Wildfires in the Cape Floristic Region: Exploring vegetation and weather as drivers of fire frequency

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Abstract

This study assessed the spatial and temporal patterns of wildfires in the Cape Floristic Region (CFR). It focused on the factors that influence fire frequency; namely vegetation age, ignition sources and weather conditions. This work was done to aid decisions on fire management in fynbos nature reserves.

Fire intervals were extracted from historical fire records in four reserves in the CFR. The study sites were the Cederberg and Hottentots-Holland (western) reserves and the Swartberg and Outeniqua (eastern) reserves, and fire records were used from 1970 to 2007. A non-parametric technique and smoothing methods were used to highlight patterns in the extracted fire intervals. Comparisons of fire frequency were made between the study sites to analyse spatial patterns of burning. The impact of anthropogenic ignitions on fire frequency was analysed to explore the affect of people on fire patterns. The relationship between fuel age and fire size was analysed to determine the influence of vegetation age on fire patterns.

Two novel methods were described in this thesis. The first method developed a technique to analyse temporal patterns in fire frequency while avoiding the impacts of temporal autocorrelation. The second method analysed the relationship between weather condition and fire events by utilising self-organising maps of synoptic states. A temporal change in the frequency of these synoptic states was tested for over the recording period. Synoptic states were used to produce two regional fire risk indicators for the CFR.

I found that fire intervals in western study areas of CFR were shorter than fire intervals in eastern study areas. The effect of anthropogenic ignition sources shortened fire intervals in all study sites; however, this was relative to the natural fire frequency of each study site. Prescribed burning as a form of fire management contributed relatively little to the total area burned in all study sites. Fuel age has a significant correlation to fire size in only the drier (Swartberg) study site. A decreasing trend in fire return intervals was found in three study sites; Cederberg, Hottentots-Holland and Outeniqua.

Synoptic states characteristic of the southern most extent of a tropical easterly wave low were correlated to frequency fire events in the western study areas. Fires in the eastern study areas were correlated to a synoptic state characteristic of a tropical temperate trough. Easterly wave lows are associated with strong atmospheric convection whereas tropical temperate troughs are associated with pre-frontal conditions and strong, hot and dry winds. The frequencies of these synoptic states were shown to have increased in recent decade.

The factors influencing fire frequency in the western CFR are predominantly sources of ignition, while the availability of fuels and suitable weather conditions restrict fires in the eastern CFR. Fire frequency has increased in the study sites where weather exerts the dominant control and this is due to the increase in synoptic states that promote wildfires. Historical records show that fire management has had little impact on the total area burned, thus fire management under climate change is unlikely to influence fire frequency.

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Chapter 1. Introduction and study sites

1.1 Introduction

Fire is a global disturbance shaping major biomes in many areas across the world. It exerts a critical control on the distribution and ecological properties of grasslands, savannas, boreal forests and Mediterranean shrublands (Bond *et al.* 2005). There is a wide range of temporal (seasons, years, decades, centuries) and spatial (patch, regions, nations, continents) scales over which fire has influence. Variation of fire at these scales has consequences for plant communities that range from a single species life span, which impacts short-term shifts in species dominance, to several thousand years, which can affect sub-continental shifts in species distributions (Lertzman *et al.* 1998). Fire-prone ecosystems are sensitive to variation in the components of a fire regime, namely, season of burn, fire intensity, size of fires and the frequency of fires (Gill 1975). In some ecosystems, entire suites of plant species become excluded in the absence of fire, and these have therefore been termed "fire dependent ecosystems" (Bond *et al.* 2005).

Vegetation (fuel) is one of three important factors that drive the natural patterns of fire regimes. The other two are weather conditions and ignition patterns. The assumption that vegetation determines the pattern of fire behaviour (Mutch 1970) dominated the research of fire control for many years. Historically, studies on wildfires in forest ecosystems focused on fuel amount and fuel moisture as the vegetation characteristics used to describe fire patterns. Fuel amount was related to biomass accumulation rates and fuel moisture was related to the ambient weather conditions in the form of a fire danger rating index (Bessie and Johnson 1995). Weather conditions entered into these studies in the form of long term patterns in climate which effects the accumulation rates of fuels (Meyn *et al.* 2007) and short term patterns in weather affecting fuel moisture and lightning ignitions (Krawchuk *et al.* 2006).

The view that fuel properties determine fire regimes has been challenged. Bessie and Johnson (1995) found that in subalpine boreal forests, fuel accumulation in young stands impacted on fire behaviour but that in the ecosystem as a whole, weather was the more important factor overall. When observing fire behaviour they suggested that the size of the area burned depended on whether the fire weather was moderate or extreme, where the more extreme the weather, the larger the area burned and the greater the ecological significance of the fire. This suggests that there is a fuel-weather threshold where the dominant factor affecting fire behaviour changes from fuel age to weather forcing as the weather conditions range from moderate to extreme. Bessie and Johnson (1995) suggested that a lack of distinction between fires burning under moderate or extreme weather conditions is one of the reasons why fuel is thought to be so important to fire behaviour.

The hypothesis of a control threshold between fuel age and weather is particularly relevant in the Mediterranean-type regions of the world, where fire is an important part of the ecosystem's life cycle, and summer drought is an important climate feature (Keeley *et al.* 1999). The fire-prone Mediterranean-type regions of the world are (with associated vegetation types): the Mediterranean basin (shrubland), south-western Australia (kwongan), California (chaparral) and the Western Cape region, South Africa (fynbos). These regions are characterised by wet winters, hot dry summers and their shrublands all have some species with fire-stimulated reproduction (Table 1.1). Fire is therefore a key element in the dominance of these shrublands in Mediterranean-type regions. Low fuel accumulation rates means that fuel age is an important factor in fuel behaviour. Ageing fuels, as a result of fire suppression, have been at the centre of the debate around the occurrence of catastrophic fires in southern California (Minnich and Chou 1997; Moritz *et al.* 2004).

The hypothesis of a fuel-weather threshold has implications for both the biodiversity of the fynbos and its management. The fynbos biome of South Africa, known as the Cape Floristic Region (CFR), has exceptional species richness and high endemism making it one of the world's biodiversity hotspots. Fynbos is an evergreen shrubland characterised by the presence of restios, a high cover of ericoid shrubs and the common occurrence of proteoid shrubs (Taylor 1978; Kruger 1979b). Variability of the fire regime, through season, size, intensity and frequency of fires, is associated with different responses in fynbos species and can result in community composition fluctuations (Bond and Van Wilgen 1996; Thuiller *et al.* 2007). Seydack *et al* (2007) discussed the factors influencing fire patterns in the Swartberg and found multi-annual cycles in the extent of burning are a result of climatic cycles and fuel build up. They categorised two types of fire regimes for the fynbos; stable high frequency regimes in productive environments where fuel attained flammability at an early age, and more variable fire frequencies in less productive environments which had a higher dependence on vegetation age for flammability of fuels. This view stresses the importance of fuel accumulation as a factor influencing fire patterns, but suggests that once flammability has been attained other factors may play a greater role. Several studies have noted that it takes four to six years for sufficient fuel to accumulate in fynbos to attain flammability (Kruger 1977; Van Wilgen 1982; Brown *et al.* 1991). However Bands (1977) remarked that under extreme conditions fynbos as young as 3–4 years old ignited. This indicates that the threshold of fuel or weather dominance of fire patterns in fynbos can shift under extreme weather conditions.

The climate in the CFR is dominated by two synoptic-scale systems: the persistent high pressure system in the southern Atlantic and the band of westerly waves and associated low pressure systems that move from west to east between approximately 40° and 50° S (Tyson 2000). In summer the high pressure system moves southwards and blocks the passage of the frontal systems. The climate of the CFR is characterised by hot and dry summers associated with a high frequency of south easterly trade-winds. In winter the northward movement of cyclonic fronts brings rainfall to the region which diminishes to the east of the CFR. The south facing coastal mountains east of 20°E experience orographic rain in spring and autumn due to southerly winds associated with frontal systems passing to the south of the continent (Tyson 2000). This rainfall gradient from west to east across the CFR is illustrated in Figure 1.1.

Historical trends show that the atmospheric circulation over the CFR has experienced an increased frequency of strong high pressure systems from September to February (Tadross *et al.* 2005), which could have led to an increase in the hot dry winds associated with fires (pers comm. Mark Tadross, Climate Systems Analysis Group, UCT). Future climate change projections predict a drier and warmer climate than present for the CFR (Hewitson and Crane 2006) due to changes in atmospheric circulation. It has also been predicted that an expansion of convective rainfall over the interior of the CFR may bring more thunderstorms to the region (Midgley *et al.* 2005).

Fire size is a factor that is somewhat overlooked. Fire size is important for determining which fire events are truly important at the landscape level, and requires assessment when considering fuel-weather thresholds. A comparative study between small patchy fires in northern Baja California, Mexico, and large fires in neighbouring southern California led Minnich and Chou (1997) to hypothesise that fire suppression policies resulted in fuel accumulation in old vegetation stands and that this was the underlying reason for these large fires. Keeley and Fotheringham (2001) however, showed that fuel age in chaparral was not correlated to large fires and that fuel reduction management practices would not be effective in preventing large fires in this region. A recent study in the CFR, suggested that the size of fynbos fires is limited by fuel age under moderate weather conditions, but that large fires will occur under extreme weather conditions (Forsyth and Van Wilgen 2008). Extreme weather conditions are characterised by hot and dry winds associated with pre-frontal conditions. These winds desiccate most fuel to the point at which they burn (Van Wilgen *et al.* 1990). Forsyth and Van Wilgen (2008) found that the majority of the area burned in the Table Mountain National Park on the Cape Peninsula was due to a small number of large fires.

Variation in the fire regime has diverse effects on the fynbos ecosystem and monitoring the biodiversity is one of the many challenges facing management of this system (Van Wilgen *et al.* 1992). Biodiversity management has traditionally focused on a few key species representative of functional groups (Noble and Slatyer 1980; Keith *et al.* 2002). However, due to the diverse nature of fynbos, it is notoriously difficult to distinguish trends from random fluctuations (Van Wilgen *et al.* 1994). Thresholds of potential concern (TPC) operate on the principle that management can track measurable components of the fire regime so that these do not exceed the natural limits of the ecosystem. TPC has been successfully used in the savannah regions of South Africa (Van Wilgen *et al.* 1998; Bond and Archibald 2003) and would be applicable to the fynbos. TPCs set the upper and lower thresholds for different aspects of the fire regime. TPCs would be a viable alternative to monitoring biodiversity by focusing on achieving acceptable ranges of diversity within the components of a fire regime. Seasonal differences in rainfall across the CFR and different human density gradients means that the fire regime may be different in different regions. I thus compare the fire regime in different regions and analyse the effect of anthropogenic ignition sources on fire frequency.

Wildfires pose a serious threat to people and property in rural areas and along the urban-rural interface. Managing for fire risk most commonly involves burns to reduce fuel load in strategic areas to limit the spread of fires. Management burns operate under the assumption that abundance, type and availability of fuels will change the intensity, frequency and size of fires (Morgan *et al.* 2001). In the fynbos, a policy of fire suppression was implemented with European colonization of the Cape in the early 1600s where fires were "condemned as undesirable" (Bands 1977). This approach persisted until the 1970s when the then Department of Forestry adopted a policy of prescribed burning in mountain fynbos for the purposes of water catchment management and conservation (Bands 1977; Van Wilgen *et al.* 1994). Fire breaks and block burning were, and are still, commonly used to control the spread of fires (Van Wilgen *et al.* 1992). These practises are based on the hypothesis that pre-existing fine-scale landscape patch structure should self-regulate ecosystems with time-dependent fire occurrences (Minnich and Chou 1997). Keeley *et al* (1999) showed that large fires in Californian chaparral are not dependent on old age-classes of fuels, contradicting the view that young fuels stop fires. This has major implications for fire management in the chaparral where fuel reduction practices may not be effective in reducing fire risk to people and property (Keane *et al.* 2008). Similar conclusions could be drawn in the fynbos if it were shown that fuel age did not affect the occurrence of large fires.

Management of the fynbos biome currently and into the future is a challenging task fraught with difficulties. The high diversity of fynbos means it is nearly impossible to manage for each individual species and yet it is often studies from a few select species that influence management policies. Studies based on Proteaceae and fire frequency have been used to set current fire management policies (Van Wilgen *et al.* 1992) as there are few regional scale studies on fire patterns in the CFR. This is a gap that this thesis aims to fill. This thesis therefore investigates the impacts of different factors on the fire regime and compares results between different regions. The recent digitization of historical fire records for the CFR has allowed me to analyse spatial and temporal fuel and weather dynamics in the fynbos. Using a combination of standard and novel techniques I have analysed changes in fuel age over the last 60 years as well as the relationship between fuel age and fire size. I have also analysed spatial and temporal patterns of weather conditions and fire occurrence.

1.2 Thesis layout

In order to address the issues identified above, I have structured the thesis according to the following questions:

Chapter 2: Regional comparisons of fire frequency

- Are there regional differences of fire frequency in fynbos?
- How do anthropogenic ignitions impact fire frequency?

Chapter 3: Vegetation age effects on fire size and frequency

- Are large fires the result of fuel accumulation in the fynbos?
- Is there a temporal trend with regards to fire frequency?

Chapter 4: Relating fire frequency and weather using self-organising maps of synoptic conditions

- Are there regional differences in the relationship between weather and fire occurrence?
- Can fire risk be predicted using synoptic states?

Chapters 1 and 5 make up the Introduction and Conclusion respectively.

Note to readers

Each of the data chapters was written as independent and potentially publishable units thus there is some repetition across the chapters, particularly in the introduction and methods sections.

1.3 Study sites and data

Data

Historical fire data for the Cape Floristic region were provided by the Western Cape Nature Conservation Board, henceforth referred to as CapeNature. The data set consists of over 2000 fires in and around the reserves managed by CapeNature. Fire scars were sketched on 1:50 000 maps by reserve managers and were captured as digital polygons in 2008 by the Scientific Services Department of CapeNature (De Klerk *et al.* 2007). The accuracy of the data can be considered good because every effort was made to source all available fire records and each record was independently vetted (pers comm. Helen De Klerk, Scientific Services, CapeNature). For many regions the fire records are available from the time the reserve was founded. Thus the length of historical fire records varies with each reserve and data will be presented separately for each reserve. The fire records were in GIS (Geographical Information System) format and ArcView3.3 and ArcGIS9.1 was used for this analysis.

Study sites

The Cape Fold Mountain belt dominates the landscape of the fynbos biome with mountain chains lying north-south and east-west. Most remaining areas of fynbos occur in the mountains of the CFR which are managed as water catchments and to conserve biodiversity (Van Wilgen and Richardson 1985). Historical fire data was available for 29 CapeNature reserves which are scattered throughout the CFR and study sites were selected from these based on reserve size and quality of fire records: Cederberg reserve, greater Hottentots-Holland area (including Hottentots-Holland, Jonkershoek, Groenlandberg, Theewaters, Haweqwa and Waterval reserves), greater Swartberg area (including Groot Swartberg, Towerkop, Gamkaskloof (Die Hel) and Swartberg East reserves), and greater Outeniqua area (including the Ruitersbos, Doring Rivier and Witfontein reserves). The positions of these study sites offer an opportunity for regional comparisons in the CFR (Figure 1.2). The Cederberg and Hottentots-Holland are in the western side of the CFR and the Swartberg and Outeniqua are situated in the eastern side of the CFR.

1.4 Figures

Table 1.1: The occurrence of life history traits in Mediterranean type regions. *, present; –, absent, ?, uncertain. Table adapted from Bond and Van Wilgen (1996), Table 9.1, p 212

Trait	California	Mediterranean Basin	Australia	South Africa
Fire stimulated reproduction				
Flowering				
grasses	*	*	*	*
geophytes	*	–	*	*
Seed release				
serotiny	*	*	*	*
Germination				
heat	*	*	*	*
charate	*	?	*	*
smoke	*	?	*	*
Fire survival (shrubs)				
Basal sprouts	*	*	*	*
Lignotubers	*	*	*	*
Epicormic buds	*	*	*	*
Non-sprouters	*	*	*	*

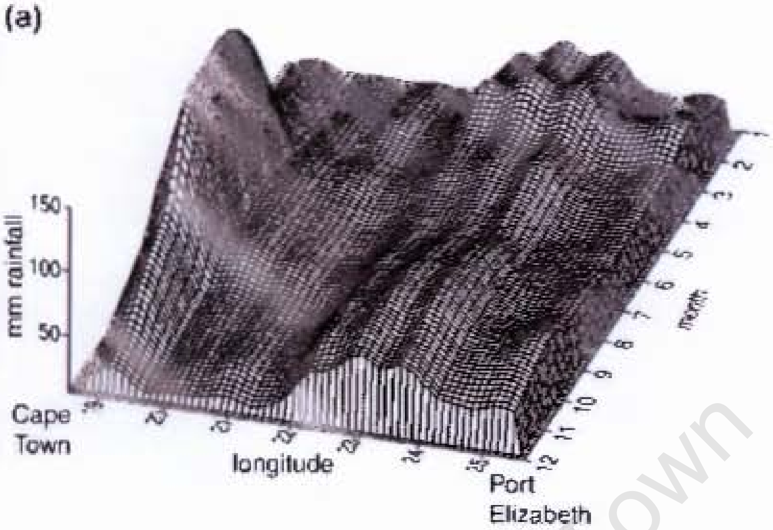


Figure 1.1: Rainfall regimes in the winter-rainfall region of southern Africa. The west–east (Cape Town to Port Elizabeth, 34^{0}S) gradient showing total annual rainfall. Figure adapted from Procheş *et al* (2005), Figure 5, p 107

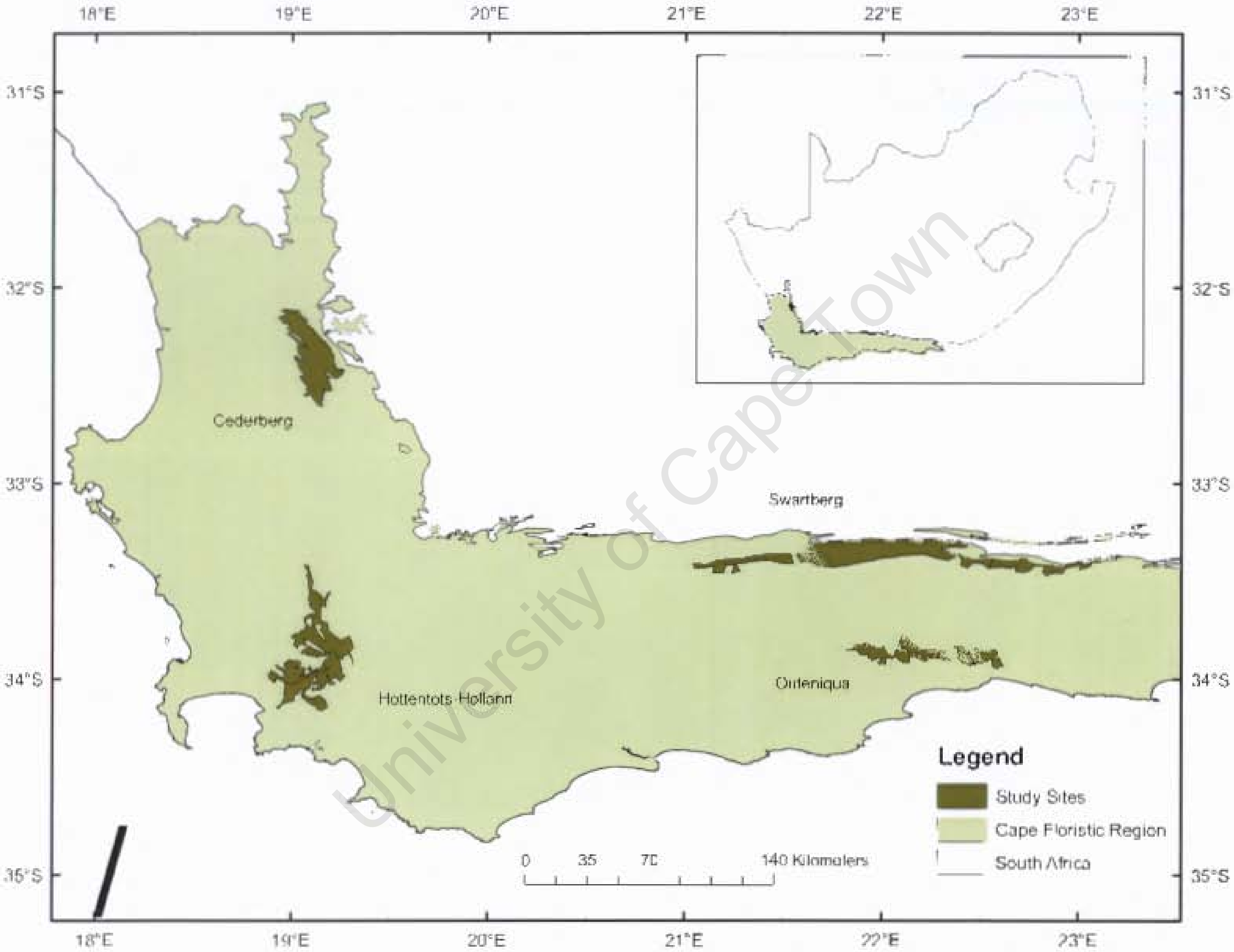


Figure 1.2: Position of the study sites (Cederberg, Hottentots-Holland, Swartberg and Outeniqua) within the Cape Floristic Region, South Africa

Chapter 2. Regional comparisons of fire frequency

2.1 Introduction

The Cape Floristic Region (CFR) in south-western South Africa is a recognised biodiversity hotspot (Mucina and Rutherford 2006). The fynbos, as it is commonly known, contains over 9000 species, 64% of which are endemic to this region (Goldblatt and Manning 2000). Fire plays an important role in the maintenance of fynbos species diversity (Bond and Van Wilgen 1996) and studies have shown that variation in the fire regime, defined as the season, intensity, size and frequency of fires, are important for the co-existence of many species (Kruger 1977; Van Wilgen 1981b; Van Wilgen *et al.* 1990; Richardson and Van Wilgen 1992; Clark *et al.* 2002; Thuiller *et al.* 2007).

