in the province (Forsyth et al. 2010), this study aimed to strengthen the understanding of the drivers of wildland fire behaviour (i.e. wildland fire risk) in the Limietberg Conservation Area.

To achieve the research aim, the following objectives had been set:

1. Analyse a number of fires in order to identify potential patterns that may exist between a range of drivers that contribute towards overall fire risk
2. Examine the factors driving both fire danger and fire behaviour, including climate, topography, slope and fuel
3. Examine the factors driving fire frequency and regime
4. Determine possible ecological damage caused by the last 10 – 20 years of wildfire events in the Limietberg Conservation Area as measured by post-fire seedling ratios of *Proteaceae* and *Leucadendron* species.

CHAPTER 2: REVIEW OF RELEVANT LITERATURE AND CONCEPTUAL FRAMEWORK

Disaster risk science as a discipline is extremely difficult to define, but at a fundamental level essentially comprises two main components, namely the concepts of disaster (usually in the form of a natural hazard) and risk. Disasters are defined as a serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources (Holloway & Roomaney 2008). A disaster is a function of the risk process, and typically results from the combination of some form of hazard (most likely to be natural in origin), conditions of vulnerability and insufficient capacity or measures to reduce the potential negative consequences of risk (Holloway & Roomaney 2008). Risk is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions (Holloway & Roomaney 2008). Conventionally risk is expressed by the notation Risk = Hazards x Vulnerability. Some disciplines also include the concept of exposure to refer particularly to the physical aspects of vulnerability (Holloway & Roomaney 2008). Disaster risk science is therefore by its very nature a multi-disciplinary field. The concept of wildfire hazards is no different, also drawing from many different disciplines, all of which have contributed to the literary and academic debate surrounding the natural phenomenon in some way or form. For the purpose of this study it was decided to focus on four distinct areas of literature, namely: Prevailing Theoretical Approaches to Understanding Disaster Risk, Wildfire as a Natural Hazard, Vulnerability and Wildfire Risk Management.

2.1 Prevailing Theoretical Approaches to Understanding Disaster Risk

The choice of conceptual framework is the first body of literature that needs to be considered. This is possibly the most critical set of literature as it is the one that determines the lens through which the natural hazard will be analysed (Moir 2009).

Over half of the world’s terrestrial ecosystems are dependent on fire to maintain ecological structure and function and are naturally fire prone (Shlisky et al. 2007; Wilson et al. 2010). Natural disasters usually strike quickly with little or no warning, and the impact of these disasters is almost always devastating. In the context of the Western Cape, wildfires are an expected risk. The area is dominated by fynbos, which is a fire-adapted vegetation. Fire is therefore critical for maintaining the ecological functioning of fynbos vegetation and fires at appropriate intervals is an essential part of fynbos ecology (Van Wilgen 1981; Bond 1980; Bond et al. 1984; Cowling & Richardson 1995). Such fires would usually ignite under natural circumstances every 10 – 14 years, and exercise the role of maintaining the ecological functioning of fynbos (Forsyth et al. 2010). This however is changing, largely as a result of the expansion of invasive plant species throughout the fynbos biome. This has drastically altered the nature of these fires to the point where there is the potential for detrimental impacts to people and their assets (Forsyth et al. 2010). There is also an increasing probability of these fires escalating to develop into large wildland fires as a result of the increase of full loads due to increased alien invasion and an associated increase in the intensity of wildland fires (Forsyth et al. 2010). This is not to say that fires that occur in uninvaded stands of fynbos do not also result in detrimental impacts on people and their assets, but merely makes the point that the contribution of alien invasive species has the potential to exacerbate the potential risk posed by wildland fires (Forsyth et al. 2010). No country is ever ready for the devastation left behind as a result of a major environmental disaster, and this is particularly true for the nations of the global south, where the effects of a major disaster can often be crippling (Cannon 2008). The consequences of largescale wildfire disaster events are not to be underestimated and can have an enormous financial impact. The commercial sectors of forestry and agriculture suffer extensive financial loss every year as a result of uncontrolled fires. Both sectors invest substantially in fire protection measures. There is also substantial investment on the part of the regional municipalities, and an out of control wildfire can often result in dire financial consequences (Forsyth et al. 2010). Such an occurrence was investigated by Moir (2009) in the Jonkershoek Valley, where there were many issues arising from the associated costs of dealing with the suppression and consequences of a devastating wildland fire event.

Although it is difficult to predict when such disasters will occur, it is of vital importance to have a plan of action in place for the time when these instances do occur (Moir 2009). It is crucial therefore to have an understanding of the underlying risk factors for frequently occurring disasters, and to identify the critical vulnerability characteristics that contribute to the severity of these impacts. A disaster only occurs when a hazard has an impact on a vulnerable population. It is consequently essential to identify in advance those people or environments who may suffer from a particular impact in order to plan effectively. Examining components of vulnerability allows us to understand what causes some to be more at risk from a hazard than others. We can then analyse the interconnections of vulnerability and resilience (Cannon 2008).

The conceptual framework that I intend to use for this study is Pelling's Vulnerability framework (Pelling 2003). In this framework, environmental risk (disasters with a natural trigger) is presented as a product of both physical pressures in the form of an environmental hazard and human vulnerability. Pelling deconstructs vulnerability into three dimensions (Figure 2-1) shaped by global social and economic pressures.

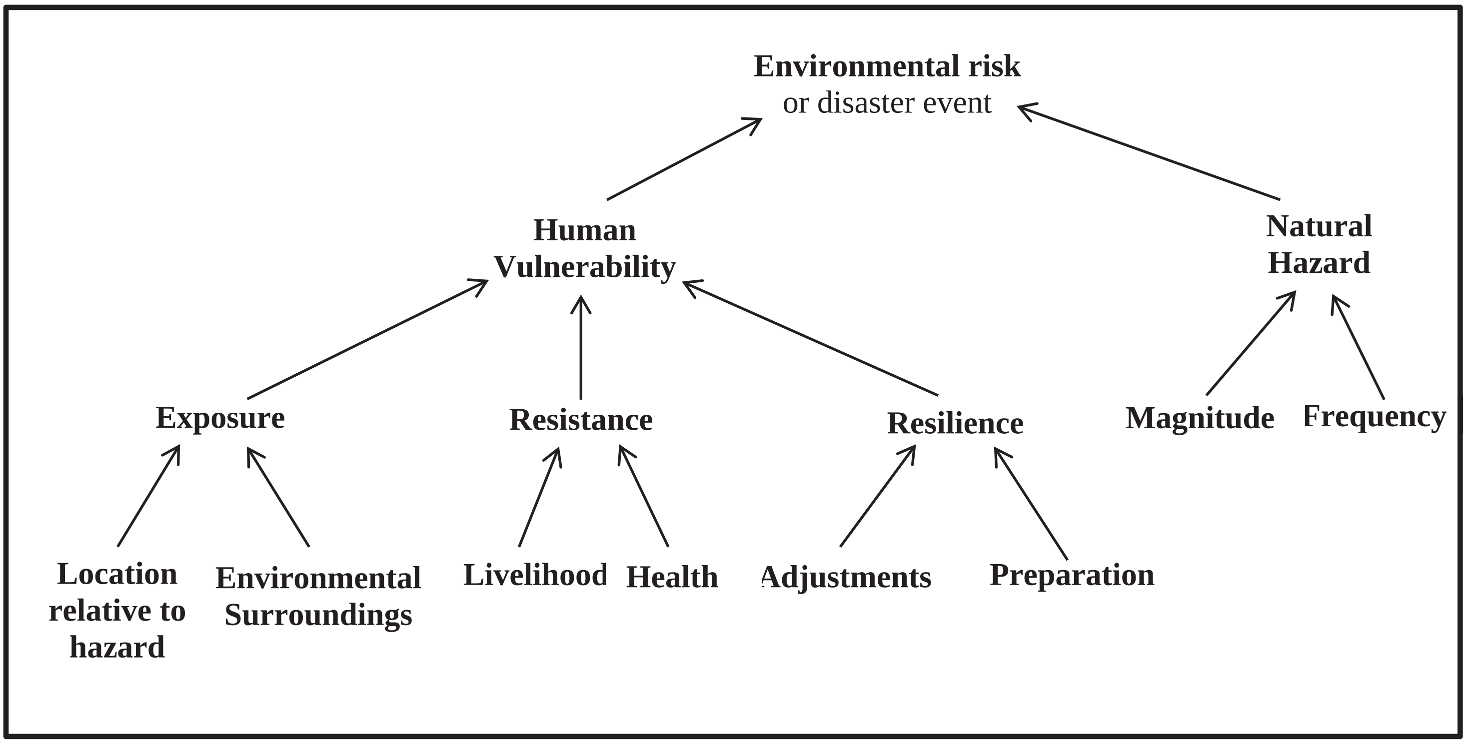

Figure 2-1 Pelling Vulnerability Model (Pelling 2003).

These dimensions are: Exposure (physical location, environmental surroundings), Resistance (livelihoods, health) and Resilience (coping/adaptation, preparedness) (Pelling 2003). Pelling's Vulnerability Framework also encompasses the five components of vulnerability as stated by Cannon (2008).

There are five components of vulnerability that should be considered when planning for the effects of potential disasters. These include livelihood strength and resilience, wellbeing and base-line status, self-protection, social protection and governance. These components are all interlinked and interrelated, crucial to the design of policies to reduce vulnerability (Cannon 2008).

Exposure is largely a product of physical location and the character of the built environment. Pelling further deconstructs this component into two factors: physical location and environmental surroundings. Both of these factors are particularly relevant to wildfire events within the context of the Western Cape Province and South Africa as a whole (Pelling 2003).

Resistance reflects the economic, psychological and physical health and represents the capacity of an individual or group of people to withstand the impact of a hazard. If resistance is low, even the effects of a small hazard can lead to a failure of the system. The frequency of the repeated flare-ups of wildfires may well have an effect on the resilience of an affected community (Pelling 2003).

Resilience to a natural hazard is defined as the ability to cope with or adapt to hazard stress. Pelling further deconstructs this component into two factors: coping/adaptation and preparedness. When dealing with a disaster that is as dynamic and unpredictable as a wildfire, it is essential to not only be prepared, but also to be able to adapt quickly to the situation. This is particularly true when dealing with wildland fire events, where the movement and effects of the fire were often difficult to predict (Pelling 2003).

The Pelling Vulnerability Framework approach combines both physical and human vulnerability factors in a way that makes it fit very well with research centred around the effects of wildfires. Consequently it is an ideal choice for this study (see Appendix A for a more detailed diagram).

Wildfires are a complex phenomenon and behave in a way that is substantially different to other natural hazards. The Pelling Vulnerability Framework presents a generalised approach to natural hazards and does not necessarily encompass the full complexity of the wildfire hazard. It was necessary therefore to adapt the Pelling Vulnerability Framework in such a way that the Natural Hazard component could deal with the analysis of a wildfire more specifically.

Gould (2005) presents the dynamics of wildfires as being composed of two categories: Fire Danger and Fire Behaviour. Fire danger, as defined by Gould (2005) is the sum of all factors that affect the inception, spread, the difficulty of control of fires, and the damage they cause. Fire danger can only be fully realised when all potentials are present. There must therefore be a chance of ignition, sufficient fuel and value to damage.

Gould (2005) presents fire danger as the result of both constant and variable fire danger factors affecting the development, spread and difficulty of control of fires and the damage they cause. Constant factors are those that change slowly and vary with location such as slope and fuel.

Variable factors are those that change rapidly with time but can influence extensive areas such as wind speed, relative humidity and temperature.

Fire behaviour is a descriptive term used to designate what a fire does and how it behaves. It is an estimate of what a fire will do and relates to the intensity and rate of spread of a specific fire. It is perceived as a product of environmental factors that interact with each other, namely fuel, topography, weather and the dynamics of the fire. The latter includes the rate of spread, fire intensity, combustion rate, fire growth /acceleration, potential spotting and crown fires (Gould 2005).

The concepts of fire danger and fire behaviour, as stated by Gould (2005), are seen as central to the understanding of the wildfire natural hazard. It was therefore essential to incorporate these concepts into the Pelling Vulnerability Framework in order to enhance its usefulness in tackling the complex nature of the wildfire hazard. The framework was therefore adapted by the researcher of this study (see Appendix A) to include fire behaviour as an additional component to the natural hazard component of the framework, which would act in combination with the pre-existing factors of frequency and magnitude provided by Pelling (2003). The inclusion of fire behaviour in the framework was seen as essential, as it is a component that is unique to the wildfire hazard and which allows an analysis that will be more specific to the hazard and allows for a greater level of scrutiny and more detailed analysis that would not be possible without its inclusion.

The Pelling Vulnerability Framework includes the concept of magnitude as a component of the natural hazard. Magnitude is a measure of the intensity or the severity of the event as well as a measure of the size of the event and the amount of energy released. This concept of magnitude was seen as being analogous to the concept of fire danger presented by Gould (2005). By using fire danger as a surrogate for magnitude, it allows for a more detailed breakdown of what would constitute the magnitude of a wildfire event and allowed for a more detailed approach that would focus specifically on the dynamics of the wildfire natural hazard.

The amalgamation of the approaches of Pelling (2003) and Gould (2005) allow for an enhanced framework adapted specifically to cope with the complexities associated with the wildfire natural hazard. By further deconstructing the components of the wildfire hazard, it allows for a framework that will add an additional level of scrutiny and understanding of the drivers of wildfire events and aid the conceptual understanding of the wildfire hazard that will help not only in guiding the research process, but also in structuring the thesis as a whole.

Holloway and Roomaney (2008) define risk as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions. Conventionally risk is expressed by the notation Risk = Hazards x Vulnerability. The inclusion of the concepts of fire danger and fire behaviour from Gould (2005) has helped to develop the natural hazard component of the framework; it was felt that perhaps the vulnerability component was also somewhat lacking for the application of wildfire hazard analysis, and could also be further developed.

The concept of vulnerability in the Pelling Vulnerability Framework deals only with the aspect of human vulnerability, and so the framework fails to take into account vulnerability from an environmental perspective. Wildfires in South Africa have the potential to cause environmental loss if untimely or extreme in nature, particularly in areas where land is transformed or degraded especially as a result of alien plant invasions (Forsyth et al. 2010). The concept of ecological vulnerability is central to our understanding of the wildfire hazard in the context of South Africa, and it is therefore crucial that it is included as part of the adapted framework. Ecological vulnerability has consequently been included as an additional component to the concept of vulnerability as part of the adapted framework of Pelling (2003) and Gould (2005).

The adapted framework combines the ideas of Pelling (2003) and Gould (2005) that allows for a more focused approach to analysing the wildfire disaster events. It combines aspects of both the natural hazard and vulnerability in a way that allows for a novel approach that is appropriate for a natural phenomenon that is not only complex but unique.

2.2 Wildfire as a Natural Hazard

Following the example of Gould (2005) the dynamics of the wildfire natural hazard have been broken down into two components: fire danger and fire behaviour. The literature applicable to each of these phenomena has been evaluated in the sections that follow.

2.2.1 Fire Danger

Fire danger is presented by Gould (2005) as the result of both constant and variable fire danger factors affecting the development, spread and difficulty of control of fires and the damage they cause. As mentioned previously, constant factors are those that change slowly and vary with location, such as slope and fuel. Variable factors are those that change rapidly with time but can influence extensive areas such as wind speed, relative humidity and temperature. It is the combination of these constant and variable factors that determines dangerous fire conditions. Fire danger is a measure of the intensity or the severity of the event, a measure of the size of the event and the amount of energy released.

Syphard et al. (2006) investigated the effects of frequent fires in the Southern California shrublands. The coastal ranges and interior foothills of Southern California support shrubland vegetation that is adapted to the Mediterranean climate of the region, characterized by winter rain and summer drought. These are conditions which share many parallels with those of the South Western Cape of South Africa, and the fire regime that is experienced as part of the Fynbos ecology in the Cape Floristic Region.

Syphard et al. (2006) suggest that the Californian chaparral shrublands are quite flammable due to low decomposition rates, high dead-to-live fuel ratios, dense community structure, and low fuel moisture. The fire season in southern California occurs from late summer through fall when the fuel moisture is lowest and when strong winds are most likely to occur. Under high-wind conditions, fire cannot be effectively controlled until the wind dies down or the fire runs out of fuel. Therefore, chaparral typically burns in large, stand-replacing, high-intensity fires. The conditions associated with high intensity fires as suggested by Syphard et al. (2006) fit well with the concept of fire danger as presented by Gould (2005).

Syphard et al. (2006) also refer to the aspect of human interventions adding a further dimension to fire danger/intensity. They refer especially to human-population expansion and associated land-use change, and also fire-management policies such as suppression and prescribed fire, which undoubtedly alter the fire regime of a particular region. It has been suggested that fire suppression has successfully excluded fire and allowed the build-up of old fuel age classes, which have resulted in fewer, yet larger and more intense fires (Brown et al. 1991; Seydack et al. 2007; Syphard et al. 2006). There is however some debate on this subject, as many feel that climate and meteorological factors such as wind speed and temperature, is one of the main drivers of immensely large intense fires (Keeley 2003; Keeley & Fotheringham 2001; Keeley et al. 1999).

Based on the work presented by Syphard et al. (2006) and others, it is clear at this stage that fire danger is largely driven by meteorological factors in the form of wind and temperature conditions and aspects relating to the availability, abundance and quality of fuel/biomass. Many of these aforementioned factors are closely linked to fire intensity, which could be seen as one of the critical contributing factors of fire danger. It is important to note at this stage, that although much of the literature focuses on extreme wildland fire events, that fire danger as a concept should be viewed as a continuum that includes high, intermediate and low intensity fires that occur across a spectrum of levels of fire danger (Gould 2005).

Smith et al. (2004) suggest that fire intensity is an indicator of energy output. Fire intensity is usually determined by the quantity of fuel available, its moisture level and the rate at which it combusts. Higher available fuel levels and lower fuel moisture levels generally result in increased fire intensity. Fire intensity is predominantly controlled by fuel load and moisture, and weather conditions (Fernandes 2001; Ryan & Williams 2010).

Forsyth et al. (2010) suggest that in the context of South Africa, it is possible in some cases to have extreme fire episodes, where the wildfires exceed the boundaries of any municipality. In some cases it is even possible to have many major fires break out almost simultaneously across wide stretches of the country. The periods where this sort of phenomenon typically occurs is usually marked by extreme dryness and strong gusty winds followed by a long rainless period.

Forsyth et al. (2010) add that there has been an increased trend in the occurrence of what has been termed megafires. There has in fact been an epidemic of megafires that have occurred globally over the last 15 years. In addition to climate change driving this recent phenomenon, contributing human factors include biomass burning associated with land clearing, increasing available fuel loads caused by land abandonment (afforestation, revegetation), fuel build-up from historical fire suppression (e.g. Australia, western North America), and people as an omnipresent ignition source.

The literature surrounding aspects relating to fire danger present some interesting arguments. There appears to be consensus amongst researchers within this literary domain that fuel is one of the dominant factors influencing fire danger or at the very least fire intensity which forms a major contributing factor to fire behaviour (Smith et al. 2004; Syphard et al. 2006; Forsyth et al. 2010). This of course relates to two key components of fuel, quantity and condition. Both of these components are linked to the age of the fuel and the overall dryness of the fuel, which could perhaps be expressed more simply as ‘readiness to burn’ (Smith et al. 2004; Syphard et al. 2006; Forsyth et al. 2010). This has been particularly useful in guiding this particular research project, as it helps to expand upon the topic of fuel, which while introduced by Gould (2005) as a fundamental component of fire danger is not explained well and Gould (2005) is relatively vague on the contributing factors of fuel. The contribution of meteorological factors in the form of wind conditions and relative humidity are mentioned in almost all of the research investigated, and it seems to be the case that both of these factors are seem as critical drivers of fire behaviour (Smith et al. 2004; Syphard et al. 2006; Forsyth et al. 2010). Relative humidity is also seen to not only have a role in affecting weather conditions during the course of a fire event in collaboration with wind speed, but also in its role of affecting the condition of fuel and its readiness to burn, possibly with some collaboration with wind conditions and effects on evapotranspiration (Smith et al. 2004; Syphard et al. 2006; Forsyth et al. 2010).

There are also some noticeable differences that are apparent between the work of Gould (2005) and other literature that was consulted. Gould (2005) includes temperature as one of the contributing meteorological factors that influence fire danger, however, temperature does not seem to be presented in much of the research surrounding aspects of fire danger as a major contributing factor (Smith et al. 2004; Syphard et al. 2006; Forsyth et al. 2010). Syphard et al. (2006) and Forsyth et al. (2010) also make reference to the influence of rainfall and its contribution to facilitating conditions where there is a build-up of biomass, creating conditions where threre are larger quantities of fuel available to burn. This is interesting, as Gould (2005) does not make reference to rainfall specifically as a contributing meteorological factor, but may perhaps include this as part of fuel. What is also interesting is that there is very little reference to slope with regards to fire danger. The prevailing consensus seems to be that the driving factors of fire danger include wind conditions, relative humidity and the quantity and condition of fuel (Smith et al. 2004; Syphard et al. 2006; Forsyth et al. 2010).

2.2.2 Fire Behaviour

Fire behaviour is a descriptive term used to designate what a fire does and how it behaves. It is an estimate of what a fire will do and relates to the intensity and rate of spread of a specific fire (Gould 2005). It is perceived as a product of environmental factors which interact with each other, namely fuel, topography, weather and the dynamics of the fire which includes the rate of spread, fire intensity, combustion rate, fire growth/acceleration, potential spotting and crown fires (Gould 2005).

The term fire behaviour is used to describe the magnitude, direction, and intensity of fire spread, and fire behaviour could perhaps be seen as the reaction of fire to a particular environment (Noble et al. 1980; Keeley 2009). Fire behaviour refers to the manner in which fuel ignites, flame develops and fire spreads. In wildland fires, this behaviour is influenced by how fuel, weather and topography interact (Noble et al. 1980; Keeley 2009). The behaviour of a fire often depends on fuels, but other factors or variables may include where the fuel is situated and how near it is to other sources of fuels, the weather, and the shape of the terrain (Noble et al. 1980; Keeley 2009).

Understanding the behaviour of fynbos wildfires is crucial for adequate planning in the face of the perpetual risk faced in the form of wildland fire risk. Van Wilgen et al. (1985) investigate fire behaviour in South African fynbos vegetation. They suggest that fire is a feature of these ecosystems, and highlight the need to be able to describe wildfires adequately. Van Wilgen et al. (1985) suggest that the major driver of wildfires per se or fire behaviour specifically is biomass or fuel. Their results showed that a range of fire behaviour parameters could reasonably be expected in fynbos. These were based largely on biomass and rate of spread estimates. Fires in fynbos spread faster and burn with a greater intensity than fires that occur in other fire dependent vegetation types (such as savannah and grassland) despite similarities in biomass (Forsyth et al. 2010; Van Wilgen et al. 1985). This is thought to be linked to the low moisture content characteristic of fynbos vegetation (Van Wilgen et al. 1985). Low decomposition rates, high dead-to-live fuel ratios, dense community structure as seen in similar Mediterranean ecosystems such as the Californian chaparral are also believed to be some of the key drivers of fire behaviour (Syphard et al. 2006).

It is clear that fuel load is also a key driver of fynbos fires. Van Wilgen & Richardson (1985) investigated the effects of alien shrub invasions on vegetative structure and fuel load. Fynbos vegetation is susceptible to invasion by alien shrubs. As a result of these invasions, the nature of the fuel load is altered and this will affect fire behaviour. Invasion often results in considerable changes in the natural community structure of fynbos. This usually manifests as an increase in the number and size of dominant shrubs and an introduction of trees into a treeless vegetation type at the expense of understorey herbs and shrubs. Understorey shrubs are extremely important in determining fire behaviour. They are, together with dead material, responsible for carrying fire which would in turn ignite larger dominant shrubs. As understorey plants are largely eliminated by alien invasion, these dominant shrubs would only be ignited under extreme conditions. Fires are therefore ignited more easily in pristine fynbos vegetation. Under moderate conditions, fires in fynbos will spread faster and burn with a greater intensity than in invaded vegetation. However, under extreme conditions, alien invaded sites will burn with a much higher intensity and unpredictable behaviour (Van Wilgen & Richardson 1985).

Forsyth et al. (2010) suggest that fire behaviour is strongly influenced by four factors: fuels, climate and weather, ignition agents and people. The fuel type, continuity, structure, moisture, and amount are critical elements of fire occurrence and spread (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006). For example, for fires to spread there needs to be fuel continuity, which means that at least 30% of the landscape may need to have fuel; thus sufficient precipitation is required during the season preceding the fire season for the growth of sufficient fuels to be available to regularly carry fire on the landscape.

Forsyth et al. (2010) go on to explain that although the amount of fuel, or fuel load, affects fire activity as a minimum amount of fuel is required for fire to start and spread, fuel moisture largely determines fire behaviour, and has been found to be an important factor in the extent of area burned (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006).

Weather and climate – including temperature, precipitation, wind, and atmospheric moisture – are critical aspects of fire activity. Numerous studies suggest that temperature is the most important variable affecting wildland fire, with higher temperatures leading to increased fire activity. Higher temperatures increase evapotranspiration, as the ability for the atmosphere to hold moisture increases rapidly with higher temperatures, thereby decreasing fuel moisture. In addition, higher temperatures may lead to a lengthening of the fire season. Precipitation is also an important variable in fire activity but timing of precipitation during the fire season rather than the amount is usually the most important aspect (Forsyth et al. 2010).

Slope is thought to affect fire danger in quite a significant way. Though not measurable, slope can have a tremendous effect on the accessibility of the fire by rescue workers and fire-fighters. Slope is also thought to contribute to the rate of spread of the fire, adding to the momentum as the fire surges downhill.

Slope and topography together have a major effect on both the flaming combustion phase and fire ignition. Mid to upper slope areas tend to be more flammable as a result of drier soil conditions and drier vegetation that occur as a result of better water drainage. Combustion of dry vegetation requires less water evaporation, and less energy before ignition (Hely & Alleaume 2006). Fire burning uphill is also thought to propagate at a faster rate than fire that is spreading downhill or on flat terrain (Alexander 1982). When fire burns uphill, the radiation energy released by the flames augments the preheating of the adjacent fuel which is in close proximity to the flame, caused as a result of the steep slope angle. This increases the rate at which the fire spreads (Alexander 1982).

Slope can have a profound effect on fire conditions. On slopes, the less dense air next to the surface (warmed by the surface) forms a pathway for this lighter air to rise along the slope causing a draft. Cooler air to replace the warmer, less dense air comes from below. Consequently local winds usually blow up-slope during the day. Because of the local, up-slope winds, wildfires usually burn up-slope. The steeper the slope, the more rapidly the fire will burn up-slope (and more intensely) (Hely & Alleaume 2006). The reason is because of both greater radiant heat and greater convective heat.

A fire will spread uphill because of the preheating of the fuel and the up-slope draft unless the general wind is strong enough to overcome these two forces. The flames are closer to the fuel on the uphill side and they receive more radiant heat. This results in more preheating and faster igniting of the fuel (Alexander 1982). The heated air rises along the slope increasing the draft that further increases the rate of spread. As a result of winds blowing up-slope, more convective heat also reaches the fuel in front of the fire and it is pre-heated more quickly to the ignition temperature (Alexander 1982).

There is consensus from the literature dealing with the topic of fire behaviour that fuel is for the most part the major contributing factor (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006, Van Wilgen et al. 1985; Van Wilgen & Richardson 1985). What is important to understand is the way in which fuel acts as a driver of fire behaviour. With regards to fire behaviour, it is the arrangement and density of fuel that is of critical importance, specifically with regards to the fuel continuity and the fuel load (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006, Van Wilgen et al. 1985; Van Wilgen & Richardson 1985). This is not to be confused with the contribution of fuel to fire danger, where we are focusing on the condition, age and readiness to burn of the fuel rather than the quantity and spatial arrangement. There is also mention of the contribution of the impact of alien invasive species, specifically to how the nature of the fuel continuity and density are altered as a result of the introduction of these species, a critical issue to consider when investigating the contribution of fuel to fire behaviour (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006, Van Wilgen et al. 1985; Van Wilgen & Richardson 1985). This is consistent with what is expressed by Gould (2005) in his definition of fire behaviour, who describes fire behaviour as a product of the interaction of environmental factors, fuel being chiefly amoung these. It would make sense given this view point that the arrangement of fuel (possibly influenced by topography and slope) should be seen as the major driving factor of fire behaviour (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006, Van Wilgen et al. 1985; Van Wilgen & Richardson 1985).

Slope is also seen as a driving factor of determining fire behaviour by influencing the rate of spread of the fire. This can occur in one of two ways, either through the preheating of fuel through what is commonly referred to as the ‘chimney effect’ as the fire moves uphill through interaction with updrafts in topographically complex areas, or by adding momentum as the fire surges downhill (Alexander 1982; Hely & Alleaume 2006). There is also the contribution of slope and topography to the accessibility of the fire by rescue workers that needs to be considered.

Though there are similarities between the concepts of fire danger and fire behaviour, it is important to understand that fire behaviour refers more to the spatial extent of fire in terms of the movement and overall surface area covered. The research on fire behaviour is extensive, and there is a large amount of literature available. All the research emphasizes the importance of understanding and predicting fire behaviour. The general consensus amongst researchers within the domain of fire behaviour is that biomass and fuel form the major contributing factor to fire behaviour (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006, Van Wilgen et al. 1985; Van Wilgen & Richardson 1985). It is important to understand that the contribution of fuel with respect to fire behaviour refers to the fuel type, continuity and spatial arrangement rather than the condition of the fuel, as was the case with fire danger (Cruz & Gould 2009; Forsyth et al. 2010; Gould 2005; 2006, Van Wilgen et al. 1985; Van Wilgen & Richardson 1985). There is also reference to the influence of slope and topography in helping to determine the arrangement and continuity of fuel, which fits well with the definition of fire behaviour, which is perceived to be heavily influenced by physical environmental factors (Noble et al. 1980; Gould 2005; Keeley 2009). The structure and arrangement of vegetation is also considered as vitally important, especially when one considers how this may be altered as a result of the introduction of alien invasive species.