Fire frequency is often used as the main descriptor of a fire regime. This is because of the relative ease of obtaining this data, i.e. from fire scars on tree rings (Swetnam and Betancourt 1998), charcoal in sediment deposits (Clark 1990), satellite data (Gill *et al.* 2000), stand origin maps (Van Wagner 1978; Johnson 1979) and mapped fire history (Brown *et al.* 1991; Morgan *et al.* 2001; Seydack *et al.* 2007). Fire frequency is defined as the average number of fires that occur at a point over a fixed period of time (Li 2002). The reciprocal of this, fire interval, is often more ecologically useful (Kruger 1979a). Fire interval is defined as the average number of years between the occurrence of fires at a given point (Li 2002). The distribution of fire intervals, rather than the average, can be used to understand the dynamics of fire regimes in a landscape (McCarthy *et al.* 2001). This is especially important for the fynbos as the frequency of fires is one of the main factors in species coexistence (Thuiller *et al.* 2007).

Statistical distributions are commonly used to quantify the variability in fire frequency (Moritz *et al.* 2004). The theory of fire interval distributions is based on mortality and hazard functions (Johnson and Gutsell 1994) and many studies have contributed to this field (Heinselman 1973; Clark 1989; Johnson and Gutsell 1994; Clark 1996; Reed *et al.* 1998; Polakow and Dunne 1999; McCarthy *et al.* 2001). Assumptions of spatial and temporal homogeneity are implicit in these statistical distributions, but, due to the stochastic nature of fire occurrence, these assumptions are not easily met (Clark *et al.* 2002). Non-parametric estimation techniques and smoothing methods

(Schoenberg *et al.* 2003) can be used as an alternative to these functions for highlighting the overall trends in fire frequency.

Unravelling the complex interactions of driving forces of fire frequency are important for the effective management of the CFR (Seydack *et al.* 2007). The three principal driving forces in a fire regime are fuel dynamics, weather conditions and ignition sources (Morgan *et al.* 2001). Recent debate in Mediterranean-type ecosystems has centred around the dominance of fuels and weather forces under fluctuating environmental conditions (Minnich and Chou 1997; Keeley *et al.* 1999; Vázquez *et al.* 2002) with marginal mention of anthropogenic influences. The effect of people on fire regimes comes in the form of additional ignition sources (Van Wilgen 1982; Vázquez *et al.* 2002; Mermoz *et al.* 2005), fuel manipulation (Bradstock *et al.* 1998b) and extinguishing fires (Keeley *et al.* 1999). These impacts contribute to the variability of a fire regime and are important factors to take into account when managing a fire-prone environment. Of particular importance to the CFR is the addition of ignition sources in the landscape as the fynbos fire regime is mostly not ignition-saturated (Seydack *et al.* 2007).

This study quantifies the variation in fire frequency along the rainfall gradient in the CFR using non-parametric estimation techniques. It also investigates the impact of anthropogenic ignition sources on fire frequency.

2.2 Methods

Fire frequency can be lower at higher elevation due, among other factors, to lower ambient temperatures and additional rainfall (Bessie and Johnson 1995). The elevation in the study sites ranged from 300m to 2100m therefore topographical effects were analysed by checking that fire frequency did not change with elevation. To test for this the elevation of 1000 random points were recorded over the study sites. The number of fires at each point (from 1940 to 2007) was calculated. The results were plotted to identify if any relationship exists between fire frequency and elevation and a LOWESS smoother (Cleveland 1981) was added to the plot to highlight any relationship.

Fires in the CFR are most common in the austral summer months and summer spans two calendar years. Therefore a fire year for the southern hemisphere is defined from July to June; for example, 1 July 1998–30 June 1999 would be the 98/99 fire year. In this analysis the first calendar year in a fire year was used for calculating fire intervals. From the above example any fire occurring in the 98/99 fire year is given 1998 as the year from which to calculate fire intervals for preceding or subsequent fires. If the month in which a fire burned was unknown, then the fire year cannot be determined. Month was not recorded for 4% of fire records. By arbitrarily choosing the calendar year of the burn as the fire year we may be introducing a bias in the analysis towards longer fire intervals. For these records the fire month was determined by a randomization process.

Fire and ecology

The principle aim of this study was to examine the frequency of fires in the fynbos so that we can draw conclusions about the fire regime. Probability densities were used to show the frequency of fire intervals in each study site. Fire intervals describe the relationship between vegetation age and fire frequency. Mutch (1970) proposed that fire behaviour is controlled by the vegetation patterns in the landscape. This hypothesis led to work on fuel loads and the fitting of statistical distributions to fuel accumulation rates (Van Wagner 1978; Johnson 1979). These methods, described in detail by Johnson and Gutsell (1994), require spatial and temporal homogeneity whereas the aims of this thesis are to examine trends in spatial and temporal heterogeneity. Non-parametric estimation techniques are thus sufficient to display the underlying patterns in the distribution of fire patterns.

Fire intervals can be determined when areas are burned more than once, thus fire intervals can be extracted from areas where fire polygons overlap. Fire polygons in each study site were intersected to produce a map of overlapping fire areas. This created a mosaic of fire history polygons (FHP) each with an individual fire history. The set of fire intervals between successive fires were calculated for each "fire history polygon" using fire years.

The fire interval distribution, $f(t)$, is a probability density function. It is the probability of a piece of landscape burning with a fire interval of t years. Computationally, the probability density extracts the proportion of a historical fire event (base fire) that reburned with a fire interval t. Suppose there are a total of N fire history polygons, FHP_1, … FHP_i, … FHP_N. Each polygon has an area, B_i, the associated area of the base fire, A_i, and the fire interval t_i (number of years) between the base fire and the reburn, where the t_i are integers.

Let

$$f(t_i) = \frac{B_i}{A_i} \tag{1}$$

where $i = 1 \ldots N$. The scatter plot of values $(t_i, f(t_i))$ is smoothed to produce a probability density function.

The approach can be illustrated using the simple case of three overlapping fires (Figure 2.1). In this hypothetical landscape three fires occurred in a 15 year period; fire X, which burned 15 years ago, fire Y which burned 10 years ago and fire Z which burned in the current year. Fire Y reburned a proportion of the landscape that was originally burned by X and fire Z reburned proportions of both X and Y. This generates four fire history polygons, FHP_1, FHP_2, FHP_3 and FHP_4. The probability of burning with the fire interval of 5, 10 and 15 years can be calculated for this landscape from equation (1) as follows:

$$f(5) = \frac{FHP_3 + FHP_4}{X}$$

$$f(10) = \frac{FHP_1 + FHP_4}{Y}$$

$$f(15) = \frac{FHP_2}{X}$$

The probability density of fire return intervals may be examined in a scatterplot in which all values of (t, f(t)) are plotted.

The intersection of all of the fire polygons in each study site created a large number of FHP. A weighted moving average algorithm (see appendix 2.6) was used to smooth the scatter plots of the probability densities of the fire intervals and thus highlight overall trends. To express the variation in the data, the 95% confidence intervals were calculated for each fire return interval. This was done with a standard bootstrapping technique where the weighted moving average algorithm was calculated for 1000 subsamples of the data set. For each fire interval, the 2.5% and 97.5% values of the smoothed subsamples were identified as an indication of the range of possible values for each point. These intervals are plotted as points above and below each smoothed *f(t)* value. The smoothed scatter plot was normalized so that the area under the curve is equal to one. This ensures that the total probability of burning with a fire return interval in the range of 1 to 38 years is equal to one. Therefore any variant of the smoothed scatter plot within the 95% confidence interval would also have to abide by this constraint, i.e. a smoothed line connecting all of the 97.5% points would not be possible as the area under this curve would be greater than one.

The ignition source of fire intervals was used to determine the effect of human activities on fire frequency. By definition, fire intervals are periods of time between two fires, thus the ignition source of the second fire determines the cause of a particular fire interval. For example a management prescribed burn creates a management fire interval whereas a lightning fire creates a natural fire return interval. Ignition sources were divided into four categories; Unknown ignition sources, Natural ignitions (including lightning and sparks from falling rocks), Management ignitions (from prescribed burns) and Accidental ignitions (including escaped prescribed burns, mechanical ignition sources and other fires started by people). The area burned by fires resulting from each ignition source was summed and divided by the total area burned in each study site.

2.3 Results

Data

There were 2100 fires in the data set, which ranged from 1 ha to 24 165 ha in area (I excluded fires less than 1 ha from the data set). Fifteen percent of the fires were larger than 1 000 ha. Prescribed management burns were the source of 19% of the fires on record, 20% were recorded as accidental ignition sources. Natural ignition sources were recorded for 22% of the fires and the remaining 39% of the fire records had unknown ignition sources.

The earliest fires were recorded in the 1930s but there are many more records in the latter part of the 20th century than the earlier decades. Figure 2.2 shows the pattern of record keeping over the past 80 years. The number of fires recorded per annum has increased in the latter half of this period. However the change in recording patterns was due to an increase in the number of small and moderately sized fires being recorded (Seydack *et al.* 2007). This change has less of an impact on annual area burned as seen in Figure 2.3. This study used the more consistent recordings for the entire CapeNature data set of the latter half of the century, taken from the first year that exceeds the mean, 1970. This analysis thus spans the 38-year period from 1970 to 2007.

The annual area burned in Figure 2.3 shows multi-year cycles of large fires in the Swartberg, Hottentots-Holland and Outeniqua. Fire size in the Cederberg is less cyclic and suggests that this study site may be more uniform with regard to stand age.

Topographic effects on average fire return times are negligible as seen in Figure 2.4, with the exception of the highest elevations, i.e. above 2000 meters. Only 2.6% of the area sampled is above 2000m and thus we can conclude that the effect of elevation on fire frequency is insignificant at the scale of this study.

Fire regime

The seasonal burning patterns of the four study sites are shown in Figure 2.5. The two study sites in the western CFR (Cederberg and Hottentots-Holland) show strongly seasonal summer burning. The two easterly study sites (Swartberg and Outeniqua) show a more even distribution in burn season.

The probability densities (Figure 2.6) are the frequency of fire intervals in each study site and show a predominance of short (<10 years) fire intervals in the western CFR and longer (~15 years) fire intervals in the east. The plots in Figure 2.6 were produced using all of the fire intervals extracted from the data, regardless of the causes of the fires. They show the underlying pattern in the large spread of points from the fire interval extraction. The solid line is the smoothed scatter plot highlighting the underlying distribution of the data. Dotted lines are the 95% confidence intervals of the smoothed $f(t)$ value for each fire interval. The distribution of fire return intervals is uni-modal in the Swartberg and Outeniqua, but multi-modal in the Cederberg and Hottentots-Holland. The Cederberg has the greatest variation around each fire interval. In all study sites long fire intervals (>30 years) are infrequent because the likelihood of a piece of vegetation remaining unburned for long periods of time is low.

Comparing the cumulative probability densities, Figure 2.7, shows the range of fire return intervals between the different study sites. The cumulative probability density from 0.4 to 0.6 gives the range of vegetation ages by which 40–60% of the landscape has burned. The Cederberg ranges from 11 to 16 years, the Hottentots-Holland ranges from 9 to 12 years, the Swartberg ranges from 13 to 15 years and the Outeniqua ranges from 16 to 19 years. The data in Table 2.1 was extracted from Figure 2.7 and shows that the Hottentots-Holland has the highest (12%) incidence of short fire intervals (defined as < 5 years) and the Outeniqua has the smallest (3%).

Fynbos stands in the Outeniqua (33%) and Cederberg (26%) were more likely to burn with fire intervals longer than 20 years.

Different ignition sources result in different patterns in the probability density in the fynbos. Figures 2.8 to 2.11 show the probability density functions for the different causes of fires in each study site. The Cederberg (Figure 2.8) has a greater tendency to burn at short (<5 years between fires) intervals under the influence of anthropogenic accidental ignitions. Natural ignition probability densities have a greater spread between 5 to 20 years between fires. The high probability density (0.08) of burning with one year between fires under accidental ignitions may be due to the frequent burning of grass verges along roadsides. Natural and unknown fires account for the majority of the area burned (>80000ha) where management fires were an order of magnitude smaller (~6000ha).

The range of probability densities for the Hottentots-Holland (Figure 2.9) is 5–10 years for accidental fires and 10–15 years for natural fires. The tendency for vegetation to burn at short intervals between fires is echoed in the management burns at 8–12 years between fires. Management prescribed burns targeted stand ages of 18–22 years. This all results in a very low (<1%) probability of burning with fire intervals longer than 27 years. Fires with unknown ignitions accounted for most of the total area burned (>54000ha) and accidental fires accounted for the next largest area (~30000ha). Management fires were an order of magnitude smaller (~7000ha).

The probability densities of the Swartberg (Figure 2.10) are distinctly split between anthropogenic ignition sources (accidental and management) and natural ignitions sources. The anthropogenic fire return intervals range from 5–10 years between fires, while the natural fire return intervals range from 10–20 years between fires. The probability density of the fire return intervals of unknown source follows the same pattern as the natural probability densities. This suggests that these unknown ignition sources were of natural origin. Natural and unknown fires accounted for the greatest total are burned (>70000ha), while anthropogenic fires were an order of magnitude smaller (~4500ha).

The probability density of the management fire intervals in the Outeniqua (Figure 2.11) ranges over shorter years between fires (5–15 years between fires) than either the accidental fire return intervals (12–20 years between fires) or the natural fire return intervals (18–25 years between fires). Accidental fires accounted for the greatest area burned (~13000ha), with natural fires the next largest (~8000ha).

Table 2.2 shows the relative proportions of each study site by fires of different ignition sources. The majority of the Cederberg was burned by unknown (45%) and natural (44%) fires. The Hottentots-Holland was burned mainly by unknown (53%) and accidental (29%) fires. A significant proportion of the Swartberg was burned by natural fires (74%) while area burned in the Outeniqua was mainly due to accidental (45%) and natural (30%) fires. There is a clear north-south division between the study sites when the percentages of area burned by accidental fires are compared. The Hottentots-Holland and Outeniqua had 29% and 45% burned, respectively, by accidental fires, whereas the Cederberg and Swartberg had 5% and 3% burned respectively.

2.4 Discussion

A regional comparison of fire patterns across the CFR was undertaken by quantifying the seasonality and frequency of fires in four study sites. Results showed a difference in the season of fire occurrence along a longitudinal gradient, Figure 2.5. Fires burn a greater area in summer in the two study sites in the west (Cederberg, Hottentots-Holland). The Outeniqua and Swartberg in the east showed a less visible seasonal trend. The difference in seasonal burning patterns may be attributed to the seasonal differences in weather between the two regions. The western CFR experiences hot and dry summers with strong south easterly winds; conditions which may be conducive to fires. By contrast the Outeniqua Mountains in the eastern CFR act as a barrier to moist coastal air resulting in orographic uplift and predominantly moist conditions (~800ml per year). The Swartberg Mountain range north of the Outeniqua is much drier (~300ml per year) but still has the characteristic eastern CFR pattern of even annual rainfall. Fires in the eastern CFR thus occur in any season as long as there is a long enough dry period for the fuel moisture levels to drop (Horne 1981). The seasonal climatic differences between the sites may go a long way to describe the seasonal longitudinal differences in fire patterns.

Fire intervals in Figure 2.6 show that there is a longitudinal gradient with regards to fire frequency. The Cederberg and Hottentots-Holland have a greater frequency of fire intervals less than 10 years whereas the Swartberg and Outeniqua have a greater frequency of fire intervals between 10 and 20 years. We can therefore conclude that fires are more frequent in the western study sites than in the eastern study sites. This conclusion is reinforced by Figure 2.7 and Table

2.1 which allow for a regional comparison between study sites and show that a greater proportion of the Hottentots-Holland and Cederberg burn with less than 10 years between fires.. The short fire intervals are the most ecologically significant as they affect the reproductive stages of fynbos species. The predominance of fire intervals less than 10 years in the Cederberg and Hottentots-Holland will favour fast-maturing species over late-maturing species. The converse is true for the study sites in the eastern CFR. One could thus expect divergence in the flowering patterns across a longitudinal gradient with divergence in fynbos life histories as the western region adapted to short fire intervals and the eastern evolved with long fire intervals. Studies on species richness have shown a strong east-west gradient with greater species diversity in the south west of the CFR then the south east (Linder 1991; Cowling and Lombard 2002). These studies make little mention of the role of fire in these regions and conclude that the geographical distributions of species density "coincide with a transition from the reliable winter-rainfall zone (west) to the less reliable non-seasonal rainfall zone (east)" (Cowling and Lombard 2002). My results suggest that the regional differences in fire frequency should be considered in future studies of this kind.

The influence of people on the fire regime results in shorter fire intervals in all of the study sites. This is evident from the results in Figures 2.8–2.11 where accidental ignitions resulted in fire intervals shorter than the natural fire intervals. From these results it is clear that people influence the fire regime by adding ignition sources to the landscape. This conclusion has been made in many other fire-prone ecosystems around the world. Vázquez *et al* (2002) found that shorter fire return intervals were associated with intentional fires across all vegetation types in Spain and in fact "cause of ignition best explained the patterns of forest fire characteristics". Increases in human population in California have been correlated to increases in fire frequency in chaparral through increases in sources of ignition (Keeley *et al.* 1999; Keeley and Fotheringham 2001).

The two southern study sites (Outeniqua and Hottentots-Holland) have the largest proportional area burned by human activities, Table 2.2. These two study sites are located closer to densely populated urban areas and would have a higher fire risk from adjacent properties. The northern study sites (Cederberg and Swartberg) are in more isolated rural areas and have proportionally less area burned by accidental fires. Then, at least for these records, human ignition frequencies are greater in urban than in rural settings. This latitudinal anthropogenic gradient is significant in terms of the origin of fires but it did not affect the stronger longitudinal gradient of shorter fire intervals in the west and longer fire intervals in the east. This implies that although human activities can result in shorter fire intervals the magnitude of the shortening is relative to the frequency of the natural fire intervals. Thus the underlying causes for the differences between study sites (be it climatic controls or vegetation) still holds regardless of human interference.

Fire management of the fynbos ecosystem is notoriously difficult (Van Wilgen *et al.* 1992) and as can be seen from Table 2.2, management burns contribute very little to the total area burned in each study site. Due to the sensitivity of fynbos to fire season, management burns must be undertaken during the peak fire season, but on days when conditions are safe for prescribed burning. This places serious constraint on the time available to burn and changes in weather can often result in run-away fires. The steep topography of the Cape Fold Mountains limits the accessibility of these areas, adding to the challenges of prescribed burning. One can see from Table 2.2 that management fires have not made a significant contribution to the total area burned in any of the study sites. This is despite the considerable resources employed from in block burning the 1970s to 1990s(Van Wilgen *et al.* 1994). A policy of 'natural burning zones' is more suitable to the remote mountainous regions of the CFR. This policy allows naturally ignited fires to burn without management intervention, while accidental fires are extinguished (Van Wilgen *et al.* 1992; Seydack *et al.* 2007).

The natural burning zone policy becomes impractical in more densely populated regions of the CFR where the risk of fires spreading from neighbouring properties is higher. In these areas management might prefer to adopt the Thresholds of Potential Concern (TPC) strategy proposed by Van Wilgen et al (1998). This strategy was introduced as an alternative to the hierarchical monitoring method proposed by Noss (1990) for managing biodiversity. TPC operates on the principle that management can track measurable components of the fire regime so that these do not exceed the natural limits of the ecosystem (Van Wilgen *et al.* 1998). For instance, late summer and early autumn fires are best for seeding recruitment of Proteaceae (Bond 1984) and so the TPC for this family would include early spring and winter fires. Therefore in areas of higher risk of accidental fires, management need only suppress fires that exceed the TPC. From Figure 2.7 we can see that the TPC could be defined separately for each study site to account for the differences in fire frequency between different regions of the CFR.

2.6 Appendix

Weighted moving average algorithm

The smoothing was undertaken using a weighted moving average algorithm, modified from that developed by Summers *et al* (1992), which was based in turn on McConalogue (1970), the smoothing algorithm used for example, in the high level statistical programming language GenStat (Payne *et al.* 2007). The algorithm uses the multiple estimated values of $f(t)$ for each fire interval t, and those of neighbouring values of t to produce a composite probability density function $f(t)$ for each fire interval t, t=1,2,...Y, where Y is the maximum number of fire years, in this case 38 years.

In estimating $f(T)$ for a particular target year T, T=1,...38, the algorithm uses all N values of (t_i, $f(t_i)$), and weights them in two ways. Firstly it takes account of the interval between t_i and T, in such a way that if $|T- t_i|$ is large, $f(t_i)$ makes a weighted contribution to $f(T)$. This is achieved through the weighted function

$$w_i = e^{-\frac{1}{v}(T-t_i)^2}$$

where v is a appropriate smoothing constant. The larger the value of v, the smaller the contribution to $f(T)$. By experimentation, I used the value 20 for v.

Secondly, the weight of $f(t_i)$ in the calculation of $f(T)$ was larger if the area A_i of the fire polygon was larger. I used the area A_i as the weighting factor; however, alternative possibilities are $\sqrt{A_i}$ and $log\, A_i$. This yielded

$$f(T) = \sum_{i=1}^{N} A_i w_i f(t_i),$$

this provided the overall shape of the probability density function. This was then normalized so that the area under the curve is equal to 1, thus satisfying the condition of a density function.

2.7 Figures

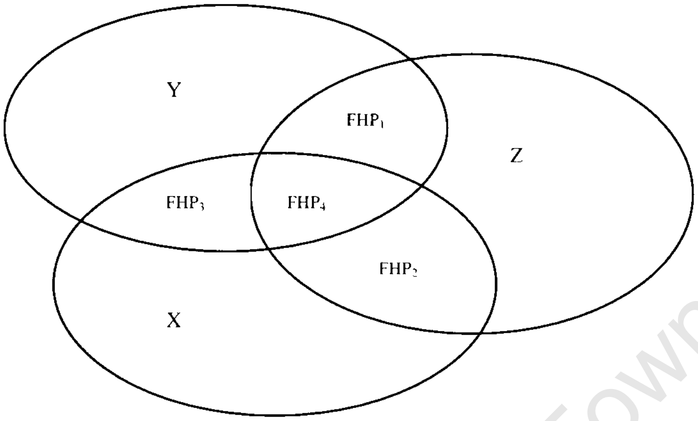


Figure 2.1: Simplified case of three fires in a landscape. Fire X burned 15 years before present, fire Y burned 10 years before present and fire Z burned in the current year. Regions of overlap create fire history polygons FHP_1, FHP_2, FHP_3 and FHP_4

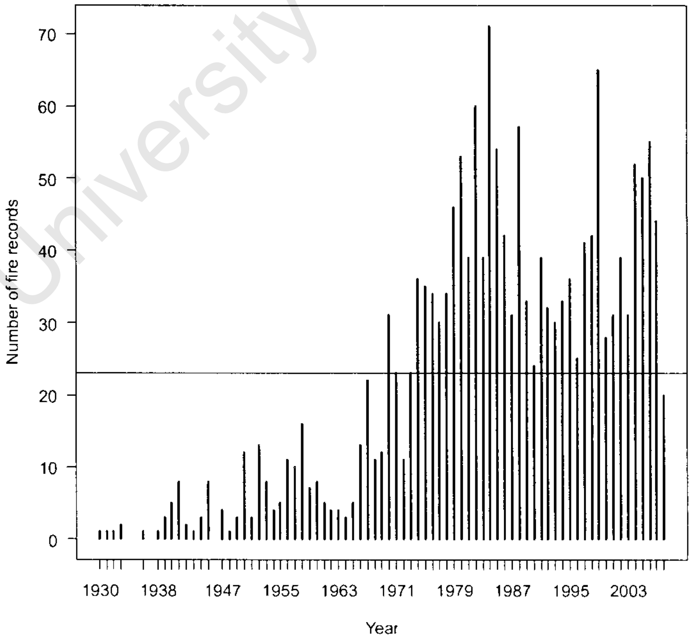


Figure 2.2: Number of fire records per year for the entire CapeNature historical fire dataset in the Cape Floristic Region. The mean is plotted as a horizontal line

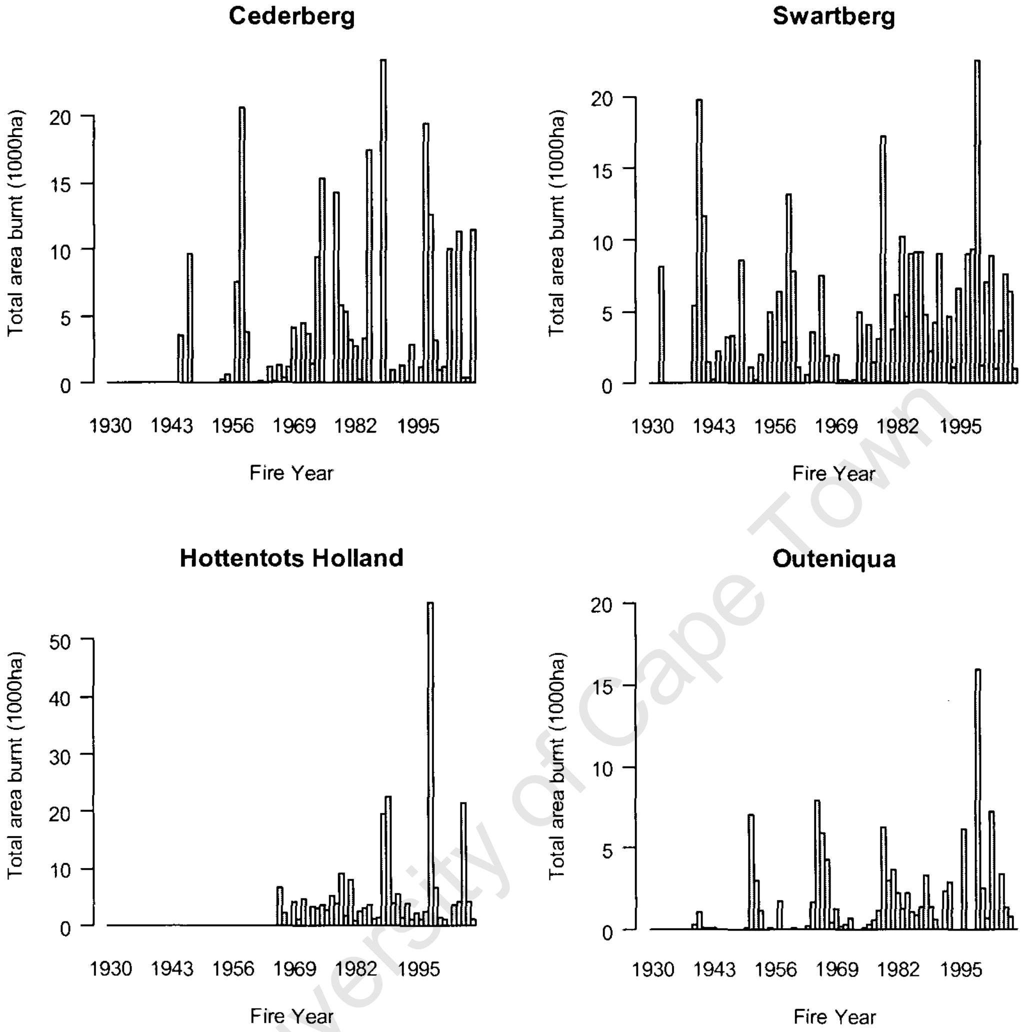


Figure 2.3: Annual area burned according to the mapped historical fire records for four study sites in the Cape Floristic Region

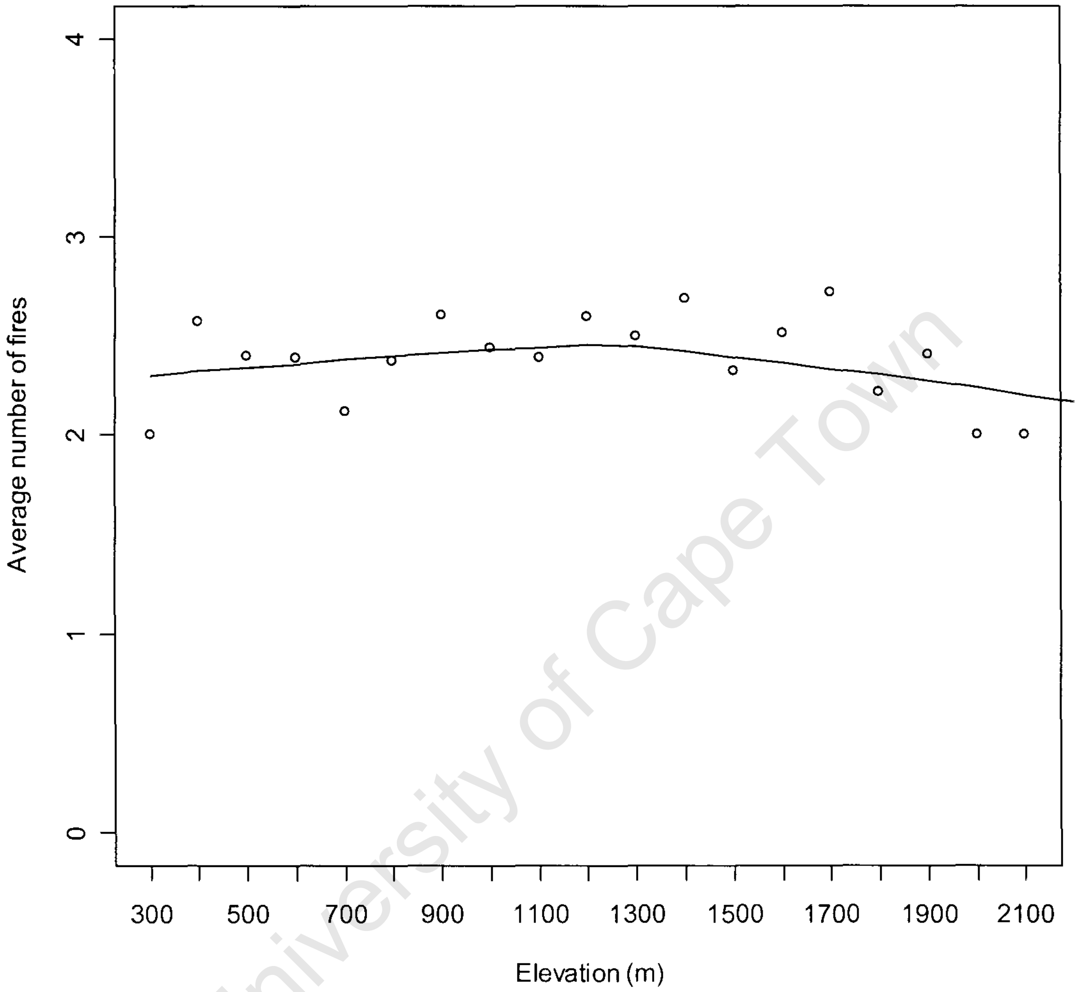


Figure 2.4: Mean number of fires for 1000 random points distributed over the four study sites in the Cape Floristic Region. Fire records from 1970 to 2007 were used. Line fitted by LOWESS smoothing function

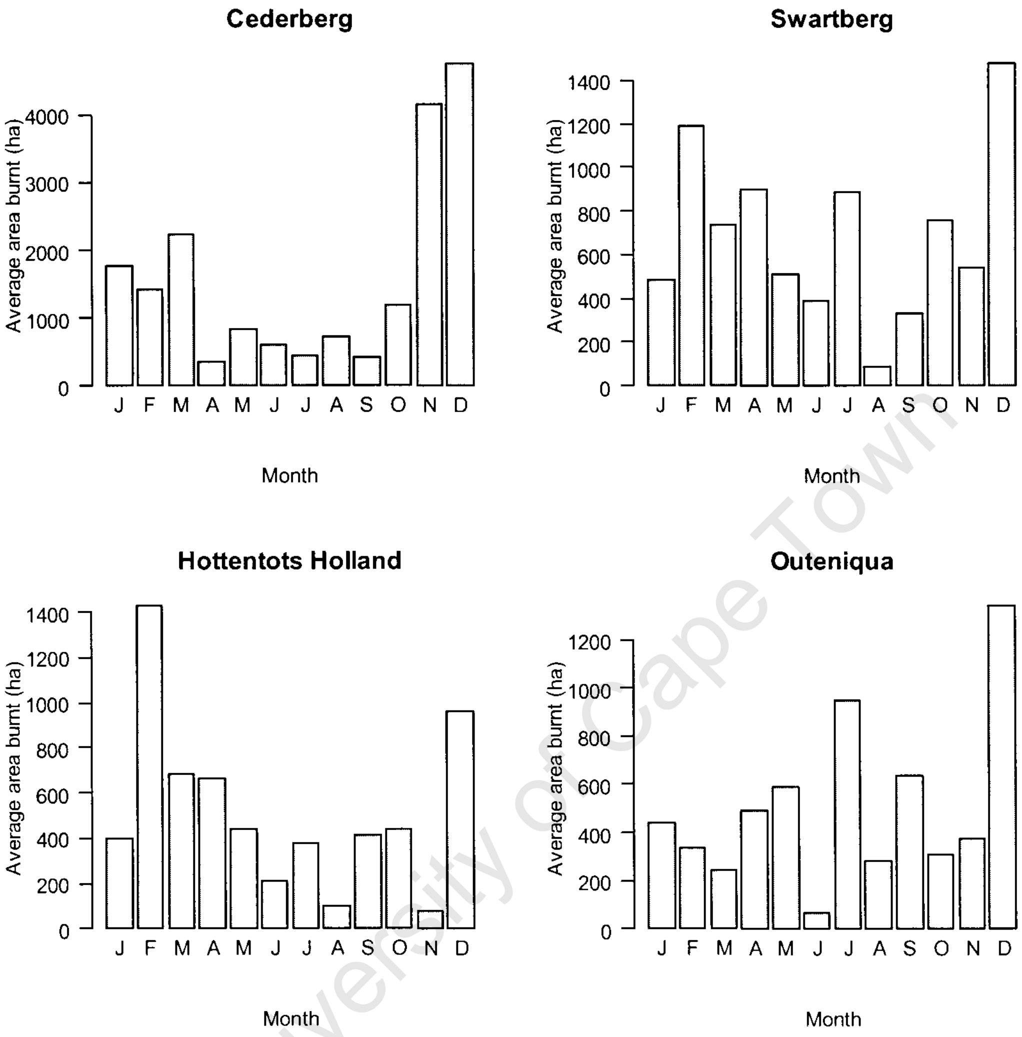


Figure 2.5: Seasonal variation in the average area burned for four study sites in the Cape Floristic Region (1970–2007). Dec, Jan, Feb – summer. Mar, Apr, May – autumn. Jun, Jul, Aug – winter. Sep, Oct, Nov – spring. Cederberg and Hottentots-Holland are in the west of the CFR and Swartberg and Outeniqua are in the east

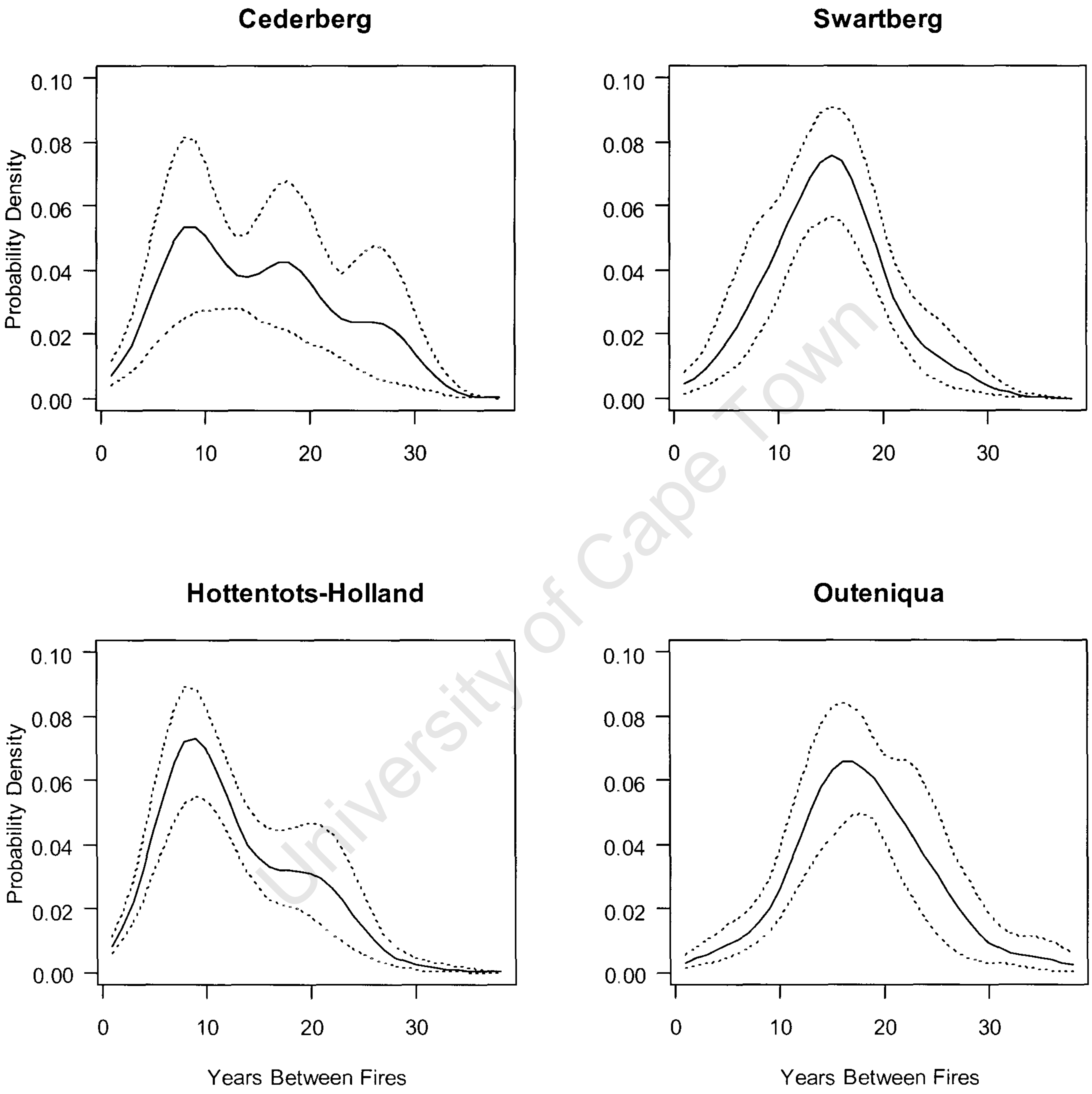


Figure 2.6: Probability density of fire intervals for each of the study sites in the Cape Floristic Region. The solid line is the smoothed scatter plot of all fire intervals (regardless of ignition cause) and the dotted lines are the 95% confidence intervals showing the variation in the data