2.3 Vulnerability

Vulnerability is defined as the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility to the impact of hazards (Holloway & Roomaney 2008). In the context of disaster risk science, vulnerability is one of the fundamental elements that constitutes our understanding of risk, which is conventionally expressed by the notation Risk = Hazards x Vulnerability (Holloway & Roomaney 2008). The concept of vulnerability as discussed previously, is central to discussions relating to the impact of natural hazards, and must therefore be considered as part of the research process (Pelling 2003). Typically, vulnerability is presented in the form of human vulnerability, but, in the case of this study which focuses on the very specific risk posed by wildland fire events, ecological vulnerability is also considered as a major contributing factor in the overall vulnerability context relating to fire risk. Within this section relating to vulnerability it was consequently decided to focus on three key areas, namely: human vulnerability, ecological vulnerability and fire frequency. While fire frequency is viewed in terms of the adapted conceptual framework (Appendix A) used for this study as a component of the natural hazard, it made sense to cover this literature here as a result of the relative contribution that fire frequency makes towards the element of exposure which forms one of the core drivers of vulnerability (Pelling 2003; Cannon 2008; Holloway & Roomaney 2008).

2.3.1 Human Vulnerability

In the face of increasing wild-fire risk, particularly with regard to the urban-wildland interface, it is important to consider the way in which local authorities and the affected community respond to the threat of a fire hazard as they are often the first line of defence in a major fire disaster situation. The actions of the threatened community can often play a pivotal role in affecting the overall consequences of a wild-fire event. Human vulnerability is defined as the factors (usually social and economic in origin) which increase the susceptibility of society or communities to the impact of hazards (Holloway & Roomaney 2008). This body of literature (Rohrman 2000; Pelling 2003; Tibbits & Whittaker 2007; McLennan & Birch 2005; Cannon 2008; Holloway & Roomaney 2008; McAneney et al. 2009) has emerged only recently, but raises some interesting points for consideration. Australian academics are at the forefront of this type of disaster research and often provide a somewhat novel and progressive approach to dealing with these issues which is seen by many as being quite controversial. The wildfire risk conditions in Australia share many parallels with those of South Africa and allows for a very useful and interesting comparison.

McAneney et al. (2009) investigated bushfire risk to the urban environment in Australia. In terms of property loss, the potential threat is greatest at the urban–bushland interface and quantifying this threat is essential for developing rational planning regulations and fair and realistic insurance premiums. They suggest that the raw loss statistics often conceal the role individual homeowners may play in defending homes and increasing the likelihood of survival of both themselves and their homes. Australian fire authorities now encourage homeowners to be either prepared to defend their homes or evacuate early, well before the fire front approaches. This policy is quite unique amongst countries with significant bushfire risks and clearly puts the actions of residents as central in the protection of lives and property. The actual loss in a bushfire is a random variable that depends upon a host of variables including whether or not it intersects a populated area, the disposition of threatened houses and human intervention. People enjoy living close to the greenery and will continue to do so despite the bushfire risk. It is crucial therefore that people are aware of how to respond to the threats of bushfires in order to mitigate their individual risk.

Tibbits & Whittaker (2007) examine the effectiveness of the strategy of the Australian authorities which advise residents to make a decision to prepare, stay and defend their properties from bushfires or leave well before the fire arrives in their area. The ‘stay and defend or leave early’ policy is underpinned by strong evidence that well-prepared houses can be successfully defended and that late evacuation is a dangerous strategy. Australian fire authorities and the communities they serve have achieved great success in reducing losses of life and property from bushfires. Evidence that ordinary people can protect their homes from bushfires by staying with and actively defending them has informed the development of the ‘stay and defend or leave early’ policy, which has become the centrepiece of community bushfire safety strategies in Australia. This is a unique approach to community safety for bushfires when compared with international approaches, where mass evacuation is the norm. Fire authorities encourage residents of bushfire prone areas to decide, prior to the start of each fire season, whether they will prepare, stay and defend their property from bushfires or leave well before the fire arrives in their area. Research on infrastructure ignition during bushfires supports the assertion that well-prepared houses can be successfully defended and can provide safe refuge during the main passage of the fire front. Tibbits & Whittaker (2007) suggest that equipping and encouraging people to decide whether they will prepare, stay and defend their properties from bushfires or leave early, provided they act on their decision, is the single most important strategy for protecting people and property from bushfires.

Rohrman (2000) adds to this debate and suggests that if active participation of residents is to be achieved, motivating risk information/communication/education campaigns are vital. People exposed to hazards need to be optimally informed about risk characteristics, preventative measures, appropriate behaviours during emergencies, and they must understand their own responsibility. Authorities have to compose pertinent planning, prepare coping strategies and effectively communicate the relevant information to residents and communities as a whole.

McLennan & Birch (2005) add a further dimension to the role of the community in responding to wildfire events by exploring the role of volunteer fire fighters. They suggest that emergency response to accidents and natural disasters is very dependent on a trained workforce of emergency services volunteers: fire, rescue, medical, care and relief.

Vulnerability, together with the characteristics of the natural hazard, forms a critical component of what we define as disaster risk. Vulnerability in the form of human vulnerability is of particular significance, and the action of people in the face of ever increasing disaster risk is of the utmost importance (Rohrman 2000; Pelling 2003; Tibbits & Whittaker 2007; McLennan & Birch 2005; Cannon 2008; Holloway & Roomaney 2008; McAneney et al. 2009). Human vulnerability occurs as the result of two characteristics: exposure and capacity (Pelling 2003; Cannon 2008; Holloway & Roomaney 2008). This certainly fits well with the literature that surrounds the concept of human vulnerability.

In terms of exposure, the urban interface results in increased exposure of people to the effects of natural hazards. In the case of fire specifically, this can potentially lead to significant risk to the loss of property (Pelling 2003; Tibbits & Whittaker 2007; Holloway & Roomaney 2008; McAneney et al. 2009). This is where the capacity of communities at risk of exposure is absolutely critical. The response strategies of stay and defend or early evacuation are advocated as suitable strategies in the face of unavoidable fire risk (Rohrman 2000; Holloway & Roomaney 2008; McAneney et al. 2009). Public awareness is also essential to this process, fulfilling the role of creating an informed and educated response, allowing for the successful implementation of early warning systems, creating a co-ordinated response to fire hazards, and encouraging community involvement (Rohrman 2000; Holloway & Roomaney 2008; McAneney et al. 2009).

In this particular research project, the contribution of human vulnerability was excluded as a result of the context and location of the selected study site, where human vulnerability does not form part of the risk profile of the study area, given that it is a nature conservation area located in an isolated mountain catchment. The researcher, however, chose to still include human vulnerability as a component of the conceptual framework (Appendix A) so that it may still be applied in situations where human vulnerability is of critical concern and a contributing factor.

2.3.2 Ecological Vulnerability

As mentioned previously, the dominant vegetation type in the Western Cape is fynbos vegetation which is a fire dependent system. It is critical to have an understanding of the fire requirements of natural systems in order to manage fire risk effectively.

Wilson et al. (2010) suggest that over half of the world’s terrestrial ecosystems are dependent on fire to maintain ecological structure and function and that fire regimes in these regions have a profound ecological role that can be strongly influenced by weather and climate.

Newton et al. (2006) suggest that fire has an important role to play in fynbos vegetation, directly influencing plant growth, survival and reproduction. Fire also impacts upon seed and seedling dynamics. Plant survival strategies following fire may be vegetative (e.g. resprouting) and/or reproductive (e.g. fire stimulated seed germination). Newton et al. (2006) investigated the nut-fruited Restionaceae, which make use of both resprouting and seed germination following a fire. Fire-stimulated seed germination is important in Mediterranean-type ecosystems globally. Species in which seed germination is directly or indirectly stimulated by the occurrence of fire typically possess soil-stored seeds that require a fire cue for germination. The effects of storage regime and fire cues (heat and charate) on seed viability and germination were investigated in the nut-fruited Restionaceae species, *Cannomois virgata*. Seed deterioration in soil-stored seed was not significantly different to laboratory-stored seed. A marked improvement in germination of soil-stored seed was observed on exposure to charate from a fire (Newton et al. 2006).

Brown & Botha (2004) suggest that the propagation of fynbos plants from seed is often difficult, as the seeds of many species are dormant when shed and require very specific environmental 'messages' or cues before they will germinate (Brown & Botha 2004). Fire provides the major cues for germination, and species are thought to germinate in response to temperature and exposure to smoke (Brown & Botha 2004).

Le Maitre & Midgley (1992) also make reference to the importance of fire in the reproductive ecology of fynbos species. This may take the form of either fire stimulated flowering or the germination of seeds through the direct or indirect stimulation of fire, a trait that is prominent in many fynbos species (Le Maitre & Midgley 1992).

2.3.3 Fire Frequency

Polakow & Dunne (1999) define the term 'fire frequency' as the recurrence patterns focusing on either return intervals (the time intervals between successive burns) or the fire-cycle (the time period required to burn an area. Temporal and spatial variation in the fire regime is crucial for the maintenance of biodiversity in fynbos (Cowling & Gxaba 1990; Thuiller et al. 2007). It is important to recognise that there is no 'optimum' fixed fire regime for conserving biodiversity in fynbos since such an unchanging regime would invariably lead to the impoverishment of diversity by repeatedly favouring certain species over others (Cowling 1987; Bond & Van Wilgen 1996). Seydack et al. (2007) suggest that while fire is the principal driving force in fynbos dynamics, spatiotemporal variability in the fire regime, fire frequency and seasonality are recognised as crucial in the maintenance of biodiversity (Cowling 1987; Bond & Van Wilgen 1996).

Syphard et al. (2009) suggest that periodic wildfire is an important natural process in Mediterranean-climate ecosystems, but increasing fire frequency threatens the fragile ecology of these regions. As population density increases, human ignitions and fire frequency also increase. The association between higher population densities and fire suggests that regardless of differences between land-cover types, natural fire regimes, or overall human population, the presence of people in Mediterranean-climate regions strongly affects the frequency of fires (Syphard et al. 2009). Population growth in areas now sparsely populated presents a conservation concern. Species in the Cape Floristic Region tend to be locally abundant but have small ranges and limited dispersal capabilities (Cowling & Lombard 2002; Wilson et al. 2010). It follows therefore that if the fire return interval is repeatedly too short, even in a small area, species might become not only locally extinct, but globally extinct (Wilson et al. 2010). Considering the sensitivity of plant species to repeated burning and the global conservation significance of Mediterranean-climate ecosystems, conservation planning needs to consider the human influence on fire frequency (Goldblatt & Manning 2002). Fine-scale spatial analysis of relationships between people and fire may help identify areas where increases in fire frequency will threaten ecologically valuable areas.

Vlok & Yeaton (2000) advocate that fire frequency can have dramatic effects on the species composition within a community. In Mediterranean-type shrublands, the fire regime can affect the proportion of sprouting to non-sprouting species in a community. Short fire cycles of 3–10 years generally favour sprouting species, while longer intervals between fires (>10 years) tend to favour non-sprouting species. A general increase in fire frequency, coupled with cool spring burns, in Mediterranean-type shrublands of South Africa may cause local extinction of non-sprouting species (Vlok & Yeaton 2000).

Forsyth et al. (2010) defines the “fire regime” as the history of fire in a particular vegetation type or area including the frequency, intensity and season of burning; it is the combination of elements that typifies fires in a given region, under assumed natural conditions (Myers et al. 2007; Ryan & Williams 2010). Fire regimes are ecological drivers that shape the functioning, structure and composition of the ecosystem, and fire frequency forms a particularly integral part of the fire regime. If the frequency, intensity, type, season or size of fires diverges from the natural range of variation under which the ecosystem evolved, the ecosystem structure and processes will change (Forsyth et al. 2010; Myers et al. 2007; Ryan & Williams 2010).

The exact return period between fires, and the time during the dry season when fires are ignited, hardly makes any difference to the outcome, unless they are taken to extremes. Fynbos ecosystems, are sensitive to certain changes in fire recurrence intervals. They have species which survive fires only as seeds and take several years to flower and produce sufficient seeds to re-establish viable populations after fires (Vlok & Yeaton 2000). However, the minimum intervals between fires can be longer than the time needed for the fynbos to accumulate sufficient fuel to burn. In these cases managers need to ensure that fire recurrence intervals are not too short for these species to survive because only a small change in the fire interval is needed to result in local extinction (Forsyth et al. 2010).

Applying a fixed regime selects for some species, and disadvantages others (Vlok & Yeaton 2000). If we wish to maintain a diverse and fire-resilient fauna, flora and landscape, we need to plan for fire regimes that allow for, and even promote, variability within broad limits. However, the presence of alien invasive species, specifically plants, creates a special fire-related hazard, which increases environmental vulnerability to inappropriate veldfires (Forsyth et al. 2010).

2.4 Wildfire Risk Management

The third body of literature which is key to this study is that related to wildfire risk management (Forsyth et al. 2000; Borchers 2005; Kruger et al. 2006; Tolhurst 2006; Moir 2009). In recent years, heightened attention to the social dimensions of wildfire has led to discussions of wildfire risk. Hazards as a result of wildfires are becoming an ever increasing problem, particularly in South Africa where the urban edge is expanding rapidly, resulting in more people being at risk.

Most disaster mortality and asset destruction is intensively concentrated in very small areas exposed to infrequent but extreme hazards. However, low-intensity damage to housing, local infrastructure, crops and livestock, which interrupts and erodes livelihoods, is extensively spread within many countries and occurs very frequently. Such damage represents a significant and largely unaccounted for facet of disaster impacts (UNGAR 2009). Climate change is already changing the geographic distribution, frequency and intensity of natural hazards and threatens to undermine the resilience of poorer countries and their citizens to absorb loss and recover from disaster impacts. This combination of increasing hazard and decreasing resilience makes climate change a global driver of disaster risk (UNGAR 2009). A failure to address the underlying risk drivers will result in dramatic increases in disaster risk and associated poverty outcomes. In contrast, if addressing these drivers is given priority, risk can be reduced, human development protected and adaptation to climate change facilitated (UNGAR 2009). There is a need to promote greater synergy in hazard monitoring and risk identification, leading to comprehensive multi-hazard risk assessment, through the functional integration of the actions of scientific and technical bodies responsible for meteorology, geology and geophysics, oceanography and environmental management (UNGAR 2009).

Each country has its own unique risk profile or signature with different kinds and proportions of extensive, intensive and emerging risks. To reduce their risks, there is need to adopt a mix of prospective, corrective and compensatory risk management strategies together with strategies to manage disasters and anticipate emerging risks (UNGAR 2011).

The risks, uncertainties, and social conflicts surrounding wildfire are often uncharacteristic when compared to other natural hazards, and have defied conventional approaches to planning and decision-making (Borchers 2005; Tolhurst et al. 2006). The adoption of technological innovations such as risk assessment, decision analysis, and landscape simulation models has been limited. The main elements of bushfire management need to be identified. The way in which these elements interact with each other needs to be assessed, and decisions need to be taken relating to what level of resources are allocated to each element and how important each element was, alone and in combination, to reducing the level of bushfire risk (Borchers 2005; Tolhurst et al. 2006).

Forsyth et al. (2010) recognise the need for periodic fire as an important ecological process, and also that some wildfires are inevitable. This is also further complicated by what is termed as the urban-wildland boundary. This means that houses and other property are at risk from wildfires and that fire suppression for non-ecological reasons will be required from time to time. It also means that prescribed fires need to be planned and conducted carefully to avoid the risk of damage. Widespread alien plant invasions also add a further dimension to these issues and bring added requirements in terms of fire management. The management of a fire dependent ecological system that is in close proximity to densely populated urban areas invites criticism, and managers need good information on past fires to support their actions. In addition, densely settled areas bring increased risks of unwanted ignitions. Managers need to be able to identify areas that would be at risk if such fires occurred, so that these areas could be afforded additional protection.

Kruger et al. (2006) acknowledge the need for a better understanding of the patterns of wildfire risk. In this study they attempt to develop the first approximation of the veldfire risk profile for South Africa drawn from readily available ecological information, vegetation maps. The results show that nearly seventy per cent of the area of South Africa is subject to a significant level of wildfire risk and fifty-seven per cent is subject to high or extreme risk. These results clearly highlight the need for a more detailed analysis of vegetation together with land cover information that will provide the basis for a more accurate veldfire risk assessment system for the country. In addition, proper reporting of veldfires and a thorough review of archival information on veldfires will allow better risk assessment for wildfires (Kruger et al. 2006).

If there is one thing that is abundantly clear from the literature, it is that there is a need to understand the dynamics of wildfires, both in terms of an ecological or risk management perspective. The use of fire mapping and archival data is highlighted as an important step in this process, as well as the reporting and documenting of fire events. This is a gap that this study hopes to address, through the use of applied statistical techniques to various sources of primary and archival data including: meteorological data obtained from the South African Weather Services (SAWS); historical fire records and data relating to the physical environmental characteristics of the study area obtained from Cape Nature and Stellenbosch University; and post-fire seedling monitoring obtained from Cape Nature and sampling carried out by the researcher.

CHAPTER 3: RESEARCH METHODS AND STATISTICAL TECHNIQUES

The drivers of wildfire behaviour, severity and magnitude were investigated by means of a combination of statistical methods and geospatial mapping techniques. The drivers, as indicated in the conceptual framework (Appendix A), developed from the amalgamation of work presented by Pelling (2003) and Gould (2005), will be analysed for a wide range of fire hazards selected from the recorded fire history of the study area.

3.1 Fire Size Distribution

The extent of the burn scar (measured in hectares) will be used as a proxy for wildfire severity and magnitude. In order to facilitate a more detailed analysis of the fire history of the Limietberg Conservation Area, a system of fire size classes was created. More insight into the trends in burned area could be derived from separating the burned area into ten fire size classes. Studies such as Parisien et al. (2004) and Cui & Perera (2008) have used fire size classification in studies that involve the analysis of fire, particularly with respect to investigating patterns of fire regime. Following Archibald et al. (2009) fire sizes in this study were classified as indicated in Table 3-1. Each fire size class was named by letters A to J respectively. In total there were 121 fires that were analysed from the fire history of the Limietberg Conservation Area as part of the study. The fire size classes were selected based on the system used by Archibald et al. (2009) in conjunction with the frequency distribution observed within the fires analysed. This process of defining fire size classes took into account the range in fire sizes and ensured that there was not a classification system that was not too coarse in order to accommodate for the variability in fire sizes that was observed. A frequency distribution of the number of fires in each size class is illustrated in Figure 3-1.

Table 3-1 Fire Size Classification

A	< 25ha	31
B	25 - 100ha	15
C	100 - 250ha	12
D	250 - 500ha	12
E	500 - 1000ha	13
F	1000 - 2500ha	14
G	2500 - 5000ha	15
H	5000 - 10000ha	5
I	10000 - 25000ha	2
J	> 25000ha	2

Figure 3-1 Frequency distribution of the number of fires present in each size class for the period 1980 – 2010 for the Limietberg Conservation Area.

Grouping the fires into size classes in this way allows for a more in-depth analysis of how the different drivers and contributing factors combine to create conditions associated with fires of different sizes and levels of severity. It allows for fires that are of a similar size to be compared and also for fires from different sizes to be compared.

3.2 Statistical Analysis

The bulk of the procedures used in the research method employed the use of statistical techniques in the form of multiple regression and ordination techniques. The pre-treatment of data and testing for normality was also a consideration in the application of the method.

3.2.1 Normality of Data

In statistics, normality tests are used to determine whether a data set is well-modelled by a normal distribution or not, or to compute how likely an underlying random variable is to be normally distributed (Clarke & Warwick 1994). For most statistical techniques, it is a requirement that data is normally distributed in order for various statistical techniques to be performed (McDonald 2009). All variables used as part of the statistical analysis component of the methodology were tested for normality using the distribution fitting option in *Statistica Version 11*. The data were tested both in its raw form as well as its log transformed form. In all instances the data were not normally distributed, so it was necessary to transform the data before the application of statistical techniques.

In statistical data analysis, data need to be prepared before models can be built or algorithms can be used. In this context, preparing the data means transforming them prior to the analysis so as to ease the algorithm's job (McDonald 2009). Often, the rationale will be to alter the data so that the hypotheses, on which the algorithms are based, are verified, while at the same time preserving their information content intact. One of the most basic transformations is normalisation (McDonald 2009).

In the instance of this research, data has been normalised by utilizing the pre-treatment facility of *Primer Version 6*. The pre-treatment option in *Primer Version 6* makes use of a system called variable (column) normalisation. Using this system, variables can be compared consistently in terms of information content with respect to the target variable. This issue is most important for algorithms and models that are based on some sort of distance, such as the Euclidean distance (Clarke & Warwick 1994). As the Euclidean distance is computed as a sum of variable differences, its result greatly depends on the ranges of the variables (McDonald 2009). Should a variable express a dynamic (or variance) that is significantly larger in scale than the others, then its value will mostly dictate the value of the distance, merely ignoring the values of the other variables. Should those variables be of some importance, the distance would compromise the result obtained from any algorithm (McDonald 2009).

To avoid the latter situation, variables (columns) are rather normalised to the same 'dynamic range', with no units (they become a-dimensional values). In the methodology used in the pre-treatment option in *Primer Version 6*, variables are supposed normally distributed with distinct means and variances. In such a case, the idea is to centre all variables so they have a zero mean and divide them by their standard deviation so that they all express unit variance. The transformed variables are then what are called 'z-scores' in the statistical literature (McDonald 2009). They are expressed in 'number of standard deviations' in the original data. Most of the transformed values lie within the [-1, 1] interval.

3.2.2 Correlation and Multiple Regression

Correlation is a concept based upon the notion of co-variance. Two varying quantities are said to co-vary when, whenever one is increasing in value, the other does so too, and conversely when one is decreasing in value. Two correlated quantities vary together so that they actually seem to interact (McDonald 2009).

In statistical terms, when the varying quantities are described as random variables X and Y, covariance has a specific meaning. Covariance is the expected value (denoted E[.] here) of the product between deviations of each variable from its mean (McDonald, 2009).

$$\mathrm{Cov}(X,Y) = E[(X - E(X))\,(Y - E(Y))]$$

When both variables take values larger than their respective means, their product is highly positive. When one of them takes a value higher than its mean while the other takes a value lower than its mean, the product is largely negative (McDonald 2009).

Correlation is computed like the covariance, except that it normalized so as to take values between -1 and 1, no matter which quantities are considered. It is defined as Cov(X,Y) / (std(X) std(Y)) where std(X) is the square root of the variance of X (its standard deviation) and is known as the Pearson Product Moment correlation (McDonald 2009).

A correlation of +1 between two variables indicates perfect co-variation, while a value of -1 indicates a perfect anti-variation; when one of the variables is increasing, the other is decreasing, and vice versa. As far as continuous variables are concerned, the correlation is directly linked to the (normalized) error made by a linear model when one of the variables is used to predict the other and vice versa (McDonald 2009).

In statistics, multiple regression is a method of correlation analysis that is used when there are three or more measurement variables. One of the measurement variables is the dependent (Y) variable. The rest of the variables are the independent (X) variables. The purpose of a multiple regression is to find an equation that best predicts the Y variable as a linear function of the X variables. There is also a "hidden" nominal variable that groups the measurement variables together (McDonald 2009).

One of the uses of multiple regression is to try to understand the functional relationships between the dependent and independent variables, to try to see what might be causing the variation in the dependent variable (McDonald 2009).

The basic idea is that an equation is found, like this:

$$Y_{exp} = a + b_1x_1 + b_2x_2 + b_3x_3 \ldots$$

The Y_{exp} is the expected value of Y for a given set of X values. b_1 is the estimated slope of a regression of Y on X_1, if all of the other X variables could be kept constant, and so on for b_2, b_3, etc; a is the intercept. Values of b_1, etc. (the "partial regression coefficients") and the intercept are found that minimize the squared deviations between the expected and observed values of Y. How well the equation fits the data is expressed by R^2, the "coefficient of multiple determination." This can range from 0 (for no relationship between the X and Y variables) to 1 (for a perfect fit, no difference between the observed and expected Y values). The P-value is a function of the R^2, the number of observations, and the number of X variables (McDonald 2009).

When the purpose of multiple regression is understanding functional relationships, the important result is an equation containing standard partial regression coefficients, like this:

$$Y'_{exp} = a + b'_1x'_1 + b'_2x'_2 + b'_3x'_3 \ldots$$

where b'_1 is the standard partial regression coefficient of Y on X_1. It is the number of standard deviations that Y would change for every one standard deviation change in X_1, if all the other X variables could be kept constant. The magnitude of the standard partial regression coefficients provides information about the relative importance of different variables; X variables with bigger standard partial regression coefficients have a stronger relationship with the Y variable (McDonald 2009).

Regression analysis has been used as part of the statistical methodologies during the analysis of meteorological and physical environmental variables in this research.

3.2.3 Ordination

Ordination in the simplest of definitions is a statistical method of representing data in a graphical or visual way, from which we can make inferences about samples. An ordination is a map of samples, usually in two or three dimensions, in which the placement of the samples, rather than representing their simple geographical location, reflects their similarity (Clarke & Warwick 1994). It is the spatial representation of samples plotted by the ordination process that is of importance. The distances between samples on the ordination attempt to match the corresponding dissimilarities in the sample structure (Clarke & Warwick 1994). Points that are grouped nearby share a similarity and points that are grouped further apart are dissimilar (Clarke & Warwick 1994).

While not necessarily common to the field of geography and environmental science, ordination techniques are widely used in biological applications, particularly when analysing community structure of organisms (Clarke & Warwick 1994). The merits of ordination techniques are now well-established in ecological applications, and comparative studies have consistently demonstrated their reliability (Clarke & Ainsworth 1993). Fire is a particularly complex natural phenomenon, with many drivers and contributing factors. Simple statistical techniques such as linear regression were not able to provide an adequate means of analysing the many variables that combine in creating the conditions necessary for the occurrence of a fire, and indeed, would only allow for the analysis of a single variable across fire size classes.

Given that our understanding of fire suggests that it occurs as a result of the combination of several drivers or contributing factors (Gould 2005), and not necessarily as the result of the effect of a single variable, the study required a method of analysis that would allow for the comparison of several variables between samples. Ordination techniques provide a multi-dimensionally scaled approach to the analysis of samples which allows for the comparison of several variables. This methodology provides a unique and informative way of analysing the fire history of the Limietberg Conservation Area and perhaps gaining a greater understanding of the conditions under which fires will occur. There are two ordination techniques which were used to analyse the data as part of this research: Principal Components Analysis and Multi-Dimensional Scaling.

3.2.3.1 Principal Components Analysis (PCA)

Principal Components Analysis (PCA) is the longest established method of ordination. It is an ordination method which is most practically useful to the multivariate analysis of environmental data (Clarke & Warwick 1994), which makes it an ideal choice of method for application to an environmental phenomenon such as fire. It is a widely encountered ordination method and of fundamental importance to research (Clarke & Warwick 1994).

The variable factors that influence fire danger and fire behaviour were analysed using PCA ordination techniques. All data used as part of the ordination analyses was pre-treated using the pre-treatment option in *Primer Version 6* as the data was not already normally distributed.

The starting point of a PCA is the original data matrix rather than a derived similarity matrix. The data array is thought of as defining the positions of samples in relation to axes representing the full set of fire parameters (Clarke & Warwick 1994). PCA is one of the most popular dimensionality reduction methods. It is a linear method, meaning that the transformation between the original data and the new lower dimensional representation is a linear projection. Its main purpose is dimensionality reduction, but it can also be used to explore relationships between variables (Demsar et al. 2012).

PCA is seen as an ordination method that is particularly useful as a tool in the multivariate analysis of environmental data (Clarke & Warwick 1994). Conventionally, the data will be arranged in a matrix of p columns representing the variables by n rows, representing the samples (Clarke & Warwick 1994). The variables will be a mixture of both physical landscape parameters (e.g. slope) and other environmental measurements (e.g. temperature, relative humidity, wind speed).

In a multi-dimensional visualisation of the environmental data matrix, the samples are points which are referred to as environmental axes (Clarke & Warwick 1994). It is important to realise that one of the fundamental issues to take into consideration with an ordination that involves environmental data, is that there will be a wide variety and mix of measurement scales and units (Clarke & Warwick 1994). The units on each of the axes differ, and have no natural connection with each other. It is therefore essential that when performing a PCA ordination with environmental data, that the data is normalised so that all of the axes have comparable (dimensionless) scales. Prior transformation of data was therefore essential before performing the PCA analysis (Clarke & Warwick 1994). In the case of this study, data was transformed using *Primer Version 6* before running the PCA analysis.

One of the major strengths of the approach is that the output of the PCA method is conceptually simple and relatively easy to interpret (Clarke & Warwick 1994). While the algebraic basis of the PCA algorithm is a complex process, the output of the PCA is relatively easily understood (Clarke & Warwick 1994). The PCA is also very easily performed computationally and the results are obtained very quickly (Clarke & Warwick 1994). The axes are interpretable, especially with environmental analysis which allows for a more in-depth analysis of the contributions and interactions of each of the variables (Clarke & Warwick 1994). The methodology is also considered to be well suited to the analysis of environmental data.