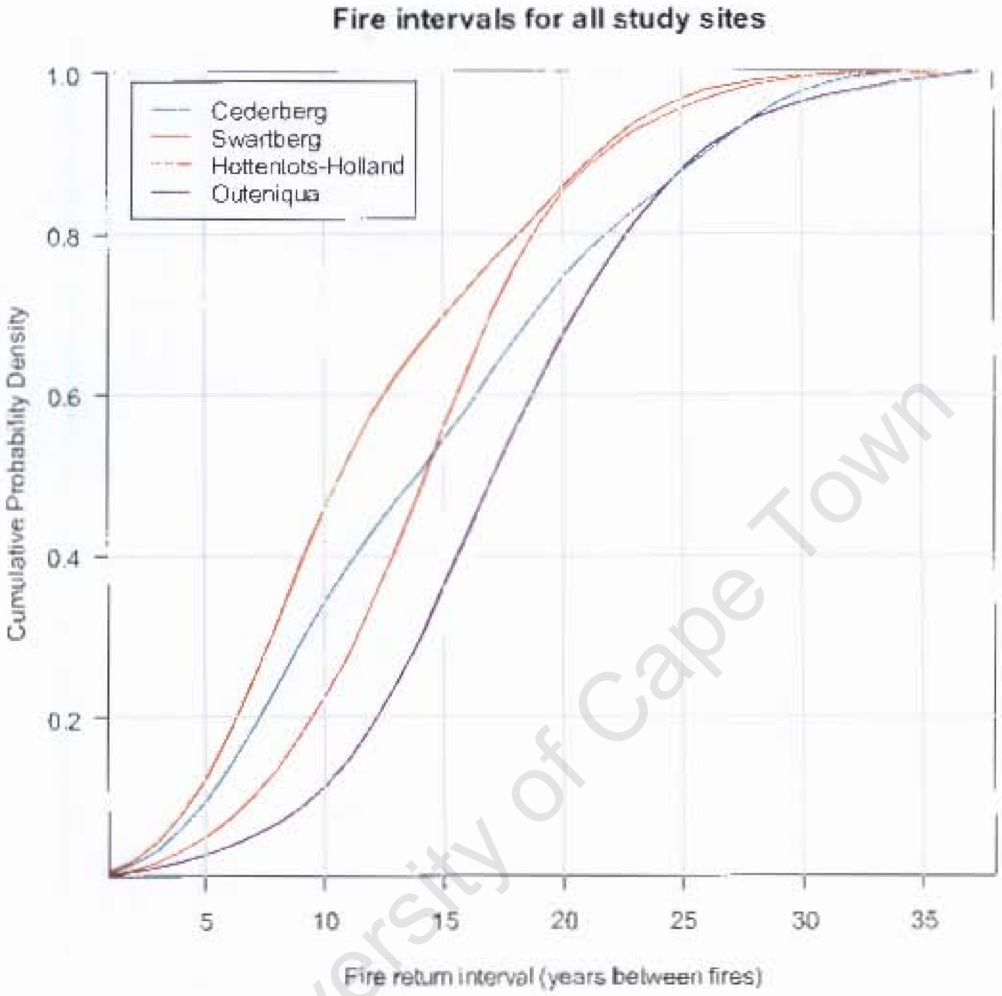


Figure 2.7: Comparison of the cumulative probability densities between four study sites in the Cape Floristic Region. The turquoise line represents the Cederberg, the brown line represents the Hottentots-Holland, the orange line represents the Swartberg and the purple line represents the Outeniqua

Table 2.1: Comparison of percentage area burned by five year interval vegetation ages for each study site in the Cape Floristic Region

Vegetation age	Cederberg	Hottentots-Holland	Swartberg	Outeniqua
<5	9%	12%	5%	3%
<10	34%	46%	22%	11%
<15	54%	70%	56%	36%
<20	74%	86%	85%	67%

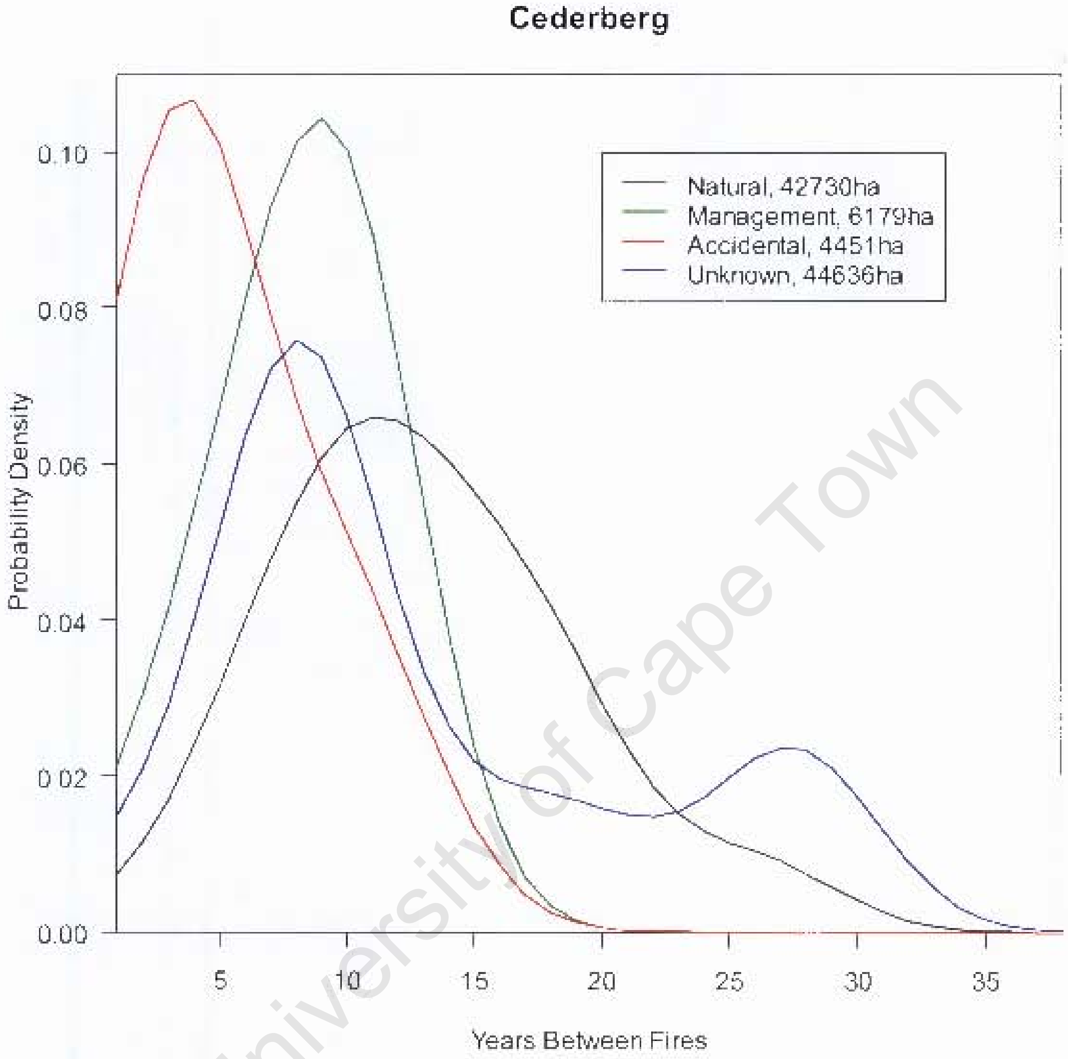


Figure 2.8: Smoothed scatter plots of the probability density of fire return intervals for the Cederberg. The black line represents the fire intervals resulting from a natural burn. The green line represents fire intervals resulting from a prescribed management burn. The red line represents fire intervals resulting from a fire with an anthropogenic ignition source. The blue line represents the fire intervals resulting from a fire of unknown ignition source.

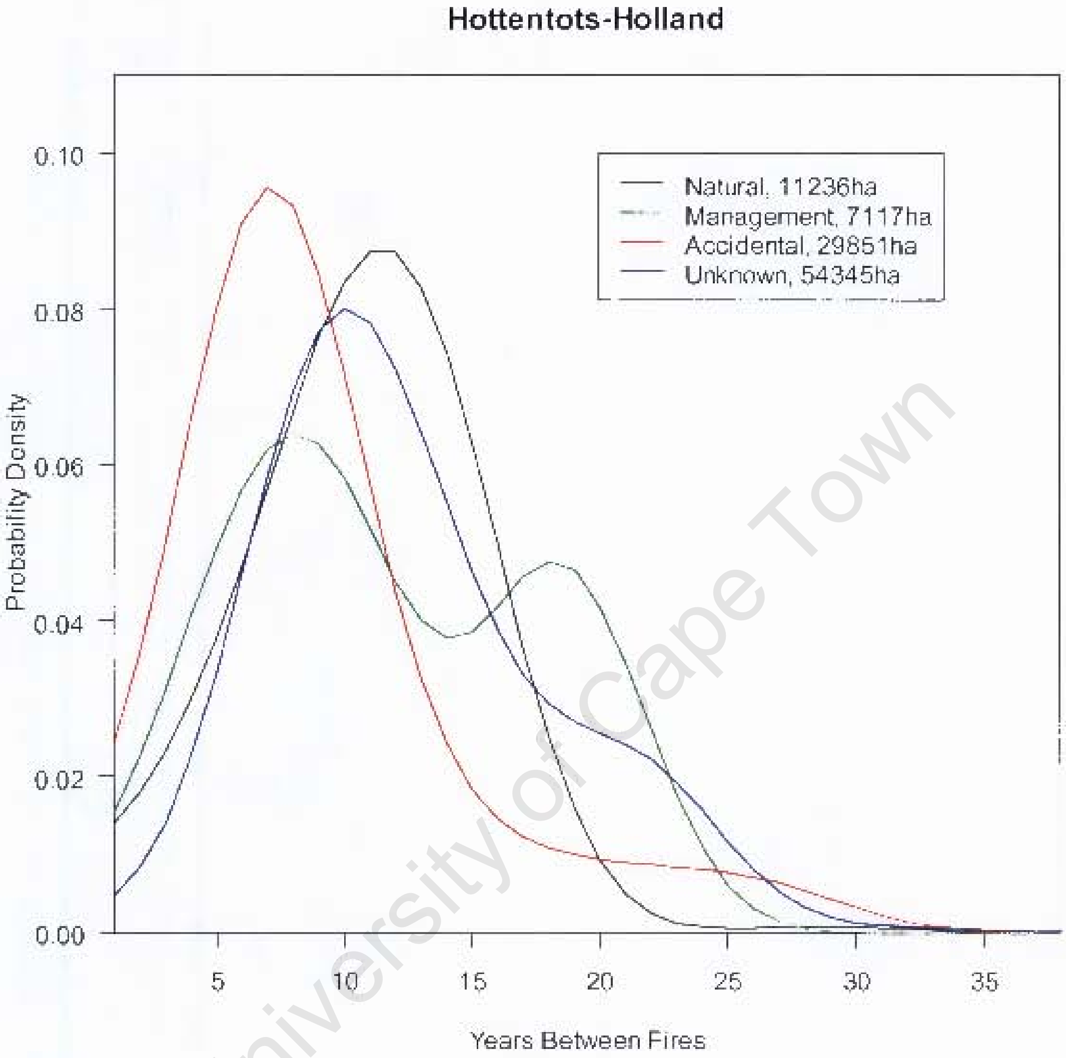


Figure 2.9: Smoothed scatter plots of the probability density of fire return intervals for the Hottentots-Holland. The black line represents the fire intervals resulting from a natural burn. The green line represents fire intervals resulting from a prescribed management burn. The red line represents fire intervals resulting from a fire with an anthropogenic ignition source. The blue line represents the fire intervals resulting from a fire of unknown ignition source.

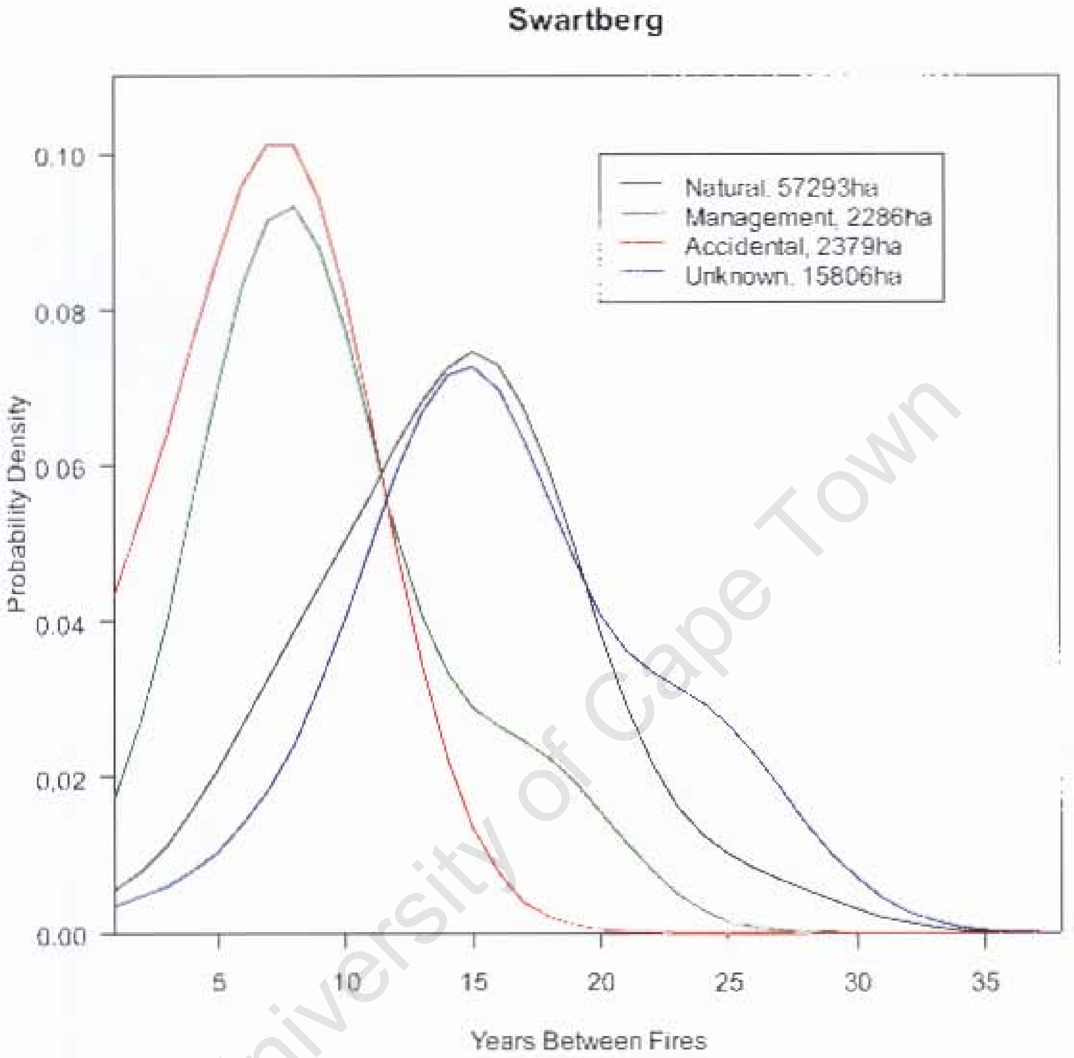


Figure 2.10: Smoothed scatter plots of the probability density of fire return intervals for the Swartberg. The black line represents the fire intervals resulting from a natural burn. The green line represents fire intervals resulting from a prescribed management burn. The red line represents fire intervals resulting from a fire with an anthropogenic ignition source. The blue line represents the fire intervals resulting from a fire of unknown ignition source.

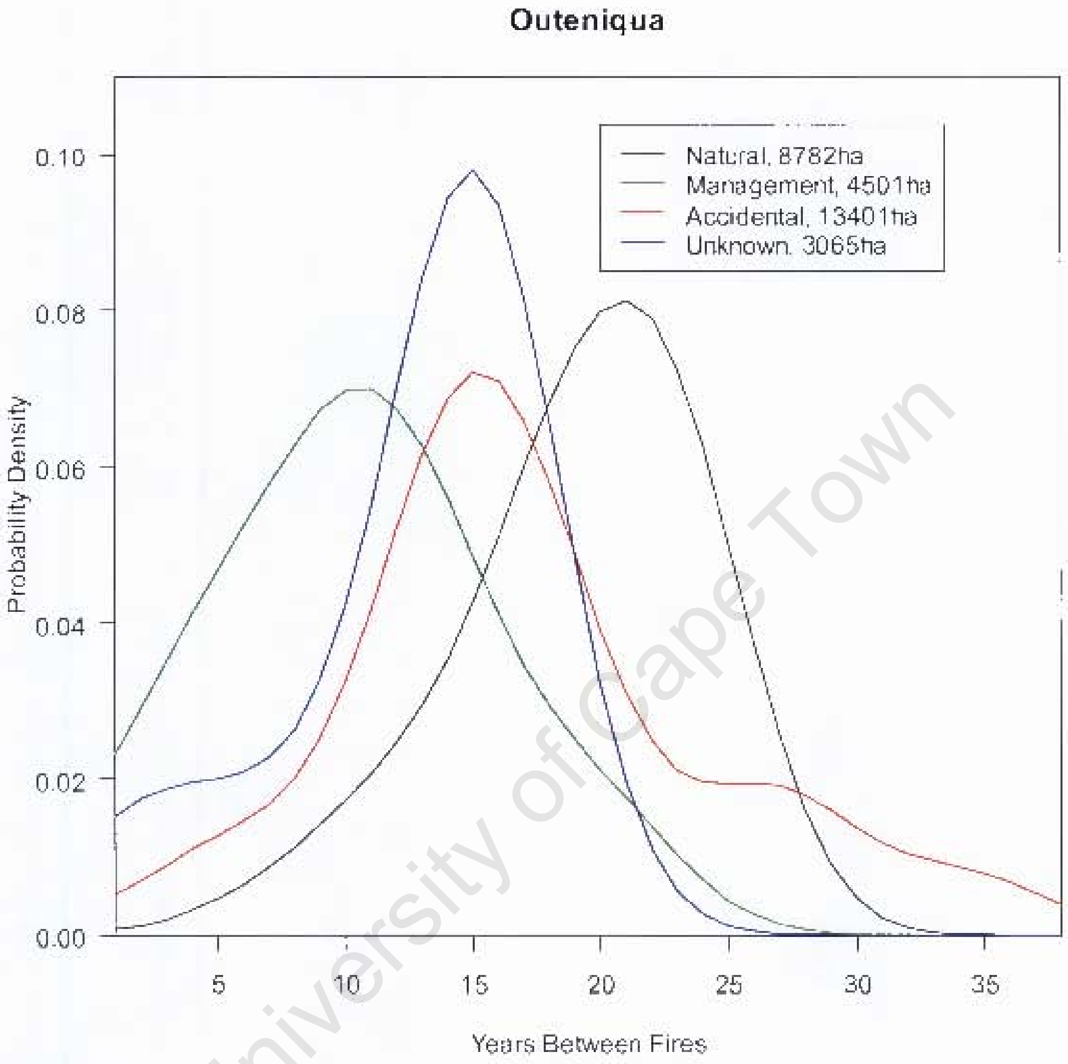


Figure 2.11: Smoothed scatter plots of the probability density of fire return intervals for the Outeniqua. The black line represents the fire intervals resulting from a natural burn. The green line represents fire intervals resulting from a prescribed management burn. The red line represents fire intervals resulting from a fire with an anthropogenic ignition source. The blue line represents the fire intervals resulting from a fire of unknown ignition source.

Table 2.2: Proportional area burned by different sources of fires for the four study sites in the Cape Floristic Region. Fire data from CapeNature for 1970 to 2007

	Natural	**Management**	**Accidental**	**Unknown**
Cederberg	44%	6%	5%	45%
Hottentots-Holland	11%	7%	29%	53%
Swartberg	74%	3%	3%	20%
Outeniqua	30%	15%	45%	10%

Chapter 3. Vegetation age effects on fire size and frequency

3.1 Introduction

Large fires have drawn much media attention in recent years due to the extensive damage they can cause to human property and livelihoods. Fuel accumulation, as a result of fire suppression, have been at the centre of the debate around the occurrence of catastrophic fires in southern California (Minnich and Chou 1997; Moritz *et al.* 2004). A comparative study between small patchy fires in northern Baja California, Mexico, and large fires in neighbouring southern California, USA, led Minnich and Chou (1997) to hypothesise that fire suppression policies resulted in fuel accumulation in old vegetation stands and that this was the underlying reason for these large fires. Keeley and Fotheringham (2001) however, showed that fuel age in chaparral was not correlated to large fires and that fuel reduction management practices would not be effective in preventing large fires in this region.

This debate has relevance in the fynbos of South Africa where periodic large fires contribute to the majority of the total area burned (Forsyth and Van Wilgen 2008). A history of fire suppression (Bands 1977) and a recent expansion of urban areas (Midgley *et al.* 2005) contribute to the risk to people and property from large fires in the CFR. Effective fire protection measures are necessary to reduce the risk of large wildfires to people and property. This is only possible with an accurate understanding of the drivers of large fires. Therefore the first aim of this study is to establish whether there is a relationship between fire size and fuel age.

It has been hypothesised that large fires are driven by extreme weather conditions (Bessie and Johnson 1995; Moritz 2003; Forsyth and Van Wilgen 2008). For the CFR these conditions are a combination of hot, dry and windy days where fuel moisture levels become very low. It has been forecast that such conditions may become more prevalent in the future due to climate change (Tadross *et al.* 2005).

An increase in climatic forcing would lead to an increase in fire frequency and this would have adverse effects on fynbos biodiversity. Variability in the elements of a fire regime (fire frequency, intensity, season and size) is important for the coexistence and diversity of species in fynbos communities (Van Wilgen *et al.* 1992), as long as the variability falls within accepted limits. Short fire intervals (<5 years between fires) can exclude non-sprouting from a region due to the slow maturation of these species (Van Wilgen 1981b). However, fuel loads in young fynbos are generally thought to be too small to carry a fire before most non-sprouters have flowered (4–6 years) (Richardson and Van Wilgen 1992). There are exceptions to this rule where extreme weather conditions result in young fuels igniting (Bands 1977). Since an increased frequency of short fire return intervals would threaten biodiversity in the fynbos, the second objective of this study aims to explore temporal changes in the burning patterns of young fuels.

3.2 Methods

The analysis of temporal and spatial patterns of fire intervals was used to achieve the two aims of this study. The age of vegetation burned by a large fire can show a relationship between fire size and fuel age, whereas the cumulative proportions of vegetation age classes can be used to explore a temporal change in fire frequency. The method for extracting fire intervals is described in Chapter 2, Section 2.2.

Quantification of the fuel age burned by different sized fires was done by using the median fuel age of a fire. The median is a more correct representation of the average fire interval than the mean, because the distribution of fuel ages burned can not be assumed to be normally distributed (Chapter 2). By noting the distribution of median fire return intervals with fire size one can say whether large fires are as a result of fire suppression. A scatterplot of fire size verses median fire interval was plotted and a one sided regression analysis was calculated to quantify the significance of the resulting relationship.

The second objective of this study was to examine the burning patterns in young fuels through time. The conventional method for examining temporal trends in fire frequency is to divide the sample period into temporally distinct epochs and compare the distribution of fire intervals between each time period (Reed *et al.* 1998). The choice of the split between time periods is usually linked to changes in external influences on fire regimes, such as a change in management policy or climatic conditions. This method is best suited to long sample periods where trends can be distinguished from the natural variability of stochastic disturbances. There is a degree of temporal autocorrelation in woody fuels, such as fynbos, where the effects of a large fire can be observed in the landscape for many years after the event (Morgan *et al.* 2001). This is due to the initial slow accumulation rates of fuels and thus the selection of temporal splits affects the resulting fire interval distributions. Another major limitation to this technique is that the entire study site needs to burn at least once so that initial vegetation ages can be calculated. This limits the length of time available for analysis. Consistent recording is also needed from the beginning to the end of the sample time period. An initial analysis of the fire records in the study sites revealed that the sample period of the fire records was too short to overcome the above mentioned limitations. Thus a novel approach was developed to investigate temporal variations in fire frequency.

My approach focused on the area that burned in a particular year in the fire record, and then recorded the fire intervals at which those same areas reburned, i.e. looking forward through time to extract the fire intervals from a fixed spatial frame of reference. This approach allowed me to use a longer time period of the fire records than the previous chapter. I was able to consider fire history polygons (FHP) originally burned as early as the 1970s and then look forward through time at when those FHPs reburned. The median values were calculated from extracted fire intervals by converting the area associated with each FHP into a percent of the original area burned. The median is thus the vegetation age at which 50% of the original area has reburned. A graphical representation of this concept can be seen in Figure 3.1. A one sided linear regression was used to test for a temporal trend. For significant study sites the parameterised linear model was used to calculate the difference between expected fire intervals from 1970 to 2007.

3.4 Results

Fire size has a substantial impact on the total area burned in each study site. The total area burned per year (Figure 3.2) shows that large fires have been a constant feature in each study site throughout the recording period. Large fires burn between 15 000ha to 20 000ha in the Cederberg, Swartberg and Hottentots-Holland, with a single exception of 1999 fire year in Hottentots-Holland where the combination of three large fires burned over 50 000ha. Large fires in the Outeniqua burned 10 000ha on average, due to the smaller size of this study site. There is a significant relationship between fuel age and fire size in the Swartberg, where large fires burn older vegetation stands (Figure 3.3). There is no significant relationship between fire size and fuel age in the Cederberg, Hottentots-Holland and Outeniqua study sites (Figure 3.3).

Temporal trend of median fire intervals extracted forward through time from fixed spatial frames of reference are shown in Figure 3.4. The Cederberg, Hottentots-Holland and Outeniqua all show significant trends of decreasing fire intervals through time. The Swartberg has no significant temporal trend. The parameterised linear models for the three significant study sites are as follows: for the Cederberg

$$g(t) = 13.76 - 0.226t, \qquad (1)$$

for the Hottentots-Holland

$$g(t) = 12.66 - 0.226t \qquad (2)$$

and for the Outeniqua

$$g(t) = 18.57 - 0.315t \qquad (3)$$

where *g(t)* is the expected fire interval for *t*, the year from which the fixed spatial frame of reference is taken. A comparison between the expected fire intervals for 1970 and 2000 (Table 3.1) shows that in this 30 year period the Cederberg fire intervals have declined by 6.8 years, the Hottentots-Holland fire intervals have declined by 6.8 years and the Outeniqua fire intervals have declined by 9.5 years.

3.5 Discussion

The results in Figure 3.3 show that large fires have a widely spread median fuel age and thus large fires burn a variety of vegetation ages. There is a significant relationship between fire size and fuel age in the Swartberg study site, but not in the Cederberg, Hottentots-Holland or Outeniqua. The Swartberg is one of the driest regions in the CFR and thus fuel accumulation rates may be slower. This suggests that the large fires in the Swartberg are largely determined by fuel characteristics and support the hypothesis that fuel characteristics determine fire behaviour (Mutch 1970). However, the other three study sites contradict this hypothesis and suggest that large fires in the Cederberg, Hottentots-Holland and Outeniqua are influenced by other factors. This fits with the hypothesis that large fires burn most of the area in fire-prone ecosystems, as one would expect these large fires to burn through a mosaic of fuel ages. This hypothesis is supported by Mortiz *et al* (2004) who show that most of the area burned by wildfires in the chaparral of southern California are a result of a small number of fires that burned large areas under extreme weather conditions. Keeley *et al* (1999) also showed that the fuel age of chaparral did not influence fire size. The two alternative results in Figure 3.3 suggest that fynbos biome may be an applicable study area for the fuel-weather threshold debate.

The aim of this analysis was to quantify temporal changes in fire intervals. This can be a challenging task given the stochastic nature of a fire regime. Since there is a large degree of natural variation in the temporal and spatial scales of fires, high-quality time series are required to accurately distinguish temporal trends in fire history from background noise. Conclusions from temporal trends analyses are uncertain with short data sets. Studies in systems with long average fire return times need many times this average to determine a trend from the natural variability in stochastic systems. Westerling *et al* (2006) identified temporal trends in fire history for western US forests using 34 years of data for an ecosystem. They concluded that wildfire activity had suddenly increased in the mid-1980s in response to changes in climate. Marsden (1982) has shown that fires in this region occur in temporal clumps so that some years may have a large area burned while others have a much smaller area burned. He concludes that this was usually a result of the irregular occurrence of severe weather. In light of this result it can be concluded that the time series used by Westerling *et al* (2006) would not have been long enough to distinguish the difference between a temporal change in fire frequency or large fire clumping in these western forests. This example demonstrates the difficulties of temporal analyses of fire histories.

Detecting temporal change in fire frequency is important for many reasons; e.g. determining the impact of climate change (Swetnam 1993), predicting temporal changes in the biodiversity of fire-prone ecosystems (Keane *et al.* 2008) and assessing changing risk to people and property on the urban-rural boundary (Pausas *et al.* 2008). Temporal changes in fire frequency, in a time series analysis, have been defined as a combination of two or more homogeneous statistical distributions and result in a mixed empirical observations (Johnson and Gutsell 1994). A common method to partition mixed distributions into homogeneous distributions is to divide a time series into temporally distinct epochs based on changing external influences on fire (Reed *et al.* 1998). For example, to divide the time series into periods of different fire management policies. By analysing the separate time periods with statistical distributions, conclusions may be drawn about the effect of these external forces. A limitation to this method however, is that there is a large degree of temporal autocorrelation in time dependant fire-prone ecosystems such as fynbos. Thus, a large fire towards the end of one time period will dominate the fire frequency distribution for several years (Brown *et al.* 1991; Johnson and Gutsell 1994). Distinct sample periods would thus need to be sufficiently long so as to limit the effect of autocorrelation. The 38 year fire history used in this study would not be able to overcome this limitation if it were divided into successive distinct sample periods.

A novel approach was developed in this study that allowed me to exclude the impacts of temporal autocorrelation. The method illustrated in Figure 3.1 uses the area burned in a sample year and extracts the future fire intervals for that fixed spatial frame of reference. In this manner a fire interval distribution can be extracted for each year in the time series. The fire interval values at which 50% of the original area reburned was used to detect a temporal trend in fire frequency. From Figure 3.4 it can be seen that there is a lot of variation in the data, but that there is a significant temporal trend in the Cederberg, Hottentots-Holland and Outeniqua study sites. This change could be the result of increased human pressure in some areas, a change in fuel characteristics due to invasive alien plants, an increased frequency of extreme weather events or a combination of any of these factors. However, the rate at which the fire intervals are decreasing in the two western study sites (Equations 1 and 2) suggests that the factors driving change in these two areas is the same. Population densities around the Hottentots-Holland are greater than the Cederberg due to its proximity to large urban centres; therefore increased human pressure is unlikely to be the cause of this temporal trend. The impact of invasive alien vegetation was beyond the scope of this thesis and thus this factor cannot be discounted. A detailed analysis of the relationship between fire occurrence and weather follows in the next chapter, which will assist in analysing the cause of the observed temporal trend.

The results for both the fire size and changing fire frequency analyses in this chapter have implications for management of biodiversity in the fynbos. The size of a fire affects the heterogeneity of the landscape where greater patchiness is linked to higher diversity (Clark *et al.* 2002). A fine mosaic of vegetation ages is believed to be better for recruitment between patches where the distance covered by species reliant on dispersal is important for recolonising burned sites (Forsyth and Van Wilgen 2008). Changes in structure and composition of fynbos impacts on the habitat of animals (Kruger and Bigalke 1984). Fire events are temporally autocorrelated so there is a legacy of past fire events in a landscape (Morgan *et al.* 2001). The effects of a large fire will thus be visible in the landscape for many years after the event.

Although fire season, size and intensity have been shown to impact on landscape ecology, fire frequency is often cited as the key component of a fire regime to affect community diversity (Kruger 1977; Noble and Slatyer 1980; Bradstock *et al.* 1998a; Clark *et al.* 2002). Short fires intervals (less than juvenile periods) favour rapidly maturing species and have a detrimental effect on large seed reproducing shrubs typically in the Proteaceae family (Van Wilgen 1981b). The elimination of these species can cause dramatic structural changes to the vegetation (Van Wilgen 1982) with consequences for the processes mediating species co-existence (Thuiller *et al.* 2007). Thus increasing fire frequencies has major implications for biodiversity in the CFR.

3.7 Figures

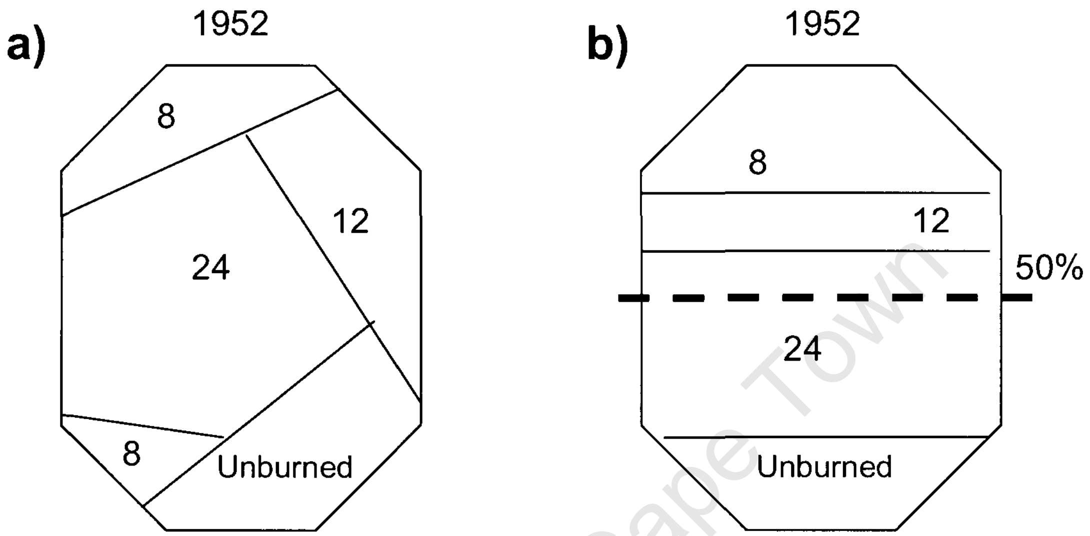


Figure 3.1: Simplified representation of a) fire interval extraction (of 8, 12 and 24 years between fires and unburned Fire History Polygons) from a fixed spatial reference (a fire scar from 1952) and b) calculating the median fire interval at which 50% of the 1952 fire scar reburned

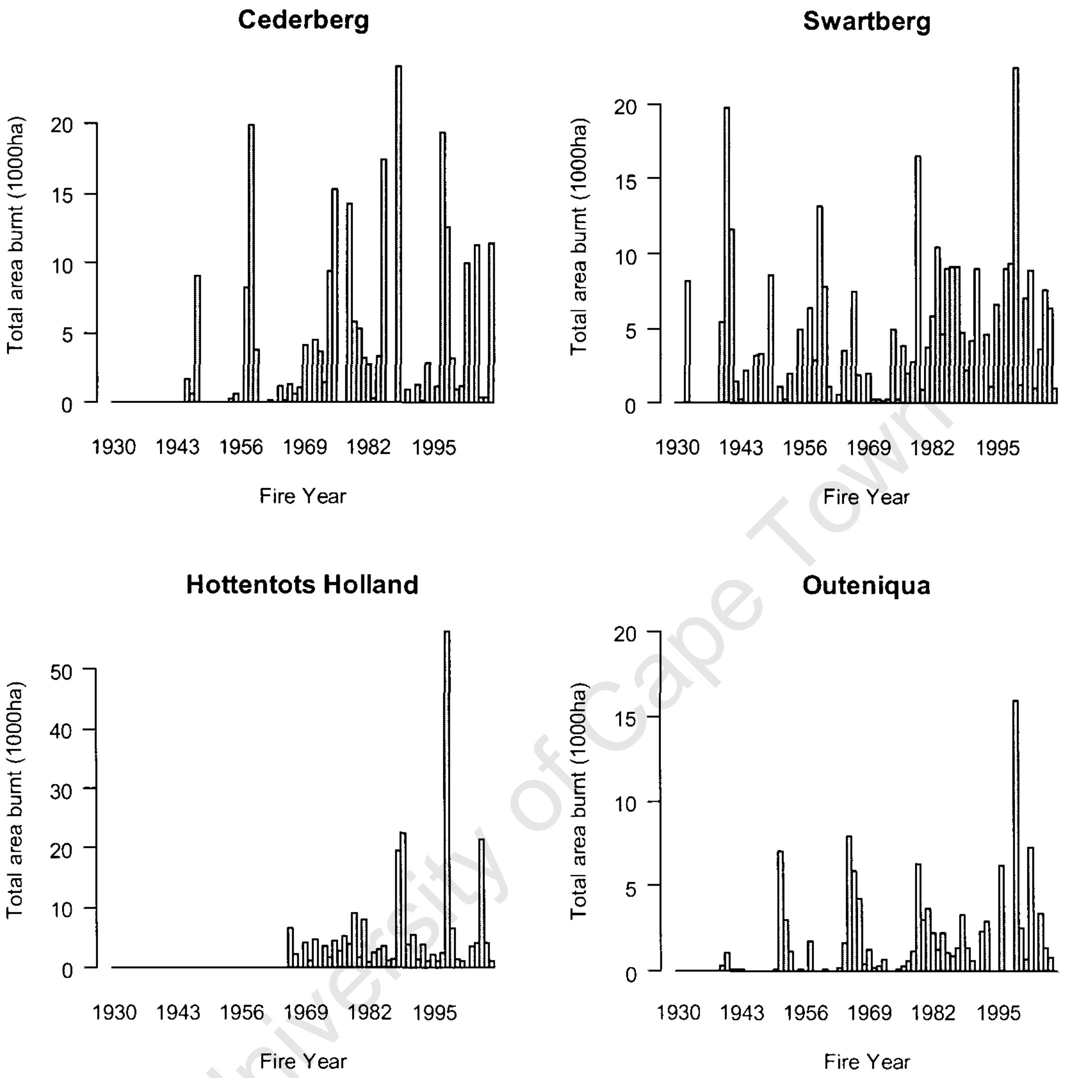


Figure 3.2: Annual area burned according to the mapped historical fire records for four study sites in the Cape Floristic Region