One of the weaknesses of PCA is that there is little flexibility in defining dissimilarity (Clarke & Warwick 1994). An ordination, at its most fundamental level, is essentially a technique that converts dissimilarities of composition between samples into distances (Clarke & Warwick 1994). Based on the method used to compute these distances, there may be some inaccuracy when plotting axes. This also leads to another shortcoming of PCA, which is that its distance-preserving properties are sometimes poor (Clarke & Warwick 1994). Conceptually, a PCA ordination is conceived in a 3-dimensional space, but the output is projected in a 2-dimensional ordination plane (Clarke & Warwick 1994). This may lead to some inaccuracy when plotting the axes within the ordination plane of the output of the PCA. To accommodate for this potential inaccuracy, the PCA ordination was run several times and the results compared to ensure that the most likely ordination pattern is selected to be analysed.

3.2.3.2 Non-Metric Multi-Dimensional Scaling

Non-metric multi-dimensional scaling (MDS) is an ordination method that makes use of a more complex algorithm. It is, however, very simply described and understood, and few assumptions need to be made about the data, which make it the most widely applicable and effective method of ordination available (Clarke & Warwick 1994).

The variable factors that influence fire danger and fire behaviour were analysed using MDS ordination techniques. All data used as part of the ordination analyses was pre-treated using the pre-treatment option in *Primer Version 6* as the data was not already normally distributed. Data used for the MDS analysis was run through a resemblance matrix prior to analysis.

What distinguishes the MDS from the PCA first and foremost is that it focuses on the similarity between samples and not the dissimilarity. The starting point of the MDS method is the application of a similarity or resemblance matrix after data has been tested for normality (Clarke & Warwick 1994). The purpose of an MDS can therefore be simply stated: it constructs a plot or configuration of samples, in a specified number of dimensions, which attempts to satisfy all the conditions imposed by the similarity matrix (Clarke & Warwick 1994).

One of the major strengths of the approach is that although the numerical algorithm that underpins it is undeniably complex, the MDS itself is relatively simple in concept and in terms of its functional purpose, it is clear what it is attempting to achieve (Clarke & Warwick 1994). It is also based on the relevant sample information. MDS is also generally applicable, and can be applied validly in a wide variety of situations, with fewer assumptions necessary with regards to the nature and quality of the data when using MDS when compared to other ordination methods (Clarke & Warwick 1994).

MDS is a fairly robust method of ordination, and as such does not have many weaknesses. There is however the problem that convergence to the global minimum of stress is not guaranteed. The nature of the MDS algorithm makes it necessary to repeat each analysis several times, from different starting configurations, to be fairly confident that a solution re-appears several times and is indeed the global minimum of the stress function (Clarke & Warwick 1994). Another weakness is that the algorithm places most weight on the large distances. When the distances computed between samples is large, there is the possibility of some inaccuracy in placement (Clarke & Warwick 1994).

There seems to be general consensus in the available literature that MDS can be recommended as one of the more robust ordination methodologies. It has a number of practical advantages stemming from the fact that it is flexible and lacks assumptions (Clarke & Warwick 1994). One of the main advantages of MDS is its greater ability to represent more complex relations accurately in low-dimensional space, which makes it extremely useful and applicable to research involving the analysis of fire.

3.2.4 Fire Danger and Fire Behaviour Analysis

The drivers of fire danger and fire behaviour were analysed by making use of multiple regression and ordination statistical techniques. This will include the use of Principal Component Analysis (PCA) and Non-Metric Multi-Dimensional Scaling (MDS) which were performed in *Primer Version 6*. The decision to analyse both fire danger and fire behaviour as one entity came about as a result of the fact that both components of fire risk are driven by very similar factors. The composition of environmental factors for each of the individual fires sampled were analysed using PCA and MDS ordination techniques. This allowed for a multi-dimensional analytical approach that investigated how individual factors interact to create conditions that result in different fire sizes, and determine their significance to the disaster event and also the extent to which the driver contributes to the severity and magnitude of the event. The statistical analysis also included the use of correlation statistics in the form of multiple regression analysis using *Statistica 11*. Each of the drivers were analysed as follows:

Multiple Regression Analysis

- Slope: The median slope was correlated with the size of the burn scar (ha)
- Fuel: Total rainfall received in the months preceding the fire was used as a proxy for biomass and correlated with the size of the burn scar (ha)
- Topography: The co-efficient of variation of slope was correlated with the size of the burn scar (ha)
- Wind Speed: Both the mean wind speed and maximum wind speed for the period of the fire was correlated with the size of the burn scar (ha).
- Temperature: Both the mean and maximum temperature for the period of the fire was correlated with the size of the burn scar (ha).
- Relative Humidity: Both the mean and minimum relative humidity for the period of the fire was correlated with the size of the burn scar (ha)
- Fire Danger Index (FDI): The McArthur FDI (McArthur 1966, McArthur 1967) will be calculated using both the mean and extreme weather variables and was correlated with the size of the burn scar (ha)

PCA and MDS Ordination

- Slope: The median slope was used as part of the PCA and MDS ordination analysis
- Fuel: Total rainfall received in the months preceding the fire was used as a proxy for biomass and was used as part of the PCA and MDS ordination analysis
- Topography: The co-efficient of variation of slope was used as part of the PCA and MDS ordination analysis
- Wind Speed: The mean wind speed and maximum wind speed for the period of the fire were used as part of the PCA and MDS ordination analysis.
- Temperature: The mean temperature and maximum temperature for the period of the fire were used as part of the PCA and MDS ordination analysis.
- Relative Humidity: The mean relative humidity and minimum relative humidity for the period of the fire were used as part of the PCA and MDS ordination analysis.

Each of the variables were tested for normality using the Chi-Squared goodness of fit test in *Statistica 11*. All variables were then transformed, should it be required, using the pre-treatment options in *Primer Version 6* before commencing with ordination.

3.3 Analysis of Ecological Vulnerability and Fire Frequency

The ecological impacts of fires and fire frequency were assessed using post fire regeneration (Proteaceae parent:seedling) monitoring techniques. This involved practical fieldwork and data collection following the method of Bond et al. (1984).

The recruitment success of serotinous Proteaceae species, which do not resprout after fire, were used as an indicator of post-fire regeneration success of fynbos vegetation (Vlok & Yeaton 2000). Only non-sprouting *Protea* and *Leucadendron* species were used in these surveys.

Regeneration in burnt proteoid shrublands was assessed by surveying up to four replicate sample grids in each of the selected burnt areas (Bond et al. 1984). Proteaceae monitoring took place on all burnt areas larger than 10 hectares, regardless of whether the fire was caused by natural (lightning, rock falls, etc.) or unnatural (block burn, arson, etc.) incidents. Analysis can only occur within 12 – 18 months after the fire. This aspect of the study, therefore, only focuses on burnt areas from 2010 and 2011 that did not burn again in 2012. This period was stipulated in order to standardise the error in terms of seedling mortality in older veld so that the first winter rains will have fallen after the fire in order to facilitate seed germination; and as most species that are going to germinate after a fire in an area will have done so within a year after the fire and so will be present in seedling form (De Klerk et al. 2007).

In the case of this particular study area, the Limietberg Conservation Area, there were three potential burn scars identified: 2 from 2010 and 1 from 2011 (Fig 3-2 and 3-3). All of these burn scars were suitable in terms of size, however the burn scars from 2010 had to be excluded from the study. Unforeseen delays in obtaining the research permit and access to the reserve meant that the burn scar age criteria were exceeded. Analysis can only occur within 12 – 18 months after the fire and in the case of the 2010 burn scars, this period was over 20 months and analysis of these sample sites was no longer viable. There were also several fires that burnt within the Bains’ Kloof area where the 2010 scars were located in early 2012 which also would have compromised sampling efforts in this area.

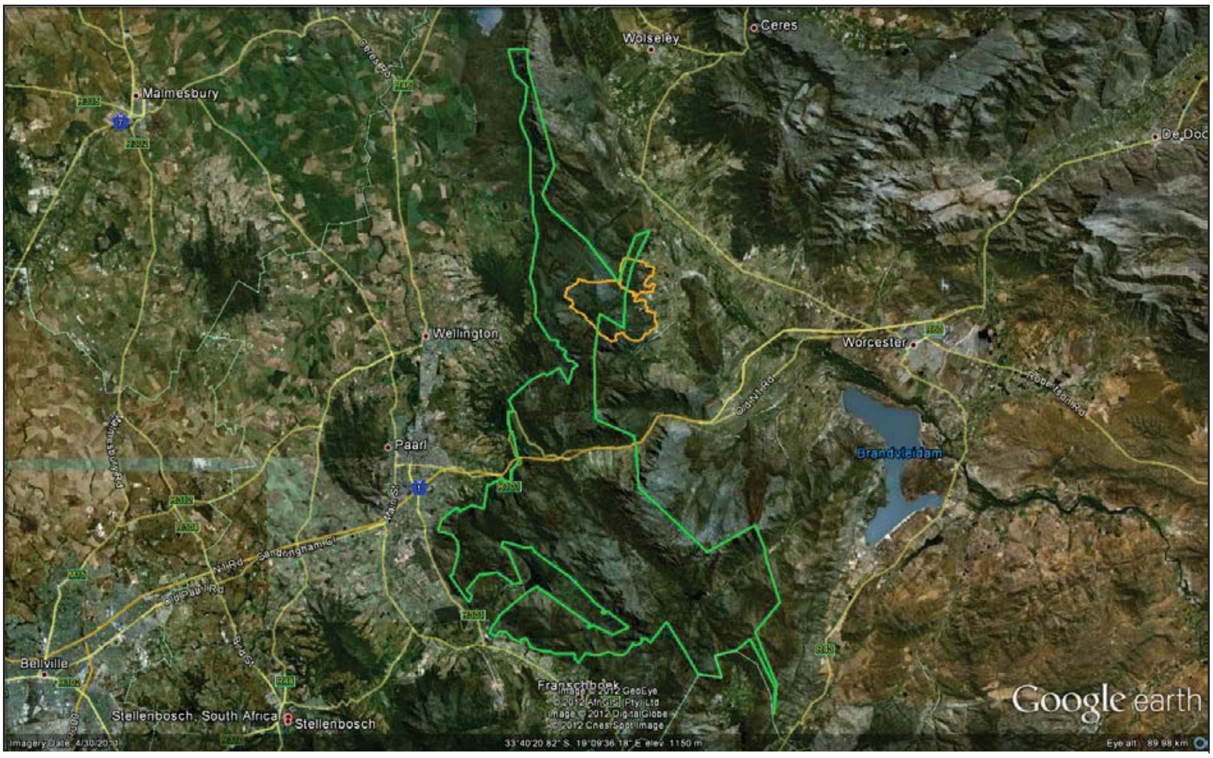

Figure 3-2: Aerial photograph indicating the study area, the Limietberg Conservation Area and the potential burn scars from 2010 used for sampling. (Courtesy of Google Earth 4/5/2011)

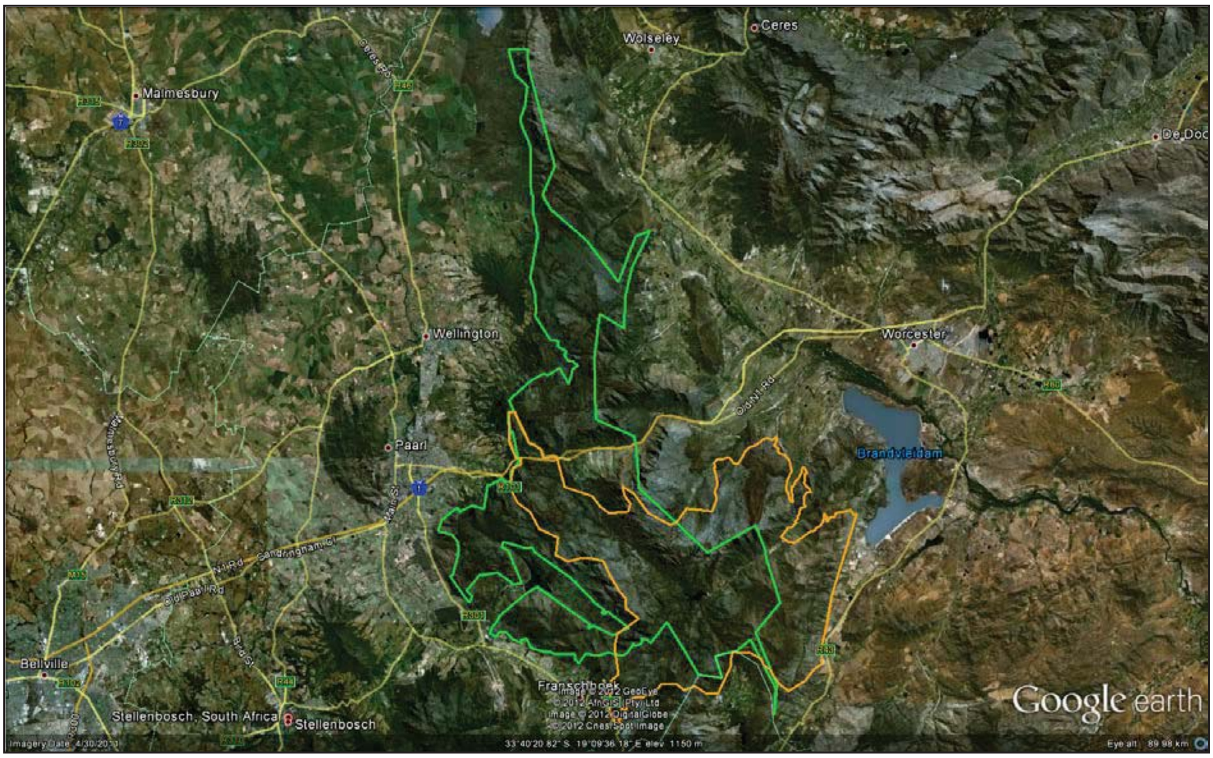

Figure 3-3: Aerial photograph indicating the study area, the Limietberg Conservation Area and the potential burn scar from 2011 used for sampling. (Courtesy of Google Earth 4/5/2011)

The 2011 burnt area was however deemed to be suitable for sampling, and arrangements were made for sampling to occur in February 2011. The selection of plots to be sampled within the burnt area encompasses a range of issues, chief among these being accessibility. The method used for the post fire regeneration (Proteacae parent:seedling) monitoring requires that there must be at least one survey completed for every 500 ha of burnt area, up to a maximum of 4 surveys for one fire, even if the burnt area is larger than 2000 ha (De Klerk et al. 2007). In the case of the 2011 burnscar, with a total burnt area of approximately 35494 ha; this meant that 4 surveys would be required. In the case of this particular burn scar, where more than one survey is required, the intention is to try and vary the location of the plots as much as possible to ensure that a variety of different habitat types are sampled (i.e. different slopes and altitudinal level) (De Klerk et al. 2007).

As the 2011 burn scar covers a vast area, it was decided to concentrate on sampling from a particular portion of the burn scar, as it was simply not feasible to try and cover the entire extent of the burnt area. The Old N1 road which runs through the middle of the reserve was considered as the best access route from which to collect samples. A portion of land that falls within the 2011 burn scar was not available for sampling as it is privately owned, and access to this area was therefore not possible (Fig. 3-4). This was a great pity, as it was the only access point to some of the flatter habitat areas within the sampling area.

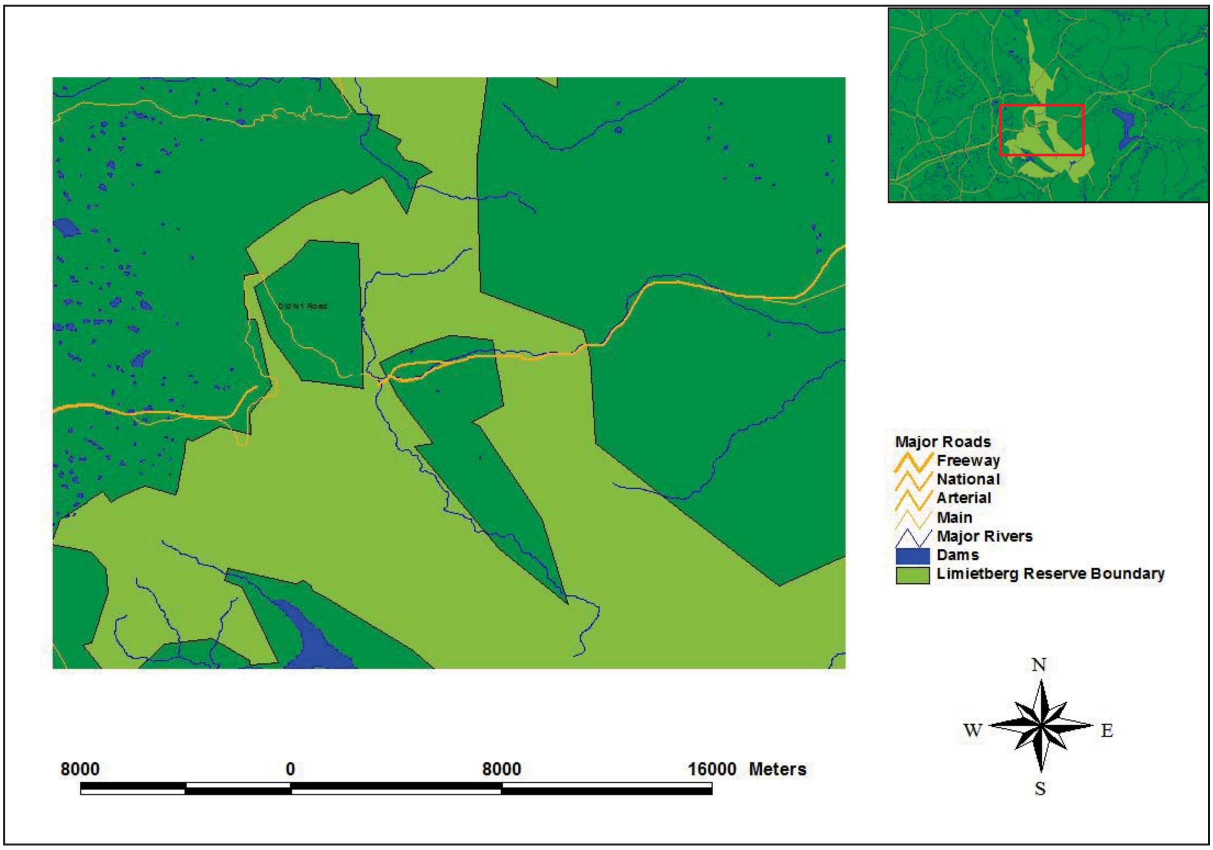

Figure 3-4: Privately owned sections of the study area that could not be used for sampling.

Other difficulties that were encountered included a large troop of baboons that were very active in the area at the time of sampling. Out of concern for safety, this meant that a fairly large section of the area identified for sampling was not available for sampling. Several prospective sites, although accessible were also deemed to not be suitable as they were not large enough to obtain a large number of samples.

As a result of these constraints, 3 plots were sampled along the Old N1 road, as indicated in Figure 3-5. These plots consisted of one north-facing slope and 2 south-facing slopes.

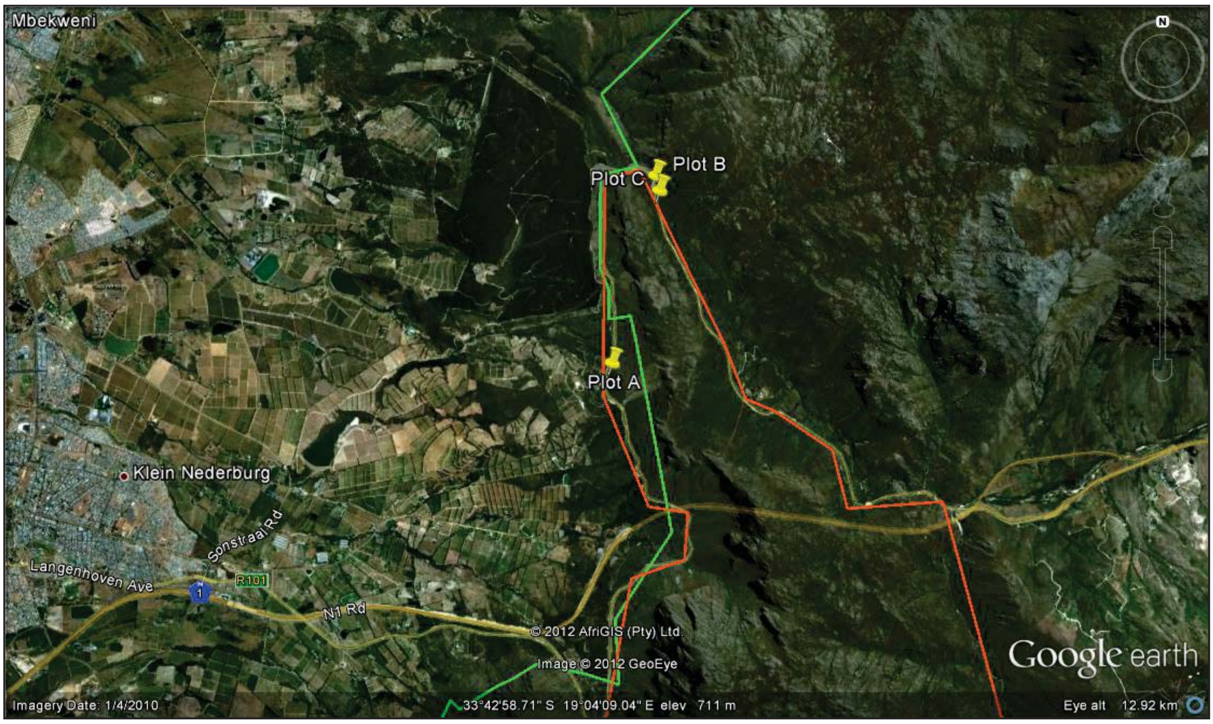

Figure 3-5: Location of the plots which were used for sampling from 2011 burn scar. (Courtesy of Google Earth 1/4/2010)

A group of six people, working in pairs, carried out the sampling. In order to ensure that the method would be carried out successfully, a list of all non-sprouting Protea and Leucadendron species that occur within the reserve, complete with photographs and descriptions, was compiled and distributed. Included with this was information on how to identify burnt parents of the more common species (namely *P. nerifolia* and *P. repens*) and also information on how to identify the seedlings of the aforementioned species.

Sampling was carried out using the method indicated in Figures 3-6 and 3-7 taken from De Klerk et al. (2007). It was ensured at all sites that sampling did not occur within 20 metres of a vehicle track or footpath, as Protea seed tend to collect against road embankments and more seedlings than normal tend to establish along such obstructions (De Klerk et al. 2007). The first site was sampled with all sampling members present in order to address any questions and to ensure consistency of the method throughout the sampling process. It was decided that each pair would complete 30 replicate 1 m X 1 m plots within each of the sample areas, following the pattern of Figures 3-6 and 3-7, with 5 m intervals between each plot. This resulted in 15 plots in one direction and 15 plots in the return direction with a gap of 5m between each row. It was decided that there would be a gap of 15 m between pairs at the start of sampling in each area (Fig 3-8).

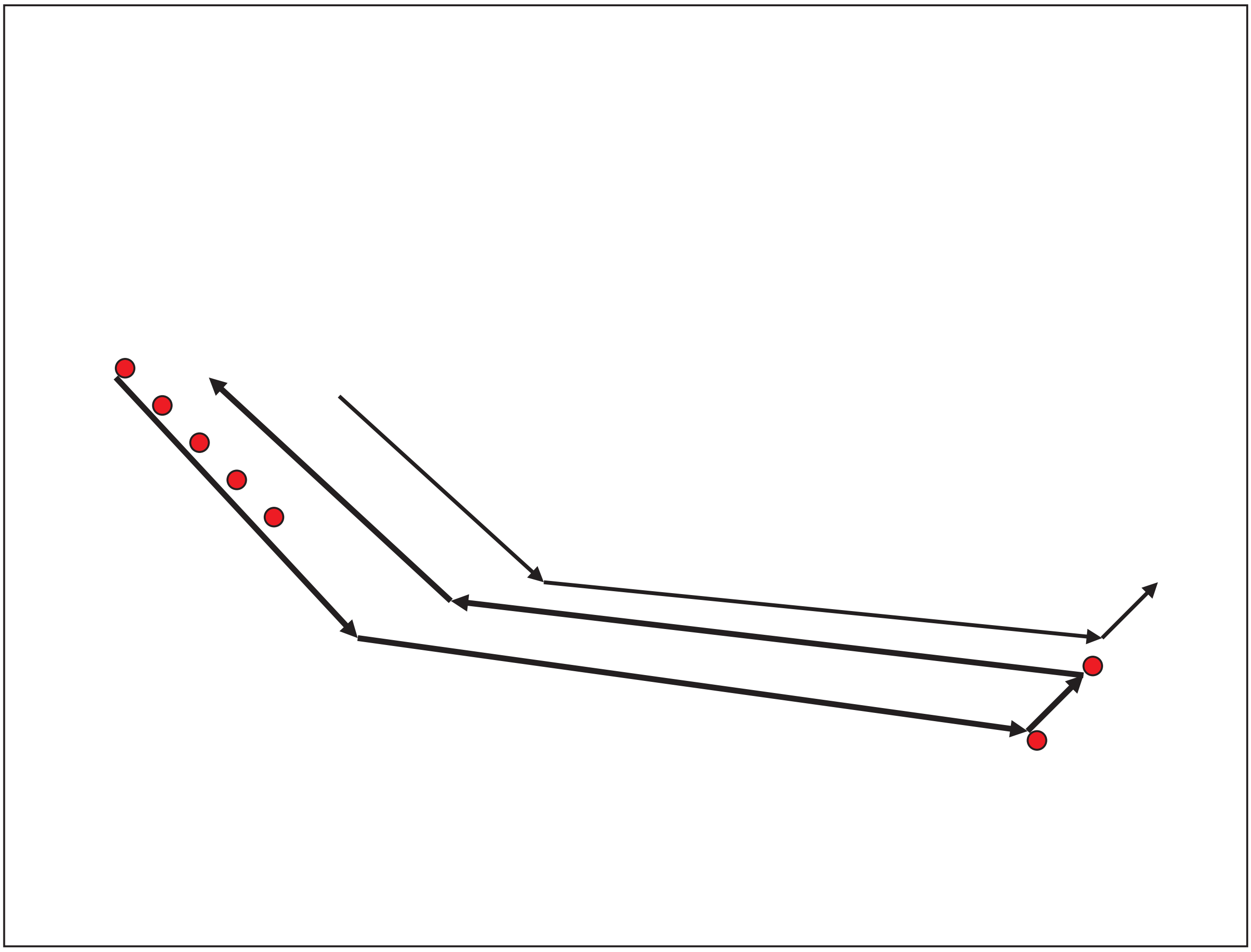

Figure 3-6. Potential site where post-fire monitoring survey could be carried out. (De Klerk et al. 2007)

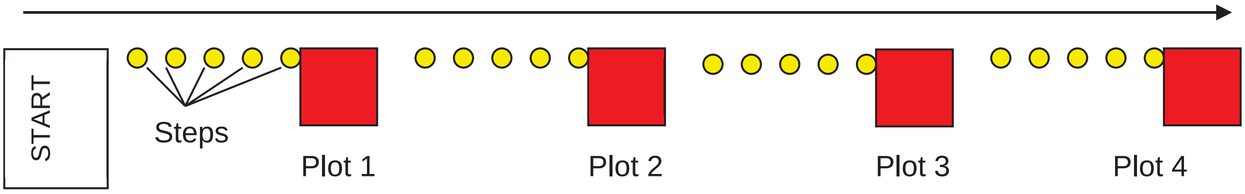

Figure 3-7. Layout of 1m x 1m plots as observer walks through the post-fire monitoring survey area. (De Klerk et al. 2007)

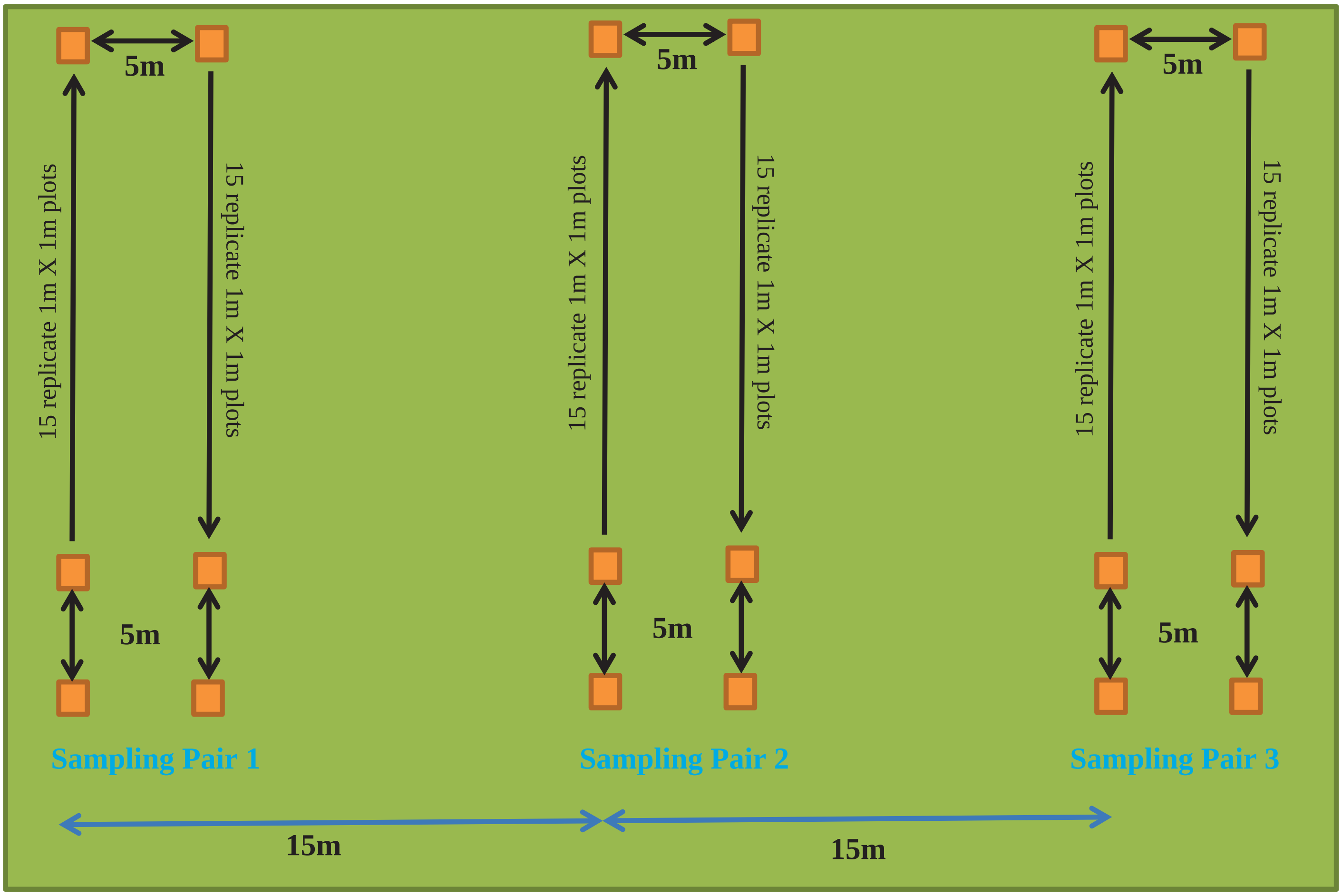

Figure3-8: Sampling method used during the post fire regeneration sampling.

Within each 1 m X 1 m plot, the number of parent plants and seedlings of all non-sprouting Protea and Leucadendron species were counted and recorded on the monitoring sheet. Only live seedlings were counted, dead seedlings were ignored (De Klerk et al. 2007). As far as possible, the number of parent plants and species were recorded per species. Plots were predominantly dominated by *P. nerifolia* and *P. repens* which were easily identified by making use of the materials provided. There were however a few other species present. In these instances, samples were taken to be used for proper identification later. Within the 1m X 1m plots, only female (cone-bearing) Leucadendron parent plants were counted and recorded. The reason for this is that it is often impossible to discern the male (not cone-bearing) plants after a fire. To account for this, the number of female Leucadendron parent plants were eventually doubled in the results in order to obtain a reasonable index of the total number of mature Leucadendron plants that were present in the area before the fire (De Klerk et al. 2007).

The study made use of data sampled by the researcher together with data obtained from Cape Nature. Data was analysed in *Microsoft Excel* by plotting the ratio of seedlings to parents against the month in which the fire occurred and the age of the veld prior to the occurrence of the fire, according to the methods of Vlok & Yeaton (2000) and De Klerk et al. (2007). Post-fire regeneration was also assessed on both north and south facing slopes, as north facing slopes are exposed to greater incoming solar radiation in the southern hemisphere, such that plants on the northern slopes experience greater water stress (Van der Merwe & Van Rooyen 2011), particularly in the dry summer months in the fynbos.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents findings derived from the consolidation of secondary data and field research. Specifically, it provides an in-depth analysis of the fire history of the Limietberg Nature Reserve between 1999 and 2010. The findings in this chapter are organized into five sections. The first section presents an analysis of the factors that are considered the most likely drivers of the fire danger and fire behaviour. This includes mostly statistical analysis using descriptive statistical techniques but does make use of data derived from geospatial methods. The second section presents an analysis of ecological recovery and fire frequency. The ecological impacts of fires were assessed using post-fire regeneration (Proteaceae parent:seedling) monitoring techniques. This involved practical fieldwork and data collection following the method of Bond et al. (1984).

4.1 Multiple Regression Analysis of Factors Influencing Fire Danger and Fire Behaviour

Multiple regression was used to analyze the factors that are thought to be the most likely drivers of the fire danger and fire behaviour, namely: slope and topography; Fuel; Wind Speed; Temperature; Relative humidity and lastly the McArthur FDI (McArthur 1967) which represents a composite of the variables observed.

4.1.1 Slope and Topography

Fire danger is presented by Gould (2005) as the results of both constant and variable fire danger factors affecting the development, spread and difficulty of control of fires and the damage they cause. Slope would be classified as one of the constant factors that forms part of fire danger. Constant factors are those that show little change and vary with location, of which slope would be an excellent example. Topography is seen as one of the contributing factors to fire behaviour, and refers to the surface shape and features. It is a measure of the ruggedness of the terrain.

The summary statistics for the multiple regression analysis of the constant factor variables (slope, fuel and topography) presented in Table 4-1 indicated an adjusted R^2 statistic had a value of -0.04, which means that the predictor variables tested showed a large amount of variability and the model was not a good fit for the data sampled. The p-value of 0.74 in this instance would indicate that the result is not statistically significant.

Table 4-2 presents a regression summary of the multiple regression correlation analysis run on the constant factor variables, namely rainfall/fuel, slope and topography. The beta coefficient of b = 398.26 for slope indicates that there is a strong relationship present between slope and size of burn scar. The p-value of 0.74 in this instance however would indicate that the result is not statistically significant. The beta coefficient of b = 7200.13 for topography indicates that there is an extremely strong relationship present between topography and size of burn scar. The p-value of 0.28 however would indicate that the result is once again not statistically significant.

Table 4-1 Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis) for Rainfall/Fuel, Slope and Topography

Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis)	
Statistic	Value
Multiple R	0.17
Multiple R^2	0.03
Adjusted R^2	-0.04
F(3,47)	0.42
p	0.74
Standard Error of Estimate	5597.52

Table 4-2 Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis) for Rainfall/Fuel, Slope and Topography

	Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis)					
N=51	b*	Standard Error of b*	b	Standard Error of b	t(47)	p-value
Intercept			-1062.13	7085.35	-0.15	0.88
Rainfall/Fuel	-0.03	0.15	-0.48	2.48	-0.19	0.85
Slope	0.06	0.16	398.26	1185.38	0.34	0.74
Topography	0.17	0.16	7200.13	6570.81	1.1	0.28

4.1.2 Fuel

Fuel would also be considered one of the constant factors that contribute towards fire danger and fire behaviour, as it will also change slowly and vary with location. It is an aspect of the physical location within which the fire occurs. Fuel as a driving factor of fire danger and fire behaviour influences each of these phenomenon differently. In terms of fire behaviour, the amount and arrangement of fuel, often referred to as biomass, is considered by many to be one of the most critical factors influencing the inception, spread and severity of a fire (Forsyth et al. 2010). At the most elementary level, a fire cannot burn unless it has fuel. In terms of fire danger, while biomass also plays a role, it is the condition of fuel and the ‘readiness to burn’ that is of vital importance (Smith et al. 2004; Ryan & Williams 2010).

Fuel was measured by using the method of comparing the amount of rainfall received in the period preceding the fire season as a proxy for biomass. This follows the premise that a high amount of rainfall received in the rainy season preceding the fire season will result in a build-up of biomass. A regression analysis was performed by correlating burned area with the total amount of rainfall received during a 5 month period preceding the dates of the fire. The study made use of meteorological data obtained from SAWS taken from the weather stations located closest to the study area.

The summary statistics for the multiple regression analysis of the constant factor variables presented in Table 4-1 indicates an adjusted R^2 statistic had a value of -0.04, which means that the predictor variables tested showed a large amount of variability and the model was not a good fit for the data sampled. The p-value of 0.74 in this instance would indicate that the result is not statistically significant.

Table 4-2 presents a regression summary of the multiple regression correlation analysis run on the constant factor variables. The beta coefficient of b = -048 indicates that there is a weak negative relationship present between rainfall/fuel and size of burn scar. The p-value of 0.85 in this instance indicates that the result is not statistically significant.

4.1.3 Wind Speed

As stated previously, fire danger is presented by Gould (2005) as the results of both constant and variable fire danger factors affecting the development, spread and difficulty of control of fires and the damage they cause. Wind speed would be considered as one of the variable factors that can change rapidly with time but can influence extensive areas. It is certainly the prevailing perception that wind speed can affect the severity of a fire quite significantly and can often be responsible for dramatic changes in the rate at which a fire is able to spread. Syphard et al. (2006) suggest that under high-wind conditions, fire cannot be effectively controlled until the wind dies down or the fire runs out of fuel.

In the regression analysis of the wind speed data obtained from SAWS, when correlating wind speed against burned area, one would expect to see a relationship present, especially given the prevailing perception that high-wind conditions can significantly alter the spread and ability to control a fire. Tables 4-3 and 4-4 show the results of the multiple regression correlation analysis between mean wind speed, mean temperature, mean relative humidity and burned area.

Table 4-3 Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis) for Mean Weather Variables

Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis)	
Statistic	Value
Multiple R	0.28
Multiple R²	0.08
Adjusted R²	0.02
F(3,47)	1.38
p	0.26
Standard Error of Estimate	5437.52

Table 4-4 Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis) for Mean Weather Variables

	Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis)					
N=51	b*	Standard Error of b*	b	Standard Error of b	t(47)	p-value
Intercept			-13250.4	7587.43	-1.75	0.09
Mean Temperature	0.23	0.15	215.1	134.17	1.61	0.12
Mean Relative Humidty	0.24	0.15	116.1	72.46	1.61	0.12
Mean Wind Speed	0.08	0.14	197.2	354.96	0.56	0.51

Table 4-3 presents a regression summary of the multiple regression correlation analysis run on the mean weather variables. The beta value (b) is a measure of how strongly each predictor variable influences the criterion variable, in this case, how strongly each of the weather variables contributes towards the burn scar area. The beta is measured in units of standard deviation. Thus, the higher the beta value the greater the impact of the predictor variable on the criterion variable (McDonald 2009). In the situation where there is more than one predictor variable, one cannot compare the contribution of each predictor variable by simply comparing the correlation coefficients. The beta regression coefficient is computed to allow one to make such comparisons and to assess the strength of the relationship between each predictor variable to the criterion variable (McDonald 2009). In the case of wind speed, the beta regression coefficient was very high, with a value of $b = 354.96$. This would indicate that there was a very strong relationship present and that wind speed accounts for a very large contribution to size of the burn scar. The p-value of 0.12 in this instance however would indicate that the result is not statistically significant.

R is a measure of the correlation between the observed value and the predicted value of the criterion variable. R Square (R^2) is the square of this measure of correlation and indicates the proportion of the variance in the criterion variable which is accounted for by the model (McDonald 2009). In essence, this is a measure of how good a prediction of the criterion variable we can make by knowing the predictor variables. However, R square tends to somewhat over-estimate the success of the model when applied to the real world, so an Adjusted R Square value is calculated which takes into account the number of variables in the model. This Adjusted R Square value gives the most useful measure of the success of the model (McDonald 2009). In the case of the multiple regression analysis run using the mean weather variables, the adjusted R^2 statistic had a value of 0.02, which means that the predictor variables tested accounted for approximately 2% of the variance in the criterion variable. This may perhaps be perceived as a relatively sizeable contribution, however, not as influential a contribution as would be expected. The p-value of 0.26 in this instance, however would indicate that the result is not statistically significant.

Very similar results were obtained when performing the multiple regression analysis on the extreme weather variables. Tables 4-5 and 4-6 show the results of the multiple regression correlation analysis performed using the extreme weather variables. The beta coefficient for maximum wind speed of $b = 416.25$ would once again indicate that maximum wind speed is a very strong contributing factor to size of burn scar. The p-value of 0.12 in this instance would indicate that the result is not statistically significant. The adjusted R^2 value of 0.02 would suggest that the predictor variables tested accounted for approximately 2% of the variance in the criterion variable. The p-value of 0.28 in this instance would indicate that the result is not statistically significant.

Table 4-5 Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis) for Extreme Weather Variables

Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis)	
Statistic	Value
Multiple R	0.28
Multiple R²	0.08
Adjusted R²	0.02
F(3,47)	1.32
p	0.28
Standard Error of Estimate	5446.43

Table 4-6 Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis) for Extreme Weather Variables

	Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis)					
N=51	b*	Standard Error of b*	b	Standard Error of b	t(47)	p-value
Intercept			-586.13	6987.91	-0.08	0.93
Maximum Temperature	0.062	0.15	48.75	117.85	0.41	0.68
Minimum Relative Humidity	-0.04	0.16	-16.2	64.95	-0.25	0.81
Maximum Wind Speed	0.24	0.15	416.25	264.17	1.58	0.12

4.1.4 Temperature

Temperature is also considered as one of the variable factors that can change rapidly with time but can influence extensive areas. While intrinsically linked to fire danger, temperature is not perceived to be one of the major contributing factors, often seen as secondary to the role of fuel or wind speed.

Table 4-3 presents a regression summary of the multiple regression correlation analysis run on the mean weather variables. The beta coefficient of b = 215.1 indicates that there is a strong relationship present between mean temperature and size of burn scar, which is consistent with what would be expected in terms of the hypothesised relationship. The p-value of 0.12 in this instance however is very low, and would therefore indicate that the result is not statistically significant.

The summary statistics for the multiple regression analysis of the mean weather variables presented in Table 4-4 indicated an adjusted R^2 statistic had a value of 0.02, which means that the predictor variables tested accounted for approximately 2% of the variance in the criterion variable. The p-value of 0.26 in this instance however would indicate that the result is not statistically significant.

Tables 4-5 and 4-6 present the results of the multiple regression correlation analysis performed using the extreme weather variables. Very similar results were obtained when performing the multiple regression analysis on the extreme weather variables. The beta coefficient for maximum temperature of $b = 48.75$ would indicate that there is a positive relationship present between maximum temperature and size of burn scar, but it is not as strong a relationship as was observed with the mean temperature and it would therefore not be as strong a contributing factor to size of burn scar. The p-value of 0.68 in this instance however would indicate that the result is not statistically significant. The adjusted R^2 value of 0.02 would suggest that the predictor variables tested accounted for approximately 2% of the variance in the criterion variable. The p-value of 0.28 in this instance however would indicate that the result is not statistically significant.

4.1.5 Relative Humidity

Relative humidity is also considered as one of the variable factors that can change rapidly with time but can influence extensive areas. Relative humidity is often perceived as one of the major drivers of fire danger, as it is seen as strongly linked to what would be referred to as “dry conditions” or drought.

Smith et al. (2004) suggest that fire intensity is an indicator of energy output. Fire intensity is usually determined by the quantity of fuel available, its moisture level and the rate at which it combusts. Higher available fuel levels and lower fuel moisture levels generally result in increased fire intensity. Fire intensity is predominantly controlled by fuel load and moisture, and weather conditions (Fernandes 2001; Ryan & Williams 2010).

Low levels of relative humidity essentially means that there is low moisture content in the air. Relative humidity is quite closely linked to the dynamics of the fuel, as dry fuel burns more readily. It is for this reason that relative humidity is seen as one of the major drivers of fire danger.

Table 4-3 presents a regression summary of the multiple regression correlation analysis run on the mean weather variables. The beta coefficient of $b = 72.46$ indicates that there is a reasonably strong relationship present between mean relative humidity and size of burn scar. The p-value of 0.12 in this instance however is very low, and would therefore indicate that the result is not statistically significant.

The summary statistics for the multiple regression analysis of the mean weather variables presented in Table 4-4 indicated an adjusted R^2 statistic had a value of 0.02, which means that the predictor variables tested accounted for approximately 2% of the variance in the criterion variable. The p-value of 0.26 in this instance however would indicate that the result is not statistically significant.

Tables 4-5 and 4-6 present the results of the multiple regression correlation analysis performed using the extreme weather variables. The results obtained from multiple regression analysis on the extreme weather variables differed from those obtained from the analysis of the mean weather variables with respect to relative humidity. The beta coefficient for minimum relative humidity of $b = -16.2$ would indicate that there is a relatively weak negative relationship between minimum relative humidity and size of burn scar. A negative relationship would be consistent with what would be expected from relative humidity as a contributing factor to size of burn scar, given that the assumption would be that size of the burn scar would be largest when relative humidity is low. The p-value of 0.81 in this instance however would indicate that the result is not statistically significant. The adjusted R^2 value of 0.02 would suggest that the predictor variables tested accounted for approximately 2% of the variance in the criterion variable. The p-value of 0.28 in this instance however would indicate that the result is not statistically significant.

4.1.6 Fire Danger Index (FDI)

The study made use of McArthur Fire Danger Index (FDI) data for the analysis of weather data as it relates to the fire (McArthur 1967). FDI is considered to be a good indicator for conditions that would be favourable for the spread of a fire. It is important to note that the FDI only takes weather conditions into account and does not include all factors affecting the development, spread and difficulty of control of fires and the damage they cause (e.g. fuel and the chance of ignition). The total concept of fire danger is impossible to embody in a single, practical index. The FDI therefore focuses on variable factors that have the potential to change rapidly with time but can influence extensive areas. These factors include wind speed, relative humidity and temperature (Gould 2005; Sharples et al. 2008; Bradstock et al. 2009; Kraaij et al. 2012).

The FDI is seen as an expert assessment of the difficulty of suppression of a fire burning under those conditions. The main use of an FDI is for public awareness and also for suppression awareness, used to guide response to fire and to inform fire fighting teams when they should be put on stand-by (Gould 2005; Sharples et al. 2008; Bradstock et al. 2009; Kraaij et al. 2012).

The FDI classification system makes use of five different categories for fire behaviour based on the value of the FDI generated for each day, and range from 0-100 (Appendix B). Fire conditions are considered dangerous with an FDI score of 45 and above. There are three categories of FDI which are of particular interest with relation to weather conditions that would be conducive to exacerbating the spread and difficulty to suppress a fire. A category yellow FDI is classified as dangerous fire conditions, with an FDI of between 46-60. A category orange FDI is classified as very dangerous fire conditions, with an FDI of between 61-74. A category red FDI is classified as extremely dangerous, with an FDI of between 75-100.

Figures 4-1 and 4-2 show the frequency distribution of FDI values for each of the fires sampled. The FDI was calculated for each of the fires by making use of the formula, procedure and data provided by SAWS. The FDI was calculated twice, once using the mean variables and once using the extreme variables. The decision to use FDI as part of the multiple regression analysis came from the hypothesis that the individual contribution of each of the variable fire danger factors investigated may not have a large effect on fire burn scar, but that they may act in combination to create conditions conducive to the spread of a fire. FDI was therefore used as a composite measure of the contributions of temperature, wind speed and relative humidity together with an adjustment for rainfall.

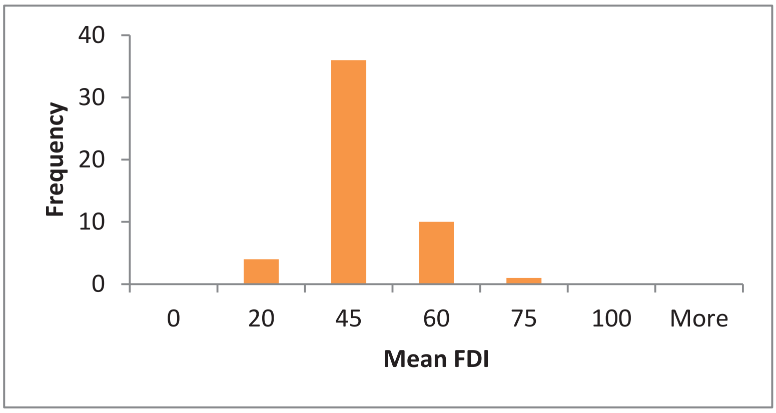

Figure 4-1: Distribution of Mean Fire Danger Index (FDI) scores

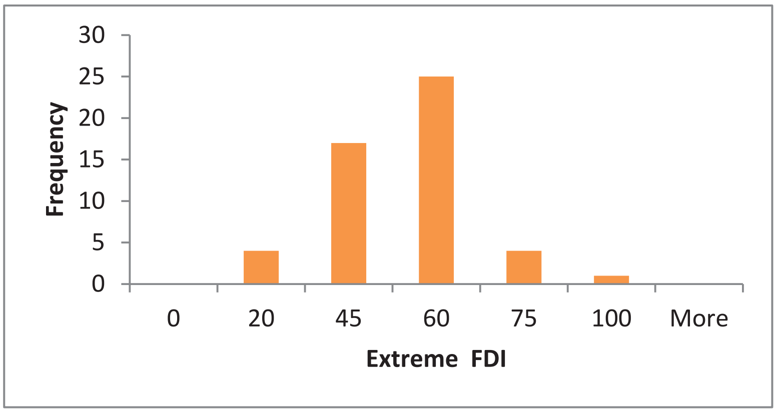

Figure 4-2: Distribution of Mean Fire Danger Index (FDI) scores

In both instances, whether looking at the distribution of mean FDI or extreme FDI, the vast majority of the values fall within the range of 45-75. This is to be expected as most fires sampled occurred within the summer fire season when one would expect higher temperatures and low relative humidity, the two factors that have the greatest influence on the FDI calculations.

By using the FDI as a composite measure of the variable factors driving fire danger, namely temperature, wind speed and relative humidity, it allowed for a correlation with the interaction of these variables. This was an important step, as given the complex nature of the interactions between the driving factors of fire danger, it was thought that while the individual contribution of each variable was minimal, the combination of factors that result in a high FDI value could yield a more useful result.

Table 4-7 shows the summary of the results obtained for the multiple regression analysis of FDI. The results obtained gave a much better indication of how the variable factors of fire danger contribute towards the size of the fire burn scar. The analysis of the mean FDI had a beta coefficient of b = -303.52 which would indicate that a strong negative relationship is present between FDI and size of burn scar. This is contrary to what would be expected, however, it does stand to reason that an FDI created from mean weather data may not correlate well with size of the burn scar as it is hypothesised that it is extreme weather that usually exacerbates fire danger. The p-value of 0.07 would indicate that the relationship is not statistically significant, however, while this is true for the 95% confidence interval, the p-value is very small and the result should therefore not be totally disregarded.

Table 4-7 Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis) for FDI

Summary Statistics for Dependent Variable: Size of Burn Scar (Regression Analysis)	
Statistic	Value
Multiple R	0.34
Multiple R^2	0.12
Adjusted R^2	0.08
F(3,47)	3.23
p	0.05
Standard Error of Estimate	5269.54

The analysis of the extreme FDI values also yielded a very interesting result (Table 4-8). The beta coefficient of b = 312.622 would suggest that there is a strong positive relationship present between extreme FDI and size of burn scar. This is consistent with what would be expected, and would suggest that when weather variables combine in extreme circumstances, they contribute in a significant way to the size of the burn scar. The p-value of 0.017977 would indicate that this relationship is statistically significant. The adjusted R^2 value of 0.081778 would suggest that the predictor variables tested accounted for only approximately 8.1% of the variance in the criterion variable. The p-value of 0.048446 in this instance however would indicate that the result is statistically significant.

Table 4-8 Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis) for FDI

	Regression Summary for Dependent Variable: Size of Burn Scar (Regression Analysis)					
N=51	b*	Standard Error of b*	b	Standard Error of b	t(47)	p-value
Intercept			-148.84	3067.61	-0.05	0.96
Mean FDI	-0.53	0.29	-303.52	164.65	-1.84	0.07
Extreme FDI	0.71	0.29	312.62	127.59	2.45	0.02

4.2 PCA and MDS Ordination Analysis of Factors Influencing Fire Danger and Fire Behaviour

This study made use of ordination techniques in the analysis of the factors influencing fire danger and fire behaviour.

4.2.1 Temperature, Wind Speed and Relative Humidity

Two ordination techniques were used to analyze the data as part of this research, namely: Principal Components Analysis and Multi-Dimensional Scaling.

While not necessarily common to the field of geography and environmental science, ordination techniques are widely used in biological applications, particularly when analysing community structure of organisms (Clarke & Warwick 1994). The merits of ordination techniques are now well-established in ecological applications, and comparative studies have consistently demonstrated their reliability (Clarke & Ainsworth 1993). Fire is a particularly complex natural phenomenon, with many drivers and contributing factors. Simple statistical techniques such as linear regression were not able to provide an adequate means of analysing the many variables that combine in creating the conditions necessary for the occurrence of a fire, and indeed, would only allow for the analysis of a single variable across fire size classes.

Principal component analysis is appropriate when one has obtained measures on a number of observed variables and wish to develop a smaller number of artificial variables (called principal components) that will account for most of the variance in the observed variables (Clarke & Warwick 1994). Interpretation of the principal components is based on finding which variables are most strongly correlated with each component, i.e., which of these numbers are large in magnitude, the farthest from zero in either positive or negative direction (Clarke & Warwick

1994). Which numbers are considered to be large or small is of course a subjective decision. One needs to determine at what level the correlation value will be of importance. In the context of this research, a correlation value above 0.5 is deemed important.

Figures 4-3 and 4-4 show the plot of the PCA ordination run on the mean weather variables, namely temperature, wind speed and relative humidity. The plots displayed some interesting results, and show the average plot based on several applications of the methodology. Fires of different size classes were plotted spatially based on dissimilarity. It is interesting to note that there was some grouping observed, with larger fires grouping together and smaller fires locating on the periphery. Of particular interest in this instance were both of the category I fires and the category J fire, which grouped closely and seemed to be influenced by similar factors.

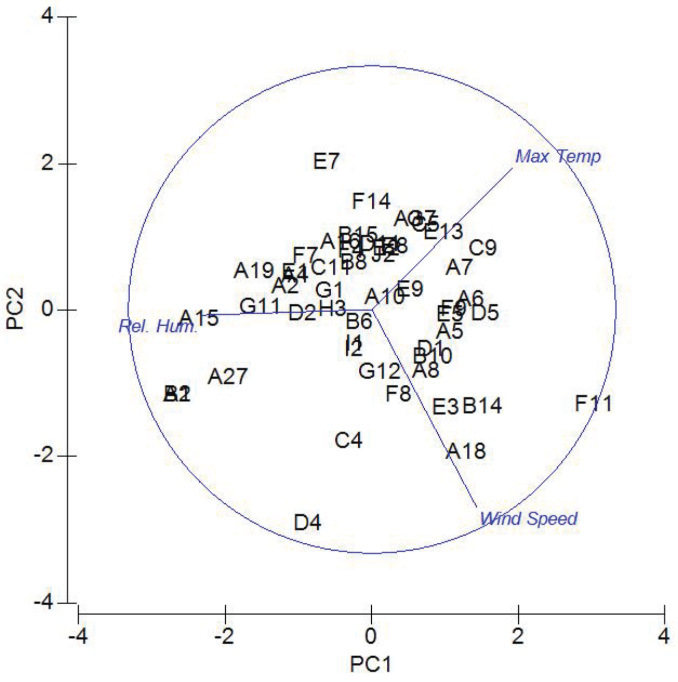

Figure4-3: Principal Component Analysis (PCA) 2 – dimensional plot using the mean variable factor data

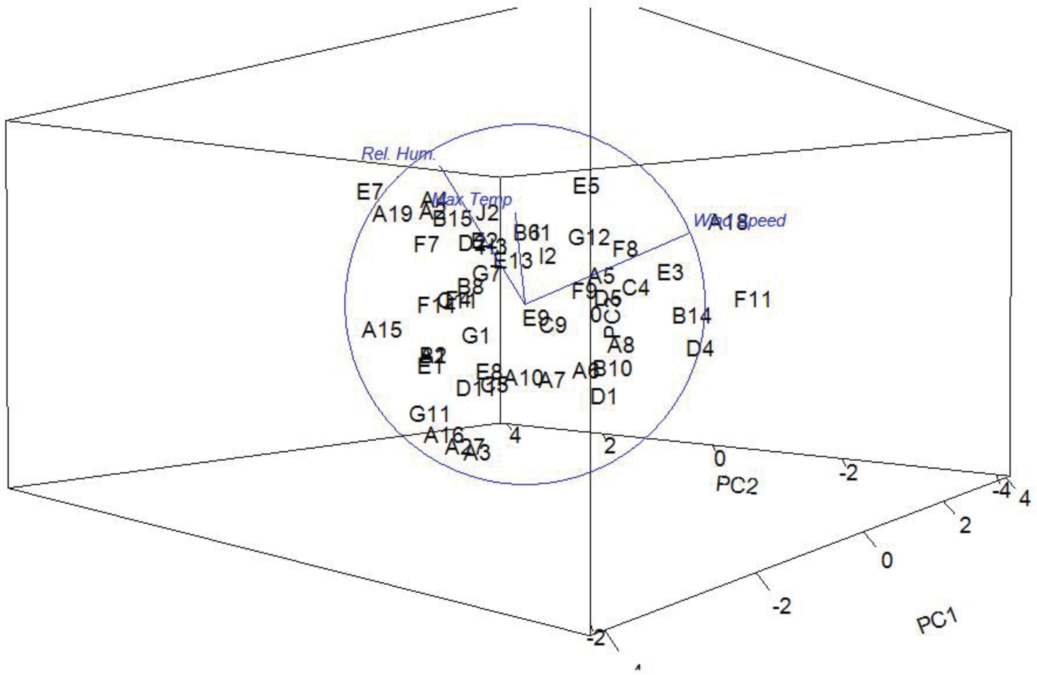

Figure4-4: Principal Component Analysis (PCA) 3 – dimensional plot using the mean variable factor data

In order to understand the arrangement and placement of samples, it is important to analyse the axes and vectors that are generated as part of the PCA ordination to understand the combination of factors that influence the grouping of samples. Table 4-9 shows the Eigenvectors from the Principal Component Analysis (PCA) using the mean variable factor data. It essentially shows the proportion of weighted contribution of each of the variables to each of the principal components (PC's). Each of the PC's has one variable that is a major contributing factor (e.g. PC3 is mainly influenced by relative humidity) but it is important to note that each is composed of a combination of all three variables.