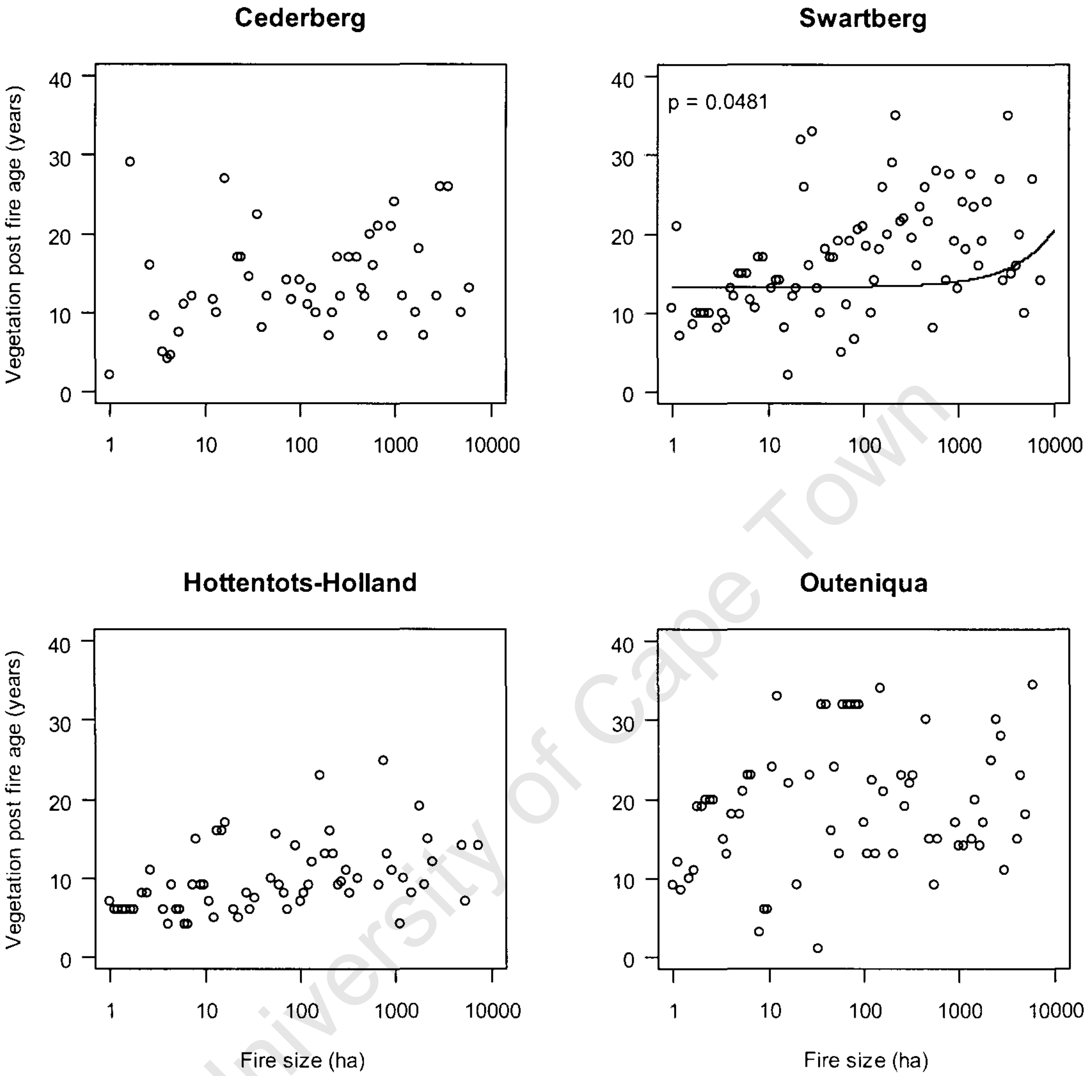


Figure 3.3: Median vegetation age burned by different fire sizes for the four study sites in the Cape Floristic Region. Fire size is plotted on a log scale. There is a significant relationship in the Swartberg study site between the median fuel age and fire size

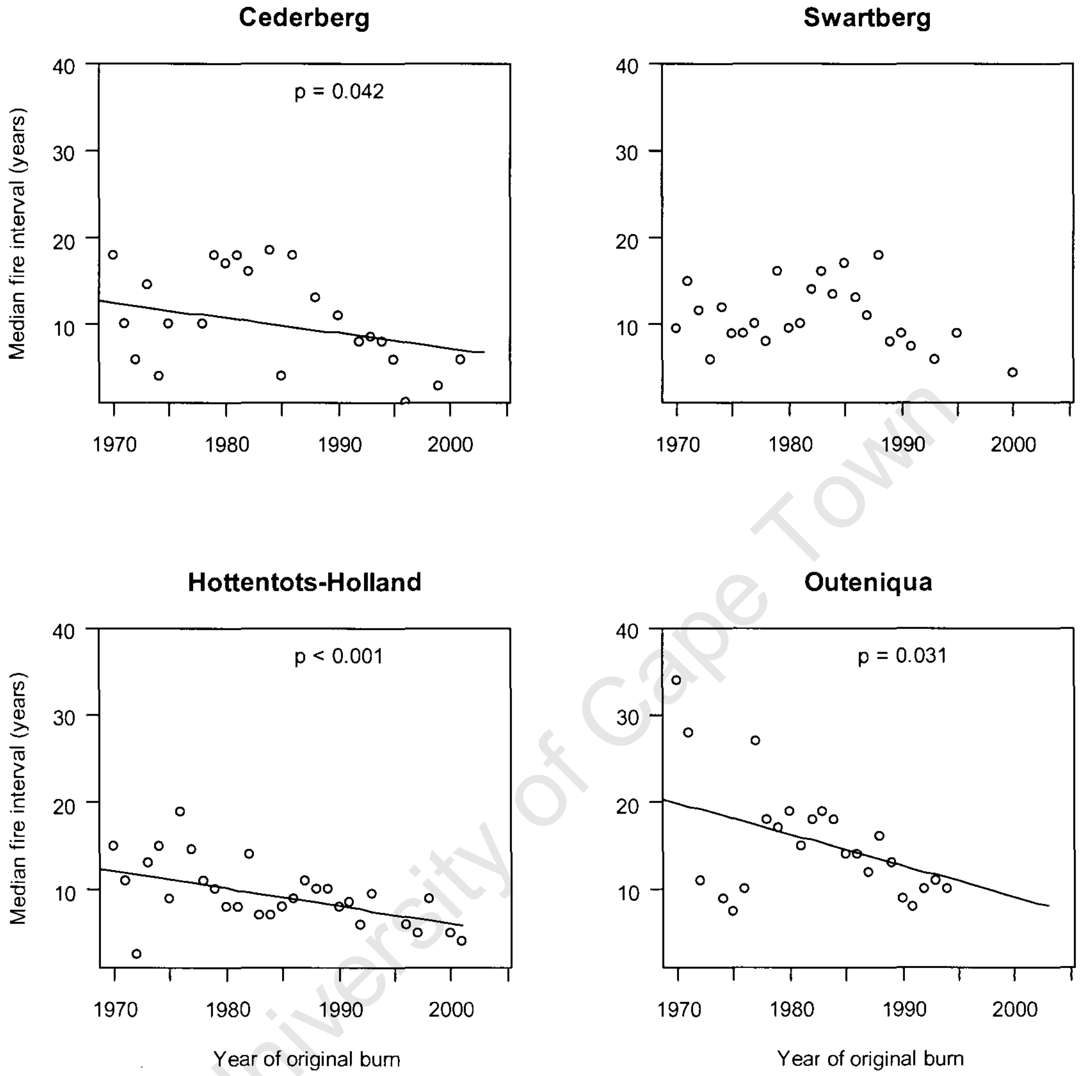


Figure 3.4: Temporal trend of fire intervals extracted forward through time from the fixed spatial reference frame of fire scars from a specific fire year. These 'years of original burn' range from 1970 to 2000 for four study sites in the Cape Floristic Region. The Swartberg study site did not have a significant temporal trend

Table 3.1: Expected fire intervals using the parameterised linear models to compare temporal change in fire frequency for three study sites in the Cape Floristic Region. The Swartberg has no significant temporal trend.

	Expected fire intervals		**Difference**
	1970	**2000**	(years)
Cederberg	13.8	7	6.8
Hottentots-Holland	12.7	5.9	6.8
Outeniqua	18.6	9.1	9.5

Chapter 4. Relating fire frequency and weather using self-organized maps of synoptic conditions

4.1 Introduction

The Cape Floristic Region (CFR) in South Africa is a fire-prone Mediterranean-type ecosystem adapted to a given range of fire frequencies (Kruger and Bigalke 1984). The periodicity of fire is reliant on vegetation age, the rate of ignitions and weather conditions that facilitate fires. The field of meteorology is a vast resource that can be used to analyse the relationship between weather conditions and fire patterns. However, past investigations into fire weather for the fynbos have centred around fire danger indices (Van Wilgen 1981a; Van Wilgen 1984a; Van Wilgen 1984b; Van Wilgen *et al.* 2003a; Van Wilgen *et al.* 2003b) with the exception of a few unpublished studies (Juhnke 1985; Coop 2004). Fire danger indices are typically developed for a specific region using empirical data on fires and weather conditions (e.g. the Australian McArthur system is developed for eucalyptus forests). A fire danger rating model has not been developed for the fynbos biome of South Africa. Analyses of meteorological processes have been used as an alternative to fire danger rating systems (Juhnke 1985; Millán *et al.* 1998) thus, using synoptic states, I developed a novel approach to quantifying the relationship between fire events and weather. The principle aim of this work is to identify spatial and temporal patterns in the frequency of weather events associated with fire occurrence.

The climate of the CFR is strongly affected by shifts in the position of the band of westerly waves, and associated low pressure systems, and the persistent high pressure system in the southern Atlantic. The seasonal shift of these systems northwards in winter brings rain to the region in the form of cold fronts, whereas the southward shift of the south Atlantic high pressure system blocks the passage of these fronts in summer (Tyson 2000). Characterising the continuous movement of these systems can be done using self-organising maps (SOMs) to identify the primary features of the synoptic-scale circulation of the region (Hewitson and Crane 2002).

SOMs provide a non-linear alternative to principle component analysis to describe data structure and can be viewed as a form of cluster analysis where a multi dimensional array of data points is assigned a distribution of nodes. Thus a multi-dimensional data set of weather variables can be described by a number of representative synoptic states. Hewitson and Crane (2002) provide a detailed description of how SOM nodes are calculated.

SOMS have been used to describe synoptic-scale circulation changes over time as well as relating synoptic-scale circulation features to regional events. Hewitson and Crane (2002) used this technique to relate synoptic-scale circulation features to precipitation data for Pennsylvania, USA; Main (1997) used SOMs to analyse seasonal patterns in atmospheric circulation over southern Africa and Coop (2004) analysed fire vulnerability of the south western Cape, South Africa, with climate change simulations. I therefore saw opportunity to apply SOMs to fire occurrence data in order to identify spatial and temporal patterns in the relationship between fires and weather.

4.2 Methods

Self Organising Maps

Self-organising maps (SOMs) are used to analyse the discrete conditions that describe a continuous system (Kohonen 1997). SOMs have many different applications, one of which is the analysis of weather (Hewitson and Crane 2002). Weather is a continuous process that is divided up into discrete synoptic states for descriptive purposes. The analysis of weather involves the measurement of many variables to describe each day. This creates multi-dimensional data sets that can then be analysed using SOMs. Unlike other cluster techniques, SOMs don't aim to identify clusters in the data; instead they try to identify archetypal points that represent the area of data around it (Crane and Hewitson 2003). These representative points are called nodes. Each node represents the archetypal state of the surrounding data with similar states being located close to each other and dissimilar states being located far apart in the SOM space.

SOMs can be customised, providing diverse opportunities for analysis. The user specifies the degree of generalisation by specifying the number of nodes. Having many nodes will capture a wider array of weather states, but the difference between synoptic states will be small. Fewer nodes increase the generalisation of the classification so the difference between the synoptic states becomes greater, but some of the detail is lost. The distinction between different nodes becomes important when comparing properties of different synoptic states.

One of the key advantages to using SOMs for synoptic climatology is the ability to visualise the relationships between the nodes. A single descriptive variable can be used to represent the characteristics of the nodes. For synoptic states this can be done by displaying the characteristic sea level pressure charts for each node. This creates a simple visual display of each of the synoptic states, see Figure 1.

The number of nodes chosen for this classification was twelve. Thus everyday can be represented by a node number from 1 to 12 according to its specific synoptic conditions. This number accurately represents the circulation patterns over the Western Cape while still ensuring that the nodes are dissimilar. It is important to note that nodes do not represent a temporal progression of synoptic states; rather they are spatial archetypes of clustered data. Temporal progression of nodes is indicative of synoptic circulation and can follow any order (e.g. node 5→ 5→ 8→ 9→ 6); although some flow patterns are more common than others.

Data

The weather data used in this analysis is area-averaged gridded data sets from the US National Center for Environmental Protection – National Center for Atmospheric Research (NCEP-NCAR) reanalysis project. Data was obtained from the start of 1970 to the end of 2007. The Climate Systems Analysis Group (CSAG) at the University of Cape Town analysed these data with a SOM software package, SOM_PAK (Kohonen *et al.* 1995), which classified the weather patterns in the Western Cape into 12 typical synoptic states.

The fire data used in this analysis are described in Chapter 1.3. Fire records from the 1970s to the present were included in this study, matching the time span for which weather records are available. Fires with missing dates were removed from the dataset, as these could not be matched up to a specific day's synoptic conditions. Small, management fuel prescribed burns were removed from the analysis as specific weather condition are selected for burning (Juhnke 1985). Including these fires would skew the results towards poor synoptic burning conditions.

Large fires contribute to a vast proportion of the total area burned in the fire records, but they account for very few of the total number of fires on record. Fires are thus weighted by the log of their area in all analyses.

The relative frequency of each of the 12 nodes was calculated by summing the total number of days mapping to each node and dividing by the total number of days in the data set. The node value for the day on which each fire started burning was recorded, and thus the 'fire frequency' for each node was calculated. The seasonal pattern of nodes was analysed by calculating the frequency of each node in spring, summer, autumn and winter.

The purpose of this study is to investigate whether a relationship exists between synoptic states and fire occurrence. To examine this, the following hypothesis was set up:
H_0: There is no relationship between fire occurrence and synoptic states
H_1: There is a relationship between fire and synoptic states.
The date of each fire was mapped to one of the twelve nodes and in that way a count of the number of fires occurring under each synoptic state was produced. Chi-squared tests were performed on the observed frequency of fire day nodes against the expected frequency of all nodes in the data set. This test shows whether or not the 'fire weather' for each study site was a random subset of the general weather patterns and allows us to conclude that fires do or don't tend to burn under specific synoptic states. The residual difference was calculated between the expected frequency of each node, based on its frequency from 1970 to 2007, and the frequency of each node on the day of a fire. The nodes with the greatest residuals are responsible for significance of the chi-squared results. Thus these are the synoptic conditions that 'promote' wild fires.

Chi-squared tests were used to test for a temporal change in the frequency of each node. These results were displayed by decade. The frequency of nodes in each decade was used as the expected frequency against which to test the frequency of nodes in the subsequent decades.

All results are displayed visually with the same node layout as Figure 4.1. Absolute values for frequency calculations may differ between study sites in proportion to the differing number of fire records for each site. Thus all results have been scaled so that the largest circles in each figure are the same size. The absolute value of the largest result is always given.

To test whether synoptic states can be used as a measure of fire risk, independent fire data were compared to the fire weather identified above. A fire risk indicator was created from the 12 nodes by ordering them according to the residuals from the chi-squared tests from least to most significant. This was done for both the eastern and western CFR. To test for the effectiveness of these proposed fire risk indicators I used fire records from nearby reserves and plotted the area burned by each fire against the ordered node values. Fire records from the Grootwinterhoek and Vrolijheid reserves were used to test the 'western region fire risk indicator' and records from the Kammanasie, Grootvadersbos and Gamkaberg reserves were used to test the 'eastern region fire risk indicator'. The nodes are treated as factors and so box and whisker plots are drawn for the fires that occurred in each synoptic state.

4.3 Results

Synoptic states over southern Africa

The sea level pressure charts that describe each node are shown in Figure 4.1. Figure 4.2 shows the frequency of each node throughout the entire data period. Note that the corner nodes, nodes 1, 3, 10 and 12, occur with the greatest frequency. This indicates that these nodes are representative of more stable synoptic states. The less frequent nodes (nodes 5, 8 and 11) of Figure 4.2 indicate transitional states. The frequency distribution of days mapping to each SOM node is fairly uniform with a 3% difference between areas of highest and lowest frequency.

The weather in the Western Cape is predominantly affected by the South Atlantic high pressure system from the west and frontal systems from the south. A typical progression of a frontal system can be seen by following nodes 2→ 4→ 7→ 10. The front, a low pressure system, moves from west to east usually over a period of four days and is a common winter flow pattern (Figure 4.3). This brings cooler temperatures and rain to the Western Cape. The South Atlantic high pressure dominates the weather patterns in summer when it is at its southern most extent, thus blocking the northward progression of polar fronts. It also moves from east to west and its onshore movement (nodes 8, 11 and 12, Figure 4.1) results in hot, dry, sunny conditions and the characteristic south easterly winds over the Western Cape. When the South Atlantic high pressure system moves offshore (nodes 3, 6 and 9), a warm tropical air mass, known as an easterly wave low, descends from the north and is associated with strong convective activity.

Synoptic states and fire events

Table 4.1 reports the results from the chi-squared tests against the expected node frequencies of Figure 4.2 and the observed node frequencies of Figure 4.4. It shows that there is a significant difference between the observed fire weather frequencies and the expected frequency of all nodes in the 38 year sample period. This is true for each study site. It can therefore be concluded that there is a significant relationship between synoptic states and fire events.

The residual difference between the observed and expected frequencies from the above test can be used to explore which synoptic states have the strongest influence on fire events. It is the positive residuals (Figure 5) which identify the nodes associated with fire weather. Residual for the Cederberg showed a significant relationship between fire occurrence and weather on days mapping to nodes 3, 9 and 6. Fire weather in the Hottentots-Holland mapped to nodes 3, 6, 9, 8 and 12. The Swartberg had a high frequency of fire occurrence on days mapping to node 2 and 6, and the Outeniqua fire weather mapped to node 2.

A temporal trend in node frequency was tested for by using a chi-squared test with the node frequencies of a particular decade as the expected pattern against the observed node frequencies in subsequent decades. All tests where highly significant concluding that there has been a significant change in the frequency of nodes through time (Table 4.2).

Synoptic states as an indicator of fire risk

I created two regional indicators of fire risk due to the clear difference in fire weather between the eastern and western parts of the CFR. The residuals of the western study sites (Cederberg and Hottentots-Holland) were summed for increasing fire risk. In ascending risk the order of the 12 nodes for the 'western region fire risk indicator' is as follows:

node 10 node 7 node 1 node 4 node 11 node 2 node 5 node 8 node 12 node 9 node 6 node 3.

Thus node 10 is the least likely to be associated with a fire event and node 3 is the most likely.

The residuals for the Swartberg and Outeniqua were summed and ordered the 'eastern region fire risk indicator' for increasing fire risk as follows:

node 10 node 7 node 8 node 11 node 12 node 9 node 4 node 1 node 5 node 3 node 6 node 2.

As for the western region, node 10 is the least likely to experience a fire, but node 2 is the most likely.

The box and whisker plots show the mean area burned as a bold line; the lower and upper quartiles as the bottom and top lines of the box; the 5th and 95th percentiles are the limits of the lines extending out of the box and the open circles above each plot show the outlying values, i.e. the very large fires. In the western region (Figure 4.7) node 3 has the highest number of outlying values. This translates as the synoptic state with the greatest fire risk has the largest number of extremely large fires associated with it. Similarly the other high fire risk nodes are also associated with extremely large fires. The only node that breaks this pattern is node 2, but this can be attributed to the berg wind conditions associated with this node. In the eastern region (Figure 4.8) the pattern of increased fire size with increasing fire risk is visible by examining the largest fires. The three highest risk nodes have the highest number of large fires associated with them, shown by the outlying values.

4.4 Discussion

This chapter has introduced a powerful tool for the generalisation of weather systems. SOMs create an array of easily visualised synoptic states encompassing a continuous set of weather conditions. I have used the SOM nodes to show that the there is a significant relationship between fire occurrence and specific synoptic states (Table 4.1). Studies on the meteorological effect on fire behaviour have generally been confined to the creation of complex indices which relate fire hazard potential to variables such as wind speed, relative humidity and temperature (Millán *et al.* 1998). In this chapter I have used the technique of self-organising maps to relate fire events to specific weather conditions.