Table 4-9: Eigenvectors from the Principal Component Analysis (PCA) using the mean variable factor data

Variable	PC1	PC2	PC3
Mean Temperature	0.576	0.581	0.575
Mean Relative Humidity	-0.695	-0.023	0.719
Mean Wind Speed	0.431	-0.814	0.391

When analysing the placement of the larger fires (in particular I1 and I2) it seems that many of these fires tend to be influenced largely by PC1 and PC3. This was observed with the vast majority of the fires from category F, G and I. It is important to note at this stage that visual observation and analysis of the PCA plot was carried out using the 3-dimensional model which can be viewed freely from any angle and rotated to any position by making use of *Primer Version 6*. This allowed for a more detailed analysis which is crucial given that the PCA is a 3-dimensional output. It is unfortunately not possible to adequately replicate this in print as is the case with Figures 4-3 and 4-4.

From Table 4-9, we can get a good idea of what the major contributing variables are for PC1 and PC3. Temperature appears to contribute relatively equally across all of the PC's, but it is a significant contributing factor in both PC1 and PC 3. Based on our decision to use a level of 0.5 as an indication of a significant contribution, it is clear that temperature is a significant contributing factor to all of the PC's, but not overly so. The most notable contributing factor to both PC1 and PC3, and consequently to the largest fires is relative humidity, while in both cases the contribution of wind speed seems negligible in comparison. It would appear then that while temperature is a contributing factor across all fires regardless of size, relative humidity seems to be a major determining factor for larger fires. It is important to note however that while relative humidity appears to be the primary measure of both PC1 and PC3, its contribution to each is different. In PC1 the negative value of -0.695 would indicate that PC1 correlates most strongly with relative humidity, and the principal component therefore increases with decreasing relative humidity, this means that larger fires are associated with low relative humidity. In the case of PC3 the contribution of relative humidity is a positive relationship. Larger fires, particularly those of categories I and J tend to be more influenced in their groupings by PC1 than by PC3, which would suggest that they are grouping as a result of conditions where there are high temperatures and low relative humidity. The influence of PC3 on these fires could then perhaps be attributed to the high contribution of temperature to PC3 (Bessie & Johnson 1995; Bradstock et al. 2009; Bradstock et al. 2010).

Smaller fires, mainly those belonging to size category A, tend to be grouped closest to PC2 but are also influenced by PC3. PC2 differentiates from PC1 and PC3 in that it is very heavily influenced by wind speed. In PC2 the contribution of wind speed is negative, with a value of -0.814, which would indicate that PC2 correlates most strongly with wind speed, and the principal component therefore increases with decreasing wind speed. It would suggest then that low wind speed is a fairly significant contributing factor in smaller less severe fires, and that smaller fires occur in conditions where there are high temperatures and minimal wind (Bessie & Johnson 1995; Bradstock et al. 2009; Bradstock et al. 2010). Medium sized fires tend to cluster towards the middle of the PCA ordination plot, which would suggest that each of the variables contributes relatively equally and that these fires are not particularly heavily influenced by any of the variables sampled. Consequently, medium-sized fires do not help us understand fire drivers in this mountainous study area, and most information comes from very large fires, which are influenced by a combination of low relative humidity and steep slopes, or very small fires, which are influenced by high temperatures and high wind speeds (Bessie & Johnson 1995; Weir 2007; Bradstock et al. 2009; Bradstock et al. 2010; Holsten et al. 2013).

Table 4-10 shows the Eigenvalues from the Principal Component Analysis (PCA) using the mean variable factor data. Table 4-10 shows the relative contribution of each of the variables sampled and gives a percentage for the amount of variance that can be explained by each of the variables (Bessie & Johnson 1995; Weir 2007; Bradstock et al. 2009; Bradstock et al. 2010; Holsten et al. 2013).

Table 4-10: Eigenvalues from the Principal Component Analysis (PCA) using the mean variable factor data

PC	**Eigenvalues**	**% Variation**	**Cumulative % Variation**
1	1.34	44.6	44.6
2	0.978	32.6	77.2
3	0.684	22.8	100.0

PC1 is responsible for 44.6% of the variation observed in the PCA plot. The main contributing factor of PC1 is relative humidity, but there was also a significant contribution from temperature. As this was a negative relationship present with relative humidity and a positive relationship present with temperature, it means that the placement of 44.6% of the samples was as a result of conditions where there was low relative humidity and high temperatures present. Temperature is weighted equally and fairly heavily in all of the PC's, and is therefore one of the major driving factors responsible for variation in the plot, as its contribution is consistent throughout. This related well to published literature on fire drivers in a range of landscapes from flat savannah/woodland (Le Maitre et al. 2002; Smith et al. 2004; Forsyth et al. 2010; Ryan &Williams 2010) to Mediteranean areas (Brown et al. 1991; Le Maitre & Brown 1992; Seydack et al. 2007) and mountainous areas (Fernandes 2001; Syphard et al. 2009; Wilson et al. 2010). It was the only variable to have a significant contribution in all of the PC's. The remaining percentage variation can be attributed to PC2 and occurs as a result of minimal wind speed and the large proportion of small fires sampled.

A multi-dimensional scaling (MDS) ordination was also plotted using the mean weather variables. Figures 4-5 and 4-6 show the Multi-Dimensional Scaling (MDS) 2-dimensional and 3-dimensional plots using the mean variable factor data. Non-Metric Multi-Dimensional Scaling (MDS) is an ordination method that makes use of a more complex algorithm. It is however very simply described and understood, and few assumptions need to be made about the data, which make it the most widely applicable and effective method of ordination available (Clarke & Warwick 1994).

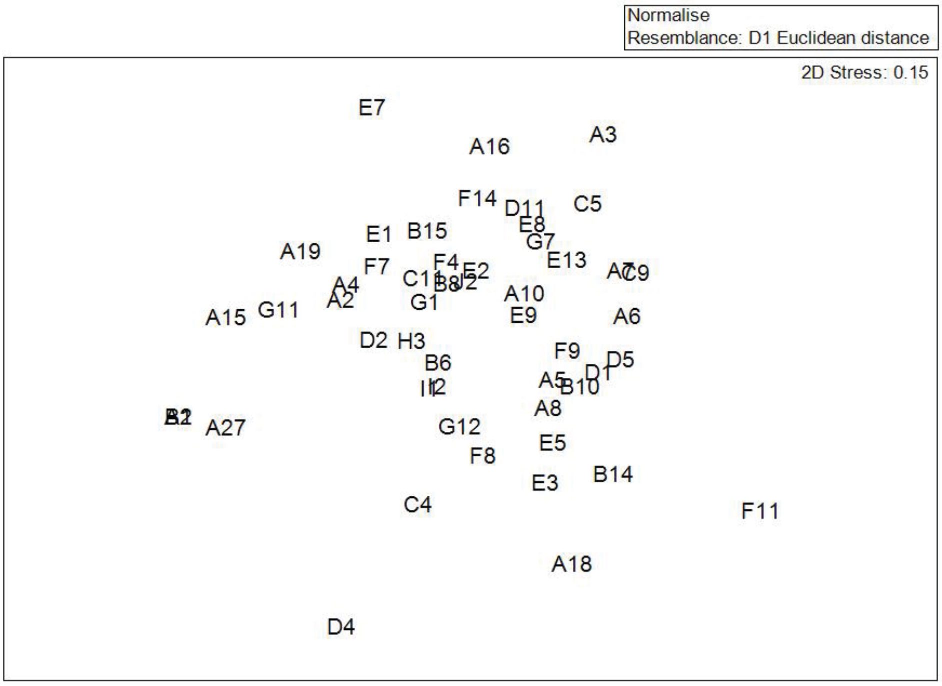

Figure4-5: Multi-Dimensional Scaling (MDS) 2 – dimensional plot using the mean variable factor data

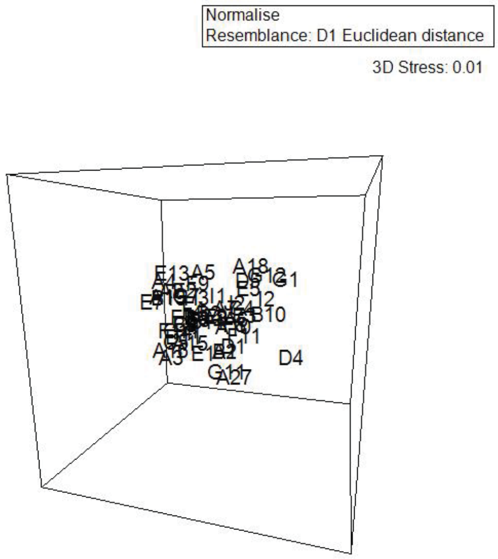

Figure4-6: Multi-Dimensional Scaling (MDS) 3 – dimensional plot using the mean variable factor data

What distinguishes the MDS from the PCA first and foremost is that it focuses on the similarity between samples and not the dissimilarity. The starting point of the MDS methodology is the application of a similarity or resemblance matrix after data has been tested for normality (Clarke & Warwick 1994). The purpose of an MDS can therefore be simply stated: it constructs a plot or configuration of samples, in a specified number of dimensions, which attempts to satisfy all the conditions imposed by the similarity matrix (Clarke & Warwick 1994).

Figure 4-5 shows the plot of the Multi-Dimensional Scaling (MDS) 2 – dimensional plot using the mean variable factor data. What is immediately apparent upon an initial inspection is that it is remarkably similar to the plot observed in the PCA methodology in Figure 4-3. As with the PCA analysis, there was some grouping observed, with larger fires grouping together and smaller fires locating on the periphery. Of particular interest in this instance were the category I and J fires which again grouped closely and seemed to be influenced by similar factors.

Figures 4-7 and 4-8 show the Principal component analysis plots of the extreme weather data in both 2 and 3 dimensions. It was important to perform the analysis using extremes of the weather variables, as it was hypothesised that these extreme changes may well be responsible for significant changes in both fire danger and fire behaviour (Bessie & Johnson 1995; Gould 2005; Bradstock et al. 2009; Bradstock et al. 2010). Weather variables are described by Gould (2005) as contributing factors that are able to change rapidly and affect large areas. It was therefore important to analyse the potential effects of the extremes of the weather variables that were sampled as part of the research. This was also supported by the results of the multiple regression analysis performed on the FDI, which represents a combination of important weather variables that impact on fire spread and behaviour (Bessie & Johnson 1995; Sharples et al. 2008; Bradstock et al. 2009; Bradstock et al. 2010).

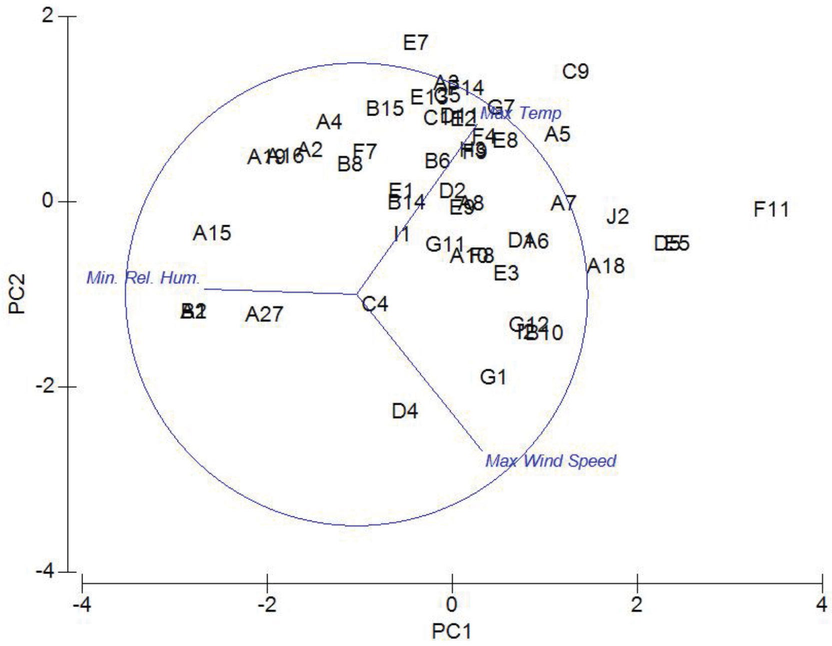

Figure4-7: Principal Component Analysis (PCA) 2 – dimensional plot using the extreme variable factor data

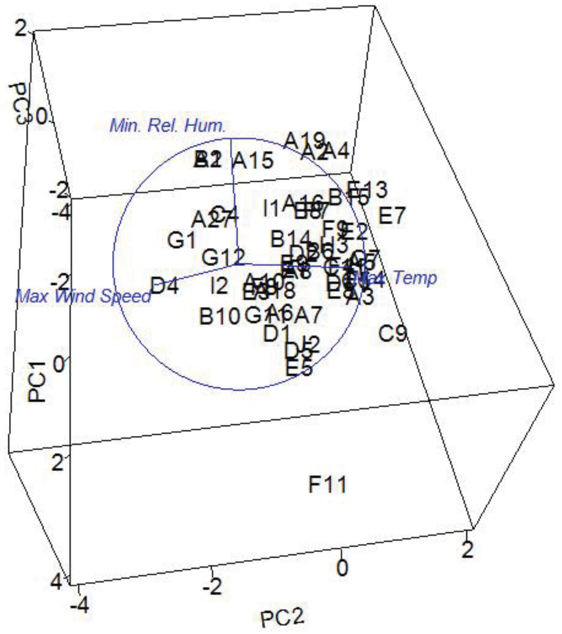

Figure4-8: Principal Component Analysis (PCA) 3 – dimensional plot using the extreme variable factor data

The FDI data generated from the extreme weather values showed a positive correlation with size of the fire burn scar that was statistically significant (Tables 4-7 and 4-8). In the context of this research, the extreme weather variables used during the analysis were maximum temperature, maximum wind speed and minimum relative humidity.

As with the PCA of the mean weather variables, there is some grouping observed, with larger fires grouping separately from small and medium fires. Category I and G fires seem to group relatively close together and are most strongly influenced by PC1. Table 4-11 indicates the Eigenvectors from the Principal Component Analysis (PCA) using the extreme variable factor data.

Table 4-11: Eigenvectors from the Principal Component Analysis (PCA) using the extreme variable factor data

Variable	**PC1**	**PC2**	**PC3**
Maximum Temperature	0.522	0.735	0.433
Minimum Relative Humidity	-0.656	0.022	0.754
Maximum Wind Speed	0.544	-0.678	0.494

From the table we can see that PC1 has a significant contribution from all of the variables sampled, with each showing a value greater than 0.5. The values of 0.522 for temperature and 0.544 for wind speed indicate a positive relationship, and means that the principal component will increase with an increase in either maximum temperature or maximum wind speed. The largest contributing factor for PC1 is relative humidity, where there is a negative relationship present with a value of -0.656. This means that the principal component will increase when there is a decrease in relative humidity. This would indicate that large fires tend to occur in conditions where there are high temperatures, strong winds and low relative humidity. This is consistent with the results observed in Figures 4-3 and 4-4 using the mean weather variables which also suggest that temperature and relative humidity are key driving factors (Bessie & Johnson 1995, Weir 2007; Bradstock et al. 2009; Bradstock et al. 2010; Holsten et al. 2013).

Medium fires tend to group together, and appear to be influenced by PC2. PC2 has a significant contribution from both temperature and wind speed. The primary component of this principal component is maximum temperature, with a very large weighting of 0.735. This suggests that medium fires tend to occur during extreme temperature conditions, when the maximum temperatures are very high. There is a negative relationship present with wind speed, although it is also a significant contribution to the principal component with a value of -0.678. This means that the principal component will increase with a decrease in the maximum wind speed. The contribution of relative humidity is extremely low for medium sized fires when considering mean values of environmental variables, with a value of 0.022, which would mean that the effect of this variable on the principal component is negligible. Note that this is in contrast with what was observed with large fires. Medium fires, therefore seem to occur under conditions where there are extremely high temperatures and low winds. The negative relationship with wind speed and the lack of influence from relative humidity could account for the difference in the rate of spread and severity observed in medium fires as opposed to larger fires, with extreme temperatures being the major driving factor.

Small fires are clustered towards the top of the ordination plot, and seem to be influenced mostly by PC3. There is a very strong contribution from relative humidity of 0.754, which would explain the small size of the fires, as when the relative humidity is high, it will be much more difficult for the moisture to evaporate into the air. Although less than 0.5, it is interesting to note that there is a large, and possibly combined, contribution from wind speed and temperature which probably account for the fire occurring at all.

Table 4-12 indicates the eigenvalues from the Principal Component Analysis (PCA) using the extreme variable factor data. The eigenvalues show the relative contribution of each of the variables sampled and gives a percentage for the amount of variance that can be explained by each of the variables. PC1 is responsible for 54.3% of the variation observed in the PCA. What this suggests is that 54.3% of the samples were influenced by conditions where there were high temperatures, strong winds and low relative humidity.

Table 4-12: Eigenvalues from the Principal Component Analysis (PCA) using the extreme variable factor data

PC	**Eigenvalues**	**% Variation**	**Cumulative % Variation**
1	1.63	54.3	54.3
2	0.847	28.2	82.6
3	0.522	17.4	100.0

Figures 4-9 and 4-10 show the Multi-Dimensional Scaling (MDS) 2-dimensional and 3-dimensional plots using the extreme variable factor data. What is clear on inspection is that it is remarkably similar to the plot observed in the PCA methodology in Figure 4-7. As with the PCA analysis, there was some grouping observed, with larger fires grouping together and smaller fires locating on the periphery.

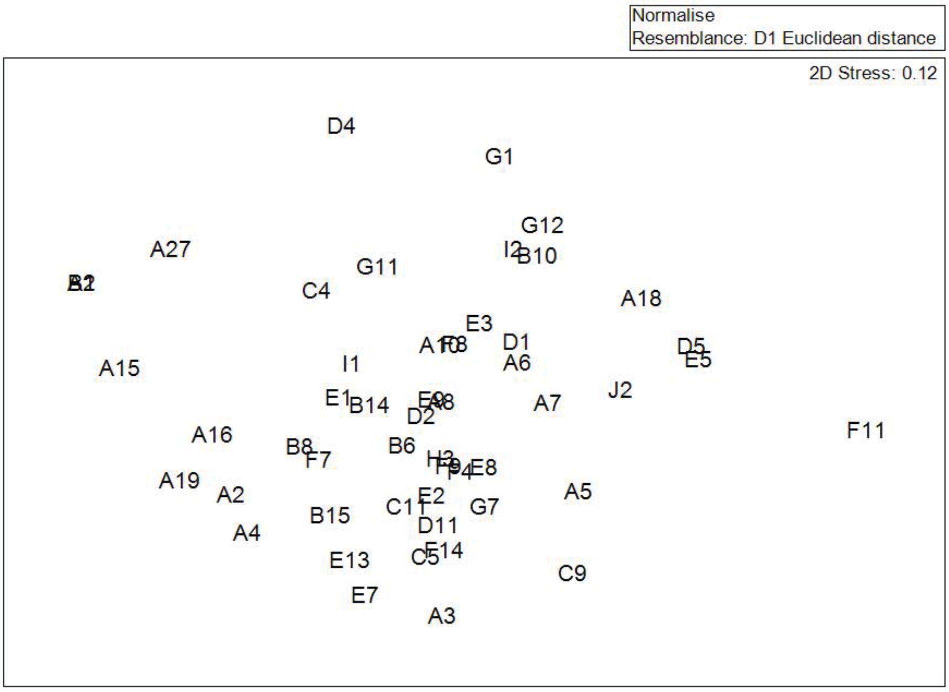

Figure 4-9: Multi-Dimensional Scaling (MDS) 2 – dimensional plot using the extreme variable factor data

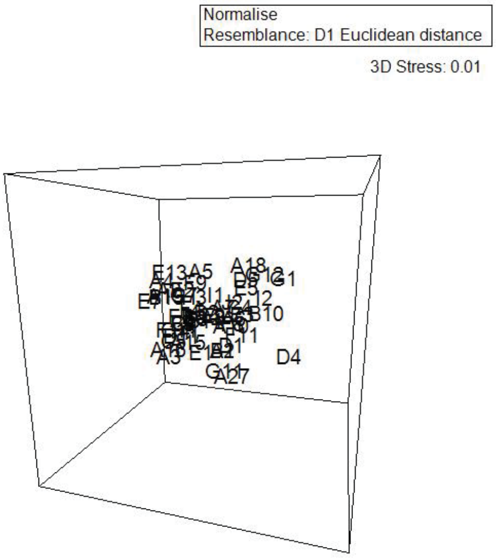

Figure 4-10: Multi-Dimensional Scaling (MDS) 3 – dimensional plot using the extreme variable factor data

4.2.2 Rainfall/Fuel, Slope and Topography

As with the analysis of the weather variables, two types of ordination methodologies were used in the analysis of rainfall/fuel, slope and topography. These factors represent the more physical factors or environmentally based factors. These are factors that remain relatively constant during the duration of a fire. Gould (2005) identifies these variables as constant factors that change slowly or vary with location, such as slope, topography and fuel.

Figures 4-11 and 4-12 show the 2-dimensional and 3-dimensional plots for the PCA analysis that was run on the constant variable factors: namely rainfall/fuel, slope and topography. Rainfall in this instance was used as a proxy for fuel (Van Wilgen & Scholes 1997). There was some grouping observed, again with larger fires placed more towards the centre and smaller fires being located on the periphery, however there was much less dispersion of samples and all fires regardless of size appear to be influenced by similar factors.

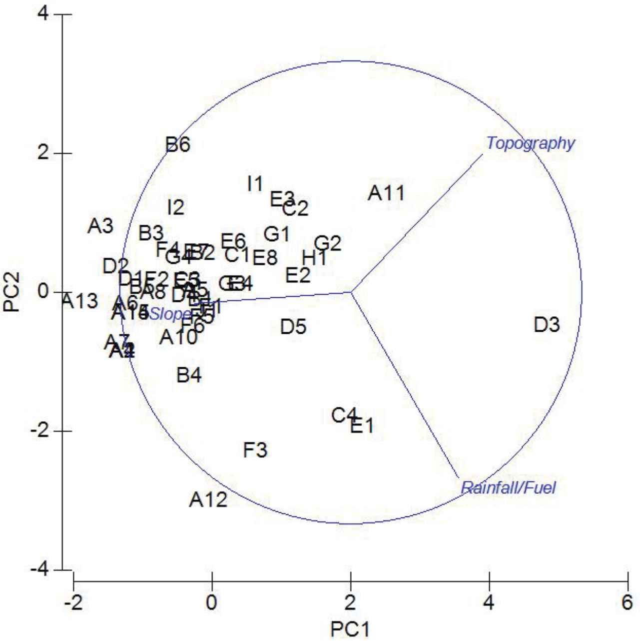

Figure4-11: Principal Component Analysis (PCA) 2 – dimensional plot using Rainfall/Fuel, Slope and Topography

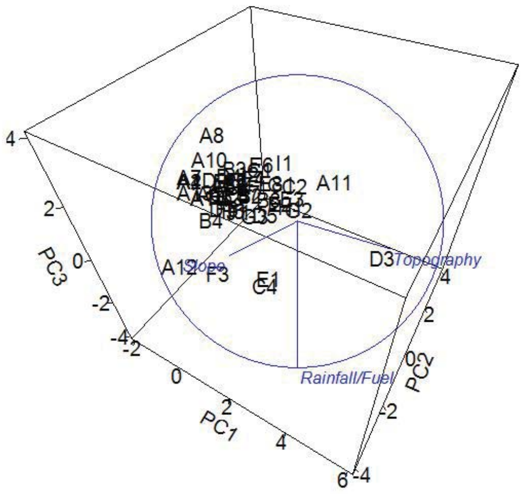

Figure4-12: Diagram showing the Principal Component Analysis (PCA) 3 – dimensional plot using Rainfall/Fuel, Slope and Topography

Table 4-13 shows the eigenvectors from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope and Topography. Large and medium fires tend to be influenced most strongly by PC1 and PC3. This is not particularly clear from the 2-dimensional plot in Figure 4-11, but a detailed inspection of the 3-dimensional PCA plot in Figure 4-12 shows this to be the case. It is interesting to note that all of the principal components are influenced quite strongly by topography.

Table 4-13: Eigenvectors from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope and Topography

Variable	**PC1**	**PC2**	**PC3**
Rainfall/Fuel	0.465	-0.801	-0.377
Slope	-0.677	-0.048	-0.734
Topography	0.570	0.597	-0.565

Topography gives an indication of the ruggedness of the terrain, and is measured as the co-efficient of variation of slope in the area, using the slope data obtained from the University of Stellenbosch and calculated using *Microsoft Excel 2010*. It is interesting to note that topography has a strong effect on all fires that have occurred within the sample area, which is a declared Mountain Catchment Area consisting of rugged mountains with significant variation in heights and slope (Alexander 1982; Hely & Alleaume 2006; Holden & Jolly 2011). Both PC1 and PC3 have slope as the major contributing factor, with PC1 having a value of -0.677 for slope and PC3 having a value of -0.734 for slope. This means that the principal component will increase with a decrease in the slope. While both PC1 and PC3 are driven mainly by slope, the fundamental difference between them is the contribution of topography. Topography is a significant contributing factor in both PC1 and PC3, but it has a positive relationship in PC1 and negative relationship with PC3. This means that PC1 will increase with an increase in topography and PC3 will increase with a decrease in topography. This means that fires that are influenced more by PC1 tend to occur in more topographically complex areas and fires that are influenced more by PC3 will tend to occur in areas that are less topographically complex areas.

Smaller fires, particularly those of category A, that is the smallest fires that took place in the study area, seem to be strongly influenced by PC3 as they are clustered close to the top of the ordination plot. PC3 is primarily driven by a negative relationship with slope, but also has a negative relationship with topography as a large contributing factor. What this means is that the principal component increases with a decrease in either slope or topography. Smaller fires will therefore tend to occur in flatter, less topographically complex areas. Conversely, large fires, which are predominantly influenced by PC1 and PC3, tend to occur through topographically complex terrain, probably driven as we noted earlier, by preheating of fuel and updrafts related to slope (Alexander 1982; Hely & Alleaume 2006; Holden & Jolly 2011).

What is interesting to note across all of the principal components is that general lack of contribution from rainfall/fuel. The amount and arrangement of fuel, often referred to as biomass, is considered by many to be one of the most critical factors influencing the inception, spread and severity of a fire (Fernandes 2001; Ryan & Williams 2010). It is therefore surprising that fuel did not show more of a contribution to the principal components during the analysis. This may be as a result of the over-riding impact of relative humidity and slope in this mountainous study area (Fernandes 2001; Ryan & Williams 2010).

Table 4-14 shows the eigenvalues from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope and Topography. The eigenvalues show the relative contribution of each of the variables sampled and gives a percentage for the amount of variance that can be explained by each of the variables. PC1 is responsible for 51.5% of the variation observed in the PCA. What this suggests is that 51.5% of the samples were influenced by conditions where there is topographical complexity together with flatter slopes. There was also a fair contribution of fuel in this principal component, which is less than 0.5 but should not be ignored as a contributing factor, as it is one of the fundamental differences between PC1 compared with PC2 and PC3. The variability in the PCA plot then is primarily influenced by a high level of topographical complexity, flatter slopes and to a lesser extent, the availability of fuel.

Table 4-14: Eigenvalues from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope and Topography

PC	**Eigenvalues**	**% Variation**	**Cumulative % Variation**
1	1.55	51.5	51.5
2	0.919	30.6	82.1
3	0.536	17.9	100.0

Figures 4-13 and 4-14 show the Multi-Dimensional Scaling (MDS) 2 – dimensional and 3-dimensional plots using the constant variable factor data. What is clear on inspection is that it is remarkably similar to the plots observed in the PCA methodology in Figures 4-11 and 4-12. As with the PCA analysis, there was some grouping observed, with larger fires and medium fires grouping together and smaller fires locating on the periphery. The plot of the MDS can therefore serve as confirmation of the relationships observed in the PCA plots for the constant variable factors.

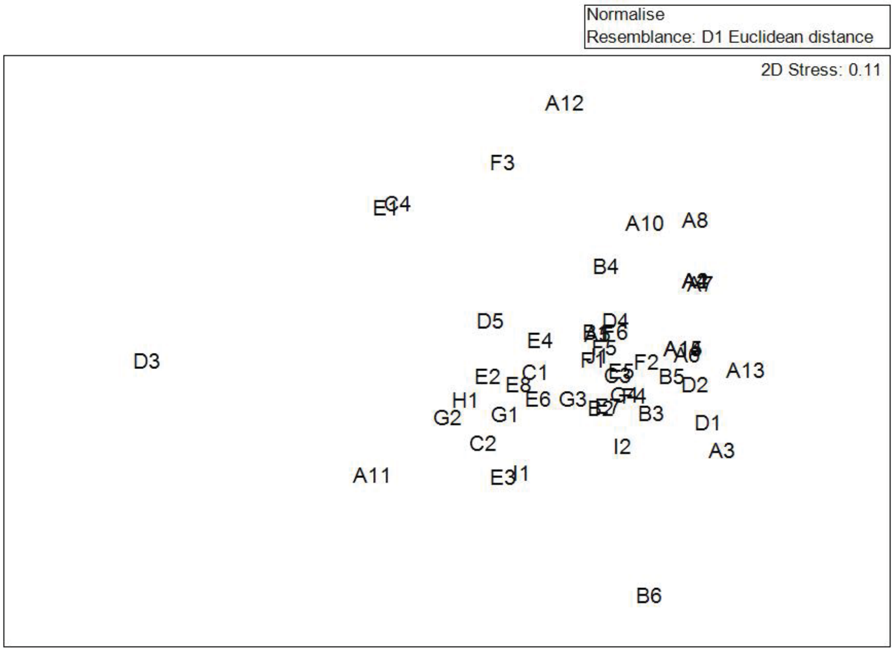

Figure4-13: Multi-Dimensional Scaling (MDS) 2 – dimensional plot using Rainfall/Fuel, Slope and Topography

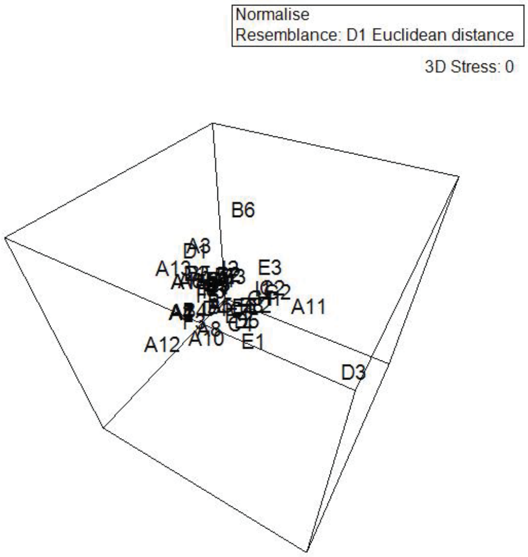

Figure4-14: Multi-Dimensional Scaling (MDS) 3 – dimensional plot using Rainfall/Fuel, Slope and Topography

4.2.3 Analysis of All Contributing Factors of Fire Danger and Fire Behaviour

One of the major strengths of the ordination methodologies used in conducting this research, namely Principal Component Analysis (PCA) and Non-Metric Multi-Dimensional Scaling (MDS), is that it allows for a range of variables to be compared across samples. In the case of a complex natural hazard phenomenon such as veldfires, this is an incredibly useful tool in attempting to understand the relationship between factors that drive fire danger and fire behaviour across a range of different fire size classes. Ordination techniques have already been applied to Gould's (2005) constant and variable factors separately, but PCA and MDS analyses were also applied to all factors together to see what combinations and interactions between these factors result in the different fire size classes that have been investigated and also to observe general trends across all fires within the Limietberg Conservation Area.

All factors were analysed using both PCA and MDS ordination techniques. Two sets of analyses were done, the first using the mean weather variables and the second using the extreme weather variables. In both cases the data for rainfall/fuel, slope and topography were the same, as these are constant factors and not as readily susceptible to change as is the case with the weather variables.

Figures 4-15 and 4-16 show the 2-dimensional and 3-dimensional plots of the PCA ordination using rainfall/fuel, slope, topography and mean weather variables. Once again there was grouping observed, with large and medium fires grouping together and smaller fires (especially those of category A) locating on the periphery. The plot is more difficult to interpret as there are now five principal components as opposed to three in the previous examples. This makes a visual analysis much more challenging, even when using the 3-dimensional view in *Primer Version 6*. It is, however still possible to interpret in a meaningful way and to extract useful insights as to why fires of different sizes have grouped together. In the analysis of the more complex PCA plots, as is the case with Figures 4-15 and 4-16, it was necessary to consult the eigenvectors and eigenvalues during the initial visual inspection to gain a better understanding of how samples grouped together.

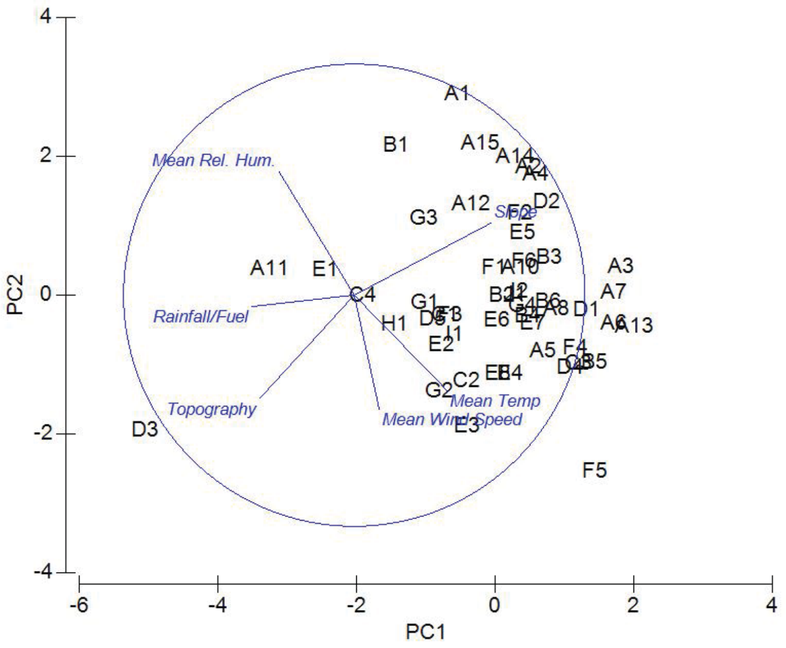

Figure4-15: Principal Component Analysis (PCA) 2 – dimensional plot using Rainfall/Fuel, Slope, Topography and Mean Weather Variables

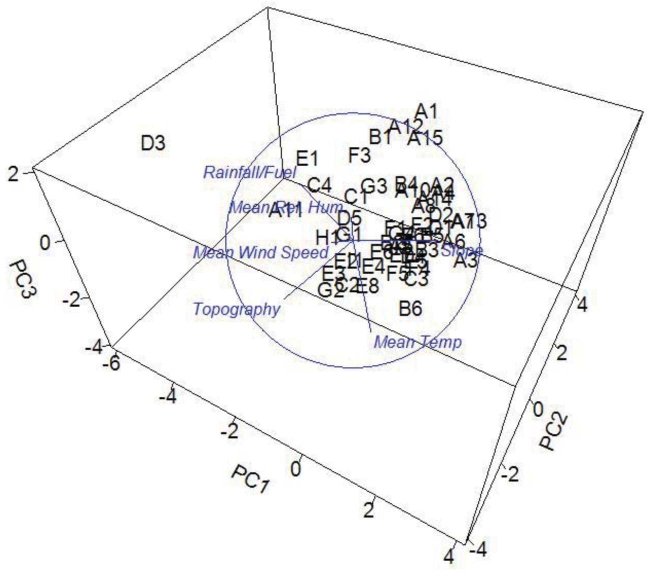

Figure4-16: Principal Component Analysis (PCA) 3 – dimensional plot using Rainfall/Fuel, Slope, Topography and Mean Weather Variables

From the initial visual inspection of the PCA plots, it would appear that most fires are strongly influenced by PC1 and PC2. This is confirmed when consulting Table 4-15 which shows the eigenvalues from the Principal Component Analysis (PCA) using rainfall/fuel, slope, topography and the mean weather variables. Table 4-15 indicates that PC1 is responsible for 28.1% of the variation observed, and PC2 is responsible for 20.9%. This means that cumulatively PC1 and PC2 are responsible for almost half of the variation observed in the PCA plot.

Table 4-15: Eigenvalues from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope, Topography and Mean Weather Variables

PC	Eigenvalues	% Variation	Cumulative % Variation
1	1.68	28.1	28.1
2	1.25	20.9	48.9
3	1.03	17.1	66.1
4	0.933	15.5	81.6
5	0.593	9.9	91.5

Table 4-16 shows the eigenvectors from the Principal Component Analysis (PCA) using rainfall/fuel, slope, topography and mean weather variables. This allows us to assess the relative contribution of each of the variables to each of the principal components, in this case, PC1 and

PC2 which are the principal components of interest. Based on our assigned significance level of 0.5 as a level of significance for correlation, there is one main driving factor that influences PC1 which is slope, with a value of 0.594. PC2 also has only one main driving factor, which is relative humidity. It may come across as rather surprising that the weather variables have not made more of a contribution to the principal components, however, given that this analysis was using the mean weather data, this is not totally unexpected when one considers the results of the previous multiple regression and ordination analyses where extreme weather data was found to have more of an impact. What is clear from the analysis is that slope was certainly one of the main driving factors. This is consistent with the results analysed with Figures 4-11 and 4-12 in the PCA analysis of the constant factor variables (Alexander 1982; Hely & Alleaume 2006; Holden & Jolly 2011).

Table 4-16: Eigenvectors from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope, Topography and Mean Weather Variables

Variable	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
Rainfall/Fuel	-0.447	-0.050	0.443	-0.560	-0.484
Slope	0.594	0.313	0.024	-0.031	-0.180
Topography	-0.411	-0.448	-0.514	0.106	0.111
Mean Temperature	0.402	-0.412	-0.463	-0.310	-0.528
Mean Relative Humidity	-0.325	0.533	-0.332	0.410	-0.571
Mean Wind Speed	0.109	-0.496	0.463	0.640	-0.341

Figures 4-17 and 4-18 show the Multi-Dimensional Scaling (MDS) 2-dimensional and 3-dimensional plots using rainfall/fuel, slope, topography and mean weather variables. Once again the MDS plot is remarkably similar to the plots observed in the PCA methodology in Figures 4-15 and 4-16. As with the PCA analysis, there was some grouping observed, with larger fires and medium fires grouping together and smaller fires locating on the periphery. The plot of the MDS can therefore serve as confirmation of the relationships observed in the PCA plots for the constant variable factors.

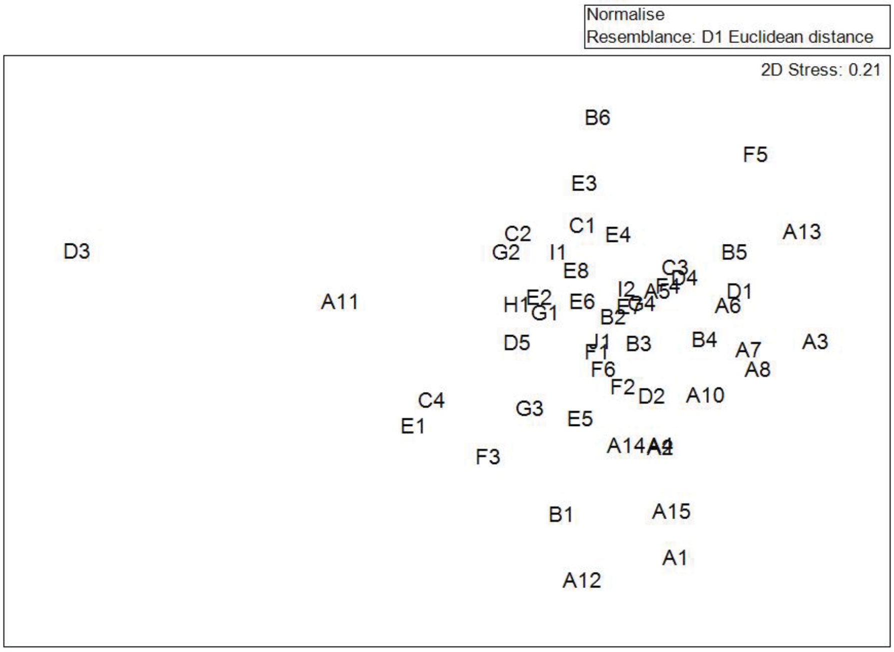

Figure4-17: Multi-Dimensional Scaling (MDS) 2 – dimensional plot using Rainfall/Fuel, Slope, Topography and Mean Weather Variables

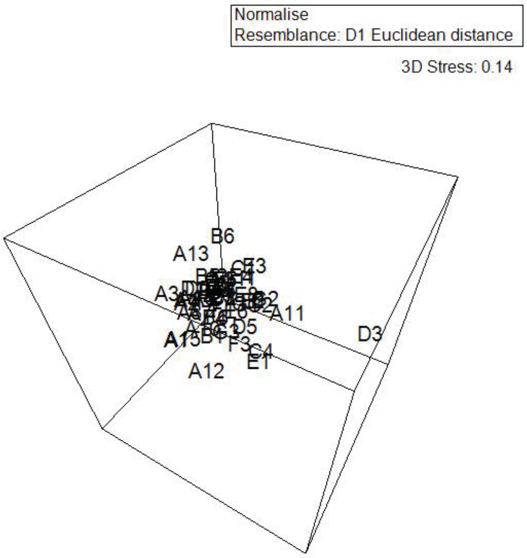

Figure4-18: Multi-Dimensional Scaling (MDS) 3 – dimensional plot using Rainfall/Fuel, Slope, Topography and Mean Weather Variables

Figures 4-19 and 4-20 show both the 2-dimensional and 3-dimensional plots of the Principal Component Analysis (PCA) using rainfall/fuel, slope, topography and extreme weather variables. There is some grouping observed, with large and medium fires grouping together towards the centre of the plot and smaller fires towards the top.

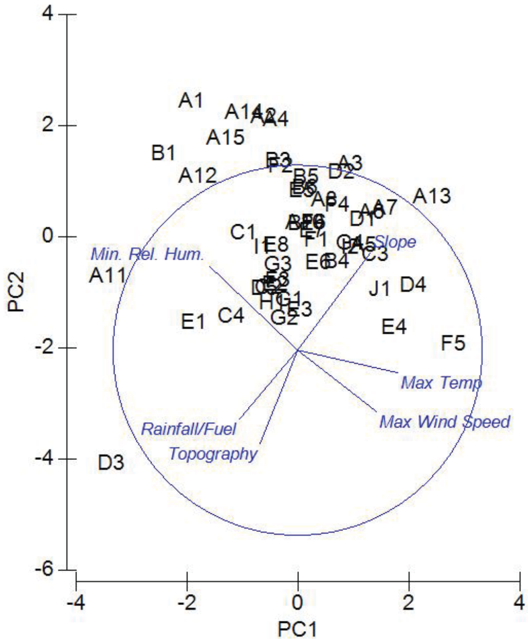

Figure4-19: Principal Component Analysis (PCA) 2 – dimensional plot using Rainfall/Fuel, Slope, Topography and Extreme Weather Variables

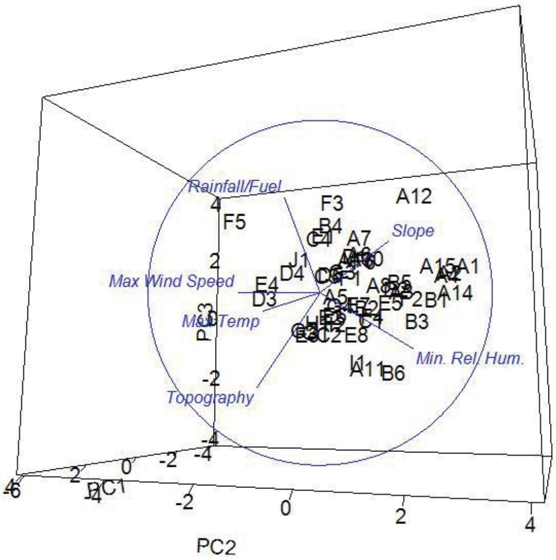

Figure4-20: Principal Component Analysis (PCA) 3 – dimensional plot using Rainfall/Fuel, Slope, Topography and Extreme Weather Variables

From the initial visual inspection of the PCA plots, it would appear that most fires are strongly influenced by PC1 and PC2. This is confirmed when consulting Table 4-17 which shows the eigenvalues from the Principal Component Analysis (PCA) using rainfall/fuel, slope, topography and the extreme weather variables. Table 4-17 indicates that PC1 is responsible for 28.0% of the variation observed, and PC2 is responsible for 26.0%. This means that cumulatively PC1 and PC2 are responsible for more than half of the variation observed in the PCA plot.

Table 4-17: Eigenvalues from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope, Topography and Extreme Weather Variables

PC	Eigenvalues	% Variation	Cumulative % Variation
1	1.68	28.0	28.0
2	1.56	26.0	54.0
3	0.975	16.3	70.2
4	0.881	14.7	84.9
5	0.563	9.4	94.3

Table 4-18 shows the eigenvectors from the Principal Component Analysis (PCA) using rainfall/fuel, slope, topography and extreme weather variables. This allows us to assess the relative contribution of each of the variables to each of the principal components, in this case, PC1 and PC2 which are the principal components of interest. PC1 is driven by 3 main factors: maximum temperature, minimum relative humidity and maximum wind speed. In the case of relative humidity, it is a negative relationship which is observed. PC1, which is responsible for the largest portion of the variation observed in the PCA plot, increases when there is an increase in maximum temperature, maximum wind speed and a decrease in relative humidity. PC2 has 2 main factors that influence the principal component, namely slope (0.524) and topography (-0.504). There is also a fairly large contribution from relative humidity, which can potentially be explained by the effect of the slope and topography in creating fire conditions that prepare the fuel by drying it out as a result of warming the air. This occurs as a result of steep slopes, as may be the case in PC2. The combination of factors resulting from PC1 and PC2 indicate that fires were mostly influenced by high temperatures, steep slopes and low levels of topographical complexity.

Table 4-18: Table showing the Eigenvectors from the Principal Component Analysis (PCA) using Rainfall/Fuel, Slope, Topography and Extreme Weather Variables

Variable	PC1	PC2	PC3	PC4	PC5
Rainfall/Fuel	-0.315	-0.374	0.723	0.207	-0.057
Slope	0.393	0.524	0.187	0.201	0.578
Topography	-0.203	-0.504	-0.559	0.289	0.484
Maximum Temperature	0.541	-0.122	-0.170	0.546	-0.556
Minimum Relative Humidity	-0.480	0.456	-0.315	-0.119	-0.344
Maximum Wind Speed	0.426	-0.331	-0.041	-0.722	-0.026

Figures 4-21 and 4-22 show the Multi-Dimensional Scaling (MDS) 2 – dimensional and 3-dimensional plots using rainfall/fuel, slope, topography and extreme weather variables. Once again the MDS plot is remarkably similar to the plots observed in the PCA methodology in Figure 4-19 and 4-20. As with the PCA analysis, there was some grouping observed, with larger fires and medium fires grouping together and smaller fires locating on the periphery. The plot of the MDS can therefore serve as confirmation of the relationships observed in the PCA plots for the constant variable factors.

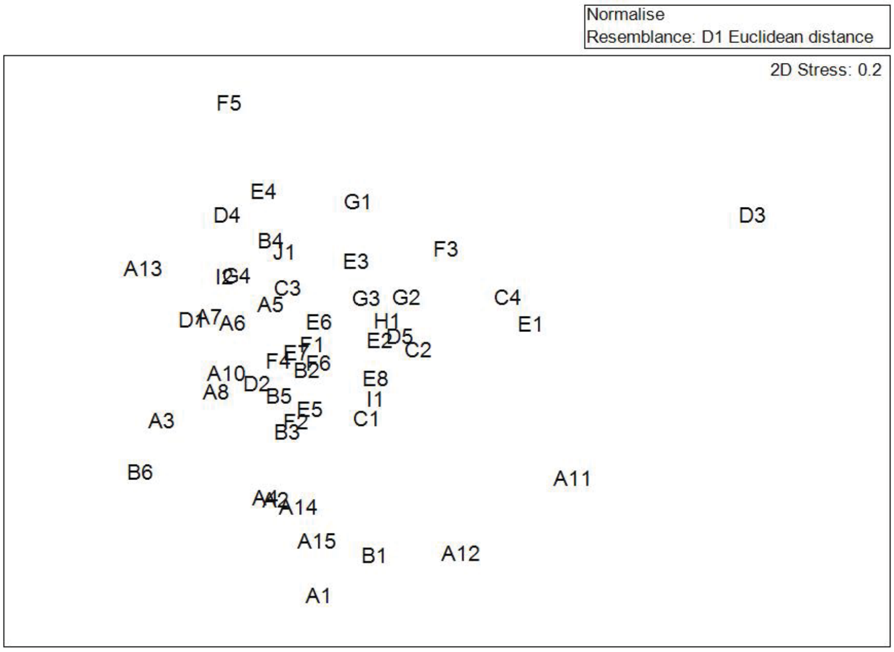

Figure4-21: Multi-Dimensional Scaling (MDS) 2 – dimensional plot using Rainfall/Fuel, Slope, Topography and Extreme Weather Variables

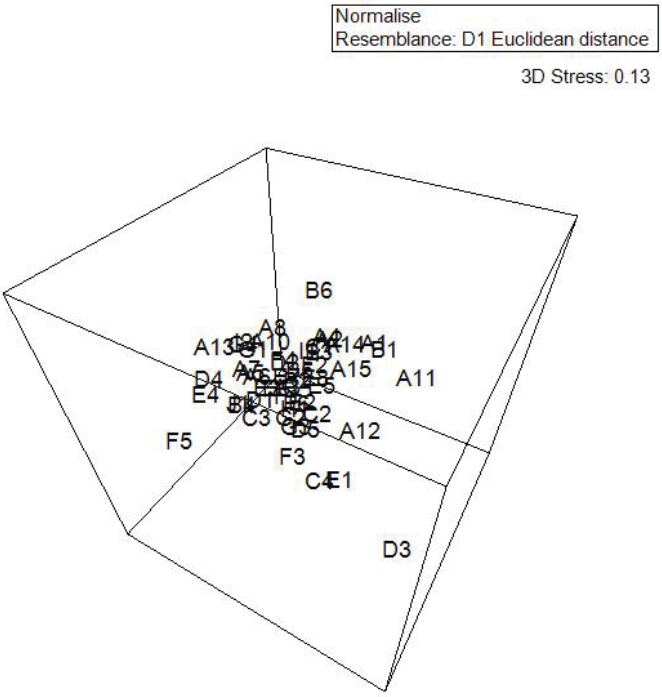

Figure4-22: Multi-Dimensional Scaling (MDS) 3 – dimensional plot using Rainfall/Fuel, Slope, Topography and Extreme Weather Variables

4.3 Analysis of Ecological Vulnerability and Fire Frequency

The ecological impacts of fires were assessed using post-fire regeneration (Proteaceae parent:seedling) monitoring techniques. This involved practical fieldwork and data collection following the method of Bond et al. (1984), as adapted for Cape Nature (Vlok & Yeaton 2000; De Klerk et al. 2007).

The recruitment success of serotinous Proteaceae species, which do not resprout after fire, were used as an indicator of post-fire regeneration success of fynbos vegetation (Vlok & Yeaton 2000). Only non-sprouting *Protea* and *Leucadendron* species were used in these surveys.

In the case of the Limietberg Conservation Area, the post fire regeneration (proteaceae parent:seedling) monitoring made use of a combination of data sampled as part of the research process together with archival data of previous sampling carried out by Cape Nature. Figure 4-23 shows the sampling sites from which data was obtained for the Post Fire Regeneration Monitoring (Proteaceae Parent:Seedling Monitoring) in the Limietberg Conservation Area as part of this study. The study made use of sampling data obtained from fires which occurred in 2003, 2004, 2005, 2006, 2010 and 2011. The sites were also well dispersed over the study area, which allowed for the entire area to be represented in the analysis of the post fire plant recovery.

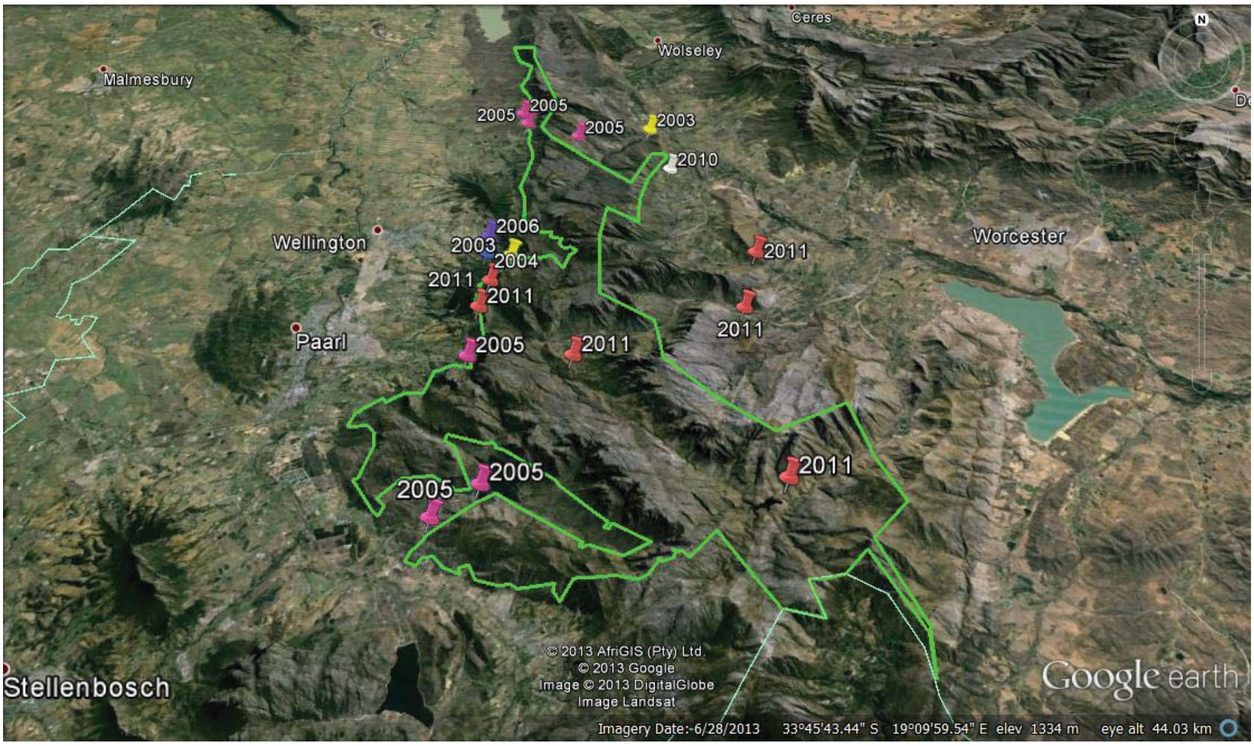

Figure4-23: Sampling sites from which data was obtained for the Post Fire Regeneration Monitoring (Proteaceae Parent:Seedling Monitoring) in the Limietberg Conservation Area. (Courtesy of Google Earth 28/11/2013)

The study made use of four different species in the assessment of the ecological recovery: *Protea laurifolia*, *Protea nerifolia*, *Protea repens* and *Leucadendron rubrum*. Not all species were found or sampled at every site, but each was well represented in enough sites sampled to allow for inclusion in analysis. It is important to note that sampling carried out by the researcher of this study and sampling carried out by Cape Nature that was used as part of this research were sampled using the same methodology and collection techniques.

Fire regimes are ecological drivers and are responsible for shaping the functioning, structure and composition of the ecosystem (Forsyth et al. 2010). If the frequency, intensity, type, season or size of fires diverges from the natural range of variation under which the ecosystem evolved, the ecosystem structure and processes will change (Forsyth et al. 2010). Alteration of key elements of a fire regime may cause current or long-term conditions that threaten the persistence of native plant populations associated with that fire regime (Vlok & Yeaton 2000; Forsyth et al. 2010). Figure 4-24 shows the effect of fire season on regeneration of *Protea* and *Leucadendron* species in the Limietberg Conservation Area.

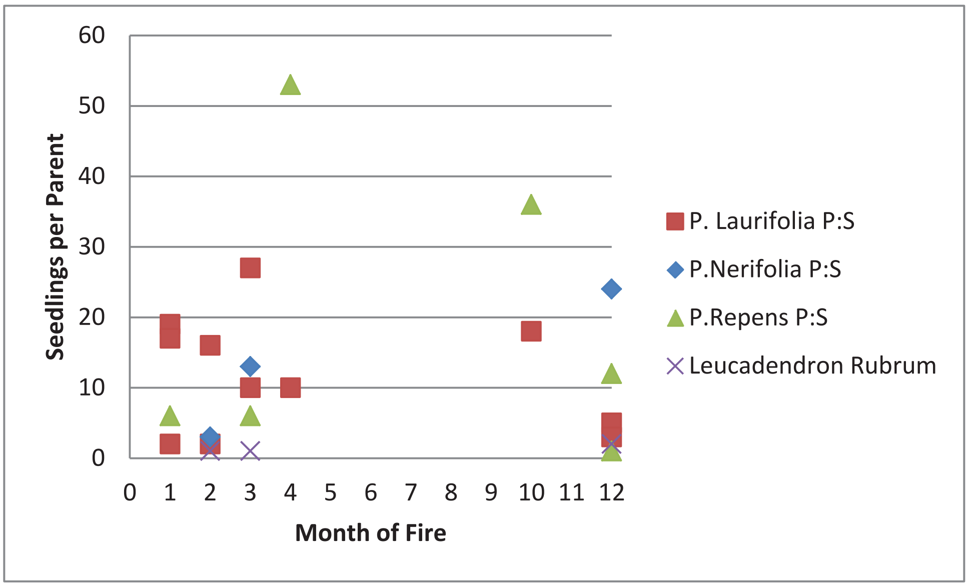

Figure4-24: Effect of fire season on regeneration of Protea and Leucadendron Species in the Limietberg Conservation Area

In general recruitment seems to be good, especially in the *Proteaceae*. Number of seedlings per parent appears to be greater after fires that have occurred in March and April, probably as a result of this being just before the rainy season. *P. repens* appears to be the most prolific, but *P. laurifolia* has also performed well. This result follows those of Bond (1983), Bond et al. (1984), Mustart et al. (2012), Rutherford et al. (2011) and Kraaij et al. (2013). There is very poor recruitment observed in *L. rubrum*. It would seem that the fire regime that operates within the Limietberg Conservation Area has not affected the post fire recruitment of *Proteaceae* and ecological recovery of these species after a fire event seems to enable post-fire replacement of adult populations at adequate levels. The Limietberg Conservation Area also receives a good supply of rainfall during the rainy season, which may also account for the successful recruitment rate. The protected area forms the catchments of the Berg and Breede Rivers as well as for the Theewaterskloof, Voëlvlei, Wemmershoek, Brandvlei and Stettynskloof dams.

Another critical concern is the age at which the veld is burning. It is essential that veld burns at a stage of maturity within the life cycle of the plants under consideration, where it is able to respond adequately with regards to seeding. The age of the veld and the fire return interval are therefore of particular concern. Figure 4-25 shows the effect of veld age on regeneration of *Proteaceae* and *Leucadendron* species in the Limietberg Conservation Area.