The most remarkable result is the clear divide between synoptic states and fire events in the eastern and western CFR. Nodes 3, 6, and 9 contributed the most to the significance of the chi-squared tests in both the Cederberg and the Hottentots- Holland. These nodes are associated with an easterly wave low (the low pressure extending southwards from the north) and can cause convective activity over these study sites. Lightning is associated with strong convective systems (Tadross *et al.* 2005) and is a known cause of fires in these study sites. These nodes are also characterised by strong south-westerly winds.

Node 2 made the greatest contribution to the significant relationship between weather and fire events in both eastern study sites (Swartberg and Outeniqua). Node 2 shows a feature called a tropical temperate trough, which is a linkage of the easterly wave low pressure system in the north of the map and cold fronts as they pass to the south of the country. These tropical temperate troughs propagate from the western half of the country to the east as a solid cloud band that stretches in a NW-SE direction and are preceded by hot, dry north-westerly winds known as berg winds. Berg winds are analogous to foehn winds in other parts of the world.

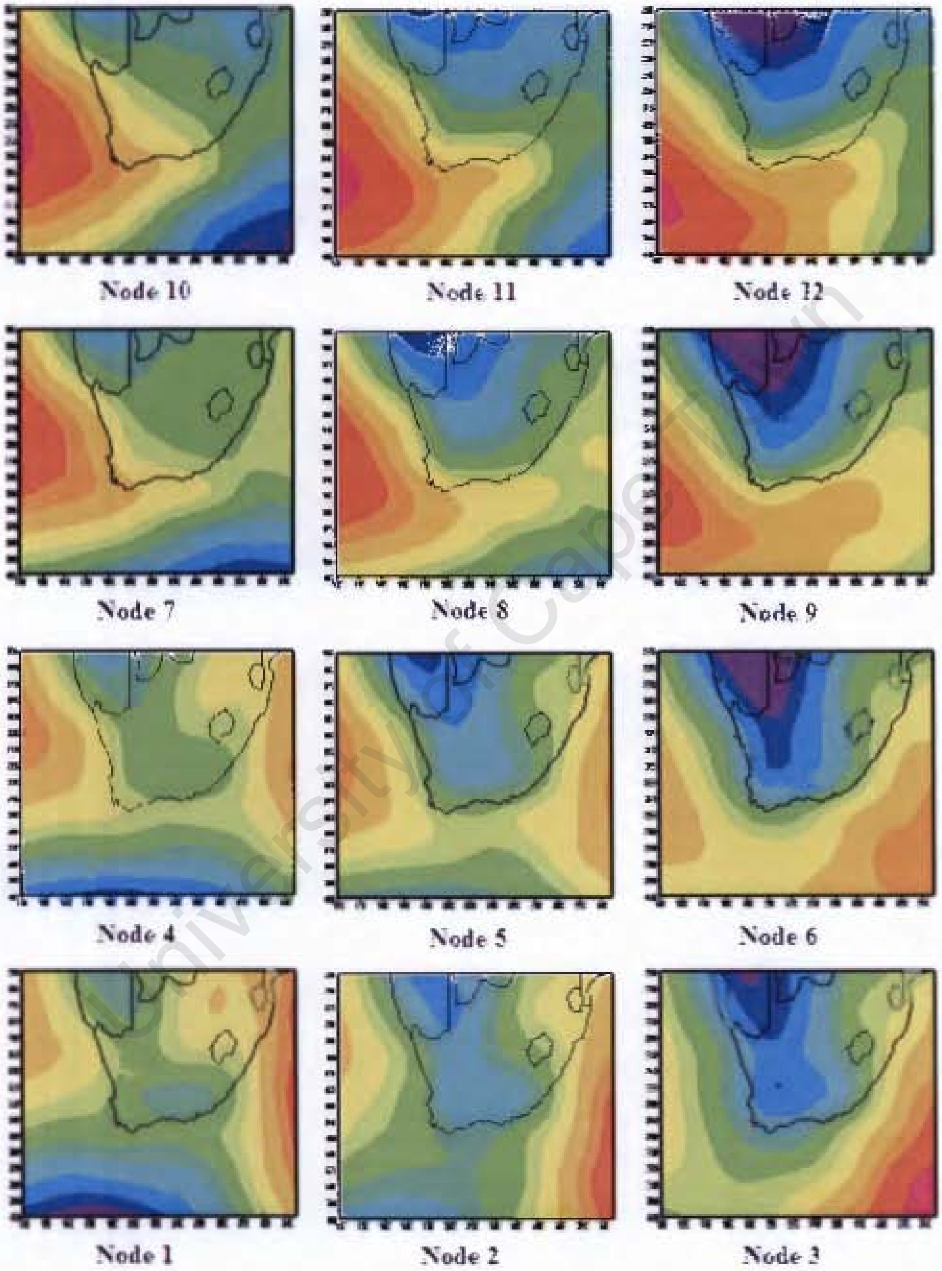
Van Wilgen (1981a) found most fires in the CFR were associated with southerly to south-easterly winds, with the exception of the south eastern region, where fires were associated with south-westerly to north westerly winds. Horne (1981) also found that fires in the southern CFR were associated with westerly winds. These two studies support the results found in this study and highlight the regional differences between fire patterns in the eastern and western CFR.

One of the aims of this thesis is to identify temporal trends in the fire regions. Since a significant relationship exists between fire and weather and analysis of temporal trends in the synoptic states was undertaken. Figure 4.6 showed that there have been slight shifts in node frequencies in the past four decades. The nodes most relevant to fire occurrence (nodes 2, 3 and 6) all show an increase in frequency through time. Studies on the atmospheric circulation over the Western Cape have shown that although there is a lot of variability in historical weather patterns, there has been an increase in the frequencies of strong high pressure systems. These can lead to an increase in hot dry berg winds (Tadross *et al.* 2005). This is supported by the substantial increase in node 2 between the 2000-2008 period. The future climate for the CFR is likely to be warmer and drier than the present, according to predictions from empirical downscaling models (Hewitson and Crane 2006).

Currently, fire risk in the CFR is assessed with the aid of the US fire danger rating system (Van Wilgen *et al.* 2003b). The system uses weather data in a complex model to simulate trends in the moisture content of fuels and requires daily weather records. By contrast the fire risk indicators created in this chapter are a demonstration of the simplicity of using synoptic states to quantify fire risk. This basic technique was able to produce regional-scale fire risk indicators for the CFR based on the regional differences of fire promoting weather. One of the advantages of SOMs is that the user can specify the desired number of nodes, thus selecting the scale of the study. This entire analysis can be repeated using a larger number of synoptic states (e.g. 24 or 36 or 63) for a more detailed analysis of fire weather. this feature should be of particular interest to fire managers as there is the potential to identify fine-scale fire weather patterns for particular regions of interest. Another advantage of SOMs is that they are used for regional forecasting and climate change simulations (Hewitson and Crane 2006). Thus future frequency of fire weather can easily be simulated.

The original application of SOMs to synoptic climatology aimed specifically to assist in the improvement of regional climate models in simulating climate variability, regional climate change and extreme events (Hewitson and Crane 2002). From this list of application, fires can be classified as extreme events. Once a SOM has been created, using historical meteorological data, any subsequent day can be mapped to an existing node based on the similarity of synoptic conditions. In this chapter I have shown that SOM nodes can be used to identify fire weather and then be easily arranged into a fire risk indicator. This approach to fire weather has the practical advantage of being helpful to a user who has only a rudimental knowledge of weather analysis.

4.6 Figures



Node 10 Node 11 Node 12

Node 7 Node 8 Node 9

Node 4 Node 5 Node 6

Node 1 Node 2 Node 3

Figure 4.1: Sea level pressure conditions (red = high pressure, blue = low pressure) representing the twelve archetypical daily climatic states (nodes) that occur throughout a typical year in southern Africa, as determined by SOM analysis. Note that the numbering order does not imply any tendency for these nodes to occur in a temporal sequence, or an indication of the relative frequency of these nodes.

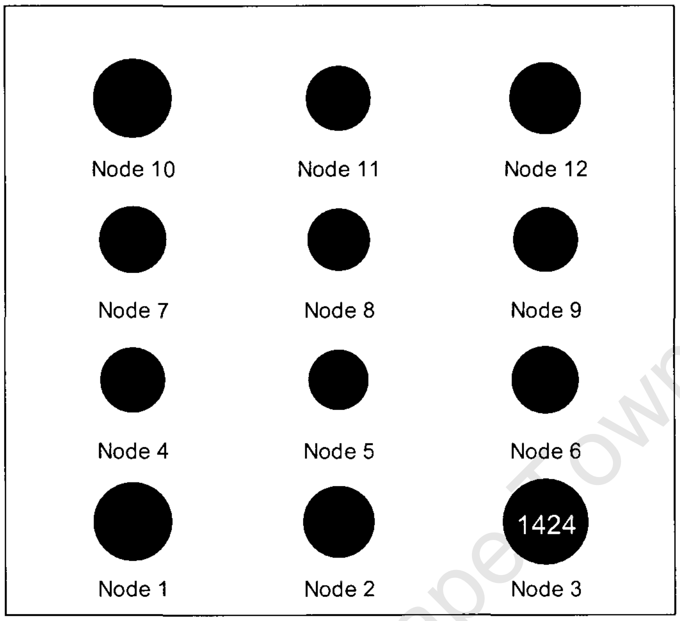


Figure 4.2: Visual mapping of the node frequency over the entire sample period (1970-2007) in the Cape Floristic Region. Results are scaled according to the largest value

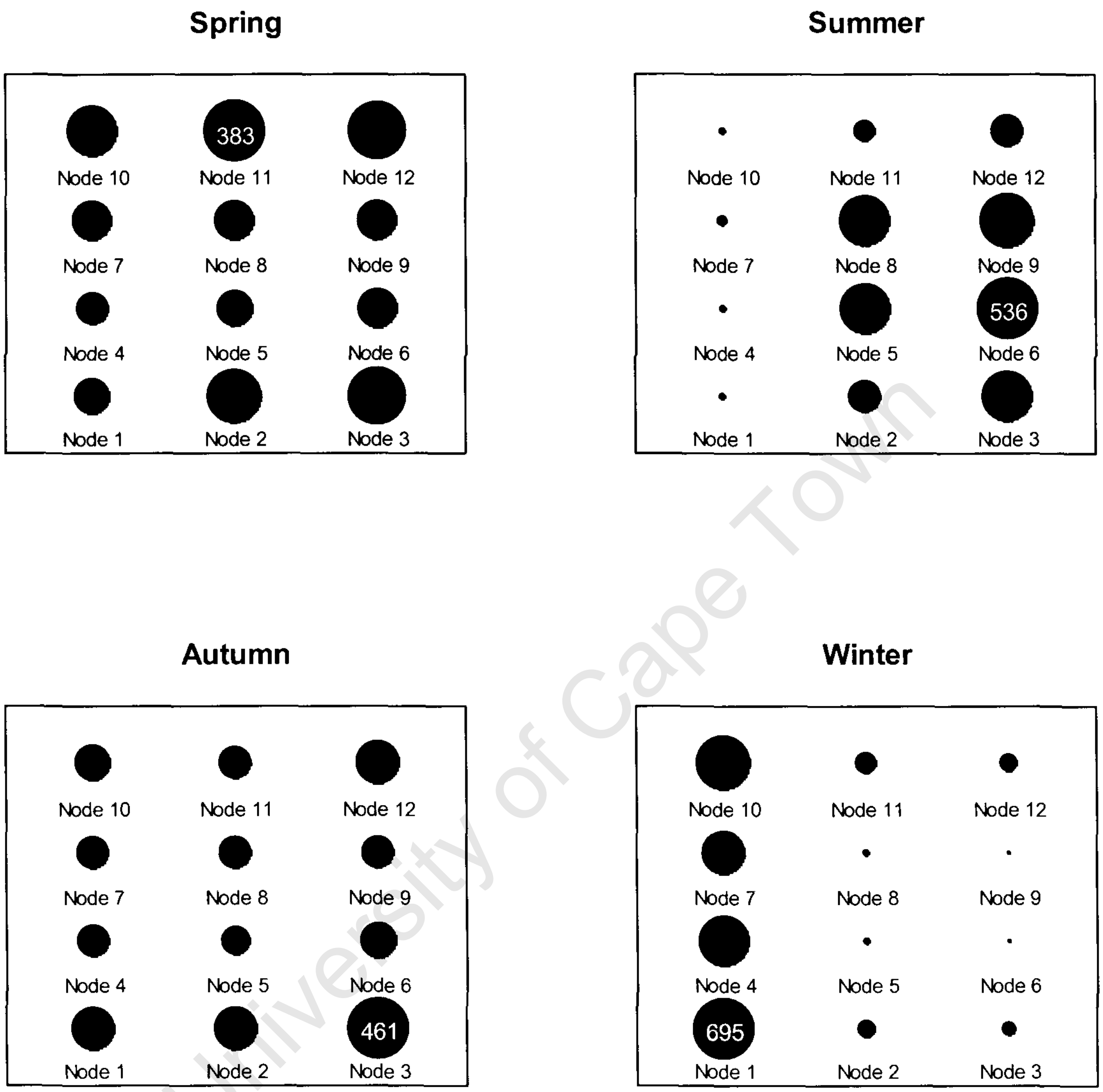


Figure 4.3: Visual mapping of the seasonal frequency nodes for the four study sites in the Cape Floristic Region. Results are scaled according to the largest value in each study site

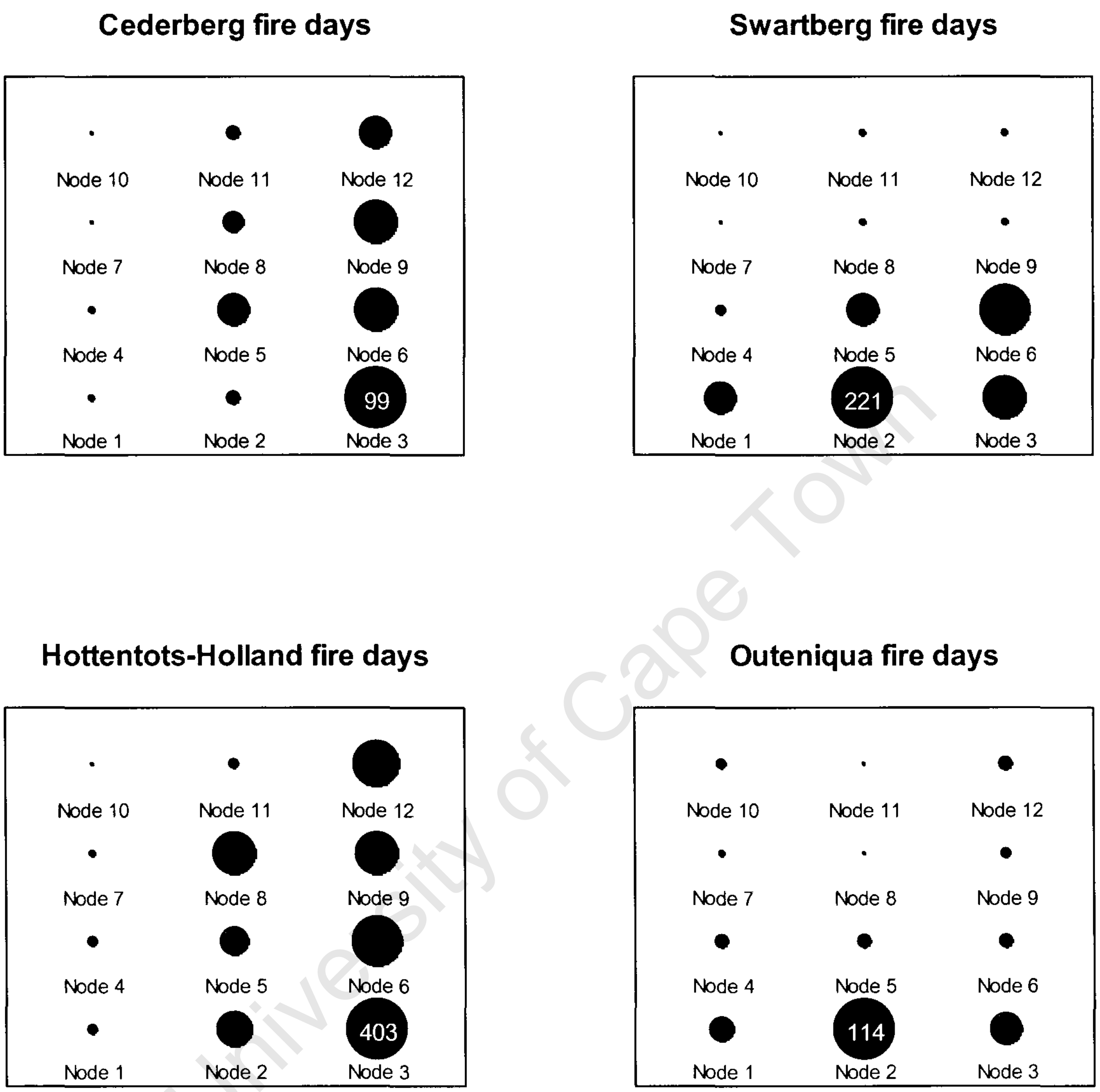


Figure 4.4: Visual mapping of the frequency of fire weather for the four study sites in the Cape Floristic Region. Results are scaled according to the largest value in each study site

Table 4.1: Chi squared tests the frequency of fire weather events against the frequency of all nodes for four study sites in the Cape Floristic region. *11 degrees of freedom

Region	Chi-squared value*	p-value
Cederberg	27.8641	0.003
Hottentots-Holland	188.5197	<0.001
Swartberg	125.6661	<0.001
Outeniqua	62.1642	<0.001

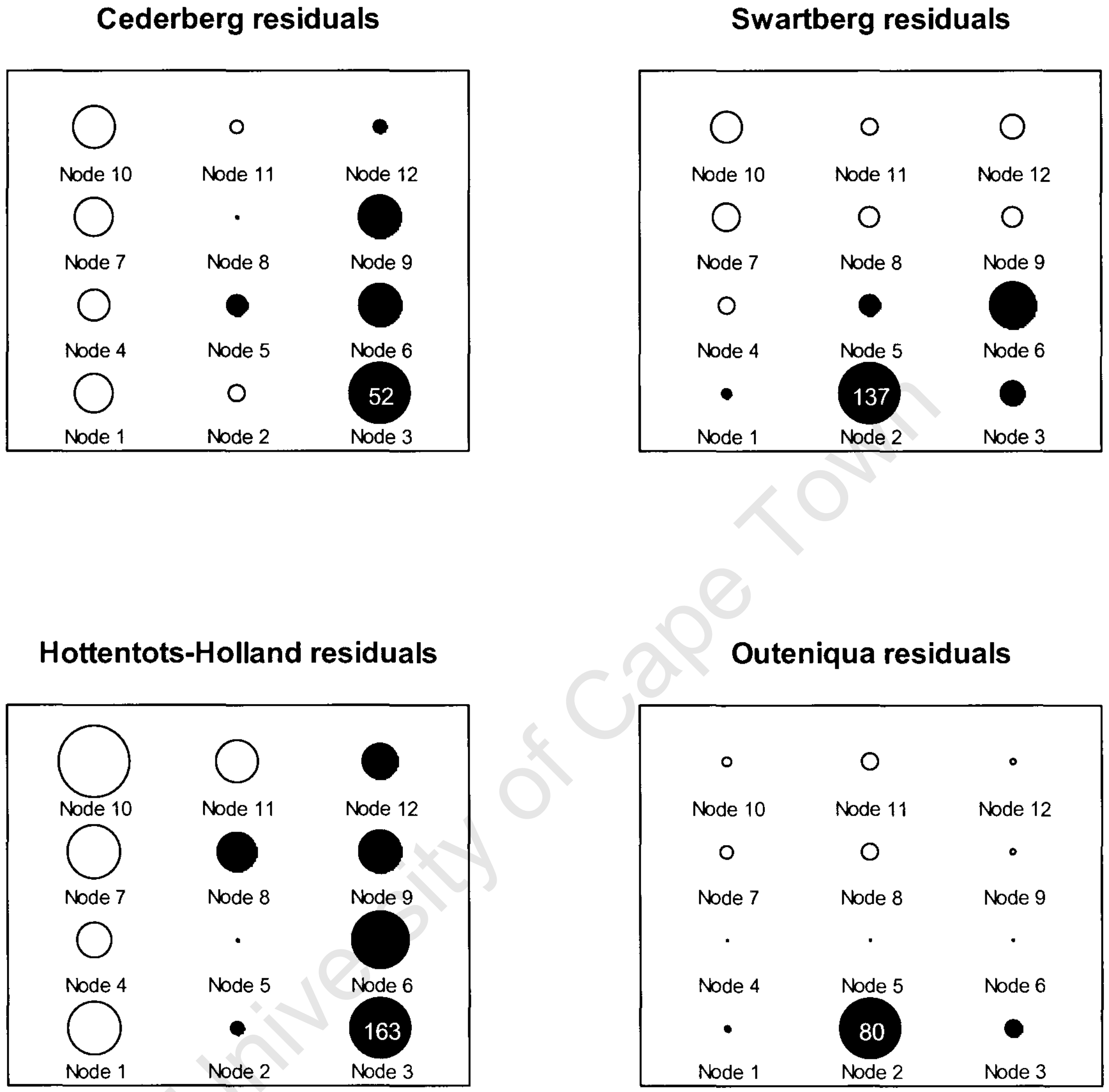


Figure 4.5: Visual mapping of the residuals of chi-squared test that discerned the occurrence of fire events verses node frequency for the four study sites in the Cape Floristic Region. Closed circles are positive residuals, representing a significantly higher frequency of occurrence than expected, open circles are negative residuals. Results are scaled according to the largest value in each study site