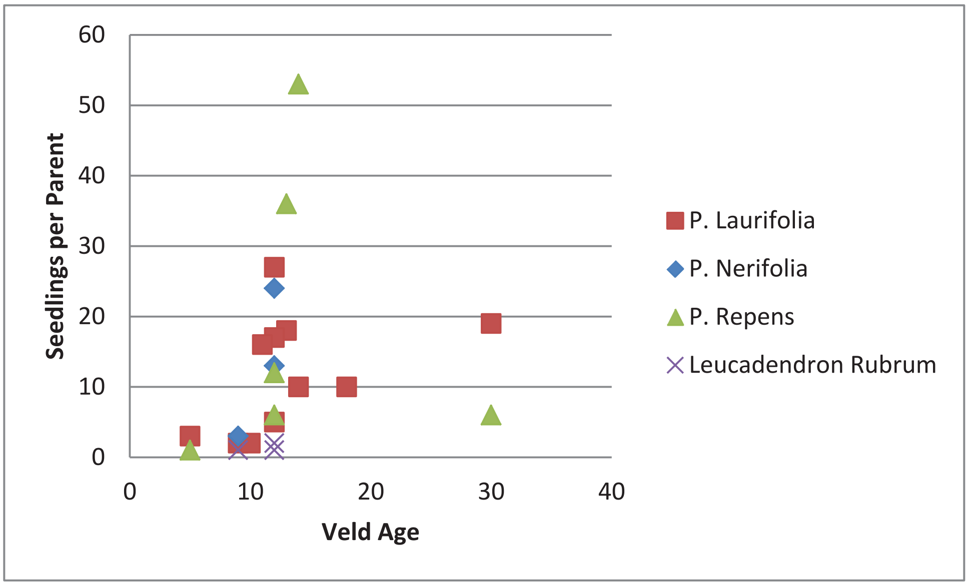

Figure4-25: Effect of veld age on regeneration of Protea and Leucadendron Species in the Limietberg Conservation Area

The observed parent:seedling ratios show what would be expected in terms of pre-fire veld age, based on comparisons with Bond et al. (1984) and Kraaij et al. (2013). The highest recruitment (i.e. most seedlings per parent) occurs at a veld age of approximately 12 years or more (Le Maitre et al. 2002; Forsyth et al. 2010). Once again it is interesting to note that *P. repens* and *P. laurifolia* have shown good recruitment success, especially within the 10-15 year veld age. Of concern is the recruitment of *L.rubrum*. It would appear that the current fire regime operating within the Limietberg Conservation Area favours the recruitment of *Proteaceae* rather than *Leucadendron*. Recruitment was observed to be poor in fires where the veld age was of approximately 20 years or greater and also at the maximum veld age sampled of 30 years, which is consistent with what has been observed in similar research that has been carried out using the post-fire regeneration methodology (Bond et al. 1984; Le Maitre et al. 2002; Forsyth et al. 2010). It would appear however, based on the fires sampled, that in most cases the fire return interval occurs when veld is at the prime burning age, and has not had an adverse effect on the ecological recovery of the area.

Figures 4-26 and 4-27 show the effect of fire season on regeneration of *Proteaceae* and *Leucadendron* species on north and south facing slopes respectively in the Limietberg Conservation Area. There was considerable variation in recruitment success for different species for any given site. When sampling, a number of sites were selected with both north and south facing slopes, with the understanding that recruitment may differ depending on the aspect of the slope. Indeed, given that slope has been such a significant contributing factor in the analysis preceding the ecological recovery analysis, it certainly came as no surprise that aspect would have an impact on the post-fire recruitment of seedlings and regeneration of fuel/biomass.

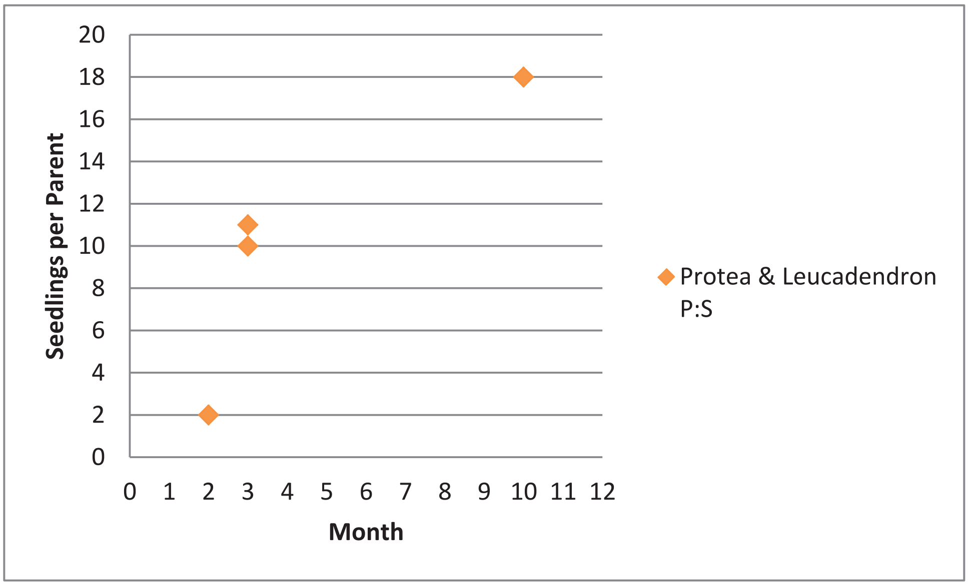

Figure4-26: Effect of fire season on regeneration of Protea and Leucadendron Species on north facing slopes in the Limietberg Conservation Area

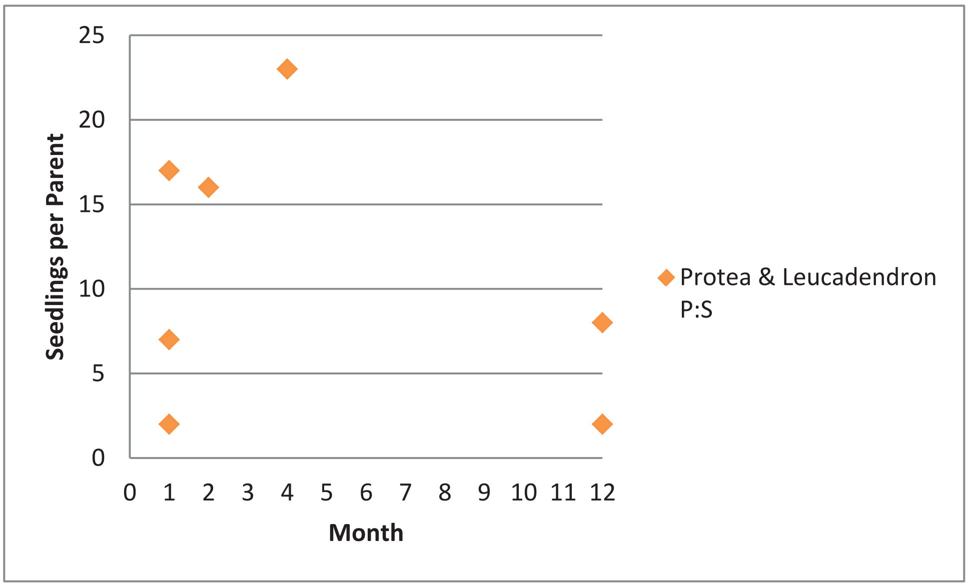

Figure4-27: Effect of fire season on regeneration of Protea and Leucadendron Species on south facing slopes in the Limietberg Conservation Area

The Limietberg Conservation Area, as a mountainous catchment area, is characterised by steep slopes and a large degree of topographic complexity. Recruitment was observed to be higher on south facing slopes, especially during March and April which would fall within the rainy season. The south facing slopes would be considered to be the cooler slopes that tend to stay wetter for longer, as they would be exposed to a larger amount of rainfall, it would follow therefore that recruitment would be higher and occur at a much faster rate on the south facing slopes as opposed to the north facing slopes (Bond et al. 1984; Le Maitre et al. 2002; Forsyth et al. 2010; Kraaij et al. 2013). In addition, southern slopes experience less water stress during the summer months (Van der Merwe & Van Rooyen 2011).

Figures 4-28 and 4-29 show the effect of veld age on regeneration of *Proteaceae* and *Leucadendron* Species on north and south facing slopes respectively in the Limietberg Conservation Area. As with the results for the effect of the fire season, greater recruitment was observed on the south facing slopes as opposed to the north facing slopes. As a result of the south facing slopes being considered to be the wetter slopes, and exposed to less water stress and to a larger amount of rainfall, this is very much the conditions that exist within the context of the Limietberg Conservation Area, and it would suggest that recruitment would be higher and occur at a much faster rate on the south facing slopes as opposed to the north facing slopes (Bond et al. 1984; Le Maitre et al. 2002; Forsyth et al. 2010; Kraaij et al. 2013). It is not surprising then to observe that the highest recruitment seems to occur at much younger veld ages on the south facing slopes.

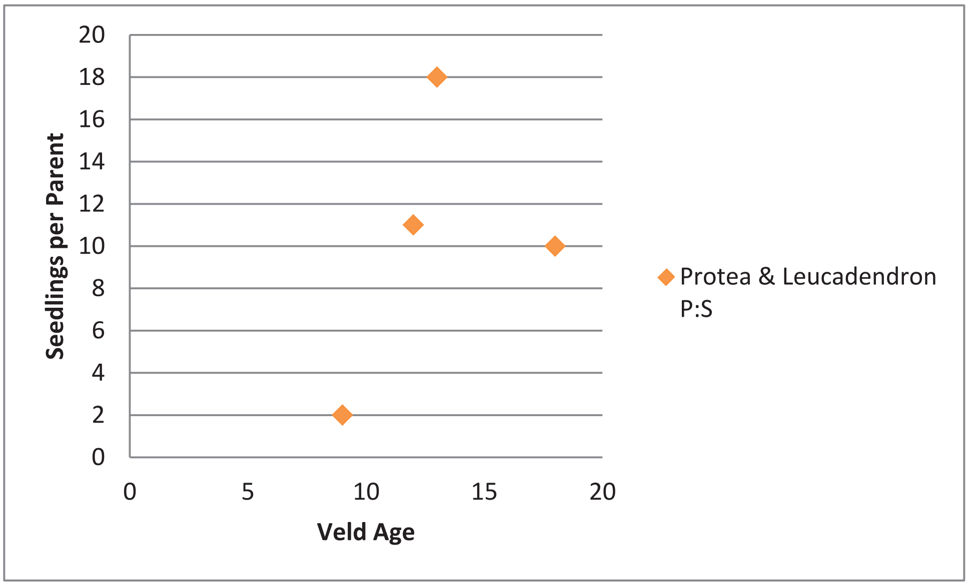

Figure4-28: Effect of veld age on regeneration of Protea and Leucadendron Species on north facing slopes in the Limietberg Conservation Area

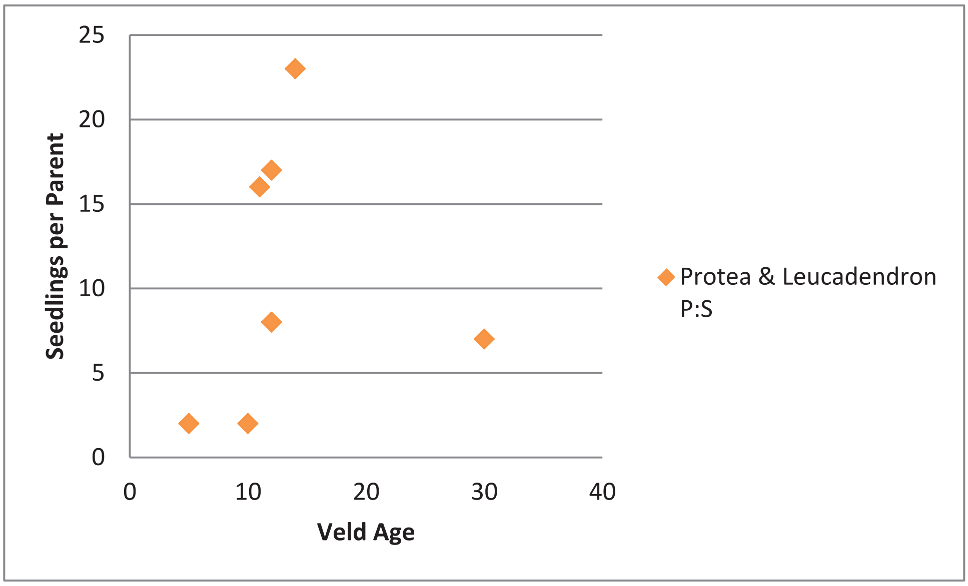

Figure4-29: Effect of veld age on regeneration of Protea and Leucadendron Species on south facing slopes in the Limietberg Conservation Area

In general, the overall assessment of fire frequency and ecological recovery of *Proteaceae* and *Leucadendron* species in the Limietberg Conservation Area shows some very pleasing results. For the majority of the fires sampled, the fire regime appears to occur with a frequency that is conducive to adequate levels of ecological recovery, as measured by some of the slower-maturing non-sprouting plant species, with the fire return interval occurring in most cases at a time when vegetation is at the prime burning age of approximately 15 years. *Proteaceae* species, especially *P. repens* and *P. laurifolia* were observed to have had pleasing recruitment success and have shown good post-fire ecological recovery. There is however concern about the recruitment of *Leucadendron* species, which have not fared as well by comparison. It could be that while the current fire regime which prevails in the Limietberg Conservation Area favours the recruitment of *Proteaceae*, it does not favour *Leucadrendron*. It has also been observed that recruitment is higher on south facing slopes, which are exposed to a greater degree of rainfall. The findings of the post-fire regeneration (*Proteaceae* parent:seedling) monitoring techniques are consistent with those observed in similar research and literature where the techniques have been used (Bond et al. 1984; Le Maitre et al. 2002; Forsyth et al. 2010; Kraaij et al. 2013). The recruitment of *P. repens* and *P. laurifolia* observed in sampling was found to be similar to that observed by Bond et al. (1984), particularly *P. repens* which also exhibited the same general pattern of high seedling to parent quotients in post-fire recovery. A significant difference in the findings however was the recruitment success of *L. rubrum*, which was observed by Bond et al. (1984) to have responded with high regeneration rates after fires. This would perhaps suggest that the fire regime has changed in a way that is beneficial to *Proteaceae*, but not to *Leucadendron* species, possibly allowing the *Proteaceae* to out-compete the *Leucadendron* species. The recruitment of *P. nerifolia* was found to be greater than that observed by Kraaij *et al.* (2013), especially for veld age of greater than 10 years. Comparison with the prevailing literature shows that recruitment success within the context of the Limietberg Conservation Area is occurring at adequate levels and suggests that the fire regime is conducive to favourable ecological recovery, and allows for the successful post-fire recovery of fynbos.

4.4 Discussion

The Western Cape Province in South Africa is home to one of the most diverse plant communities in the world (Myers et al. 2007; De Klerk et al. 2008), and has one of the highest concentrations of plant species in any temperate ecosystem in the world. The dominant vegetation is both fire-prone and fire-dependant (Le Maitre and Midgley 1992; Van Wilgen & Scott 2001; Brown & Botha 2004).

The Western Cape in particular is emerging as a province that is increasingly prone to disaster events, and it faces a wide variety of threats, particularly in the form of environmental risks (Holloway & Roomaney 2008; Forsyth et al. 2010). The Western Cape is characterised by a mosaic of urban and natural areas with substantial urban infringement, and is often badly invaded by alien plant species. The consequences of large wildfire disaster events are often devastating and far reaching (Le Maitre and Midgley 1992; Van Wilgen & Scott 2001; Brown & Botha 2004).

Wildland fire occurrence and behaviour are complex phenomena driven by fuel (vegetation), topography, slope and weather. Wildland fire challenges management wherever it occurs (Keeley 2003; Gould 2005; Gould 2006; Myers 2007; Fujioka et al. 2009). The dimensions of the fire problem largely reflect the characteristics of the fire environment: vegetation (fuel), topography/slope and weather/climate for any given place and time period (Keeley 2003; Gould 2005; Gould 2006; Myers 2007; Fujioka et al. 2009).

An understanding of the factors that govern the incidence and spread of large fires is therefore needed to support effective planning of fire mitigation and suppression, along with planning for ecological and urban interface management (Brown et al. 1991; Borchers 2005; Gould 2006; Forsyth & Van Wilgen 2007; Bradstock et al. 2009). Such an understanding is required not only to predict their incidence, but also to evaluate how this may shift under global change. The incidence and size of fires is influenced by a range of factors, such as ignition sources, fuels, terrain and weather (Brown et al. 1991; Borchers 2005; Gould 2006; Forsyth & Van Wilgen 2007; Bradstock et al. 2009).

4.4.1 Application of the Conceptual Framework

Using a combination of weather/climate and physical environmental data obtained from SAWS, Cape Nature and Stellenbosch University together with field data sampled and collected as part of the research, the driving factors that influence fire danger, fire behaviour, fire frequency and ecological recovery were assessed using a variety of statistical techniques. What was clear from the outset of the research was that as a natural hazard phenomenon, wild fires are extremely complex and function in a way that is fundamentally different to other natural hazards (Gould 2005; Bradstock et al. 2009; Forsyth et al. 2010). The focus of the research first and foremost was to gain an understanding of the complexity of wild fires and to create a framework which would serve the purpose of guiding the research and its focus. This was a critical step in the undertaking of the research, and one which guided the direction of the research and its eventual outcomes in a significant way. The creation of the adapted framework using the work of Pelling (2003) and Gould (2005) offered an insightful method of linking the prevailing theoretical approaches and hypotheses relating to our understanding of the concept of wild fire risk drivers in a way that allowed for a practical application to the research (Appendix A). It was through this approach that the methodology was influenced during the research and it offered a structure which allowed a much more cohesive and analytical approach to the investigation of wild fire risk within the context of the Limietberg Conservation Area. The natural hazard component of the adapted conceptual framework formed the basis of the bulk of the analysis and the main focus of the research.

The theoretical approach used in this research was in line with what would be required from a variety of related research fields to investigate a broad range of factors influencing fire risk, and enabled the incorporation of several different types of literature to be accessed as part of the research. This research primarily focused on two components of the adapted framework: the natural hazard and ecological vulnerability.

The approach to understanding of the components of the natural hazard, in this instance fire, primarily made use of the concepts of fire danger and fire behaviour as presented by Gould (2005). This approach was found to be well established and accepted in the literature. Bradstock et al (2009) and Fujioka et al (2009) both make use of the concepts as part of their research and have both presented work on understanding the drivers of fire behaviour and fire danger as major contributing elements to our understanding of fire as a natural hazard. The use of the concepts of fire danger and fire behaviour in research was found to be a well-established practice, and much of the literature that focused on understanding the complexity of fire risk made use of these concepts in guiding research (Myers et al. 2007; Forsyth et al. 2010).

If one thing is abundantly clear from the literature, it is that there is consensus about the nature of fire as a natural hazard being complex with influences from many different contributing factors. It is the relative contribution of these factors which is the source of some debate, and there does generally seem to be a divide between those that favour weather/climate as the chief contributing factor and those that advocate physical environmental characteristics. Much of the support in favour of the contribution of weather and climate to fire danger and fire behaviour comes from the proponents of the fire danger index (FDI) rating system (Gould 2005; Sharples et al. 2008; Bradstock et al. 2009). Bradstock et al. (2009) advocate that the effects of wind, air temperature and humidity at the time of fire are ‘ambient’ drivers of fire size. This is a view shared by Bessie & Johnson (1995) who suggest that fire behaviour is determined primarily by weather variation.

The roles of relative humidity in particular has received a great deal of research interest, both Holsten et al. (2013) and Weir (2007) are strong proponents of the contribution of relative humidity to fire danger and fire behaviour and its use as a valuable tool in prediction models and fire indices.

While considered a physical environmental component to fire hazard risk, fuel/biomass has a strong link with weather and climate, and it is a well-established connection within fire literature (Van Wilgen 1981; Bessie & Johnson 1995; Wilson et al. 2010). Fernandes (2001) advocates that the amount and quality of fuel is central to understanding fire behaviour, and this is linked to the contribution of relative humidity and ambient temperature. There seems to be much consensus on the contribution of fuel to the spread, severity, difficulty of suppression and intensity of fires and its link with causal meteorological drivers such as rainfall, relative humidity and temperature (Smith et al. 2004; Gould 2006; Myers et al. 2007).

The remaining physical environmental factors of slope and topography are also the subject of considerable research, though perhaps not as well established as the effects of weather, climate and fuel. Slope can have a profound effect on fire conditions, particular with respect to the convection effect of air movement on slopes that create conditions of pre-heating in fuels (Hely & Alleaume 2006). This is a view shared by Alexander (1982) who suggests that fire burning uphill propagates at a faster rate than fire that is spreading downhill or on flat terrain. When fire burns uphill, the radiation energy released by the flames augments the preheating of the adjacent fuel which is in close proximity to the flame, caused as a result of the steep slope angle. This increases the rate at which the fire spreads (Alexander 1982). Holden & Jolly (2011) also suggest the possible link between slope and the variation in weather conditions. Fire danger rating systems commonly ignore the contribution of fine scale, topographically-induced weather variations, which suggests that the contribution of slope to fire danger and behaviour needs to be examined in more detail (Holden & Jolly 2011).

While much research and literature is available on the contributing factors of fire behaviour and fire danger, and the field is well-established, there appears to be very little literature available that is all encompassing in its approach in investigating and analysing the interactions and contributions of the driving factors of natural fire hazards. Given the accepted understanding that wild fires are a complicated phenomenon, with complex interactions occurring between contributing factors, both climatic and physical, it seems surprising that there is not a larger body of literature focusing on the combined interactions of all factors relating to fire danger and fire behaviour. Bradstock et al. (2010) and Cruz & Gould (2009) are perhaps some of the few examples where the contribution of all factors relating to fire are analysed together. Bradstock et al. (2010) advocate that such an approach is crucial in informing the debate about the relative importance of land management (i.e. manipulation of fuels) versus other factors (weather and terrain) on fire regimes. Forsyth et al. (2010) and Gould (2005) concur with this assessment, and suggest that a greater understanding of the complex interactions between factors that influence the inception, severity, behaviour and difficulty of suppression of fires need to be better researched and reported on. This is a gap which this project has attempted to address, by investigating both climatic and physical factors influencing fire danger and fire behaviour, through the lens of an adapted conceptual framework (Pelling 2003; Gould 2005).

4.4.2 Application of Regression and Ordination

In order to fully investigate the complex interactions and relative contributions of each of the driving factors of fire danger and fire behaviour, an approach was required that would allow for the analysis of multiple variables of differing origin and scales. The use of statistical methods is well-established in the biological and geographical fields, and provided the best means of analysis (Clarke & Warwick 1994; McDonald 2009). Multiple Regression and Ordination techniques in the form of principal component analysis (PCA) and non-metric multi-dimensional scaling (MDS) were selected as suitable methods for the analysis of the factors influencing fire danger and fire behaviour.

Multiple regression was used to assess the individual contribution of each of the variables to fire size, and was primarily used as a source of comparison for the results obtained with the PCA and MDS ordination techniques. The methodology proved to be largely ineffective in the analysis of the climatic and environmental factors, most likely as a result of the difference in scale that occurs between each of the variables, which makes comparison very difficult due to differences in variation (McDonald 2009). It was also hypothesised that results of individual contributions of factors, particularly weather variables, would not be significant as it is the contribution of several factors, through complex interactions that are thought to influence fire danger and fire behaviour. There was, however, one statistically significant result which was obtained when comparing the fire danger index (FDI), which was calculated using the extreme weather variables, to size of burn scar. The results of Tables 4-7 and 4-8 indicate the FDI calculated using the extreme weather variables (maximum temperature, maximum wind speed, minimum relative humidity). The beta coefficient of b = 312.62 indicated a strong positive relationship between extreme FDI and size of burn scar, with a p-value of 0.02 showing that the relationship is statistically significant. This is consistent with what would be expected, and would suggest that when weather variables combine in extreme circumstances, that contribute in a significant way to the size of the resulting fire size. Indeed, the result is in line with work presented by Bradstock et al. (2009) who suggest that the effects of wind, air temperature and humidity at the time of fire are ‘ambient’ drivers of fire size. It is noteworthy that this relationship was only observed with the extreme weather variables, and would suggested that while the effect of weather is significant, it is perhaps limited to extreme situations where conditions are particularly severe. This is consistent with the work of Gould (2005) who suggests that weather can have an enormous impact as a result of the fact that it is able to change rapidly and affect large areas.

The use of PCA and MDS ordination techniques proved to be an extremely effective instrument for the analysis of the complex interactions between factors influencing fire danger and fire behaviour. Ordination techniques, while common in biological applications, is not a method that is typically used in the field of geography and environmental studies (Clarke & Warwick 1994). It did prove, however, to be a very valuable method, and allowed for an extremely in-depth analysis of fire danger and fire behaviour. The PCA in particular was very useful in that it generates principal components influenced by the contribution of each of the variables sampled and allows for an analysis based on combinations and patterns common to several samples. This, coupled with the size distribution criteria applied to the fires sampled (Table 3-1) allowed for a very detailed analysis of the interactions of the driving factors of fire danger and fire behaviour for a variety of fire sizes. The use of the fire size classification proved to be very effective, and was a method found to be fairly common and well-established in its usage in the relevant literature (Parisien et al. 2004; Forsyth & Van Wilgen 2007; Cui & Perera 2008; Archibald et al. 2009). MDS was used in effect as a control for the PCA methodology to corroborate the results and to act as confirmation that the plot in fact provided a good indication of the relationships observed. Ordination plots using PCA and MDS techniques were created using weather variables (mean and extreme), physical variables and all factors (using both mean and extreme weather data).

A consistent observation regarding all of the plots was that there was definite grouping observed, where large and medium fires tended to be grouped together separately from smaller fires. The largest fires of categories I and J tended to cluster together in plots. The ability to observe this spatial grouping of fires from different size classes was useful during analysis, and can certainly be regarded as a strength of the PCA and MDS methods.

What makes the PCA ordination in particular a powerful analytical tool is the fact that the axes that are generated are interpretable and relatively simple to understand. Analysis of the weather data across the various fire sizes produced some interesting results. For analysis of the large fires, the results of the analysis of the PCA and MDS plots indicated that large fires are most strongly influenced by conditions where there are high temperatures, strong winds and low relative humidity. This was found to be consistent in both the plot using the mean variables and the plot using the extreme variables. It was also consistent with what was observed in the results of the multiple regression of the FDI calculated using the extreme weather variables. Small and medium fires were found to be influenced by similar factors with regards to weather, which would generally be the combination of high temperatures and minimal winds. It is interesting to note that temperature was found to be a significant contributing factor across all of the principal components of all plots, both with the mean and extreme variables, though not always the main contributing factor. It is also interesting to note that the main distinguishing factor differentiating the large fires from the small and medium fires was the contribution of low relative humidity. These findings are consistent with what was observed in the literature relating to the contribution of meteorological factors to fire danger and fire behaviour (Bessie & Johnson 1995; Weir 2007; Bradstock et al. 2009; Holsten et al. 2013). Holsten et al. (2013) and Weir (2007) in particular advocate that relative humidity be considered as one of the key driving factors driving fire danger and fire behaviour.

The PCA and MDS ordination analysis of the physical environmental factors (fuel, slope and topography) also yielded some extremely interesting results. The results indicated that there was a strong influence as a result of slope and topography. Large and medium fires were found to occur in conditions where slope was low and topographical complexity was high. These results were extremely interesting and unexpected as it is in complete contradiction to the prevailing theories present in the literature (Alexander 1982; Hely & Alleaume 2006; Ryan & Williams 2010). Alexander (1982) and Hely & Alleume (2006) are both strong proponents of the convection effect created by air currents on steep slopes creating pre-heating of fuel to exacerbate fire danger and behaviour. The contribution of topographical complexity, however, was consistent with what was observed in the literature. The research of Holden and Jolly (2011) and Bradstock et al. (2010) who suggest that there is a strong relationship present between large fires and a high degree of topographical complexity. It could perhaps be the case that the influence of topography is more profound than that of slope alone and that in the absence of topographical complexity, slope may be more influential on fire danger and fire behaviour.

The final PCA and MDS ordination analysis was performed using all the factors that are thought to drive fire danger and fire behaviour, both meteorological and physical. This included all of the variables used in the previous analyses including temperature, wind speed, relative humidity, fuel, slope and topography. The PCA and MDS ordination techniques were particularly useful in this application, and allowing for the in-depth analysis of all factors involved with fire danger and fire behaviour was informative and enlightening. The analysis of different size categories was somewhat difficult, as the plots now involved five principal components as opposed to three in the previous ordination analyses. However, it was possible to determine common trends that influence large and medium fires. From the results of the PCA, it was clear that the main driving factors of fires are high maximum temperatures, low relative humidity, strong wind speeds, steep slopes and a high degree of topographical complexity. It is interesting to note that the impact of weather variables had far more influence than the physical environment variables.

The findings are indeed consistent with what was observed in the literature. The strong influence of weather variables is in agreement with the work of Van Wilgen (1981), Bradstock et al. (2009) and Wilson et al. (2010) who advocate that high temperatures and high wind speeds have a profound effect on fire danger and fire behaviour. The strong influence of low relative humidity is also consistent with the prevailing theories of Weir (2007) and Holsten et al. (2013) who suggest that it is a strong contributing factor. The overall influence of weather supports the rather large body of literature dedicated to the impact of meteorological factors as a critical influence on fire danger and fire behaviour, and adds support to the proponents of the use of weather indices and prediction models such as the fire danger index (FDI) (Gould 2005; Sharples et al. 2008). The findings also support the growing body of literature with regards to the contribution of physical environmental factors, such as slope and topography. While not as influential as the weather variables in their contribution to fire danger and fire behaviour, slope and topography both contributed significantly. Fire danger and fire behaviour correlated with steep slopes and a high degree of topographical complexity, which is consistent with the work of

Alexander (1982), Hely & Alleaume (2006) and Holden & Jolly (2011). The overall findings and combination of factors with their relevant contributions were also found to be consistent with the body of literature where all factors have been assessed together (Cruz & Gould 2009; Forsyth et al. 2010). Bradstock et al. (2010) found that weather condition was the dominant influence on fire severity, and that fire were found to be most strongly affected by weather variables, with secondary influences of topography and fuel also significant. This is fairly similar and consistent with what was observed in this study.