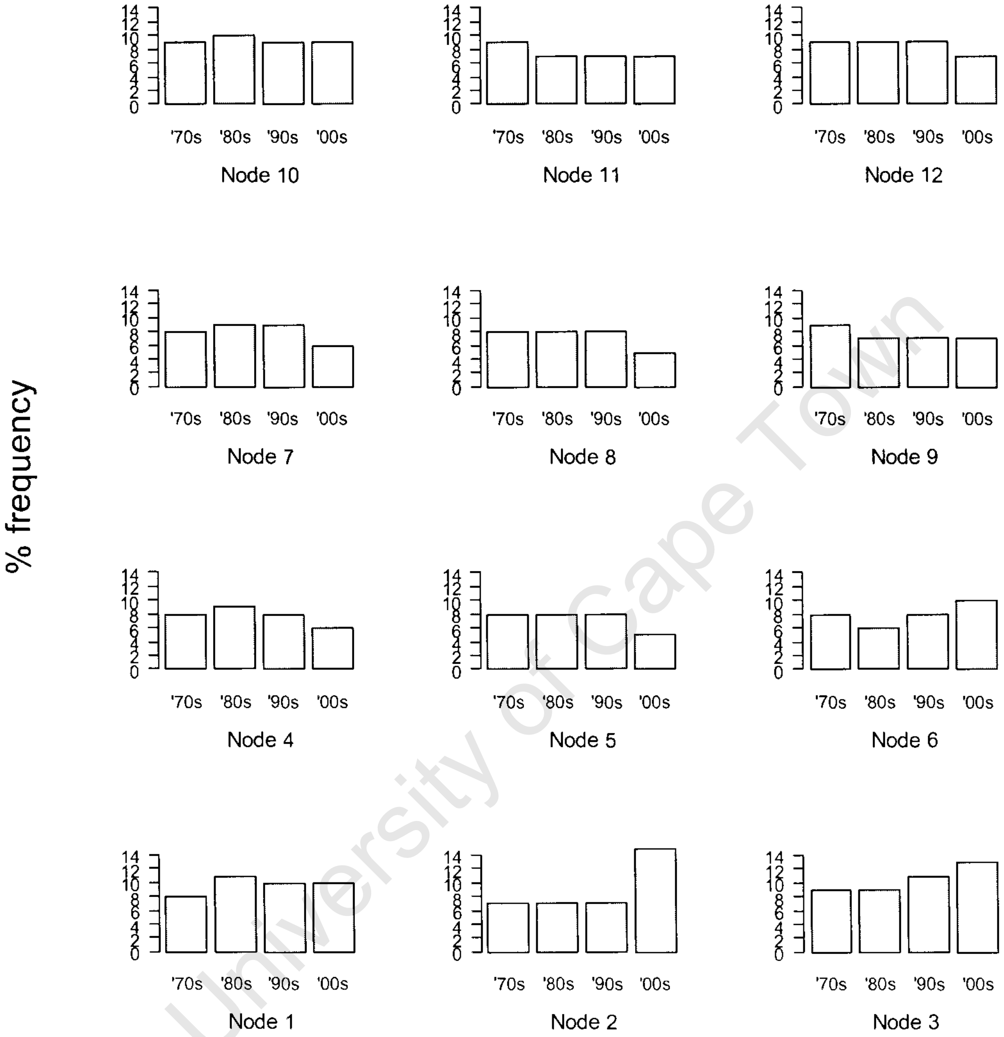


Figure 4.6: Temporal frequency of each node per decade for the entire weather data set (1970-2007) over the Cape Floristic Region

Table 4.2: Results from chi-squared tests for temporal changes in decadal node frequencies using all of the weather data from 1970-2007. *11 degrees of freedom

	Decade	Chi-squared value*	p-value
Expected	1970s		
Observed	1980s	92.8041	<0.001
	1990s	63.4399	<0.001
	20002008	524.0346	<0.001
Expected	1980s		
Observed	1990s	57.8029	<0.001
	20002008	598.4748	<0.001
Expected	1990s		
Observed	20002008	346.0151	<0.001

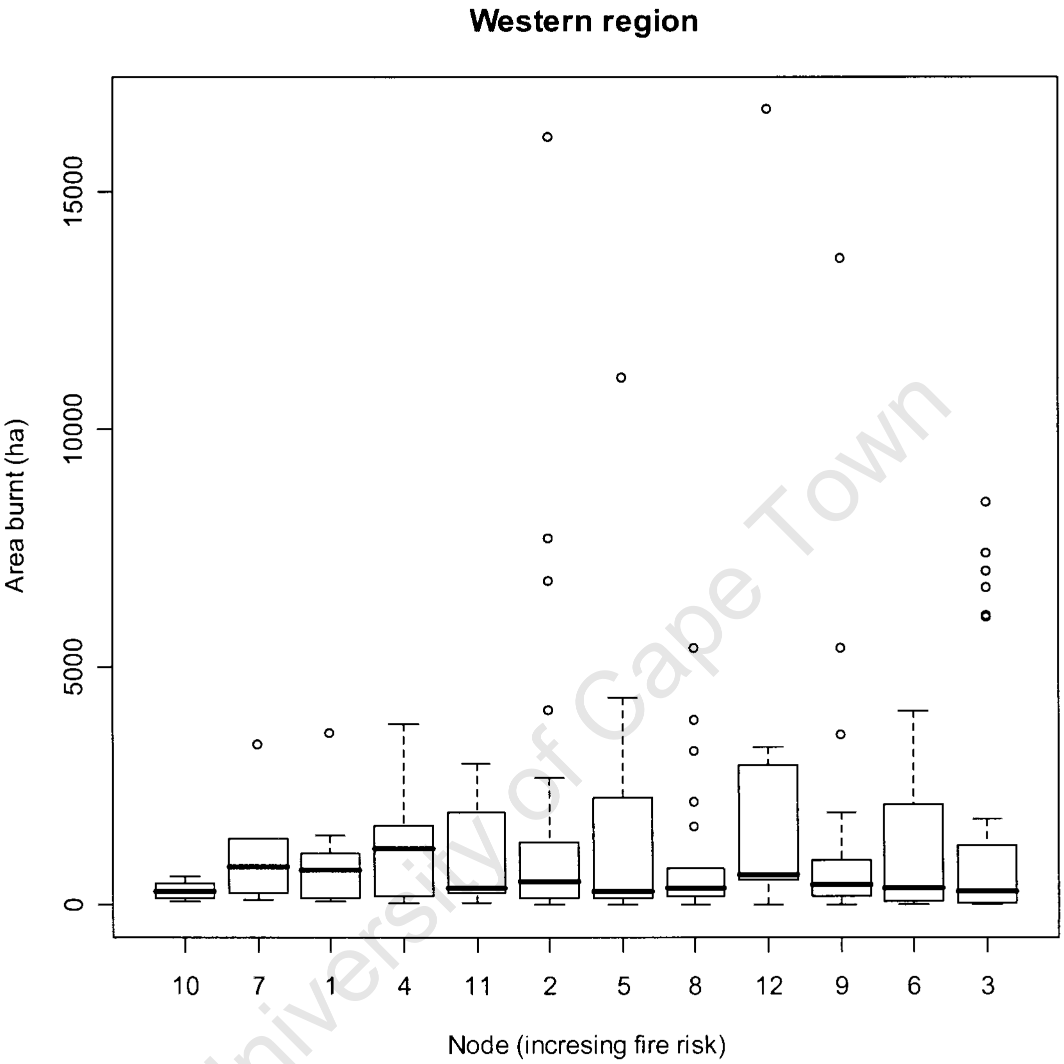


Figure 4.7: Analysis of independent fire data from the Grootwinterhoek and Vrolijheid reserves to test the effectiveness of the fire risk indicators for the Western Cape Floristic Region

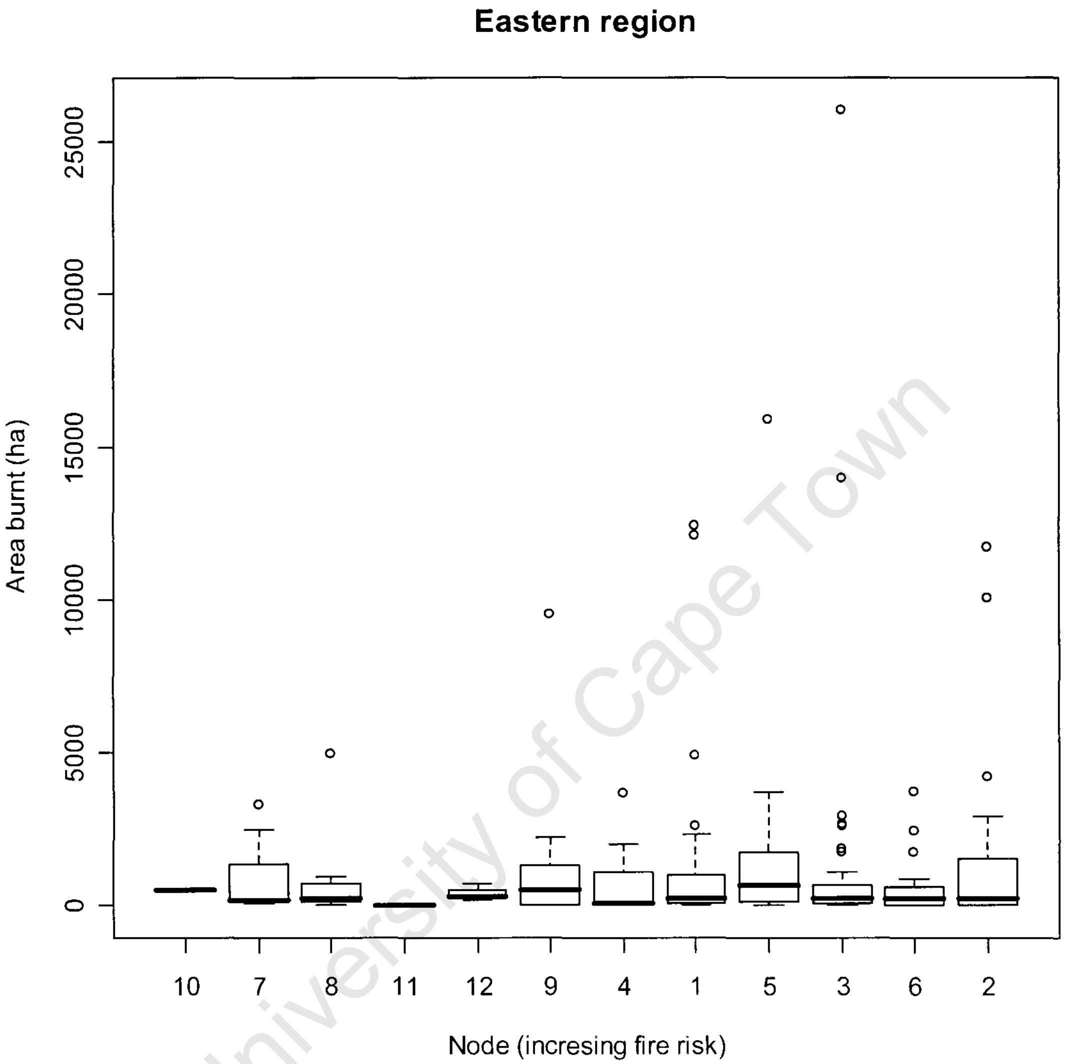


Figure 4.8: Analysis of independent fire data from the Kammanasie, Grootvadersbos and Gamkaberg reserves to test the effectiveness of the fire risk indicators for the Eastern Cape Floristic Region

Chapter 5. Conclusion

This study was conducted in order to assess the spatial and temporal patterns of wildfire in the Cape Floristic Region (CFR). One of the aims of the study was to identify the factors influencing fire frequency in this region. The spatial component of this study focussed on the impacts of vegetation age (years between fires) on regional fire frequencies and fire size and also analysed the relationship between synoptic-scale weather conditions and fire events. The temporal component of this study focussed on the changing age at which vegetation burned through time as well as the changing frequency of synoptic conditions associated with fire events. The results from these analyses have implications for fire management in the CFR.

Mutch's (1970) fuel limitation hypothesis that vegetation patterns determine fire behaviour was tested in the four study sites by analysing the impact of fuel age on fire size. My results showed that this hypothesis only holds for the driest study site (Swartberg) and that large fires in the other study sites are not correlated to fuel age. These results support Seydack's (2007) classification of two types of fire regimes in the fynbos. Type 1 fire regimes occur in areas of low productivity (drier regions) where fire spread is limited by fuel accumulation and hence vegetation age is a controlling factor on fuel behaviour. Type 2 fire regimes occur in productive fynbos regions where vegetation flammability is attained at a relatively young age (4-6 years). This type of fire regime is limited by suitable fire weather conditions and rates of ignition. The Cederberg, Hottentots-Holland and Outeniqua, have Type 2 fire regimes and the Swartberg has Type 1. These results put the fynbos ecosystem into context with regards to the fuel control debate in other Mediterranean-type ecosystems. Minnich and Chou (1997) proposed that fire suppression had led to large fires in southern California based on the fuel limitation hypothesis. However, Keeley *et al* (1999) and Moritz *et al* (2004) have since shown that fuel age did not correlate to fire size. The results in southern California and for three of the study sites in the CFR have implications for fire risk management on the urban-rural boundary where fuel reduction policies may be inefficient measures of protection against large fires.

An analysis of fire frequency showed that study sites in the western CFR had shorter fire frequencies than study sites the east. This conclusion is based on the evidence from the distribution of fire intervals in Chapter 2. These results are reinforced by the outcomes from other studies on fire frequency in the Cederberg (Brown *et al.* 1991) and the Swartberg (Seydack *et al.*

2007). However, this is the first time that a study has done a regional comparison of fire interval distributions in the Cape Floristic Region.

Fire intervals were characterised by their ignition sources to assess the impact of people in these natural environments. People influence the fire regime in two ways; they add additional ignition sources to the landscape that result in accidental fires, and they deliberately burn parts of the landscape for management purposes. Study sites closer to urban regions (Hottentots-Holland and Outeniqua) had a greater proportion of their total area burned by accidental fires than those in remote regions (Cederberg and Swartberg). A common concern in Mediterranean-type ecosystems is that anthropogenic ignition sources can impact on biodiversity by significantly decreasing fire return intervals (Vázquez *et al.* 2002). However the shorter fire intervals resulting from anthropogenic ignition sources did not alter the fire frequency significantly in the fynbos. The most compelling evidence for this is the Outeniqua study site. This study site has the lowest proportion of short (<10 years between fires) fire intervals and yet it has the highest proportion of accidental fires.

It has been shown that while fuel accumulation is an important factor in determining fire patterns, the regional difference in fire frequencies may be a result of other factors. Studies have shown that weather can have an impact on fire behaviour at many scales (Van Wilgen 1984b; Juhnke 1985; Van Wilgen and Richardson 1985; Swetnam 1993; Moritz 1997; Swetnam and Betancourt 1998; Morgan *et al.* 2001; Forsyth and Van Wilgen 2008) and thus a synoptic-scale analysis of fire weather was undertaken. Using self-organising maps of atmospheric circulation, 12 representative synoptic states were defined for the weather patterns of the CFR. Synoptic states that promote fires were identified and a regional difference was noted. Synoptic states characteristic of hot and dry winds (berg winds) were associated with fires in the eastern study sites while synoptic states characteristic of convective weather and lightning were associated with fires in the western study sites. This difference in synoptic scale forcing of fires influences two aspects of fire regimes: season and severity.

The seasonal difference between fire events in the western and eastern study sites is similar to the seasonal frequencies of the synoptic states associated with fires in each region. Fires in the western study sites burned predominantly in summer. Hot and dry conditions associated with the south Atlantic high pressure system dominate summer weather patterns and the convective weather conditions associated with lightning and fire events are becoming more common. This suggests that the western CFR is ignition limited where fuels dry out in summer and will burn when ignition sources (i.e. lightning) are available. The dynamics in the eastern study sites were slightly different as fires burned in all seasons. Fires are most common under berg wind conditions which suggest that these hot dry winds are needed to lower fuel moisture levels enough so that ignition sources can result in a fire. This suggests that, provided there is sufficient fuel accumulation, the eastern CFR is limited by weather events that promote fires. The synoptic states from which the above conclusions were drawn were used to create regional fire risk indicators. Tests against independent fire data showed that synoptic states can be used to predict large fire events. They can be developed into a simple tool that will aid fire risk assessment at regional to local scales.

The temporal component of this thesis analysed changes in fire frequency and fire weather over the period of record (1970-2007). The frequency of fires has increased through time in three of the four study sites (Cederberg, Hottentots-Holland and Outeniqua). The novel technique described in Chapter 3 used fixed spatial reference frames to extract fire intervals forward through time. Median fire intervals significantly decreased through time in these three study sites and thus I can conclude that fires have become more frequent in these regions of the CFR. Evidence that this trend may be a result of changing weather patterns was presented in Chapter 4. The frequency of synoptic states has changed in the past four decades and the synoptic states associated with berg winds and convective conditions have increased. The rate of change of fire frequency was the same in the two western study sites (Cederberg and Hottentots-Holland) and this further supports the idea that it is the regional impacts of changing atmospheric circulation that has driven change in fire frequency. This is the first study in the CFR to link changing fire patterns with a change in climate.

The conclusions of this thesis have significant implications for fire management in the Cape Floristic Region. Fuel accumulation is not the predominant controlling factor on fire patterns in the fynbos (apart from perhaps in the drier regions) and therefore fuel manipulation methods are ineffective management tools in these areas. A major review of the underlying hypotheses behind fire management policies is needed. It would be advisable to focus fire management to the urban-rural edges and to let the natural vegetation burn on its own accord. Results have shown that management fires have burned proportionately little (3-15%) of the total area burned by fires in the study sites. Thus fire management under climate change is unlikely to influence fire frequency.

In conclusion it can be stated that this study achieved its aim of describing spatial and temporal patterns of wildfires in the Cape Floristic Region. The factors influencing fire frequency in the western CFR are predominantly sources of ignition, while the availability of fuels and suitable weather conditions restrict fires in the eastern CFR. Fire frequency has increased in the study sites where weather exerts the dominant control and this is due to the increase in synoptic states that promote wildfires. Fire managers should concentrate their efforts on the urban-rural edges where fire risk to people and property is a priority. There is little that fire managers can do to affect natural fire patterns in the mountainous regions of the Cape Floristic Region.

Future Research

This study highlights the need for further research to address the following questions:

- What impact has invasive alien vegetation had on fuel loads through time?
- How do preceding synoptic states affect fire events?
- What are the future climate change simulation impacts for fire weather in the Cape Floristic Region?
- What are the outcomes of applying SOMs to other fire-prone ecosystems?

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