One of the noticeable irregularities or surprising outcomes of the research was the limited influence of fuel. Given the large body of research dedicated to the impact of fuel to fire danger and behaviour, fuel would have been expected to be one of the dominant contributing factors in the PCA and MDS ordination analysis. While this may seem surprising at first, on closer inspection of the literature, it is understandable why this may in fact be the case. The vast majority of the literature that deals with the contribution of fuel to fire behaviour and fire danger also deals with the significant contribution of weather, most notably temperature and relative humidity, and its roles in influencing the condition of fuel prior to burning. Fernandes (2001) speaks of the roles of temperature in conditioning fuel prior to fires. Bessie & Johnson (1995) suggest that during extreme weather conditions, the relative importance of fuels diminishes since all stands achieve the threshold required to permit crown fire development, and that fire behaviour is determined primarily by weather variation rather than fuel variation associated with stand age (Bessie & Johnston 1995). It is clear then that while there is no doubt that fuel is a contributing factor, it is the impact of weather variables primarily that is of primary importance, which is consistent with the findings of this research.

4.4.3 Application of Post-Fire Regeneration (Proteaceae parent:seedling) Monitoring

The fire frequency and ecological recovery was assessed using post-fire regeneration (Proteaceae parent:seedling) monitoring techniques as used by Bond et al. (1984) and adapted for use by Cape Nature by Vlok & Yeaton (2000) and De Klerk et al. (2007). The use of the methodology is well-established in the literature, and its use within the context of this research was consistent with current usage of the methodology in the prevailing literature (Mustart et al. 2011; Rutherford et al. 2011; Kraaij et al. 2013). The overall assessment of fire frequency and ecological recovery of Proteaceae and Leucadendron species in the context of the Limietberg

Conservation Area shows some very promising results. For the majority of the fires sampled, the fire regime appears to occur in a time frame that is conducive to adequate levels of ecological recovery, as confirmed by the measurement of the slower-maturing non-sprouting plant species that were sampled as part of the methodology, with the fire return interval occurring in most cases at a time when vegetation is at the prime burning age of approximately 15 years (Forsyth et al. 2010).

Proteaceae species, most notably *P. repens* and *P. laurifolia* were observed to have had good recruitment success and have shown good post-fire ecological recovery. The findings of the post-fire regeneration (Proteaceae parent:seedling) monitoring techniques were found for the most part to be consistent with those observed in similar research and literature where the techniques have been used (Bond et al. 1984; Kraaij et al. 2013). The recruitment of *P. repens* and *P. laurifolia* observed in sampling were consistent with those observed by Bond et al. (1984), particularly *P. repens* which was also observed to have the same general pattern of high seedling to parent quotients in post-fire recovery. The recruitment of *P. nerifolia* was found to be greater than that observed by Kraaij et al. (2013), especially for veld age of greater than 10 years.

There is however concern about the recruitment of *Leucadendron* species, which have not fared as well by comparison. It could be that while the current fire regime which prevails in the Limietberg Conservation Area favours the recruitment of *Proteaceae*, it does not favour *Leucadrendron*. A significant difference in the findings however was the recruitment success of *L. rubrum*, which was observed by Bond et al. (1984) to have responded with high regeneration rates after fires.

It has also been observed that recruitment is higher on south facing slopes, which are exposed to a greater degree of rainfall (Van der Merwe & Van Rooyen 2011). This would perhaps suggest that the fire regime has changed in a way that is beneficial to *Proteaceae*, but not to *Leucadendron* species, possibly allowing the *Proteaceae* to out-compete the *Leucadendron* species. Comparison with the prevailing literature shows that recruitment success within the context of the Limietberg Conservation Area is occurring at adequate levels and suggests that the fire regime is conducive to favourable ecological recovery.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

If there is one thing that is abundantly clear from this research, it is that there needs to be greater recognition that fire as a natural hazard is a complex phenomenon, and there is still much work to be done before it is to be more fully understood (Gould 2005; Forsyth et al. 2010). There is a need to acknowledge that wildfires are a complex phenomenon and that multiple data sources and skills are required to fully understand and manage wildfire events (Moir 2009).

One of the goals of this study was to investigate ways in which all the drivers that affect fire danger and fire behaviour, both meteorological and physical, could be analysed so that the contribution of each variable could be assessed and the combinations and interactions of factors for fires of different sizes and levels of severity could be assessed. The use of the adapted conceptual framework of Pelling (2003) and Gould (2005) was seen as a critical step in this process, as it helped to guide the research in a meaningful way, and the use of a framework in this way can certainly be recommended, especially when confronting a topic as complex as wild fires. The use of fire size categories following the work of Parisien et al. (2004), Forsyth & Van Wilgen (2007), Cui & Perera (2008) and Archibald et al. (2009) was also seen as a critical turning point in the research process, and should be seen as an extremely useful analytical tool in research involving factors driving fire danger and fire behaviour.

The study made use of several statistical techniques that allowed for the analysis of multiple variables across samples, a step that was critical to the outcomes of the research. There were three methodologies used as part of this research: Multiple Regression, Principal Component Analysis (PCA) and Non-metric Multi-dimensional Scaling (MDS).

The use of multiple regression as an analytical tool for the analysis of the driving factors of fire danger and fire behaviour was found to be ineffective. There are several reasons as to why this may have been the case. The first arises from the underlying assumptions of the multiple regression method itself. Multiple regression assumes that there will be a linear relationship present between variables which may not necessarily be the case (McDonald 2009). Errors are also distributed in the same way, with all independent variables being distributed identically (McDonald 2009). The use of the least squares method to fit the distribution, as is the case with multiple regression, may not be what is considered to be the most optimal method (McDonald 2009). The second set of problems that may arise for the use of multiple regression stems from the data itself. Multi-collinearity may occur, where explanatory variables could be highly correlated, but not perfectly so. This may lead to very unstable and imprecise estimates

(McDonald 2009). There is also the potential effect of influential data points, where certain observations may have a disproportionate influence on the regression line. This could be the result of bad data or an error in the data collection process, or it may even be the case that the observation gives us information about what happens outside the "normal" range of a particular explanatory variable (McDonald 2009). Based on the experience of using the technique in this study, it cannot be recommended for use in the analysis of fire.

The use of the PCA and MDS ordination techniques, however, proved to be extremely effective in the analysis of fire danger and fire behaviour, and investigating the relative contribution of each of the driving factors across a range of different fire sizes. The use of these techniques in the analysis of fire as a natural hazard can be strongly recommended. Small and medium fires were found to be influenced by similar factors with regards to weather, which would generally be the combination of high temperatures together with minimal winds. For analysis of the large fires, the results of the analysis of the PCA and MDS plots indicated that large fires are most strongly influenced by conditions where there are high temperatures, strong winds and low relative humidity. Large and medium fires were also found to occur in conditions where slope was low and topographical complexity was high. The results of the ordination analysis indicated that the main driving factors of fires are high maximum temperatures, low relative humidity, strong wind speeds, steep slopes and a high degree of topographical complexity. It is interesting to note that the impact of weather variables had far more influence than the physical environment variables, and while there is no doubt that fuel is a contributing factor, it is the impact of weather variables that is of primary importance.

The use of post-fire regeneration (Proteaceae parent:seedling) monitoring techniques was seen as extremely useful and produced results that were easily comparable to the prevailing literature to make inferences on the ecological vulnerability of the study area (Bond et al. 1984; De Klerk et al. 2007; Kraaij et al. 2013). The use of post-fire regeneration (Proteaceae parent:seedling) monitoring techniques was seen as effective, and can be recommended for practical applications in future fire research. *Proteaceae* species, most notably *P. repens* and *P. laurifolia* were observed to have had good recruitment success and have shown good post-fire ecological recovery, and were observed to have a general pattern of high seedling to parent quotients in post-fire recovery. The recruitment of *P. nerifolia* was found to be greater than that observed by Kraaij et al. (2013), especially for veld age of greater than 10 years. It has also been observed that recruitment is higher on south facing slopes, which are exposed to a greater degree of rainfall (Van der Merwe & Van Rooyen 2011). This would perhaps suggest that the fire regime has changed in a way that is beneficial to *Proteaceae*, but not to *Leucadendron* species, possibly allowing the *Proteaceae* to out-compete the *Leucadendron* species. Comparison with the prevailing literature shows that recruitment success within the context of the Limietberg Conservation Area is occurring at adequate levels and suggests that the fire regime is conducive to favourable ecological recovery.

The findings of the thesis presented an insightful evaluation of fire as a complex natural hazard. Though the statistical techniques employed are not necessarily novel, they were applied in an innovative and unconventional way, and adapted to an application in wildfire analysis in the context of a complex geographical area. Ordination, a method usually used in biological taxonomic research, allowed for the comparison of multiple contributing variables (both meteorological and physical environmental) that fit well with the way in which the hazard is defined in the conceptual framework used in this research (Appendix A).

If one returns to the definition of risk, where risk= hazards x vulnerability, the research presents a valid method that addresses the concept of wildfire risk in an adequate manner. The PCA and MDS methods provided a method that allowed for a detailed analysis of the relative contribution of the driving factors that influence the wildfire hazard. As a natural hazard, fire is complex and the ordination methods employed were able to cope with this complexity well. This allowed for the identification of patterns between a range of drivers that contribute towards overall fire risk, that is interpretable and that provides a greater insight not only to the individual contribution of each of the driving factors, but also the relationships and interactions between them.

In terms of the way in which vulnerability is defined in the context of this research, post-fire regeneration (Proteaceae parent:seedling) monitoring techniques was seen as extremely useful as an assessment of ecological vulnerability. Vulnerability is seen as the combination of exposure and capacity (Cannon 2008). In terms of capacity in the case of this study, fynbos is a fire-adapted vegetation, and therefore has a high capacity to deal with the impact of wildfire as a natural hazard, indeed, it forms an essential component of the reproduction and ecology (Le Maitre & Midgley 1992, Forsyth et al. 2010). It is important to note, however that there is a threshold at which this capacity is exceeded, but in the case of this study, the regeneration of *Proteaceae* and *Leucadendron* species was found to be occurring at satisfactory levels (Bond et al. 1984; De Klerk et al. 2007; Kraaij et al. 2013). In terms of exposure, given that the study area is a conservation area, exposure to the risk of ignition is high, with continuous bands of fuel ready to burn. When one considers the overall risk profile of the area over the fire history, while the exposure is high, the vegetation is well adapted to fire, and in terms of vulnerability the ecological recovery is occurring at acceptable levels. In terms of the hazard component, conditions exist which are conducive to the occurrence of fire, with the contribution of relative humidity, high winds, topography and slope exacerbating fire danger and fire behaviour. The Limietberg Conservation Area therefore provides conditions that are favourable for fire as a natural hazard, but wildfires occur at a rate that is not detrimental to the ecological recovery of the area. While not included in this study, given the location and context of the study area, it is important that human vulnerability also be taken into consideration when applying the adapted conceptual framework used in this research in other studies, should it be applicable (Pelling 2003; Gould 2005).

In conclusion, it is clear that there is still much work to be done in understanding the complex interactions between factors that influence fire danger and fire behaviour. It is highly recommended that methods used in this study be considered by national and local authorities as a basis for the development of a national fire data base that can be used in the formulation of current and future fire management strategies.

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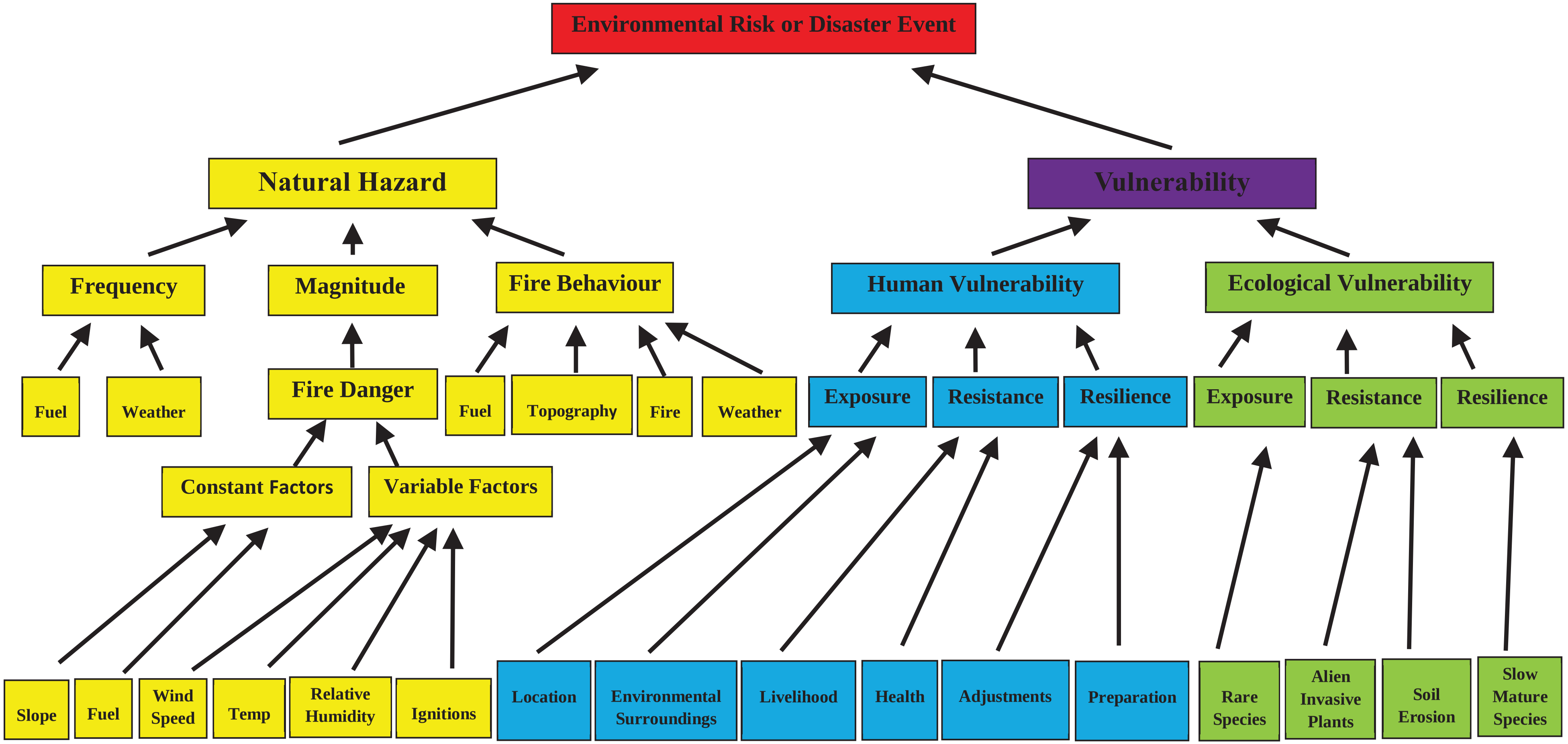
APPENDICES

Appendix A	Adapted Conceptual Framework combining work of Pelling (2003) and Gould 2005)
Appendix B	Fire Danger Index (FDI) Categories
Appendix C	Raw Data Used for Analyses

APPENDIX A

Adapted Conceptual Framework combining work of Pelling (2003) and Gould 2005)

Adapted Framework combining work of Pelling (2003) & Gould (2005)



APPENDIX B

McArthur Fire Danger Index (FDI) Categories

South African
Weather Service

FIRE DANGER INDEX CLASSIFICATION

STAGE	FIRE BEHAVIOR	FDI
BLUE	SAFE	00 - 20

FLAME LENGTH : 0 - 1 m

Low fire hazard. Controlled burn operations can normally be executed with a reasonable degree of safety.

STAGE	FIRE BEHAVIOR	FDI
GREEN	MODERATE	21 - 45

FLAME LENGTH : 1 - 1.2 m

Although controlled burning operations can be done without creating a fire hazard, care must be taken when burning on exposed, dry slopes. Keep a constant watch for unexpected wind speed and direction changes.

STAGE	FIRE BEHAVIOR	FDI
YELLOW	DANGEROUS	46 - 60

FLAME LENGTH : 1.2 - 1.8 m

Controlled burning not recommended when fire danger index exceeds 45.Aircraft should be called in at early stages of a fire.

STAGE	FIRE BEHAVIOR	FDI
ORANGE	VERY DANGEROUS	61 - 74

FLAME LENGTH : 1.8 - 2.4 m

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.

STAGE	FIRE BEHAVIOR	FDI
RED	EXTREMELY DANGEROUS	75-100

FLAME LENGTH : >2.4 m

All personnel and equipment should be removed from the field. Fire teams, labour and equipment are to be placed on full stand-bay. At first sign of smoke, every possible measure should be taken in order to bring the fire under control in the shortest possible time. All available aircraft are to be called for without delay.

Limitation

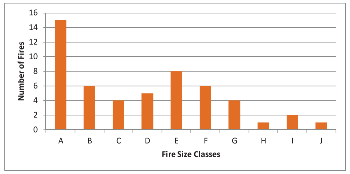
The User shall not at any time, disclose or divulge the Specified Data to any person whomsoever except on a need to know basis to those of its employees and officers who require knowledge thereof. The User will treat the Information as private and confidential to SAWS and will take all reasonable precautions to protect the Information from unauthorised use, reproduction or distribution. The South African Weather Service (SAWS) does not give any representation or warranty that the Specified Data contains no errors, is complete or up to date or will not infringe any third party intellectual property rights. The User assumes the sole risk of interpreting and applying the Specified Data and SAWS is not in any way liable for any loss, damage or injury suffered by the User or any other person, due to the use or possession of the Specified Data or the existence of errors in the Specified Data.

APPENDIX C

Raw Data used for Analysis

Year	Start Date	End Date	Size of Burn Scar	Label	Mean Temp	Max Temp	Mean Rel. Hum.	Min. Rel. Hum.	Mean Wind Speed	Max Wind Speed	Rainfall/Fuel	Slope	Topography	FDI Mean Values	FDI Mean with Wind Adjustment	FDI Extreme Values	FDI Extreme with Wind Adjustment
2009	28/06/2009	28/06/2009	0.0164	A1	15.0	15.0	88.0	88.0	2.6	2.6	707.6	5	0.00	13.8	13.8	13.8	13.8
2009	28/06/2009	28/06/2009	0.0351	A2	30.2	31.8	88.0	88.0	2.6	2.6	707.6	5	0.00	29.5	29.5	31.1	31.1
2005	05/12/2005	05/12/2005	0.0735	A3	29.0	34.0	51.0	51.0	0.0	0.0	382.8	6	0.24	41.9	41.9	47.1	47.1
2009	28/06/2009	28/06/2009	0.1341	A4	31.7	34.7	88.0	88.0	2.6	2.6	707.6	5	0.00	31.0	31.0	34.1	34.1
2010	31/01/2010	31/01/2010	0.2445	A5	33.4	42.9	65.0	65.0	5.3	7.1	657.0	4.5	0.16	41.3	46.3	51.1	56.1
2010	10/02/2010	10/02/2010	0.3095	A6	31.8	32.0	53.0	53.0	3.7	7.1	657.0	5.5	0.13	44.1	49.1	44.3	49.3
2010	10/02/2010	10/02/2010	0.3123	A7	32.3	36.0	53.0	53.0	2.7	7.1	657.0	5	0.00	44.6	44.6	48.4	53.4
2005	01/01/2005	01/01/2005	0.3383	A8	27.7	32.0	61.0	61.0	5.2	5.2	382.8	4	0.00	36.8	41.8	41.3	46.3
2010	21/03/2010	22/03/2010	1.6097	A10	27.8	28.4	62.0	59.0	2.5	6.1	657.0	4	0.00	36.6	36.6	38.4	43.4
2009	05/04/2009	05/04/2009	4.2501	A11	20.3	20.3	87.0	87.0	1.2	1.2	707.6	3	0.47	19.6	19.6	19.6	19.6
2002	14/01/2002	14/01/2002	4.3393	A12	26.0	26.0	61.0	75.0	0.0	0.0	1602.9	5	0.00	35.1	35.1	30.0	30.0
2007	23/12/2007	24/12/2007	9.4242	A13	30.5	38.1	68.5	62.0	9.0	11.4	579.8	6	0.10	37.0	47.0	47.3	57.3
2009	21/07/2009	21/07/2009	10.0534	A14	29.3	29.3	91.0	91.0	1.8	1.8	707.6	5.5	0.13	27.4	27.4	27.4	27.4
2009	13/03/2009	14/03/2009	18.7768	A15	15.0	15.0	75.0	72.0	2.0	2.6	707.6	5.5	0.13	18.6	18.6	19.7	19.7
2009	28/06/2009	28/06/2009	25.8843	B1	15.0	15.0	88.0	88.0	2.6	2.6	707.6	4.5	0.16	13.8	13.8	13.8	13.8
2010	05/04/2010	06/04/2010	32.2868	B2	31.3	33.2	78.5	65.0	4.3	3.7	657.0	5	0.28	34.1	39.1	41.1	46.1
2005	03/03/2005	03/03/2005	37.9098	B3	31.7	29.7	74.0	74.0	2.2	2.2	382.8	5	0.20	36.2	36.2	34.1	34.1
2001	20/12/2001	26/12/2001	46.4168	B4	27.7	27.8	58.0	54.0	4.7	9.7	1065.4	5	0.11	37.9	42.9	39.6	49.6
2010	08/01/2010	10/01/2010	83.5504	B5	29.7	29.7	58.0	68.0	7.1	4.1	657.0	5.5	0.18	40.1	50.1	36.4	41.4
2005	19/01/2005	21/01/2005	97.3994	B6	36.0	36.0	80.0	77.0	2.3	2.5	382.8	6	0.49	38.4	38.4	39.5	39.5
2007	24/12/2007	24/12/2007	132.2847	C1	23.0	24.0	75.0	75.0	6.5	6.5	579.8	4	0.22	26.9	31.9	27.9	32.9
2006	17/01/2006	17/01/2006	160.1897	C2	32.5	34.8	56.0	56.0	1.1	1.1	629.3	4	0.40	43.7	43.7	46.1	46.1
2008	05/02/2008	06/02/2008	206.2901	C3	36.7	42.0	56.0	46.0	3.1	3.3	696.0	5	0.22	48.0	53.0	57.2	62.2
2003	22/10/2003	23/10/2004	221.6230	C4	29.8	34.5	75.0	60.0	1.9	2.1	1706.5	4.5	0.32	33.9	33.9	44.3	44.3
2008	06/02/2008	07/02/2008	274.6129	D1	26.7	29.0	55.5	46.0	4.2	5.5	696.0	6	0.24	37.9	42.9	43.8	48.8
2000	23/12/2000	26/12/2000	285.5528	D2	28.5	32.6	83.5	65.0	3.2	4.9	479.4	5.5	0.15	29.4	34.4	40.5	45.5
2002	06/06/2002	06/06/2002	299.6186	D3	15.2	15.2	75.0	58.0	7.5	7.5	1602.9	2	0.51	18.8	28.8	25.1	30.1
2006	27/12/2006	29/12/2006	365.9623	D4	35.0	40.0	59.0	50.0	5.0	11.1	629.3	4.5	0.13	45.2	50.2	53.7	63.7
2001	31/01/2001	01/02/2001	459.3122	D5	29.5	34.6	61.0	56.0	1.0	2.0	1065.4	4	0.25	38.7	38.7	45.9	45.9
2003	31/01/2003	03/02/2003	550.3147	E1	25.4	27.3	73.0	59.0	0.9	2.3	1706.5	4	0.27	30.1	30.1	37.2	37.2
1999	22/01/1999	27/01/1999	638.7236	E2	35.8	38.7	75.0	70.0	2.8	4.3	890.4	4	0.32	40.1	40.1	44.9	49.9
2010	18/01/2010	20/01/2010	664.7117	E3	29.7	29.7	66.0	58.0	7.1	7.6	657.0	4.5	0.45	37.1	47.1	40.1	45.1
2008	08/02/2008	10/02/2008	709.2471	E4	38.0	39.5	74.0	46.0	5.8	10.8	696.0	4	0.19	42.7	47.7	54.6	64.6
2008	17/04/2008	19/04/2008	720.6334	E5	39.2	40.2	86.0	72.0	0.4	1.2	696.0	5	0.21	39.5	39.5	45.7	45.7
2004	01/04/2004	03/04/2004	757.9078	E6	30.8	36.3	61.0	56.0	1.4	4.1	512.1	4	0.23	40.0	40.0	47.6	52.6
2006	13/12/2006	15/12/2006	761.7999	E7	31.7	31.7	65.0	63.0	3.3	5.3	629.3	5	0.27	39.5	44.5	40.3	45.3
2008	21/01/2008	25/01/2008	954.9854	E8	38.5	40.2	67.0	79.0	2.9	4.0	696.0	4	0.27	45.8	50.8	43.1	48.1
1999	08/01/1999	13/01/1999	1436.8159	F1	31.6	36.8	73.0	62.0	1.7	4.2	890.4	5	0.24	36.5	36.5	45.9	50.9
2007	24/04/2007	26/04/2007	1683.4697	F2	31.4	31.4	83.0	74.0	1.9	2.4	579.8	5	0.16	32.6	32.6	35.9	35.9
2002	10/01/2002	10/01/2002	1793.4315	F3	29.0	29.0	73.0	58.0	6.4	6.4	1602.9	5	0.15	33.8	38.8	39.3	44.3
2004	19/12/2004	22/12/2004	2007.4502	F4	34.0	38.0	63.0	71.0	4.6	5.6	512.1	5	0.22	42.7	47.7	43.8	48.8
1999	13/06/1999	14/06/1999	2177.4036	F5	35.7	40.0	47.5	19.0	8.7	9.1	890.4	5	0.20	50.1	60.1	65.1	75.1
1999	28/03/1999	02/04/1999	2405.4991	F6	34.6	36.8	70.0	57.0	0.7	1.7	890.4	5	0.18	40.7	40.7	47.8	47.8
2010	08/03/2010	10/03/2010	2577.0783	G1	27.3	27.3	72.0	72.0	2.1	11.8	657.0	4	0.33	32.4	32.4	32.4	42.4
1999	15/03/1999	21/03/1999	3201.5937	G2	37.5	40.2	68.0	64.0	2.2	4.4	890.4	4	0.42	44.4	44.4	48.7	53.7
1999	13/12/1999	20/12/1999	4004.3931	G3	20.6	24.2	73.0	48.0	0.9	3.4	890.4	5	0.31	25.1	25.1	38.1	43.1
2007	07/02/2007	09/02/2007	4162.5307	G4	29.7	31.4	76.0	68.0	5.7	11.1	579.8	5	0.23	33.4	38.4	38.1	48.1
1999	13/02/1999	17/02/1999	7713.3938	H1	30.1	36.8	80.00	67.00	3.4	4.9	890.4	4	0.38	32.3	37.3	44.1	49.1
2005	25/12/2005	06/01/2006	12362.7989	I1	30.0	30.0	79.00	76.00	4.7	5.9	382.8	4	0.34	32.6	37.6	33.7	38.7
2005	08/12/2005	10/12/2005	12935.7879	I2	28.7	28.7	77.00	61.00	4.6	10.1	382.8	5	0.28	32.0	37.0	37.9	47.9
1999	25/02/1999	17/03/1999	35503.2554	J1	36.6	37.5	78.00	48.00	3.2	8.5	890.4	5	0.22	39.7	44.7	51.8	61.8

A	< 25ha	15
B	25 - 100ha	6
C	100 - 250ha	4
D	250 - 500ha	5
E	500 - 1000ha	8
F	1000 - 2500ha	6
G	2500 - 5000ha	4
H	5000 - 10000ha	1
I	10000 - 25000ha	2
J	> 25000ha	1



Year	Fire Code	Area	Label	Fire Intensity	Slope	Vegetation Age before Burn	P. Laurifolia Actual		P. Laurifolia Ratio		P. Nerifolia Actual		P. Nerifolia Ratio		P. Repens Actual		P. Repens Ratio		L. Rubrum Actual		L. Rubrum Ratio		Total All Proteas Actual		Total All Proteas Ratio		Total Proteas and Leucadendrons Actual		Total Proteas and Leucadendrons Ratio	
2003	LMB_10_2003_01			E	N	13	30	553	1	18					1	36	1	36					32	589	1	18	32	589	1	18
2003	LMB_02_2003_01				N	9	23	37	1	2	7	20	1	3					4	1	4	1	30	57	1	2	34	58	1	2
2004	LMB_04_2004_01				S	14	28	272	1	10					12	635	1	53					38	907	1	23	38	907	1	23
2005	LMB_12_2005_03			A	S	12	35	157	1	5	37	886	1	24	26	316	1	12	92	210	1	2	98	1359	1	13	190	1569	1	8
2005	LMB_12_2005_05			C	S	5	172	414	1	3					61	79	1	1					233	493	1	2	23	493	1	2
2006	LMB_01_2006_04			A	S	30	19	130	1	19					0	6	0	6					19	136	1	7	19	136	1	7
2010	LMB_03_2010_01			E	N	18	12	118	1	10													12	118	1	10	12	118	1	10
2011	LMB_01_2011_01				S	10	28	50	1	2													28	50	1	2	28	50	1	2
2011	LMB_01_2011_02				S	12	29	491	1	17													29	491	1	17	29	491	1	17
2011	LMB_02_2011_02				S	11	19	300	1	16													19	300	1	16	19	300	1	16
2011	LMB_03_2011_04			E	N	12	30	826	1	27	298	3850	1	13	93	511	1	6	26	34	1	1	421	5187	1	13	473	5221	1	11